The Determining of Optimum Protocol Strategies for Half-Duplex Telemetry Communication Links

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Dissertation Presented for the
Degree of Doctor of Philosophy at the
University of Stellenbosch

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October 2002

Declaration

I, the undersigned, hereby declare that the work contained in this dissertation is my own original work and that I have not previously in its entirety or in part submitted it at any university for a degree.

Abstract

Though not so prominent as the wide band, high speed, mainstream development of data communication networks, cost and particular bandwidth limitations, still ensure extensive and continuing use of low-speed, half-duplex data link equipment. Most of these applications are radio based and aimed towards telemetry systems serving a wide range of utilities. Experience has shown that systems engineering for this type of installation, is seldom undertaken to a satisfactory analytical level. Investigation of published analyses of CSMA protocols in general, has indicated scope of extension of theoretical work to include system parameters for the type of protocol investigated in this dissertation.

This dissertation describes the mathematical modeling of such a strategy by utilising a significantly modified, finite source, transition state-matrix approach derived from queueing theory.

The contribution of the dissertation is to include system overhead parameters, such as backoff strategy, channel noise, equipment rise times, propagation- and retry delays, into the abovementioned model. The latter provides a relatively straightforward and readily applicable method for system analysis and performance prediction.

A further contribution is the presentation of a software emulation with which different strategies could be simulated, allowing for adjustment of all design parameters. The simulation is intended for parallel and confimatory use with the theoretical model.

A dual set of tools, theoretical and emulation based, is thus contributed to assist with the system design, performance prediction and protocol selection process.

Opsomming

Alhoewel nie so prominent soos die wyeband, hoëspoed, hoofstroom ontwikkeling van datakommunikasie netwerke nie, verseker koste en spesifieke bandwydte beperkings nog die uitgebreide en voortdurende gebruik van laespoed half-dupleks data verbindingstoerusting. Meeste van die toepassings is radio gebaseer en gerig op telemetriestelsels wat deur 'n wye verskeidenheid diensverskaffers benut word. Stelselontwerp vir hierdie tipe installasies word selde op analitiese vlak benader. Ondersoek van gepubliseerde analises van kontensieprotokolle in die algemeen, het ruimte aangetoon vir die uitbreiding van bestaande teoretiese werk om stelselveranderlikes soos van toepassing op die tipe protokol in hierdie proefskrif ondersoek, in te sluit.

Hierdie proefskrif beskryf die wiskundige modelering van sodanige strategie, deur gebruik te maak van 'n beduidend veranderde eindige bron, oorgangs-toestandmatriks benadering, afgelei van touteorie.

Die bydrae van hierdie proefskrif is die insluiting van oorhoofse stelselveranderlikes, soos herhaal strategie, kanaalruis, toerusting stygtye, herhaal- en voortplantingsvertragings, in bogenoemde model. Laasgenoemde verskaf 'n relatief eenvoudige en maklik toepasbare metode vir stelselanalise en werkverrigtingvoorspelling.

'n Verder bydrae is die daarstelling van 'n sagteware simulasie waarmee verskillende strategieë nageboots kan word. Verstelling van alle ontwerpparameters word ondersteun. Die simulasie is bedoel vir parallelle en bevestigende gebruik tesame met die teoretiese model.

'n Dubbele, teoreties- en simulasie gebaseerde benadering, word dus aangebied vir gebruik by stelselontwerp, gedragsvoorspelling en optimale protokolseleksie.

Acknowledgments

It would not have been possible to complete the work contained in this dissertation, without the generous assistance of the following:

Detailed and in some cases confidential, product information was put at my disposal by a number of equipment suppliers and manufacturers. Their assistance is much appreciated.

I am indebted to Prof. Tayfur Altiok of Rutgers University for a very valuable exchange of ideas, which provided insight into the problem from the perspective of a different technical discipline. It was of great use in the final definition of the model.

I wish to extend my sincere appreciation to my promotor, Prof. JJ du Plessis, who did far more than what could reasonably be expected. He acted as mentor, counselor, software debugger and provided encouragement at times of desperation, while ensuring that the necessary focus was retained when confusion reigned. Vital insight was provided without fail, when most required. Without his contribution, this work would certainly not have been successful.

My family, Adelaide, Jeanette and Adriaan, enabled me to undertake and complete this study. Thank you Adelaide, for your patience, encouragement and unselfish constant support. You deserve nothing less than my utmost gratitude. I could not have done it without you. May it be of benefit to all of us.

With humility and praise to God. Only by His grace, could this work be completed.

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Glossary

List of abbreviations and acronyms

ACK - Acknowledge
ATDMA - Asynchronous Time Division Multiple Access
BER - Bit Error Rate
BP - Backoff Period
CCITT - Consultative Committee on International Telegraphy and Telephony
CDMA - Code Division Multiple Access
CSMA - Carrier Fense Multiple Access
CRC - Cyclic Redundancy Check
CSMA/CD - Carrier Sense Multiple Access with Collision Detection
1-P CSMA - 1-Persistent CSMA
N-P CSMA - Non-Persistent CSMA
DQRAP - Distributed Queueing Random Access Protocol
EGI - Event Generation Interval
FDMA - Frequency Division Multiple Access
FIFO - First In First Out
FSK - Frequency Shift Keying
GPS - Global Positioning System
GRA - Grouped Random Access
GSM - Global System for Mobile Communications
HDLC - High Level Data Link Control
HDNB - Half Duplex Narrow Band
IEC - International Electrotechnical Commission
IEEE - Institute of Electrical and Electronic Engineers
LAN - Local Area Network
MSAP - Minislotted Alternating Priorities
OSI - Open Systems Interconnection
PODA - Priority Oriented Demand Assignment
PSK - Phase Shift Keying
RRP - Round-Robin Protocol
Rx - Receive
SCADA - Supervisory Control and Data Acquisition
SRUC - Split Reservation Upon Collision
TCP/IP - Terminal Control Protocol/Internet Protocol

TDMA	- Time Division Multiple Access
Tx	- Transmit
WAN	- Wide Area Network

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Chapter 1

Introduction

1.1 Background to the Problem Considered

1.1.1 General

The volume of all types of communication has grown enormously during the recent past, be it data, voice or visual content related.

It is also true that this growth is showing no sign of saturation or decrease. The current situation is, in fact, the opposite. The explosive expansion of the Internet is the most obvious case in point, but increased demands on available bandwidth are imposed by many other services, such as:

- Mobile personal communications.
- Geographical expansion and increased utilisation of computer LAN's and WAN's.
- Satellite and terrestrial public broadcast services.

The above are just a few examples of communication disciplines typically requiring a significant bandwidth.

With the advent and maturity of digital technologies, the definite distinction between the different forms of content is, of course, rapidly disappearing, again tending towards a consolidated wide band, spanning the various disciplines.

It is clear that the use of this finite spectrum resource usable be optimised as much as possible. To this end, many efforts are underway, such as increased bandwidth regulation and improved organisation, as seen in many countries. [SABRE-97]

Spectrum resources are also expensive and a potential source of revenue, as is very notably demonstrated by the competition for cellular communications bandwidth in several countries. Africa is no exception to this.

At the lower, implementation level, much work has been done to increase channel utilisation and throughput. Where expensive infrastructure has been established, such as satellite-, or long distance terrestrial links, the reasons are both financial and practical, i.e:

- Better utilisation of capital expenditure and increased revenue.
- Postponement of future expenditure.
- Improved client service levels.

These types of link are very prominent and present themselves as natural and immediate choices of optimisation. It is, therefore, no surprise that the bulk of practical and theoretical efforts have been and still are, being applied to this type of high throughput/wide band application.

1.1.2. Telemetry Data Communications

However, band congestion does not only occur in the domain of wide band services. In some metropolitan areas, the demand for narrow band communications, such as telemetry data links and utility speech communications, exceed the available spectrum allocation.

To this end, the inter-channel spacing for these services have fairly recently been reduced from 25 kHz to 12,5 kHz, and in some European countries, to 6,25 kHz.

Although occupying narrow bandwidth, typically 2,5 kHz, the total no. of channels may be large and the aggregate bandwidth required, is not insignificant. As far as utilisation of these channels for purposes of data transmission is concerned, this is normally effected at 1200 Baud in half-duplex mode.

Although a humble capability on the face of it, there are compelling reasons for it's popularity, such as:

- Widespread availability of system components from a good selection of suppliers.
- Relatively low capital and operational cost.
- Utilise key components, volume produced for other applications, such as standard speech communication radios, antennas and related equipment.
- Easy to implement without excessively expensive and sophisticated test- and commissioning equipment.

