DIGITAL COMMUNICATION NETWORKS INCORPORATING MOBILE DATA TERMINALS

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SUMMARY

The use of digital communication systems is increasing very rapidly. This is due to lower system implementation cost compared to analogue transmission and at the same time, the ease with which several types of data sources (data, digitised speech and video, etc.) can be mixed. The emergence of packet broadcast techniques as an efficient type of multiplexing, especially with the use of contention random multiple access protocols, has led to a wide-spread application of these distributed access protocols in local area networks (LANs) and a further extension of them to radio and mobile radio communication applications.

In this research, a proposal for a modified version of the distributed access contention protocol which uses the packet broadcast switching technique has been achieved. The carrier sense multiple access with collision avoidance (CSMA/CA) is found to be the most appropriate protocol which has the ability to satisfy equally the operational requirements for local area networks as well as for radio and mobile radio applications. The suggested version of the protocol is designed in a way in which all desirable features of its predecessors is maintained. However, all the shortcomings are eliminated and additional features have been added to strengthen its ability to work with radio and mobile radio channels. Operational performance evaluation of the protocol has been carried out for the two types of non-persistent and slotted non-persistent, through mathematical and simulation modelling of the protocol. The results obtained from the two modelling procedures validate the accuracy of both methods, which compares favourably with its precedent protocol CSMA/CD (with collision detection).

A further extension of the protocol operation has been suggested to operate with multichannel systems. Two multichannel systems based on the CSMA/CA protocol for medium access are therefore proposed. These are; the dynamic multichannel system, which is based on two types of channel selection, the random choice (RC) and the idle choice (IC), and the sequential multichannel system. The latter has been proposed in order to supress the effect of the hidden terminal, which always represents a major problem with the usage of the contention random multiple access protocols with radio and mobile radio channels. Verification of their operation performance evaluation have been carried out using mathematical modelling for the dynamic system. However, simulation modelling has been chosen for the sequential system. Both systems are found to improve system operation and fault tolerance when compared to single channel operation.

Key words

Local area data communication networks, Computer communications, Mobile radio communications, Modelling and simulation, Random multiple-access protocols.

To

MY FATHER

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LIST OF SYMBOLS

τ : End-to-end medium propagation delay time.

T : Packet time length in terms of τ.
S : Throughput of the system.
U : Average successful transmission period.
B : Average busy period.
I : Average idle period.

a : Normalised end-to-end medium propagation delay time ($a=\tau/T$).
G : Total offered load.
P_s : Probability of successful transmission of a packet.
P_f : Probability of failure.
C : Average contention period.
Y : Average value of random variable (vulenrability collision period).

γ : Normalised jamming signal period.
m : Mean arrival time (Poisson distributed).
P : Number of newly generated packets.
R : Number of retransmitted packets.
K : Total number of successful transmitted packets.
SM : Total scheduled simulation time period.
D : Average packet time delay.
TNOW(j) : Time at which a pcaket finishes successful transmission.
$\mathrm{ATRIB}(1)_j$: Packet initial arrival time.
B : Total bandwidth allocated for the system.
N : Number of sub-channels to which (B) is divided.
B_i : Sub-channel (i-th channel) bandwidth.
T_i : i-th channel packet time.
a_i : i-th channel normalised end-to-end propagation delay time.
RC : Random choice of channel selection.
IC : Idle choice of channel selection.
G_i : i-th channel offered load.
P_i : Probability of selection of the i-th channel for transmission.
t_{pre} : Preamble time duration within the packet time.
DDL : Data content in a packet.
t_{ack} : Acknowledgment time period.
f_i : i-th channel carrier frequency.
A : First listening period.
B : First carrier burst.
C : Second listening period.

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CHAPTER ONE

OBJECTIVES

1-1. INTRODUCTION

Data transmission over communications networks is becoming an important feature of every-day life. This reflects the advances in modern technology associated with the development of the computer epoch. Computer applications and usage have shown a dramatic increase in recent times to touch every-body in some way or another. Computers are used for various control purposes and for the solution of problems ranging from the trivial to the very complicated. This has created a diverse distribution of workstations and multipurpose computers in most moderate sized establishments and companies. Advances in this field led users to realise that a local communications system was required to interconnect the diverse data-processing equipment to enable better sharing of resources. This led in turn to the development of what has become known as local area networks (LANs). Local area networks employ a shared medium and a unique protocol is used to access this medium. This work involves the development of LANs which make use of packet switching broadcasting techniques. This is shown to be an attractive proposition for use in terrestrial and radio communications networks. This is so because packet switching enables various communication resources to be shared efficiently by many contending users with unpredictable demands. Some of the complex network problems are eliminated by the use of broadcasting techniques. The packet switching broadcasting technique has been shown to be an important technique for use with both local area data transmission networks and data transmission over radio and mobile radio communication networks.

Local area networks have been widely used as a means of efficient local communication in competition with other local communication networks like private automatic branch exchange (PABX) or computerised branch exchange (CBX) networks. Much work has been devoted towards its operational performance optimisation. This has resulted in a variety of LAN topologies, e.g. star, bus and ring, and several protocols for medium access control. Standardisation of each of these protocols has been a major problem, with various technical committees and standards institutions offering differing solutions. This difficulty has now been largely overcome using standards based on the seven layer model for open systems interconnection (OSI) proposed by the International Standard Organisation (ISO).

The use of radio and mobile radio communications networks is also on the increase, especially for use for voice transmission for cellular mobile radio telephony. The recent rapid increase in user numbers and the need to accommodate several kinds of services, together with a lack of available frequency spectrum, represents a major problem to which a solution has to be found. A possible solution is the application of the packet broadcasting technique based on the same principle as that proposed for use with LANs. Mobile packet radio is becoming more feasible as voice packetisation becomes a more realistic proposition. Replacing the existing low efficiency network that operates on a circuit switched principle with a packet-switched network is a crucial factor for the next generation of integrated services mobile data networks.

1-2. MAIN ISSUE BEHIND THE RESEARCH

Local area digital communication network applications have recently been receiving considerable attention. The enthusiasm among researchers to solve the local networking problems based on the emerging LAN technology has led to two further areas of investigation:

a) The rapid spread of LAN applications has created the need for their interconnection.

b) A necessity for using mobile computer terminals, especially in the urban area where police, fire brigade, gas service and many other civil services need such a facility to interact with their main base headquarters.

These two developments have resulted in the creation of what has become known as metropolitan area networks (MANs). MANs are networks which span wider geographical areas and use shared access across a multiple-access communication medium for a medium-to-large data terminal population. Such networks can also be designed to serve or interconnect local distribution communication systems. Many such local distribution systems, including local area networks or packet radio networks, provide for the sharing of a multiple-access medium allocated to a region or cell by terminals resident within this underlying area. In fact, interconnecting several LANs and accommodating mobile terminals within the LAN will provide;

1) The ability to attach more users than a single LAN can normally handle.
2) The enhancement of the total system availability by running multiple-independent subnetworks.
3) The coverage of larger geographical distances than that of single LANs.
4) The provision of an integration of services with other local systems like the PABX and the packet mobile radio communication networks.

These desirable features of connecting several LANs together, accommodating mobile terminals within the LANs and extending further the LAN protocols for mobile radio communication networks in order to use the available spectrum more efficiently have led to trials for the extension of LAN protocols for applications in radio and mobile radio digital communication networks. Trials have been made using the best-known LAN protocol, that is the carrier sense multiple-access with collision detection (CSMA/CD). Unfortunately, difficulties are encountered for the staightforward application of the protocol because of the nature of the radio channel (i.e. a time-varying channel), which is completely different than from that of the cable connection. Undetectable collisions occur when there are significant differences between the received levels of two signals at the station receivers. The main purpose of this research is to look for a protocol which can be used with the radio channel to overcome the main malfunctions of the earlier protocol. Thus, carrier sense multiple access with collision avoidance (CSMA/CA) has been proposed for use as alternative protocol for use with mobile radio channels.

The aim of the research is therefore divided into three main issues. These are;

1) The establishment of a protocol (i.e. CSMA/CA) which can be used equally in local area networks as well as those incorporating mobile terminals.

2) To extend further the idea for broadband multichannel networks so as to operate with low data rate transmission. This is found to be preferable for radio and mobile radio transmission as it leads to a reduction in error occurrence and hence to a lower cost of implementation of the system circuitry required.

3) To justify the above two ideas through the evaluation of their operational performance by modelling the two protocols using any of the known modelling methods.

1-3. METHODS FOR OBTAINING THE OBJECTIVES

There are three general approaches towards communication networks modelling. These are; measurement, analysis techniques and simulation techniques. Before selecting the method to be adopted to achieve the research requirements, a short summary of each technique is given:

1) Measurement provides the most direct means of network performance evaluation but it is also the most expensive because the network, or a prototype model, must first exist before the measurements can be taken. Also, if experimentation is required, it may not be economically feasible to suspend the operation of an ongoing network in order to perform these experiments. Experimentation may also take far too long to produce results in time for them to be of use. Finally, it may be dangerous to experiment on the real network.

2) Mathematical analysis is an alternative approach towards network performance evaluation. Since analytic models require a high degree of abstraction, considerable effort and skill may be required on the part of the network modeller to develop a performance

model which accurately reflects the system under study. The analytical model itself, however, can generally be solved rather quickly and cost effectively. However, a tractable analytic model often restricts the range of system characteristics that can be explicitly considered in a performance model.

3) In the simulation technique, the network can be modelled to an arbitrary level of detail. Simulation thus typically serves to examine selected portions of the design space in more detail. Since the system may be modelled to any arbitrary degree of detail, less abstraction is required and the process of model formulation is a more straightforward task. The solution of a simulation model requires significantly more computer time than an analytical model. In some cases, however, simulation is the only viable modelling approach. The simulation technique typically used to solve a model of a communication network or protocol is stochastic discrete-event simulation, in which various components of the actual network under study (e.g. the communication link, buffers, access strategies, network control structure) are represented within a computer program. The events that would occur during the actual operation of the network (e.g. the arrival, transmission, routing and departure of messages) are then mimicked during the execution of the program. The function of the simulation program is thus simply to generate events and then simulate the network response. The simulation program typically also performs other ancillary tasks such as recording and later analysing performance data as well and giving the results in statistical form.

These three approaches towards network performance evaluation are complementary in nature and each approach has its place in the design life-cycle of communication networks.

Before we take any step towards the choice of method to be used, we have to look at what Departmental and University resources are available. It is impossible to implement the real system to carry out measurements and impracticable to implement a prototype model of such a sophisticated and expensive system. Thus the measurement approach is not a viable proposition and the only two available methods are the mathematical and simulation modelling of the system. In fact both approaches have been used to investigate the operation performance evaluation of the CSMA/CA protocol, whereas only simulation is used to model the sequential broadband multichannel system. This is because of the complexity of the protocol, which was found difficult to express analytically.

1-4. AN OUTLINE OF THE THESIS CONTENTS

The research has been carried out progressively, commencing with a thorough literature search. The results of the search are given in chapter two, which highlights the state-of-the-art on standardisation by the International Standards Organisation (ISO) for the open system interconnection (OSI) and the types of local networks developed using this concept. Emphasis has been focused on local area networks (LANs), with their topologies and protocols, preceeded by a brief look at line encoding and types of multiplexing used with these networks. The second part of the chapter deals with a general survey of mobile communication networks, characterisation of the mobile channel and data transmission over such a channel. Finally, the chapter finishes with some concluding remarks which link the LANs protocols and their application to radio and mobile radio communication networks.

Chapter three is mainly devoted for the description of the CSMA/CA protocol operation, in which two distinctive non-persistent (slotted and non-slotted) protocols have been considered. A mathematical model is developed for each of the two protocols and compared with the well-known CSMA/CD protocol.

While mathematical modelling represents one method of system representation, chapter four deals with an alternative method of modelling the same systems using simulation. A brief outline of simulation techniques is given, and reasons why SLAM II language has been selected for the purpose of system simulation are given. The whole procedure is described in more detail. The chapter ends with a comparison of the two methods of modelling.

As a result of increasing LANs operation, some work have been carried out to improve their operation performance. The use of multichannel is one proposed technique. Chapter five, therefore, gives an overview of what has been done in this regard, and as a consequence two different protocols are proposed for use with broadband (multichannel) systems. The principle of operation is based on the same CSMA/CA protocol dealt with in chapters three and four. The first multichannel system uses the random and idle choice (RC and IC) methods of channel selection. Their utilisation performance has been assessed using analytical modelling. A second multichannel system, called the sequential protocol, is also proposed. This seems to be more suitable for radio and mobile radio communication applications. Its operation and medium accessing protocol are also discussed and, as usual, the chapter ends up with a comparison between both systems.

Due to the complexity of the sequential multichannel system, it was found difficult to analyse mathematically. The only feasible way therefore, was to simulate the system. Thus, chapter six gives an in-depth description of how simulation was achieved. The SLAM II package was used for the simulation in a similar way to that adopted in chapter four, taking into consideration the differences between the two protocols. Both non-persistent protocols have been simulated and the results collected. The influence of different factors on the system have been considered throughout the simulation procedure and a discussion of their effect has also been included in the chapter.

Finally, conclusions about the whole research is given in chapter seven. The pros and cons regarding the CSMA/CA protocol operation with single channel and multichannel are discussed. Suggestions for further work in this area towards system integration are also included in this chapter.

1-5. SUMMARY

This chapter has introduced the theme of the research carried out in the area of digital communication networks and, specifically, local area networks that involve radio and mobile radio terminals as a result of the increasing demand for this service. The latter part was devoted to an explanation of the alternative ways in which the research could have been carried out and how the selection was made taking into account the availablity of University resources. The chapter ends with a survey of the contents of the remainder of the thesis.

CHAPTER TWO

REVIEW OF PREVIOUS WORK

2-1. INTRODUCTION

Digital transmission is now preferred for use with telecommunications networks and is gradually displacing the more traditional techniques used since the first introduction of telephony. This does not mean that analogue communication is going to totally disappear but more and more of the networks are becoming digital as time goes on. This is because digital communication offers the following benefits:

1) Over the last quarter of this century, digital technology has continuously decreased in cost compared to the analogue technology. This is mainly the result of the advances that have been made in the production of VLSI technology.

2) Data integrity using regenerative repeaters rather than amplifiers. The effects of noise are not cumulative, leading to the possibility of transmission over longer distances.

3) Efficient capacity utilisation can be achieved by the extensive use of multiplexing. Digital technology makes it comparatively easy to implement cheap multiplexing systems.

4) Security and privacy techniques can be used to ensure secure communication between the parties. Encryption and cipher procedures can be readily implemented using digital technology.

5) Integration of different types of data (speech, video, telex, facsimile and other type of data) can be achieved in more efficient and cost effective ways in digital form. This leads to possibilities for an integrated service digital network (ISDN).

The last two decades have seen much effort put into implementing digital communication networks. These networks are of particular value to the manufacturing industries. These include the local networks, metropolitan area networks, wide area networks, long haul networks, radio, mobile radio and satellite networks.

2-2. LOCAL NETWORKS AND ISO-OSI ARCHITECTURE

The concept of a network arises quite naturally when several users each need to be able to be interconnected with each other. Thus a 'network' consists essentially of network switches, or nodes, interconnected by transmission links. These links can be wire, cable, radio, satellite, or optical fibres[120]. The network should accommodate many users, the limit being set by the maximum traffic that the switch can handle. It should provide either dedicated services (i.e. voice-only telephone networks), or several services (i.e. data in general, video, facsimile, etc. or mix of any of these). The network should allow many users with different services to be connected in an efficient and cost effective way. It should also provide additional services and features to allow future expansion and interconnection with other local, national and international networks.

The decrease in computer hardware cost and the accompanying increase in computer hardware capability has led to the wide use of single-function and intelligent workstations. This spread of distributed processing has created a need to interconnect workstations to form a local network. This permits data exchange between the workstations, provides backup in realtime applications and allows users to share expensive common devices. A 'local network' is therefore defined as a communication network that provides interconnection of a variety of data communicating devices within a geographically restricted area[134,135]. This definition can be expanded further, with three important elements being taken into consideration;

1) A local network provides interconnection of a variety of data communicating devices. These may include computers, word processors, line printers, storage and graphical devices, telephone systems, video, and data in general.

2) It is a communication network and not a computer network, since it is mainly dealing with the method or protocol by which the above devices can communicate, and

3) The coverage area of a local network should be well-defined in order to

differentiate it from other networks.

Another definition of a local network relates to the number of 'bits on the fly' through the network. A local network is a network where the end-to-end signal propagation delay is large compared with a single bit transmission duration and small compared with the typical massage transmission duration[12]. A list of the most common properties of local networks is given to avoid some confusion and contradictions between definitions used by some other authors [49,114,134,135,144][1];

1) The transmission data rate is high (0.1-100Mbps).

2) The distance covered by the networks is in the range 0.1-50km.

3) The error probability is very low (10^{-8}-10^{-12}).

Local networks can be divided into three categories: local area networks (LANs), high speed local networks (HSLNs) and computerised branch exchanges (CBXs) or private automatic branch exchanges (PABXs). Fig.2-1 compares other networks with LANs, HSLNs and CBXs. Although there is a clear distinction between multiprocessor (computer) networks, general purpose interface bus (GPIB) networks, RS-232 networks[2] and long-haul (global) networks on one hand and local networks on the other hand. The distinction is less clear with respect to metropolitan area networks (MANs) and wide area networks (WANs). The types of services and the range of operation of LANs, MANs and WANs as applied to the U.K. are given in Wilson and Squibb [157].

A communication standard is required to govern the procedure used for data transfer within the above networks. A communication standard defines the way in which information will be exchanged between the various electronic devices attached or connected to the networks such as computers, terminals, wordprocessors, telephones,etc.

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1) The figures given above are average values taken from various references.
2)GPIB and RS-232 are examples of early highly specialised local interconnections, but are not generally considered true networks[45].

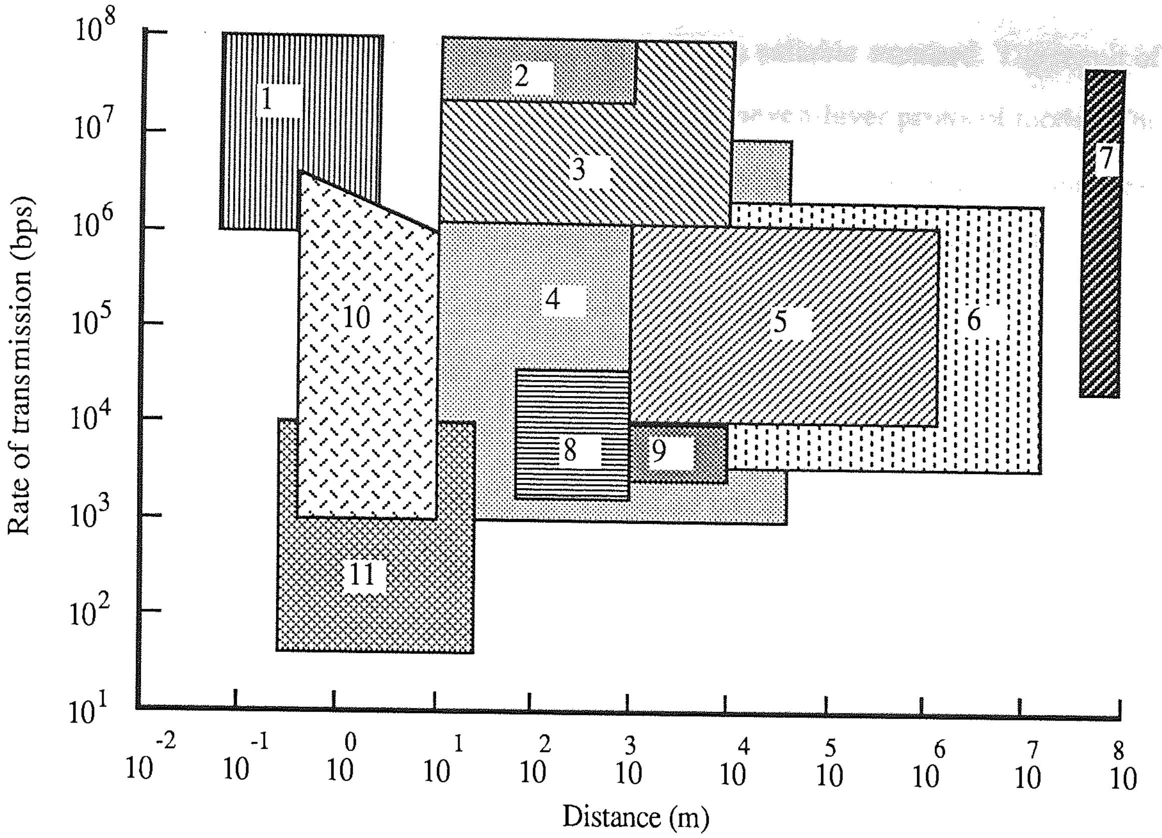

Fig.2-1. Comparison of transmission rate-distance relationship of different existing communication networks.

1- Computer mainframes (multiprocess systems)
2- High speed local networks (HSLNs)
3- Local area networks (LANs)
4- Metropolitan area networks (MANs)
5- Wide area networks (WANs)
6- Long-haul networks (global networks)
7- Satellite networks
8- Computerised branch exchange (CBX) or private automatic branch exchange (PABX)
9- Packet radio networks
10- General-purpose interface bus (GPIB)
11- RS-232 Interface networks

The standard will consist of definitions of the data to be exchanged, any additional control information that is required and how this is to be applied. In general, all devices connected to the network will be required to transfer data to other such devices. In addition, the network as a whole may be required to pass data to other network systems. It is desirable that this interchange be governed by a high degree of standardisation in order to ensure that it may be readily accomplished, especially when two or more manufacturer's products are involved. Thus, in the early 1960's work was initiated by the

International Standards Organisation (ISO) to produce a suitable standard. The result of this activity is the open systems interconnection (OSI) seven-layer protocol model. The ISO membership comprises the national standard bodies of over eighty countries, including the British Standards Institution (BSI) and American National Standards Institution (ANSI). In practice, the work on OSI has also involved significant participation by other major standard bodies, notably CCITT and Europian computer machinery association (ECMA). There is still considerable co-operation between all such bodies to ensure that any further standards developed proceed in line with the basic OSI protocol [23,113,140]. It should be stressed here that the OSI model is not concerned with specific applications of computer communication networks, but rather with structuring of the communication software that is needed to provide reliable data-transparent communication services which are independent of any specific manufacturer's equipment or conventions and to support a wide range of different applications. The seven layer ISO-OSI model comprises the following layers[23,46,49,113,120,134,140,144,165]; Physical, data link, network, transport, session, presentation and application. The ordering of layer-modelling can be seen in fig.2-2, where the connection between two hosts is only maintained through the physical layer. The OSI model defines the rules which govern how two systems may communicate, thus each layer maintains a principal function on the basis of the following (for further detail see ref. 113 and 135);

1) Each layer should perform a well-defined function.

2) A separate layer should be created where a different level of abstraction is needed.

3) The function of each layer should be chosen with an eye towards defining internationally standardised protocols.

4) The layer boundaries should be chosen to minimise the information flow across the interfaces.

5) Finally, the number of layers should be large enough to ensure distinct functions need not be thrown together in the same layer out of necessity but small enough that the architecture does not become unwieldy.

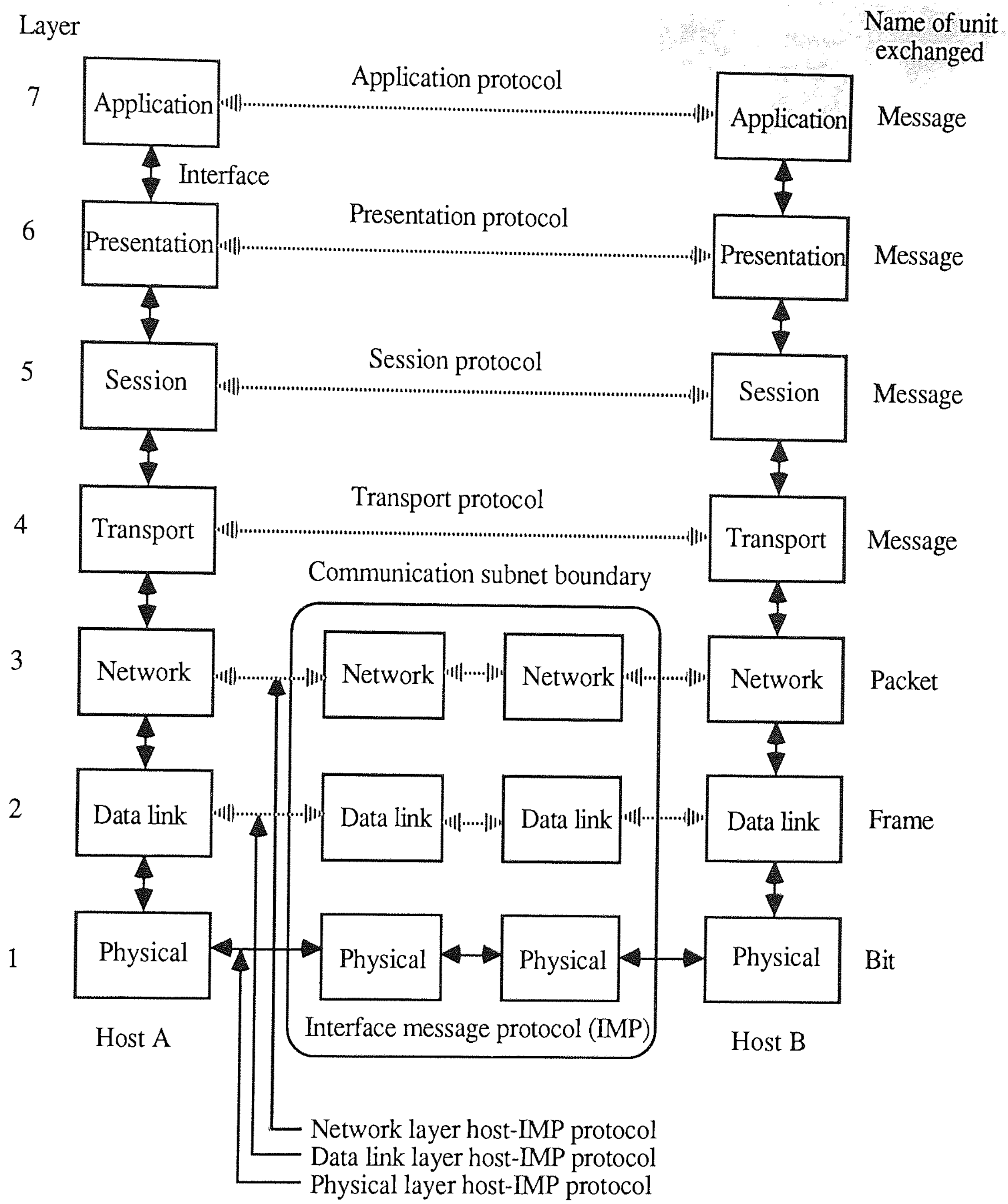

Fig.2-2. ISO-OSI seven layers model layout.

Different arrangements based on the above model have been used to connect users to the communication medium in order to form a network. The arrangement is known as the network topology. Fig.2-3 shows the basic topologies that are used with local networks. These are; mesh, star, bus (with its general tree topology) and ring. Several other topologies can be formed by the combination of any two or more of the basic

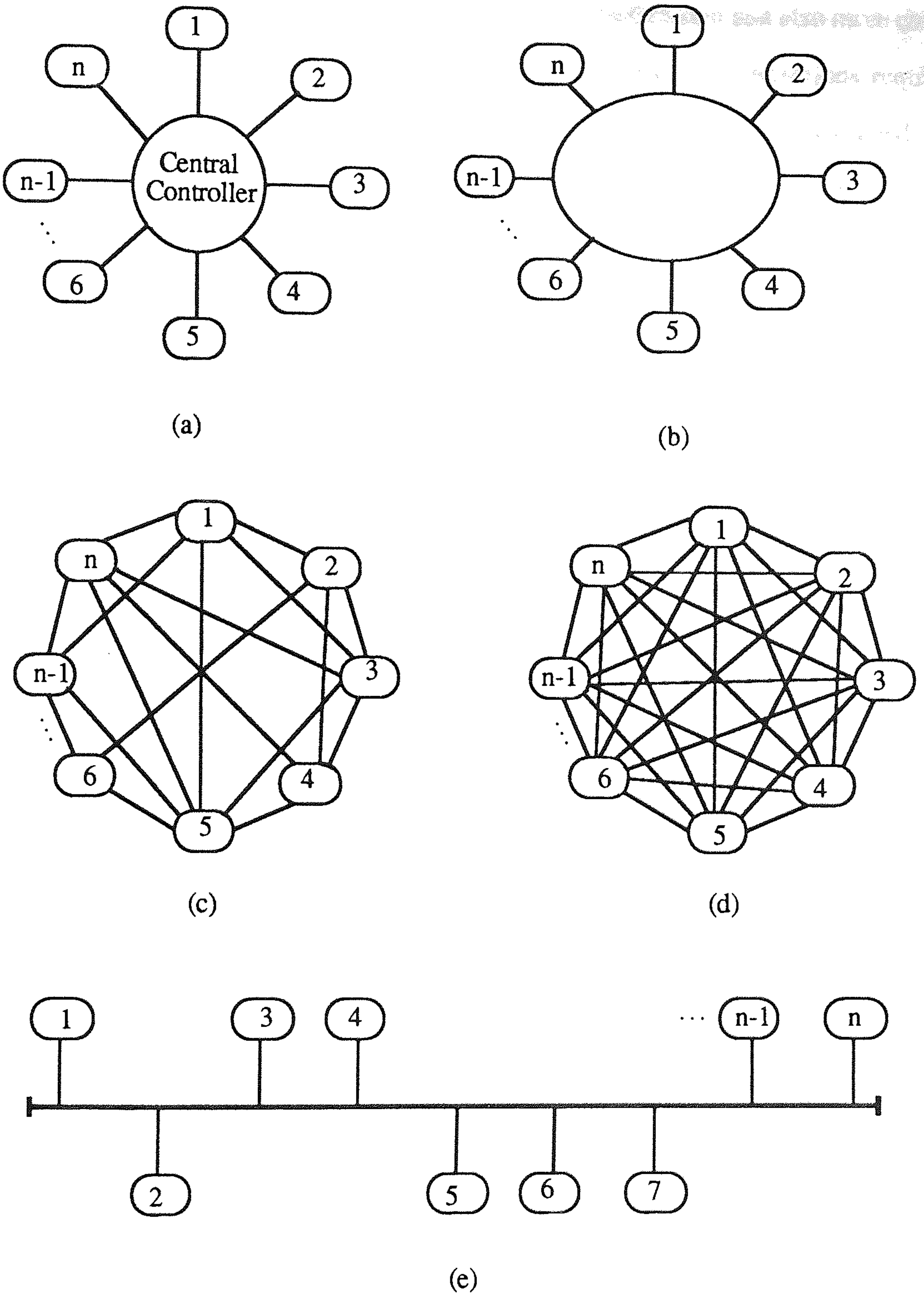

Fig.2-3. Topologies of local networks connection.

a) Star
b) Ring
c and d) Mesh (partially connected and fully connected)
e) Bus

configurations [5,146]. The use of the star, bus and ring topologies in LANs will be discussed in detail later in this chapter. The mesh topology can be either fully-connected or randomly (i.e. partially) connected. The former is more expensive and also more complex. In fact, the complexity increases in proportion to the number of connections required. The randomly connected mesh is more reliable and mostly used in the public switched telephone network (PSTN) network. Both forms of mesh topology can be considered as a series of interconnected stars.

2-2-1. LINE AND CHANNEL ENCODING FOR DATA TRANSMISSION

The most common and easiest way of representing a digital signal is for two voltage levels to represent the 1's and the 0's. However, this method is an undesirable way of encoding the data due to the reasons given below. Better encoding schemes can be used to improve performance of the transmission of digital signals through local networks. We shall consider a number of suitable codes later, but first we shall consider some of the desirable features of lines codes so as to provide a basis on which the evaluation of various codes can be based [9,65,135]:

1) Signal energy spectrum: it is desirable that the encoded signal spectrum has no low frequency components and no dc component. This allows ac coupling via transformers or capacitors, which is a desirable feature of data transmission circuits. Wide frequency spectrum requires large bandwidth for its transmission and this can also lead to increased channel interference from noise and crosstalk.

2) Timing information content (synchronisation capability): The spectrum of the encoded signal should have high energy content close to the data clock frequency. This provides easy extraction of the clock frequency at the receiving end for the purpose of transmitter-receiver synchronisation whenever that is required.

3) Error-detecting capability (unique decodability): The output symbol must be unambiguously decoded to give the original transmitted bit. It is also useful if it has some primitive error-detection capability. This can sometimes be provided simply by the nature of the encoding scheme used.

4) Transparency: The code must not impose any restrictions on the content of the

transmitted message, i.e. it must be bit-sequence-independent.

5) Efficiency: Each symbol of the code should contribute to the transmission of the incoming data.

6) Signal interference and noise immunity: Certain codes exhibit superior bit-error-rate performance in the presence of noise.

7) Cost and complexity: The complexity and cost of the encoder should be as low as reasonably possible.

Line encoding can be classified in two categories, encoding for baseband transmission and encoding for use with broadband transmission.

A) Baseband network encoding: In this category the signal is transmitted without modulation on to a carrier frequency and may be divided into two main subdivisions. The first subdivision consists of the binary codes, where the signal has only two distinctive voltage levels. These include binary non-return-to-zero (BNRZ) in its three modes of coding mark (BNRZ-L), level (BNRZ-M) and space (BNRZ-S), binary return-to-zero (BRZ), biphase encoding (BiΦ-L,M,S) (also known as Manchester, WAL1 or dipulse encoding), differential Manchester, WAL2 and Miller (delay modulation) encoding [5,9,49,65,78,120,127,134,135].

The second subdivision consists of the ternary codes, where the signal has one of three distinctive voltage levels (positive, zero and negative). These can be further divided into two sub-classes, the linear and the non-linear ternary codes. The linear ternary involves alternate mark inversion (AMI) [9,49,65,127,135,145], duobinary[9,49,127,145], modified duobinary[127] and twinned binary[9]. The non-linear ternary codes, which can also be divided into alphabetic codes that include nBmT, which means conversion n binary bits to m ternary symbols (often called PST, pair selected ternary for the special case when n=m=2), 4B3T, MS-43 and VL43 [9], and non-alphabetic codes that include high density binary with three consecutive zero substitution (HDB3),which is a modification to the AMI code, and, finally, binary with six zero's substitution

(B6ZS)[9,127].

B) Broadband network encoding: In this category the original data are modulated on to a carrier so that the line signal spectrum matches the pass-band of the transmission channel, or, for the case of free space, for radio channel transmission, or to make efficient use of the bandwidth using a carrier system in cable or optical fibre operation. The original binary data, which may be encoded in a form similar to that in A above, modulates a sinusoidal carrier in one of several formats i.e. amplitude, frequency or phase modulation. The modulation technologies applied to discrete modulating signals are usually referred to as amplitude, frequency and phase shift keying (ASK, FSK and PSK). FSK is a technique suitable for low data rate transmission. A modified version of FSK has been proposed which reduces the frequency spectrum requirements through the use of minimum shift keying (MSK) and thereby reduces the intersymbol interference. ASK is also suitable for low data rates, giving a better bandwidth utilisation than FSK. PSK is found to be superior to both ASK and FSK. A more efficient version of all the above can be obtained by the use of M-ary ASK, FSK and PSK, so that several bits can be grouped to represent one symbol. This has the facility of reducing the overall bandwidth compared to single bit transmission. Further development and better results can be obtained through a combination of ASK with PSK to form what is generally known as quadrature amplitude modulation (QAM)[49,134,135,145].

Channel impairments lead to errors in the received signal, which reduces channel utilisation. The signal may therefore be protected against the occurrence of errors by the use of error detection and correction codes. Typical examples of error-correcting codes are the block codes, convolutional codes, the cyclic redundancy check (CRC) code, automatic repeat request (ARQ) codes and may other codes derived from them [9,49,120,127,145].

2-2-2. TYPES OF MULTIPLEXING AND SWITCHING

Efficient use of the available bandwidth of the medium can be achieved by providing a connection between any pair of users only when it is needed. It is not therefore generally economical to provide a dedicated connection between every pair of users. Thus, networks should be designed to share circuits using 'multiplexing' techniques, and to share point-to-point links (channels) using 'switching' techniques[120,134].

Multiplexing is a technique that enables different signal sources (users) to transmit simultaneously on the same circuit without interfering with each other. There are several methods that can be used to do this. The first is frequency-division multiplexing (FDM), where the users each use a part of the spectrum allocated for their transmission for all of the time. The second is time-division multiplexing (TDM), often known as synchronous TDM. In TDM, the multiplexing is based on time sharing. Users communicate between each other in predefined time slots, but with the use of the whole available frequency spectrum. Both FDM and TDM are inflexible in their operation as they must be designed to carry full "busy hour" load. A modification to the TDM system is therefore used in which the multiplexing is controlled by a processor which eliminates the unused slots and allocates them to other users. Thus the full frame time is allocated amongst the active users in such a way that there is no need for synchronisation. This type of TDM is known as asynchronous or statistical or intelligent TDM. A version of this asynchronous TDM will be discussed in more detail when we consider the contention protocols [5,135]. Another technique, known as code-division multiplexing (CDM), has also been proposed [5,26,47,145,155] as an alternative to both FDM and TDM. In CDM, each signal is allocated a distinct waveform pattern by modulation with a unique code sequence (the technique is based on the signal processing concept of orthogonal signal sets like Walsh functions, Bridge functions, etc. to maintain the identity of the separate channels within the multiplexed data). All the signals are then combined for transmission over the common medium.

Communication networks can be categorised based on the architecture and the techniques used to transfer data. Two main types of networks are in common use; (a) switched communication networks and (b) broadcast networks [135]. Broadcast networks include packet radio networks, satellite networks and passive bus configured local area networks. Broadcast networks are discussed in more detail later in this chapter. Here we focus our attention on switched networks. There are several types of switching [5,53,54,134,135,144,145]. Fig.2-4 shows the main differences between them. These are:

1) Circuit switching: The essential feature of circuit switching lies in the existence of a dedicated communication path between any two users. Large holding time is required as a result of circuit establishment, data transfer and circuit disconnect. Channel capacity is therefore not used efficiently and, under heavy load, congestion may occur due to blocking in the network. It is, however, fairly well suited to speech transmission and finds its major applications in the PSTN and PABX. Circuit-switched networks may carry speech, data, facsimile and other services in digitally encoded form [5,135], as in the digitally integrated system X exchanges[4].

2) Message switching: The message is transmitted with its destination address through the network nodes from the source to the destination by a route determined by the prevailing traffic requirements. The message may be stored for a short period at any intermediate nodes. It is sometimes known as the 'store and forward' technique. It makes more efficient use of the transmission facilities than circuit switching, but the message experiences variable delay and generally longer transmission times than circuit switching. This makes it particularly unsuitable for interactive traffic[5] and congestion may occur because the intermediate nodes in the network run out of buffers storage in which to store the incoming message [114]. It finds its main applications in electronic mail systems.

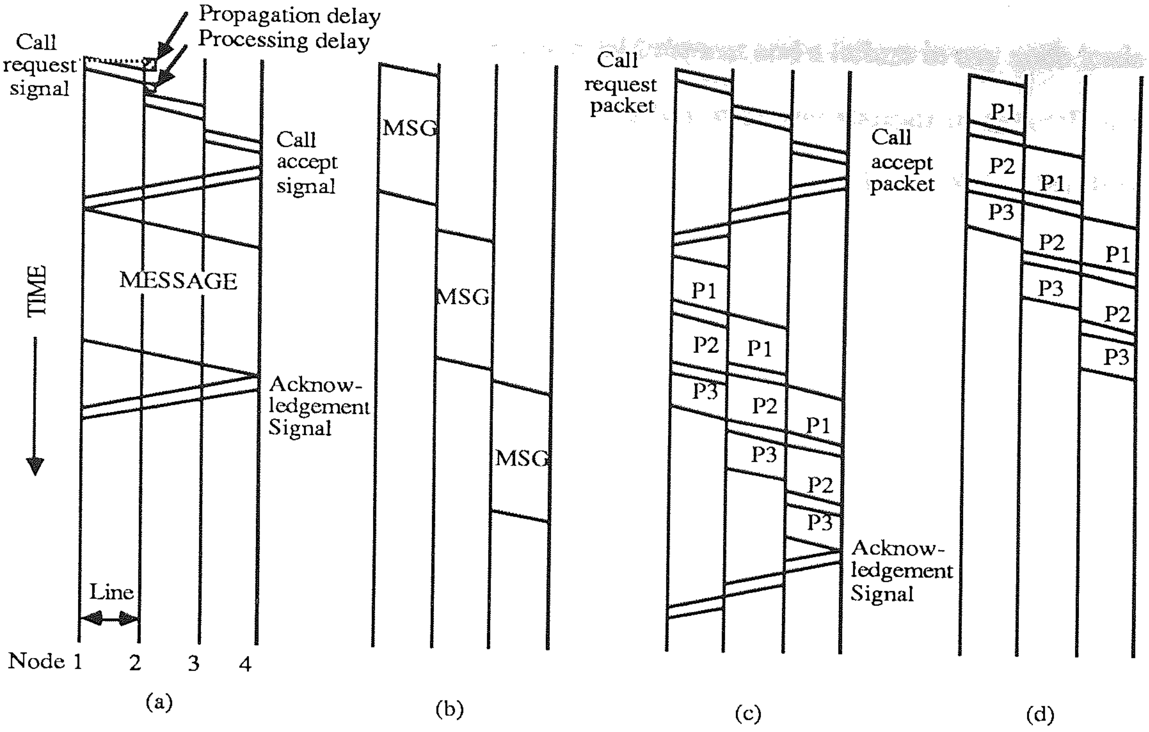

Fig.2-4. Time comparison of various communication switching techniques.
a) Circuit switching
b) Message switching
c) Virtual circuit packet switching
d) Datagram packet switching

3) Packet switching: This attempts to combine the advantages of message and circuit-switching whilst minimising their disadvantages [135]. The message is divided into smaller messages units according to the network specification requirements which are called 'packets'. The method is still a store and forward process, but since the packets are small they are quickly copied by each intermediate node and hence require smaller buffer space [5]. Two different approaches to packet switching are used. These are: a) 'datagram' , in which each packet is free to follow its individual routing decision, as with the case of message switching. b) 'virtual circuit switching' in which a logical connection is first established before any transmission takes place (this is not mean that there is a dedicated path, as in the case of circuit switching). Since each packet forming part of the same message in allocated the same transmission route, there is no need to take any further routing decision at any node they pass through. This type of operation suffers from a small delay due to logical connection establishment and a failure in any node leads to disruption of the connection. Packet switching has wide applications in general, and standards for packet switching are given in the CCITT recommendation X.25 [54]. It is used in some LAN, HSLN and WAN applications[5,120,135,144].

4) **Hybrid circuit and packet switching:** This is an attempt to overcome the overriding problem of switching delays to obtain the advantages of circuit switching for real-time services (interactive traffic) and the advantages of packet switching for bursty data services. The difficulty of the system is the complexity of the traffic analysis. This technique has been mainly used for ISDN applications [24,53,54].

2-3. LOCAL AREA NETWORKS

Local area networks (LANs) have become an important topic in the field of data communication. They will play a prominent role in data communications, networks and distributed processing in what remains from the 1980's and into the 1990's. Considerable research has been carried out recently in this area and many papers have been published on the topic. Several commercial names are associated with LAN products. For example, Aston University is installing its own LAN to come into service at the start of 1992. This is known as ACCENT (Aston Campus Communications for Europe and Ninety Two) and will include facilities for computer networks, library services, mail and many other services. It is impossible to refer to all the papers that have been published in this regards. Only those most relevant to the subject will therefore be mentioned here [5,14,23,35,39,114,134,135,146]. There are some particular features that LANs are able to offer in comparison with other types of local networks, these are:

1) High data rate, typically 1 to 10Mbps or even more.

2) Limited geographical scope, this is typically about 1km but can be extended to 10km using bridges to interconnect similar LANs. Gateways can be provided to connect into WANs and other networks.

3) Supports full connectivity. All the users should have the potential to communicate with each other, thereby achieving resource sharing.

4) All users have an equal opportunity to gain access to the network.

5) Good reliability and low data error rate which is substantially lower than in public data networks.

6) Ease of reconfiguration and maintenance.

7) Stability under high load operation.

8) Compatibility to the greatest extent possible to a variety of equipments.

9) Relatively low cost.

10) Finally, since the network is owned privately, more integration and modification can be achieved to include a variety of services.

Several types of LANs have been introduced recently and their classifications of types can be categorised according to the way the users are connected to the transmission medium. This is often known as their topology. We now briefly review various LAN topologies and medium access control protocols (MACs) and their performance evaluation. Attention will then be focused on the recent research in this field towards performance improvement.

2-3-1. LOCAL AREA NETWORKS TOPOLOGY

Topologies or types of LAN can be classified according to the method in which the users are attached to the transmission medium. In this regard we will examine only three types of LAN topology from the general topologies given in fig.2-3 for local networks. These three types have found more application in LANs than in the general local networks described earlier. Hence, only the star, bus/tree and ring topologies will be considered here.

2-3-1-1. STAR TOPOLOGY

This is a non-broadcast topology which is currently used for some commercial LANs. In this topology there is a central control switch and all users are linked via point-to-point connections through the central controller to form a 'star'. Any connection required between any two users is, therefore, controlled and routed through the control switch. Star topologies are of two kinds, either circuit switched as with PABX networks that handle voice and data, or message switched as used for linking computers to a star connected central computer. It is simple from the connection point of view and if there is any single user failure, this represents a minimal problem since it does not disrupt the system operation. The complexity of the system lies in the central switch, which requires several input/output ports and high processing intelligence to achieve the user's connection. This centralisation in system operation creates two side effects. First, connection bottleneck occurs when the controller is unable to accept more connections from users. Secondly, the reliability of the controller will be a crucial factor in the entire system operation, i.e. any fault in the controller may put the whole system out of operation. Star topology is mainly used in PABX or CBX and in some new LANs [48] a broadcast type of star network is in use. This is achieved with the use of existing telephone cable and using the IEEE802.3 CAMA/CD standard as in [31].

2-3-1-2. BUS/TREE TOPOLOGY

The bus topology is a multipoint broadcast highway, in which users are connected via their transceivers and share a single passive communication path. Each user is identified by a unique address, other users appending messages to this unique address. A development of the data bus is used in computer systems for interconnecting all the various components such as the processor, memory and peripheral controllers. It can be represented in a similar way to a free space transmission. The tree topology is a multibus configuration network, which contains more than one bus segment connected together through repeaters. Fig.2-5 shows a general case of the bus/tree topology. The bus is currently very popular and there are many LAN connections based on this principle. A good example is the well-known Ethernet[1] [91,160]. Since the process of connection is distributed, there is no need to use a central controller as with the star networks and any user can establish its own connection requirements. Two main features have to be considered in this topology:

1) Several protocols for medium-access control have been established to provide the transceivers with the necessary intelligence to share the medium and to determine which user should start transmission. This matter will be examined later in more detail.

2) The signal level on the transmission medium should be properly adjusted to prevent over-loading of the transmitter, at the same time maintaining adequate signal-to-noise ratio at the extreme far-end user's station.

The bus/tree topology can be divided into two types of LAN according to the bandwidth available for signal transmission;

A) Baseband bus LANs: In this type of LAN the digital signal at any transceiver is transmitted directly on to the bus without the need for any modulation process, e.g. Manchester encoding or some other baseband encoding scheme mentioned previously is often used. The transmission of the signal is bidirectional (broadcast) on the medium, which is usually either twisted-pair or coaxial cable. The first is used with inexpensive devices for a maximum rate of not more than 1Mbps and a distance not exceeding 1km and a hundred user stations can be attached to the bus. Coaxial cable is used for more expensive devices and either 50 or 75 ohm cable is used. Higher data rate is therefore achievable. Ethernet is a good example of a baseband bus coaxial cable linked LAN. The distance of coverage of a one segment bus can be increased by the use of repeaters, so that a tree topology is created. This cannot be done without any limitation, there being a

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1)Ethernet is a trade mark of a local area network developed jointly by Xerox, DEC and Intel Corps.. Its specification is the result of an extensive collaborative effort of the three corporations, and several years of work by Xerox on an earlier prototype Ethernet.

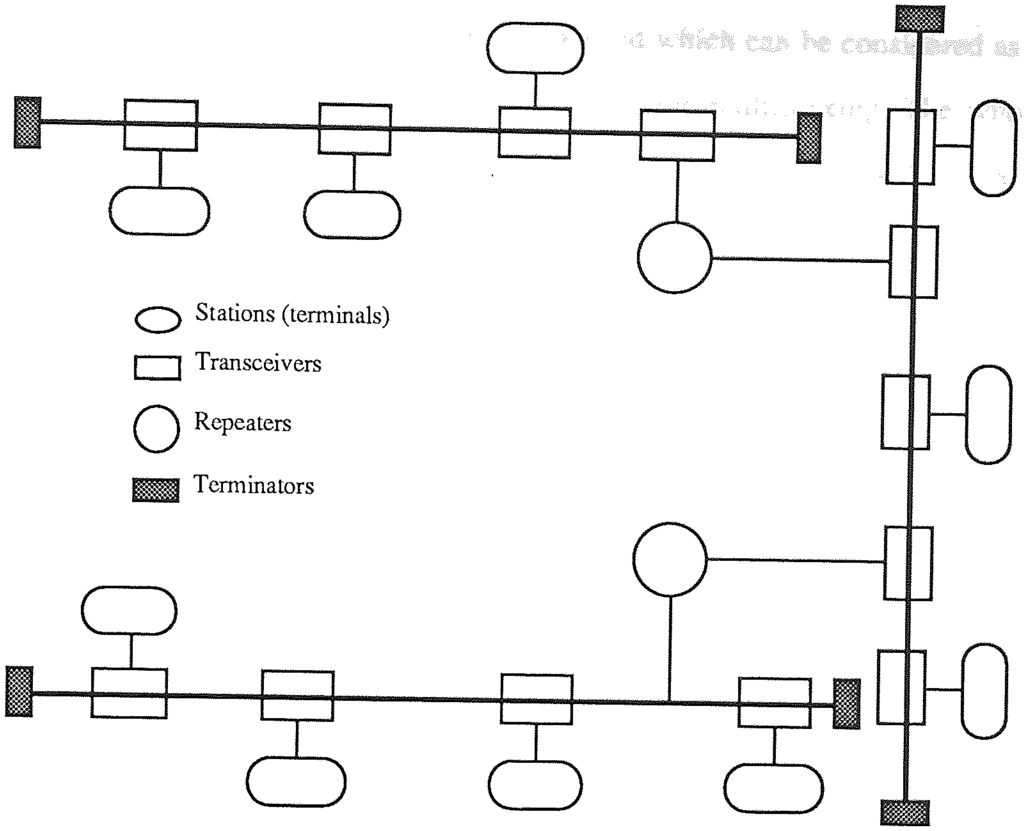

Fig.2-5. Typical extension of bus operation by connecting several buses through repeaters.

limit to the number of buses that can be so interconnected [5,14,23,35,39,91,134,135,46,157,160].

B) Broadband bus LANs: The bandwidth of transmission in this type of LAN is much higher than with baseband. Two types of broadband LAN are now in use; first, the single-channel broadband, where the entire spectrum of the transmission medium is devoted to one signal transmission. The transmission will be bidirectional and the same encoding scheme is used as with baseband. This kind is mainly applicable for HSLNs, but it has also been proposed for LANs. The second consists of the broadband multichannel system which uses the FDM multiplexing technique. In this system, the signal transmission is either unidirectional so that amplifiers can be used in order to extend the distance of transmission or bidirectional transmission. The original data always modulates a carrier with one of the broadband encoding schemes mentioned previously.

Some other new techniques are also introduced which can be considered as broadband transmission using spread spectrum code-division-multiplexing. The whole topic of broadband LAN with its application to radio transmission is discussed in detail in chapter five [23,91,120,135].

2-3-1-3. RING TOPOLOGY

The ring topology consists of several users connected to each other to form a closed-path link known as a 'ring'. The user is always connected to the ring through its repeater, which represents an active part of the path. A well-known example of this type is the Cambridge ring[1]. The repeater does the same job as that of the transceiver in the bus topology rather than that of the repeater. It is responsible for packet insertion, reception and removal to and from the ring. The transmitted packet from one user circulates in one direction until it reaches the addressed user. It is therefore unidirectional transmission topology. Removal of the packet can be done in one of two ways. First, the recipient user may remove the packet from the ring or, secondly, the recipient may make a copy of the packet while it passes through its repeater, leaving the packet to circulate until it reaches the transmitter, who is then responsible for the removal of the packet from the ring. The second option is preferable, since it leads to automatic acknowledgement, which is a useful property. In addition to this, there are several other good properties that can be obtained with the ring topology. Errors can be minimised in comparison to other topologies because the transmitted signal (packet) will be regenerated as it passes each repeater. This also means that larger distances can be covered. A further increase in area of coverage can be obtained using bridges to interconnect more than one ring as shown in fig.2-6. The main drawback of the ring lies in the fact that the failure of any repeater puts the whole ring out of operation. This can be remedied with the use of the star-ring architecture. Finally, there are several protocols available to regulate the transmission of

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1)The Cambridge ring local area network is the first known example of this type which was developed at the University of Cambridge.

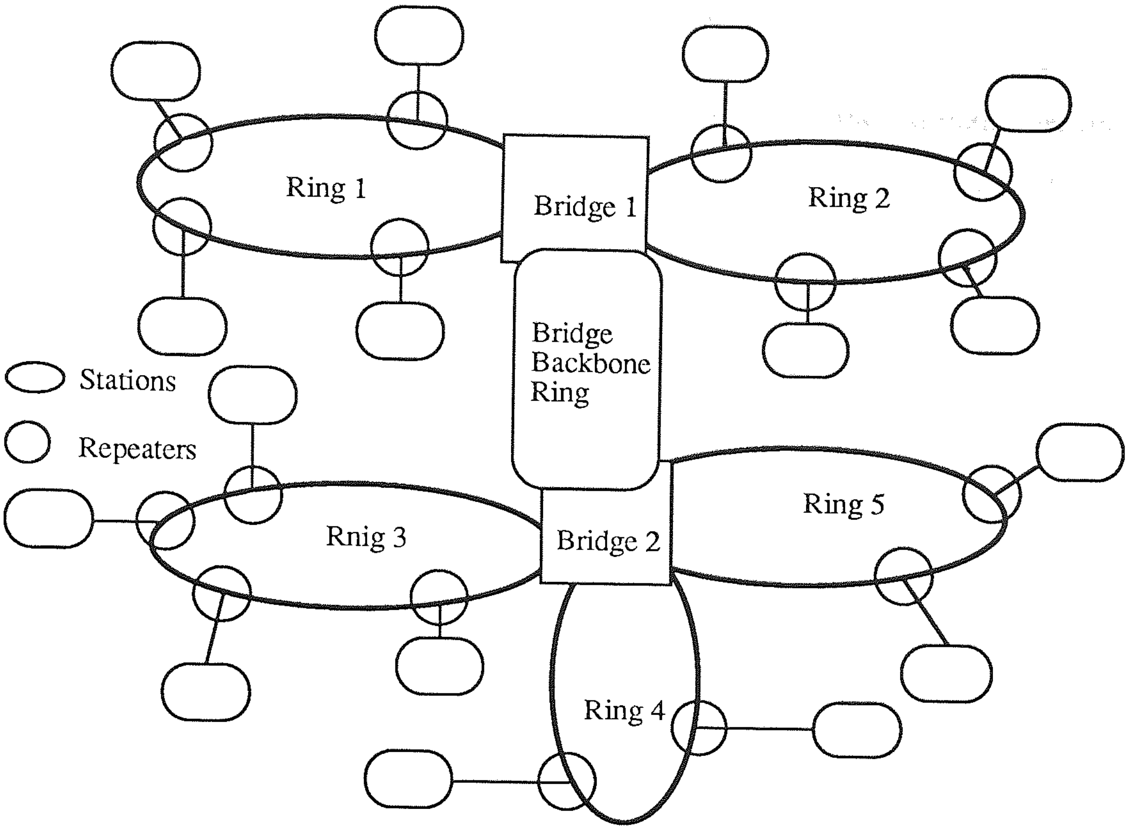


Fig.2-6. Extension of ring operation by connecting several rings through bridges.

the data on the ring. These will be discussed in more detail in the section on ring medium access control [9,14,23,35,39,49,114, 120,134,144,146].

2-3-2. MEDIUM ACCESS CONTROL

This section gives a detailed explanation about local area network medium-access control (MAC). Discussion of other broadcast networks, such as packet radio, is postponed to the end of this chapter. Only the lower three layers of the OSI model are concerned with the problems of communication on the network. These layers are the physical, data-link and network layers. In some LANs, only the lower two layers are involved and the network layer is unnecessary. This is because the messages are transmitted in addressed frames from the sender to the receiver without the necessity for the intermediate switching processes required by other networks. Thus, no routing is required to be performed by the network layer [5,14,23,29,35,49,114,120,134,135,144,146,160].

The physical layer performs encoding/decoding of the signal, preamble generation/removal and bit transmission/reception. The principal function of the data-link layer can be divided into two smaller sublayers. Firstly, the logical link control (LLC) layer performs logical interfacing between adjacent layers, assembles/disassembles data into frames, appends the frame with address and CRC field. It is also responsible for address recognition and CRC validation of the whole frame at the receiver. Secondly, the medium-access control sublayer performs the management of the communication over the link. Several protocol standards for both layers i.e. physical and data-link (with its sublayers) have been issued by the IEEE802 committee and other related institutions such as the ECMA. The IEEE802 committee issued several standards for different LAN MACs and other complementary networks such as LAN like MANs and broadband LANs. Fig.2-7 shows the structure of the IEE802 committees responsible for issuing draft standards to be approved by ANSI [59,156].

There are three basic MACs that are used with broadcast LANs. These are contention, round-robin and reservation. Some other MACs go beyond these services as we shall see later in this chapter. The classification of MACs will be based on the most commonly used topologies, the bus and the ring.

2-3-2-1. BUS MAC PROTOCOLS

The bus topology is one of the two most common topologies used with LANs. There are several MAC protocols which can be used with bus networks, these are; polling, reservation, the random multiple-access protocol CSMA/CD, token-passing bus and hybrid-bus operation. Here we will consider only three types of MAC, the random multiple-access protocol, round-robin token-bus and the hybrid bus protocol. The reader may refer to the following references [4,5,49,88,95,134,135] for details of polling and reservation protocols.

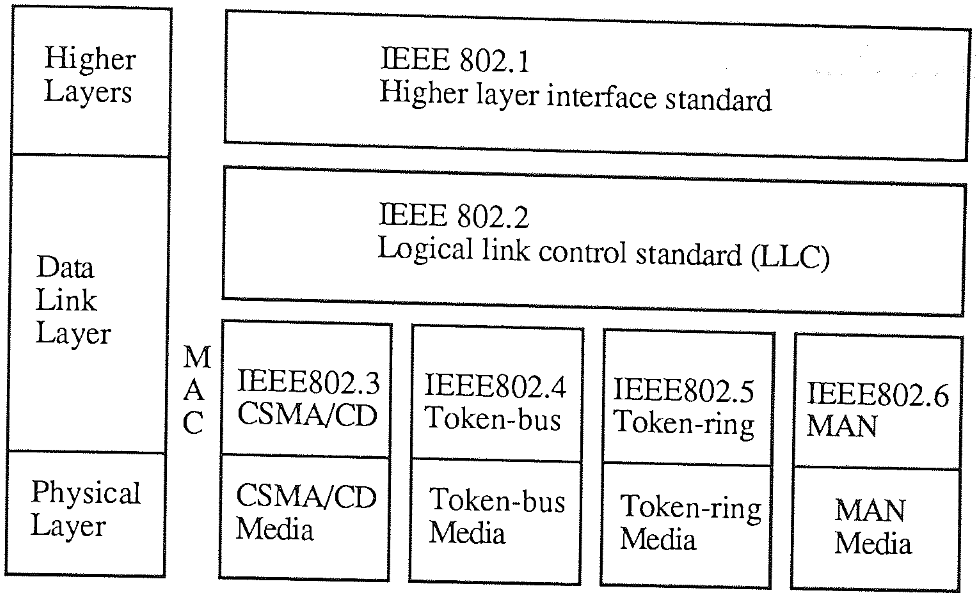


Fig.2-7. IEEE 802 Standardisation committee structure[33]. Other IEEE standardisation committee are:

IEEE 802.7: Broadband
IEEE 802.8: Optical fibre
IEEE 802.9: Integrated voice and data LAN interface

1) Random multiple-access protocol (CSMA/CD)

This technique for MAC is usually appropriate for bursty traffic. It is a contention protocol. This technique is of necessity distributed in nature, each user contending for time with other users to transmit. The most popular protocol is the carrier sense multiple access with collision detection (CSMA/CD), which is the earliest MAC strategy to be used in LANs [60,91,160]. This technique is a development of the contention protocols known as ALOHA and slotted ALOHA. These were mainly used in broadcast radio and satellite communications[1]. The ALOHA system has a low data throughput transfer because of frequent collisions. A means of sensing the transmission medium is therefore a possible solution to overcome this shortcoming. This is achieved through the use of the carrier sense multiple access (CSMA) or 'listen-before talk' (LBT) protocol [69,148]. This enables a higher throughput to be achieved in comparison with the ALOHA system. A further development to CSMA was adopted which enables the user stations not only to listen before transmitting, but also to detect a collision if one should occur. This is often referred to as 'listen-while talk' (LWT). This later version is known as the CSMA/CD protocol [91,149,160]. It is found to produce higher throughput in comparison with its predecessors ALOHA and CSMA. Two well-known examples using this mode of operation are the baseband Ethernet and the broadband MITREnet LANs.

The operation of the CSMA/CD protocol is as follows. A station with a message to transmit senses the medium through the transceiver. If the medium busy, it waits until it becomes idle. If the medium is idle it commences transmission on the medium and keeps monitoring the medium for possible collision (i.e. when more than one station commences transmission on the medium simultaneously). Providing this does not happen, the transmission will be successful. In the event of a collision, both stations involved jam the medium to give an indication to the other stations that a collision has occurred and then withdraw their transmission. Retransmission will then take place after a random timeout period to prevent repeated collision by simultaneously waiting stations.

There have been further developments of this protocol to improve its operational performance and various different modes of operation have been suggested. These include the non-persistent, slotted non-persistent, 1-persistent and slotted 1-persistent. In fact the 1-persistent mode of operation is a special case of the general p-persistent mode of operation where p=1 that is the probability to transmit is equal to 1 and transmission is not delayed to the next slot. These modes of operation will be discussed in more detail in chapter three, where we shall deal with the proposed carrier sense multiple access with collision avoidance (CSMA/CA) protocol. Other developments are the virtual-time CSMA/CD [94,98,99], CSMA/CD with channel capture [130], and with reservation [17,66], CSMA/CD with deterministic contention resolution [143] and deterministic retransmission [66] and, finally, CSMA/CD with tree algorithm for collision resolution [101].

The packet structure format of CSMA/CD used for MAC is shown in fig.2-8. This is in accordance with the IEEE802.3 Committee standard [49,71,91,134,160]. This protocol is mostly used under light load operation since the delay-throughput characteristics

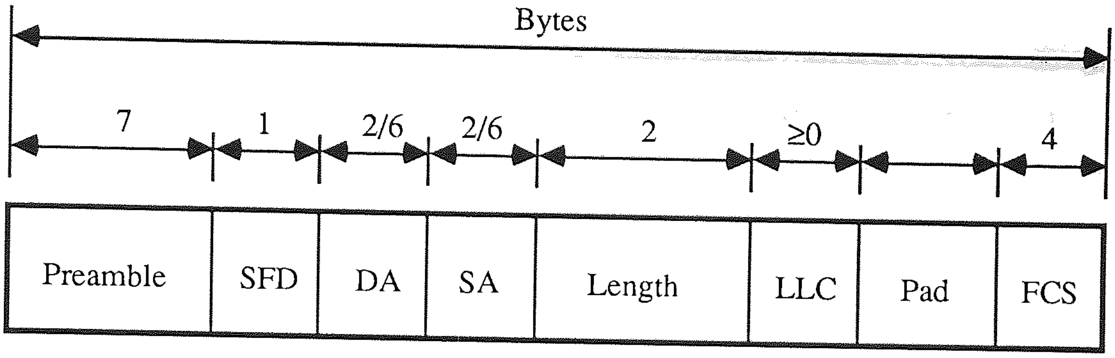


Fig.2-8. Ethernet CSMA/CD bus packet format.
SFD: Starting frame delimiter
DA: Destination address
SA: Source address
LLC: Interface field supplied by logical link control (LLC) layer
FCS: Frame check sequence

deteriorate under heavy load condition due the increase in the number of collisions on the bus. Restriction on the length of the packet is also another problem, since the packet length should be at least twice the end-to-end propagation time delay of the bus in order to be able to detect the collision.

2) Token-passing bus

In this kind of bus MAC operation, the user's stations on the bus form a logical ring sequence which may be different from their physical sequence on the bus. The control frame (token) regulates sharing the transmission medium by being passed from one station to another in a predefined logical sequence. The frame structure that is used with this type of round-robin protocol is shown in fig.2-9. The steady state operation of token-bus consists of waiting for an addressed token, transmitting data for a certain 'token holding time' upon receipt of the token, transmitting the token to a successor and monitoring the token transmission. Thus, the operation consists of alternating data-transfer and token-transfer phases. The protocol is applied to all users connected to the bus to regulate the function of addition and deletion of users, of fault management by the token holder, of ring initialisation and classes and priorities in services [5,14,23,35,39,49,61,116,134,135].

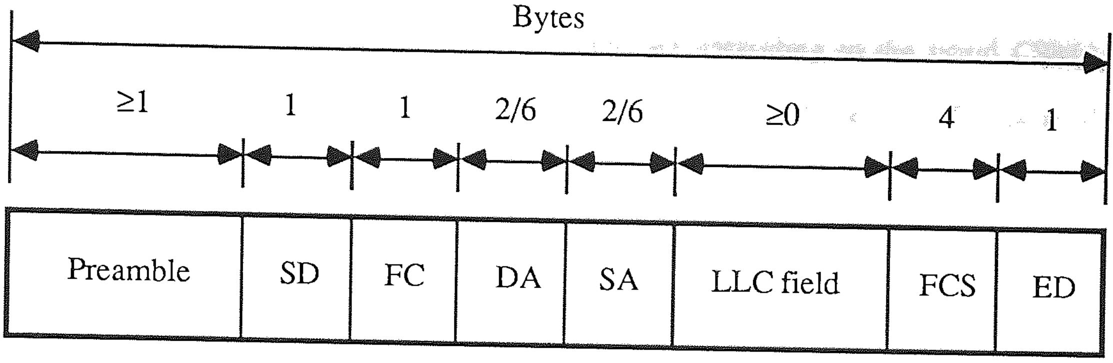


Fig.2-9. Token-bus packet format.
SD: Starting delimiter
FC: Frame control byte
DA: Destination address
SA: Source address
LLC: Interface field supplied by LLC layer
FCS: Frame check sequence
ED: Ending delimiter

The analysis and simulation of the token-bus operation performance carried out [15,62,117], shows that better throughput-delay performance is obtained compared to the CSMA/CD protocol and more stable operation is obtained at heavy load operation. However, the token-bus needs a more complex protocol algorithm. A proposal for accommodating voice and data traffic has been made using the L-EXPRESS net [8].

3) Hybrid operation of CSMA/CD and token-bus

The CSMA/CD mode of operation gives higher throughput and lower delay at light load operation, whereas the token-passing bus gives better characteristics than that of CSMA/CD at heavy load. These two facts suggest the dual operation of both protocols so as to gain improvement in overall performance of operation. Hybrid-bus operation has therefore been introduced. There are several different proposed schemes, but they have one common feature in that all of them operate in CSMA/CD mode at light load. The main differences occur when the load becomes heavier. At that time the protocol will operate in one of the following ways:

(a) Initially, only one station possesses the token from the K stations on the bus and all stations, except the one possessing the token, act according to the usual CSMA/CD protocol. The station that possesses the token behaves differently. If it is ready, it transmits the packet on sensing the medium idle. In the event of a collision, this station does not terminate its transmission but captures the medium by disabling its backoff mechanism, keeping the medium busy for twice the end-to-end propagation time and then immediately starts retransmission of its packet. At the end of its successful transmission, whether a collision was encountered or not, it will release the token to the next predefined station and so on [44].

(b) The system behaves like CSMA/CD until a collision occurs. At that time the protocol switches over to a reservation protocol based on slotting the medium time to minislots to each station's transmission until a predetermined number of packets have been successfully transmitted. The system then automatically reverts back to CSMA/CD mode [107].

(c) The change of system operation depends on the number of trials (blocks due to collisions or sensing the medium busy), a station may encounter. If it reaches a predefined limit of blocks, the station then transmits a carrier on the bus to force the bus to change protocol and immediately follows this by its packet. Then, at the end of transmission, it will release the token to its successor. This station is then responsible for reverting the protocol back to CSMA/CD after a time interval consisting of several transmission cycles. The number of transmitted packets within this interval is a measure of the offered load which decides the change of the protocol from token-passing to CSMA/CD [58].

(d) When a collision occurs, station number 1 on the bus waits until the bus is cleared and then starts transmitting synchronisation bits to inform the rest of the stations that the system will change to token protocol. After that, station 2 will sense one of two possible indications on the bus. These are, a 'P' indication when station 1 has a packet for transmission and hence should wait until station 1 finishes transmission, or an 'N' indication if station 1 has nothing to transmit. The next station then follows the same sequence until the kth station receives the token and finishes transmission, when the mode of operation will return back to CSMA/CD [102,103].

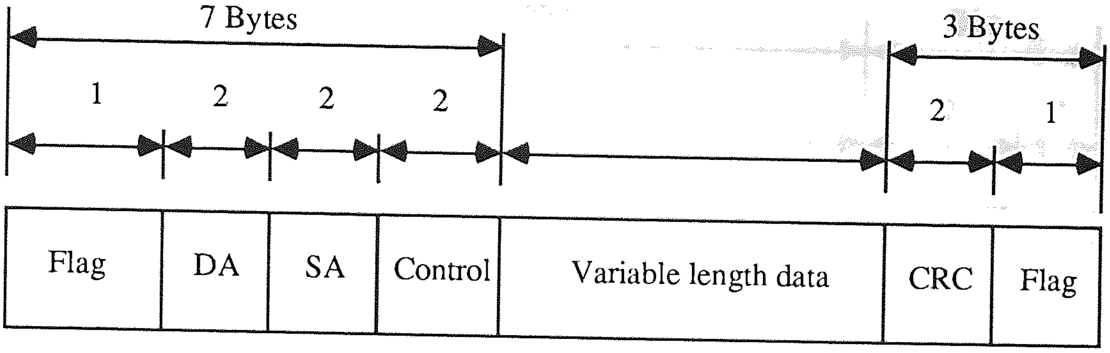
Although the above methods gives better results with respect to delay-throughput performance, they need a more sophisticated operation algorithm than that of CSMA/CD and token-bus operation. The packet structure is a mixture of those given in figs.2-8 and 9, mainly depending on the type of operation.

2-3-2-2. RING MAC PROTOCOLS

The ring normally operates using a round-robin multiple access protocol, which is a unidirectional broadcast transmission. There are four access schemes that are mainly used with the ring topology. These are; register insertion, slotted ring, token ring and contention ring [85,96,144].

1) Register insertion

With this type of ring protocol, each station is provided with a register. The size of the register is equal to the maximum frame size that is allowed for each transmission. The operation of the register insertion ring protocol is as follows. If a station has a frame in the register ready for transmission, the station waits until the medium becomes idle, usually signalled by an idle state indication. At this time the register is inserted into the ring. The frame or the packet circulates until it passes the destination receiving station and returns to the originating station. Removal of the frame takes place either at the receive station [96] or at the transmit station [134,135,144] when the frame completes one cycle. The packet structure of register insertion is shown in fig.2-10. This scheme of operation gives lower throughput compared to other ring protocols to be discussed later and needs a complex communication interface with limited packet length [5,85,96,134,135,144].



DA = Destination address
SA = Source address
CRC= Cyclic redundancy check

Fig.2-10. Register insertion ring packet format.
DA: Destination address
SA: Source address
CRC: Cyclic redundancy check

2) Slotted ring

In the slotted ring or empty slot system, the channel time is divided into fixed length slots which flow continuously around the ring. The number of slots depends mainly on the total length of the ring in 'bits'. The stations can therefore be considered as relaying a fixed number of slots to one another in a cyclic manner. The structure of each slot or frame is shown in fig.2-11. The operation of the slotted ring protocol is as follows. All the stations should always monitor the slots on the ring. Each slot contains a leading bit which tells whether the slot is empty or full. When a station wishes to transmit, it waits for an empty slot to come around, marks it full, and places its packet in that slot. This slot or frame circulates until reaching the addressed destination station, which makes a copy of that packet and marks the response bits to indicate whether the data in that packet was copied, or rejected, or whether the addressed station was busy. Once the packet comes back to the transmitting station (after having travelled around the ring), the station marks that slot empty and removes its data from the slot. In this mode of operation the transmitting station is not allowed to use another slot for another transmission until it receives and removes the previous frame. This property will keep the sequence of the received frames at the receiving side in correct order and at the same time will prevent monopolisation of the ring by one station's transmission [5,49,85,96,134,135,144].

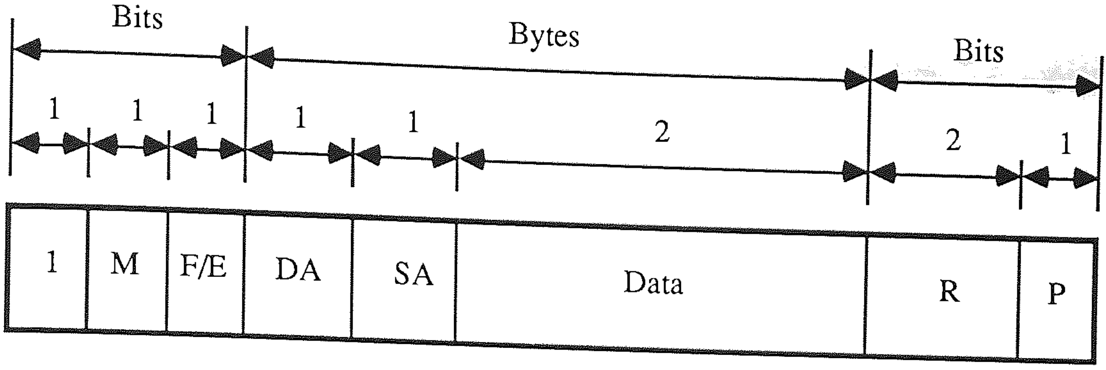


Fig.2-11. Slotted ring packet format.
DA: Destination address
SA: Source address
M: Monitor bit
F/E: Full/Empty bits
R: Response bits
P: Parity bit

The Cambridge ring is a well-known example using this mode of operation and was one of the earliest ring LANs. The advantages of this scheme are; simple in implementation, provides automatic acknowledgement and is reliable compared to register insertion. Its shortcoming lies in that the packet length is relatively short compared to the overhead and disruption of the ring will put the whole system out of operation. This can be remedied using a star-ring configuration as mentioned earlier. The solution to the short packet can be remedied by the use of the integrated Cambridge ring [52], which involves the ability to transmit simultaneously short control minipackets and longer data packets. It can also be used for interconnection of telephones and other real-time traffic. A simulation study has also been conducted for this mode of operation, which explores the suitability of the Cambridge ring for use at high speed transmission involving telephony traffic [28].

3) Token ring

This scheme of MAC involves the use of a unique bit sequence, known as the 'token', which circulates around the ring in a similar fashion to the preceding ring MACs. The right of transmission is given to any station that wishes to transmit when it receives the token. It then removes the token and starts transmission. The transmission time in this case is usually longer than that of the slotted ring, which is governed by the system requirements.The token is then added following the packet. The packet and the token circulate until they reach the destination, where the packet is copied from the ring and passed on to the transmitting station, which then releases a new token. The token will then give the next neighbouring station the opportunity for transmission and so on. The frame or packet structure of the token ring is shown in fig.2-12.

The token ring has higher efficiency under heavy load operation, but the protocol becomes less efficient when the load is light, especially if the ring length is large. As previously, the system fails completely if the ring is disrupted [5,12,14,23,35,39,49,59,85,96,114,120,134,135,141,144,156]. The disruption of the ring can be overcomed by the use of a double-loop token-ring which can generate several smaller loops or rings when any disruption occurs without disabling the whole system [115]. Voice transmission using such a protocol has been studied experimentally [34,57].

4) Contention ring

This mode of MAC operation represents an interesting combination of two of the previously mentioned MACs, these are the token-ring and the random multiple access or contention CSMA/CD bus. Hence the name 'contention-ring' is used. A brief description of the operation of this protocol is as follows:

Under light load operation and if there are no data passing the station interface (i.e. no packet on the ring), a station with data ready for transmission starts inserting its packet in a CSMA/CD mode of operation, but in a unidirectional mode since the ring is normally active. At the end of the packet transmission, this station removes its packet and releases a free token, which circulates in a similar way to token ring, giving the chance for transmission to the next stations on the way down the stream. The system has then been switched to token-ring until the token reaches the originator station that released the token.

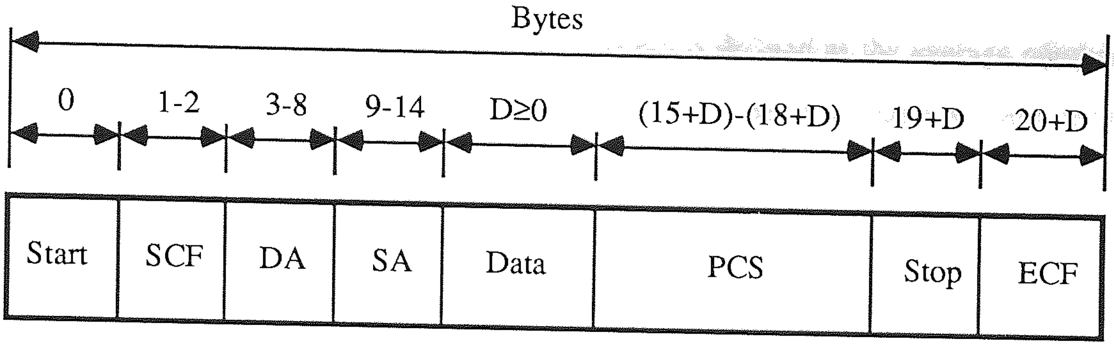


Fig.2-12. Token ring packet format.
SCF: Starting control field
DA: Destination address
SA: Source address
PCS: Packet check sequence
ECF: Ending control field

In this case, the originator station will be responsible for removing the token from the ring if no other station has used the token. By this action the station switches the system back to a contention basis. If, during the contention mode of operation, two stations start their transmission simultaneously, a collision will result (i.e. each of them will sense the transmission of the other packet). Both stations involved with the collision withdraw, wait random periods of time and attempt retransmission. The mean value of the random timeout is doubled at each consecutive collision, so that the probability of consecutive collision is reduced.

This hybrid operation will combine the good features of both modes of operation i.e. bus-CSMA/CD for light load and token-ring at heavy load, which gives better throughput characteristics and lower delay for low load but, again, it needs a more complex algorithm to achieve transmission [37,96,109,144].

2-3-3. PERFORMANCE EVALUATION COMPARISON OF LANS

The performance measures of LANs are normally evaluated based on three parameters. These parameters are the throughput, utilisation and delay of a network

[49,120,134,135,144]. The throughput of a system is defined as the average number of error-free data bits transmitted (successful transmission) between stations connected to a certain transmission medium. Throughput is, therefore, different from one system to another and mainly depends on the transmission data rate capacity of the system. However, the normalised throughput to system capacity, which is defined as the fraction of the total system capacity, is a comparable measure for different systems. The later is often called the utilisation, or the efficiency, of channel rate capacity. The last parameter is the delay of a network. This is defined as the average time delay that occurs between the time a data packet or frame is ready for transmission from a station and the completion of a successful transmission, when the last bit in that packet is received by the intended addressed station.

These three parameters are affected by other network or system variables. These are; the transmission rate or capacity of the network, the total propagation time delay, the size of the packet or the frame (this determines the length of the transmission time), the network topology, the MAC protocol, the error rate of the medium, the total number of stations or users attached to the network and the total offered load to the network from these stations [134,135].

Various publications show the performance operation comparison of the LAN protocols described so far [13,49,80,118,120,134,135,136]. A summary of their conclusions is that the random multiple-access protocol CSMA/CD is mostly preferable when the load of operation is light, since it produces a relatively higher throughput with low average time delay compared to other protocols. However, whenever the CSMA/CD protocol is heavily loaded, the time delay will rise and the throughput degrades sharply, leading to unstable operation of the system. On the contrary, the round-robin protocol token-bus and ring protocols will have the opposite characteristics. This has encouraged the proposal of hybrid-bus and contention-ring operation as a viable solution towards improving the performance of the protocols.

There is not an absolute tradeoff between the different protocols and systems, since many other factors may have their influence in this respect, such as the complexity of the system, the permissible errors allowed and the inteligibility needed (especially for speech) for proper operation, the overall cost of the system and the vulnerability of the system to minor and major faults, which determines its reliability. Another factor which may also be included in this regard is the type of services required by the system, especially how much delay is acceptable in the system without affecting the quality of the service i.e. whether it is needed to carry interactive bursty traffic.

2-4. MOBILE RADIO COMMUNICATIONS: AN INTRODUCTION

The term mobile radio communication describes any radio communication link between two terminals of which one or both are in motion or temporarily halted and of which one may actually be a fixed terminal. This definition applies to both mobile-to-mobile and mobile-to-fixed communication links. The mobile-to-mobile link could in fact consist of a mobile-to-fixed-to-mobile radio link. The term mobile applies to land vehicles, ships at sea, aircraft, and satellite communications.

The history of the work done in mobile communication commenced at the start of this century, but the main growth took place during World War II and particularly in 1950's. Present mobile radio systems consist mainly of two types;

1) Radio paging systems, which split roughly equally between those of locally on-site system applications (e.g. hospitals, factories, etc.) and the more recently introduced wide area pager systems that cover both local systems and the national system. The national system is based on the POCSAG (post office code standardisation advisory group) standard that was introduced into service in 1980 [5,97,110,147].

2) Land mobile radio. This type of mobile communications has witnessed tremendous developments since the first UK private mobile radio (PMR) was licensed in 1947. The earliest version was devoted to telephone-call exchange and this service became known as mobile telephony. However, due to the continuous rapid growth in PMR users, this has led to the establishment of the newly emerging services such as the trunked PMR, cellular radio and cordless telephones. The PMR, band III trunk system was introduced in the 1980's together with its standard protocol MP1327 and its modifications which regulate transmission in this band. This was introduced to overcome the shortage of allocated spectrum as the demand for the service increased [19,86].

The growth in mobile telephony continues and a new initiative for providing new services was introduced in 1978 in the form of the US cellular radio system AMPS (advanced mobile phone services) [79,163]. This initiative was followed by the TACS (total access communications system)[2], which defines the air interface specification of the system. The new TACS system started service in January 1985, based on the cellular mobile telephony system, and the responsibility of operation and supervision was given to British Telecom, and two other companies, Cellnet, which is a partnership of British Telecom and Securicor and Racal-Vodafone [6,33]. A good survey of all the companies dealing in the business of mobile communication may be found in [97]. British Telecom is also developing strategies for integration of cellular services with the system X digital network, which may result in a cellular system integrated with the PSTN using similar techniques to those used in the Nordic cellular system and other integrated cellular systems in other European countries like France and Germany [7,18,147].

Cellular mobile communication has found wide application all over the world and several other national systems in addition to the TACS (UK) and AMPS (USA) have emerged. These include the NMT (Nordic mobile telephone) system in the Scandinavian countries which started service in 1981, the NAMTS (Nippon automatic mobile telephone system) in Japan, the German Netz system, which includes the C and D operational modes, and several other national systems. International cooperation in this field is likely to lead to the establishment of a Pan-European cellular system, which is known as the Pan-European GSM (groupe spécial mobile) system and will include all the national systems in Europe. The trial of the GSM network started 1986 following a decision from CEPT (Conference of European Posts and Telecommunication administration), and it is anticipated that it will start public service in the early 1990's. In a recent development to the mobile communication industry, the European countries agreed to fund research or the development of GSM as part of the RACE (research and development in advanced communications in Europe) initiative and to consider how mobile/portable communications CT2 (cordless telephone) can be integrated into future broadband networks [21,138].

In mobile radio communication, two important features, network planning and mobile radio equipment design have received considerable attention. The objective is to make efficient and economical use of the allocated radio spectrum. Frequency spectrum utilisation can be achieved through the application of frequency reuse in which the geometrical area is divided into a number of cells, each of which contains one or more base stations. This is known as the cellular principle [6,78,79,87,147]. Frequency reuse refers to the use of radio channels on the same carrier frequency to cover different areas separated from one another by sufficient distance so that the co-channel interference is not objectionable. For further details about how to allocate this distance one may refer to ref.[87].

The idea of employing frequency reuse in mobile telephone services on a reduced geographical scale hints at the cellular concept. Instead of covering an entire local area from one land transmitter site with high power at high elevation, the service provider can distribute transmitters of moderate power throughout the coverage area. Each site then primarily covers some nearby sub-area, or cell, which provides services to all the mobiles within the limit of its base station transmitter power. The fictitious geometrical shape of the cell may be square or triangular however, the hexagonal is found to be the most acceptable approximation to the ideal shape which is circular [79,87]. The size of the cell may be different according to the service requirements, small cells are used in urban environments, whereas larger cell sizes can be used for rural areas. Techniques for solving congestion in the urban area are achieved either by dividing the cell into many sectors by the use of directional antennae or through the introduction of the microcellular structure [16,87,138].

Although the cellular concept has the advantage of spectrum utilisation efficiency by the use of frequency reuse, this becomes more prominent when sectorised cells and microcells are introduced. This increases the number of switch-overs from one cell site to another during the call connection time. Thus, locating and hand-off are required, especially when very small cell sizes are used (sectorised or microcell). Studies of these effects have been carried out [87,100]. The act of transferring from one channel to another is called 'hand-off', whereas locating is the process by which the base station gets up-dated information about the mobile terminal for determining whether it would be better from the point of view of signal quality and potential interference to transfer an active connection from a mobile unit to another land site.

2-4-1. MOBILE RADIO CHANNEL CHARACTERISTICS

The transmission of signals from the cell base station to the mobile terminal or visa versa through the radio channel usually does not have a line-of-sight propagation path. This is because in urban areas tall buildings will represent an obstacle and in rural areas hills cause the same problem. The transmitted signal therefore reaches the receiver antenna subject not only to the same propagation path losses that are encountered in ordinary radio communication, but they are subject also to many other factors affecting the propagation of the signal. These factors are due to the movement of the mobile and the nature of surrounding terrain. These are as follows [2,3,5,78]:

1) Attenuation of the signal with distance (path loss), in which the signal power is inversely proportional as the i-th power of distance (where $3< i <4$).

2) Short-term fading characteristics. This is due to the multipath propagation of the signal, which is mainly the result of scattering, reflection and refraction of the signal. The signal is received via different paths and the envelope of the received signal will therefore suffer from fading. The signal envelope fluctuations or fades are found to obey a Rayleigh distribution, and hence are often called 'Rayleigh fading'.

3) Shadowing or long-term characteristics due to buildings and hills and other obstacles. The received signal envelope resulting from this phenomenon obeys a log-normal distribution.

4) The Doppler effect due to the motion of the mobile. This sometimes introduces a small drift in the operating carrier frequency, leading to instability of the received signal frequency. This mainly depends on the velocity of vehicle while receiving the signal.

5) Ignition and other engine and mobile noise, impulse noise of the channel and receiver noise.

All these factors collectively make the mobile radio channel a time-varying channel, so that the transmission of signals through this channel should take these factors into account. Channel models have been proposed based on experimental measurements which have then been used to model the channel for the purposes of mathematical analysis and for simulation study [68,75,139].

2-4-2. DATA TRANSMISSION OVER RADIO AND MOBILE RADIO CHANNEL

Data transmission over radio links using line-of-sight communication has recently been proposed using packet-radio communication technology to achieve information distribution and computer communication in remote areas. This development is related to the rapidly-increasing demand to provide effective communication services for wide-spread data distribution. Investigation has been mostly limited to the study of stationary packet radio networks in which one of the oldest techniques used is the previously mentioned ALOHA and slotted ALOHA protocols. Recent studies have resulted in different types of protocols which are mainly derived from the ALOHA system[74]. An example of these systems is the CSMA protocol, which gives better performance results [69,148]. However, due to the fact that line-of-sight is not always available between two terminals while they are communicating with each other or with other terminals within the networks, the hidden terminal problem appears as an obstacle to disrupt successful transmission. This problem can be resolved by the application of the busy-tone multiple-access (BTMA) protocol [150]. However, the problem is still not completely resolved when two terminals transmit simultaneously, so that both of them will hear the busy-tone from the base station (control terminal). This will be taken as an indication that it has captured the channel because it has become busy due to its own transmission when in fact an undetected collision has taken place. A further improvement to the protocol is achieved through the use of the Rude-CSMA protocol [29,105].

Regarding land mobile radio, since today's systems use dedicated or reserved channels rather than a sharing protocol, the two primary protocols which have found wide application for packet radio data transmission are the majority-vote protocol, where the validity of transmission is decided on the higher value of successful transmission from a predefined number of transmissions, and the automatic repeat request (ARQ) technique, with all its various modes of operation (i.e. stop-and-wait ARQ, go-back-N continuous ARQ and selective-repeat continuous ARQ).

The applications of random multiple-access protocols in this field are mainly restricted by the control architecture rather than by the data packet transmission. The TACS network is a good example of using the random multiple-access ALOHA protocol [19,86] and the CSMA/CD and busy-tone multiple-access (BTMA) protocols [137] for the reverse control signalling channel from the mobile terminal to the base control station.

Some preliminary studies have been carried out on applications of random multiple-access protocols like CSMA and CSMA/CD for mobile packet radio transmission. Some earlier work carried out by Kleinrock and Tobagi [69,148,150], assumes that packet collision and the effect of the hidden terminal are the major causes of deterioration of the protocol performance operation. However, in recent papers published by Sinha and Gupta[123-125], employing the CSMA and CSMA/CD protocols for packet mobile radio transmission, their analysis of system performance depends on the probability of receiving a successful transmission or that the acknowledgement is in error due to the condition of the channel. This further reduces the protocol throughput, especially when the signal-to-noise ratio becomes very low (i.e. for the same value of offer load, higher values of throughput can be obtained when the signal-to-noise ratio is high and visa versa). We shall consider later the use of these protocols for single channel and multichannel operation.

2-5. CONCLUDING REMARKS

Following this background survey of local communications networks and radio and mobile radio communication networks, we conclude that there is considerable scope for the extension of LAN protocols to radio and mobile radio communication, as these protocols have already proved efficient from the capacity utilisation point of view. To achieve this, it is necessary to find a protocol which can be used in both LANs and in radio and mobile radio applications. It is concluded that the CSMA/CD protocol is more efficient for cable-connected LANs than it is for radio and mobile radio applications.

It is therefore suggested that the CSMA/CA (i.e. with collision avoidance) protocol is likely to be more suitable for use in both systems. In fact, the CSMA/CA protocol is interpreted in the literature in two different ways. We therefore give a short explanation of both interpretations so as to remove the confusion in meaning with the protocol we are considering.

1) A protocol which operates in a mode similar to that described earlier in the hybrid-bus operation (i.e. CSMA/CD and token-passing mode of operation). Such a mode of operation is sometimes referred to as a CSMA/CA protocol[23,114].

2) The second interpretation of a CSMA/CA protocol is one that avoids packet collision by sending a preamble before sending data to ensure that any collision is resolved before the commencement of the transmission of the data. Such a protocol is mainly used with high-speed data transmission and with radio communication [5,20,32,82-84,131, 134,135].

This second interpretation of a CSMA/CA protocol will be used throughout this research. It gives two desirable features compared to the CSMA/CD protocol when used with radio and mobile radio channels. These are;

a) It allows the station or the terminal to detect the collision during the listening periods, which enables it to make the decision more precisely as the main duty of the station in these periods is simply to monitor the channel state.

b) It uses multi-tone transmission which enables the station to distinguish its signal reflection from another transmitted signal, which in other protocols may be attributed as another transmission and thereby interpreted as a collision.

In the next chapter a detailed explanation of the protocol operation is given, followed by its performance operation evaluation using modelling of the protocol both analytically and by simulation.

2-6. SUMMARY

In this chapter a general review of a broad range about digital data communications networks and mobile radio communications is given. Attention has been focused on those networks suitable for use with packet broadcast switching for local area network application, especially the contention based random multiple-access protocols which are used with both LANs and radio and mobile radio communications networks. A general conclusion about the usage of these protocols is then drawn up at the end of the chapter. Further information about any specific topic may be obtained from the references given at the end of the thesis.

CHAPTER THREE

OPERATION AND ANALYTICAL MODELLING OF CSMA/CA PROTOCOL

3-1. INTRODUCTION

As the use of LANs increases, it is anticipated that radio and mobile radio terminals within LANs will become a necessary requirement in order to integrate and accommodate more services within a limited geographical area. To do this, let us consider fig.3-1, where several LANs need to be interconnected with each other, not only through the conventional use of cable connections, but also through radio links. This will enable computer terminals and other services from LANs and several mobile terminals to communicate with each other and to communicate with the fixed terminals that are attached to a specified LAN. This mixing of the mobile terminal distribution with the conventional LAN distribution can be regarded as a single bus local area network as shown in fig.3-2. Each terminal in the figure can represent a mobile terminal or a single fixed terminal or a single fixed LAN. All these terminals are connected to the bus, which represents free space, through their transceivers. These are responsible for the transmission and reception of the data over the channel in the form of packets, as will be described later.

The transmitted signal will propagate through free space, which is not a noiseless path as is generally the case with cable-connected systems. Furthermore, the transmission and reception paths from and to some of the terminals are not always fixed (i.e. some of the terminals are in continuous movement). The channel is thus a time-varying channel, as described in chapter (2). This needs special consideration when designing the protocol governing the transmission and reception over the medium. Packet transmission over radio and mobile radio channels using the contention protocols have been investigated, especially those using the CSMA protocol [38,69,126,148,150,151,164] and its counter-part CSMA/CD[91,149,160].

It is found that CSMA and CSMA/CD protocols are inefficient when their application is extended to the radio and mobile radio environment. This is because such protocols suffer

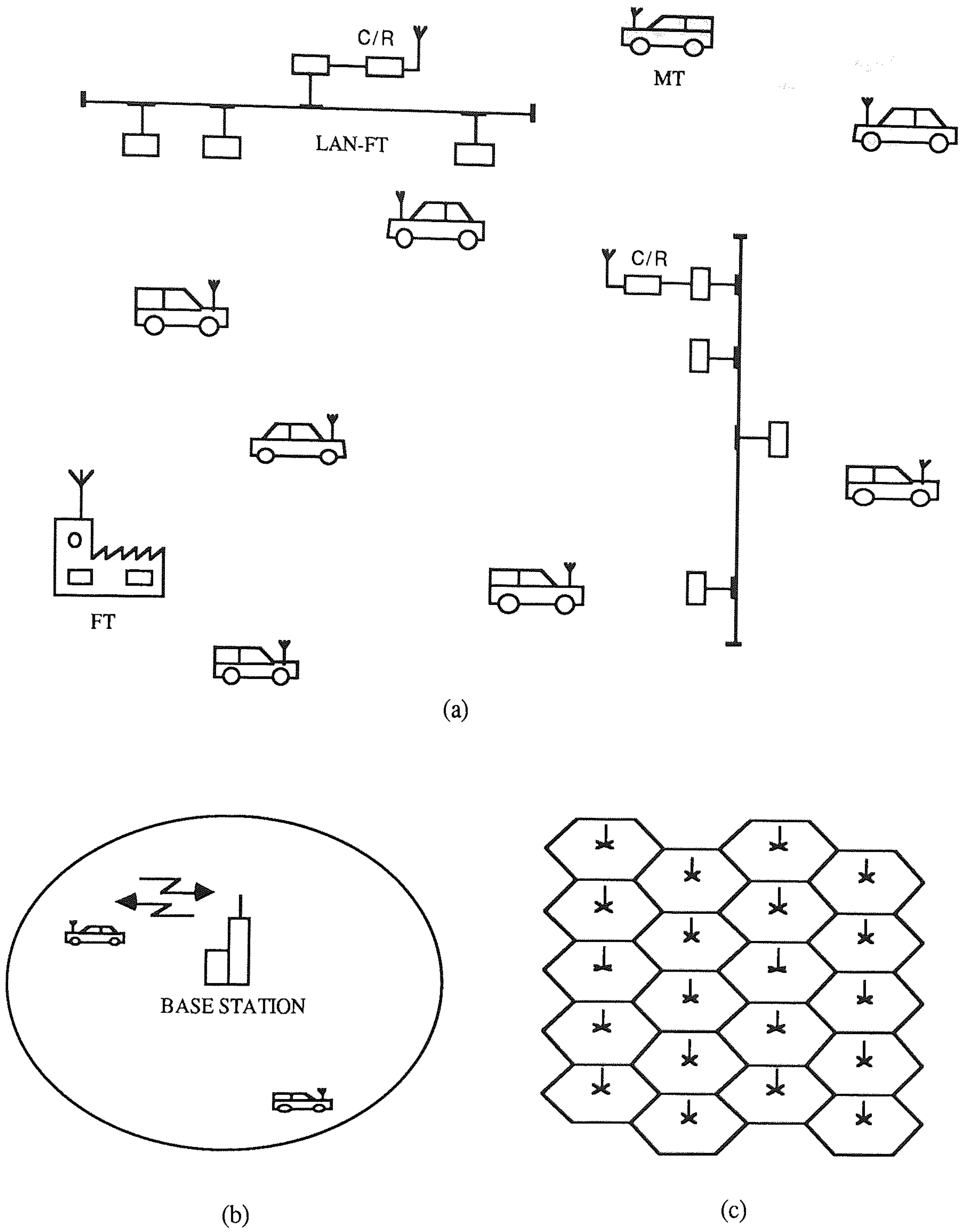


Fig.3-1. Distribution of the terminal stations for the proposed system using CSMA/CA protocol.
(a) Direct access of each terminal to communicate without the use of base station. MT, mobile terminal, FT, fixed terminal which might be a LAN and C/R cable to radio interface or vice versa.
(b) Direct access through base station, where two frequency bands are required.
(c) Same as in (b) with the cellular system.

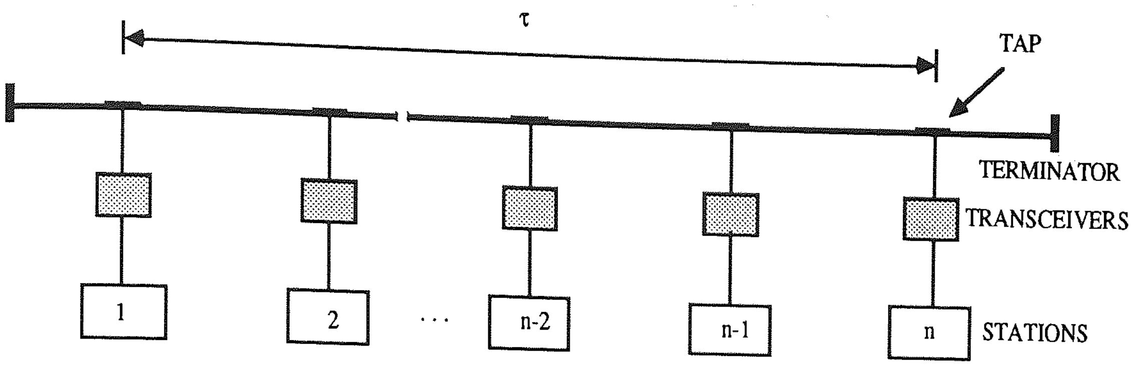


Fig.3-2. Representation of the terminal stations of fig.3-1, showing the equivalence in form to the cable-connected local area network.

from the inability to detect a collision when it occurs between a weak and a strong signal. This is due to the fact that detection of the collision is achieved while both stations are in the transmission mode and this can result in the overwhelming of the weak signal by the strong one. The use of a busy-tone will in fact modify the performance of the protocol, but only in regard to the decision as to whether a collision occurrence has taken place. If the stations are still in the contention mode, this has no effect and may lead to a complete transmission of an unsuccessful packet because both stations receive a busy-tone from the base station which they interpret as an acknowledgement of their own transmission. Another undesirable feature with CSMA and CSMA/CD is that, when there is a reflection of the transmitted signal by discontinuity or radio reflection, this will be regarded as another source of transmission and thereby considered as a collision. Both cases degrade the throughput of the system. In the first case there is an unsuccessful transmission for the whole time period of the packet when a collision has taken place. The second case leads to a withdrawal from a successful transmission. Thus, the CSMA/CA protocol has been proposed as an alternative to the CSMA and CSMA/CD protocols as a possible solution to overcome these shortcomings, as well as to add some other desirable features [10]. The operation of the CSMA/CA protocol and its packet format structure are given in the next section.