- Master Station SCADA software drivers readily available for many popular systems.

There are many applications eminently suited to this technology, such as:

- Remote monitoring and control of water distribution and sanitation services infrastructure, eg:
  Pump stations
  Purification works
  Valve and pressure control functions
  Reservoirs
- Similar application for electrical distribution components, eg:
  Substations
  Remote metering points
- Centralised monitoring and control of remote distributed industrial and commercial plant, eg:
  Mining plant
  Building services
  Fire and security systems

The required data throughput for electrical/industrial applications, is generally much higher than in the case of the abovementioned civil services and the limitation imposed by the low effective channel capacity, more onerous. Design in such instances, have to be approached with more care.

1.1.3. Telemetry Communications Systems Planning

In the course of involvement with many such installations, a few interesting observations have been made, i.e:

- Communications protocol strategies differ greatly and are company specific.
- Strategies are defined on the basis of engineering instinct with little, or no, attempt at prior analysis. In many cases, the nature of the application is not very stringent and quite tolerant to fairly wide parameter variation.
- Where the communications channel is heavily loaded, as in the case of large networks, or high rates of outstation event generation, quite significant changes in system response times can be effected by adjustment of the protocol parameters.

The above did not appear to be in keeping with sound engineering practise and led to the investigation of some relevant existing subject literature.

During this preliminary investigation it was found that although some of the available analytical work was indeed applicable to the problem at hand, most of the effort was directed towards high speed, wideband full-duplex applications, those being the most prominent. The established models for those applications, could not be directly and simply applied to the perceived problem area. In some aspects they are overly complex, while lacking in other essential areas.

It was, therefore, decided to attempt the establishment of a more formal and justifiable approach.

1.2 Objectives of the Investigation

Further to the above, the following objectives were set for the proposed investigation.

1.2.1 To obtain sufficient information about protocol strategies commonly utilised in a range of commercial products and their respective, associated hardware.

1.2.2 To investigate the applicability of existing theoretical work on such strategies.

1.2.3 To attempt an improved, formalised, theoretical approach should this investigation indicate areas relevant to the specific field of interest, not adequately addressed by existing work.

1.2.4 To develop a simulation tool modeled on actual hardware to an acceptably high degree of accuracy, which can be utilised as parallel method of system modeling and performance prediction.

1.2.5 To utilise the dual theoretical and simulation methods to determine an optimum strategy for a given set of system parameters.

1.3 Overview of the Dissertation

1.3.1 Chapter 2 provides a review of characteristics, publications and theory regarding a significant number of deterministic and nondeterministic protocols. The suitability of the different groups and sub-groups, relevant to the particular application, is discussed and identified.

In view of the above, the structure and strategy of a number of commonly utilised commercial protocols are analysed, accompanied by comments regarding their general efficiency and suitability.

Existing theory regarding performance modeling of possibly applicable protocols, or group of protocols, is reviewed in the context of the investigation. The compatibility of such theory with the specific relevant sub-group of protocols is discussed and perceived shortcomings identified.

The abovementioned aspects of the review serve as partial motivation for this dissertation.

1.3.2 Chapter 3 sets out the proposed groups of strategies to be modeled, in both simulation and theoretical format. The system parameters to be incorporated in these models are discussed, as well as the proposed data sets to be obtained, for subsequent strategy comparison.

1.3.3 Chapter 4 describes the development of the simulation model. The various hardware characteristics and their measurement is set out, together with their utilisation in the software emulation. The calibration of the model is discussed, in view of typical hardware- and system parameters. The emulation of the main strategy types and adjustment of their variables are described , together with a brief description of the overall development environment. Evidence of individual component block and overall simulation model performance, is provided.

1.3.4 Chapter 5 sets out the main protocol groups and the permutations within each group, for which simulations were performed. A comprehensive set of baseline data was thus obtained, to serve as a useful reference. The results for each set and subset of simulations are presented with associated comments. The performance between the main groups of centrally scheduled and contention protocols are compared under similar conditions, as far as possible.

Comments are subsequently provided regarding relative protocol suitability for a given system configuration.

1.3.5 The simulation process covered under Chapters 4 and 5, is demanding of CPU resources and time consuming. Chapter 6 investigates simplifications of the procedure, without sacrificing validity, although with cognisance of reduced flexibility. The correspondence of a further simplified simulation model with basic queueing theory, is also verified.

1.3.6 Chapter 7 explores the creation of a valid theoretical model for the two main protocol types under investigation. In the RRP case, this is relatively straightforward. In the contention case, it is sought to establish a theoretical base for the analysis of a narrow band, half-duplex CSMA type protocol. This approach is based on queueing theory and allows for the inclusion of system parameters not incorporated in well known analyses to date.

Good correspondence is found between simulation and theoretical data and evidence is provided regarding the usefulness of the model to predict system performance with selectable parameters not only including event generation, data format, service throughput conditions and backoff strategy, but also system overhead factors, such as channel noise, sensing rise times and propagation delay.

1.3.7 Chapter 8 summarises the theoretical modeling approach and the implications for use in system configuration and optimum strategy selection.

1.3.8 Chapter 9 provides an overall concluding summary of the dissertation and suggests avenues for further research and development in the particular field.

1.3.9 A list of references is included, as well as various Addendums. The latter contains specifications of typical hardware, more detailed software information on the simulation development environment and listings of some Matlab script files, with which some of the theoretical calculations were carried out.

1.4 Original Contributions

The original contributions of this dissertation, are as follows:

1.4.1 The utilisation of the principles of queueing theory to theoretically model the behaviour of narrow-band half-duplex contention type telemetry links.

1.4.2 Apart from the inclusion of event generation-/service rates and propagation delays, in keeping with earlier work by others, this theoretical approach also allows for the additional inclusion of backoff strategy and system overhead components, consisting of disruptive noise and channel sense/transmitter rise times as formal variables.

1.4.3 Valuable analytical work done in this field up to the present, particularly by Kleinrock, Tobagi et al, tended to concentrate on full-duplex and/or slotted operation and acknowledged the difficulty of inclusion of some of the additional parameters as abovementioned under 1.4.2. The complexity of the probabalistic approach set out in all well known relevant publications renders such inclusions very difficult. Channel noise was included in comparatively recent work [Huang-92], but the protocol analysed is not applicable to the type of system under consideration, at all. The analyses are furthermore, all based on infinite source systems, which are mathematically somewhat more convenient.

To the best of this author's knowledge, all the variables as abovementioned in 1.4.2, have not yet been included in a formalised, comprehensive, finite source theoretical model for the type of protocol under consideration. The approach followed in this dissertation is relatively simple, but allows for flexible and powerful system performance analysis and prediction. It is eminently suitable for application to practical systems design.

1.4.4 Complementary to the theoretical work, a software emulation of a typical system, is presented. The emulation models actual, typical hardware to an acceptably realistic degree and is readily adaptable to cater for different system parameters and configurations.

1.4.5 A dual set of tools, theoretically and simulation based, for interactive use in the basic system design and performance prediction process, is thus presented.

Chapter 2

Review of Protocols, Publications and Associated Theory

2.1 Introduction

The protocols covered under the following summary, are not meant to form a comprehensive list, but are the most important ones utilised for data transmission. The bias is also towards protocols more suited to non-continuous data input, such as telemetry- or computer networks, as opposed to more continuous stream data from, typically, voice or visual sources. The grouping of the various types, is not rigid either, as some overlapping does occur. It may, however, serve as a useful guide.

2.2 Centrally Scheduled and Fixed Assignment Protocols

These strategies are implemented and controlled by one, or more, central schedulers or master stations.

Operation is deterministic and subsequently, conflict free. Some of the more important examples, are as follows:

2.2.1 FDMA (Frequency Division Multiple Access)

The operation of this scheme is well known. The total available bandwidth is divided into sub-bands allocated to the individual users. The protocol is, naturally, conflict free but is somewhat wasteful of bandwidth, due to the required minimum subchannel separation. There is no centrally generated broadcast possibility and the scheme exhibits inefficient use of bandwidth under conditions of low input loading.

This protocol is virtually never used in the type of application under consideration, due to the bandwidth requirements.

In some isolated cases where a particular outstation, or a number of outstations, serve a large number of data I/O devices, a dedicated channel per outstation is sometimes utilised.

The network then behaves as a group of single access channels. Licensing for this type of configuration is not easily obtained.

2.2.2 TDMA (Time Division Multiple Access)

In this strategy, each user is allocated a dedicated time slot. One of the advantages is, that all users can simultaneously receive a central station broadcast, but will transmit at different times. There are various variations on the scheme, such as dynamic allocation of time slots in order to cater for bursty users, i.e. ATDMA (Asynchronous Time Division Multple Access). ATDMA is, of course, widely used in wideband comms link applications, mostly notably in the well known GSM (Global System for Mobile Communications) type network.

It is never utilised in the type of low-end application relevant to this investigation.

Some considerations against such use, are as follows:

- The cost associated with the relative complexity of the strategy.
- The requirement for very good timing and synchronisation between users.
- In order to render the scheme functional, all users must be within earshot of each other. Any user transmitting out of sync, will clearly be disruptive.

These aspects will be more comprehensively dealt with later.

2.2.3 CDMA (Code Division Multiple Access)

CDMA spread-spectrum strategies are becoming more widespread and popular, particularly for WAN (Wide Area Network) applications in the 2,4 GHz band and very prominently, for next generation mobile communications.

The very wide band nature of the scheme, dictates against it's use in the application under consideration.

2.2.4 Single Channel Cyclical Polling, or Round-Robin Polling (RRP)

This protocol and associated variations, are well known and popular. It is also commonly applied in low end telemetry applications, either in pure form, or as part of a mixed strategy. It is also found in some computer networks e.g. ARCNET and in industrial data communications, e.g. Profibus. The reasons for its popularity are obvious, such as:

- Inherently conflict free and stable
- Deterministic resulting in ease of implementation, simplification of driver software and error handling.
- Efficient under heavy loads
- Low demands on outstation hardware and software infrastructure, with associated low cost.

The successful use of RRP schemes is, however, subject to a few precautionary considerations, such as:

- Inefficient in networks with long propagation delays, resulting in long polling cycle times. Satellite links are a case in point.
- Inefficient under low load conditions, or with a large no. of outstations generating relatively infrequent sudden data peaks.
- The polling overhead must be low. This is generally not a problem.

In order to circumvent some of these drawbacks, but attempting to capitalise on the protocol's obvious strengths, a number of variations have been implemented. Examples are as follows:

- Adaptive polling, where groups are first polled as a whole to establish group data transmission demand. Stations are successively polled in smaller and still smaller groups, until all data has been gathered. This basically follows a binary tree structure.
- Priority polling, where stations, with known higher rate of data input are pre-identified and polled more frequently.
- Reservation RRP, where a subchannel is used to predetermine the identity of stations with available data. The two channels run simultaneously and polling is adapted dynamically in response to the obtained reservations. This is a slotted scheme.

Of the above and other undiscussed variations on the theme, only the first two could possibly find application in our particular field of interest. Their possible successful implementation will have to be judged on a case by case basis. The nature of the network and associated station/data generation profiles, will clearly have a determining influence on their viability.

The split-channel, slotted reservation scheme, is impractical due to bandwidth- and other restrictions, as dealt with later.

A formal, theoretical model of the RRP strategy, is also presented in a subsequent section.

A good review of the RRP variation protocols, is given by F. Tobagi [Tobag-80b].

2.3 Contention Protocols

This group of data transmission protocols is very important, resulting in widespread application of particularly some member strategies, in a wide variety of applications.

Some schemes are more suitable for low end telemetry systems and will, therefore, be given more attention. Others will merely be briefly mentioned in passing, for general interest.

Due to their prolific use, it is not surprising that a lot of attention has been given to their theoretical modeling and formalisation. A significant no. of variations on the basic scheme have also been described. There is a large volume of available references to this effect, but a series of landmark papers were presented by a few authors, notably Kleinrock, Tobagi, Lam and Molle [Klein-75a], [Klein-75b], [Lam-75], [Molle-75], [Tobag-80b].

Some of the analysis are very valuable and represent definitive work in this particular field. They are, however, not always generally applicable and have been done with the bulk of commonly encountered applications in mind.

These are very often of the wideband, high throughput type, in contrast with the narrow band, low rate networks under consideration.

Practical, real world problems, such as noise, are mostly not taken into account. A few of the most important strategies, and their associated available performance models, will now be summarised. Some comments regarding their applicability, are also presented.

2.3.1 ALOHA Protocol

First implemented on a computer network on the campus of the University of Hawaii, this scheme consists of a number of stations sharing a common communications channel.

A station with data in the transmission buffer merely transmits the data regardless, upon it's availability. Should an acknowledgement not be received after a preset timeout, the information is re-transmitted, upon the assumption that a collision has occurred in the channel. The performance of this scheme is shown in Fig 2.1, as an effective data throughput/data demand relationship. (Recreated from [Tobag-80b] and [Tanen-89]).

It is obvious that the performance of this strategy deteriorates very rapidly under load. Utilisation of the communications channel resource is poor. Where the maximum available throughput is low and the operation half-duplex, requiring the acknowledge message to share the same scarce resource, this utilisation is even worse. RF channel noise, a reality in the systems under consideration, will aggravate the situation even more.

From the above, it should be clear why no instance could be found where ALOHA has been implemented in the considered field.

2.3.2 Slotted ALOHA

Roberts [Tanen-89] [Stall-94] [Rom-90] has presented a scheme to double the throughput of an ALOHA channel by using fixed transmission packet lengths on a slotted timebase. See Fig 2.1.

Apart from still containing the basic problems abovementioned for pure ALOHA, the additional complication of the slotted timebase renders the implementation impractical in our case, as discussed later.

2.3.3 CSMA Protocol

(a) Description:

This very important protocol was first modeled by Kleinrock & Tobagi [Klein-75c]. The operation of the scheme is well known and can be summarised as follows:

A station with ready data senses the shared communications channel for activity. If none is detected, the data is immediately transmitted. If the channel is busy, a re-transmission, or backoff timer, is set according to some strategy. Upon expiry of the timer, the process is repeated until a transmission could be made. This is the non-persistent case. After transmission, a timer is set to check for return of an acknowledge message from the master station. If this timer expires before receipt of the acknowledged message, the process is repeated.

In the case of unslotted CSMA, the backoff process is either 1-persistent or non-persistent. In the 1-persistent case, the station upon detecting a busy channel, keeps on sensing the channel. Upon sensing the channel free, transmission takes place immediately, i.e., with probability = 1. This equivalent to the non-persistent case where the backoff time is set to nil.

The non-persistent CSMA expression as derived by Kleinrock & Tobagi [Klein-75c] is:

$$S = \frac{Ge^{-aG}}{G(1+2a)+e^{-G}} \tag{2.1}$$

where:

S = Channel throughput

a = Ratio of propagation time / packet transmission time

G = Traffic demand

This expression is plotted in Fig 2.2, for various values of a. It is clear how long propagation times increase the vulnerable period and conversely, decrease channel throughput.

Again from [Klein-75c], the 1- persistent case is obtained as:

$$S = \frac{G[1+G+aG(1+G+aG/2)]e^{-G(1+2a)}}{G(1+2a)-(1-e^{aG})+(1+aG)e^{-G(1+a)}} \tag{2.2}$$

Equation (2.2) is plotted in Fig 2.3.

It is evident that the performance of this approach is significantly inferior to non-persistent CSMA, due to the increased competition for access and resultant increased collision rate.

It could also be viewed as the incurrence of an overall increased system overhead, to resolve conflicts and reschedule transmissions.

(b) Comments:

A few comments on the above results, are of relevance:

(i) The authors assumed that the traffic demand is Poisson distributed. This assumption, according to many sources, is fair. (Apart from any fairness, the proofs are mathematically virtually impossible without this assumption).

(ii) The expressions were initially derived using probabilities to calculate transmission success/failure rates, taking into account cycle times, the vulnerable portion of each cycle, data input rate and distribution.

(iii) This protocol as well as others, were also subsequently analysed by Tobagi, Gerla et al [Tobag-78], using Markov chain theory. The results confirmed the earlier findings of Kleinrock and Tobagi. Little's result is utilised for determining of delay times. More about that later.

(iv) The backoff process is implicit in the expressions, but the backoff time is not defined as an explicit variable.

(v) The expressions are also derived assuming an infinite data source population. This is, of course, not always the case.

(c) Optimization techniques:

Lam & Kleinrock [Lam-75] investigated the possibility of preventing network instability in both slotted and unslotted non-persistent CSMA, by dynamic adjustment of the backoff strategy. They developed an expression allowing for minimising of the average data packet throughput delay. The result, however, assumed that each station knew the status of every other station in the network. This is clearly invalid in a practical situation.