3-2. BASIC OPERATION OF CSMA/CA PROTOCOL

The basic operation of the CSMA/CA protocol can easily be seen from its packet structure shown in fig.3-3. Referring to fig.3-2, the transceiver of each station or terminal is completely responsible for the procedure that should be followed in order to transmit a packet on the channel. The total end-to-end propagation time delay of the channel (τ), represents the transmission time across the full diameter of a circular coverage area. A station with data ready for transmission adopts the sequence depicted in the packet format of fig.3-3. The sequence is as follows:

1) **The acquisition period:** The period of time needed by the station to seize the transmission channel. This period consists of the following time periods;

A) The first listening period, equal to a time (4τ), in which the station senses the state of the transmission channel . If any transmission is detected on the channel, i.e. another station has already started transmission, the station withdraws and defers its transmission for a random period of time according to a selected protocol as described in the next section. If there is no detected transmission, the station transmits the first carrier burst.

B) The first carrier burst of time (2τ) duration. A carrier frequency is selected randomly from a range of frequencies and is sent down the channel. This carrier burst informs all other stations that data transmission is to follow from a station attached to the network.

C) The second listening period of time (3τ), which is the final period of time in the acquisition period. This is used mainly for collision analysis when a collision has been detected. If, for instance, two stations have already started their carrier burst transmission, each of them senses the carrier of the other as well as the beat frequency. In such a case, both of them withdraw and reschedule their transmission

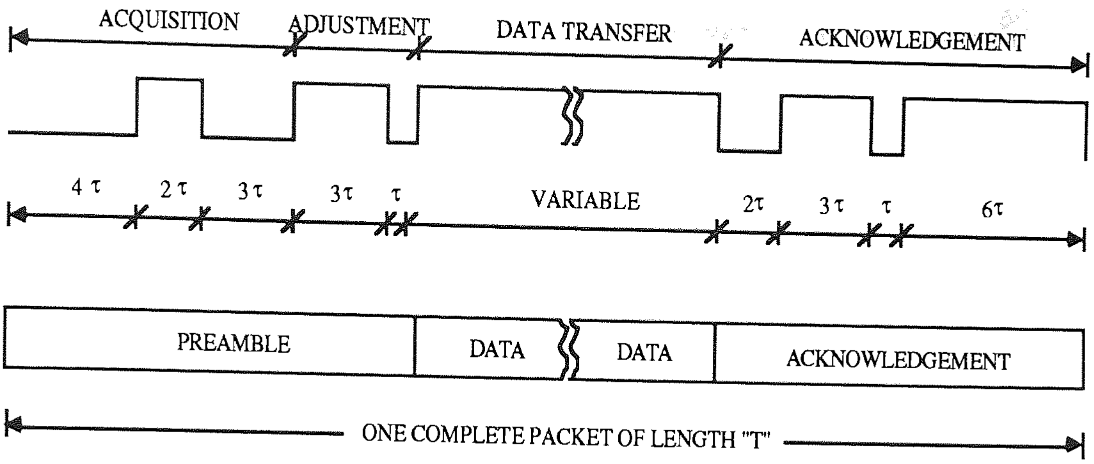


Fig.3-3. Packet format structure of the CSMA/CA protocol.

to take place according to the selected protocol.

2) The adjustment period: The period during which the recipient station adjusts to the level of the signal from the transmitting station on the channel. This period comprises the following;

D) The second carrier burst for a period of (3τ). This period is required for synchronisation purpose between the receiving and transmitting terminal station. At the same time, this period is required for the recipient station to adjust its receiver amplification gain according to the strength of the received signal strength and to synchronise with the incoming data stream. The latter mainly applied for cable connected LAN rather than for mobile radio application.

E) Data preparation time for a time period of (τ). This is sometimes needed by the transmitting station to prepare the data frame ready for transmission from a higher level. Its omission has no effect on the operation of the protocol.

3) Data transfer period: The period of time devoted for data transmission. Its duration is variable according to the system requirements. An approximate figure of

(100-1000)τ is reasonable for most LAN and radio applications.

4) The acknowledgement period: This period is different from the preceding three periods in that it is allocated for the recipient station to acknowledge to the transmitting station the validity of the data that it has received. In this case, the recipient station will act as the transmitter and the transmitting station as the receiver. It consists of the following periods;

G) A carrier burst of a period of time of (3τ), needed for the reverse adjustment of gain and synchronisation purposes as described in (D).

H) Acknowledgement preparation time of period (τ). As before, this may not necessarily be needed in every case.

I) The acknowledgement period of time (6τ), which carries the necessary information about the validity of the previous transmission.

It can be seen from fig.3-3, that there is also shown a period (F). This occurs as a consequence of the ending of transmission and the start of the acknowledgement and is of variable duration. It can be almost zero when the two stations involved are very close to each other and its maximum value of (2τ) occurs when the two stations are located at the extreme ends of the transmission medium. The latter case is represented in fig.3-3.

3-3. THE PROTOCOL

The protocols that are selected for CSMA/CA operation are of the non-persistent type. These are chosen because they give better throughput characteristics than any of the other protocols mentioned in chapter (2) and in the references[10,49,69,134,135,154]. Better throughput is obtained due to the random nature of the transmission, which leads to a reduction of collisions and increases the probability of successful transmission, especially when the load to the network becomes relatively high. Non-slotted and slotted non-persistent CSMA/CA protocols are therefore now considered.

3-3-1. THE NON-PERSISTENT CSMA/CA

The protocol operates as shown in the flow chart of fig.3-4. Any station with a packet ready for transmission will take the following steps;

1) If the channel is sensed idle during carrier sensing, immediately start the first listening period.

2) If the channel is sensed busy, or becomes busy during the first listening period (A), the terminal station withdraws its packet transmission and reschedules its transmission after waiting a random period of time drawn from a probabitity distribution. After the random waiting period, the channel is checked again and the algorithm is repeated from (1) above.

3) If the channel is still idle at the end of the first listening period, the first carrier burst is transmitted. A carrier is randomly chosen by each terminal station from a selection of several carrier frequencies or tones. This is done to enable the station's transceiver to distinguish between a genuine collision and the reflection of its own transmission which might occur, as described earlier.

4) If a collision occurs during the second listening period (B) because two stations start their carrier transmission simultaneously, the collision occurrence is detected either by receiving a carrier frequency which is not equal to the one transmitted or the beat frequency of both carrier transmissions resulting from the collision. In such a case, both stations involved with the collision should withdraw and abort their transmission and wait for a random delay time before reattempting transmission. On the other hand, if the station receives a carrier of the same frequency as its own, this should be ignored and

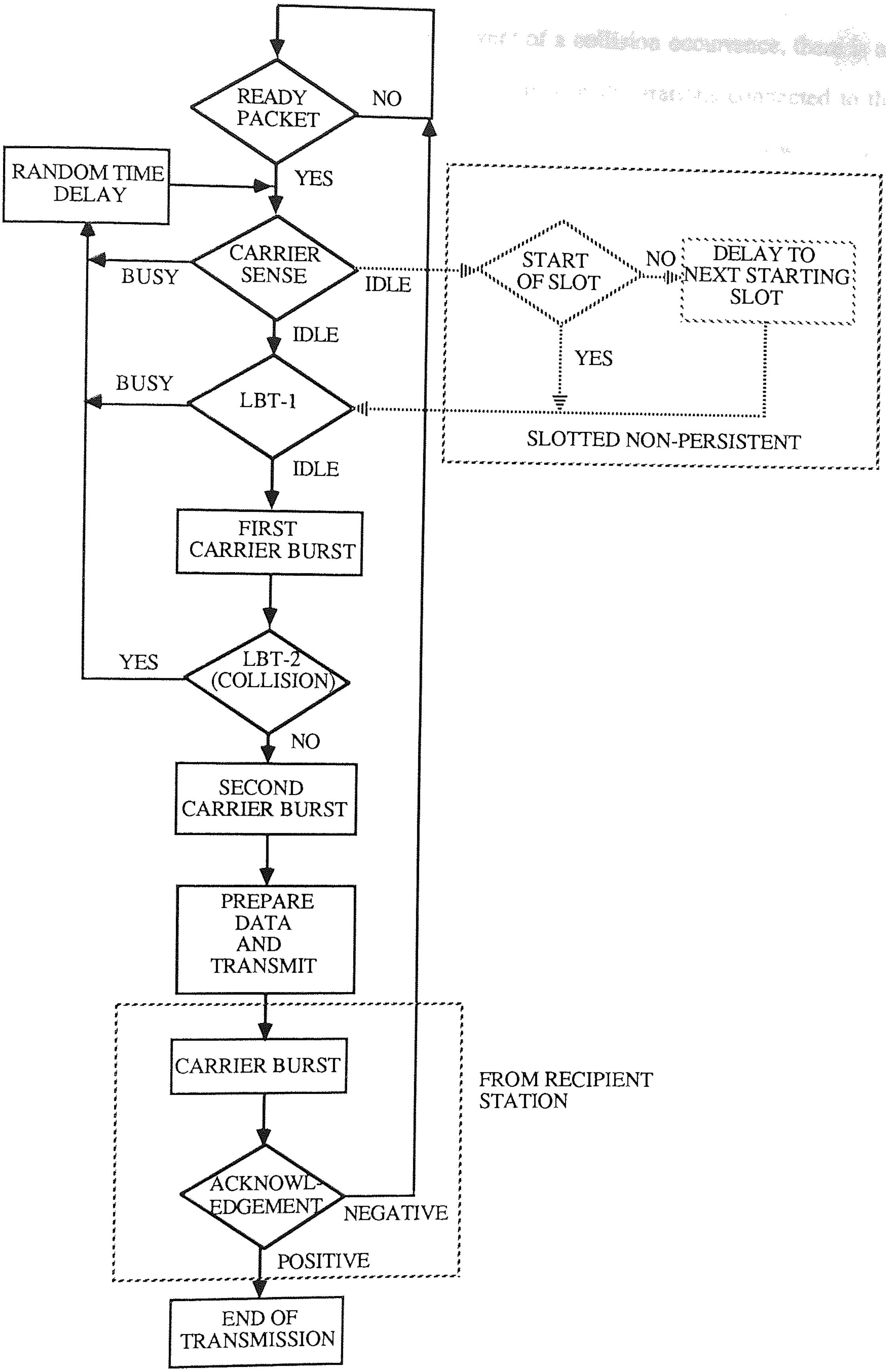


Fig.3-4. Medium access control of the CSMA/CA protocol for packet transmission for non-persistent and slotted non-persistent cases.
LBT-1: Listen-before-talk-1 (the first listening period)
LBT-2: Listen-before-talk-2 (the second listening period)

treated as a false collision indication. In the event of a collision occurrence, there is no need to transmit a jamming signal to inform the rest of the stations connected to the network, as the case of the CSMA/CD protocol, because the beat frequency will act as a collision indication to the rest of the stations, thereby giving the priority of the transmission to those stations involved in the collision event. The protocol is therefore built on the principle of collision resolution before any initiation of data transmission.

5) If there is no collision, adjustment and synchronisation of the receiving station takes place by sending the second carrier burst. This is followed by data transfer, after it has been prepared from the higher level. A limitation on the maximum period of data transmission is placed by the system requirement to prevent hogging of the channel. There is no limitation on the minimum period, as is the case with CSMA/CD.

6) After completion of the transmission, the validity of transmission should be verified during the acknowledgement period (the bottom dotted box in fig.3-4). If a positive acknowledgement is received by the transmitter, the transmission of that packet is complete. However, retransmission is required when a negative acknowledgement is received.

3-3-2. THE SLOTTED NON-PERSISTENT CSMA/CA

In this protocol, the initiation and termination of the transmission time of each station is synchronised by dividing the transmission time into slots. Each slot is equivalent to the time required by the signal to cover a distance between the most distant stations of the network (i.e. two stations laying at the opposite sides of the diameter of the coverage circle). This time represents the end-to-end propagation time delay (τ). The protocol is similar in operation to that of the non-slotted case described earlier. The main difference between the two protocols is shown by the addition of the dotted box to the side of the previous fig.3-4. This appears between the carrier sensing of the channel and the first

listening period (A) and causes the protocol to operate as follows;
If the channel is sensed idle:

1) start the first listening period (A) immediately if the packet arrival is exactly at the start of a slot, otherwise;
2) wait until the beginning of the next slot to start the first listening period (A). This results in the delaying the transmission until the beginning of the next slot.

3-4. THROUGHPUT DETERMINATION BY ANALYTICAL MODELLING OF CSMA/CA PROTOCOL

One of the performance evaluations of the CSMA/CA protocol is the medium utilisation or channel throughput. This can be determined by mathematical analysis. Channel throughput is usually defined as the fraction of the total channel capacity which is used for successful transmission. In system operation, the channel will be in one of two possible states at any moment of time. These two states are the busy state and the idle state and, together, complete one full cycle of system operation. This is naturally a random process. The busy state can be defined as the period of time that the channel either carries a successful message transmission or is contending to seize the channel i.e. the decision about transmission has not yet been taken. The latter may lead to a collision (unsuccessful transmission), which results in a wasting of the channel time. However, the channel is still busy. The idle state is defined as the period of time when there is no transmission on the channel. From above, the channel throughput can therefore be given by;

$$S = \frac{\bar{U}}{(\bar{B} + \bar{I})} \qquad (3\text{-}1)$$

where $\bar{U}$, represents the average time that a cycle of the channel is busy and used for successful transmission (i.e. free from collision), $\bar{B}$ is the average busy time (successful plus unsuccessful transmission), and $\bar{I}$ is the average idle time.

Using equation (3-1), the two cases of non-persistent and slotted non-persistent CSMA/CA protocol will be examined in order to determine the throughput of the protocols. However, before we proceed further with the analysis we shall make some assumptions that will simplify the derivation procedure.

3-4-1. ASSUMPTIONS

There are several assumptions that may be made which simplify the analysis. Some of these are mentioned in the references[10,49,69,82,83,134,135], but since the CSMA/CA protocol is a variant of those analysed in the references and operates in a different environment, further assumptions are added here. These assumptions made in the analysis are:

1) Each station can transmit only one packet at a time. The packet time duration is (T) and consists of multiple slots. This represents one complete entity consisting of the preamble, data transfer and acknowledgement periods as it shown in fig.3-3.

2) The packet length is always very large with respect to the slot time and also large compared with the preamble and the acknowledgment times (i.e. the normalised slot time to packet time $a=\tau/T$ is in the range 0.01-0.001).

3) The channel traffic is generated from an infinite population source and has a Poisson distribution with an arrival rate for both newly arrived and rescheduled packets, of (G/T) packets per second, where G represents the total offered load.

4) The station will not initiate transmission if it has received an indication that another station has already sensed the channel and commenced transmission. This means that carrier sense takes no time to sense the state of the channel. Instead, it withdraws and waits for the next opportunity within the next idle period for transmission.

5) All stations are uniformly distributed on a circular two-dimensional plane, the

transmission/reception is omnidirectional and all stations are within range of each other.

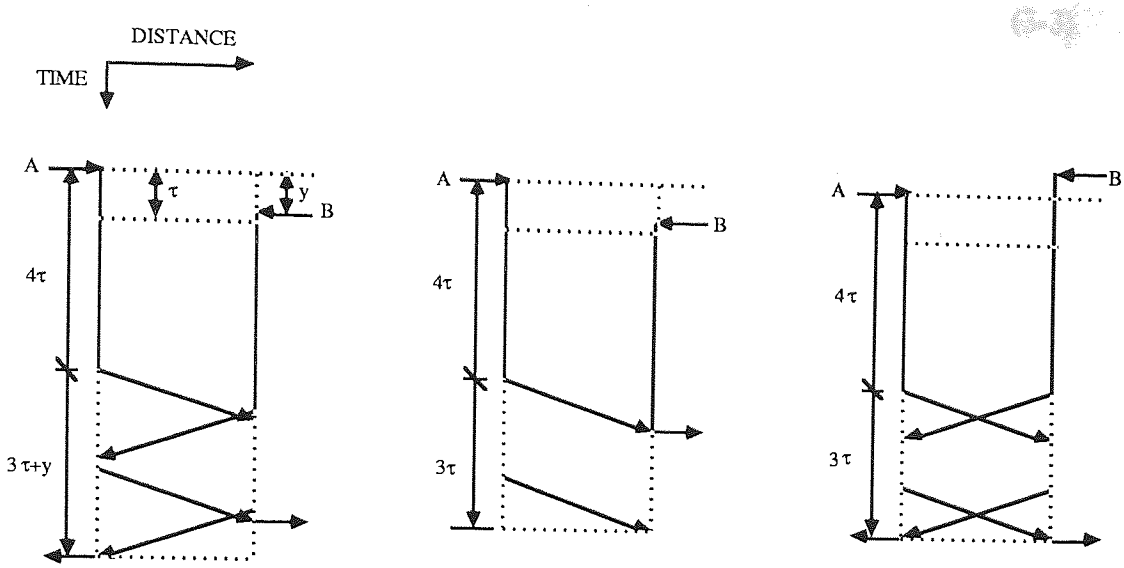
6) The collision resolution takes place after complete reception of the first carrier burst by both colliding stations. This is, in fact, the worst case necessary to give the station enough time to investigate the collision. This in turn will cause the value of the throughput of the system to be at its minimum value.

7) Referring back to fig.3-3, although the first listening period (A) is considered as a part of the packet, throughout the calculation of the throughput this period will be accounted for as a part of the idle period. This is because there is no transmission within this period. This gives the lowest limit for the system throughput. The contention period therefore always starts from the first carrier burst.

8) The unsuccessful transmission is always attributed to a collision occurrence rather than due to any other impairments on the channel like impulsive noise, fading etc. as discussed in chapter (2), which lead to an increase in the probability of receiving a packet or the acknowledgement in error. Acknowledgments are always assumed to be positive.

3-4-2. NON-PERSISTENT CSMA/CA

The procedure adopted by any station in order to transmit a packet is governed by the flow diagram given in fig.3-4. Fig.3-5 is a reconfigured version of fig.3-3. It has been reconfigured on a timing basis so that the periods of time representing the busy period and the contention period are made clear. The calculation will therefore make use of fig.3-5a in order to determine the value of the contention period. In the figure, station (A) is shown as a reference station to which other stations are referred to determine whether they are in collision or not. The vulnerable period for collision occurrence is when two stations simultaneously start their transmission within the same slot, i.e. the vulnerable period is of duration (τ). We will determine each of the three periods given in eqn.(3-1) individually.



BOTH WITHDRAW
(a)

ONLY ONE WITHDRAW
(b)

BOTH WITHDRAW
(c)

Fig.3-5. Contention time of CSMA/CA protocol with respect to a reference station 'A', showing only the acquisition time period, in order to determine the time required by a terminal station to seize the medium for:
(a) Non-persistent case, (b and c) Slotted non-persistent case.

We start with the mean busy period of time, which is given by;

$$\bar{B} = P_s(T+\tau) + (1-P_s)\,\bar{C} \qquad (3\text{-}2)$$

where P_s is the probability of successful transmission and $\bar{C}$ is the mean contention time period. The first term of eqn.(3-2) represents a successful transmission, while the second term represents the contention of an unsuccessful transmission. The term $(1-P_S)$ represents the probability of failure.

To find the value of $\bar{B}$ it is necessary to find the probability of successful transmission and the contention period. The probability of successful transmission mainly depends on the size of the slot time and the total offered load (G). It is therefore given by[10,69];

$$P_s = P\{\ 0 \text{ arrival in } \tau \text{ second}\ \} = e^{-aG} \tag{3-3}$$

The average value of the contention period can be determined from fig.3-5, which represents the time taken by the reference station to discover that its transmission has been involved in a collision. That is;

$$\bar{C} = 3\tau + \bar{Y} \tag{3-4}$$

In the above equation the value of (3τ) represents the time of the first carrier burst of (2τ) when it encounters the worst case of end-to-end propagation time delay of one slot time. $\bar{Y}$ represents the average value of a random variable y which leads to collision occurrence within the vulnerable period and is bounded by $(0 \le y \le \tau)$. The value of $\bar{Y}$ can be found by extending further the assumption for the calculation of the distribution function of y. The expected value of $\bar{Y}$ is therefore given by[10,49,69];

$$\bar{Y} = \tau\left[\frac{1}{aG} - \frac{e^{-aG}}{1-e^{-aG}}\right] \tag{3-5}$$

Now, putting eqn.(3-5) into (3-4) and (3-4 and 3-3) into (3-2), we get;

$$\bar{B} = e^{-aG}(T+\tau) + \tau(1-e^{-aG})\{3 + \frac{1}{aG} - \frac{e^{-aG}}{1-e^{-aG}}\} \tag{3-6}$$

The other parameters $\bar{U}$ and $\bar{I}$ of eqn.(3-1) can be determined as follows. $\bar{U}$ is the time devoted to the transmission of a successful packet through the channel. This time is mainly affected by the packet length and the probability of success. Thus;

$$\bar{U} = P_s T = T e^{-aG} \tag{3-7}$$

The average idle period $\bar{I}$ can be calculated using assumptions 3 and 7, whence;

$$\bar{I} = \frac{T}{G} + 4\tau \tag{3-8}$$

In common with most other references, in the above equation a value of (4τ) is added to the ordinary average idle period. This is because the first listening period is assumed to be a part of the idle period within one complete cycle.

The final throughput equation for the case of the non-persistent CSMA/CA protocol can be determined by putting eqns.(3-6 to 3-8) into (3-1) and, after normalising to the packet length time, we get;

$$S = \frac{e^{-aG}}{\frac{1}{G} + 4a + e^{-aG}(1 + a) + a(1 - e^{-aG})\{3 + \frac{1}{aG} - \frac{e^{-aG}}{1 - e^{-aG}}\}} \tag{3-9}$$

A plot of equation (3-9) is shown in fig.3-6 along with that of the CSMA/CD protocol. Discussion of the results will be postponed however, until we have finished the derivation of the slotted case of non-persistent CSMA/CA.

3-4-3. SLOTTED NON-PERSISTENT CSMA/CA

The transmission in this case is as shown in fig.3-4, when the dotted box is included. The timing diagram is shown in figs.3-5b and c. In the slotted case, two facts have to be identified concerning the transmission of a packet with respect to the reference station (A).

These are; first, if the two stations have sensed the channel idle within different slot times then it is certain that both stations will start their transmission in different slots. Hence, one of them will sense the transmission of the other based on the assumption 4. In such a case, only one station withdraws and defers its transmission. However, the reference station will continue transmission, which is successful as seen from fig.3-5b. Secondly, if the two stations have already sensed the channel is idle within the same slot, they will both initiate their transmission in the next slot. This will lead to a collision and withdrawal of both stations as shown in fig.3-5c. Fig.3-5b will therefore not be taken into consideration when we calculate the contention period because it always results in a successful transmission. However, it is mentioned here to clarify any confusion between the two cases. We will therefore only consider fig.3-5c in the determination of the average contention period.

The procedure to find each individual time period is to some extent similar to that of the previous case of non-persistent, with only small variations to account for the new protocol. Thus, to find the average busy period it is required to find the probability of successful transmission. This is given by [10,49,69];

$$P_s = \frac{aGe^{-aG}}{1 - e^{-aG}} \tag{3-10}$$

The mean value of the contention period, which is simpler than the previous case since the transmission is more coordinated, is given thus;

$$\bar{C} = 3\tau \tag{3-11}$$

Putting eqns.(3-10 and 3-11) into (3-2), the average busy period becomes;

$$\bar{B} = \frac{aG\,e^{-aG}\,(T + \tau)}{1 - e^{-aG}} + 3\tau\,\{1 - \frac{aG\,e^{--aG}}{1 - e^{-aG}}\} \tag{3-12}$$

In a similar way, the average values of the successful transmission period and the idle period can be written respectively as;

$$\bar{U} = T\,P_s = \frac{T\,aG\,e^{-aG}}{1 - e^{-aG}} \tag{3-13}$$

$$\bar{I} = \frac{T\,P_s}{G} + 4\tau = \tau\left(\frac{e^{-aG}}{1 - e^{-aG}} + 4\right) \tag{3-14}$$

Finally, the throughput of the slotted non-persistent case can be obtained by substituting eqns.(3-12 to 3-14) into (3-1), which yields;

$$S = \frac{G\,e^{-aG}}{G\,e^{-aG}(1 + a) + 3\{1 - e^{-aG} - aG\,e^{-aG}\} + e^{-aG} + 4(1 - e^{-aG})} \tag{3-15}$$

The plot of the above equation is shown in fig.3-7. Further investigation of the performance of this protocol follows in the next sections.

3-4-4. NUMERICAL RESULTS

The numerical results of both eqns.(3-9 and 3-15), are obtained by running a simple program written in PASCAL for different values of offered load G and for different values of a (the normalised slot time , which can be varied by changing the packet length). The results reveal that the CSMA/CA protocol (both non-persistent and slotted non-persistent) gives similar results to that of the CSMA/CD protocol. The throughput for both the cases of non-persistent and slotted non-persistent CSMA/CD can be rewritten respectively as[10,49,154];

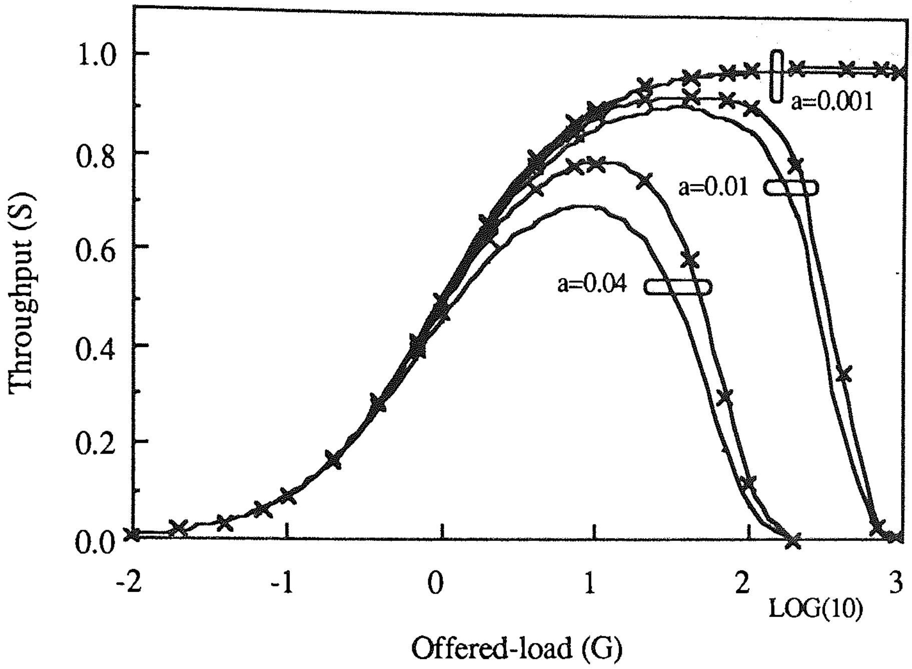


Fig.3-6. Channel throughput vs. offered load of non-persistent CSMA/CA and CSMA/CD for different values of a (different values of packet length).
——— CSMA/CA.
—x—x— CSMA/CD.

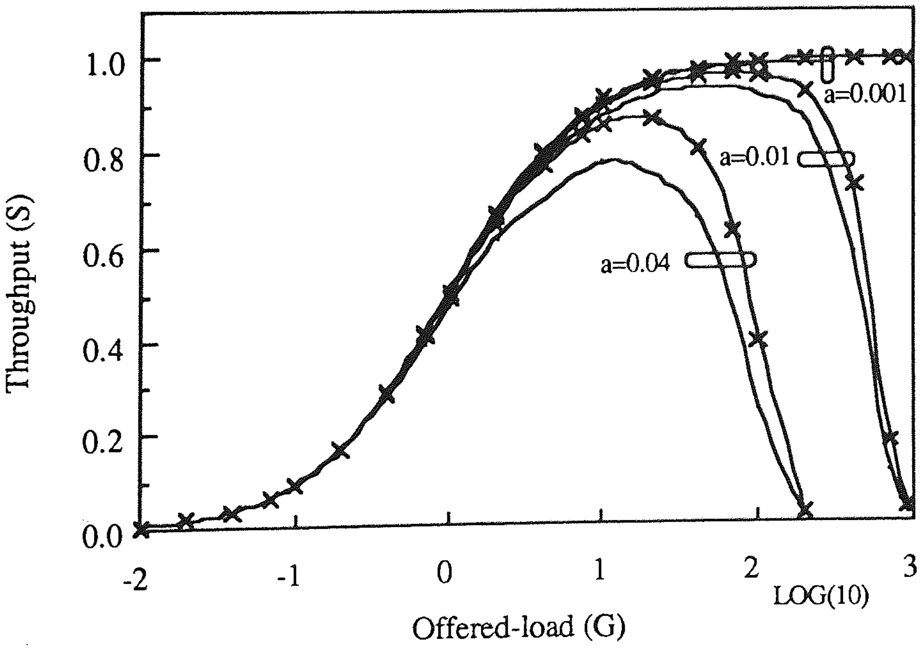


Fig.3-7. Channel throughput vs. offered load of slotted non-persistent CSMA/CA and CSMA/CD for different values of a (different values of packet length).

$$S = \frac{e^{-aG}}{e^{-aG} + a\,(1 - e^{-aG})(\gamma + 2) + \frac{1}{G}\,(2 - e^{-aG})} \qquad (3\text{-}16)$$

$$S = \frac{G\,e^{-aG}}{G\,e^{-aG} + \gamma\,\{1 - e^{-aG} - aG\,e^{-aG}\} + \{2 + e^{-aG} - aG\,e^{-aG}\}} \qquad (3\text{-}17)$$

where γ is the normalised jamming signal which is considered to be γ=1 throughout the results comparison. This value represents the lowest assumption limit, although in most systems values of greater than one are often used. This will affect the gap between the two sets of curves for CSMA/CA and CSMA/CD. It is also clear from figs.3-6 and 3-7 that as the value of a decreases (i.e. the value of the packet length T increases or the opposite when the slot size τ decreases), the throughput of the protocols are increasing and the gap between the CSMA/CD and CSMA/CA becomes narrower, leading to an insignificant difference between both protocols. It should be stressed here that the increase in the packet length should not be left open, but a limit should be fixed according to system requirements so as to prevent monopolisation of the channel by transmission from only one station.

The values of a have been chosen so that a satisfactory operation of the protocol can be investigated with respect to theoretical and practical cases that are used in most of the systems currently in use. However, the lower limit of the CSMA/CA protocol should be well defined, since the packet structure is a variant of CSMA/CD based on the appending of the preamble at the start of each packet. This actually puts a lower limit on the packet length for it to contain information data in addition to the preamble. Such a limit should not be smaller than 15 times the slot size, leaving only two slots of information data, or 25 times when the acknowledgement period is considered as part of the packet, leaving one slot as information data. Thus, in the figures 3-6 and 3-7, values of a equal to 0.04, 0.01 and 0.001 have been taken, which is quite reasonable.

The figures also show comparable results between the case of non-persistent, which is shown in fig.3-6, and the case of slotted non-persistent shown in fig.3-7. The difference is due the fact that in the non-persistent there will always be a chance of a collision within the vulnerability time period of size equal to one slot (τ). This condition does not apply to the slotted case since the vulnerability period becomes variable in size, which sometimes takes the extreme upper bound of τ, but in reality is changeable (i.e. the vulnerable period time (t) for collision occurrence is ($0<t<\tau$)). Thus a modification of system throughput is to be anticipated, a fact which is quite obvious from fig.3-7 in comparison to fig.3-6.

3-5. DISCUSSION AND CONCLUSIONS

The analysis of the CSMA/CA protocol has revealed a slight degradation in system throughput in comparison with its counter-part CSMA/CD protocol. This outcome is the penalty for using a long preamble transmission in order to avoid collision. In spite of this property, it has other desirable features. These are;

1) It provides the system with priority for acknowledgement, which is needed for validation of transmission. In most systems this feature has the effect of increasing the efficiency of that system. On the other hand, providing the system with such a priority creates the need for a long preamble, i.e. longer listening periods, so as to prevent transmission taking place within the worst case of (2τ) delay before the acknowledgement adjustment signal is transmitted from the receiving terminal station.

2) As a result of the above property, the number of offered load packets contending to seize the channel will be reduced to half, thereby reducing the chance of collision. This is

because there is no need for the recipient station to contend with other stations for acknowledgment.

3) There is no need to transmit a jamming signal after each collision occurrence in order to inform the rest of stations or terminals, as happens with CSMA/CD. Here the beat frequency of the two carrier bursts of both stations involved with the collision will act as the jamming signal.

4) The numerical results given in the analysis may be further modified if it is assumed that the preamble time of each packet is equivalent to the packet header of some other system such as CSMA/CD. In such a case the packet header transmission before any packet transmission occupies about 7bytes. This becomes very significant, especially for systems operating with a low rate of data transmission, because the end-to-end propagation delay or the slot time may then be less than one byte time.

5) It is assumed that the first listening period of time is added to the idle time. This in fact adds another factor resulting in throughput reduction of the system.

6) The value of the acquisition and adjustment period may be varied according to the system requirement, i.e. another alternative packet format may be established by reducing the two carrier bursts to only one slot time and taking the lowest limit of the two listening periods of 3 and 2 time slots for (A) and (B) respectively. In the analysis, the periods have been chosen as a compromise between long periods and the lowest limit to enable the system to make a precise decision before any transmission.

7) A further desirable feature is that a priority can be implemented with the protocol very easily. This can be done by changing the preamble period i.e. by reducing or increasing the first listening period. Thus the network has two different types of packet structure. Those stations with priority for transmission have a packet with lower preamble duration

than those without it. Such a facility will provide some of the stations with a higher chance of transmission when they contend for seizing the channel. This is attractive when the system is needed for two different types of traffic, one of them needing near real-time transmission as, for example, for voice packets as in [56].

8) Finally, the proposed protocol can be used with the following systems:

A) With cable connected LANs as an alternative to the CSMA/CD protocol when the transmission medium becomes long. In such an application, there is a substantial increase in signal attenuation along the path leading to a weak signal of a similar to the residual noise for transmission between two stations located at the extreme ends of the transmission path. A strong signal which is transmitted from that far station will therefore overwhelm the weaker one, leading to an undetectable collision. This protocol is therefore able to resolve this problem by the use of the listening time periods.

B) With LANs that involve radio and mobile terminals which span a reasonable circular coverage area. This is because such a protocol has the ability to cope with the station's reflected signal (false collision), which in other systems may be treated as a collision. However, the hidden terminal problem may still result in some undetectable collisions, as with other systems[150].

C) On the same principle as in (B) above, but with elimination of the hidden terminal problem. This can be achieved by sacrificing half the allocated bandwidth and the use of a controlling base station as shown in fig.3-1b. In such a case, the transmission from one station terminal to another will first reach the base station, which will then relay it down the second channel towards the terminals. This transmission will also act as a busy-tone to inform all the terminals about the status of the channel. With this mode of operation, there is still the chance of collision when simultaneous transmission takes place, but this can be resolved at the base station since it stops relaying the signal on the other channel once it detects that a collision has occurred. At the same time, both stations will realise that their transmissions have not been relayed on the other channel and therefore they have encountered a collision and will stop transmission.

D) With cellular mobile radio systems in a way similar to (C) (as shown in fig.3-1c). A busy-tone is implemented with the system, as in this case the channel from the base station towards the terminals will not give an indication about the state of the channel from the terminal towards the base station. This is because the second channel in this case may be used for a transmission which is coming from another cell site through the main system control switch used with the cellular system.

3-6. SUMMARY

The chapter has focused on CSMA/CA as an alternative protocol to CSMA/CD to operate in radio and mobile radio applications. The basic structure of the packet format was given to enable the stations to transmit according to the protocols described. The operation of two versions of the CSMA/CA protocol were explained. These were the non-persistent and the slotted non-persistent. This was followed by their throughput determination. The results obtained from the analysis revealed that lower throughput is obtained with respect to CSMA/CD but this degradation is compensated for by other good characteristics of the protocol which are evident from the comparison. Simulation of the protocol is the subject of the next chapter. This enables the accuracy of the results that were given in this chapter to be validated and investigated further.

CHAPTER FOUR

MODELLING OF CSMA/CA PROTOCOL BY SIMULATION

4-1. INTRODUCTION TO SIMULATION

Communication systems and computer networks have become so complex that it is virtually impossible to determine reliably their performance by means of exact mathematical modelling techniques. However, the cost and availability of equipment means that it is usually not a viable proposition to carry out full practical testing on a complete operational system. Simulation techniques have therefore been developed as an analytical tool for such systems. A number of network simulation packages are currently available for this purpose. These packages can be used to:

1) Test mathematical models to see how well they approximate to the actual network performance.
2) Enable experimental work to be carried out in connection with an existing system without the need to disturb its operation. This is important where a system disturbance would be either very costly or would seriously affect the service quality or safety.
3) Provide prototype modelling of a proposed system before going to the expense of implementing a full working model. With large systems, a working model is not an economically viable proposition. Also the simulation model can easily be changed to see the effect of varying certain parameters on system behaviour.

The following section reviews a number of available packages and shows how a selection was made for the purpose of modelling the CSMA/CA protocol that was represented mathematically in the previous chapter.

4-2. TYPES OF SIMULATION

A number of specially oriented software packages and simulation languages have been developed which provide framework for constructing simulation models. These languages and software provide specific concepts and statements for representing the state of a system at a point in time and moving the system from state to state.

A review of those packages which are mainly employed for the design and simulation of communication networks can be found in [72,121]. Some packages based on a graphical representation of the system to be simulated are described in [64,73]. The wide variety of such techniques make it difficult, if not impossible, to consider them all in order to evaluate their effectiveness regarding their performance, simplicity, result accuracy,..etc.

The framework of most of these packages is based on the queuing networks usually used in analytical models of computer communication systems. Extension to the queuing network makes it a very flexible and expressive representation of computer communication systems[119].

There are several packages available at Aston University that are implemented on different systems. Some of them are mainly devoted to continuous system simulation, as with the case of the ACSL (advanced continuous simulation language) package. However, many others may be used for different types of simulation. Examples of these packages are SIMAN (simulation analysis)[111], and SLAM (simulation language for alternative modelling)[112]. The choice between them should be made on the basis of the type of system to be simulated and the efficiency of the package being considered. The important factors to be considered in comparing different simulation languages are; the training required to learn the language, coding considerations, portability, flexibility, processing considerations, debugging and reliability and, finally, the run-time consideration. SLAM has been selected due to the fact that it contains the facility for writing associated additional routines in ordinary Fortran together with the SLAM statements. This facility helps in opening the space so that more details may be used regarding the system parameters to be included in the simulation process. The next section is devoted for a brief explanation of the SLAM package operation.

4-3. BASIC KNOWLEDGE OF SLAM II LANGUAGE AND PACKAGE

SLAM II is a simulation oriented language which can be used for three types of simulation model. These models are mainly governed by two types of view orientations; the event orientation and the process orientation. Based on these models, a system can be simulated using one of the following three techniques, depending on the nature changes of the system parameters or variables:

1) **Network modelling** which uses the process orientation and consists of specialised symbols called nodes and branches. These symbols model elements in a process such as queues, servers, and decision points. The modelling task consists of combining these symbols into a network model which pictorially represents the system needs to be simulated. In short, a network is a pictorial representation of a process. The entities (such as packets messages, etc.) in the system flow through the network model. The pictorial representation of the system is transcribed by the modeller into an equivalent statement model for input to the SLAM processor.

2) **Continuous simulation** in which the model is coded in SLAM by specifying the differential or difference equations which describe the dynamic behaviour of the state variables. The equations are coded by the modeller in Fortran by employing a set of specially defined storage arrays, which are automatically integrated by SLAM to calculate the values of the state variables within an accuracy range prescribed by the modeller.

3) **Discrete simulation**. In this type of simulation, the system can be modelled into three different styles of simulation i.e. process oriented, event oriented or both. The modeller defines the events and the potential changes to the system when an event occurs. The mathematical-logical relationship prescribing the changes associated with the event type are coded by the modeller as Fortran subroutines. A set of standard subprograms is provided by SLAM for use by the modeller to perform common discrete event functions

such as event scheduling, file manipulation, statistics collection and random sample generation. The executive control program of SLAM controls the simulation by advancing the time and initiating calls to the appropriate event subroutine at the proper points in simulated time. Hence, the modeller is completely relieved of the task of sequencing events to occur chronologically.

In addition to the above three types, SLAM offers the use of any combination of them to simulate systems which need combined discrete-continuous changes or even to construct a combined network-discrete-continuous modelling.

In the simulation of our protocol, we used the discrete event simulation which is more applicable to simulate the CSMA/CA protocol under consideration. A procedural schedule of the discrete event simulation flow is shown in fig.4-1, which depicts how the sequence of the subroutines are initialised and how the events are called in sequence according to their occurrence in the whole simulation procedure. For further information the reader may refer to ref.[112].

4-4. MODELLING OF CSMA/CA PROTOCOL

The simulation model of the CSMA/CA protocol was built in order to investigate the accuracy of the previous analytical model and, at the same time, to measure the overall performance operation of the protocol with respect to its throughput and delay characteristics[40,41]. Before dealing with the simulation procedure that was adopted, we shall list the events that have been used and their purpose, how the packet and the channel were represented and, finally, the assumptions that were made to simplify the task.

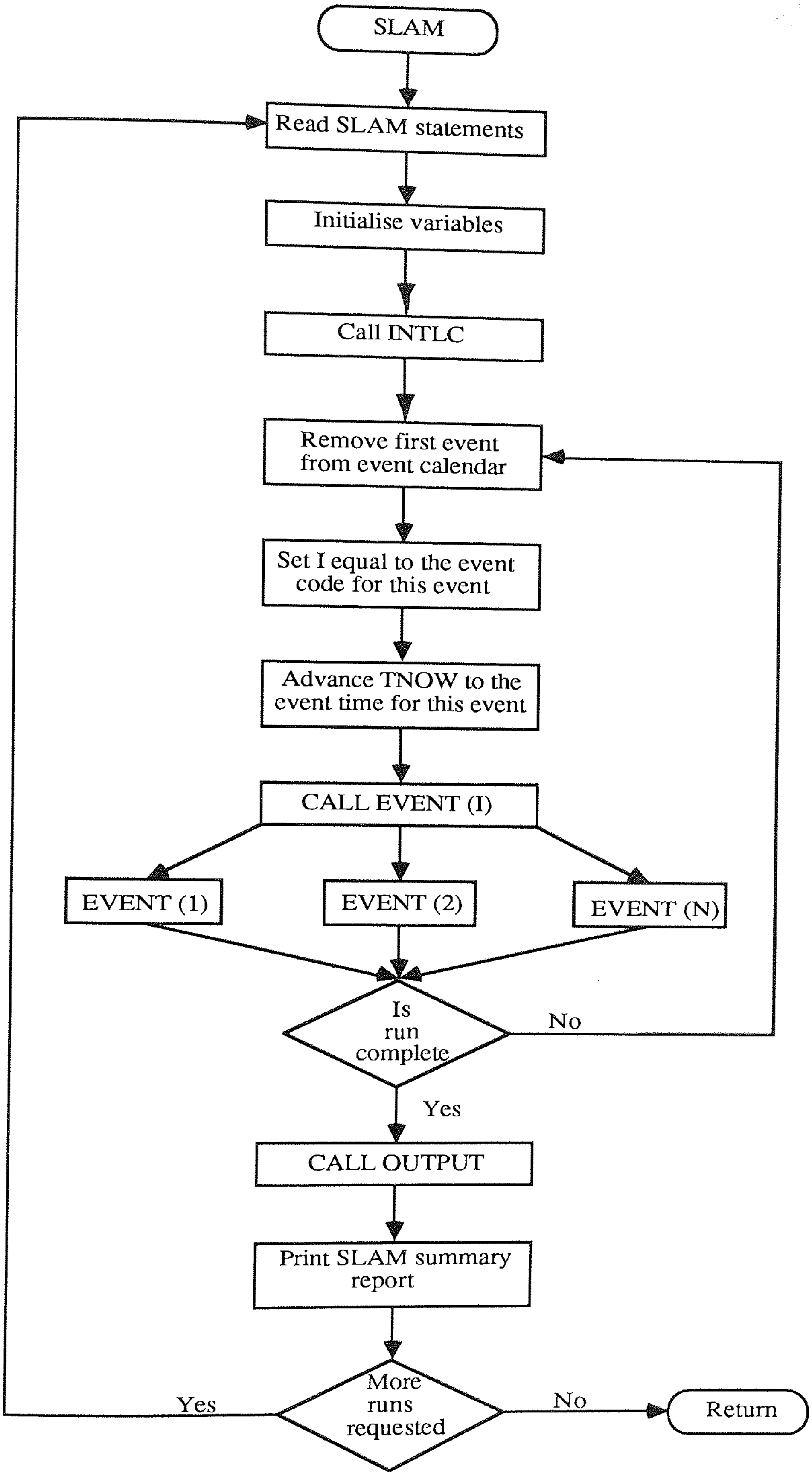


Fig.4-1. SLAM II discrete event procedural subroutines operation sequence.
INTLC: Initialisation subroutine (to initialise the program parameters).
EVENT(I): Subroutine to call the appropriate event routine during the simulation.
OUTPUT: Output subroutine called at the end of each simulation to add further processes on the results when it is required (different from the SLAM summary report).

4-4-1. FLOW OF EVENTS REPRESENTATION

In the model, which uses discrete event simulation, four events are selected to describe the behaviour of the protocol at any time in the simulation procedure. Each event is used to serve the load to the system (i.e. the packets), using its allocated servers for a specified period of time according to protocol time set-up. The four events can be seen in figs.4-2 and 4-3. The purpose of each of them is as follows:

1) **The arrival event:** This is used for the generation of the load (packets) to the system. The offered load is driven from a Poisson distribution function. This is applicable only to the newly generated load, whereas the actual total load in fact represents that of the newly arrived plus those packets that are delayed within the system. This will become clear when we proceed with the explanation of the flow procedure of the simulation process.

2) **Sensing/slotting event:** These two events are used according to whether the simulation is for the non-slotted protocol, which uses the sensing event, or the slotted case, in which the simulation time needs to be slotted and therefore the slotting event should be used. Both events are introduced to put the arrived packet (whether newly generated or retransmitted) in service when the channel is idle for a very short period of time compared to the packet length for the purpose of investigating the possibility of a collision with other packets when simultaneous transmission takes place.

3) **Delay-collision event:** This event is introduced to deal with those packets that need to be delayed for a random period of time. Such an event is needed to serve those packets which sense the channel busy, or encounter a collision. This differs from other systems where a file is used to stack all such packets based on the principle of first-come-first-served (FCFS).

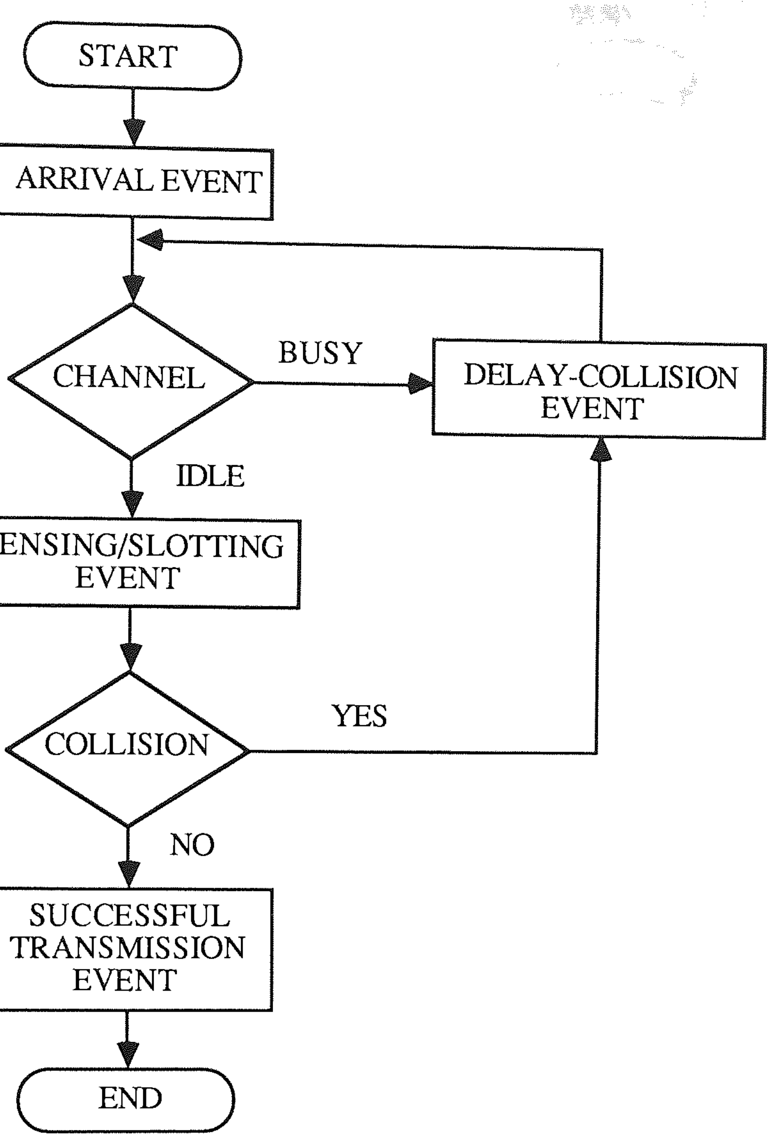


Fig.4-2. Flow of the simulation of the CSMA/CA protocol for both cases of non-persistent and slotted non-persistent.

4) Successful transmission event: This last event is reserved for providing the packets that have completed the sensing/slotting event with service for a period of time equivalent to the packet length that is used with the protocol. The server which is used in connection with this event in fact represents the network channel, which we need in order to simulate its usage with the proposed CSMA/CA protocol.

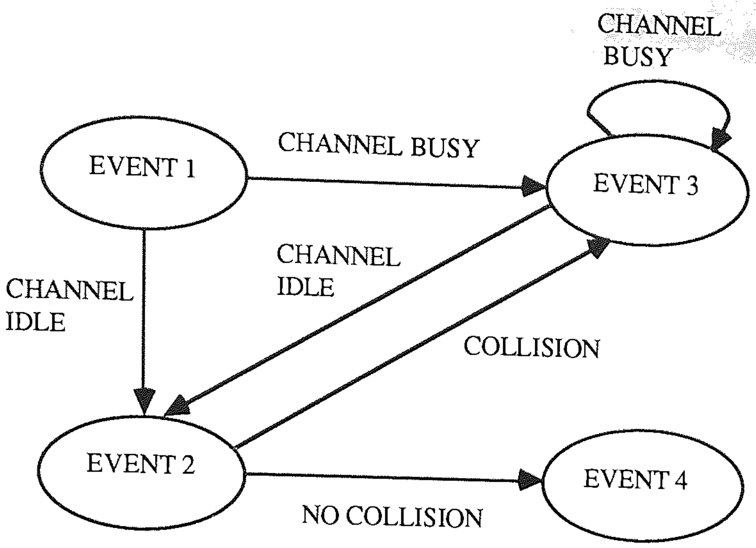


Fig.4-3. Generalised event transition diagram of the CSMA/CA protocol simulation procedure.
EVENT 1: ARRIVAL
EVENT 2: SENSING/SLOTTING
EVENT 3: DELAY-COLLISION
EVENT 4: SUCCESSFUL TRANSMISSION

4-4-2. PACKET AND CHANNEL REPRESENTATION: ATTRIBUTES AND SERVERS

The packets and the channel in the simulation model are represented by the use of the SLAM variables. An identity should therefore be specified for each packet in order to distinguish them from each other. With SLAM, each packet is represented by an entity in the system, each packet being described by three parameters. These parameters are stored in array form for each packet throughout the whole simulation period, until each packet finishes service and is discharged from the system. The parameters are saved in attribute form (ATRIB(j), where j=1,2,..., maximum allowable number with this package) for each entity or packet, where:

1) ATRIB(1), is used to store the packet initial arrival time generated by the arrival event.

2) ATRIB(2), is used to save the number of collisions encountered by a particular packet during the whole process of simulation.

3) ATRIB(3), is used to specify the number of the server which serves the packet when it has completed one of the three service events (sensing/slotting, delay-collision and successful transmission).

The channel in the model is represented by the SLAM global variable XX(I), which represents the server in the simulation. Since the protocols to be simulated share only one channel, we need therefore only one server to represent such a channel, which we shall refer to as the real channel (XX(1), in which I=1 has been allocated). The other servers (XX(I>1), i.e. I=2,3,..., maximum number allowed with the package) are allocated as dummy servers or dummy channels, which are mainly used for delaying the packets for a specified random period of time instead of saving them in file form (i.e. in a queue).

4-4-3. ASSUMPTIONS

In addition to those assumptions mentioned in chapter three, several other assumptions will be made in order to simplify the simulation of the system. These are;

1) That the arrivals from the arrival event are Poisson distributed. This can be achieved in either of two ways, directly by the use of the Poisson distribution or by the use of an exponential distribution where the time between the arrivals is exponentially distributed, when the arrivals may be considered as Poisson [112]. A factor in the simulation which disturbs this assumption is the retransmitted packets. In order to overcome this difficulty, we can either neglect this effect or violate the first assumption by using a control statement within the program to control the total number of packets within the buffer (i.e. the CALENDAR event which is used to manipulate the whole process) of the SLAM processor. In such a case, the program will stop generating new packets when the total number of packets has reached the desired value of the input offered load. Both cases have been examined and they give almost the same results.

2) The packet is represented by one complete entity consisting of the preamble period, the

data transfer period and the acknowledgement period. The latter is included because the protocol has the facility of acknowledgement priority, which enables the recipient to preempt the channel to send its acknowledgement.

3) In both the cases of non-persistent and slotted non-persistent, the packets will be delayed according to the non-persistent protocol [49,69] if the packet senses the network channel busy on its arrival. This random time delay is derived from a uniform distribution between zero and twice the packet duration.

4) If a packet is involved in a collision with other packets from other terminals, it detects the collision during the second listening period [10,20]. Each collided packet, therefore, will be delayed according to the truncated binary exponential back-off algorithm as given in [22,25,36,55,104], plus a constant time of (7τ), which is needed to resolve the collision. This constant time is accounted for by (4τ) from the first listening period, (2τ) from the first carrier burst and the worst case of propagation delay time (τ) during the second listening period [10]. This process happens without engaging the real channel so that, during the simulation, this time is not taken into consideration from the point of view of the determination of channel utilisation, since the channel is carrying no successful transmission. Although the channel is still idle, a pointer in the simulation program will indicate the time needed to clear the channel for another transmission. This pointer will therefore cause all the packets that reach the network during the collision period time (7τ) to be diverted by delaying them through the delay-collision event.

4-4-4. NON-PERSISTENT CSMA/CA PROTOCOL

In the non-persistent protocol, the model operates as is shown the flow procedure in fig.4-2 or the generalised event transition of fig.4-3. The function of the arrival event is to generate the load to the system. The interarrival time (m) of the offered-load (packets) to the system is given by the following equation;

$$m = \frac{T}{P} \tag{4-1}$$

where T is the packet duration time and P is the number of arrivals that occur within one packet time. However, according to assumption (1) previously mentioned in section 4-4-3, the total effective offered load to the system (G) is composed of that generated from the arrival event (P), as in eqn.(4-1), and those packets that need retransmission (R) from the delay-collision event.

Thus;

$$G = P + R \tag{4-2}$$

All these packets first check the channel of the network, which is represented by the global variable XX(1), according to their arrival times. Although their arrival time is stored in ATRIB(1), those packets which are retransmitted are assigned a new arrival time for the purpose of contention with the newly arrived packets. If the channel is sensed busy because there is a packet already being processed by the successful transmission event, the newly arrived packet will defer from transmission and will be directed towards the delay-collision event. The delay that a packet will encounter depends upon whether it arrives during the preamble period or during the data transmission period. The value of such a delay can be determined from Appendix (A), and consists of a random period of time derived from a uniform distribution with specified limits, plus a constant delay period when only the packet arrives during the two listening periods within the preamble time. This constant period stands for the time the packet is delayed until it receives an indication of the busy state of the channel.

Otherwise, if the channel is sensed idle, a preliminary test should be conducted on that particular packet to see whether it will encounter a collision with the packets that will succeed it or not. Such an examination is carried out using the sensing event. This means that each packet is put in service using the variable XX(1) for a period of time equal to the vulnerability range of collision ($t=\tau$). If, within this period, there are other packet arrivals, these packets will collide with the one which is still under test in the sensing event. A timer must therefore be set to give an indication to the other packets to withdraw and delay themselves according to their arrival time until the time for that collision is cleared, plus a random period of time as given in Appendix (A). At the same time, all those packets that have been involved in the collision, including the packet that finishes the sensing event, should be delayed using the delay-collision event according to a truncated binary exponential back-off algorithm [49,55,60,120,160]. However, if no packet arrives within the possible collision time period, the packet that is in service in the sensing event should be directed towards the successful transmission event, once it has completed the sensing event, for a period of time equal to one complete packet time less a period equivalent to (τ), which it has already spent in the sensing event. Thus, during the successful transmission event, the packet length (T) can be allocated for as long as the server XX(1) can be put in the busy state.

With regards to the delay-collision event, it is mainly used in the simulation in order to delay the packets randomly in time with the use of the dummy servers XX(I>1). This enables the non-persistent protocol to be achieved more easily and by a more exact method than any other means, such as the use of files (i.e. queues), to store the packets that exist in the SLAM II processor. As can be seen from fig.4-2, all those packets that encounter delay should contend with other newly arrived packets based on a new arrival time assignment in order to match the advances in the simulation real time. Such an arrival time should be updated whenever the packet uses the delay-collision event. This updating of the arrival time is only for contention purposes. The actual initial arrival time is already stored in ATRIB(1) for the purpose of packet delay determination.

4-4-5. SLOTTED NON-PERSISTENT CSMA/CA PROTOCOL

In the case of the slotted non-persistent protocol, the same procedure as described in the previous section can be adopted with some minor changes, as is shown in fig.4-2. This change includes the alteration of the sensing event to the slotting event. Since this protocol uses event slotting instead of the previously described sensing event, the new event will store every packet for a vulnerability period. This vulnerability period is different from the case of the non-slotted protocol. This period of time is variable and takes values between zero and the end-to-end propagation time (i.e. $0<t<\tau$). In order to do this, the whole simulation time should be slotted into smaller slots, each of duration equal to (τ) unit time. This is achieved by the insertion of the routine 'slot time' before event slotting takes place in both of the arrival and delay-collision events in order to slot the whole simulation time into a number of integer slots. If a packet needs delay, due to either sensing the channel busy or because a collision has occurred, that packet is delayed in a similar way to that shown in figs.4-2 and 4-3.

4-5. RESULTS OF SIMULATION

The results of the simulation are based on data fed to the simulation program in accordance with Table 4-1. Since the CSMA/CA protocol has not been yet standardised by any national or international organisation, special data were used, based on the assumptions given in sections 4-4-3 and 3-4-1. These share some common basic principles of operation with those specified for the Ethernet IEEE802.3 CSMA/CD bus standard[22,25,36,55,60,104,160], which is a 1-persistent protocol. The same algorithm is used for back-off when a collision occurs. No jamming signal is required when a collision occurs and no inter-packet time has to elapse after each successfully transmitted packet.

Table 4-1. Input data fed to the CSMA/CA simulation program.

End-to-end propagation delay (τ)[1]	5μS (1μS=unit time)
Packet time (T)	25τ,100τ and 1000τ
Preamble time duration (t_{pre})	12τ
Retransmission time delay (t_r) (random)	a) Uniform distribution (0 to T) b) Uniform distribution (0 to 10T)
Simulation time	5x10^6 unit time
Collision back-off time (random)	Truncated binary exponential back-off algorithm {0 to 7τ(2^{nc})}[2]

The results are presented in statistical form gathered from the SLAM II summary reports obtained after each run of the program (see Appendix (B)). The throughput of the protocols for the case of the non-persistent and the slotted non-persistent protocols can be obtained by setting a time persistent variable which represents the global variable to the server XX(1). This represents the real channel of the network. Also, similar results can be obtained from such a report depending on the number of observations of those packets that are transmitted successfully. From these it is possible to evaluate the following set of equations with respect to the probability of success, probability of failure, the throughput of the channel and, finally, the average delay of a packet transmitted through the channel.

Thus probability of success P_s for a given offered load is given by;

$$P_s = \frac{K}{G} \qquad (4\text{-}3)$$

---

1) This figure is based on 1km long cable-connected bus-LAN or equivalent to the diameter of a circular coverage area for radio medium as in chapter 3. The propagation speed is 2/3 the velocity of light in free space.
2) The figure is as specified for CSMA/CD protocol in refs.[49,55,60,160]. However, the 7τ replaces the multiplication factor mentioned in the references. (nc) is the maximum allowed number of collisions beyond which the packet will be discarded from the system. In the CSMA/CD case (nc=16) is assumed.

where K represents the total number of successfully transmitted packets given by the number of observations in the summary report and G is the total effective offered load given in eqn.(4-2). From this, the probability of packet failure P_f is given by;

$$P_f = 1 - P_s \tag{4-4}$$

Comparing eqns.(4-3) and (4-4) with eqns.(3-3) and (3-10) given in chapter three, the same results should be obtained for a given value of offered load for both the cases of non-persistent and slotted non-persistent, respectively.

The throughput (S) of the channel can be written as;

$$S = \frac{K.T}{SM} \tag{4-5}$$

where T is the packet time duration and SM is the total scheduled simulation time. Finally, the average delay time (D) that a packet encounters from its generation time until it finishes transmission is given by;

$$D = \frac{\sum_{j=1}^{K} \{\mathrm{TNOW(j)} - \mathrm{ATRIB(1)}_j\}}{K} \tag{4-6}$$

where TNOW(j) is the time when the ith packet has finished service from the successful transmission event and discharged from the system, and $\mathrm{ATRIB(1)}_j$ is the initial arrival time of that particular packet.

Before proceeding further in the analysis of the results, it is worthwhile writing down the equation that describes the ideal system characteristics so as to compare the results that were obtained from simulation with those obtained from the analysis in chapter three. The ideal system channel throughput can be written as;

$$S = \begin{cases} G & \text{for } G \leq 1 \\ 1 & \text{for } G > 1 \end{cases} \qquad (4\text{-}7)$$

Plots of the above equation are shown in fig.4-4 and 4-5, together with replotting of the analytical results that were shown in fig.3-6 and 3-7. For the purpose of comparison, the simulation results are also plotted in the same figure according to eqn.(4-5). As expected, the channel throughput for the case of the slotted non-persistent of fig.4-5 is superior to that of the non-persistent of fig.4-4. This is because slotting tends to reduce the number of collision occurrences as a result of reducing the vulnerability period from a constant value of (τ) in the case of non-persistent to an average smaller value of a varying time period between zero and (τ). It also shows that, in both cases, as the packet length becomes longer (i.e. as the normalised end-to-end propagation time becomes smaller), the throughput of the system becomes higher, reaching a value which is almost a full capacity of the channel when a=0.001.

The average delay that a packet will encounter on being sent through the network with the use of the protocol as given in eqn.(4-6) is shown in figs.4-6 and 4-7. It can be seen that as the offered load to the system increases, the delay is almost constant until the system becomes congested (i.e. when the number of collisions becomes high and the throughput of the system decreases), when the delay increases sharply.

The overall characteristics of average time delay-throughput performance of the two protocols is as shown in figs.4-8 and 4-9. It is clear that as the load on the system increases, the throughput of the system will increase with an insignificant increase in the delay until the system becomes bottlenecked due to the increase in the number of

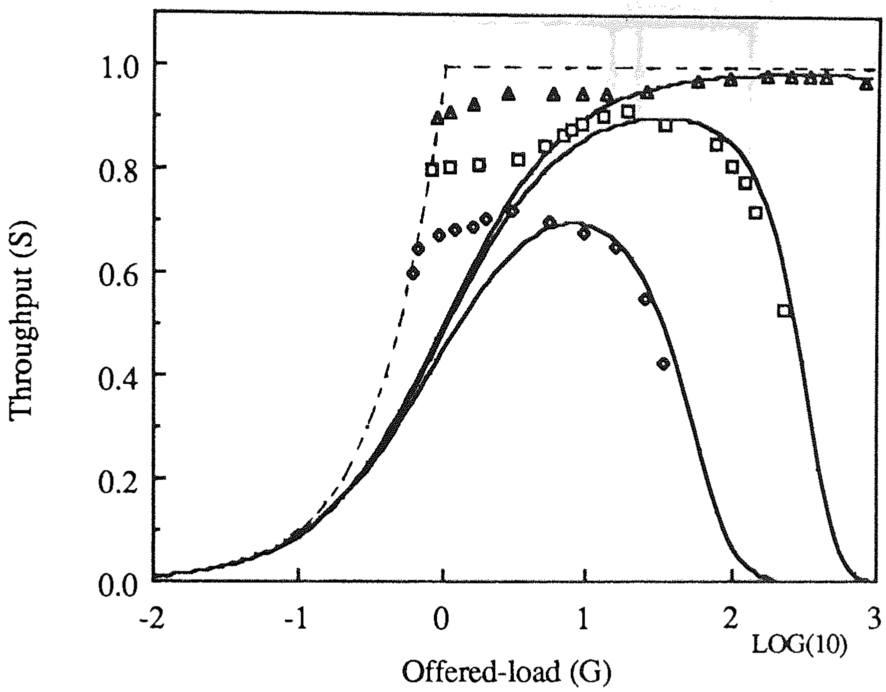


Fig.4-4. Comparison of the throughput of the non-persistent CSMA/CA protocol with the ideal case for the values of a=0.04, 0.01 and 0.001 (same as in fig.3-5).
- - - - - Ideal.
———Analytical.
◆ □ ▲ Simulation.

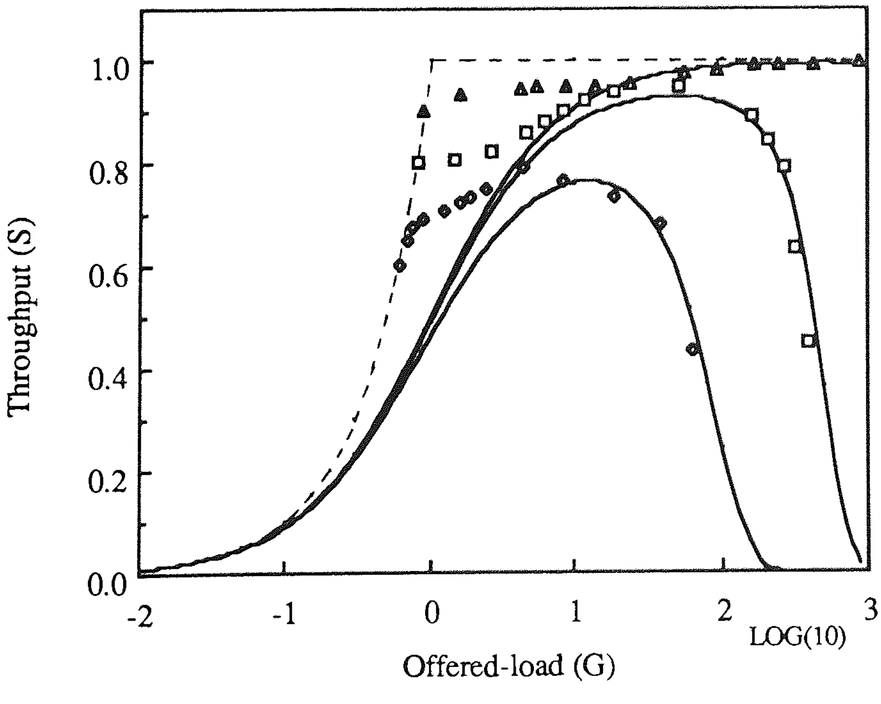


Fig.4-5. Comparison of the throughput of the slotted non-persistent CSMA/CA protocol with the ideal case for the values of a=0.04, 0.01 and 0.001 (same as in fig.3-6).

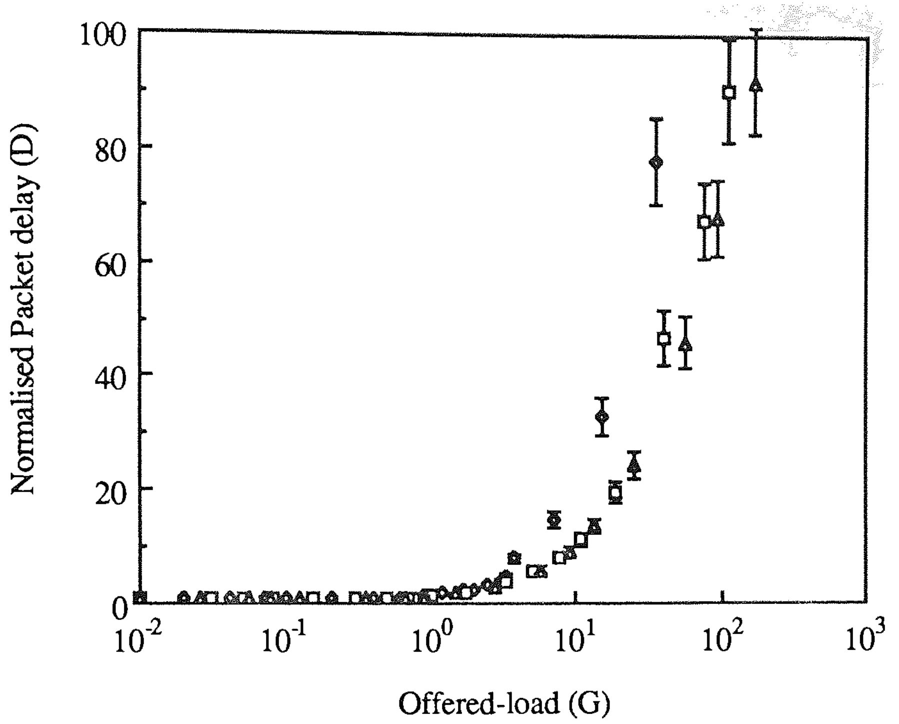


Fig.4-6. Normalised packet delay time vs. offered load of non-persistent CSMA/CA protocol, where ⧲ indicates range of values obtained.

◆ a=0.04
□ a=0.01
▲ a=0.001

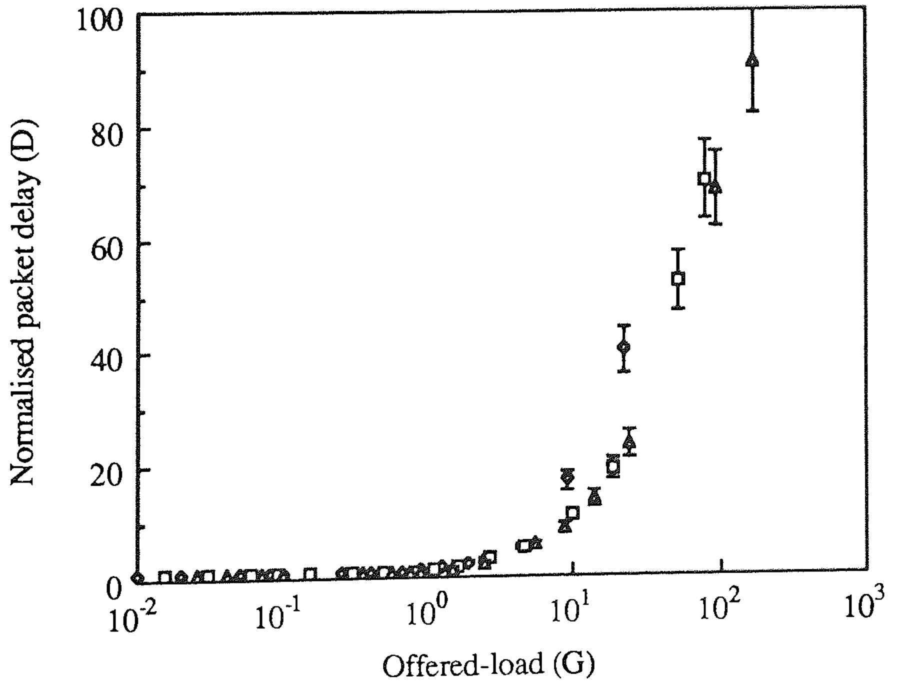


Fig.4-7. Normalised packet delay time vs. offered load of slotted non-persistent CSMA/CA protocol.

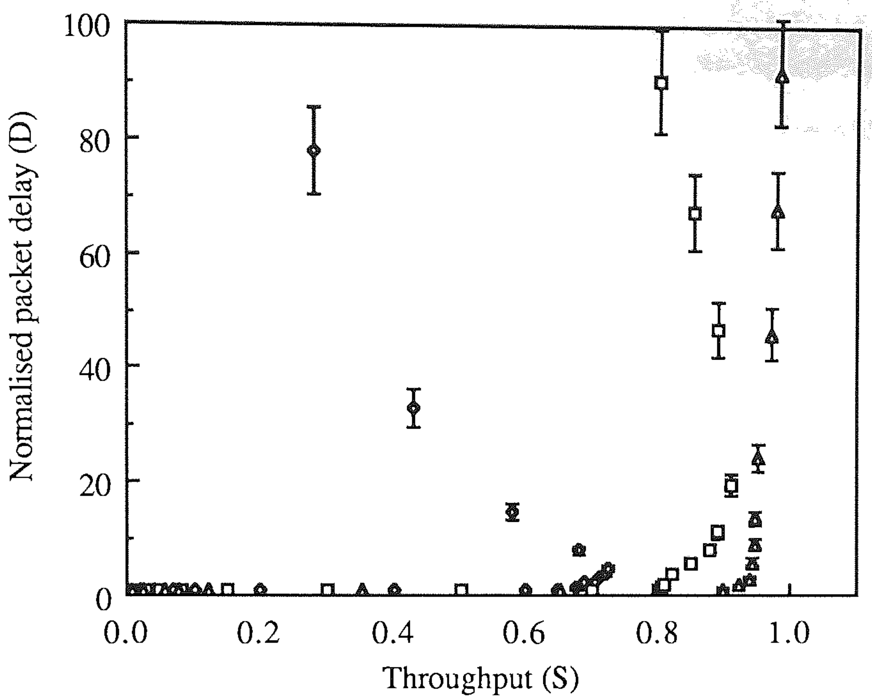


Fig.4-8. Normalised packet delay time vs. throughput of non-persistent CSMA/CA protocol for retransmission time t_r=T.

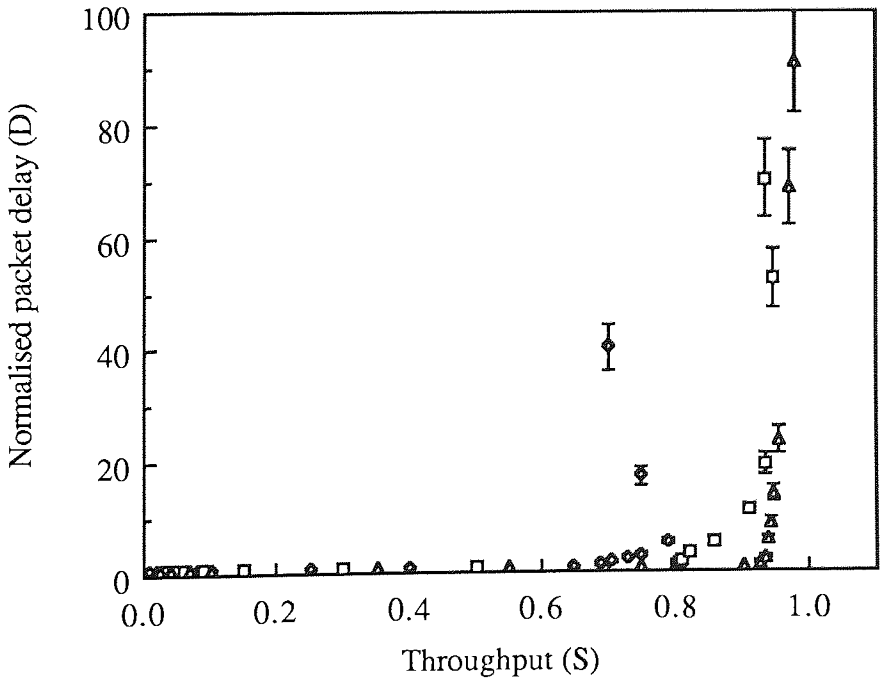


Fig.4-9. Normalised packet delay time vs. throughput of slotted non-persistent CSMA/CA protocol for retransmission time t_r=T.

collisions which leads to an increase in the number of rescheduled packets. This leads to a deterioration of the system throughput, with an increase of normalised time delay, when the protocols reach an unstable range of operation. This can also be seen from the previous two figures (4-4 and 4-5). Results are shown in figs.4-10 and 4-11 for when the maximum limit of the probability distribution is increased to 10T. In this case the range of the random retransmission time, which is derived from the above distribution, will be increased resulting in a slightly longer average delay for each packet, accompanied by a slight, though insignificant, increase in system throughput.

4-6. COMPARISON BETWEEN ANALYTICAL AND SIMULATION MODELS

Comparing the simulation model results with those of the analytical model, we would not expect a complete coincidence over the full range of system operation. This is due to two important assumptions that were made to ease the derivation of the mathematical model. These are that, firstly, the generated packets are drawn from an infinite population with no distinction being made between newly generated and retransmitted packets. Secondly, no specific back-off algorithm is included in the analysis, which is equivalent to making the back-off time for retransmission approach infinity[69]. These two assumptions are not applicable in the simulation, since the first one will lead to elimination of retransmission, whereas the second will produce a constant average packet time delay equal to the packet time when the back-off is infinity.

The range of operation of figs.4-4 and 4-5 can be divided into three regions for comparison purposes, corresponding to various values of a. At low values of offered load, the simulation and the analytical results behave similarly to the ideal case and give an excellent representation of the system. However, the analytical model lacks this property in the second half of the low load region. Under medium load, the simulation model results are superior to that of analysis. This superiority in both the second half of the low

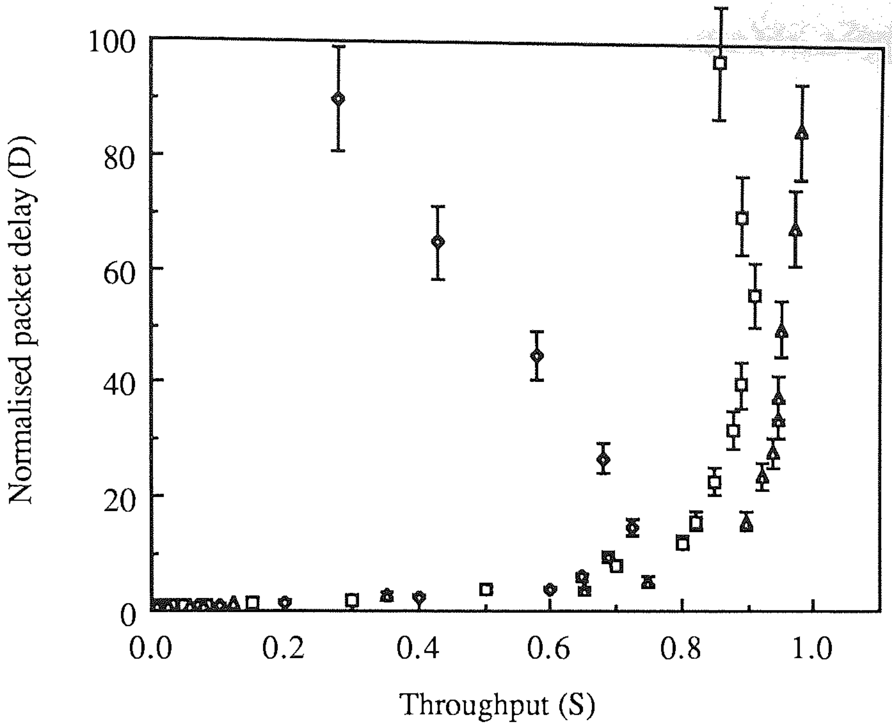


Fig.4-10. Normalised packet delay time vs. throughput of non-persistent CSMA/CA protocol for retransmission time t_r=10T.

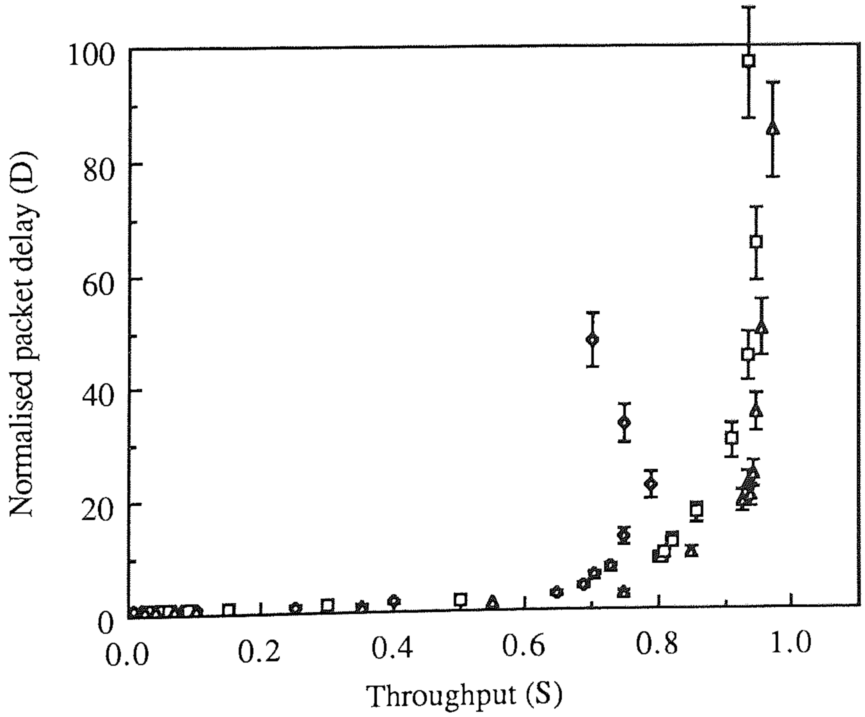


Fig.4-11. Normalised packet delay time vs. throughput of slotted non-persistent CSMA/CA protocol for retransmission time t_r=10T.

load region and the medium load region is accounted for by the fact that the truncated binary exponential back-off algorithm used in the simulation [55,69] is more effective than that assumed for the theoretical model and also by the fact that the theoretical analysis does not accurately handle retransmission. In the third region, both results almost coincide, although the theory gives a slightly higher throughput due to the fact that the retransmission time is infinite, which cannot be achieved in simulation i.e. the number of retransmissions will increase dramatically due to the congestion in the system.

It is also worthwhile mentioning that the superiority of the simulation model is also due the inclusion of the first listening period as a part of the packet, which is not included in the analytical model.

A further modification to the results is possible through the allocation of an extra attribute (ATRIB(4)) containing the location of the station. This only applies to the case of cable connected LAN systems, rather than to those that incorporate mobile terminals, as it is difficult to predict the exact location of moving terminals. This will reduce further the possibility of collision to a value which is lower than the two vulnerability periods that were mentioned earlier for both cases of non-persistent and slotted non-persistent operation.

Finally, it is important to ensure that the simulation time is sufficiently long to ascertain that the results obtained are truly representative of the actual system and not built on a short period of time which is insufficient to make a judgement on the validity of the results of the protocol. At the same time, this period should not be increased beyond a certain limit, especially when the load is very high. Under such circumstances, the network becomes congested and this leads to the accumulation of delayed and collided packets in the SLAM buffer storage. As a result of this, the simulation process becomes unstable and may therefore terminate before reaching the scheduled simulation time.

4-7. SUMMARY

This chapter commenced with an introduction to simulation and why simulation is used. A brief review of some of the simulation procedures and packages were presented to give the reader some background knowledge about this technique. Attention was then directed to the SLAM II simulation language package. A brief look was taken at the basic operation of this package and its model applications. Discrete event simulation was selected to simulate the two cases of non-persistent and slotted non-persistent CAMA/CA protocols. The results of simulation revealed that the simulation model can represent the protocol operation in a way similar to that of the analytical model.

CHAPTER FIVE

OPERATION OF BROADBAND MULTICHANNEL SYSTEMS

5-1. INTRODUCTION

Broadband networks have been introduced to use the available network bandwidth in a more economical and efficient way, at the same time allowing variable data transmission rates to be used to achieve system integration. Broadband systems have the following advantages[27,30,42,89,106,108,142,158,159]:

1) They use transmission technology readily available from a wide range of suppliers.
2) They provide adequate bandwidth for the total data communication needs of the vast majority of sites.
3) They allow multiple independent communication facilities with different grades of service to share the same physical transmission facility.
4) They provide high total capacity with cost-effective equipment by using multiple lower speed channels in an integrated system, which means that larger overall channel throughput can be obtained.
5) They support inexpensive entry level systems but expand easily to large distances and/or user populations.
6) With the use of a multichannel broadband system, the operation reliability of the network can be improved since the disruption of one channel would never put the whole network out of operation.

Two techniques for such networks have received considerable attention, as mentioned in chapter two. These are; (a) frequency division multiplex (FDM) and (b) code division multiplex (CDM). To date, several protocols have been established to work with FDM. Most of these use the CSMA/CD protocol for medium access and the majority are proposed for applications with LANs. Such broadband multichannel systems have not so far been used with mobile radio, since all existing multichannel systems for mobile radio still depend on circuit-switched protocols rather than on packet contention random multiple access protocols. A detailed survey of these systems is given in the following

Section.

An alternative system for use with broadband multichannel is one that uses the code-division multiple access (CDMA) technique. In this system, N different logical channels are allocated for the users connected to the network. The principle of signal separation between these channels is based on the orthogonal properties found in some digital sequence sets. The number of logical channels that can be used is dependent on the number of mutually orthogonal sequences in the set. If maximal length sequences are used, each bit-shifted version of the sequence is orthogonal. The number of logical channels will, in turn, limit the number of users that can be served in operating such a system. We will not go in to further details of such a system here, since our proposed systems are based on FDM multiplex. However, further information is available in the literature, for example, work reported by Smythe and Spracklen from the University of Durham and some other publications from other research institutions [63,76,77,122,128,129,132,133,155]. All of this work is concerned with the application of the technique to local area networks, including the transmission of voice on such networks.

5-2. BROADBAND SYSTEMS FOR LANS AND RADIO AND MOBILE RADIO APPLICATIONS

This section gives a brief review of work that has been carried out regarding the operation of broadband networks based on the principle of FDM and contention-based network access. It has already been shown in section 5-1 that the application of such systems results in an improvement in the overall performance of operation.

So far, two types of broadband systems have been used in LAN applications. The first is the single channel broadband [49,114,134,135,142,157], where the entire bandwidth of the transmission medium is allocated for one signal transmission and in which the transmission is bidirectional, as with the baseband system described in chapter three. The main difficulty with such a broadband system lies in the design of the bidirectional amplifiers which need to operate over a wide frequency range. The second type is the multichannel system, which can be divided into two modes of operation. The first mode of operation employs a unidirectional transmission, in which the bandwidth of the medium (cable) is divided into two distinctive frequency bands, one for each direction of transmission (often called in-bound and out-bound channel). Full connectivity of such a transmission system can be achieved by the use of a headend. This can be either passive or active. A passive headend is used when the in-bound and out-bound channels are using separate cables, whereas an active headend is used when only one cable is used. In such a case, the active headend performs the necessary frequency translation from one frequency band to another. Such broadband systems are exemplified by the Fasnet and Expressnet [81,152,153], which use the same principle of operation with a medium access control (MAC) similar to token-passing.

The second mode is bidirectional (broadcast) operation, in which the total transmission bandwidth is divided into N channels. These N channels may be allocated either statically (fixed) or dynamically for signal transmission. The simplest example of static allocation of channels is the homenet system, proposed by Natravali et al [50,92]. This uses the moveble-slot time-division-multiplexing (MSTMD) [93] for MAC, which is a version of CSMA/CD. In this scheme, the network propagation delays are reduced by dividing the area of coverage into small communities of physical proximity according to the communication demands. Each of these groups is then assigned to a particular channel and each has a headend which is used to obtain full system connectivity between the channels that are dedicated to carrying the load from different homenets. Similar work has been carried out using the CSMA/CD protocol for MAC and without the use of the headends[106]. Clearly such a mode of operation does not allocate the total system bandwidth in a globally optimum fashion.

The dynamic channel allocation scheme was originally proposed by Marsan and Roffinella [89], where the users are provided with multiple transmitter/receiver pairs, which enable them to access any channel in the network without any restriction regarding their communities. Such a mode of operation has the advantage of uniformly and automatically dividing the offered load amongst all the channels. However, the propagation delay of the network remains the same, not reducing like the previous system. Several developments and analyses have been carried out, based on the principles of operation given in [70,90,108,161,162]. Further details will be given later, as one of our proposed protocols depends on this strategy.

Extension of such protocols for application to radio and mobile radio are still in the early stages of development and several difficulties have been encountered. The application of the dynamic allocation of channels to radio systems was proposed by Willson and Rappaport [158,159] and was found to increase the trunking efficiency of the network.

5-3. MULTICHANNEL NETWORKS BASED ON CSMA/CA PROTOCOL

Two contention-based protocols are proposed based on the broadband multichannel systems. These are, the dynamic system, that operates on a similar principle to that described in section 5-2, and the sequential system. They operate with a multichannel system using the CSMA/CA protocol for medium access and are based on well-known FDM techniques[42]. In both protocols the total bandwidth of the transmission medium (B) is divided equally into a set of (N) parallel frequency bands (channels) of bandwidth (B_i, $i=1,2,\ldots,N$), each having its own carrier frequency (f_i). Guard bands are also provided to separate the channels to prevent interference. A separate control channel is also allocated in order to send the necessary control information to all the terminal stations connected to the network. Thus fig.3-1 can be reconfigured to that shown in fig.5-1, in which the transceiver of each terminal station can transmit one packet at a time on one of

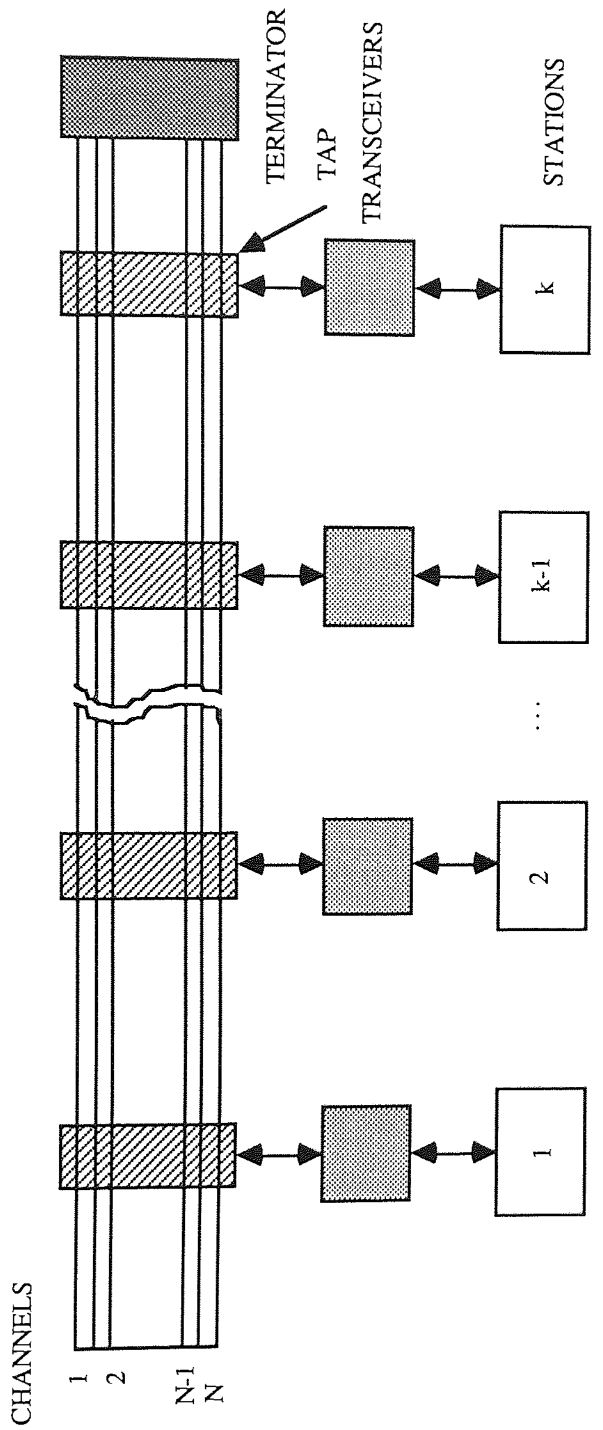


Fig.5-1. Reconfiguration of figs.3-1 and 3-2 for multichannel representation of the proposed broadband systems.

the N channels according to the protocols that will be described later. However, it can receive more than one packet at a time from several channels. Some other differences between the operation of the two protocols will be given later as appropriate.

5-4. DYNAMIC MULTICHANNEL BROADBAND NETWORK

Two modes of operation are discussed in this section, based on dynamic allocation of N parallel channels. The selection of the channel for packet transmission will either be random, called random choice (RC), when a specific channel is selected without taking its state into consideration, or the selection of the channel will be only from those which are idle and is therefore called idle choice (IC). Further details about their virtual operation are given in the following subsections, together with their throughput determination. Since the total bandwidth is divided into N channels, this will affect the transmission rate of a particular terminal compared with the rate that was determined in chapters two and three. It is therefore worthwhile writing down the following set of equations which will be needed later in the derivation of the throughput of both modes of operation [42].

$$B_i = \frac{B}{N} \tag{5-1a}$$

$$T_i = NT \tag{5-1b}$$

$$a_i = \frac{\tau}{T_i} = \frac{a}{N} \tag{5-1c}$$

where B_i is the ith channel bandwidth, N is the number of channels, T_i is the packet length transmitted over the ith channel. The total amount of data content is the same as for the packet used with single channel operation described earlier. The normalised end-to-end propagation time of the ith channel to the ith packet size is represented by a_i. The packet structure for both of the (RC) and (IC) channel selection will be the same as the packet shown in fig.3-3.

5-4-1. RANDOM CHOICE (RC) CHANNEL SELECTION

In this subsection, the operation of RC channel selection is described, together with its throughput determination, based on the procedure adopted for dynamic channel allocation described in section 5-2. The two cases of non-persistent and slotted non-persistent operation are considered.

5-4-1-1. OPERATION

In random choice (RC) channel selection, the terminal station with a packet ready for transmission will operate as shown in fig.5-2. The station randomly selects one channel from the N channels and checks its state. If that particular channel is sensed busy, the station withdraws and defers its transmission to some later time according to a specific random distribution and then selects a further channel using the same procedure. If the channel is idle, the station will commence transmission according to the CSMA/CA protocol described earlier in chapter three. The random procedure of channel selection can be achieved in two different ways, either the station will continue with the same channel until its transmission commences, even when retransmission takes place, or the station will change the selection of the channel every time a rescheduling of its packet takes place.

5-4-1-2. THROUGHPUT DETERMINATION

To determine the system throughput for the RC mode of operation, a simple alteration can be made to the throughput equation of single channel operation derived in chapter three. This alteration mainly concerns the distribution of the offered load to the ith channel (G_i) and the normalised end-to-end propagation time delay of that particular channel. The offered load in this case depends on the probability of choosing that particular channel for the transmission (P_i). Thus, the following equations are given [42];

$$G_i = GP_i\left(\frac{B}{B_i}\right) \qquad \text{(5-2a)}$$

$$P_i = \frac{1}{N} \qquad \text{(5-2b)}$$

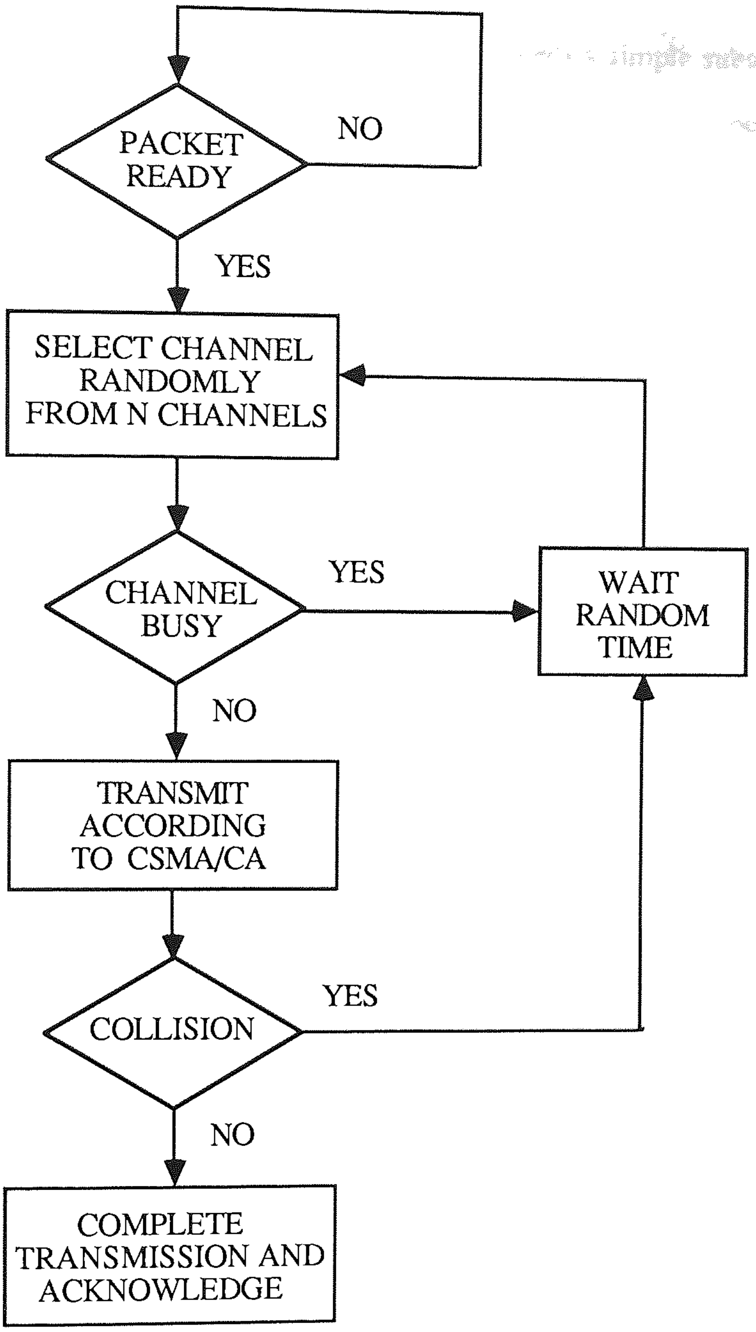


Fig.5-2. Flow of multichannel dynamic random-choice channel selection (RC) for packet transmission.

It is clear that the ith channel offered load is the same as in the previous case when substituting eqn.(5-2b) into eqn.(5-2a). This indicates that dividing the overall transmission bandwidth to lower rate channels needs longer packets to transmit the same amount of data, thereby increasing the overall offered load by the same amount. However, there are N channels to provide service to this increment in the offered load.

Now, to find the overall throughput equations needs a simple substitution of eqns.(5-1c and 5-2a) into eqns.(3-9 and 3-15) for the cases of non-persistent and slotted non-persistent protocols respectively:

$$S=\frac{e^{-aG/N}}{\frac{1}{G}+4\left(\frac{a}{N}\right)+e^{-aG/N}\left(1+\frac{a}{N}\right)+\frac{a}{N}\left(1-e^{-aG/N}\right)\left\{3+\frac{N}{aG}-\frac{e^{-aG/N}}{1-e^{-aG/N}}\right\}} \tag{5-3a}$$

$$S=\frac{Ge^{-aG/N}}{Ge^{-aG/N}\left(1+\frac{a}{N}\right)+3\left\{1-e^{-aG/N}-\left(\frac{aG}{N}\right)e^{-aG/N}\right\}+e^{-aG/N}+4\left(1-e^{-aG/N}\right)} \tag{5-3b}$$

The plot of the throughput of these two equations against various total offered loads are shown in figs.5-3 and 5-4 respectively. It is obvious that an improvement in system throughput is obtained compared to single channel operation. This improvement increases as the number of channels increases for both cases of non-persistent and slotted non-persistent, although in the latter the increment is relatively higher for the same reason mentioned earlier in Section 3-4-3.