They also developed a control algorithm based on data input control to individual stations, i.e., rejecting data under increased traffic conditions. This is also impractical, as in most telemetry installations at least, obtaining of event data is regarded as vital and as such, cannot be rejected.

The authors contend that no known solution exists for the practical case where stations do not posess complete knowledge of total network state. The only source of information to each station is, obviously, the current channel activity passing by. As a result they provide two empirical backoff control algorithms to minimise throughput delay and system lockup.

The first approach is based on system estimation, where each station keeps a record of channel history for a given number of transmission periods. This is particularly applicable to slotted CSMA, where each transmission falls neatly into a slot.

The second algorithm is much simpler and merely increases the backoff period linearly with increase in observed channel traffic.

According to their simulations, the results of both schemes are good. The average packet delay is much more linear with respect to data input increase and sudden input bursts are also better accommodated.

Although the results are encouraging, practical implementation seems to be rare. No such case has ever been personally observed. The consideration of such a control strategy, however, certainly appears to have merit.

Molle and Kleinrock [Molle-75] have also examined a scheme where a station runs a realtime clock and a pseudo-realtime clock in order to implement what is effectively, a different backoff strategy. They claim improved results over non-persistent CSMA under conditions with short propagation times. The improvement, however, appears to be relatively small and in practical cases, will have to be considered against the added complexity of hardware and software.

2.3.4 Slotted CSMA

This is basically the same strategy as normal CSMA, except that the timebase is slotted to accept fixed length data packets.

An additional variation of CSMA, i.e. p-persistent CSMA, is a further option to be considered. Operation is as follows:

Should a station with ready data sense the next slot free, transmission takes place with probability $= p$.

Should transmission not take place in that particular slot the decision is deferred to the next slot with probability $= (1-p)$, where the process is repeated.

Results and analysis of this protocol is obtainable from [Klein-75c], [Tobag-80b], [Rom-90] et al. The slotted timebase renders the protocol unsuitable for the current application.

A proposal has been submitted [Raych-92] where an unslotted CSMA with CD, is implemented. The scheme and associated variants as published, utilises a full-duplex channel and is, therefore, not applicable to the investigation at hand.

2.3.5 CSMA/CD (CSMA with Collision Detect)

In this scheme, operation is as for normal non-persistent CSMA, but the transmitting station monitors the channel continuously, also during transmission. In this way, a collision with another station's emission, can be detected immediately. Such a collision is, of course, possible due to finite propagation- and receiver input transient response times. The scheme can be implemented in normal- or slotted form and presents an improvement over the CSMA equivalent.

The drawback is the obvious need for a full duplex channel, which is beyond the scope of this investigation.

2.4 Conflict Resolution Protocols

2.4.1 General

It makes eminent sense to prevent collisions caused by competition in one way or the other, of the single, shared communications channel. In order to achieve this, co-operation between stations, or prior arrangement of the communications hierarchy, is required.

A number of solutions to this significant problem, have been presented, or implemented. Some of those strategies are very elegant, but unfortunately, of very little use in the context of the present investigation. Virtually all the implementations utilise a synchronised, slotted timebase with relatively high bandwidth requirements in some cases.

The more important examples will, however, be summarised briefly for sake of interest.

2.4.2 Reservation ALOHA Protocol

This is a slotted version of ALOHA where the same slot is used by the same station all the time, until not required any more, in which case it is up for grabs. The next winning station then keeps on using the slot until the need expires, and so on.

2.4.3 FIFO Reservation Protocol

This slotted scheme makes use of a separate subchannel carrying reservation information, which continuously allocates slots to stations in need of access.

2.4.4 MSAP (Minislotted Alternating Priorities)

The timebase is divided into minislots equal to the total, transmission delay. A user i say, may keep transmitting until such time as he has data. Transmission can only commence at the start of a minislot. Should another user detect absence of carrier during the minislot following the end of the transmission from i, the next user in the allocated sequence starts transmitting. There are various methods of priority allocations, i.e. RRP or random. The scheme works well with a low number of stations.

2.4.5 Tree Resolution Algorithms

In it's most general form, the timebase is divided in slot pairs, with each slot in a pair corresponding to one branch of a tree. During recursively probing transmissions and possible collisions, a picture of the tree is built from the root up, prior to actual data transmission. In such a way, all stations build up prior knowledge of the required station activity.

They must, of course, be within earshot of one another.

A very good summary of this, and other tree resolution protocols, is to be found in [Tanen-89].

2.4.6 Ring Protocols

The most well known of these, is the Token Ring scheme, where stations are connected in a ring topology, with a control token message being continuously passed round the ring. No station may transmit if the token is not present and the first station requiring transmission, removes the token and transmits. This protocol was quite popular in computer networks up to fairly recently, before the advent of Ethernet and TCP/IP.

In another version of the ring structure, a message with a no. of bits $>=$ to the maximum no. of stations, is pre-circulated prior to transmission. Each station with data first reserves the right to transmit. Upon completing the circle, transmission takes place in accordance with pre-reservation.

2.4.7 Urn Protocol

This protocol represents yet another approach to maximise adaptation between light and heavy data loads. A good description of the protocol is found in [Tanen-89], but the total of N stations can be viewed as arranged numerically on the circumference of a circle. A window of size n rotates around the circle.

During each timeslot, all stations in the window may transmit. If no, or a successful, transmission takes place, the window is advanced in position. If a collision occurred, n is reduced by half and the process repeated until no collision is found. The size of n could, therefore, vary between 1 and N. The protocol correspondingly behaves as TDMA at one extreme and slotted ALOHA at the other.

2.4.8 DQRAP (Distributed Queuing Random Access Protocol)

This is another tree type protocol, but with minislots to sort out the channel allocation and longer dataslots for actual transmission. The scheme promises good performance on theory at least. See [Xu-93] for a full analysis.

2.4.9 PODA (Priority Oriented Demand Assignment)

This scheme has primarily been suggested for satellite traffic. Channel time is basically divided into two subframes, a information subframe and a control subframe. The control subframe contains reservation information, while the information subframe contains the actual data as well as acknowledged messages and reservations not sent in the control subframe.

There are various versions of the scheme and performance is good, particularly with long signal propagation times [Tobag-80b].

2.4.10 Co-operative Protocols

One such strategy is described in [Klein-75c]. The protocol consists of respective scheduling, contention and transmission periods. Stations issue reservation messages and compete for a token. Winning stations are known to each other and may transmit without interference.

The protocol will not work with hidden stations and the high token passing overhead is too onerous for slow, half-duplex systems.

2.4.11 Various Mixed Modes

Many mixed permutations of the above basic approaches can be found, such as:

(a) Combination CSMA/TDMA

(b) SRUC (Split Reservation Upon Collision)

(c) Mixed ALOHA

(d) GRA (Grouped Random Access)

These will not be discussed in detail and are adequately covered in [Tobag-80b], [Tanen-89] and [Stall-94].

2.5 Suitability of Slotted Protocols

As can be seen from the above, protocols with a slotted timebase are well represented in both the collision- and conflict free groups. It is, therefore, important to investigate their suitability for the type of application under discussion. A typical HDNB (Half-duplex narrow band) telemetry signal transmission consist of the following:

Pre-amble period:	150 ms min. (More if repeaters are involved)
Data transmission period:	(Bit period) × (No. of bits) where: Bit period $= 0,833$ ms at typically 1200 baud.
Post-amble period:	150 ms

Let us assume that the network contains two size configurations of outstation, ie.

A 16 I/O (Input/Output) station and

A 32 I/O station.

Let it be further assumed that 50% of the I/O of each type of station has generated events which need forwarding to the system master. It is common practise to assign 2 bytes / I/O point, allowing for time-date tag, value or state and some housekeeping bits. The data is further very frequently pre- and postceded by a combination of 128 bits. The minimum and maximum message lengths are consequently as follows:

$$\begin{aligned}\text{Minimum length} &= 150 + [(128 + (8 \times 2) \times 8) \times 0,833] + 150 \\ &= 513\,\text{ms} \\ \text{Maximum length} &= 150 + [128 + (16 \times 2) \times 8) \times 0.833] + 150 \\ &= 727\,\text{ms} \\ \text{Average length} &= 620\,\text{ms}\end{aligned}$$

Each data transmission has to be followed by an ACK (acknowledge) transmission, typically containing 128 bits, translating into a total ACK. message length of 407 ms.