5-4-2. IDLE CHOICE (IC) CHANNEL SELECTION

In this mode of operation, the terminal station will choose a channel from among only those channels which are idle. It is therefore called idle choice (IC) channel selection. In such a case, an improvement in system throughput is anticipated due to the fact that the number of rescheduled packets are reduced in comparison to the case of (RC) channel selection. Rescheduling of the packets is only needed when two simultaneous transmissions take place which leads to collision.The following two sub-subsections give the operation and throughput determination of the (IC) channel selection for both cases of non-persistent and slotted non-persistent CSMA/CA protocols.

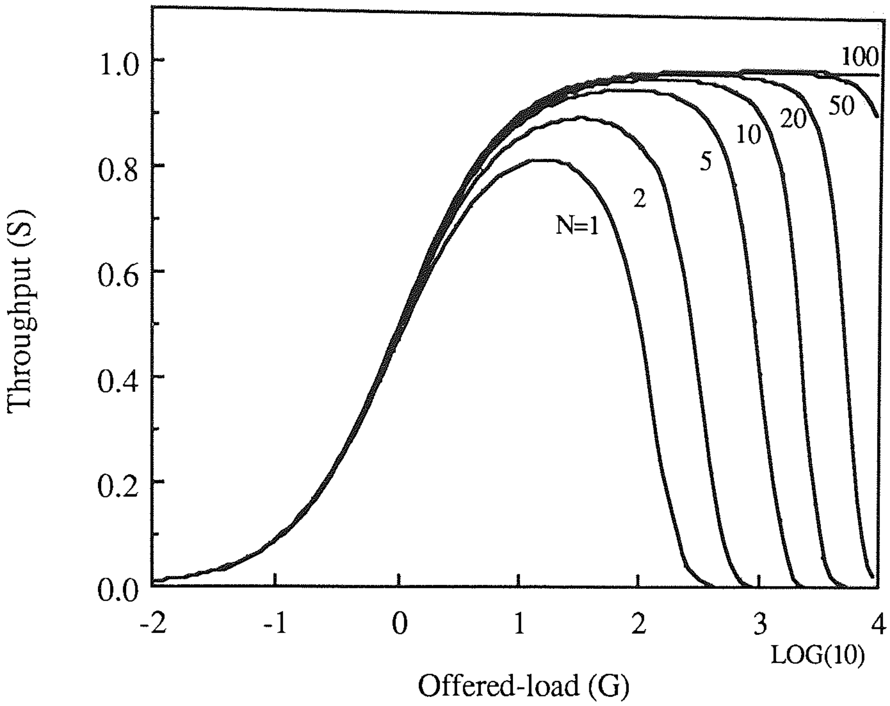


Fig.5-3. Throughput-offered load characteristics of dynamic random-choice (RC) channel selection in multichannel system with different values of number of channels N for the case of non-persistent CSMA/CA protocol medium access.

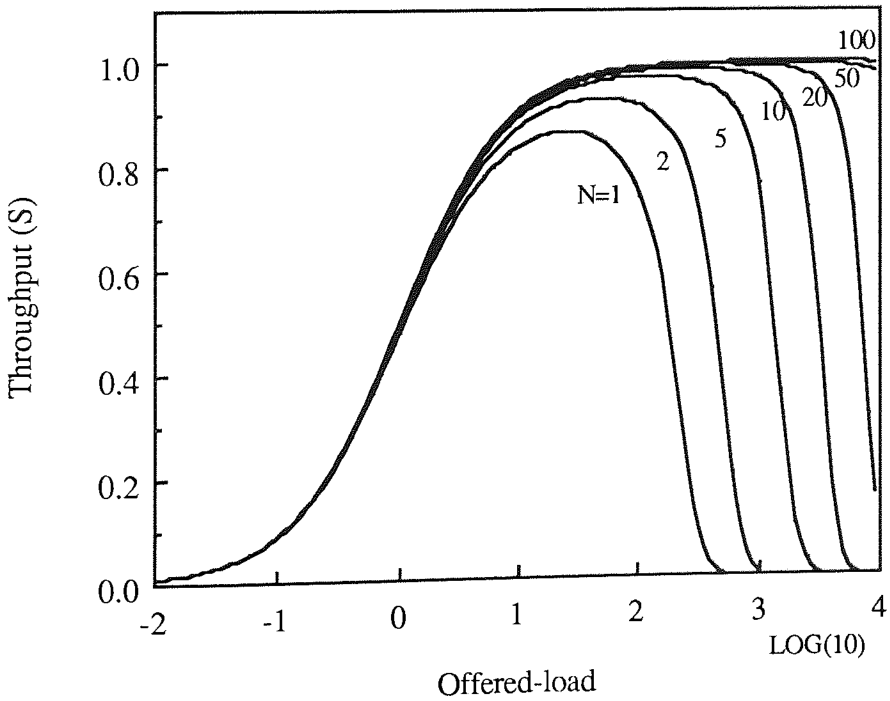


Fig.5-4. Throughput-offered load characteristics of dynamic random-choice (RC) channel selection in multichannel system with different values of number of channels N for the case of slotted non-persistent CSMA/CA protocol medium access.

5-4-2-1. OPERATION

The operation of the IC channel selection is as shown in fig.5-5. A terminal station with a packet ready for transmission will proceed as follows. All the terminal stations have complete information about the busy/idle state of all N channels. This is achieved by probing all the channels continuously and up-dating the terminal information. Thus, when a channel has been selected by a terminal station it is sure about its idle state. However, there is still one thing that has to be investigated before successful transmission takes place, the probability of collision occurrence if two transmissions have been commenced during the vulnerability period of collision. If such a thing happens, those stations involved in the collision retry again by each selecting a further channel from those which are idle.

5-4-2-2. THROUGHPUT DETERMINATION

One can determine the overall throughput of the system operating under the (IC) mode in a similar way to that of the (RC) channel selection. The only vital parameter that needs special identification is the ith channel offered load distribution. In this case, two different methods can be adopted for this purpose. The first, which is mainly applicable for a large number of channels, is also the most difficult to evaluate. It uses the assumption that while sensing the channel, the channel can be in one of three possible states. These states are; it may be sensed busy, it may be sensed idle while it is actually idle, or, finally, it may be sensed idle while it is busy i.e. during the vulnerable period of collision. Because this method of evaluating the offered load is rather difficult, it has not been adopted here. The second, which is applicable for low and medium numbers of channels, is easier to evaluate and assumes the ith channel offered load to be Poisson distributed. However, it requires a minor change to take into consideration the probability of selecting the particular channel only from those which are idle. Thus, the following set of equations can be written [89];

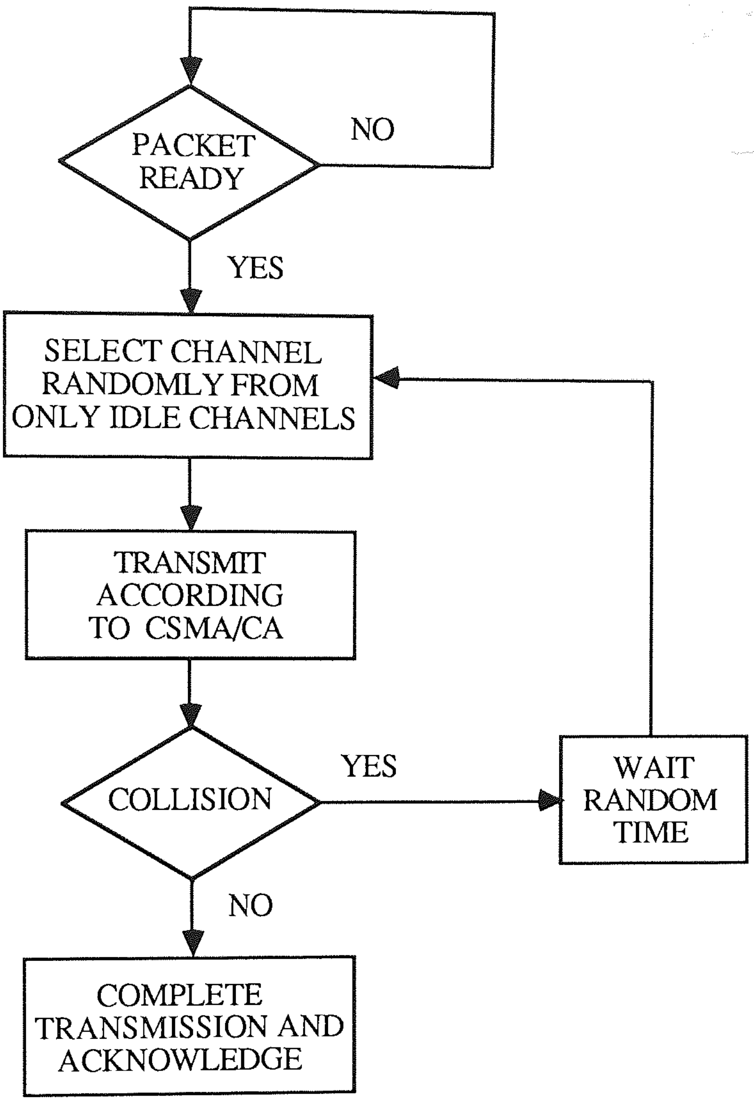


Fig.5-5. Flow of multichannel dynamic idle-choice channel selection (IC) for packet transmission.

$$G_i = \frac{G\{1 - (1 - P_i)^N}{P_i} \tag{5-4a}$$

$$P_i = \frac{1 + a_i G}{G(2a_i + 1) + e^{-a_i G}} \tag{5-4b}$$

Again, substituting eqn.(5-1c) into (5-4b) and (5-4b) into (5-4a), and then into eqns.(3-9 and 3-15), we get the overall throughput of the system for the cases of non-persistent and slotted non-persistent operation as follows:

$$S=\frac{e^{-aG_i/N}}{\frac{1}{G_i}+4\left(\frac{a}{N}\right)+e^{-aG_i/N}\left(1+\frac{a}{N}\right)+\frac{a}{N}\left(1-e^{-aG_i/N}\right)\left\{3+\frac{N}{aG_i}-\frac{e^{-aG_i/N}}{1-e^{-aG_i/N}}\right\}} \tag{5-5a}$$

$$S=\frac{G_i e^{-aG_i/N}}{G_i e^{-aG_i/N}\left(1+\frac{a}{N}\right)+3\left\{1-e^{-aG_i/N}-\left(\frac{aG_i}{N}\right)e^{-aG_i/N}\right\}+e^{-aG_i/N}+4\left(1-e^{-aG_i/N}\right)} \tag{5-5b}$$

Plots of both the above equations for different values of offered load are shown in figs.5-6 and 5-7 respectively. An improvement in overall system throughput is obtained. However, the improvement is towards the low load operation condition rather than towards the higher values, as in the case of (RC) channel selection. This is due to the nature of the (IC) mode of operation, which selects only the idle channels rather than accepting longer delay with higher throughput at high offered load.

5-5. SEQUENTIAL MULTICHANNEL SYSTEM

The sequential strategy of multichannel broadband system operation is mainly proposed to overcome the problem of the hidden terminal by allocating the available channels sequentially. It therefore, differs from the previous method from the point of view of operation and thus also has implications on the packet structure and some other parameters. The differences in the transceiver of the terminal station of fig.5-1 are [42]:

1) The transceiver operates in either of two modes of operation when it operates as a receiver. One of these modes is similar to the previous case i.e. it can receive more than one packet from different stations on different channels at the same time. The second mode is that it can receive only one packet at a time. In such a case there is an imposed restriction on the station that it should not transmit to any station which is already busy at the time. Thus, the following features should be taken into consideration:

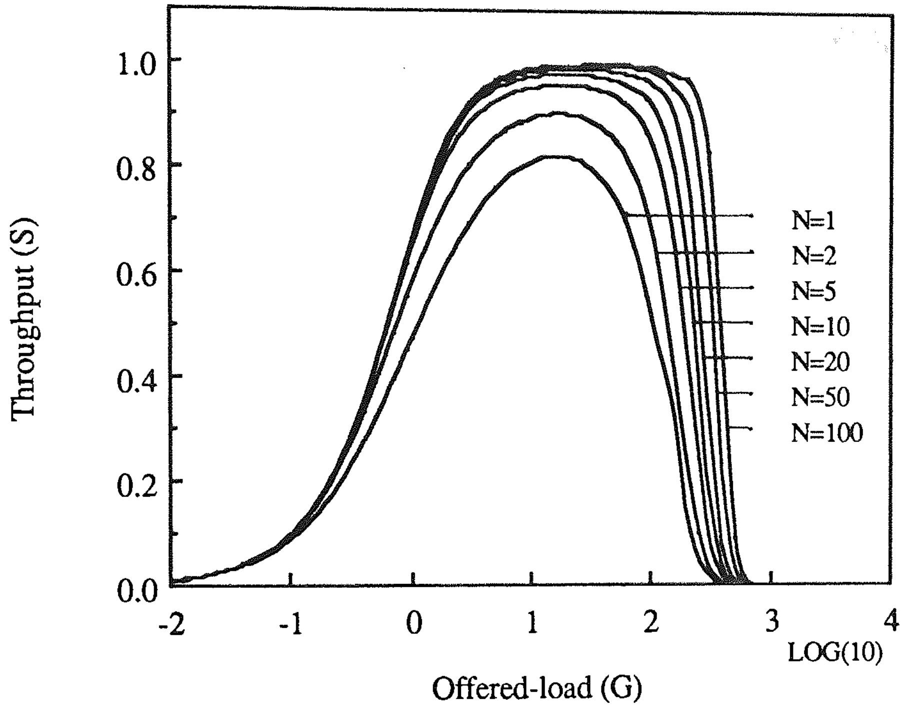


Fig.5-6. Throughput-offered load characteristics of dynamic idle-choice (IC) channel selection in multichannel system with different values of number of channels N for the case of non-persistent CSMA/CA protocol medium access.

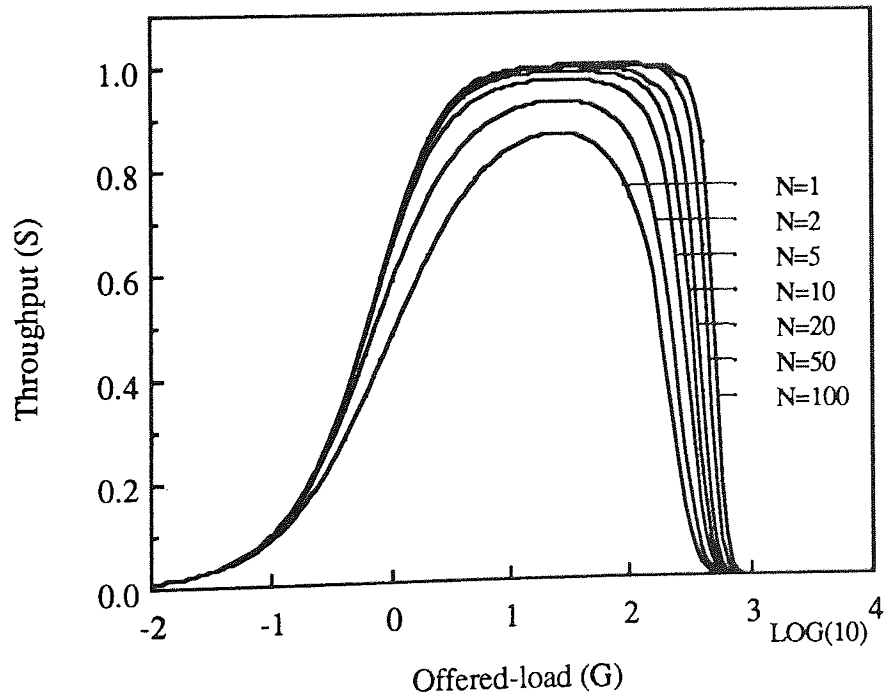


Fig.5-7. Throughput-offered load characteristics of dynamic idle-choice (IC) channel selection in multichannel system with different values of number of channels N for the case of slotted non-persistent CSMA/CA protocol medium access.

a) Each transceiver contains a stations-busy list so that each terminal station can avoid transmitting to any station which is already busy (transmitting or receiving), thus eliminating unnecessary connection.

b) Up-dating the busy list is achieved through copying the addresses of each transmission from the preamble.

c) The addresses are contained in the second carrier burst of the preamble.

2) The packet structure is different from the previous case and mainly depends on the number of operating channels and the preamble length used with the packet.

3) As mentioned earlier, an additional common control channel is required in order to transmit the necessary control information to all the terminal stations which are connected to the system. Such control information reduces the packet length when a channel is disrupted, as the packet length depends on the number of channels in use. The control information is also required by the terminal stations to enable them to skip the disrupted channel.

5-5-1. OPERATION

The operation of the sequential contention-based multichannel protocol is based on the allocation of channels sequentially to the offered load packets using the CSMA/CA protocol. To explain the way the system operates, consider the timing diagram shown in fig.5-8. The packets arrivals from different terminal stations are given the chance to be transmitted in turn, so that all the packets should first contend to seize a particular ith channel, thereafter transferring to the next channel. In the figure, channel 1 is allocated to arrival 1, which uses its packet preamble to resolve collision if necessary. At the end of the preamble time all other terminals will change and tune their carrier frequency to the next subsequent frequency band. Arrival 2 will therefore be allocated channel 2 and so on. If a simultaneous transmission is taking place from two stations

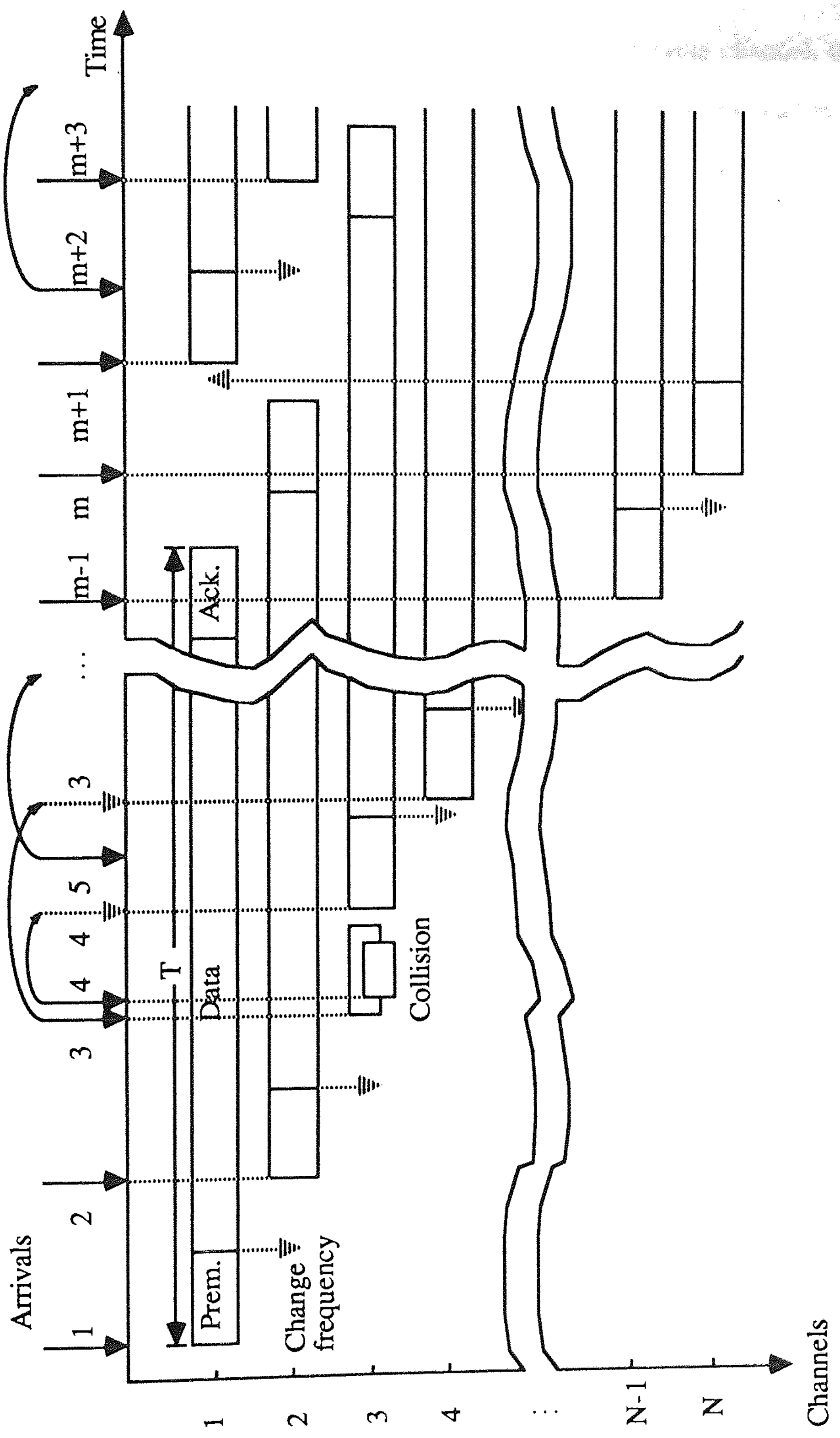


Fig.5-8. Timing diagram of channels allocation of the sequential multichannel protocol using CSMA/CA protocol for medium access.

within the vulnerability period of time (τ), both of the terminal stations will detect the collision as explained in chapter 3, and will withdraw and defer their transmission according to a specified random distribution. This case is exemplified by arrivals 3 and 4, which both withdraw and contend again to seize the same channel, until one of them succeeds in preempting that channel. If an arrival from a terminal station arrives within the preamble time but is outside the collision barrier, this arrival will be delayed according to a random distribution as with the case of arrival 5. This process will continue until the allocation of all channels is exhausted except for the last channel (N). When arrival m seizes that channel, at the end of the preamble all the terminal station's transceivers change their frequency and tune to the first channel i.e. channel 1. This is why the procedure is called sequential. At this time, arrival 1 should have completed its transmission and also have been acknowledged.

From the above and fig.5-8, it can be concluded that the ith channel sequential protocol packet length time T_i depends on the number of operating channels N and the preamble length t_{pre} i.e. the inherent delay in the CSMA/CA protocol in order to avoid collision. T_i is thus given by;

$$T_i = Nt_{pre} \tag{5-6}$$

The above equation represents the packet as a whole, and contains the preamble, the data and the acknowledgment periods. If it is required to calculate the data content to investigate the limitation of practical data duration length, this will be given by (see figs.5-8 and 3-3);

$$DDL = (N-1)t_{pre} - t_{ack} \tag{5-7}$$

From the above equation it is clear that for practical operation of the system with the condition that ($t_{pre}=t_{ack}$), the number of channels should always be greater than two (i.e. $N \geq 3$), so that at least the packet contains a data field which is equivalent in size to that of the preamble or acknowledgement period. If, however, ($t_{pre} \neq t_{ack}$), this condition is no longer met.

5-5-2. MEDIUM ACCESS CONTROL

There are two ways in which a terminal station can be connected to the network to transmit a packet to another terminal station. The difference between these two ways depends on whether the terminal station has a stations-busy list or not, that is, whether the station has not the ability to receive more than one packet at a time or not. The first scheme operates with a stations-busy list, so that a station with a message to transmit should follow totally the procedure given in fig.5-9. That is;

1) If a message is ready for transmission, the transmitting station (TS) chooses the size of its data duration according to eqn.(5-7) and fig.5-8, and should define the address of the desired recipient station (RS). Thus the ith channel packet duration should be as given in eqn.(5-6).

2) Since this protocol is operating with a stations-busy list, before the terminal station senses the medium according to the CSMA/CA protocol each transmitting station checks the stations-busy list about the state of the RS. This will lead to one of two possibilities:
A) That RS is now busy (i.e. either transmitting or receiving); therefore that particular station's transceiver is operating at another frequency band and is not available at the moment on the existing band. In this case the (TS) will proceed as follows:
i) If it has another message to another destination, it should change its packet with a new one to the new address (RS) and return to step 2 above.
ii) If, however, the (TS) has no further message, the station should keep tracking the busy list until that (RS) becomes idle.

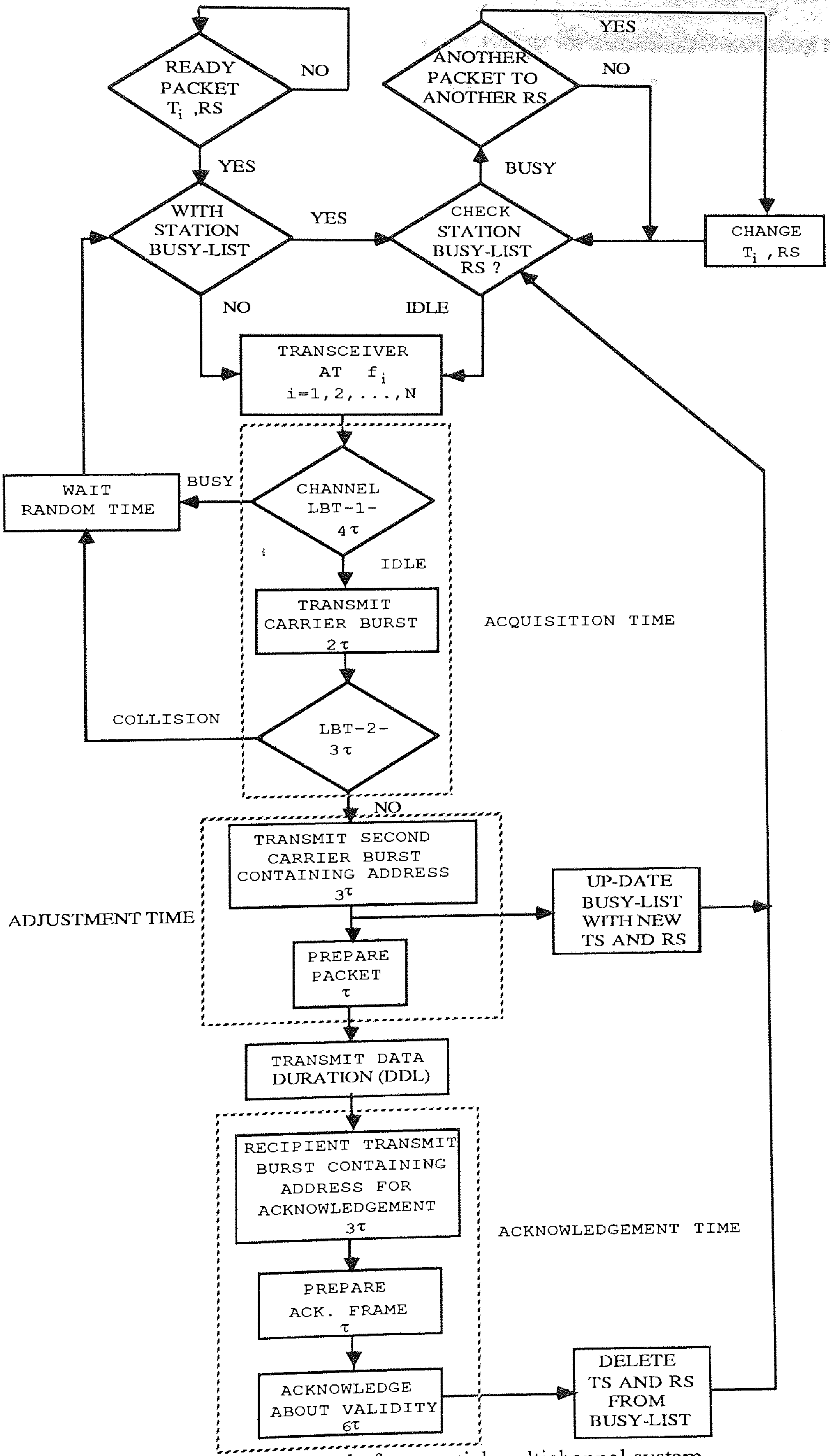


Fig.5-9. Flow of medium access control of sequential multichannel system.

B) If RS is idle, then the station will ask the transceiver for a connection according to the CSMA/CA protocol described in chapter three.

3) The transceiver is now at frequency (f_i), after following all the changes in frequency bands. The minor differences here from that of the CSMA/CA protocol are that;

A) if a collision occurs the terminal station returns to step 2 above.

B) The second carrier burst contains the addresses of both the (TS) and (RS), so that the rest of the stations will receive the information necessary to store in their busy-list before they change their frequency band to the next (B_i+1) band at the end of the preamble period (see fig.5-8).

C) The length of the packet is not the same as given in chapter three, but it is restricted as described in step 1.

D) During the acknowledgment period, the carrier burst from the RS terminal should contain the addresses of both parties concerned with that connection so that the TS can ensure that the packet is received by the desired RS terminal station.

4) Once both TS and RS have finished their transmission and acknowledgment, they automatically change their frequency to the present operating frequency band. This is achieved by tracking the change in frequency bands or by the increase in the number of the station pairs in the busy list, which indicates how many succeeding bands have been used. This will also help to get all the necessary up to date information about the state of the system so as to eliminate unnecessary future contention. The elimination of the addresses of the previous two stations from other terminal stations can be achieved by the use of a time-out period for each pair of addresses to remain in the busy list, which is equivalent to one packet duration subtracted from that of the preamble duration.

In the second scheme of operation of the sequential multichannel system there is no need to use a stations-busy list at each transceiver. This means that the transceiver is now able to receive more than one packet from different terminal stations. In such a case, the station access protocol to the medium is the same as above, which is illustrated in fig.5-9. However, the part concerning step 2 should be eliminated. This, in fact, has the advantage that it increases the throughput of the system, but it does require an increase in the size of the transceiver buffer to accept more than one packet. This will be discussed further in the following Section.

5-6. DIFFERENCES BETWEEN THE TWO SYSTEMS

Although both systems share the same principle in that they are multichannel broadband and operate on contention-based protocols, they also have their differences which might sometimes favour one or the other.

As we have seen from the two proposed systems, the dynamic allocation of channels which operates under the RC and IC channel selection has improved throughput characteristics in comparison to single channel operation. Later we will see that they also have higher throughput in comparison with the sequential system. The penalty of such an improvement is the need for a larger storage buffer at each transceiver to store several packets from several stations at the same time. This also has another implication in that further contention analysis is required for the accumulated packets at the transceiver to reach the station. Such unnecessary contention processes have been eliminated in the sequential protocol with the use of the stations-busy list.

Another important desirable feature in the sequential protocol in comparison with the dynamic RC and IC protocol that it has the ability to resolve the contention of each channel individually, after which all transceivers change their frequencies to the next channel, which has an assumed idle state. This is a good property in the sense that it will reduce the effect of undetectable collision and at the same time solve the problem of the hidden terminal.

The control channel mentioned earlier in Section 5-3 is needed in both the dynamic allocation of channels and the sequential system to pass the necessary control information to the terminal stations connected to the network so as to avoid using a disrupted channel from the N channels. Although in the sequential system the terminal stations should skip the disrupted channel, they should also reduce their packet duration time according to the new number of operating channels. Finally, priority can also easily be implemented with both dynamic and sequential systems based on the principle described in chapter three for the case of the CSMA/CA protocol, which both are using for medium access.

5-7. SUMMARY

In this chapter we dealt with the use of a broadband multichannel contention-based system based on FDM techniques. A survey of such protocols was presented, which included those used with local area networks. An extension of its application to mobile terminals was then considered. Using this principle, a dynamic multichannel system was proposed, based on the previous work using the CSMA/CA protocol for medium access. A mathematical model of such a system was also presented, based on the analysis in chapter three. A further sequential multichannel system was also proposed, with its basic operation and packet limitation. The performance evaluation of the second system is left as the subject of the next chapter, where we describe the simulation of the sequential system since it was found difficult to deal with using mathematical modelling. Finally, this chapter concluded with a comparison between the proposed systems.

CHAPTER SIX

SIMULATION OF SEQUENTIAL MULTICHANNEL SYSTEM

6-1. INTRODUCTION.

This chapter is devoted to the explanation of the simulation modelling process of the sequential multichannel contention-based protocol described in chapter five as an alternative to mathematical modelling, which was found to be rather difficult to express for such a complex access protocol. The simulation procedure which is adopted is similar to that used for the modelling of the CSMA/CA protocol given in chapter three, where the protocol is modelled using the discrete event simulation package SLAM II [112]. The two cases of non-persistent and slotted non-persistent have been considered, for the same reasons as before. However, there are a few differences which should be taken into consideration when modelling the sequential protocol as the sequential protocol will resolve the contention on the N available channels in sequence. This means there is only one queue which feeds the servers. The first difference is that the number of servers in this case is equal to the number of channels used with the system (i.e. N) and not one, as with the previous case. Another difference is that there is no need to delay the packet if an arrival happens during the transmission time except when it arrives within the preamble period of a previous packet i.e. within a contention period which has not yet been resolved. Other differences in the simulation will be given later in this chapter as given in[11,43].

6-2. EVENT REPRESENTATION AND FLOW OF SIMULATION PROCEDURE

The representation of the events for the multichannel sequential protocol are more or less similar to those that were used in chapter four to simulate the CSMA/CA protocol. Four events are chosen to represent the system behaviour according to the system operation and medium access control given in Sections 5-5-1 and 5-5-2 and depicted in figs.5-8 and 5-9. Fig.6-1 shows the event transition diagram of the simulation procedure with its four main events; new arrival, test, delay and success event. The details of the procedure are given in the following sections.

6-3. ASSUMPTIONS AND CHANNEL ALLOCATION

The assumptions mentioned in Section 4-4-3 are also applicable for sequential multichannel protocol simulation. However, for the case of the stations-busy list procedure, further assumptions have to be taken into consideration. One important difference is that every packet should have two additional attributes containing the addresses of both the sender and the recipient stations. Thus, the following attributes are considered for each packet; ATRIB(1), ATRIB(2) and ATRIB(3) as before to carry the initial arrival time for the newly generated packets, the number of collisions a packet encounters and the server number. ATRIB(4) and ATRIB(5) are assigned for the addresses of the terminal generating the packet and the receiving terminal station. These two attributes will be used to eliminate a packet when it is generated by a station which is already in the transmitting mode and to investigate the state of the recipient before the transmission of any packet takes place.

A further assumption is that any station can only transmit one packet at a time and, unlike the case discussed in chapter 4, no station is allowed to generate another packet while it still has a packet in the process of contending i.e. in the test, the delay event or in the successful transmission event.

The channel allocation with the multichannel system is also different from the case of single channel operation. Here, N servers are allocated for the N active channels, in which the global variable XX(I) (i.e. the SLAM II server) is given the values XX(I=1,...,N) for the real active channels and XX(I>N) for the dummy servers used to delay the packets in accordance with the non-persistent protocols.

6-4. MODELLING PROCEDURE

The simulation procedure is carried out for two types of non-persistent protocols, the slotted and non-slotted, as is shown in figs.6-1 and 6-2. The protocols are simulated for access protocols both where the terminal stations have a stations-busy list and where they have not. In what follows, the explanations and the results are presented only for the first case. However, the elimination of the stations-busy list is dealt with as one of the parameters affecting the overall protocol performance.

6-4-1. NON-PERSISTENT CHANNEL ACCESS

This mode of operation is simulated according to the procedure flow diagram shown in fig.6-2, using the non-persistent CSMA/CA protocol for medium accessing. The figure shows that the total offered load to the system is the sum of the newly generated packets from the new arrival event and the retransmitted packets that completed the delay event. Each packet first checks its address attributes (i.e. ATRIB(4) and ATRIB(5)). The reason for this is that a packet should not be generated from the new generation event which carries the same ATRIB(4) as a packet which is already in progress in the system. This ensures that a terminal station cannot transmit more than one packet at a time. Checking ATTRIB(5) is necessary to determine whether the terminal station wishes the transceiver to contend on the ith channel (i.e. server XX(I)) because the intended receipient terminal station is busy or whether a straightforward delaying of the packet is required. In this case the packet is directed to the delay event using the servers XX(I>N).

A similar procedure to that explained in Section 4-4-4 is followed in order to check the possibility of collision with other packets and in order to delay the packet if it arrives within the time period of preamble transmission (see appendix (A)). If none of these events occur, then that particular packet is put in the success event using the server XX(I) for a period of time equal to the packet length given by eqn.5-6. Two other things have to be done in parallel with the above:

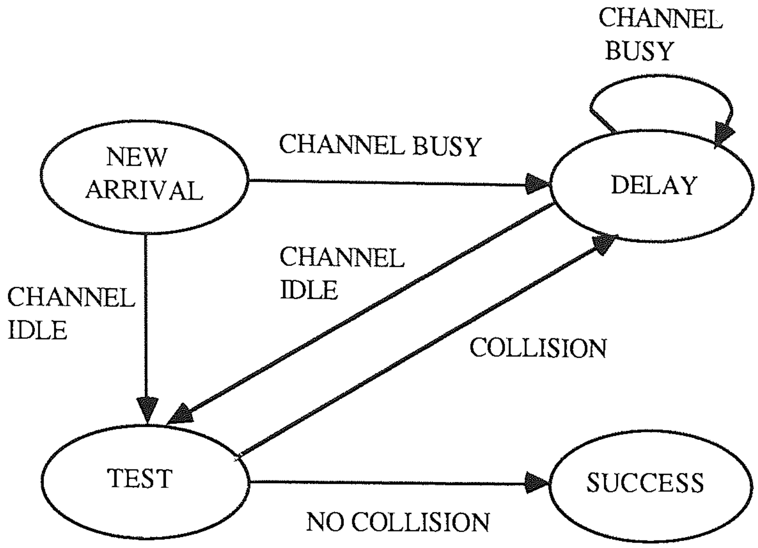


Fig.6-1. Event transition diagram of the sequential multichannel protocol simulation procedure.

1) The server number XX(I) is changed to XX(I+1) to represent the new idle channel which is available for contention to all the idle terminal stations and

2) The addresses, i.e. ATRIB(4) and ATRIB(5), are put in the stations-busy list of the other terminal stations. This is represented by a queue in the simulation program.

A similar process continues on the ith+1 channel, i.e. the server XX(I+1), until the server XX(N) is reached. Once the server XX(N) becomes busy, the unserved terminal stations will contend to seize the XX(1) server and a new round will start.

It is worth mentioning that, once a particular packet finishes its limited transmission time, it resets that particular channel, i.e. server XX(I), to the idle state and, at the same time, drops its addresses from the file which represents the stations-busy list.

6-4-2. SLOTTED NON-PERSISTENT CHANNEL ACCESS

The case when the sequential protocol uses the slotted non-persistent CSMA/CA protocol for medium accessing is similar to the previous case of non-persistent. The only

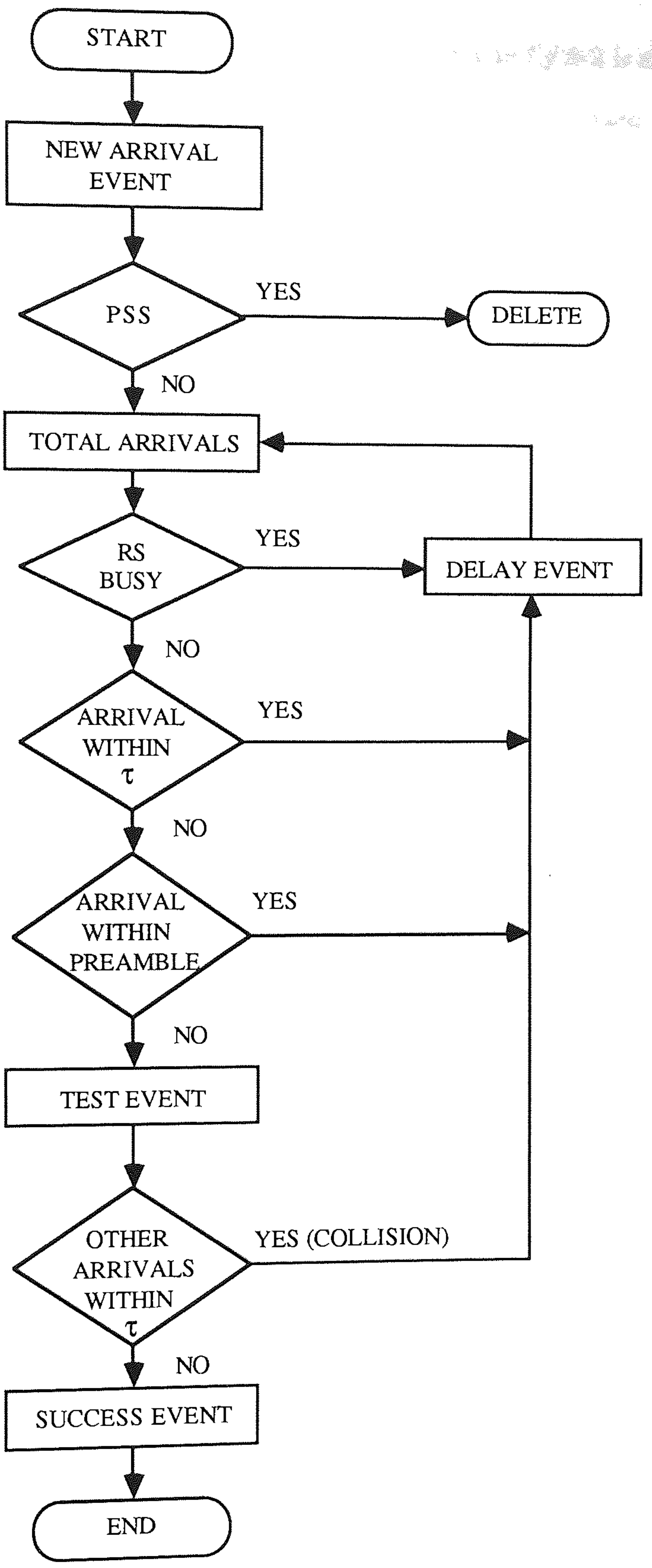


Fig.6-2. Flow of the simulation procedure of the sequential multichannel protocol using non-persistent and slotted non-persistent CSMA/CA protocol for medium access.
PSS: Packet from the same source terminal.
RS: Receiving terminal station.
τ: End-to-end propagation delay time.

difference in the flow of the simulation procedure shown in fig.6-2 is that slotting of the simulation time is required as was done in Section 4-4-5 for the slotted CSMA/CA. Such slotting of the simulation time is done before the test event takes place, whether the packet arrived from the new arrival event or from the delay event and needing a retransmission. The same end-to-end propagation time delay is considered here and therefore the slot size is equal to the value given in chapter four.

6-5. RESULTS OF SIMULATION

The results obtained from the simulation are presented in a statistical form and are obtained from the SLAM summary report as given in appendix (B) on the basis that the same amount of data has to be transmitted as when the whole system bandwidth is available. This means that transmission of N packets through the network is equivalent to the transmission of one packet in a system with bandwidth B. For this reason, the results relating to the total system offered load and the overall system throughput are normalised to the number of channels (N) used in the simulation. Thus, the total effective offered load (G) to the system given in eqn.(4-2) is given by [11,43];

$$G=\frac{P+R}{N} \tag{6-1}$$

On a similar basis, the normalised overall throughput (S) of the system is given by;

$$S=\frac{K.T_i}{SM.N} \tag{6-2}$$

The average normalised packet time delay (D) is the same as given in eqn.(4-6). i.e.

$$D=\frac{\sum_{j=1}^{K}\{TNOW(j) - ATRIB(1)_j\}}{KT_i} \tag{6-3}$$

The results discussed in this section refer to the sequential protocol that operates in conjunction with the stations busy-list, that is, the station can only receive one packet at a time from any channel. Table 6-1 shows the input data fed to the computer simulation program which produced the results discussed in the remaining part of this section and the following section. Figs.6-3 and 6-4 show plotted results of the normalised average time delay (D) of a packet when the total offered load (G) to the system is increased for both the case of nonpersistent and slotted non-persistent CSMA/CA protocols used with the sequential protocol. It can be seen from the two figures that, for a fixed value of a normalised packet delay, the system can operate at higher offered load, i.e. a higher number of packets, when the number of channels (N) is increased. This is also clear when plotting the results from eqn.(6-2) for the overall system throughput against the total offered load, as shown in figs.6-5 and 6-6. An improvement in delay towards higher offered load operation is observed, but such an improvement is accompanied by a slight degradation in the maximum attainable throughput. This degradation is due to the fact that as the offered load increases, a larger number of acknowledgments are needed. In all the above there is an improvement in the slotted case in comparison to the non-slotted for the same reasons as given in sections 3-4-4 and 4-5.

The overall performance measure of the sequential protocol is expressed in terms of its delay-throughput characteristics. This is shown in figs.6-7 and 6-8 for a preamble length equal to (12τ), which is the same as the preamble length used in chapter four. From the figures it is clear that the delay of the system is almost constant and of its lowest value in the region of stable operation. This is because the maximum limit of the retransmission time is chosen as small as possible (see Table 6-1), so that the delay of each transmitted packet is also as small as possible. Although this has no effect on the maximum attainable throughput of the sequential protocol, it does lead to the accumulation of packets that need retransmission from the delay event due to the short duration of the selected random retransmission time. The number of possible collisions will therefore increase, which in turn causes the system to operate in the unstable region (the region where the throughput

Table 6-1. Input data fed to the sequential simulation program.

Number of channels	5,10,20,50 and 100
Duration of preamble time (t_{pre})	12τ and 6τ
Stations busy-list	With and without
Retransmission time (t_r) (random)	a) Uniform distribution (0 to 10τ) b) Uniform distribution (0 to 100τ)
Number of terminal stations	500 and 100
Simulation time	4×10^6 unit time
Collision back-off time (random)	Truncated binary exponential back-off algorithm $\{0 \text{ to } 7\tau(2^{nc})\}$[1]

is declining in figs.6-5 and 6-6). The main reason why the throughput of a higher number of channels is lower than operation using a lower number of channels is because each collision has an effect on all subsequent channels. Consequently, this also has an influence on the delay of the system, which seems to be lower for a higher number of channels. This happens because most of the retransmitted packets will encounter many collisions and will be discharged from the system after exceeding a certain specified limit. However, only those packets which arrived during the stable operation are transmitted and their delay taken into account.

6-6. FACTORS AFFECTING THE SIMULATION RESULTS

There are a number of factors that have been included in the simulation to study their effect on the operation performance of the sequential protocol. The effect of these factors on system performance is discussed in this section, together with the additional requirements that are needed to achieve their implementation.

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1) The same values are valid as in Table 4-1.

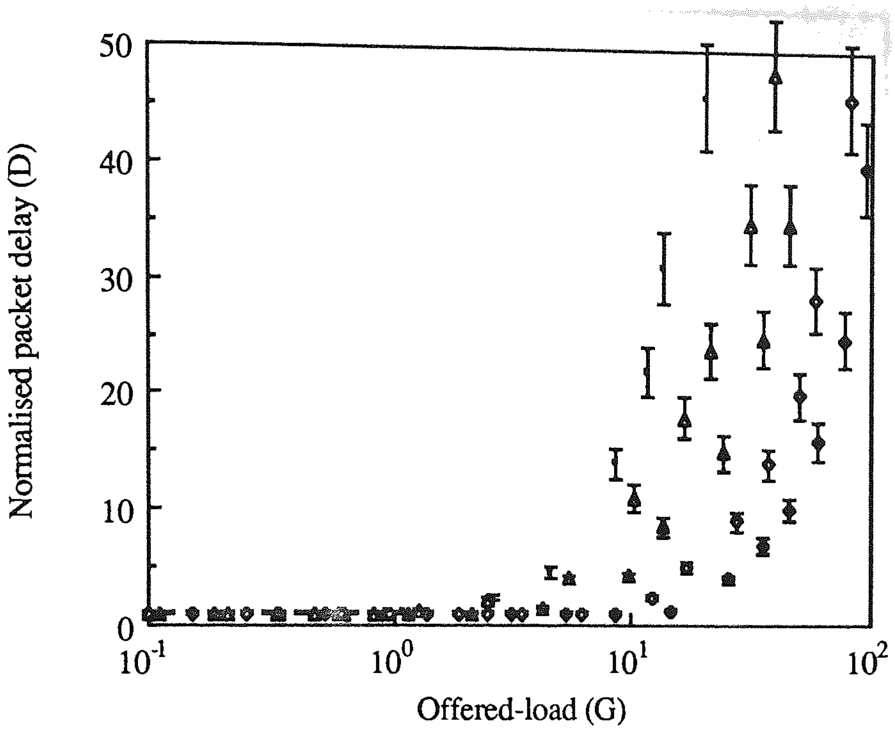

Fig.6-3. Normalised packet delay time vs. offered load of sequential multichannel system for different values of N, using non-persistent CSMA/CA protocol for medium access.

■ N=5
▲ N=10
▲ N=20
◆ N=50
● N=100

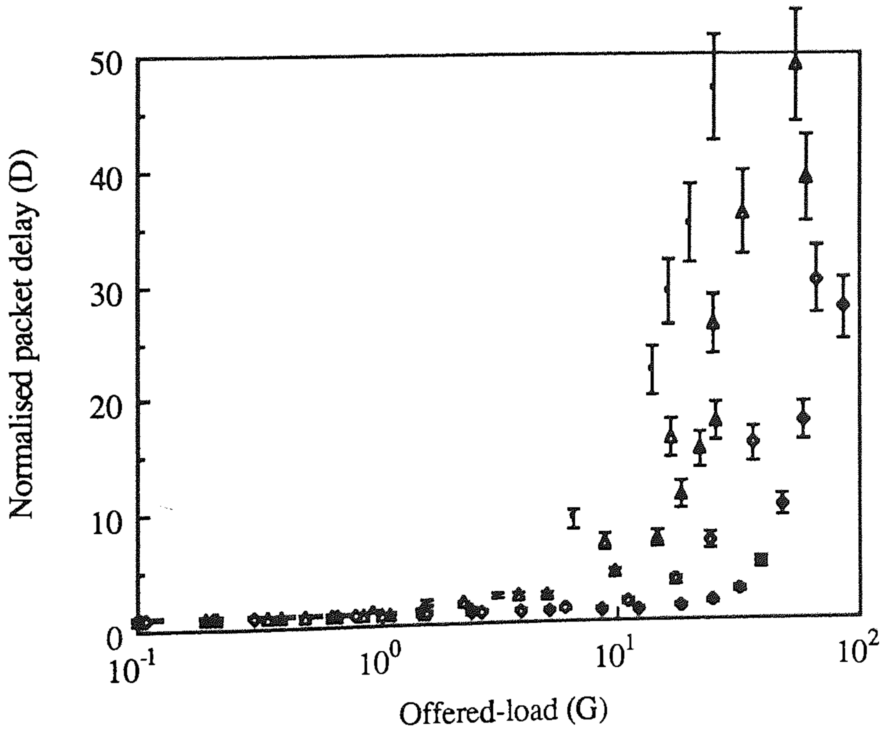

Fig.6-4. Normalised packet delay time vs. offered load of sequential multichannel system for different values of N, using slotted non-persistent CSMA/CA protocol for medium access.