If perfect scheduling is assumed, the total average transaction length is, therefore:

$$620 + 407 = 1027\,\text{ms}.$$

The actual data content is 320 + 107 ms, resulting in a occupational efficiency of 41%.

Should it now be considered to utilise a slotted timebase for the above, it is clear that allowance should be made for the maximum message length, i.e. 727 ms. A safety margin for jitter, synchronising errors etc. is required, so that the time slot cannot be chosen < 750 ms. Note that this does not allow for total I/O download from the bigger stations, which will have to occupy two messaging sessions, if required.

Again allowing for the ACK message and perfect scheduling, a total transaction time of:

$2 \times 750 = 1500$ ms is obtained. The data content is still 427 ms, resulting in an efficiency of 28%.

This is clearly inferior to the unslotted case, but there are also other problems associated with a slotted scheme, some more severe than others. These are as follows:

2.5.1 Kleinrock & Tobagi [Klein-75c] have shown that the advantage of slotted CSMA over non-slotted CSMA, is much less than in the ALOHA case, particularly in non-saturated systems. See Fig 2.4, below.

2.5.2 It is not impossible, but onerous, to synchronise the entire network and to ensure that it remains synchronised. Outstations are downloaded with time information in some systems, but normally only for tagging purposes and the level of required accuracy is far less than the requirement for slot synchronisation. Some external source, such as GPS input, could be used, but it carries a cost penalty.

2.5.3 If the idea is to slot the system in order to run a conflict free scheme, the poor data / total slot length ratio, presents an even greater drawback. If N stations are involved and a very basic bit-map allocation method is used, N transmissions must first take place to allocate the pecking order, before any actual data transfer takes place. This is a huge overhead, which could be totally unacceptable for a low bit-rate system.

2.5.4 In practical systems, it is very frequently found that all stations cannot receive transmissions from all other stations. Even worse, it is also quite common that some stations cannot even establish communications with the master station. In non-persistent CSMA based networks, the problem is solved fairly simply by using one of the within range stations as a store-and-forward site, or digipeater. This would still be possible in slotted systems, but with added complexity. The situation would be aggravated by schemes where a great deal of inter-station communications take place, such as the co-operative- or ring topology protocols, as opposed to centrally scheduled schemes.

From the above it should be clear why slotted protocols are not popular in the application under consideration. The efficiency- and cost constraints are just too great. If the system loading is constantly of such a nature that a non-persistent, unslotted CSMA scheme creates an unacceptable backlog, it would be far better to utilise one of the centrally scheduled (eg. unslotted RRP) strategies.

2.6 Comparative Summary of Protocol Performance and Applicability

The relative merits of the various protocols as discussed above, can be summarised as per Table 2.6.1, below. The characteristics of each protocol is particularly judged against its applicability to the type of system under consideration

Table 2.6.1

Protocol	**Advantages**	**Disadvantages**
FDMA	• Conflict free	• Bandwidth inefficient under low loading • Relatively wide bandwidth required
TDMA	• Conflict free • Central broadcast capability	• Complexity and cost • Requires good timing and sync • Users must be within earshot
CDMA	• Good noise immunity • Data security • Large no. of users • Conflict free	• Complexity and cost • Wide brandwidth required • Frequency band allowed not practical for considered use
RRP	• Conflict free • Inherently stable • Simple implementation • Low cost and hardware/ software overhead	• Inefficient at low load • Inefficient with long propogation times • Requires low polling overhead

Reservation RRP	• As for RRP, but higher cost and complexity	• Basically the same as for RRP, but with some performance improvement • Slotted scheme with problems as discussed
ALOHA	• Simple to implement	• Very inefficient under increased load • Rapid deterioration under noise • Ideally requires full-duplex channel • Generally channel inefficient
Slotted ALOHA	• Relatively simple to implement, disregarding slotted timebase • Factor 2 improvement over simple ALOHA	• Still retains basic problems of ALOHA, although with improvement • Slotted timebase problematic
1-persistent CSMA	• Simple to implement • Good response under low to medium loads • Unslotted timebase • Very wide implementation	• Inefficient under high loading • Possible instability under very high loading
Non-persistent CSMA and Slotted CSMA	• Relatively simple to implement • Significant improvement • over 1-P CSMA	• Same basic problems as 1-P CSMA, although improved • Slotted timebase
CSMA/CD	• Improvement over other CSMA variants • Widely used, eg. Ethernet	• Implementation more difficult • Slotted timebase • Full-duplex channel required
Reservation ALOHA	• Improvement over ALOHA, but not drastic	• Implementation more complex • Slotted timebase
FIFO RP	• Relatively good performance	• Channel and subchannel complexity • Slotted timebase
MSAP	• Good performance with low loading • Implementation fairly difficult • Conflict free	• Deteriorates under high loading • Slotted and minislotted configuration
Binary tree	• Conflict free • Good performance under high loading	• Considerable system overhead • Slotted protocol • Totally unsuited for low baud rates • Implementation relatively complex
Ring Protocols	• Conflict free and stable • Good performance under high loading • Popular with some big computer manufacturers	• Inefficient at low load • Considerable system overhead • Implementation relatively complex • Slotted timebase

Urn Protocol	• Conflict free • Good overall preformance	• Slotted timebase • Seldom implemented due to overhead
DQRAP	• Conflict free • Good overall performance	• Complexity and cost • Slotted timebase with data and minislots • Never used on telemetry
PODA	• Conflict free • Good performance with long propagation times	• Complexity • Slotted with dual frame operation • Never used on telemetry
Co-op Protocols	• Conflict free • Good performance under high loading	• Complexity and cost • High system overhead • Half-duplex operation impractical • Slotted timebase • Never used in telemetry
Mixed Mode Protocols	• Conflict free • Attempt to achieve overall good performance	• Complexity and cost • High system overhead • Slotted timebase • Too involved for telemetry applications

2.7 Some Common Industry Protocols

2.7.1 General

A few popular and widely used telemetry protocols, will now be summarised. The list given is not exhaustive, but contains representative examples of the typical groups of protocols, commonly found in practical implementations of relevant systems. Within a group, there are differences, but these are not fundamental and tend to be in accordance with individual preferences and proprietary hardware. It has generally not been found that any of the implementations have been the subject of particular analysis, but rather based on engineering instinct and experience. The popularity of a particular protocol is mostly dependent upon market penetration of the host product and rarely relates, if at all, to the differences in effectiveness between competing strategies.

2.7.2 Centrally Controlled Polling: (RRP), Sync / Async, Variable Message Length

Example : ABB Indactic

This is centrally scheduled RRP scheme with all messages constructed of 16 bit words.

Each *word* contains:

8× data bits

5× Hamming bits

3× Product specific housekeeping bits

The *poll* message contains:

3× Short words

1× Address word

1× Termination word

The outstation response is similar, except that an unspecified maximum number of data words is added. No acknowledgement is sent and error control is reliant upon the Hamming coding.

The protocol normally operates in sync., full-duplex mode, but can be configured for async. half-duplex mode for radio based telemetry systems.

2.7.3 Centrally Controlled Polling: (RRP), Async, Variable Message Length

Example 1 : Siemens Sinaut

This is another very specific, proprietary protocol, not used by anybody else. The name of the parent company ensures a large user base.

The protocol is unusual in that each 'byte' contains 11 bits, i.e.

1× Start bit

8× Data bits

1× Stop bit

1× Parity bit

The poll message contains:

1× Start byte

2× Housekeeping bytes

1× Check byte

1× Stop byte

Error checking is, therefore, done on two levels, i.e., first on a byte level by means of parity and a final checksum control.

Data return messages are similar, but contain 6 housekeeping bytes and up to 120 data bytes.

An ACK message of 1 byte only, is sent by the master station after each poll.

This protocol is not often implemented over radio links and has more commonly been used in plant automation applications with discrete cable links. Here, it has now been largely superceded by Profibus, which is not so vendor specific.

2.7.4 Centrally Controlled Polling: (RRP), Async, Variable Message Length

Example 2 : IEC 870-5-101 FT1.2

This is a relatively recent protocol defined by a technical committee of the IEC. [CoatsJ-01]. The structure of the strategy was finalised and published in 1995 and the method has seen a constant increase in popularity, particularly in Europe and the Middle East. A number of the bigger European multinational firms, as well as a many smaller ones, are now standardising on this protocol. Prominent examples are:

ABB Procontrol, Datawatt, Siemens and Tele-Control.

It is believed that this trend will continue and it is worthwhile to briefly summarise the essentials of the scheme:

The protocol more or less conforms to the first 3 layers of the 7 layer OSI model. In keeping with common European practice, it is deterministic and normally configured as a master driven, RRP strategy. It can also be set up for CSMA/CD in point-to-point full-duplex applications, but not with a master and multiple slaves. It can, furthermore, be configured for spontaneous cyclic data transmission from outstations without any master poll command or ACK response.

The more common setup, however, is the so called Balanced Communications Method, which operates as follows:

Poll request :	**Master → Outstation**
ACK request :	**Master ← Outstation**
Data request :	**Master → Outstation**

Data transmission : **Master ← Outstation**

Message frame structure is as follows:

Destination address :	0 - 2 Bytes
Source address :	1 Byte
Application layer address :	1 Byte
Checksum :	1 Byte (Hamming distance = 4)

The rest of the frame is made up of a variable no. of data bytes, up to a max. length of 255 bytes.

An unusual requirement of the protocol, is that only one single data type per message is permissible, or one type of command. This aspect, as well as the polling format set out above, will not result in a particularly efficient result, particularly for systems with low to moderate outstation event rates. The typical solution in bigger, more expensive networks would be to throw bandwidth and associated throughput at the problem. The additional cost would, to a certain extent, be offset by the reassurance that the choice of a standardised protocol would be less likely to result in over reliance on one specific vendor or product, as well as the protocol's inherent stability.

2.7.5 CSMA, Synchronous / Asynchronous, Variable Message Length

Example : Motorola Moscad MDLC

This scheme is an adaptation of the well known SDLC synchronous protocol and conforms to the OSI 7 layer model in some configurations. Synchronous operation is only be possible in full-duplex mode.

Message format is as follows:

Header, addressing, routing and housekeeping	:	20 Bytes
Data	:	8-160 Bytes
ACK	:	8 Bytes
CRC Checksum	:	8 Bytes

The protocol has been developed for use over a variety of communications media and contains very comprehensive routing and addressing options, as is evident from the 20 byte header position.

The message sequence is: **Data transmission outstation → master**
ACK transmission master → outstation

The scheme usually operates on contention for telemetry applications, but can also be configured for RRP. No information is available regarding the backoff strategy.

The protocol is very powerful, but complex and an overkill in most of the small to medium size telemetry installations. For this reason, the no. of available SCADA drivers is limited. The name of the parent company ensures good marketing and a large user base.

2.7.6 CSMA, Asynchronous, Fixed Message Length

Example : Motorola MRTU

The scheme utilises a 32 bit, fixed length message, for both **outstation → master** data, and **master → outstation** ACK transmissions. The structure contains 8 data bits, 6 error check bits and the rest are addressing, routing and other housekeeping bits. The message is pre- and postceded by the usual pre- and postamble lead-in carrier signals.

The protocol is clearly not very efficient, due to the unfavourable data period/total period ratio. Should a large volume of data require transmission, this will span multiple transmissions and acknowledgments, with resultant high channel occupation, but poor utilisation. Remote time and date tagging cannot be implemented, which is a big disadvantage in electrical network telemetry.

The protocol is easy to implement and found wide application, but more due to marketing success of the host product, than efficiency.

2.7.7 CSMA, Asynchronous, Variable Message Length - Simple Protocol

Example : Remotronics

Each transmission contains a maximum of 14 bytes (8 bits each as usual), i.e.:

Housekeeping + addressing:	1 Byte
Data:	4 - 12 Bytes in blocks of 4

Error checking (Not correction):	1 Byte

No specific information is available on the backoff strategy, except that it is set at a few seconds maximum. The scheme does not support remote time tagging.

Although vendor specific, this protocol is very typical of the approach found in many smaller systems using fairly simple equipment

2.7.8 CSMA, Asynchronous, Variable Message Length - Comprehensive Protocol, Bit Encoded

Example : Prodesign TS Series

This particular implementation has an additional handshake sequence, in that the outstation first transmits poll request upon having an event in the buffer. The sequence is as follows:

Request Poll:	**Master ← Outstation**
Go-ahead ACK:	**Master → Outstation**
Data transmission:	**Master ← Outstation**
Received ACK:	**Master → Outstation**

Poll requests and ACK's contain 16 bytes, of which 2 are used for error checking (parity and LRC checksum) and the rest for housekeeping functions.

All command sequences are encoded at bit level in the housekeeping bytes, providing a very comprehensive and powerful set of addressing, routing, time tagging and downloading options.

Data return messages contain the same basics, except that an additional 239 bytes of outstation information may be added. Total message length is restricted to 255 bytes. Outstation I/O data is encoded at 2 bytes per I/O point.

With the additional poll request and P-R ACK sequences, this protocol does impose an additional channel load. It was designed to be very flexible and secure and has been successfully applied in many wide area telemetry systems, containing one or more, repeaters as well.

Backoff time is programmable, with a minimum of 5 S, but is normally set at 15 S.

It is a typical example of a solid piece of engineering that gets the job done, but without too much attempt at optimisation.

2.7.9 CSMA, Asynchronous, Variable Message Length, ASCII based

Example : Spectrum Communications Teleranger

In this case, the various messages are built up from strings of ASCII characters, translating into 1 byte per character. The message composition is, therefore, less compact than in the previous case, but the scheme compensates by not sending:

Station → Master Poll Requests, or

Master → Station Proceed Commands.

The full sequence is, therefore:

Data transmission: **Master ← Outstation**

Received ACK: **Master → Outstation**

Message format is as follows:

Data transmission : **Master ← Outstation:**

Housekeeping, containing addressing,

Routing, etc.: 9 Bytes

Data: Approximately 19 bytes per outstation module,

(dependent upon module type) resulting in approximately 2 bytes per outstation I/O point

Checksum and termination: 4 Bytes

Received ACK: **Master → Outstation**

Header as before: 9 Bytes

Checksum and termination: 4 Bytes

Maximum backoff time is normally set at $5\,S$. As the protocol is sometimes also used with discrete cabling, there is no formal restriction on max. message length, but it is normally limited to 255 bytes for radio links. Remote event time tagging is fully supported.

The protocol is comprehensive, flexible and secure and has had wide market acceptance.

Once again, no particular attempt at optimisation has been made. The success of the strategy is more dependent upon the quality and market penetration of the host product. The ASCII nature of the message format simplifies debugging on site, as the transaction content is easily viewed by plugging in a display on to the RS 232 communications port between modem and CPU.

2.8 Summary and Conclusions

With reference to the above, it could be summarised and concluded as follows:

2.8.1 A large no. of deterministic and non-deterministic protocols have been defined, with far more variations found for the latter group

2.8.2 With the exception of a few variations of RRP, all the conflict free schemes require a slotted timebase.

2.8.3 Due to the slow, half-duplex mode of operation and the characteristics of the equipment commonly utilised, a slotted timebase would not be feasible and any theoretical advantage gained by it's prospective use, is more than offset by the limitations imposed thereon due to equipment and system layout limitations. This is a major factor in reducing the very large number of possible access strategies, to only a few suitable for serious consideration in the implementation under investigation.

2.8.4 In spite of the better low-load performance offered by 1-P CSMA over deterministic RRP schemes, the latter is still very popular. To this effect, two formats, ie. DNP-3 and IEC-870-5-101 are finding wide and increasing international application.

2.8.5 Protocols implemented by large, international firms, are although comprehensive, generally not optimised for efficiency, but designed to cater for a wide range of applications and specific in-house hardware. Their market penetration is typically due to the parent firm's size and related product exposure.

2.8.6 The schemes utilised by some of the smaller suppliers of telemetry equipment, are generally somewhat simpler, although still very versatile. No real attempt towards optimisation in a particular application is found.

Some of the industry CSMA protocols discussed above, such as the versions from Spectrum Communications and Prodesign, are typical examples of this approach where the schemes are not only used in telemetry, but in other data acquisition installations as well.

The philosophy is normally of the order:
If it works, use it and don't change unless absolutely necessary.

2.8.7 The predicted behaviour and performance of all the investigated protocols, have been analysed to a large extent. However, the analyses of some of the relevant schemes are acknowledged by the authors to contain limitations. This is particularly true when viewed in the context of the applications under consideration.

System overhead conditions, such as equipment response times, retry delays as a result of channel noise disturbance and backoff strategy parameters, are not included as quantified, formal parameters.