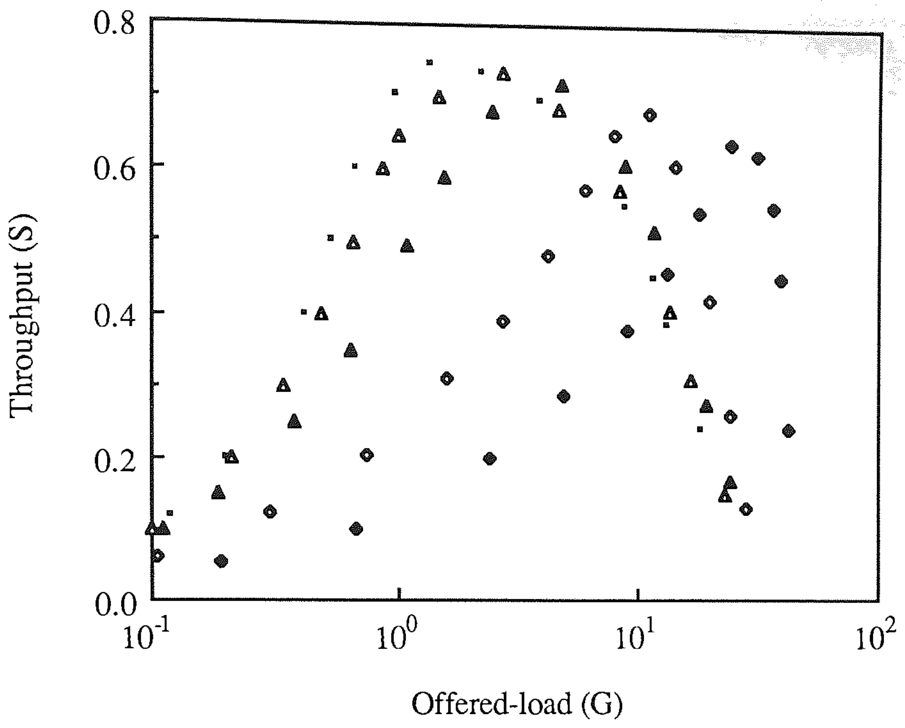

Fig.6-5. Throughput vs. offered load of sequential multichannel system for different values of N,using non-persistent CSMA/CA protocol for medium access.

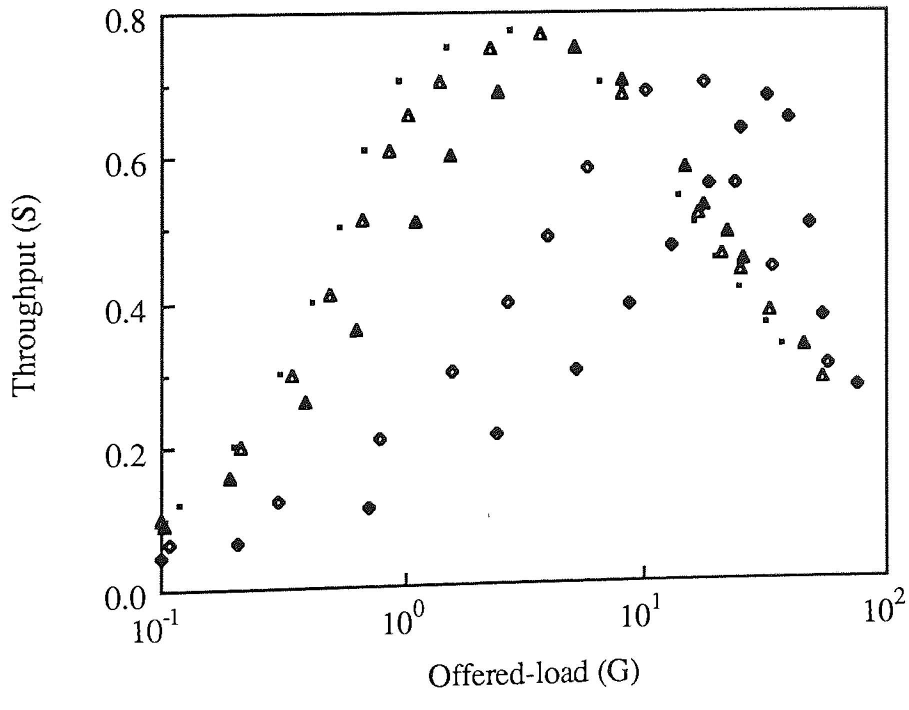

Fig.6-6. Throughput vs. offered load of sequential multichannel system for different values of N,using slotted non-persistent CSMA/CA protocol for medium access.

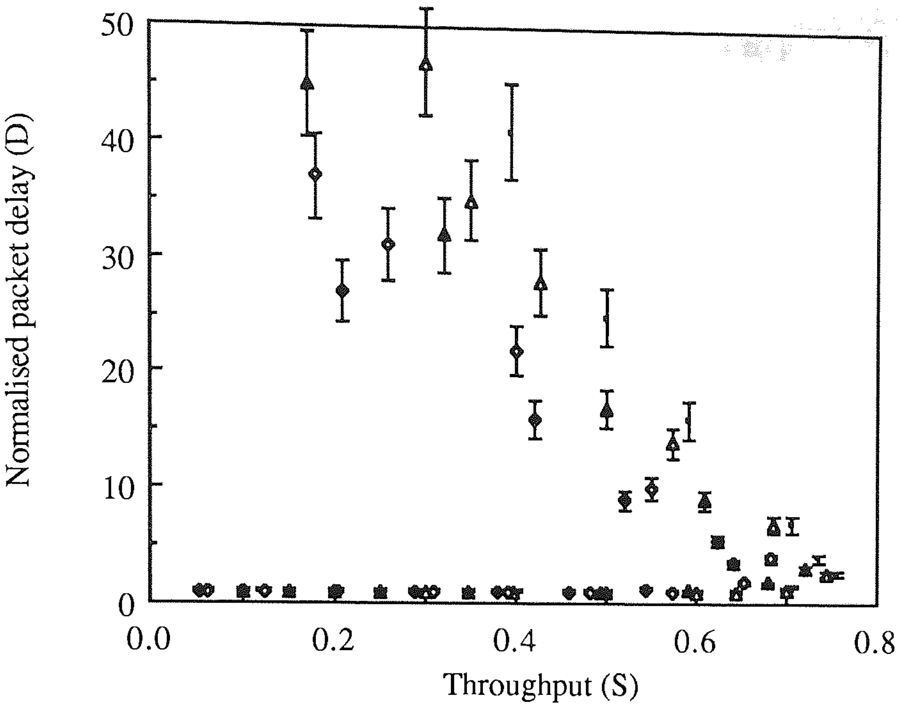

Fig.6-7. Normalised packet delay time vs. throughput of sequential multichannel system for different values of N, using non-persistent CSMA/CA protocol for medium access.

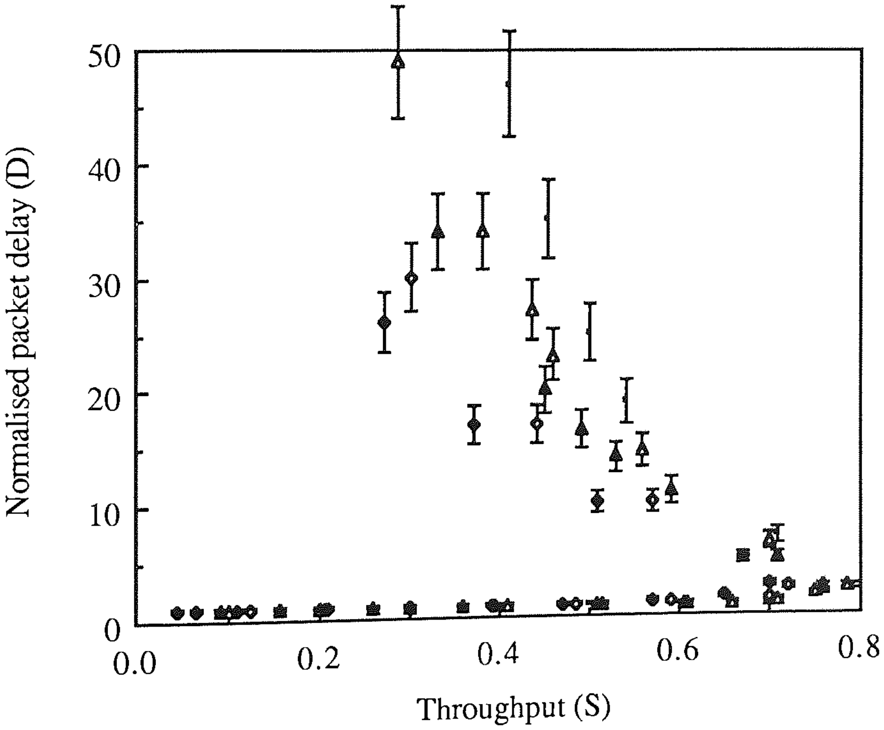

Fig.6-8. Normalised packet delay time vs. throughput of sequential multichannel system for different values of N, using slotted non-persistent CSMA/CA protocol for medium access.

6-6-1. ELIMINATION OF STATIONS-BUSY LIST

Elimination of the stations-busy list needs a slight change to the simulation flow procedure (see fig.6-2) as there is then no need to investigate the state of the recipient terminal station to which a particular packet is addressed. The decision point marked (RS-BUSY) in the flow diagram is therefore no longer needed and should be by-passed. This change tends to increase the throughput of the system and the average delay is decreased. This is because, in this case, there is no need to delay some of the packets which are intended to be transmitted to a station which is either transmitting or receiving (i.e. to a busy station). However, this improvement is not obtainable without cost. The penalty of providing such a facility is to increase the buffer space of each station to accept more than one packet from different stations through several channels simultaneously. Another drawback is that the accumulation of these packets in the storage buffer of each station needs further control to regulate their arrival to the required application level. Figs.6-9 and 6-10 show the improvement in throughput over that shown in figs.6-5 and 6-6 for such an alteration in the protocol. Although it is not very large, it does modify the operation performance of the sequential protocol.

6-6-2. RETRANSMISSION TIME DELAY

The retransmission delay time is defined as the random amount of time a station has to wait until it is given the chance for retransmission. This happens when a packet either discovers that the recipient terminal station is busy, senses the ith channel busy or when it encounters a collision. This amount of time-out is usually derived from a specific distribution in the simulation process (see Table 6-1). The same distribution is chosen for the case of collision occurrence as was previously used in chapter four, which is a binary exponential back-off algorithm (see Table 6-1) [49,55,120,160]. However, the distribution for delaying the packets when they either find the receiving terminal busy or sense the channel busy has been chosen as a uniform distribution with predefined limits.

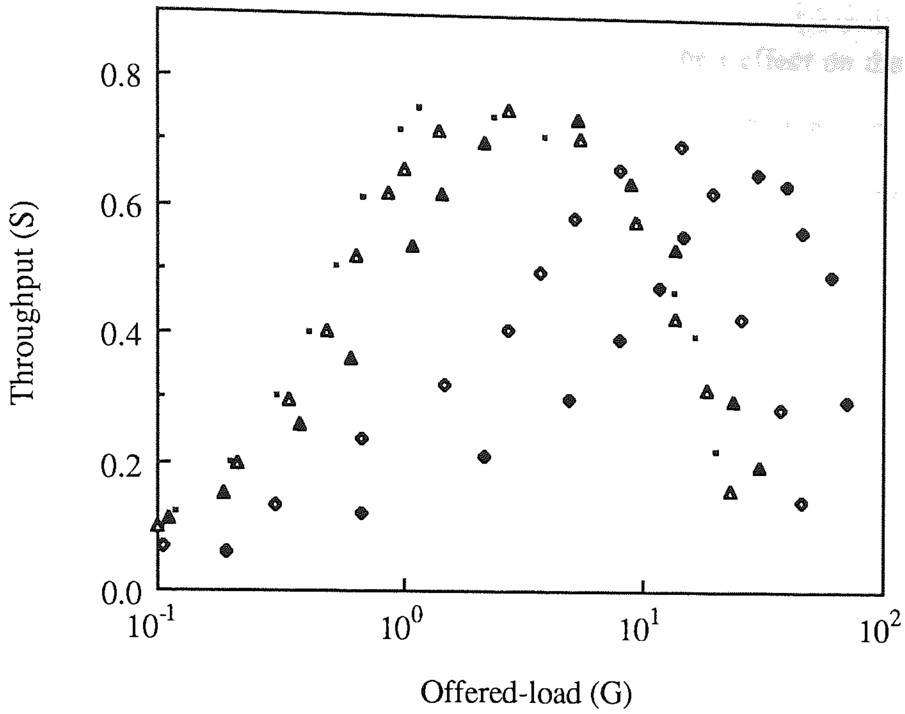

Fig.6-9. Throughput vs. offered load of sequential multichannel system for different values of N, using non-persistent CSMA/CA protocol for medium access (stations busy-list is eliminated).

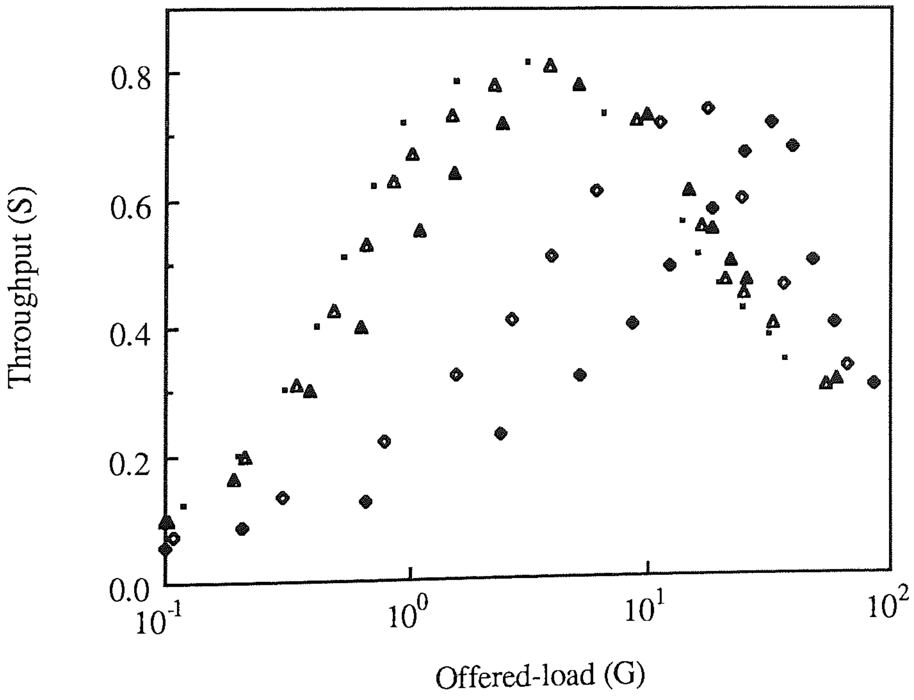

Fig.6-10. Throughput vs. offered load of sequential multichannel system for different values of N, using slotted non-persistent CSMA/CA protocol for medium access (stations busy-list is eliminated).

The limits of such a distribution are varied to see their effect on the simulation results obtained. Since the packet length is variable with the change of either the number of operating channels or the preamble length, it is not used as a reference to specify the limits. Instead the slot size (i.e. the worst case of end-to-end propagation time delay τ which is equivalent to 5 time units) is used. The upper limit of the uniform distribution is varied from a very low value of about 10 slots to a relatively high value of 100 slots. The effect of such variation on the simulation results obtained is shown in figs.6-11 and 6-12, where all the other parameters remain unchanged. It is evident that the overall operation performance of the sequential protocol is modified i.e. higher throughput is obtained but at a higher delay time compared to figs.6-7 and 6-8. This modification is due to the fact that when the range of selection of the random retransmission time is increased, the chance of collision will be reduced and only occurs at a higher load compared to the previous case.

6-6-3. NUMBER OF STATIONS CONNECTED TO THE NETWORK

The number of stations connected to the network has an indirect effect on the overall performance of the system. This is evident because increasing or decreasing the number of terminal stations connected to the network means increasing or decreasing the amount of overall generated traffic (packets) needed to be transmitted through that particular network. Such a phenomenon has a direct influence on the sequential protocol when it operates with the use of the stations busy-list. However, it has no effect on the system when it operates without the stations busy-list, i.e. as described in section 6-6-1. For a given system traffic load, decreasing or increasing the number of terminal stations increases or decreases the probability of finding the intended recipient terminal station busy and consequently increases or decreases the number of packets that need retransmission. Thus, it has a direct effect on the throughput of the system due to the fact the it either reduces or increases depending on the number of successful packets transmitted through the system. Typical examples of such an effect are shown in

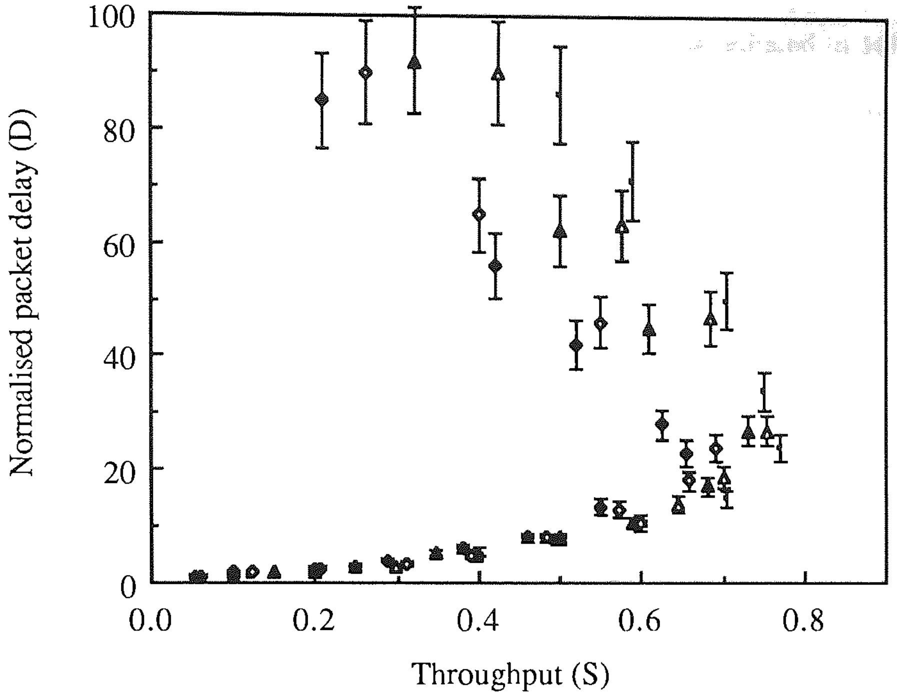

Fig.6-11. Normalised packet delay time vs. throughput of sequential multichannel system for different values of N, using non-persistent CSMA/CA protocol for medium access (retransmission time is changed to become t_r=100τ).

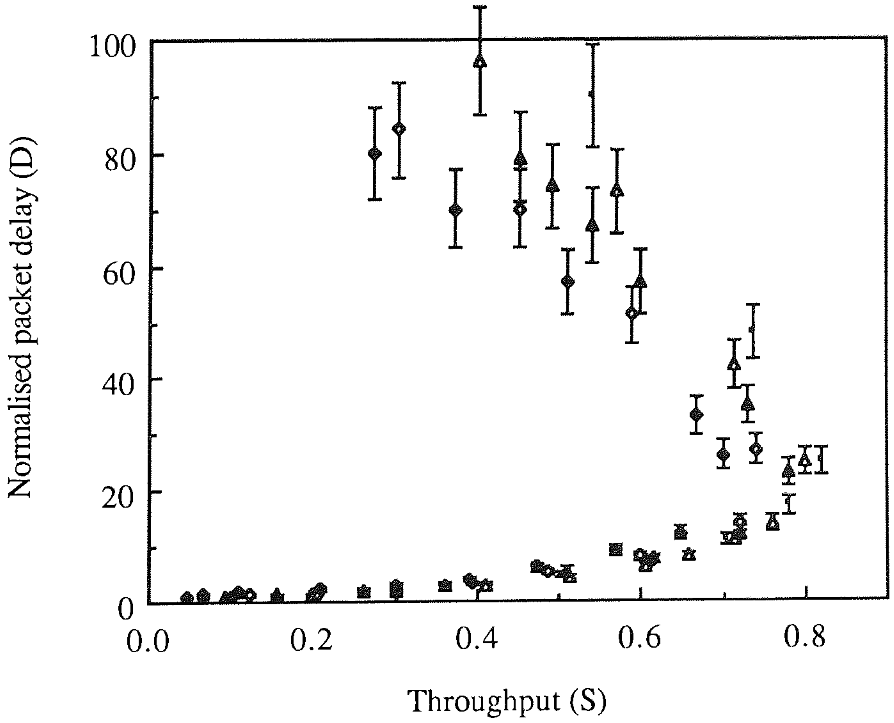

Fig.6-12. Normalised packet delay time vs. throughput of sequential multichannel system for different values of N, using slotted non-persistent CSMA/CA protocol for medium access (retransmission time is changed to become t_r=100τ).

figs.6-13 and 6-14, in which the number of stations is reduced to 100. From the figures, the throughput of the system is decreased by an amount which is proportional to the number of packets that are delayed. This is because the intended receiving terminal station is busy while the i-th channel is idle and therefore the station misses an opportunity of successful transmission.

6-6-4. PREAMBLE LENGTH

The packet consists of the preamble and a data field, the length of which is a function of the number of operating channels. Changing the preamble length therefore influences the packet length and thereby the utilisation of the system channels. So far in our simulation, the only factor which is taken into consideration is the number of operating channels and it has been shown that with an increase in N the protocol can operate at a higher offered load. However, this has been calculated for only one value of preamble length. Increasing or decreasing the preamble length will vary the time taken by any station to seize a particular channel and let the system change frequency to the next idle channel in sequence. It has been shown that reducing the preamble length to a lower value will have two effects [43];

1) It will reduce the packet length, which is an undesirable feature, because it has been shown that reducing the packet length tends to reduce the throughput of the system.

2) It will reduce the time taken by a terminal station to seize a particular channel and thereby accelerate the time the sequential protocol takes to change channels. This means, for a given offered load to the system, the number of packets that will be included in a successful transmission will be higher than those which are delayed due to sensing that a particular channel is busy. This is as a consequence of the fact that the busy sensing period of the channel is also reduced.

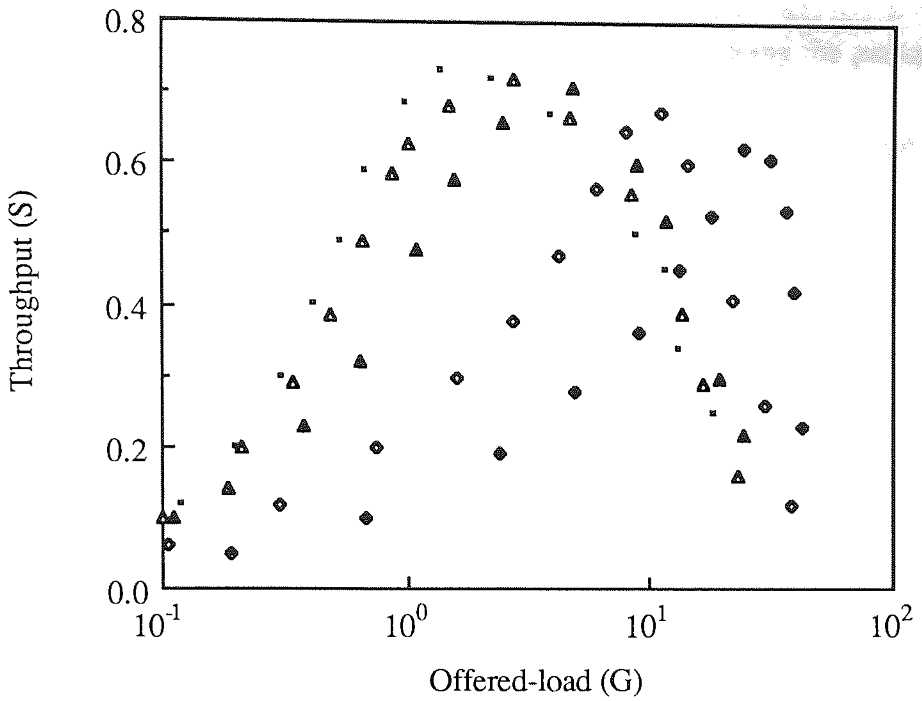

Fig.6-13. Throughput vs. offered load of sequential multichannel system for different values of N, using non-persistent CSMA/CA protocol for medium access (number of stations is decreased to 100).

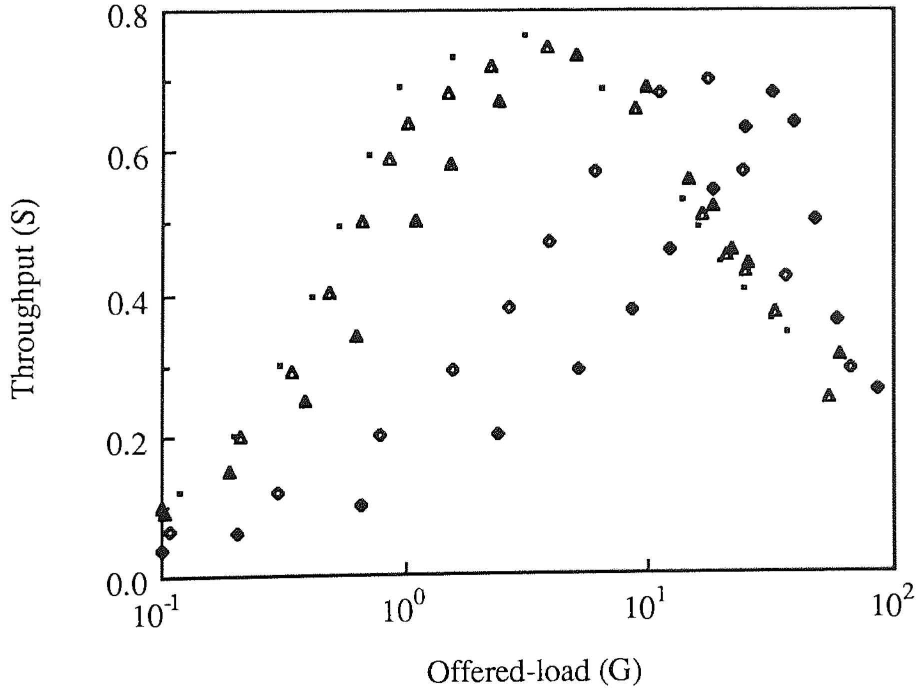

Fig.6-14. Throughput vs. offered load of sequential multichannel system for different values of N, using slotted non-persistent CSMA/CA protocol for medium access (number of stations is decreased to 100).

Investigation of this effect has been carried out by reducing the preamble length to the simulation to half its previous value to become (6τ). It can be seen from figs.6-15 and 6-16 that the maximum attainable throughput of the system is improved compared to the previous case given in figs.6-5 and 6-6. The overall delay-throughput performance of the system is also improved, as can be seen by comparing figs.6-17 and 6-18 to figs.6-7 and 6-8. Thus the sequential protocol throughput for a given number of channels depends on the preamble length.

Again, the length of the preamble period cannot be reduced without limit since, in the sequential protocol, such a delay is needed to avoid collision. Thus the lower limit is the same as that given in chapter three and four for practical operation of the system.

6-7. GENERAL CONCLUSIONS

Simulation has been used to model the sequential multichannel protocol to avoid the use of a complicated mathematical procedure. The effect of certain parameters has been included which would be difficult, if not impossible, to handle in mathematical modelling of the protocol. Combination of all previous effects are gathered in figs.6-19 and 6-20 for a fixed number of operating channels (N=10). An alternative way of defining the normalised packet delay is to regard the full bandwidth of the system to be available for each packet transmission. In such a case the delay of the protocol shown in figs.6-3 and 6-4 may be represented as shown in figs.6-21 and 6-22 in accordance with [90]. This means that delay is not considered on a packet basis but on the same amount of information that is transmitted through the system as if the whole bandwidth is available.

Comparing the results obtained in this chapter with those of the dynamic channel allocation (RC and IC channel selection) given in chapter five, it is clear that dynamic channel allocation produces higher overall channel throughput compared to the sequential protocol discussed in this chapter. However, an important feature of the sequential

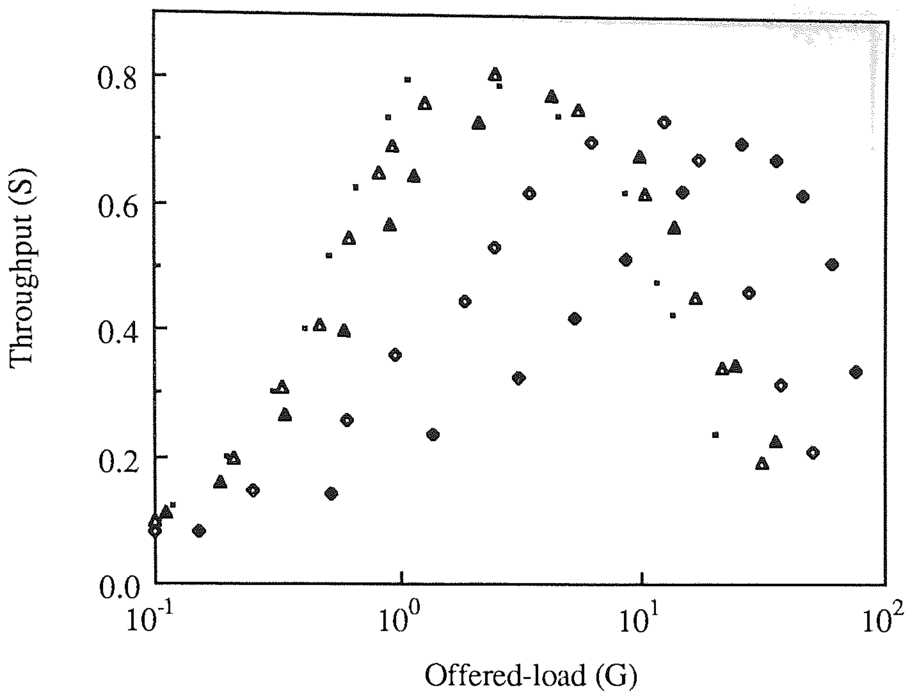

Fig.6-15. Throughput vs. offered load of sequential multichannel system for different values of N, using non-persistent CSMA/CA protocol for medium access (preamble time period is decreased to half).

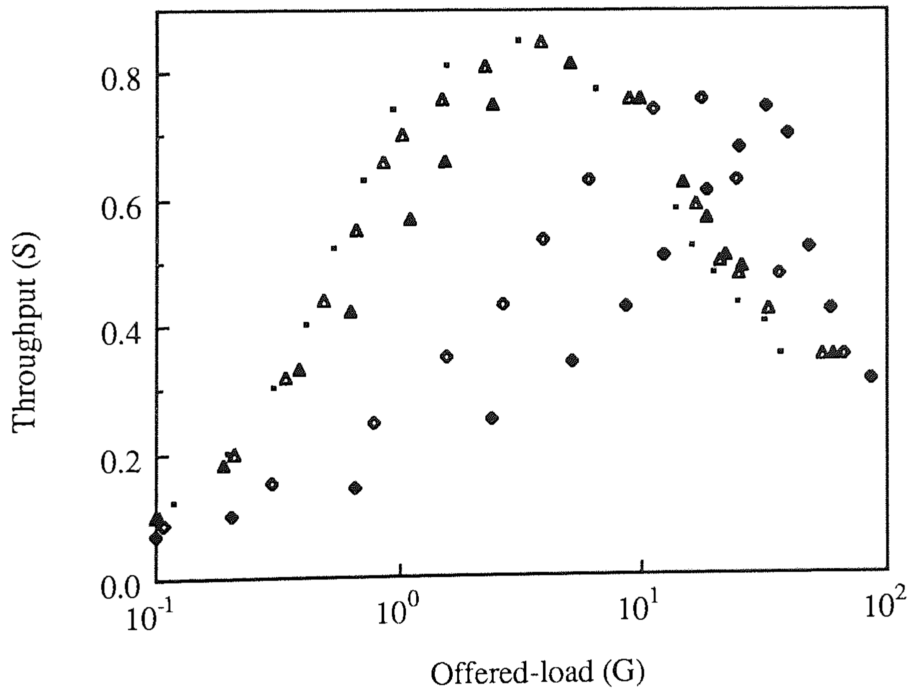

Fig.6-16. Throughput vs. offered load of sequential multichannel system for different values of N, using slotted non-persistent CSMA/CA protocol for medium access (preamble time period is decreased to half).

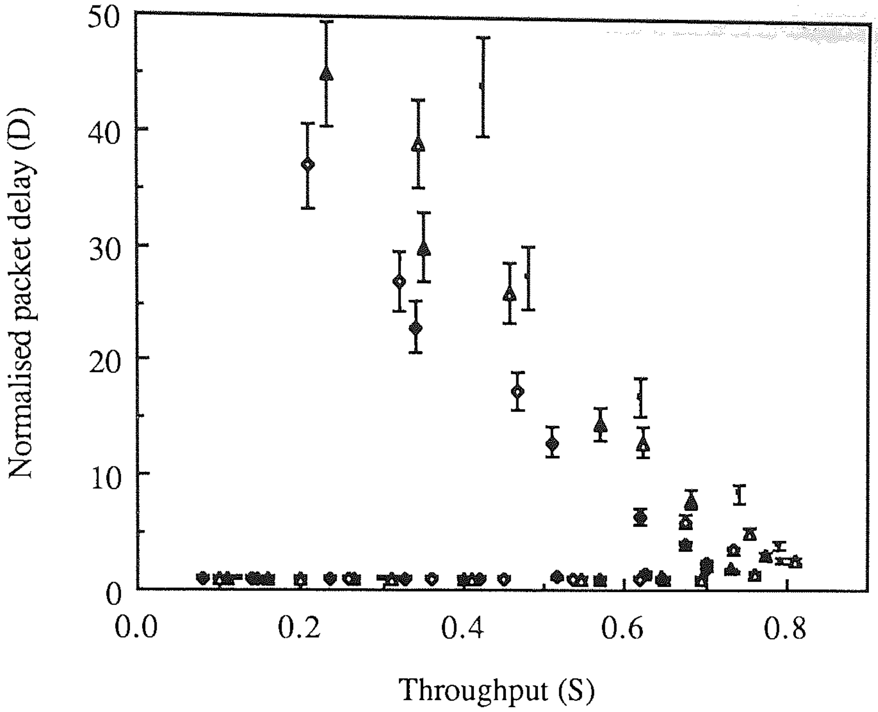

Fig.6-17. Normalised packet delay time vs. throughput of sequential multichannel system for different values of N, using non-persistent CSMA/CA protocol for medium access (preamble time period is decreased to half).

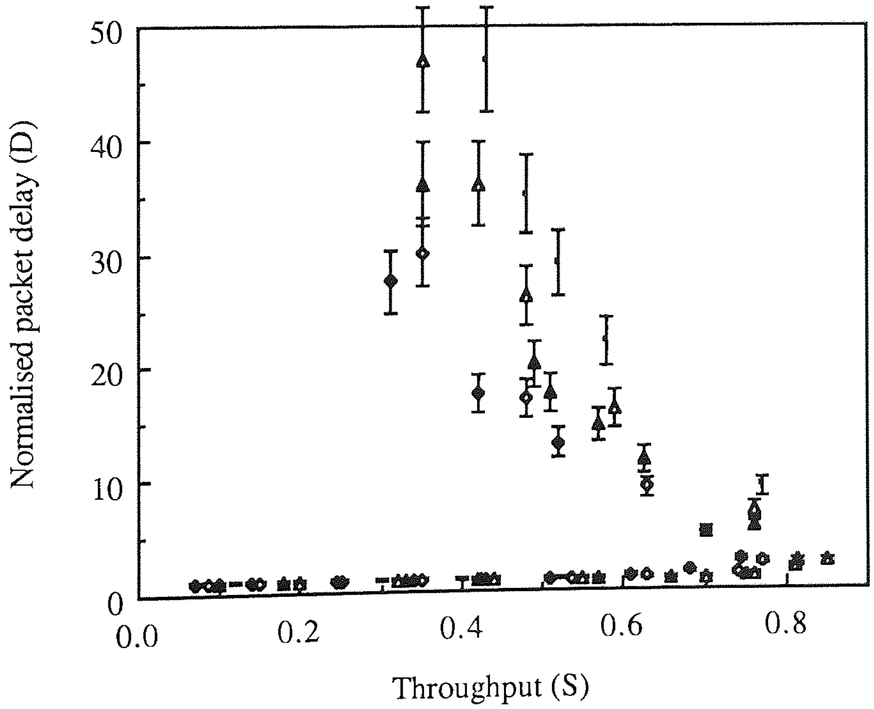

Fig.6-18. Normalised packet delay time vs. throughput of sequential multichannel system for different values of N, using slotted non-persistent CSMA/CA protocol for medium access (preamble time period is decreased to half).

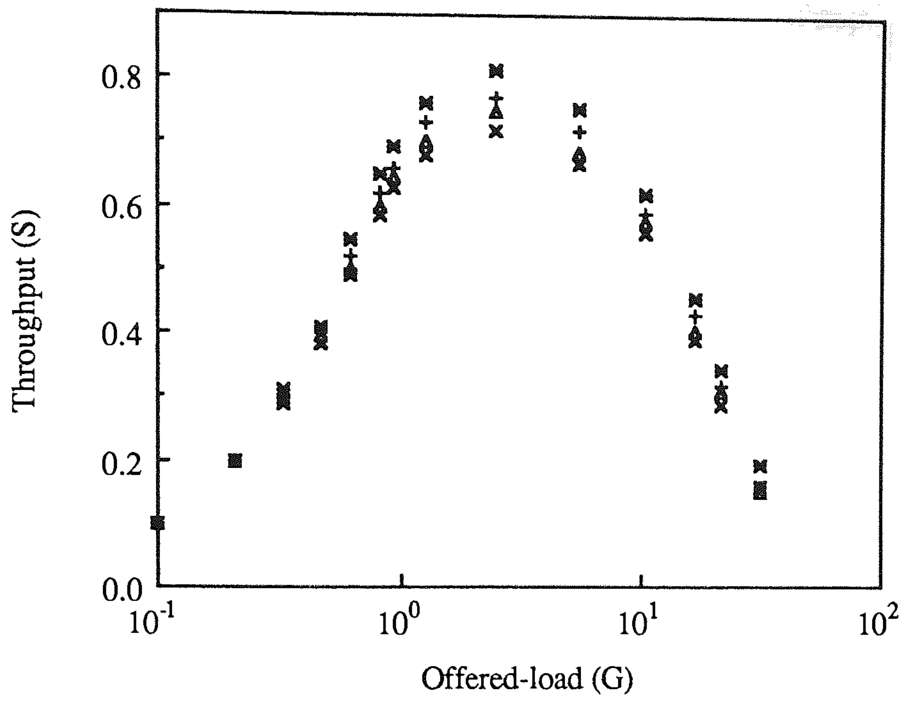

Fig.6-19. Throughput vs. offered load of sequential multichannel system combining the effect of the previous factors for N=10, using non-persistent CSMA/CA protocol for medium access.

▲ Full preamble length
\+ Without stations-busy list
× Number of stations reduced to 100
✖ Half preamble length

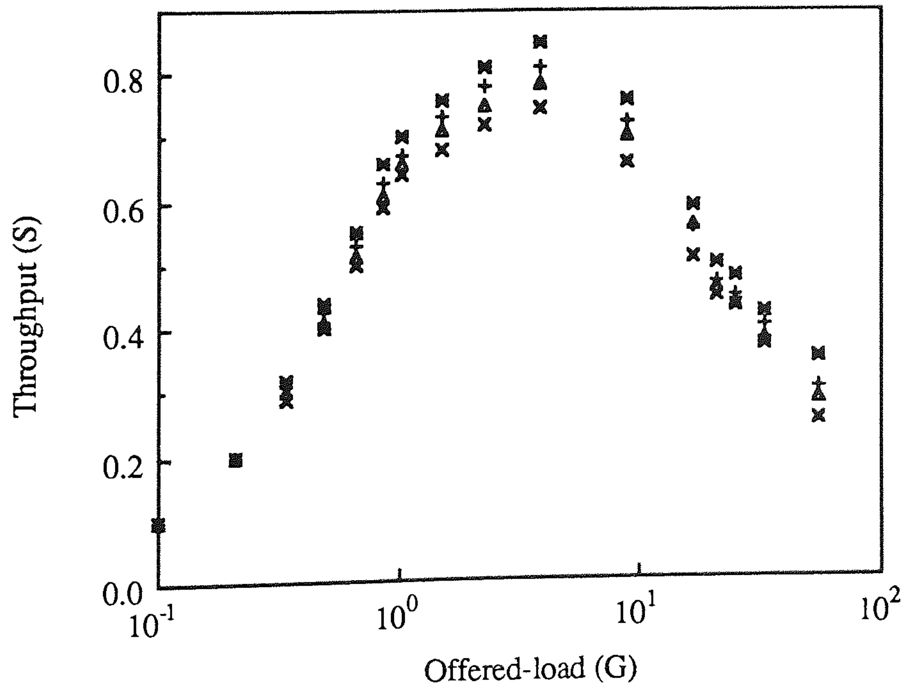

Fig.6-20. Throughput vs. offered load of sequential multichannel system combining the effect of the previous factors for N=10, using slotted non-persistent CSMA/CA protocol for medium access.

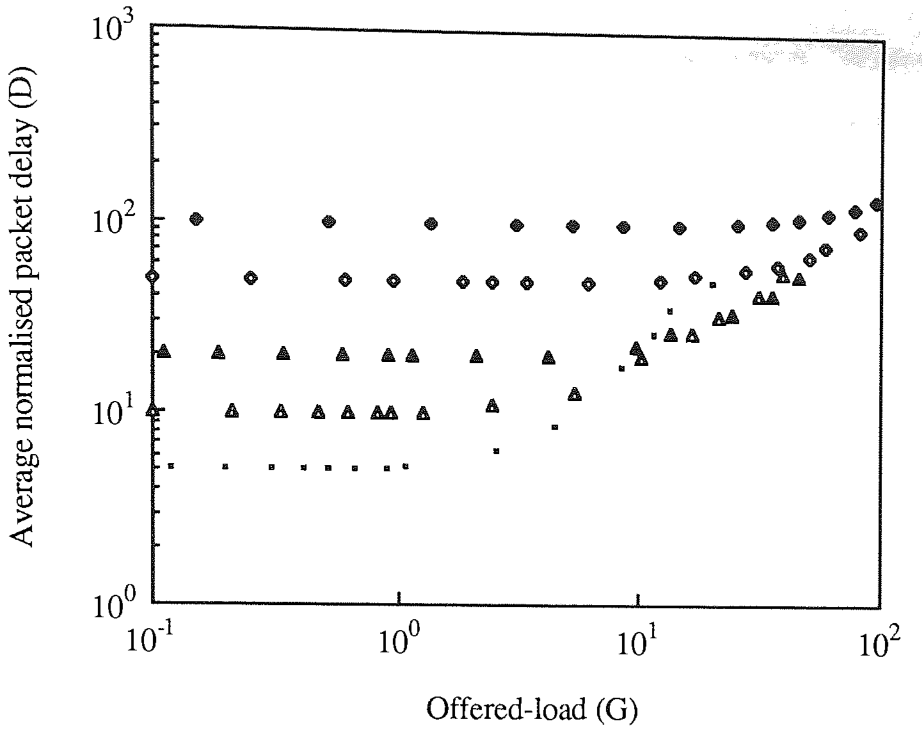

Fig.6-21. Alternative representation of fig.6-3, when the delay is considered with regard to transmission of the same packet when the full bandwidth of the channel is available.

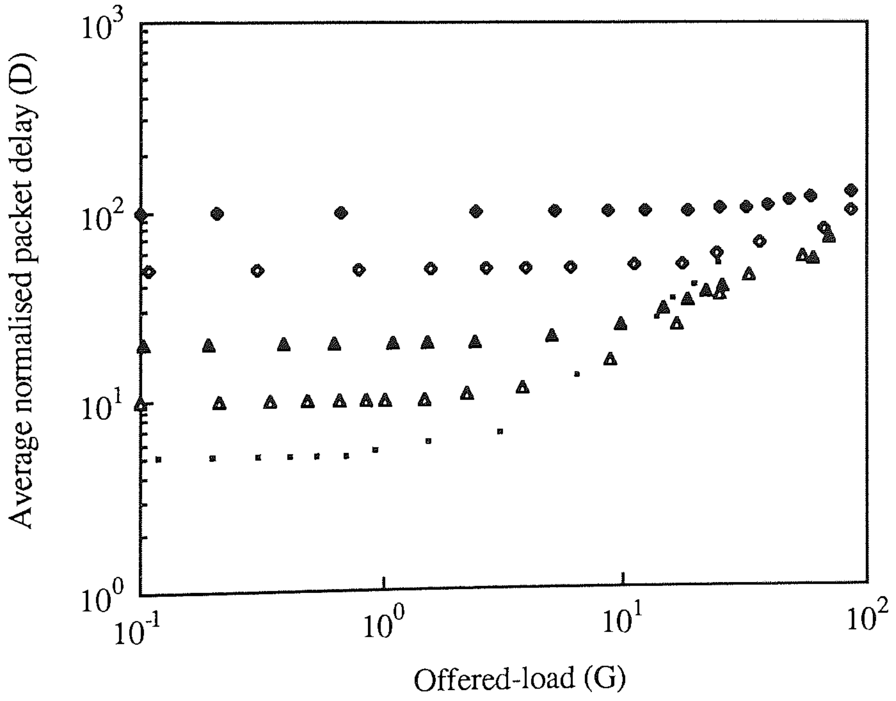

Fig.6-22. Alternative representation of fig.6-4, when the delay is considered with regard to transmission of the same packet when the full bandwidth of the channel is available.

protocol make it useful for radio and mobile radio applications. This feature relates to the hidden terminal problem and ensures that the terminal is always available when the contention random multiple access protocols are used with a fading channel. In the dynamic channel allocation protocol, it is necessary to use multiple busy-tones to identify all those channels which are busy at any instant. These busy-tones need to be allocated a part of the spectrum and also need additional intelligence at each terminal station. This problem is overcome in the sequential protocol by migrating all non-active terminal stations to a new frequency band (channel), which is usually idle and ready to accept contention from them.

The reliability of the simulation results given in this chapter is a matter which needs some further investigation. The simulation of the protocol is based on the principle that the simulation time should be long enough for a true representation of the system to be carried out. Thus, the simulation time requires to be sufficiently long to allow a sufficient number of packets to be transmitted through the system. The number of packets that can be transmitted through the system in the simulation time of 4 million time units is of the order of 20,000 to 120,000, depending on the number of channels in operation and the length of the preamble used.

6-8. SUMMARY

A brief explanation of the simulation procedure that was adopted to simulate the sequential multichannel protocol has been given in this chapter. Attention was mainly focused on the difference between this simulation procedure and that given in chapter four, where the same tool was used for system simulation. The results obtained are based on techniques similar to those discussed in chapter four regarding the delay-throughput for the sequential protocol. Analysis of results was carried out, including variations in the protocol and other parameters that affect the performance. A general conclusion is drawn that the sequential protocol gives lower system utilisation in comparison to the dynamic channel allocation protocol. However the degradation is compensated for by other important features which make it useful in radio and mobile radio applications.

CHAPTER SEVEN

CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER WORK

7-1. ADVANTAGES AND DISADVANTAGES OF CSMA/CA PROTOCOL

The CSMA/CA protocol resolves some of the difficulties encountered by the extension of the contention random multiple access protocol to the radio and mobile radio channel. This is because these contention protocols, which use packet broadcast switching, are found to produce better channel utilisation than any other types of multiplexing technique. These protocols have already found extensive application in local area data communication networks and computer communications. The recent growth in computer applications, accompanied by the spread of digital communications due to the fall in overall system implementation cost, has meant that further research effort has been put into the use of these protocols in radio and mobile radio communication systems. Unfortunately, difficulties have been encountered because of the time-varying (fading) nature of the channel. The CSMA/CA protocol has therefore been suggested as an alternative protocol. This is shown to give better performance than its rival contention protocols. This protocol operates on the principle of resolving the collision rather than detecting it. It also has other attractive features, which include the following;

1) The protocol uses the overhead (preamble period) not only for synchronisation purposes, as with its rival protocols, but also for resolving the collision when it occurs.
2) The problem of false collision can be easily detected and eliminated when it occurs. False collision occurs when the terminal station's transceiver treats the reflection of its own signal transmission as transmission from another terminal, which leads to the abortion of a successful transmission.
3) The priority of acknowledgement provided by the protocol to all users connected to the network will improve the overall capacity utilisation of the channel (throughput) by a proportion which is equivalent to the reduction in the number of collisions, since there is no need for the recipient terminal station to contend with other stations to acknowledge the validity of the data received.
4) Priority for transmission for certain terminals can be easily implemented with this

protocol. This can be achieved by readjustment of the preamble period so that it will be shorter for those terminals that operate with priority. A longer preamble period is used for those terminals that operate without priority.

5) The hidden terminal problem, which is a major obstacle with the application of contention protocols to radio channels, can be avoided to some extent by the use of busy tone as illustrated previously or through the use of two distinctive frequency bands for transmission and reception. In the latter, self acknowledgement is also achieved, which is a very desirable feature since the period of time already allocated for the acknowledgement may thereby be used for data transmission, thus increasing the channel throughput. However, the increase in the protocol throughput is accompanied with sacrificing half the allocated bandwidth of the channel.

6) In the event of a collision, the protocol uses the beat-frequency, instead of the jamming signal used with the CSMA/CD protocol, as an indication to the rest of the terminals that a collision has occurred so that a further chance of transmission will be given to those terminal stations involved in the collision.

7) Finally, although the CSMA/CA protocol is proposed mainly for radio and mobile radio communication systems, it can also be used for cable connected LANs.

Since the CSMA/CA protocols are proposed to overcome the deficiencies of the CSMA/CD protocol when used with radio channels, the proposed protocols also embrace most of the advantages of their CSMA/CD counter-parts. The only disadvantages of the protocols are that they use a longer overhead (preamble period) compared to that of the CSMA/CD protocols, where they are necessary for the resolution of collision.

7-2. ADVANTAGES AND DISADVANTAGES OF DYNAMIC AND SEQUENTIAL MULTICHANNEL SYSTEMS

The multichannel operation of the contention random multiple access protocols has been suggested as a measure to overcome the shortcoming of the single channel operation and, at the same, time to add some other features which enhance the overall operation performance and reliability of the system. Thus, the multichannel operation can provide:

1) Low-rate transmission, which is a desirable characteristic for transmission over radio and mobile radio channels (fading channels).

2) Increase in system operation reliability since, with multichannel operation, a disruption in one of the multiple channels would not put the whole system out of operation but only that particular faulty channel.

3) Relatively higher overall system utilisation (throughput) can be achieved with the use of the dynamic multichannel system in comparison with single channel operation. This is because, when a collision occurs, it effects only a small part of the overall channel utilisation. In single channel operation, this has a direct influence on the whole channel bandwidth utilisation.

4) With the use of the sequential multichannel system, the problem of the hidden terminal no longer exists since all those terminal stations which are not involved in transmission will migrate to the next idle channel which is clear from any transmission. Terminal stations therefore never initiate transmission which will interfere with other existing packet transmissions on the other channels due to the inability to sense weak signals.

7-3. MODIFICATION TOWARDS SYSTEM INTEGRATION

Since with the CSMA/CA protocol it is very easy to implement a priority for transmission the protocol is useful where several different types of data traffic source are using the same network. Such sources generally comprise two types of traffic, speech packets and data packets. The data packets, which are usually a bursty type of traffic and can accept delay (i.e. the delay is not a major issue) should operate with no priority. The length of the packet preamble is therefore longer (i.e. its first listening period is longer). The speech packets in which delay cannot be tolerated, or only a certain limited short period delay can be accepted, needs real-time transmission. Those packets can therefore use the priority that is provided by the protocol.

7-4. GENERAL REMARKS AND CONCLUSIONS

The results of the research work can be summarised as following:

1) A proposal is made for a contention protocol that can be used for radio and mobile radio communication as an alternative to CSMA/CD as used in local area networks.

2) A description of the protocol is given and it merits compared to other protocols which operate in a similar mode.

3) A mathematical model has been implemented to investigate its operational performance for comparison with its predecessors.

4) Further validation of the mathematical model has been carried out by building a software simulation model to enable the accuracy of the results obtained from the analysis to be verified.

5) Some pitfalls which prevented the straightforward application of the protocols were identified.

6) Further developments in the method of operation are proposed consisting of two multichannel protocols which operate with the CSMA/CA protocol for medium access. These two protocols compensate for each others shortcomings.

7) An explanation of a dynamic multichannel protocol which involves two modes of operation are described. These modes are the random choice channel selection (RC) and the idle choice channel selection (IC).

8) Two mathematical models have been used to investigate their performance.

9) A description of the operation of the sequential multichannel protocol is given, including the method of channel access used. The reasons for the choice of this protocol

are also given.

10) Finally, a simulation software model has been built to evaluate its performance. Several factors have been included to determine their effect on the results obtained.

7-5. RECOMMENDATIONS FOR FURTHER WORK

The following further work is suggested to improve the overall performance of the proposed protocol.

1) The CSMA/CA protocol may be operated on a reservation basis when the load exceeds a certain limit. This will overcome two problems. Firstly the deterioration in channel utilisation when the system operates in the unstable region due to the increase in the number of collisions. Secondly, the elimination of the hidden terminal problem by the use of controlled access. In such a case, a controller is necessary to maintain a fair distributed access to the channel from the several terminal stations attached to the network.

2) With the multichannel operation, although in the dynamic channel operation a higher throughput was obtained compared to the sequential system, a reduction in throughput is the penalty for reducing the effect of the hidden terminal problem by resolving the channels in turn. The system operation may be modified so that the system can operate in the stable mode after reaching its maximum attainable throughput. This will be achieved when both multichannel protocols operate under the reservation access control for all the channels as in (1) above.

3) Finally, with the multichannel systems, different transmission rates can be obtained when the whole bandwidth is divided to several channels with different transmission rate capability. The terminal stations attached to the network can then select the most appropriate channel to match its rate of transmission. With this operation, the system can be further modified so that higher utilisation of the overall channel bandwidth can be

achieved, at the same time integrating the network to include several types of service.

7-6. SUMMARY

In this chapter, the overall conclusions about the advantages and disadvantages of the proposed CSMA/CA protocol were given. The advantages and disadvantages of the multichannel system, whether dynamic or sequential were also given. Proposals have been made for system integration to include more than one type of traffic in the network. Further work that can be done to complement the research described in this thesis has been suggested, which will further improve the system performance.

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APPENDICES

APPENDIX (A)

PROCEDURE OF DELAYING PACKETS FOR RETRANSMISSION

This appendix gives the procedure by which a packet will be delayed for transmission when the packets either find the channel busy during their first arrival or re-attempted transmission (i.e. arrive during the preamble time of a preceding packet which is using the successful transmission event) or when a collision is occurred. Appendix (C) gives the list of the simulation programs.

Fig.A-1 shows the generalised procedure by which a packet is delayed regardless of the length of the preamble period when the preceding packet has acquired the real channel represented by the server XX(I). This is valid for both the simulation procedures that were adopted in chapter three for CSMA/CA protocol and the sequential multichannel system discussed in chapter six. However, the last decision point in the figure will be bypassed in the sequential case since at that time, the packet arrival will be in the next succeeding channel.

Fig.A-2 shows the procedure by which the packets directly involved in a collision are delayed according to an exponential back-off algorithm and for those packets which detected the collision without any involvement with it (i.e. sensed the channel before the collision is cleared). The direct involvement in a collision occurs when two or more packets arrive within the vulnerability period of collision (τ).

Throughout figs.A-1 and A-2, the delay of the packets is fulfilled through the dummy servers of XX(I) i.e. when I takes values greater than the number of real channels (I>1 for the CSMA/CA case as in chapter four or I>N for the sequential case as in chapter six).

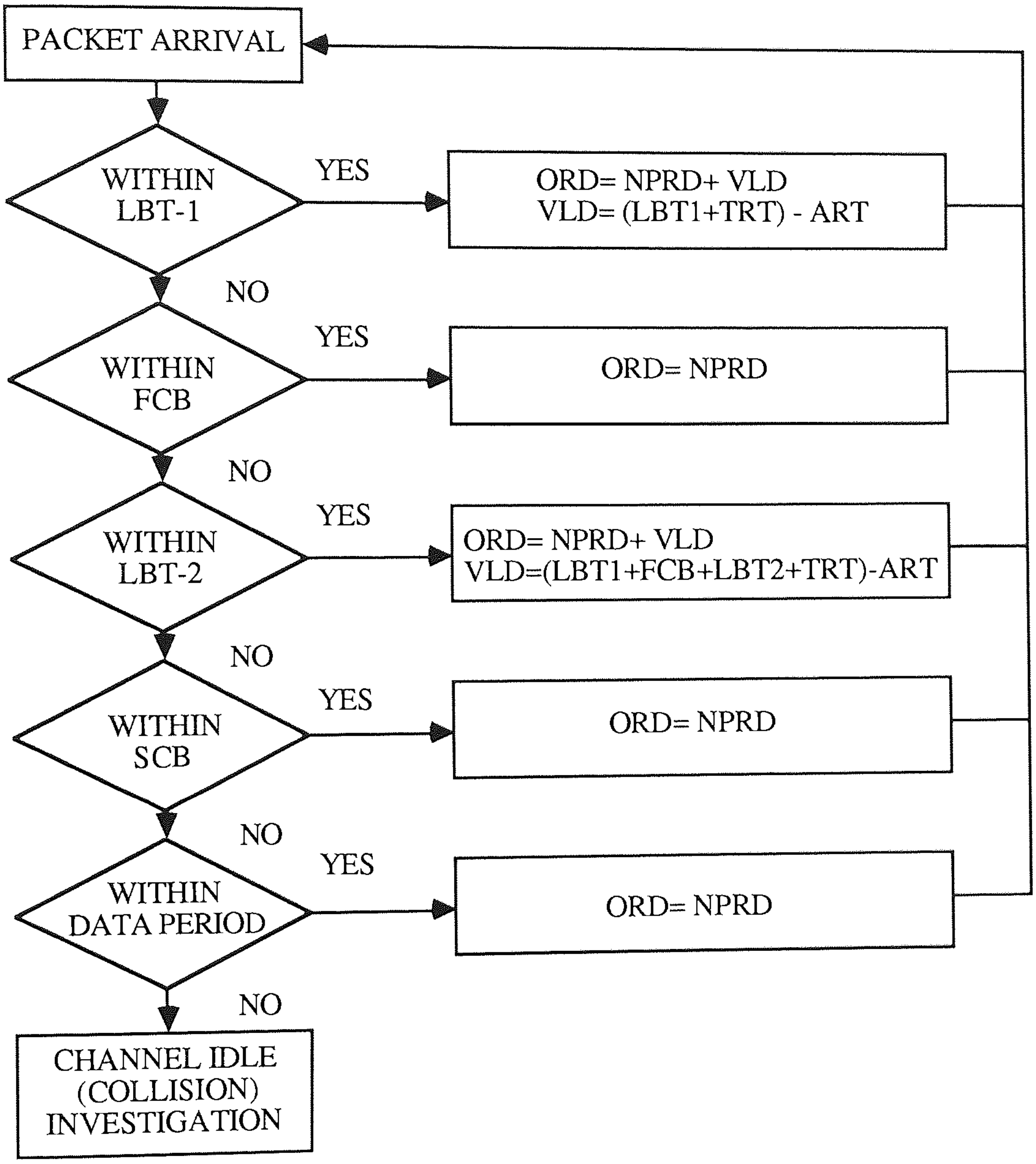

Fig.A-1. Generalised procedure for delaying packets for CSMA/CA and sequential multichannel protocols when the channel sensed busy with respect to a succeeding successfully transmitted packet using the the server XX(I) (real channel or channels).

ORD: Overall random delay.
NPRD: Non-persistent random delay (as given in Table 4-1 and 6-1).
VLD: Variable listening delay.
LBT1: First listening period.
FCB: First carrier burst.
LBT2: Second listening period.
SCB: Second carrier burst.
ART: Packet arrival time (up dated).
TRT: Timer indicates the start of successful transmission (up dated).

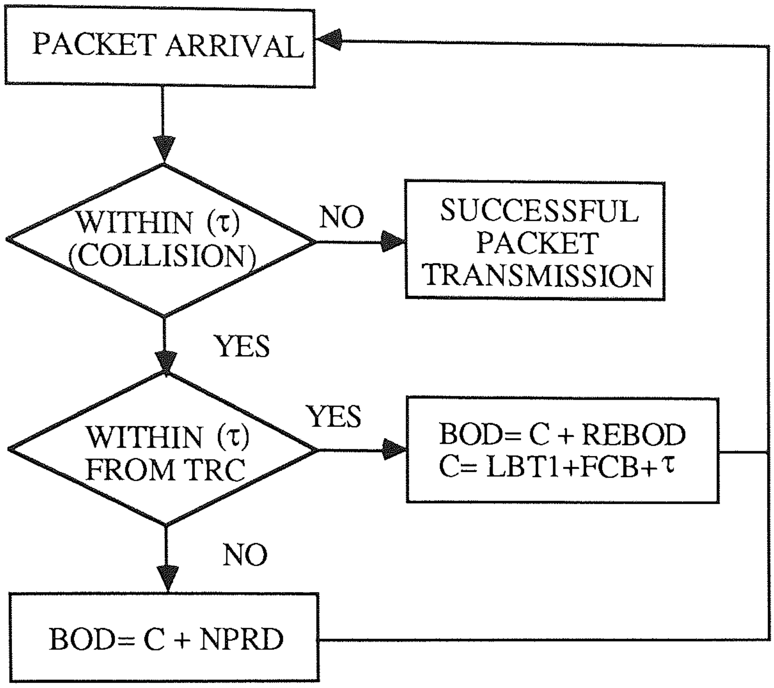

Fig.A-2. Generalised procedure for delaying packets for CSMA/CA and sequential multichannel protocols when collision occurs for those involved in collision and those packets detected the collision.

TRC: Timer indicates collision occurrence.
BOD: Back-off delay.
C: Constant, its value is given in the figure.
REBOD: Random exponential back-off delay (as given in Table 4-1 and 6-1).
NPRD: Non-persistent random delay as in fig.A-1.

APPENDIX (B)

SLAM-II SUMMARY REPORT

This appendix shows the SLAM-II summary report which displays the statistical results collected from the simulation program according to the user written subroutine at the end of each simulation run. This is applicable for both simulation methods that are adopted in chapter three when CSMA/CA protocol is simulated and the multichannel sequential protocol which is simulated in chapter six.

The output results provided by the report can be seen in fig.B-1, which is the same for both systems simulated. However, the figure given is actually for the sequential multichannel system. From the figure, the results can be divided into three categories. The first category of statistical results is given for the variable in the simulation program based on discrete observation and includes the results statistics collected within the simulation model by the COLCT statements. This is exemplified by the number of packets successfully transmitted, deleted or delayed and the average time delay for those successfully transmitted packets. The second category of the statistical results is for time-persistent variables that corresponds to the global variables XX(I) (i.e. the servers). This kind of result is represented in the figure by the channels whether used to represent the real channel (as in chapter three) or channels (as in chapter six) or the dummy channels used only for the purpose of delaying the packets. The third and last category is the statistical results collected from the simulation program which correspond to the files used in the simulation including the CALENDAR event file. This gives the number of packets buffered in each file and their average waiting time during the simulation period. These files can represent queues if it is required in the simulation. In the program, file (1) is used in the sensing/slotting event of chapter three or test event of chapter six to save the packet for a short period of time to investigate collision. However, file (2), which is only used in chapter six, is used to represent the stations busy-list.

Finally, the results shown in the figure are for the slotted case, N=5 and the total offered load (G=0.9112), which corresponds to G=(P+R)/N (see eqn.6-1). The newly generated load (P=3.5 packets/packet time). The simulation time interval is $2x10^6$ unit time and the end-to-end propagation delay time (τ=2.5 unit time).

```
1


                                S L A M   I I   S U M M A R Y   R E P O R T


                         SIMULATION PROJECT BROADBAND LAN               BY ABDULLATIF M. GLASS

                         DATE  8/26/1987                                RUN NUMBER    1 OF    1


                         CURRENT TIME   0. 2000E+07
                         STATISTICAL ARRAYS CLEARED AT TIME  0. 0000E+01



                         **STATISTICS FOR VARIABLES BASED ON OBSERVATION**

                     MEAN         STANDARD      COEFF. OF      MINIMUM       MAXIMUM       NUMBER OF
                     VALUE        DEVIATION     VARIATION      VALUE         VALUE         OBSERVATIONS

DELPKTS1          0. 1440E+03   0. 8299E+02   0. 5763E+00   0. 1000E+01   0. 2870E+03        287
DELPKTS3          0. 1000E+01   0. 0000E+01   0. 0000E+01   0. 1000E+01   0. 1000E+01          1
DELYPBS1          0. 1460E+03   0. 8415E+02   0. 5764E+00   0. 1000E+01   0. 2910E+03        291
DELYPBS3          0. 1683E+04   0. 9718E+03   0. 5773E+00   0. 1000E+01   0. 3366E+04       3366
TOTCOLP1          0. 1850E+02   0. 1054E+02   0. 5695E+00   0. 1000E+01   0. 3600E+02         36
TOTCOLP2          0. 1040E+03   0. 5990E+02   0. 5760E+00   0. 1000E+01   0. 2070E+03        207
TOTCOLP3          0. 8600E+02   0. 4951E+02   0. 5757E+00   0. 1000E+01   0. 1710E+03        171
DCPKTS1           0. 1500E+01   0. 7071E+00   0. 4714E+00   0. 1000E+01   0. 2000E+01          2
DCPKTS3           0. 7000E+01   0. 3894E+01   0. 5563E+00   0. 1000E+01   0. 1300E+02         13
TOTPKTS           0. 2359E+05   0. 1362E+05   0. 5773E+00   0. 1000E+01   0. 4717E+05      47173
DELAYTM           0. 1513E+03   0. 1839E+02   0. 1216E+00   0. 1475E+03   0. 1764E+04      47173
COUNT             0. 7197E+04   0. 4155E+04   0. 5773E+00   0. 1000E+01   0. 1439E+05      14392



                         **STATISTICS FOR TIME-PERSISTENT VARIABLES**

                     MEAN         STANDARD      MINIMUM        MAXIMUM       TIME          CURRENT
                     VALUE        DEVIATION     VALUE          VALUE         INTERVAL      VALUE

CHANNEL 1 UTILIZ  0. 6959E+00   0. 4600E+00   0. 0000E+01   0. 1000E+01   0. 2000E+07   0. 1000E+01
CHANNEL 2 UTILIZ  0. 6958E+00   0. 4600E+00   0. 0000E+01   0. 1000E+01   0. 2000E+07   0. 1000E+01
CHANEL  3 UTILIZ  0. 6958E+00   0. 4601E+00   0. 0000E+01   0. 1000E+01   0. 2000E+07   0. 0000E+01
CHANEL  4 UTILIZ  0. 6958E+00   0. 4601E+00   0. 0000E+01   0. 1000E+01   0. 2000E+07   0. 1000E+01
CHANEL  5 UTILIZ  0 6958E+00    0 4601E+00    0. 0000E+01   0. 1000E+01   0. 2000E+07   0. 1000E+01
CHANEL  6 UTILIZ  0. 7920E-01   0 2701E+00    0 0000E+01    0. 1000E+01   0. 2000E+07   0. 0000E+01
CHANEL 10 UTILIZ  0. 3040E-03   0. 1743E-01   0 0000E+01    0. 1000E+01   0. 2000E+07   0. 0000E+01
CHANEL 20 UTILIZ  0. 0000E+01   0. 0000E+01   0 0000E+01    0 0000E+01    0. 2000E+07   0 0000E+01
CHANEL 50 UTILIZ  0. 0000E+01   0. 0000E+01   0. 0000E+01   0 0000E+01    0. 2000E+07   0. 0000E+01
CHANEL 80 UTILIZ  0. 0000E+01   0 0000E+01    0. 0000E+01   0. 0000E+01   0. 2000E+07   0. 0000E+01
CHANEL 90 UTILIZ  0 0000E+01    0. 0000E+01   0 0000E+01    0. 0000E+01   0. 2000E+07   0. 0000E+01
CHANL 100 UTILI   0. 0000E+01   0 0000E+01    0. 0000E+01   0. 0000E+01   0. 2000E+07   0 0000E+01
CHANL 101 UTILI   0. 0000E+01   0 0000E+01    0 0000E+01    0. 0000E+01   0. 2000E+07   0 0000E+01
CHANL 110 UTILI   0. 0000E+01   0. 0000E+01   0 0000E+01    0. 0000E+01   0 2000E+07    0. 0000E+01
CHANL 120 UTILI   0. 0000E+01   0. 0000E+01   0. 0000E+01   0. 0000E+01   0. 2000E+07   0 0000E+01
CHANL 150 UTILI   0. 0000E+01   0 0000E+01    0 0000E+01    0. 0000E+01   0. 2000E+07   0 0000E+01
CHANL 200 UTILI   0 0000E+01    0 0000E+01    0 0000E+01    0 0000E+01    0. 2000E+07   0. 0000E+01
CHANL 250 UTILI   0 0000E+01    0 0000E+01    0. 0000E+01   0. 0000E+01   0. 2000E+07   0. 0000E+01



                         **FILE STATISTICS**

                                                                                  AVERAGE
FILE    ASSOC NODE           AVERAGE       STANDARD     MAXIMUM     CURRENT     WAITING TIME
NUMBER  LABEL/TYPE           LENGTH        DEVIATION    LENGTH      LENGTH

  1                          0. 0001       0. 0094         1           0           0 8489
  2                          3 4792        0. 5485         5           4         147 4943
  3           CALENDAR       4 5709        0. 5913        10           5          58 4389
```

Fig.B-1. SLAM-II summary report for discrete event simulation model.

DELPKTS1: Deleted packets at event-1.
DELPKTS3: Deleted packets at event-3.
DELYPBS1: Delayed packets at event-1.
DELYPBS3: Delayed packets at event-3.
TOTCOLP1: Total collided packets at event-1.
TOTCOLP2: Total collided packets at event-2.
TOTCOLP3: Total collided packets at event-3.
DCPKTS1: Deleted collided packets at event-1.
DCPKTS2: Deleted collided packets at event-3.
TOTPKTS: Total packets successfully transmitted.
DELAYTM: Delay time (average) of those successfully transmitted packets.
COUNT: Counter to count the total retransmitted packets.
CHANNEL(1-5): Real channels of the network.
CHANL(6-250): Dummy channels for non-persistent packet delay.

APPENDIX (C)

LIST OF SIMULATION PROGRAMS

A list of simulation programs are given in this appendix. These include samples of the programs adopted for the single channel non-persistent and slotted non-persistent CSMA/CA protocols simulation that are given in chapter 4 and the programs that are used to simulate the sequential multichannel system for both the non-persistent and the slotted non-persistent channel access protocols. These programs are given for only one case of each of them. The simulation programs may be slightly altered in order to change certain parameters that effect the results obtained, especially with regards to the delay of the protocol. This is also valid for the case of the sequential multichannel protocol, although the changes in this case are slightly greater as, for example, the program needs to be altered according to whether the system operates with or without stations-busy list, the length of the preamble, the number of terminal stations connected to the network and, finally, the retransmission delay time that is adopted. The flow charts of these programs are given in chapters 4 and 6 respectively. However, the way in which the packets are delayed for retransmission is given in appendix (A). Thus, the list of the programs in the following pages will be for the following cases;

1) Program 1 is for the non-persistent CSMA/CA protocol simulation.
2) Program 2 is for the slotted non-persistent CSMA/CA protocol simulation.
3) Program 3 is for the sequential multichannel protocol simulation using the non-persistent CSMA/CA protocol for channel access.
4) Finally, program 4 is for the squential multichannel protocol simulation using the slotted non-persistent CSMA/CA protocol for channel access.

PROGRAM (1)

```
C******************************************************************
C*THIS PROGRAM SIMULATES THE CONTENTION OF A NON-PERSISTENT**
C**CSMA/CA PROTOCOL FOR DETERMINATION OF ITS AVERAGE DELAY****
C**AND THROUGHPUT CHARACTERISTICS UNDER DIFFERENT OFFERED***
C***********************LOAD CONDITION**************************
C******************************************************************
C
C****************************************
C*****MAIN PROGRAM*******************
C****************************************
    PROGRAM MAIN
    DIMENSION NSET(200000)
    PARAMETER (MEQT=100,  MSCND=25,  MENTR=25,  MRSC=75,
   1MARR=50, MGAT=25, MHIST=50,  MCELS=500, MCLCT=50,
   2MSTAT=50, MEQV=100, MATRB=100, MFILS=100, MPLOT=10,
   3MVARP=10, MSTRM=10, MACT=100, MNODE=500, MITYP=50,
   4MMXXV=250)
    PARAMETER (MVARP1=MVARP+1)
    COMMON/SCOM1/ATRIB(MATRB), DD(MEQT), DDL(MEQT), DTNOW,
    1II, MFA, MSTOP,NCLNR, NCRDR, NPRNT, NNRUN, NNSET,
   2NTAPE, SS(MEQT), SSL(MEQT),TNEXT, TNOW, XX(MMXXV)
    SPECIAL COMMON SCOM1
    COMMON QSET(200000)
    SPECIAL COMMON
    EQUIVALENCE (NSET(1),QSET(1))
    NNSET=200000
    NCRDR=15
    NPRNT=16
    NTAPE=17
    CALL SLAM
    STOP
    END
C*************************************
C*****SAMPLE SUBROUTINE EVENT*****
C*************************************
    SUBROUTINE EVENT(I)
    GO TO (1,2,3,4)I
  1 CALL ARIVL
    RETURN
  2 CALL SENSING
    RETURN
  3 CALL DELCOL
    RETURN
  4 CALL SUCCESS
    RETURN
    END
C*********************************************************
C****SUBROUTINE INITIALIZATION OF SIMULATION PROGRAM****
C*********************************************************
    SUBROUTINE INTLC
    COMMON/SCOM1/ ATRIB(100),DD(100),DDL(100),DTNOW,
    1II,MFA,MSTOP,NCLNR,NCRDR,NPRNT,NNRUN,NNSET,NTAPT,
    2SS(100),SS(100),SSL(100),TNEXT,TNOW,XX(250)
    COMMON/UCOM1/ MEDLEN,OFDLOAD,ETEPT,PKTTIME,
   1TOTPKTS,IDEL,TIMERC,TIMERT,TIMERT1,DELYD,DELYC,
```

```
   2DELYT,DELPKTS
C
C*****READ VALUES OF MEDIUM LENGTH AND OFFERED-LOAD
C*****TO THE NETWORK
C
    READ(NCRDR,101)MEDLEN
    READ(NCRDR,105)OFDLOAD
    CALL COLCT(OFDLOAD,5)
 101  FORMAT(2X,F7.2)
 105  FORMAT(2X,F10.4)
C
C*****XX(N) IS BUSY STATUS OF CHANNEL N
C
    DO 5 N=1,250
  5  XX(N)=0.0
    CALL SCHDL(1,0.0,ATRIB)
    TOTPKTS=0
    DELPKTS=0
    TIMERC=0.0
    TIMERT=0.0
    TIMERT1=0.0
    COUNT=0
    RETURN
    END
C*********************************************
C*****SUBROUTINE ARRIVAL OF THE PACKETS*****
C*********************************************
    SUBROUTINE ARIVL
    COMMON/SCOM1/ ATRIB(100),DD(100),DDL(100),DTNOW,
     1II,MFA,MSTOP,NCLNR,NCRDR,NPRNT,NNRUN,NNSET,NTAPE,
    2SS(100),SSL(100),TNEXT,TNOW,XX(250)
    COMMON/UCOM1/ MEDLEN,OFDLOAD,ETEPT,PKTTIME,
   1TOTPKTS,IDEL,TIMERC,TIMERT,TIMERT1,DELYD,DELYC,
   2DELYT,DELPKTS
C
C*****SCHEDULE NEXT PACKET ARRIVAL ACCORDING TO
C*****POISSON DISTRIBUTION
C
    INTEGER NRAN
     PROPSPD=2.0E+08
    ETEPT=(MEDLEN/PROPSPD)*1000000.0
    PKTTIME=1000.0*ETEPT
    AMEAN=PKTTIME/OFDLOAD
    IF(NNQ(NCLNR).GE.(INT(OFDLOAD)+1)) RETURN
     AINRVLT=NPSSN(AMEAN,2)
     CALL SCHDL(1,AINRVLT,ATRIB)
C
C*****SET-UP ATTRIBUTES OF THE PACKET(ITS ARRIVAL TIME,
C*****NUMBER OF COLLISIONS ENCOUNTERED AND SERVER NUMBER)
C
    CARIVLT=TNOW
     IF(CARIVLT.GT.0.0) GO TO 30
     IDEL=1
  10 IF(XX(1+IDEL).EQ.0.0) GO TO 20
     IDEL=IDEL+1
     GO TO 10
  20 ATRIB(1)=CARIVLT
      ATRIB(2)=0.0
     ATRIB(3)=1+IDEL
```

```
      XX(1+IDEL)=1.0
      TIMERT=ATRIB(1)
      CALL SCHDL(2,ETEPT,ATRIB)
      RETURN
   30 IDEL=1
   40 IF(XX(1+IDEL).EQ.0.0) GO TO 50
      IDEL=IDEL+1
      GO TO 40
   50 IF(XX(1).EQ.1.0) GO TO 70
      IF((CARIVLT-TIMERT).LT.ETEPT) GO TO 90
      IF((CARIVLT-TIMERC).LT.(8.0*ETEPT)) GO TO 120
      ATRIB(1)=CARIVLT
      ATRIB(2)=0.0
      ATRIB(3)=1+IDEL
      TIMERT=CARIVLT
      XX(1+IDEL)=1.0
      CALL SCHDL(2,ETEPT,ATRIB)
      RETURN
C*****THE CHANNEL(SYSTEM) IS BUSY, DELAY THIS PACKET
   70 ATRIB(1)=CARIVLT
      ATRIB(2)=0.0
      ATRIB(3)=1+IDEL
      HVALUE=2.0*PKTTIME
      DELYD=UNFRM(0.0,HVALUE,1)
      XX(1+IDEL)=1.0
      CALL SCHDL(3,DELYD,ATRIB)
      RETURN
C*****COLLISION HAPPENED RESCHEDULE THE PACKET
C*****FOR RETRANSMISSION
   90 ATRIB(1)=CARIVLT
      TIMERC=CARIVLT
      NCOL=1
      ATRIB(2)=NCOL
      VLO=0.0
      VHI=2.0**NCOL
      NRANC=UNFRM(VLO,VHI,1)
      DELYC=ETEPT*NRANC+7.0*ETEPT
      XX(1+IDEL)=1.0
      ATRIB(3)=1+IDEL
      CALL SCHDL(3,DELYC,ATRIB)
      IF(NNQ(1).GT.0.0) GO TO 100
      CALL FILEM(1,ATRIB)
  100 RETURN
C*****DELAY THIS PACKET DUE TO PREVIOUS COLLISION
C*****WITH OTHER TWO PACKETS
  120 ATRIB(1)=CARIVLT
      ATRIB(2)=0.0
      ATRIB(3)=1+IDEL
      DELYT=UNFRM(0.0,PKTTIME,1)
      XX(1+IDEL)=1.0
      CALL SCHDL(3,DELYT,ATRIB)
      RETURN
      END
C****************************************
C*****SUBROUTINE LISTENING PERIOD******
C****************************************
      SUBROUTINE SENSING
      COMMON/SCOM1/ ATRIB(100),DD(100),DDL(100),DTNOW,
     1II,MFA,MSTOP,NCLNR,NCRDR,NPRNT,NNRUN,NNSET,NTAPE,
```

```
     2SS(100),SSL(100),TNEXT,TNOW,XX(250)
      COMMON/UCOM1/ MEDLEN,OFDLOAD,ETEPT,PKTTIME,
     1TOTPKTS,IDEL,TIMERC,TIMERT,TIMERT1,DELYD,DELYC,
     2DELYT,DELPKTS
      INTEGER NRAN
      IDD=ATRIB(3)
      TIME=ATRIB(1)
      NCOL1=ATRIB(2)
      XX(IDD)=0.0
      IF(NNQ(1).GT.0.0) GO TO 310
C*****SUCCESSFULL TRANSMISSION
      XX(1)=1.0
      ATRIB(1)=TIME
      ATRIB(2)=NCOL1
      ATRIB(3)=1
      TIMERT1=TIMERT
      CALL SCHDL(4,PKTTIME,ATRIB)
      RETURN
C*****COLLISION WITH ANOTHER SUCCEEDING PACKET HAPPENED
  310 IDEL=1
  320 IF(XX(1+IDEL).EQ.0.0) GO TO 330
      IDEL=IDEL+1
      GO TO 320
  330 ATRIB(1)=TIME
      NCOL1=NCOL1+1
      ATRIB(2)=NCOL1
      ATRIB(3)=1+IDEL
      TIMERT=TIMERT1
      VLO=0.0
      VHI=2.0**NCOL1
      NRAND=UNFRM(VLO,VHI,1)
      DELYC=6.0*ETEPT+NRAND*ETEPT
      XX(1+IDEL)=1.0
      CALL SCHDL(3,DELYC,ATRIB)
      CALL RMOVE(1,1,ATRIB)
      RETURN
      END
C***********************************************
C*****SUBROUTINE SUCCESSFULL TRANSMISSION*****
C***********************************************
      SUBROUTINE SUCCESS
      COMMON/SCOM1/ ATRIB(100),DD(100),DDL(100),DTNOW,
     1II,MFA,MSTOP,NCLNR,NCRDR,NPRNT,NNRUN,NNSET,NYAPE,
     2SS(100),SSL(100),TNEXT,TNOW,XX(250)
      COMMON/UCOM1/ MEDLEN,OFDLOAD,ETEPT,PKTTIME,
     1TOTPKTS,IDEL,TIMERC,TIMERT,TIMERT1,DELYD,DELYC,
     2DELYT,DELPKTS
      JJ=ATRIB(3)
      XX(JJ)=0.0
      TOTPKTS=TOTPKTS+1
      CALL COLCT(TOTPKTS,1)
      DELAYTM=TNOW-ATRIB(1)
      CALL COLCT(DELAYTM,2)
      RETURN
      END
C****************************************************
C*****SUBROUTINE DELAY-COLLISION REPRESENTATION****
C********************OF THE PACKETS********************
C****************************************************
```

```
      SUBROUTINE DELCOL
      COMMON/SCOM1/ ATRIB(100),DD(100),DDL(100),DTNOW,
     1II,MFA,MSTOP,NCLNR,NCRDR,NPRNT,NNRUN,NNSET,NTAPE,
     2SS(100),SSL(100),TNEXT,TNOW,XX(250)
      COMMON/UCOM1/ MEDLEN,OFDLOAD,ETEPT,PKTTIME,
     1TOTPKTS,IDEL,TIMERC,TIMERT,TIMERT1,DELYD,DELYC,
     2DELYT,DELPKTS
      INTEGER NRAN
      COUNT=COUNT+1
      CALL COLCT(COUNT,4)
      IXD=ATRIB(3)
      XX(IXD)=0.0
      RARIVLT=TNOW
      ATIME=ATRIB(1)
      COLN=ATRIB(2)
      IF(COLN.EQ.16.0) GO TO 600
      IDEL=1
  400 IF(XX(1+IDEL).EQ.0.0) GO TO 420
      IDEL=IDEL+1
      GO TO 400
  420 IF(XX(1).EQ.1.0) GO TO 450
      IF((RARIVLT-TIMERT).LT.ETEPT) GO TO 500
      IF((RARIVLT-TIMERC).LT.(7.0*ETEPT)) GO TO 550
      ATRIB(1)=ATIME
      ATRIB(2)=COLN
      ATRIB(3)=1+IDEL
      XX(1+IDEL)=1.0
      TIMERT=RARIVLT
      CALL SCHDL(2,ETEPT,ATRIB)
      RETURN
C*****THE CHANNEL(SYSTEM) IS BUSY, DELAY THIS PACKET
  450 ATRIB(1)=ATIME
      ATRIB(2)=COLN
      ATRIB(3)=1+IDEL
      HVALUE=2.0*PKTTIME
      DELYD=UNFRM(0.0,HVALUE,1)
      XX(1+IDEL)=1.0
      CALL SCHDL(3,DELYD,ATRIB)
      RETURN
C*****COLLISION HAPPENED WITH OTHER PRECEEDING PACKET
C*****RESCHEDULES THIS PACKET FOR LATER RETRANSMISSIOM
  500 ATRIB(1)=ATIME
      TIMERC=RARIVLT
      COLN=COLN+1
      ATRIB(2)=COLN
      VLO=0.0
      M=COLN
      VHI=2.0**M
      NRAND=UNFRM(VLO,VHI,1)
      DELYC=NRAND*ETEPT+7.0*ETEPT
      XX(1+IDEL)=1.0
      CALL SCHDL(3,DELYC,ATRIB)
      IF(NNQ(1).GT.0.0) GO TO 510
      CALL FILEM(1,ATRIB)
  510 RETURN
C*****DELAY THIS PACKET DUE TO PREVIOUS COLLISION
  550 ATRIB(1)=ATIME
      ATRIB(2)=COLN
      ATRIB(3)=1+IDEL
```

```
      DELYT=UNFRM(0.0,PKTTIME,1)
      XX(1+IDEL)=1.0
      CALL SCHDL(3,DELYT,ATRIB)
      RETURN
  600 DELPKTS=DELPKTS+1
      CALL COLCT(DELPKTS,3)
      RETURN
      END
C***********************END OF PROGRAM*****************
```

PROGRAM (2)

```
C*****************************************************
C**THIS PROGRAM SIMULATES THE CONTENTION OF A SLOTTED***
C***NON-PERSISTENT CSMA/CA PROTOCOL FOR DETERMINATION**
C**OF ITS AVERAGE DELAY AND THROUGHPUT CHARACTERISTICS*
C*******UNDER DIFFERENT OFFERED LOAD CONDITIONS**********
C*****************************************************
C
C************************************
C*****MAIN PROGRAM******************
C************************************
      PROGRAM MAIN
      DIMENSION NSET(200000)
      PARAMETER (MEQT=100, MSCND=25, MENTR=25, MRSC=75,
     1 MARR=50, MGAT=25, MHIST=50, MCELS=500, MCLCT=50,
     2MSTAT=50, MEQV=100, MATRB=100, MFILS=100, MPLOT=10,
     3 MACT=100, MNODE=500, MITYP=50,  MMXXV=250)
      PARAMETER (MVARP1=MVARP+1)
      COMMON/SCOM1/ATRIB(MATRB), DD(MEQT), DDL(MEQT), DTNOW,
     1II, MFA, MSTOP,NCLNR, NCRDR, NPRNT, NNRUN, NNSET,
     2NTAPE, SS(MEQT), SSL(MEQT),TNEXT, TNOW, XX(MMXXV)
      SPECIAL COMMON SCOM1
      COMMON QSET(200000)
      SPECIAL COMMON
      EQUIVALENCE (NSET(1),QSET(1))
      NNSET=200000
      NCRDR=15
      NPRNT=16
      NTAPE=17
      CALL SLAM
      STOP
      END
C*********************************
C*****SAMPLE SUBROUTINE EVENT*****
C*********************************
      SUBROUTINE EVENT(I)
      GO TO (1,2,3,4)I
    1 CALL ARIVL
      RETURN
    2 CALL SENSING
      RETURN
    3 CALL DELCOL
      RETURN
    4 CALL SUCCESS
      RETURN
      END
C**************************************************
C**SUBROUTINE INITIALIZATION OF SIMULATION PROGRAM**
C**************************************************
      SUBROUTINE INTLC
      COMMON/SCOM1/ ATRIB(100),DD(100),DDL(100),DTNOW,
     1II,MFA,MSTOP,NCLNR,NCRDR,NPRNT,NNRUN,NNSET,NTAPE,
     2SS(100),SSL(100),TNEXT,TNOW,XX(250)
      COMMON/UCOM1/ MEDLEN,OFDLOAD,ETEPT,PKTTIME,
     1TOTPKTS,IDEL,TIMERC,TIMERT,TIMERT1,DELYD,DELYC,
     2DELYT,SLOT,DELPKTS
```

```
C
C*****READ THE VALUES OF MEDIUM LENGTH AND OFFERED
C*****LOAD TO THE NETWORK
C
      READ(NCRDR,101)MEDLEN
      READ(NCRDR,105)OFDLOAD
 101  FORMAT(2X,F7.2)
 105  FORMAT(2X,F10.4)
C
C*****XX(N) IS BUSY STATUS OF CHANNEL N
C
      DO 5 N=1,250
    5 XX(N)=0.0
      CALL SCHDL(1,0.0,ATRIB)
      TOTPKTS=0
      DELPKTS=0
      TIMERC=0.0
      TIMERT=0.0
      TIMERT1=0.0
      COUNT=0
      RETURN
      END
C**********************************************
C*****SUBROUTINE ARRIVAL OF THE PACKETS*****
C**********************************************
      SUBROUTINE ARIVL
      COMMON/SCOM1/ ATRIB(100),DD(100),DDL(100),DTNOW,
     1II,MFA,MSTOP,NCLNR,NCRDR,NPRNT,NNRUN,NNSET,NTAPE,
     2SS(100),SSL(100),TNEXT,TNOW,XX(250)
      COMMON/UCOM1/ MEDLEN,OFDLOAD,ETEPT,PKTTIME,
     1TOTPKTS,IDEL,TIMERC,TIMERT,TIMERT1,DELYD,DELYC,
     2DELYT,SLOT,DELPKTS
C
C*****SCHEDULE NEXT PACKET ARRIVAL ACCORDING TO
C*****POISSON DISTRIBUTION
C
      INTEGER NRAN
      PROPSPD=2.0E+08
      ETEPT=(MEDLEN/PROPSPD)*1000000.0
      PKTTIME=1000.0*ETEPT
      AMEAN=PKTTIME/OFDLOAD
      AINRVLT=NPSSN(AMEAN,2)
      CALL SCHDL(1,AINRVLT,ATRIB)
C
C*****SET-UP ATTRIBUTES OF THE PACKET(ITS ARRIVAL TIME,
C*****NUMBER OF COLLISIONS ENCOUNTERED AND SERVER NUMBER)
C
      CARIVLT=TNOW
      IF(CARIVLT.GT.0.0) GO TO 30
      IDEL=1
   10 IF(XX(1+IDEL).EQ.0.0) GO TO 20
      IDEL=IDEL+1
      GO TO 10
   20 ATRIB(1)=CARIVLT
      ATRIB(2)=0.0
      ATRIB(3)=1+IDEL
      XX(1+IDEL)=1.0
      TIMERT=ATRIB(1)
      CALL SCHDL(2,ETEPT,ATRIB)
```

```
      RETURN
   30 IDEL=1
   40 IF(XX(1+IDEL).EQ.0.0) GO TO 50
      IDEL=IDEL+1
      GO TO 40
   50 IF(XX(1).EQ.1.0) GO TO 70
      IF((CARIVLT-TIMERT).LT.ETEPT) GO TO 90
      IF((CARIVLT-TIMERC).LT.(8.0*ETEPT)) GO TO 120
C*****SLOT THE ARRIVAL TIME TO MULTI-SLOTS
C*****(ONE SLOT EQUAL TO END-T0-END PROPAGATION TIME)
      AMOD=CARIVLT-(INT(CARIVLT/ETEPT)*ETEPT)
      IF(AMOD.EQ.0.0) GO TO 60
      SLOT=ETEPT-AMOD
      ATRIB(1)=CARIVLT
      ATRIB(2)=0.0
      ATRIB(3)=1+IDEL
      TIMERT=CARIVLT+SLOT
      XX(1+IDEL)=1.0
      CALL SCHDL(2,SLOT,ATRIB)
      RETURN
   60 ATRIB(1)=CARIVLT
      ATRIB(2)=0.0
      ATRIB(3)=1+IDEL
      TIMERT=CARIVLT
      XX(1+IDEL)=1.0
      CALL SCHDL(2,ETEPT,ATRIB)
      RETURN
C*****THE CHANNEL(SYSTEM) IS BUSY, DELAY THIS PACKET
   70 ATRIB(1)=CARIVLT
      ATRIB(2)=0.0
      ATRIB(3)=1+IDEL
      HVALUE=2.0*PKTTIME
      DELYD=UNFRM(0.0,HVALUE,1)
      XX(1+IDEL)=1.0
      CALL SCHDL(3,DELYD,ATRIB)
      RETURN
C*****COLLISION HAPPENED RESCHEDULE THE PACKET
C*****FOR RETRANSMISSION
   90 ATRIB(1)=CARIVLT
      TIMERC=CARIVLT
      NCOL=1
      ATRIB(2)=NCOL
      VLO=0.0
      VHI=2.0**NCOL
      NRANC=UNFRM(VLO,VHI,1)
      DELYC=ETEPT*NRANC+7.0*ETEPT
      XX(1+IDEL)=1.0
      ATRIB(3)=1+IDEL
      CALL SCHDL(3,DELYC,ATRIB)
      IF(NNQ(1).GT.0.0) GO TO 100
      CALL FILEM(1,ATRIB)
  100 RETURN
C*****DELAY THIS PACKET DUE TO PREVIOUS COLLISION
C*****WITH OTHER TWO PACKETS
  120 ATRIB(1)=CARIVLT
      ATRIB(2)=0.0
      ATRIB(3)=1+IDEL
      DELYT=UNFRM(0.0,PKTTIME,1)
      XX(1+IDEL)=1.0
```

```
      CALL SCHDL(3,DELYT,ATRIB)
      RETURN
      END
C*****************************************
C*****SUBROUTINE LISTENING PERIOD******
C*****************************************
       SUBROUTINE SENSING
      COMMON/SCOM1/ ATRIB(100),DD(100),DDL(100),DTNOW,
       1II,MFA,MSTOP,NCLNR,NCRDR,NPRNT,NNRUN,NNSET,NTAPE,
      2SS(100),SSL(100),TNEXT,TNOW,XX(250)
      COMMON/UCOM1/ MEDLEN,OFDLOAD,ETEPT,PKTTIME,
     1TOTPKTS,IDEL,TIMERC,TIMERT,TIMERT1,DELYD,DELYC,
     2DELYT,SLOT,DELPKTS
      INTEGER NRAN
      IDD=ATRIB(3)
      TIME=ATRIB(1)
      NCOL1=ATRIB(2)
       XX(IDD)=0.0
       IF(NNQ(1).GT.0.0) GO TO 310
C*****SUCCESSFULL TRANSMISSION
       XX(1)=1.0
      ATRIB(1)=TIME
      ATRIB(2)=NCOL1
      ATRIB(3)=1
      TIMERT1=TIMERT
      CALL SCHDL(4,PKTTIME,ATRIB)
      RETURN
C*****COLLISION WITH THE SUCCEEDING PACKET HAPPENED
  310 IDEL=1
  320 IF(XX(1+IDEL).EQ.0.0) GO TO 330
      IDEL=IDEL+1
      GO TO 320
  330 ATRIB(1)=TIME
      NCOL1=NCOL1+1
      ATRIB(2)=NCOL1
      ATRIB(3)=1+IDEL
      TIMERT=TIMERT1
      VLO=0.0
      VHI=2.0**NCOL1
      NRAND=UNFRM(VLO,VHI,1)
      DELYC=6.0*ETEPT+NRAND*ETEPT
       XX(1+IDEL)=1.0
      CALL SCHDL(3,DELYC,ATRIB)
      CALL RMOVE(1,1,ATRIB)
      RETURN
      END
C******************************************
C*****SUBROUTINE SUCCESSFULL TRANSMISSION*****
C******************************************
       SUBROUTINE SUCCESS
      COMMON/SCOM1/ ATRIB(100),DD(100),DDL(100),DTNOW,
       1II,MFA,MSTOP,NCLNR,NCRDR,NPRNT,NNRUN,NNSET,NYAPE,
      2SS(100),SSL(100),TNEXT,TNOW,XX(250)
      COMMON/UCOM1/ MEDLEN,OFDLOAD,ETEPT,PKTTIME,
     1TOTPKTS,IDEL,TIMERC,TIMERT,TIMERT1,DELYD,DELYC,
     2DELYT,SLOT,DELPKTS
      JJ=ATRIB(3)
       XX(JJ)=0.0
      TOTPKTS=TOTPKTS+1
```

```
      CALL COLCT(TOTPKTS,1)
      DELAYTM=TNOW-ATRIB(1)
      CALL COLCT(DELAYTM,2)
      RETURN
      END
C************************************************
C***SUBROUTINE DELAY-COLLISION REPRESENTATION***
C****************OF THE PACKETS********************
C************************************************
      SUBROUTINE DELCOL
      COMMON/SCOM1/ ATRIB(100),DD(100),DDL(100),DTNOW,
      1II,MFA,MSTOP,NCLNR,NCRDR,NPRNT,NNRUN,NNSET,NTAPE,
      2SS(100),SSL(100),TNEXT,TNOW,XX(250)
      COMMON/UCOM1/ MEDLEN,OFDLOAD,ETEPT,PKTTIME,
     1TOTPKTS,IDEL,TIMERC,TIMERT,TIMERT1,DELYD,DELYC,
     2DELYT,SLOT,DELPKTS
      INTEGER NRAN
      COUNT=COUNT+1
      CALL COLCT(COUNT,4)
      IXD=ATRIB(3)
       XX(IXD)=0.0
      RARIVLT=TNOW
      ATIME=ATRIB(1)
      COLN=ATRIB(2)
      IF(COLN.EQ.16.0) GO TO 600
      IDEL=1
  400 IF(XX(1+IDEL).EQ.0.0) GO TO 420
      IDEL=IDEL+1
      GO TO 400
  420 IF(XX(1).EQ.1.0) GO TO 450
      IF((RARIVLT-TIMERT).LT.ETEPT) GO TO 500
      IF((RARIVLT-TIMERC).LT.(7.0*ETEPT)) GO TO 550
C*****SLOT THE NEW ARRIVAL TIME
      AMOD=RARIVLT-(INT(RARIVLT/ETEPT)*ETEPT)
      IF(AMOD.EQ.0.0) GOTO 430
      SLOT=ETEPT-AMOD
      ATRIB(1)=ATIME
      ATRIB(2)=COLN
      ATRIB(3)=1+IDEL
      TIMERT=RARIVLT+SLOT
       XX(1+IDEL)=1.0
      CALL SCHDL(2,SLOT,ATRIB)
      RETURN
  430 ATRIB(1)=ATIME
      ATRIB(2)=COLN
      ATRIB(3)=1+IDEL
       XX(1+IDEL)=1.0
      TIMERT=RARIVLT
      CALL SCHDL(2,ETEPT,ATRIB)
      RETURN
C*****THE CHANNEL(SYSTEM) IS BUSY, DELAY THIS PACKET
  450 ATRIB(1)=ATIME
      ATRIB(2)=COLN
      ATRIB(3)=1+IDEL
      HVALUE=2.0*PKTTIME
      DELYD=UNFRM(0.0,HVALUE,1)
       XX(1+IDEL)=1.0
      CALL SCHDL(3,DELYD,ATRIB)
      RETURN
```

```
C*****COLLISION HAPPENED WITH OTHER PRECEEDING PACKET
C*****RESCHEDULES THE PACKET FOR LATER RETRANSMISSION
 500 ATRIB(1)=ATIME
     TIMERC=RARIVLT
     COLN=COLN+1
     ATRIB(2)=COLN
     VLO=0.0
     M=COLN
     VHI=2.0**M
     NRAND=UNFRM(VLO,VHI,1)
     DELYC=NRAND*ETEPT+7.0*ETEPT
     XX(1+IDEL)=1.0
     CALL SCHDL(3,DELYC,ATRIB)
     IF(NNQ(1).GT.0.0) GO TO 510
     CALL FILEM(1,ATRIB)
 510 RETURN
C*****DELAY THIS PACKET DUE TO PREVIOUS COLLISION
 550 ATRIB(1)=ATIME
     ATRIB(2)=COLN
     ATRIB(3)=1+IDEL
     DELYT=UNFRM(0.0,PKTTIME,1)
     XX(1+IDEL)=1.0
     CALL SCHDL(3,DELYT,ATRIB)
     RETURN
 600 DELPKTS=DELPKTS+1
     CALL COLCT(DELPKTS,3)
     RETURN
     END
C*******************END OF PROGRAM****************
```