Most of the analysed protocols assume full-duplex operation with a relatively high throughput rate as well, which is in contrast with the type of strategy under investigation

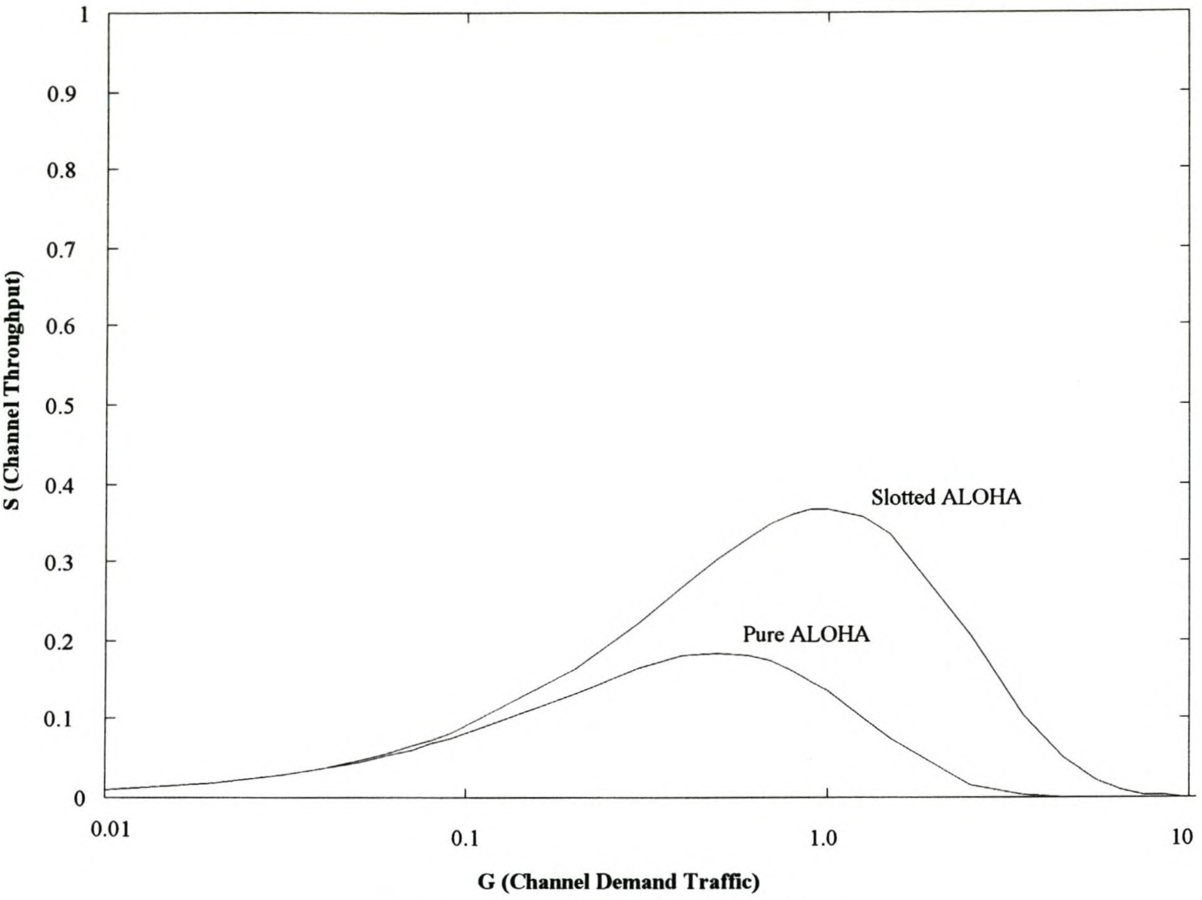

Fig. 2.1 - ALOHA Channel Throughput

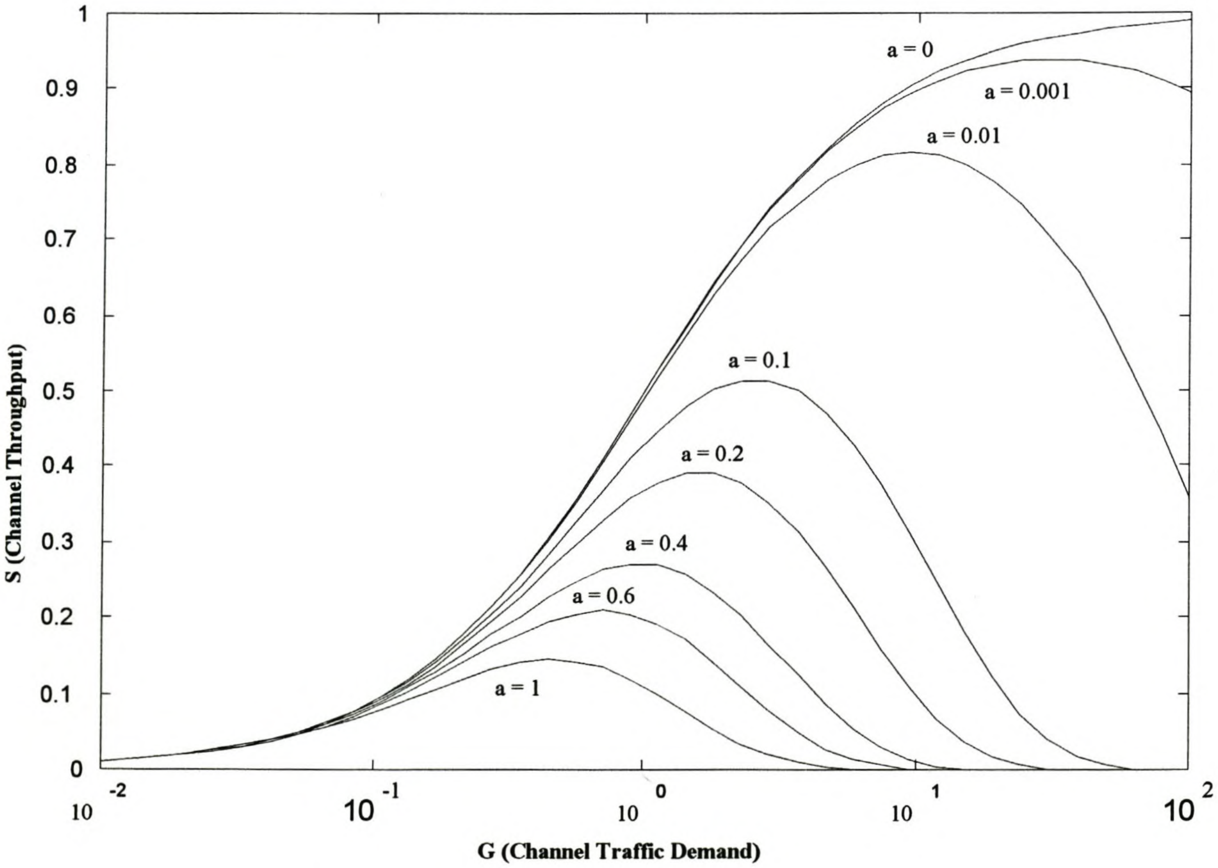

Fig. 2.2 - Nonpersistent CSMA Channel Throughput

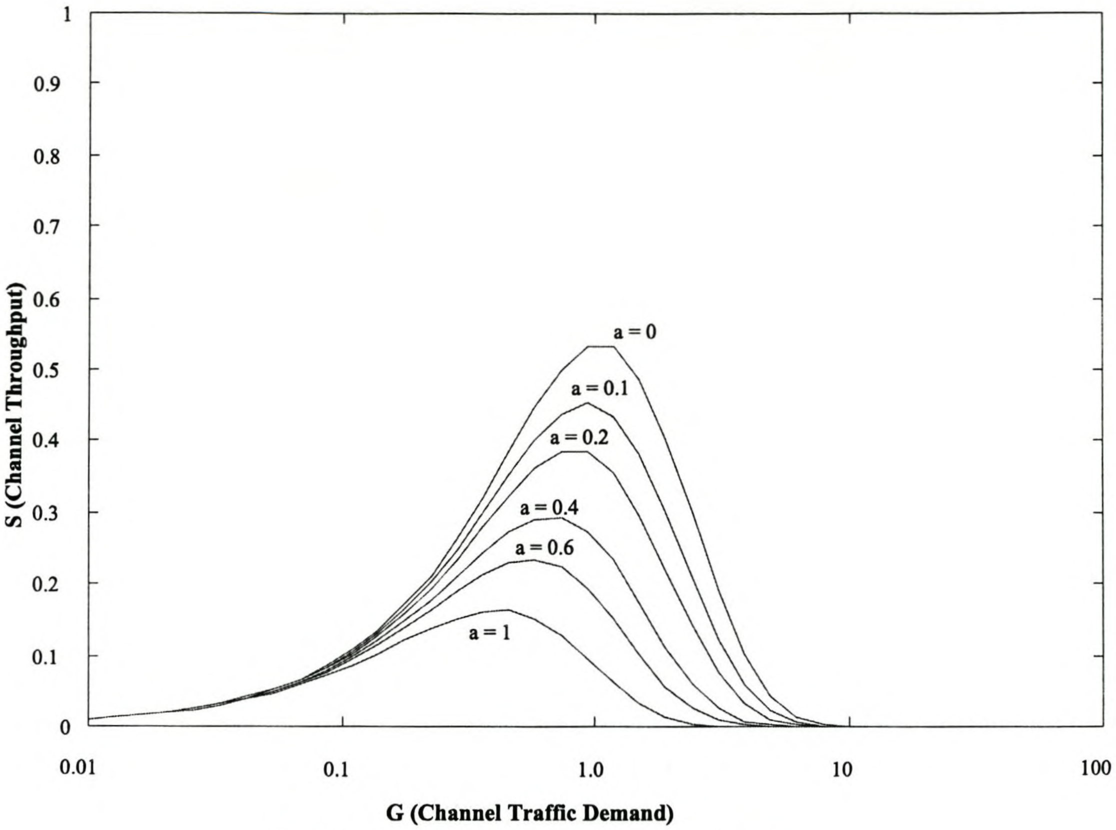

Fig. 2.3 - 1-Persistent CSMA Channel Throughput

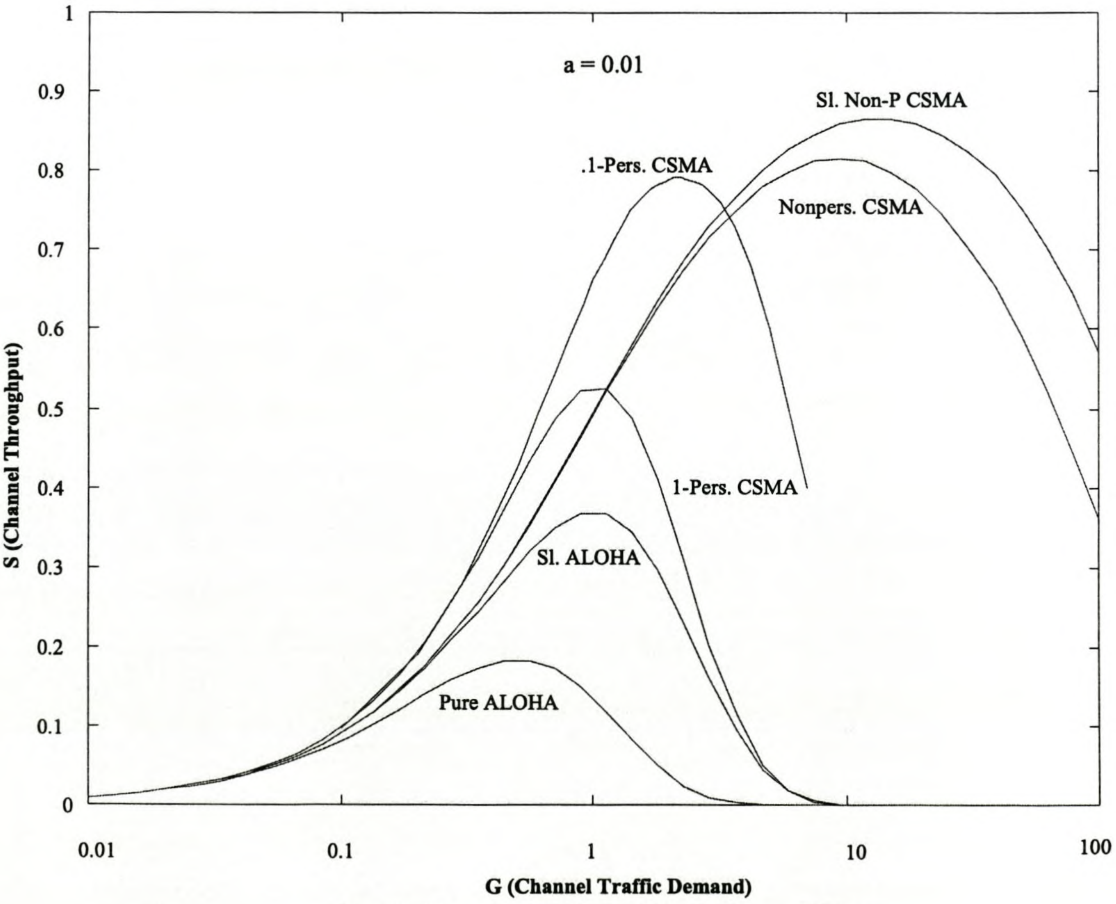

Fig. 2.4 - Throughput for Various Random Access Modes

Chapter 3

Proposed Method of Investigation

3.1 General

Subsequent to the review referred to in the previous section, it was concluded as follows:

- No exact model appears to have been formulated for the proposed area of investigation.
- There is a need for a formalised method to enable the selection of an optimum protocol for a given application. This is also applicable to the choice of associated protocol parameters.
- It would be very useful to have a set of theoretical and practical simulation tools, to assist with the above.

With the above purpose in mind, the approach as set out in the following paragraphs, was suggested.

3.2 Hardware Modeling

In order to create practical and realistic simulation tools, it is proposed that the characteristics and performance of typical industry standard hardware be modeled in software. This would include all encoding, transmission, channel characteristics, reception, decoding and error handling.

This then, would serve as a vehicle for investigation of the various protocol strategies.

3.3 Strategy Modeling

Apart from creating a suitable hardware model, it was clear that simulation of the most important and commonly used protocols, would also be required. These protocols in their different formats are:

- Centrally scheduled (RRP)
- RRP with channel noise included
- Contention (non-persistent)
- Contention with channel noise included
- Contention with channel noise and system overhead parameters included
- Simplified contention
- Very basic contention

From the previous section, it is clear that within a strategy group, there are differences in implementation. It is also clear that these differences are not fundamental and it was viewed as acceptable to emulate typical, as opposed to all, representative examples.

3.4 Simulations

Simulations would be run for the following options:

- RRP with different outstation configurations and varying channel noise.
- Contention with:

  Different outstation configurations

  Varying channel noise

  Different backoff strategies
- Simplified contention, audited against the full version to ensure validity.
- Very basic contention, to check model fundamentals.