PROGRAM (3)

```
C*****************************************************************
C****THIS PROGRAM SIMULATES THE CONTENTION OF SEQUENTIAL*****
C****MULTICHANNEL NETWORKS FOR N-CHANNELS WITH THE USE OF**
C****OF NON-PERSISTENT CSMA/CA PROTOCOL FOR MEDIUM ACCESS****
C**IN ORDER TO DETERMINE THE  AVERAGE DELAY AND THROUGHPUT**
C***OF THE NETWORK UNDER DIFFERENT OFFERED LOAD CONDITIONS**
C*****************************************************************
C
C******************************************
C*****MAIN PROGRAM**********************
C******************************************
   PROGRAM MAIN
   DIMENSION NSET(200000)
   PARAMETER (MEQT=100,  MSCND=25,  MENTR=25,  MRSC=75,
  1 MARR=50,  MGAT=25, MHIST=50,  MCELS=500, MCLCT=50,
  2 MSTAT=50, MEQV=100, MATRB=100, MFILS=100, MPLOT=10,
  3 MVARP=10, MSTRM=10, MACT=100, MNODE=500, MITYP=50,
  4 MMXXV=250)
   PARAMETER (MVARP1=MVARP+1)
   COMMON/SCOM1/ATRIB(MATRB),DD(MEQT),DDL(MEQT),DTNOW,
   1II,MFA,MSTOP,NCLNR,NCRDR,NPRNT NNRUN,NNSET,NTAPE,
  2SS(MEQT),SSL(MEQT),TNEXT, TNOW, XX(MMXXV)
   SPECIAL COMMON SCOM1
   COMMON QSET(200000)
   SPECIAL COMMON
   EQUIVALENCE (NSET(1),QSET(1))
   NNSET=200000
   NCRDR=15
   NPRNT=16
   NTAPE=17
   CALL SLAM
   STOP
   END
C************************************
C*****SAMPLE SUBROUTINE EVENT*****
C************************************
   SUBROUTINE EVENT(I)
   GO TO (1,2,3,4)I
  1 CALL ARIVL
   RETURN
  2 CALL ENDTRN
   RETURN
  3 CALL DELCOL
   RETURN
  4 CALL SUCCESS
   RETURN
   END
C******************************************************
C**SUBROUTINE INITIALIZATION OF SIMULATION PROGRAM**
C******************************************************
   SUBROUTINE INTLC
   COMMON/SCOM1/ ATRIB(100),DD(100),DDL(100),DTNOW,
   1II,MFA,MSTOP,NCLNR,NCRDR,NPRNT,NNRUN,NNSET,NTAPE,
   2SS(100),SSL(100),TNEXT,TNOW,XX(250)
   COMMON/UCOM1/ MEDLEN,NCHANLS,TOTALCAP,TNUMSTNS,
```

```
     1OFDLOAD,ETEPT,JDCC,N,PKTTIME,TIMERC,TIMERT,
     2TIMERT1,DELPKTS1,DELPKTS3,DELYPBS1,DELYPBS3,
     3TOTCOLP1,TOTCOLP2,TOTCOLP3,DCPKTS1,DCPKTS3,
     4TOTPKTS,COLPTW,COUNT
C
C*****READ THE VALUES OF MEDIUM LENGTH, NUMBER OF
C*****CHANNELS, TOTAL CAPACITY OF THE SYSTEM,
C*****MAXIMUM NUMBER OF STATIONS AND OFFERED-LOAD
C
      READ(NCRDR,101)MEDLEN
      READ(NCRDR,102)NCHANLS
      READ(NCRDR,103)TOTALCAP
      READ(NCRDR,104)TNUMSTNS
      READ(NCRDR,105)OFDLOAD
 101  FORMAT(2X,F7.2)
 102  FORMAT(2X,I4)
 103  FORMAT(2X,F11.2)
 104  FORMAT(2X,F7.2)
 105  FORMAT(2X,F10.4)
C
C*****XX(N) IS BUSY STATUS OF CHANNEL N
C
      DO 5 N=1,NCHANLS+150
    5 XX(N)=0.0
      CALL SCHDL(1,0.0,ATRIB)
      N=1
C     PKTTIME=ETEPT*(12.0*FLOAT(NCHANLS)-2.0)
      TOTPKTS=0
      DELPKTS1=0
      DELPKTS3=0
      DCPKTS1=0
      DCPKTS3=0
      DELYPBS1=0
      DELYPBS3=0
      COLPTW=0
      TOTCOLP1=0
      TOTCOLP2=0
      TOTCOLP3=0
      TIMERC=0.0
      TIMERT=0.0
      TIMERT1=-30.0
      COUNT=0
      RETURN
      END
C**********************************************
C*****SUBROUTINE ARRIVAL OF THE PACKETS*****
C**********************************************
      SUBROUTINE ARIVL
      COMMON/SCOM1/ ATRIB(100),DD(100),DDL(100),DTNOW,
     1II,MFA,MSTOP,NCLNR,NCRDR,NPRNT,NNRUN,NNSET,NTAPE,
     2SS(100),SSL(100),TNEXT,TNOW,XX(250)
      COMMON/UCOM1/ MEDLEN,NCHANLS,TOTALCAP,TNUMSTNS,
     1OFDLOAD,ETEPT,JDCC,N,PKTTIME,TIMERC,TIMERT,
     2TIMERT1,DELPKTS1,DELPKTS3,DELYPBS1,DELYPBS3,
     3TOTCOLP1,TOTCOLP2,TOTCOLP3,DCPKTS1,DCPKTS3,
     4TOTPKTS,COLPTW,COUNT
C
C*****SCHEDULE NEXT PACKET ARRIVAL
C
```

```
      REAL NPD
      INTEGER NRAN
      PROPSPD=2.0E+08
      ETEPT=(MEDLEN/PROPSPD)*1000000.0
      AMEAN=ETEPT*(12.0*FLOAT(NCHANLS)-1.0)/OFDLOAD
      AINRVLT=NPSSN(AMEAN,2)
      CALL SCHDL(1,AINRVLT,ATRIB)
C
C*****SET UP ATTRIBUTES, ADDRESS, NUMBER OF
C*****COLLISIONS AND DELAY OF THIS PACKET
C
      CARIVLT=TNOW
      NTXADRS=UNFRM(1.0,TNUMSTNS,1)
   10 NTRADRS=UNFRM(1.0,TNUMSTNS,1)
      IF(NTRADRS.EQ.NTXADRS) GO TO 10
      IF(CARIVLT.GT.0.0) GO TO 15
      ATRIB(1)=CARIVLT
      ATRIB(2)=NTXADRS
      ATRIB(3)=NTRADRS
      ATRIB(4)=0.0
      ATRIB(5)=N
      XX(N)=1.0
      TIMERT=ATRIB(1)
      CALL SCHDL(2,ETEPT,ATRIB)
      CALL FILEM(2,ATRIB)
      RETURN
C*****CHECK THE TRANSMITTER ADDRESS AT THE
C*****BUSY-LIST STATIONS(FILE NO.2)
   15 NEXT=MMFE(2)
C*****IF NEXT EQUAL TO ZERO, THERE ARE NO
C*****ENTRIES IN FILE NO.2
      IF(NEXT.EQ.0) GO TO 150
   20 CALL COPY(-NEXT,2,ATRIB)
      MTXADRS=ATRIB(2)
      IF(NTXADRS.EQ.MTXADRS) GO TO 50
      IF(NEXT.EQ.MMLE(2)) GO TO 30
      NEXT=NSUCR(NEXT)
      GO TO 20
   30 NEXT=MMFE(2)
   40 CALL COPY(-NEXT,2,ATRIB)
      MTRADRS=ATRIB(3)
      IF(NTXADRS.EQ.MTRADRS) GO TO 50
      IF(NEXT.EQ.MMLE(2)) GO TO 60
      NEXT=NSUCR(NEXT)
      GO TO 40
   50 DELPKTS1=DELPKTS1+1
      CALL COLCT(DELPKTS1,1)
C     CALL RMOVE(1,NCLNR,ATRIB)
      RETURN
C*****CHECK THE RECEIVER ADDRESS AT THE
C*****BUSY-LIST STATIONS(FILE NO.2)
   60 NEXT=MMFE(2)
   70 CALL COPY(-NEXT,2,ATRIB)
      MTXADRS=ATRIB(2)
      IF(NTRADRS.EQ.MTXADRS) GO TO 110
      IF(NEXT.EQ.MMLE(2)) GO TO 80
      NEXT=NSUCR(NEXT)
      GO TO 70
   80 NEXT=MMFE(2)
```

```
 90 CALL COPY(-NEXT,2,ATRIB)
    MTRADRS=ATRIB(3)
    IF(NTRADRS.EQ.MTRADRS) GO TO 110
    IF(NEXT.EQ.MMLE(2)) GO TO 150
    NEXT=NSUCR(NEXT)
    GO TO 90
110 DELYPBS1=DELYPBS1+1
    CALL COLCT(DELYPBS1,3)
    JDEL=1
120 IF(XX(NCHANLS+JDEL).EQ.0.0) GO TO 130
    JDEL=JDEL+1
    GO TO 120
130 ATRIB(1)=CARIVLT
    ATRIB(2)=NTXADRS
    ATRIB(3)=NTRADRS
    ATRIB(4)=0.0
    ATRIB(5)=NCHANLS+JDEL
    XX(NCHANLS+JDEL)=1.0
    ACQUST=2.0*ETEPT
    CALL SCHDL(3,ACQUST,ATRIB)
    RETURN
C*****CHECK THE PRECEDING PACKETS AND THEIR TIMERS
150 IF((CARIVLT-TIMERT).LT.ETEPT) GO TO 250
    VLO=0.0
    VHI=12.*ETEPT*N
    NPD=UNFRM(VLO,VHI,1)
    JDEL=1
160 IF(XX(NCHANLS+JDEL).EQ.0.0) GO TO 170
    JDEL=JDEL+1
    GO TO 160
170 ATRIB(1)=CARIVLT
    ATRIB(2)=NTXADRS
    ATRIB(3)=NTRADRS
    ATRIB(4)=0.0
    ATRIB(5)=NCHANLS+JDEL
    IF((CARIVLT-TIMERC).GE.(7.0*ETEPT)) GO TO 180
C*****DELAY THIS PACKET DUE TO PREVIOUS COLLISION
    XX(NCHANLS+JDEL)=1.0
    CALL SCHDL(3,NPD,ATRIB)
    RETURN
180 IF((CARIVLT-TIMERT).GE.(4.0*ETEPT)) GO TO 190
    DELYLSTN=(4.0*ETEPT+TIMERT)-CARIVLT
    TOTLDELY=NPD+DELYLSTN
    XX(NCHANLS+JDEL)=1.0
    CALL SCHDL(3,TOTLDELY,ATRIB)
    RETURN
190 IF((CARIVLT-TIMERT).GT.(6.0*ETEPT)) GO TO 200
    TOTLDELY=NPD
    XX(NCHANLS+JDEL)=1.0
    CALL SCHDL(3,TOTLDELY,ATRIB)
    RETURN
200 IF((CARIVLT-TIMERT).GE.(9.0*ETEPT)) GO TO 210
    DELYLSTN=(9.0*ETEPT+TIMERT)-CARIVLT
    TOTLDELY=NPD+DELYLSTN
    XX(NCHANLS+JDEL)=1.0
    CALL SCHDL(3,TOTLDELY,ATRIB)
    RETURN
210 IF((CARIVLT-TIMERT).GE.(12.0*ETEPT)) GO TO 230
    TOTLDELY=NPD
```

```
      XX(NCHANLS+JDEL)=1.0
      CALL SCHDL(3,TOTLDELY,ATRIB)
      RETURN
C
C*****THIS IS THE FIRST ENTRY(PACKET) TO THE NETWORK
C*****OR THE FIRST ARRIVAL TO THE NEXT IDLE CHANNEL
C
  230 XX(N)=1.0
      ATRIB(5)=N
      TIMERT=CARIVLT
      CALL SCHDL(2,ETEPT,ATRIB)
      CALL FILEM(2,ATRIB)
      RETURN
C
C*****COLLISION WAS HAPPENED WITH TWO PACKETS
C
  250 IF(NNQ(1).EQ.1) GO TO 280
      ATRIB(1)=CARIVLT
      ATRIB(2)=NTXADRS
      ATRIB(3)=NTRADRS
      ATRIB(4)=1
C     IF(ATRIB(4).GE.2) COLPTW=COLPTW+1
      TOTCOLP1=TOTCOLP1+1
      CALL COLCT(TOTCOLP1,5)
      JCOL=1
  260 IF(XX(NCHANLS+JCOL).EQ.0.0) GO TO 270
      JCOL=JCOL+1
      GO TO 260
  270 VLO=0.0
      M=ATRIB(4)
      VHI=2.0**M
      NRAND=UNFRM(VLO,VHI,1)
      TOTALT=7.0*ETEPT+7.0*ETEPT*FLOAT(NRAND)
      ATRIB(5)=NCHANLS+JCOL
      TIMERC=CARIVLT
      XX(NCHANLS+JCOL)=1.0
      CALL SCHDL(3,TOTALT,ATRIB)
      CALL FILEM(1,ATRIB)
      RETURN
  280 DCPKTS1=DCPKTS1+1
      CALL COLCT(DCPKTS1,8)
      RETURN
      END
C*******************************************
C*****SUBROUTINE END OF TRANSMISSION*****
C*******************************************
      SUBROUTINE ENDTRN
      COMMON/SCOM1/ ATRIB(100),DD(100),DDL(100),DTNOW,
     1II,MFA,MSTOP,NCLNR,NCRDR,NPRNT,NNRUN,NNSET,NTAPE,
     2SS(100),SSL(100),TNEXT,TNOW,XX(250)
      COMMON/UCOM1/ MEDLEN,NCHANLS,TOTALCAP,TNUMSTNS,
     1OFDLOAD,ETEPT,JDCC,N,PKTTIME,TIMERC,TIMERT,
     2TIMERT1,DELPKTS1,DELPKTS3,DELYPBS1,DELYPBS3,
     3TOTCOLP1,TOTCOLP2,TOTCOLP3,DCPKTS1,DCPKTS3,
     4TOTPKTS,COLPTW,COUNT
      REAL NPD
      INTEGER NRAN
      IF(NNQ(1).GT.0) GO TO 310
C*****SUCCESSFULL TRANSMISSION
```

```
      XX(N)=1.0
      ATRIB(5)=N
      TIMERT1=TIMERT
      N=N+1
      IF(N.EQ.(NCHANLS+1)) N=1
      PKTTIME=ETEPT*(12.0*FLOAT(NCHANLS)-2.0)
      CALL SCHDL(4,PKTTIME,ATRIB)
      RETURN
C*****COLLISION
  310 XX(N)=0.0
C     TIMERC=ATRIB(1)
      CTIME=ATRIB(1)
      ITXADRS=ATRIB(2)
      ITRADRS=ATRIB(3)
      COLNS=ATRIB(4)
      TIMERT=TIMERT1
      COLNS=COLNS+1
      IF(COLNS.GE.2) COLPTW=COLPTW+1
      TOTCOLP2=TOTCOLP2+1
      CALL COLCT(TOTCOLP2,6)
      CALL RMOVE(1,1,ATRIB)
      CALL RMOVE(NNQ(2),2,ATRIB)
      JCOL=1
  320 IF(XX(NCHANLS+JCOL).EQ.0.0) GO TO 330
      JCOL=JCOL+1
      GO TO 320
  330 VLO=0.0
      M=COLNS
      VHI=2.0**M
      NRAND=UNFRM(VLO,VHI,1)
      TOTALT=6.0*ETEPT+7.0*ETEPT*FLOAT(NRAND)
      ATRIB(1)=CTIME
      ATRIB(2)=ITXADRS
      ATRIB(3)=ITRADRS
      ATRIB(4)=COLNS
      ATRIB(5)=NCHANLS+JCOL
      XX(NCHANLS+JCOL)=1.0
      CALL SCHDL(3,TOTALT,ATRIB)
      RETURN
      END
C*************************************************
C*****SUBROUTINE SUCCESSFUL TRANSMISSION*****
C*************************************************
      SUBROUTINE SUCCESS
      COMMON/SCOM1/ ATRIB(100),DD(100),DDL(100),DTNOW,
     1II,MFA,MSTOP,NCLNR,NCRDR,NPRNT,NNRUN,NNSET,NYAPE,
     2SS(100),SSL(100),TNEXT,TNOW,XX(250)
      COMMON/UCOM1/ MEDLEN,NCHANLS,TOTALCAP,TNUMSTNS,
     1OFDLOAD,ETEPT,JDCC,N,PKTTIME,TIMERC,TIMERT,
     2TIMERT1,DELPKTS1,DELPKTS3,DELYPBS1,DELYPBS3,
     3TOTCOLP1,TOTCOLP2,TOTCOLP3,DCPKTS1,DCPKTS3
     4TOTPKTS,COLPTW,COUNT
      JJ=ATRIB(5)
      XX(JJ)=0.0
      CALL RMOVE(1,2,ATRIB)
      TOTPKTS=TOTPKTS+1
      CALL COLCT(TOTPKTS,10)
      DELAYTM=TNOW-ATRIB(1)
      CALL COLCT(DELAYTM,11)
```

```
      RETURN
      END
C*******************************************************
C*****SUBROUTINE DELAY-COLLISION REPRESENTATION*****
C*************** OF THE PACKETS*************************
C*******************************************************
      SUBROUTINE DELCOL
      COMMON/SCOM1/ ATRIB(100),DD(100),DDL(100),DTNOW,
     1II,MFA,MSTOP,NCLNR,NCRDR,NPRNT,NNRUN,NNSET,NTAPE,
     2SS(100),SSL(100),TNEXT,TNOW,XX(250)
      COMMON/UCOM1/ MEDLEN,NCHANLS,TOTALCAP,TNUMSTNS,
     1OFDLOAD,ETEPT,JDCC,N,PKTTIME,TIMERC,TIMERT,
     2TIMERT1,DELPKTS1,DELPKTS3,DELYPBS1,DELYPBS3,
     3TOTCOLP1,TOTCOLP2,TOTCOLP3,DCPKTS1,DCPKTS3
     4TOTPKTS,COLPTW,COUNT
      REAL NPD
      INTEGER NRAN
      COUNT=COUNT+1
      CALL COLCT(COUNT,12)
      IDD=ATRIB(5)
      XX(IDD)=0.0
      RARIVLT=TNOW
      ATIME=ATRIB(1)
      JTXADRS=ATRIB(2)
      JTRADRS=ATRIB(3)
      COLN=ATRIB(4)
      NEXT1=MMFE(2)
      IF(NEXT1.EQ.0) GO TO 510
  400 CALL COPY(-NEXT1,2,ATRIB)
      MTXADRS=ATRIB(2)
      IF(JTXADRS.EQ.MTXADRS) GO TO 430
      IF(NEXT1.EQ.MMLE(2)) GO TO 410
      NEXT1=NSUCR(NEXT1)
      GO TO 400
  410 NEXT1=MMFE(2)
  420 CALL COPY(-NEXT1,2,ATRIB)
      MTRADRS=ATRIB(3)
      IF(JTXADRS.EQ.MTRADRS) GO TO 430
      IF(NEXT1.EQ.MMLE(2)) GO TO 440
      NEXT1=NSUCR(NEXT1)
      GO TO 420
  430 DELPKTS3=DELPKTS3+1
      CALL COLCT(DELPKTS3,2)
      RETURN
C*****RECEIVING ADDRESS
  440 NEXT2=MMFE(2)
  450 CALL COPY(-NEXT2,2,ATRIB)
      MTXADRS=ATRIB(2)
      IF(JTRADRS.EQ.MTXADRS) GO TO 480
      IF(NEXT2.EQ.MMLE(2)) GO TO 460
      NEXT2=NSUCR(NEXT2)
      GO TO 450
  460 NEXT2=MMFE(2)
  470 CALL COPY(-NEXT2,2,ATRIB)
      MTRADRS=ATRIB(3)
      IF(JTRADRS.EQ.MTRADRS) GO TO 480
      IF(NEXT2.EQ.MMLE(2)) GO TO 510
      NEXT2=NSUCR(NEXT2)
      GO TO 470
```

```
C*****DELAY
 480 DELYPBS3=DELYPBS3+1
     CALL COLCT(DELYPBS3,4)
     JDEL=1
 490 IF(XX(NCHANLS+JDEL).EQ.0.0) GO TO 500
     JDEL=JDEL+1
     GO TO 490
 500 ATRIB(1)=ATIME
     ATRIB(2)=JTXADRS
     ATRIB(3)=JTRADRS
     ATRIB(4)=COLN
     ATRIB(5)=NCHANLS+JDEL
     XX(NCHANLS+JDEL)=1.0
     ACQUST=2.0*ETEPT
     CALL SCHDL(3,ACQUST,ATRIB)
     RETURN
C*****CHECK THE PRECEDING PACKETS AND THEIR TIMERS
 510 IF((RARIVLT-TIMERT).LT.ETEPT) GO TO 600
     VLO=0.0
     VHI=12.*ETEPT*N
     NPD=UNFRM(VLO,VHI,1)
     JDEL=1
 520 IF(XX(NCHANLS+JDEL).EQ.0.0) GO TO 530
     JDEL=JDEL+1
     GO TO 520
 530 ATRIB(1)=ATIME
     ATRIB(2)=JTXADRS
     ATRIB(3)=JTRADRS
     ATRIB(4)=COLN
     ATRIB(5)=NCHANLS+JDEL
     IF((RARIVLT-TIMERC).GE.(7.0*ETEPT)) GO TO 540
C*****DELAY DUE TO PREVIOUS COLLISION
     XX(NCHANLS+JDEL)=1.0
     CALL SCHDL(3,NPD,ATRIB)
     RETURN
 540 IF((RARIVLT-TIMERT).GE.(4.0*ETEPT)) GO TO 550
     DELYLSTN=4.0*ETEPT+TIMERT-RARIVLT
     TOTLDELY=NPD+DELYLSTN
     XX(NCHANLS+JDEL)=1.0
     CALL SCHDL(3,TOTLDELY,ATRIB)
     RETURN
 550 IF((RARIVLT-TIMERT).GT.(6.0*ETEPT)) GO TO 560
     TOTLDELY=NPD
     XX(NCHANLS+JDEL)=1.0
     CALL SCHDL(3,TOTLDELY,ATRIB)
     RETURN
 560 IF((RARIVLT-TIMERT).GE.(9.0*ETEPT)) GO TO 570
     DELYLSTN=9.0*ETEPT+TIMERT-RARIVLT
     TOTLDELY=NPD+DELYLSTN
     XX(NCHANLS+JDEL)=1.0
     CALL SCHDL(3,TOTLDELY,ATRIB)
     RETURN
 570 IF((RARIVLT-TIMERT).GE.(12.0*ETEPT)) GO TO 580
     TOTLDELY=NPD
     XX(NCHANLS+JDEL)=1.0
     CALL SCHDL(3,TOTLDELY,ATRIB)
     RETURN
C*****THIS IS THE FIRST ARRIVAL TO THIS CHANNEL
 580 XX(N)=1.0
```

```
      ATRIB(5)=N
      TIMERT=RARIVLT
      CALL SCHDL(2,ETEPT,ATRIB)
      CALL FILEM(2,ATRIB)
      RETURN
C*****COLLISION WAS HAPPENED WITH ANOTHER PACKET
  600 IF(NNQ(1).EQ.1) GO TO 660
      COLN=COLN+1
      ATRIB(4)=COLN
      IF(ATRIB(4).GE.2) COLPTW=COLPTW+1
      TOTCOLP3=TOTCOLP3+1
      CALL COLCT(TOTCOLP3,7)
      JCOL=1
  620 IF(XX(NCHANLS+JCOL).EQ.0.0) GO TO 640
      JCOL=JCOL+1
      GO TO 620
  640 VLO=0.0
      M=ATRIB(4)
      VHI=2.0**M
      NRAND=UNFRM(VLO,VHI,1)
      TOTALT=7.0*ETEPT+7.0*ETEPT*FLOAT(NRAND)
      ATRIB(1)=ATIME
      ATRIB(2)=JTXADRS
      ATRIB(3)=JTRADRS
      ATRIB(5)=NCHANLS+JCOL
      TIMERC=RARIVLT
       XX(NCHANLS+JCOL)=1.0
      CALL SCHDL(3,TOTALT,ATRIB)
      CALL FILEM(1,ATRIB)
      RETURN
  660 DCPKTS3=DCPKTS3+1
      CALL COLCT(DCPKTS3,9)
      RETURN
      END
C***********************END OF PROGRAM**************
```

PROGRAM (4)

```
C************************************************************
C****THIS PROGRAM SIMULATES THE CONTENTION OF SEQUENTIAL****
C****MULTICHANNELNETWORKS FOR N-CHANNELS WITH THE USE OF*
C*****SLOTTED NON-PERSISTENT CSMA/CA PROTOCOL FOR MEDIUM****
C******ACCESS IN ORDER TO DETERMINE THE THROUGHPUT AND******
C*******AVERAGE DELAY OF THE NETWORK UNDER DIFFERENT*******
C****************OFFERED- LOAD CONDITIONS********************
C************************************************************
C
C*****************************************
C*****MAIN PROGRAM***********************
C*****************************************
    PROGRAM MAIN
    DIMENSION NSET(200000)
    PARAMETER (MEQT=100,  MSCND=25,  MENTR=25,  MRSC=75,
   1  MARR=50, MGAT=25, MHIST=50,  MCELS=500, MCLCT=50,
   2  MSTAT=50, MEQV=100, MATRB=100, MFILS=100, MPLOT=10,
   3  MVARP=10,  MSTRM=10, MACT=100, MNODE=500, MITYP=50,
   4  MMXXV=250)
    PARAMETER (MVARP1=MVARP+1)
    COMMON/SCOM1/ATRIB(MATRB),DD(MEQT),DDL(MEQT),DTNOW,
   1II,MFA,MSTOP,NCLNR,NCRDR,NPRNT,NNRUN,NNSET,NTAPE,
   2SS(MEQT),SSL(MEQT),TNEXT,TNOW,XX(MMXXV)
    SPECIAL COMMON SCOM1
    COMMON QSET(200000)
    SPECIAL COMMON
    EQUIVALENCE (NSET(1),QSET(1))
    NNSET=200000
    NCRDR=15
    NPRNT=16
    NTAPE=17
    CALL SLAM
    STOP
    END
C**********************************
C*****SAMPLE SUBROUTINE EVENT*****
C**********************************
    SUBROUTINE EVENT(I)
    GO TO (1,2,3,4)I
  1 CALL ARIVL
    RETURN
  2 CALL SLOTING
    RETURN
  3 CALL DELCOL
    RETURN
  4 CALL SUCCESS
    RETURN
    END
C******************************************************
C***SUBROUTINE INITIALIZATION OF SIMULATION PROGRAM***
C******************************************************
    SUBROUTINE INTLC
    COMMON/SCOM1/ ATRIB(100),DD(100),DDL(100),DTNOW,
  1 II,MFA,MSTOP,NCLNR,NCRDR,NPRNT,NNRUN,NNSET,NTAPE,
  2 SS(100),SSL(100),TNEXT,TNOW,XX(250)
```

```
      COMMON/UCOM1/ MEDLEN,NCHANLS,TOTALCAP,TNUMSTNS,
     1 OFDLOAD,ETEPT,JDEL,N,PKTTIME,TIMERC,TIMERT,
     2 TIMERT1,DELPKTS1,DELPKTS3,SLO,DELYPBS1,DELYPBS3,
     3 TOTCOLP1,TOTCOLP2,TOTCOLP3,DCPKTS1,DCPKTS3,
     4 TOTPKTS,COLPTW,COUNT
C
C*****READ THE VALUES OF MEDIUM  LENGTH, NUMBER OF
C*****CHANNELS, TOTAL CAPACITY OF THE SYSTEM,
C*****MAXIMUM NUMBER OF STATIONS AND OFFERED-LOAD
C
      READ(NCRDR,101)MEDLEN
      READ(NCRDR,102)NCHANLS
      READ(NCRDR,103)TOTALCAP
      READ(NCRDR,104)TNUMSTNS
      READ(NCRDR,105)OFDLOAD
  101 FORMAT(2X,F7.2)
  102 FORMAT(2X,I4)
  103 FORMAT(2X,F11.2)
  104 FORMAT(2X,F7.2)
  105 FORMAT(2X,F10.4)
C
C*****XX(N) IS BUSY STATUS OF CHANNEL N
C
      DO 5 N=1,NCHANLS+150
    5 XX(N)=0.0
      CALL SCHDL(1,0.0,ATRIB)
      N=1
      TOTPKTS=0
      DELPKTS1=0
      DELPKTS3=0
      DCPKTS1=0
      DCPKTS3=0
      DELYPBS1=0
      DELYPBS3=0
      COLPTW=0
      TOTCOLP1=0
      TOTCOLP2=0
      TOTCOLP3=0
      TIMERC=0.0
      TIMERT=0.0
      TIMERT1=0.0
      COUNT=0
      RETURN
      END
C***********************************************
C*****SUBROUTINE ARRIVAL OF THE PACKETS*****
C***********************************************
      SUBROUTINE ARIVL
      COMMON/SCOM1/ ATRIB(100),DD(100),DDL(100),DTNOW,
     1 II,MFA,MSTOP,NCLNR,NCRDR,NPRNT,NNRUN,NNSET,NTAPE,
     2 SS(100),SSL(100),TNEXT,TNOW,XX(250)
      COMMON/UCOM1/ MEDLEN,NCHANLS,TOTALCAP,TNUMSTNS,
     1 OFDLOAD,ETEPT,JDEL,N,PKTTIME,TIMERC,TIMERT,
     2 TIMERT1,DELPKTS1,DELPKTS3,SLO,DELYPBS1,DELYPBS3,
     3 TOTCOLP1,TOTCOLP2,TOTCOLP3,DCPKTS1,DCPKTS3,
     4 TOTPKTS,COLPTW,COUNT
C
C*****SCHEDULE NEXT PACKET ARRIVAL
C
```

```
      REAL NPD
      INTEGER NRAN
      PROPSPD=2.0E+08
      ETEPT=(CABLEL/PROPSPD)*1000000.0
      AMEAN=ETEPT*(12.0*FLOAT(NCHANLS)-1.0)/OFDLOAD
      AINRVLT=NPSSN(AMEAN,2)
      CALL SCHDL(1,AINRVLT,ATRIB)
C
C*****SET UP ATTRIBUTES, ADDRESS, NUMBER OF
C*****COLLISIONS AND DELAY OF THIS PACKET
C
      CARIVLT=TNOW
      NTXADRS=UNFRM(1.0,TNUMSTNS,1)
   10 NTRADRS=UNFRM(1.0,TNUMSTNS,1)
      IF(NTRADRS.EQ.NTXADRS) GO TO 10
      IF(CARIVLT.GT.0.0) GO TO 15
      ATRIB(1)=CARIVLT
      ATRIB(2)=NTXADRS
      ATRIB(3)=NTRADRS
      ATRIB(4)=0.0
      ATRIB(5)=N
      XX(N)=1.0
      N=N+1
      TIMERT=ATRIB(1)
      PKTTIME=ETEPT*(12.0*FLOAT(NCHANLS)-1.0)
      CALL SCHDL(4,PKTTIME,ATRIB)
      CALL FILEM(2,ATRIB)
      RETURN
C*****CHECK THE TRANSMITTER ADDRESS AT THE
C*****BUSY-LIST STATIONS(FILE NO.2)
   15 NEXT=MMFE(2)
C*****IF NEXT EQUAL TO ZERO, THERE ARE NO
C*****ENTRIES IN FILE NO.2
      IF(NEXT.EQ.0) GO TO 150
   20 CALL COPY(-NEXT,2,ATRIB)
      MTXADRS=ATRIB(2)
      IF(NTXADRS.EQ.MTXADRS) GO TO 50
      IF(NEXT.EQ.MMLE(2)) GO TO 30
      NEXT=NSUCR(NEXT)
      GO TO 20
   30 NEXT=MMFE(2)
   40 CALL COPY(-NEXT,2,ATRIB)
      MTRADRS=ATRIB(3)
      IF(NTXADRS.EQ.MTRADRS) GO TO 50
      IF(NEXT.EQ.MMLE(2)) GO TO 60
      NEXT=NSUCR(NEXT)
      GO TO 40
   50 DELPKTS1=DELPKTS1+1
      CALL COLCT(DELPKTS1,1)
      RETURN
C*****CHECK THE RECEIVER ADDRESS AT THE
C*****BUSY-LIST STATIONS(FILE NO.2)
   60 NEXT=MMFE(2)
   70 CALL COPY(-NEXT,2,ATRIB)
      MTXADRS=ATRIB(2)
      IF(NTRADRS.EQ.MTXADRS) GO TO 110
      IF(NEXT.EQ.MMLE(2)) GO TO 80
      NEXT=NSUCR(NEXT)
      GO TO 70
```

```
 80 NEXT=MMFE(2)
 90 CALL COPY(-NEXT,2,ATRIB)
    MTRADRS=ATRIB(3)
    IF(NTRADRS.EQ.MTRADRS) GO TO 110
    IF(NEXT.EQ.MMLE(2)) GO TO 150
    NEXT=NSUCR(NEXT)
    GO TO 90
110 DELYPBS1=DELYPBS1+1
    CALL COLCT(DELYPBS1,3)
    JDEL=1
120 IF(XX(NCHANLS+JDEL).EQ.0.0) GO TO 130
    JDEL=JDEL+1
    GO TO 120
130 ATRIB(1)=CARIVLT
    ATRIB(2)=NTXADRS
    ATRIB(3)=NTRADRS
    ATRIB(4)=0.0
    ATRIB(5)=NCHANLS+JDEL
    XX(NCHANLS+JDEL)=1.0
    ACQUST=2.0*ETEPT
    CALL SCHDL(3,ACQUST,ATRIB)
    RETURN
C*****CHECK THE PRECEDING PACKETS AND THEIR TIMERS
150 IF(CARIVLT.LT.TIMERT1) GO TO 250
    VLO=0.0
    VHI=5.0*ETEPT
    NPD=UNFRM(VLO,VHI,1)
    JDEL=1
160 IF(XX(NCHANLS+JDEL).EQ.0.0) GO TO 170
    JDEL=JDEL+1
    GO TO 160
170 ATRIB(1)=CARIVLT
    ATRIB(2)=NTXADRS
    ATRIB(3)=NTRADRS
    ATRIB(4)=0.0
    ATRIB(5)=NCHANLS+JDEL
    IF((CARIVLT-TIMERC).GE.(7.0*ETEPT)) GO TO 180
C*****DELAY THIS PACKET DUE TO PREVIOUS COLLISION
    XX(NCHANLS+JDEL)=1.0
    CALL SCHDL(3,NPD,ATRIB)
    RETURN
180 IF((CARIVLT-TIMERT).GE.(4.0*ETEPT)) GO TO 190
    DELYLSTN=(4.0*ETEPT+TIMERT)-CARIVLT
    TOTLDELY=NPD+DELYLSTN
    XX(NCHANLS+JDEL)=1.0
    CALL SCHDL(3,TOTLDELY,ATRIB)
    RETURN
190 IF((CARIVLT-TIMERT).GT.(6.0*ETEPT)) GO TO 200
    TOTLDELY=NPD
    XX(NCHANLS+JDEL)=1.0
    CALL SCHDL(3,TOTLDELY,ATRIB)
    RETURN
200 IF((CARIVLT-TIMERT).GE.(9.0*ETEPT)) GO TO 210
    DELYLSTN=(9.0*ETEPT+TIMERT)-CARIVLT
    TOTLDELY=NPD+DELYLSTN
    XX(NCHANLS+JDEL)=1.0
    CALL SCHDL(3,TOTLDELY,ATRIB)
    RETURN
210 IF((CARIVLT-TIMERT).GE.(12.0*ETEPT)) GO TO 220
```

```
      TOTLDELY=NPD
      XX(NCHANLS+JDEL)=1.0
      CALL SCHDL(3,TOTLDELY,ATRIB)
      RETURN
C
C*****THIS IS THE FIRST ENTRY(PACKET) TO THE NETWORK
C*****OR THE FIRST ARRIVAL TO THE NEXT IDLE CHANNEL
C
  220 AMOD=CARIVLT-(INT(CARIVLT/ETEPT)*ETEPT)
      IF(AMOD.EQ.0.0) GO TO 230
      ATRIB(5)=NCHANLS+JDEL
      XX(NCHANLS+JDEL)=1.0
      SLO=ETEPT-AMOD
      TIMERT1=CARIVLT+SLO
      CALL SCHDL(2,SLO,ATRIB)
      RETURN
  230 XX(N)=1.0
      ATRIB(5)=N
      N=N+1
      IF(N.EQ.(NCHANLS+1)) N=1
      TIMERT=CARIVLT
      PKTTIME=ETEPT*(12.0*FLOAT(NCHANLS)-1.0)
      CALL SCHDL(4,PKTTIME,ATRIB)
      CALL FILEM(2,ATRIB)
      RETURN
C
C*****COLLISION WAS HAPPENED WITH TWO PACKETS
C
  250 IF(NNQ(1).EQ.1) GO TO 280
      ATRIB(1)=CARIVLT
      ATRIB(2)=NTXADRS
      ATRIB(3)=NTRADRS
      ATRIB(4)=1
      TOTCOLP1=TOTCOLP1+1
      CALL COLCT(TOTCOLP1,5)
      JDEL=1
  260 IF(XX(NCHANLS+JDEL).EQ.0.0) GO TO 270
      JDEL=JDEL+1
      GO TO 260
  270 VLO=0.0
      M=ATRIB(4)
      VHI=2.0**M
      NRAND=UNFRM(VLO,VHI,1)
      TOTALT=7.0*ETEPT+7.0*ETEPT*FLOAT(NRAND)
      ATRIB(5)=NCHANLS+JDEL
      TIMERC=CARIVLT
      XX(NCHANLS+JDEL)=1.0
      CALL SCHDL(3,TOTALT,ATRIB)
      CALL FILEM(1,ATRIB)
      RETURN
  280 DCPKTS1=DCPKTS1+1
      CALL COLCT(DCPKTS1,8)
      RETURN
      END
C****************************************
C*****SUBROUTINE SLOTTING THE TIME*****
C****************************************
      SUBROUTINE SLOTING
      COMMON/SCOM1/ ATRIB(100),DD(100),DDL(100),DTNOW,
```

```
     1 II,MFA,MSTOP,NCLNR,NCRDR,NPRNT,NNRUN,NNSET,NTAPE,
     2 SS(100),SSL(100),TNEXT,TNOW,XX(250)
      COMMON/UCOM1/ MEDLEN,NCHANLS,TOTALCAP,TNUMSTNS,
     1 OFDLOAD,ETEPT,JDEL,N,PKTTIME,TIMERC,TIMERT,
     2 TIMERT1,DELPKTS1,DELPKTS3,SLO,DELYPBS1,DELYPBS3,
     3 TOTCOLP1,TOTCOLP2,TOTCOLP3,DCPKTS1,DCPKTS3,
     4 TOTPKTS,COLPTW,COUNT
      REAL NPD
      INTEGER NRAN
      IXX=ATRIB(5)
       XX(IXX)=0.0
      IF(NNQ(1).GT.0) GO TO 310
C*****SUCCESSFULL TRANSMISSION
       XX(N)=1.0
      ATRIB(5)=N
      TIMERT=TNOW
       N=N+1
       IF(N.EQ.(NCHANLS+1)) N=1
      PKTTIME=ETEPT*(12.0*FLOAT(NCHANLS)-1.0)
      CALL SCHDL(4,PKTTIME,ATRIB)
      CALL FILEM(2,ATRIB)
      RETURN
C*****COLLISION
  310 CTIME=ATRIB(1)
      ITXADRS=ATRIB(2)
      ITRADRS=ATRIB(3)
      COLNS=ATRIB(4)
C     TIMERC=TNOW
      COLNS=COLNS+1
      IF(COLNS.GE.2) COLPTW=COLPTW+1
      TOTCOLP2=TOTCOLP2+1
      CALL COLCT(TOTCOLP2,6)
      CALL RMOVE(1,1,ATRIB)
      JDEL=1
  320 IF(XX(NCHANLS+JDEL).EQ.0.0) GO TO 330
      JDEL=JDEL+1
      GO TO 320
  330 VLO=0.0
      M=COLNS
      VHI=2.0**M
      NRAND=UNFRM(VLO,VHI,1)
      TOTALT=6.0*ETEPT+7.0*ETEPT*FLOAT(NRAND)
      ATRIB(1)=CTIME
      ATRIB(2)=ITXADRS
      ATRIB(3)=ITRADRS
      ATRIB(4)=COLNS
      ATRIB(5)=NCHANLS+JDEL
       XX(NCHANLS+JDEL)=1.0
      CALL SCHDL(3,TOTALT,ATRIB)
      RETURN
      END
C*************************************************
C*****SUBROUTINE SUCCESSFUL TRANSMISSION*****
C*************************************************
      SUBROUTINE SUCCESS
      COMMON/SCOM1/ ATRIB(100),DD(100),DDL(100),DTNOW,
     1 II,MFA,MSTOP,NCLNR,NCRDR,NPRNT,NNRUN,NNSET,NYAPE,
     2 SS(100),SSL(100),TNEXT,TNOW,XX(250)
      COMMON/UCOM1/ MEDLEN,NCHANLS,TOTALCAP,TNUMSTNS,
```

```
     1 OFDLOAD,ETEPT,JDEL,N,PKTTIME,TIMERC,TIMERT,
     2 TIMERT1,DELPKTS1,DELPKTS3,SLO,DELYPBS1,DELYPBS3,
     3 TOTCOLP1,TOTCOLP2,TOTCOLP3,DCPKTS1,DCPKTS3,
     4 TOTPKTS,COLPTW,COUNT
      JJ=ATRIB(5)
      XX(JJ)=0.0
      CALL RMOVE(1,2,ATRIB)
      TOTPKTS=TOTPKTS+1
      CALL COLCT(TOTPKTS,10)
      DELAYTM=TNOW-ATRIB(1)
      CALL COLCT(DELAYTM,11)
      RETURN
      END
C******************************************************
C*****SUBROUTINE DELAY-COLLISION REPRESENTATION******
C********************OF THE PACKETS********************
C******************************************************
      SUBROUTINE DELCOL
      COMMON/SCOM1/ ATRIB(100),DD(100),DDL(100),DTNOW,
     1 II,MFA,MSTOP,NCLNR,NCRDR,NPRNT,NNRUN,NNSET,NTAPE,
     1 SS(100),SSL(100),TNEXT,TNOW,XX(250)
      COMMON/UCOM1/ MEDLEN,NCHANLS,TOTALCAP,TNUMSTNS,
     1 OFDLOAD,ETEPT,JDEL,N,PKTTIME,TIMERC,TIMERT,
     2 TIMERT1,DELPKTS1,DELPKTS3,SLO,DELYPBS1,DELYPBS3,
     3 TOTCOLP1,TOTCOLP2,TOTCOLP3,DCPKTS1,DCPKTS3,
     4 TOTPKTS,COLPTW,COUNT
      REAL NPD
      INTEGER NRAN
      COUNT=COUNT+1
      CALL COLCT(COUNT,12)
      IDD=ATRIB(5)
      XX(IDD)=0.0
      RARIVLT=TNOW
      ATIME=ATRIB(1)
      JTXADRS=ATRIB(2)
      JTRADRS=ATRIB(3)
      COLN=ATRIB(4)
      NEXT1=MMFE(2)
      IF(NEXT1.EQ.0) GO TO 510
  400 CALL COPY(-NEXT1,2,ATRIB)
      MTXADRS=ATRIB(2)
      IF(JTXADRS.EQ.MTXADRS) GO TO 430
      IF(NEXT1.EQ.MMLE(2)) GO TO 410
      NEXT1=NSUCR(NEXT1)
      GO TO 400
  410 NEXT1=MMFE(2)
  420 CALL COPY(-NEXT1,2,ATRIB)
      MTRADRS=ATRIB(3)
      IF(JTXADRS.EQ.MTRADRS) GO TO 430
      IF(NEXT1.EQ.MMLE(2)) GO TO 440
      NEXT1=NSUCR(NEXT1)
      GO TO 420
  430 DELPKTS3=DELPKTS3+1
      CALL COLCT(DELPKTS3,2)
      RETURN
C*****RECEIVING ADDRESS
  440 NEXT2=MMFE(2)
  450 CALL COPY(-NEXT2,2,ATRIB)
      MTXADRS=ATRIB(2)
```

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      IF(JTRADRS.EQ.MTXADRS) GO TO 480
      IF(NEXT2.EQ.MMLE(2)) GO TO 460
      NEXT2=NSUCR(NEXT2)
      GO TO 450
  460 NEXT2=MMFE(2)
  470 CALL COPY(-NEXT2,2,ATRIB)
      MTRADRS=ATRIB(3)
      IF(JTRADRS.EQ.MTRADRS) GO TO 480
      IF(NEXT2.EQ.MMLE(2)) GO TO 510
      NEXT2=NSUCR(NEXT2)
      GO TO 470
C*****DELAY
  480 DELYPBS3=DELYPBS3+1
      CALL COLCT(DELYPBS3,4)
      JDEL=1
  490 IF(XX(NCHANLS+JDEL).EQ.0.0) GO TO 500
      JDEL=JDEL+1
      GO TO 490
  500 ATRIB(1)=ATIME
      ATRIB(2)=JTXADRS
      ATRIB(3)=JTRADRS
      ATRIB(4)=COLN
      ATRIB(5)=NCHANLS+JDEL
      XX(NCHANLS+JDEL)=1.0
      ACQUST=2.0*ETEPT
      CALL SCHDL(3,ACQUST,ATRIB)
      RETURN
C*****CHECK THE PRECEDING PACKETS AND THEIR TIMERS
  510 IF(RARIVLT.LT.TIMERT1) GO TO 600
      VLO=0.0
      VHI=5.0*ETEPT
      NPD=UNFRM(VLO,VHI,1)
      JDEL=1
  520 IF(XX(NCHANLS+JDEL).EQ.0.0) GO TO 530
      JDEL=JDEL+1
      GO TO 520
  530 ATRIB(1)=ATIME
      ATRIB(2)=JTXADRS
      ATRIB(3)=JTRADRS
      ATRIB(4)=COLN
      ATRIB(5)=NCHANLS+JDEL
      IF((RARIVLT-TIMERC).GE.(7.0*ETEPT)) GO TO 540
C*****DELAY DUE TO PREVIOUS COLLISION
      XX(NCHANLS+JDEL)=1.0
      CALL SCHDL(3,NPD,ATRIB)
      RETURN
  540 IF((RARIVLT-TIMERT).GE.(4.0*ETEPT)) GO TO 550
      DELYLSTN=4.0*ETEPT+TIMERT-RARIVLT
      TOTLDELY=NPD+DELYLSTN
      XX(NCHANLS+JDEL)=1.0
      CALL SCHDL(3,TOTLDELY,ATRIB)
      RETURN
  550 IF((RARIVLT-TIMERT).GT.(6.0*ETEPT)) GO TO 560
      TOTLDELY=NPD
      XX(NCHANLS+JDEL)=1.0
      CALL SCHDL(3,TOTLDELY,ATRIB)
      RETURN
  560 IF((RARIVLT-TIMERT).GE.(9.0*ETEPT)) GO TO 570
      DELYLSTN=9.0*ETEPT+TIMERT-RARIVLT
```

```
      TOTLDELY=NPD+DELYLSTN
      XX(NCHANLS+JDEL)=1.0
      CALL SCHDL(3,TOTLDELY,ATRIB)
      RETURN
  570 IF((RARIVLT-TIMERT).GE.(12.0*ETEPT)) GO TO 580
      TOTLDELY=NPD
      XX(NCHANLS+JDEL)=1.0
      CALL SCHDL(3,TOTLDELY,ATRIB)
      RETURN
C*****THIS IS THE FIRST ARRIVAL TO THIS CHANNEL
  580 AMOD=RARIVLT-(INT(RARIVLT/ETEPT)*ETEPT)
      IF(AMOD.EQ.0.0) GO TO 590
      ATRIB(5)=NCHANLS+JDEL
      XX(NCHANLS+JDEL)=1.0
      SLO=ETEPT-AMOD
      TIMERT1=RARIVLT+SLO
      CALL SCHDL(2,SLO,ATRIB)
      RETURN
  590 XX(N)=1.0
      ATRIB(5)=N
      N=N+1
      IF(N.EQ.(NCHANLS+1)) N=1
      TIMERT=RARIVLT
      PKTTIME=ETEPT*(12.0*FLOAT(NCHANLS)-1.0)
      CALL SCHDL(4,PKTTIME,ATRIB)
      CALL FILEM(2,ATRIB)
      RETURN
C*****COLLISION WAS HAPPENED WITH ANOTHER PACKET
  600 IF(NNQ(1).EQ.1) GO TO 660
      COLN=COLN+1
      ATRIB(4)=COLN
      IF(ATRIB(4).GE.2) COLPTW=COLPTW+1
      TOTCOLP3=TOTCOLP3+1
      CALL COLCT(TOTCOLP3,7)
      JDEL=1
  620 IF(XX(NCHANLS+JDEL).EQ.0.0) GO TO 640
      JDEL=JDEL+1
      GO TO 620
  640 VLO=0.0
      M=ATRIB(4)
      VHI=2.0**M
      NRAND=UNFRM(VLO,VHI,1)
      TOTALT=7.0*ETEPT+7.0*ETEPT*FLOAT(NRAND)
      ATRIB(1)=ATIME
      ATRIB(2)=JTXADRS
      ATRIB(3)=JTRADRS
      ATRIB(5)=NCHANLS+JDEL
      TIMERC=RARIVLT
      XX(NCHANLS+JDEL)=1.0
      CALL SCHDL(3,TOTALT,ATRIB)
      CALL FILEM(1,ATRIB)
      RETURN
  660 DCPKTS3=DCPKTS3+1
      CALL COLCT(DCPKTS3,9)
      RETURN
      END
C*******************END OF PROGRAME******************
```