- Full contention for a limited selection of permutations to validate emulation for system overhead parameters other than noise.

The above would then provide a useful frame of reference, against which the theoretical models could be calibrated and checked.

3.5 Theoretical Modeling

It is proposed that an attempt should be made to create theoretical models of the above protocols, to predict the performance of their similarly configured real-world equivalents. These models should be created for both the RRP and contention groups, including system parameters, such as noise, equipment rise times, progation delay, retries and backoff strategy.

3.6 Comparison of Theoretical and Simulation Results

The theoretical predictions and simulation results should then be compared for each protocol type. If necessary, the model could be adapted to compensate for any unaccounted parameters and subsequently, confirmed by renewed simulation results.

This process should ideally provide a parallel theoretical and practical approach to predict the performance of installations of the type under consideration.

3.7 Concepts and Summary

The basic concepts and summary of the proposed investigation, can be summarised as follows:

3.7.1 To create a software model, of commonly encountered hardware and contributing system parameters, as realistic and accurately, as possible.

3.7.2 To enable the utilisation of this model to simulate and consequently predict, the performance of protocol strategies relevant to the application, allowing for their variation to suit individual system applications.

3.7.4 To obtain a basic set of data against which further simulation and analytical results can be measured.

3.7.4 To further develop an analytical means by which the performance of various relevant strategies could be predicted, to an acceptable degree of confidence.

The formalised approach should allow for inclusion of all system parameters, including overhead and backoff strategy.

Chapter 4

Emulation of System Models and Model Verification

4.1 Basic Approach

4.1.1 Protocols

It is impractical to emulate all possible protocols and it was decided to concentrate on representative examples from the two main groups, relevant to this investigation, i.e.

(a) Centrally Scheduled (RRP) and

(b) Contention (CSMA)

Variations within the two types are, however, catered for.

4.1.2 Hardware

The typical hardware subsystem components encountered in this type of system and commonly used in commercially available products, would be generated in software, as realistically as possible.

This software model could then be used as a basic building block in the overall strategy emulation.

4.1.3 Simulation Vehicle

No suitable complete simulation tool could readily be found with which to emulate the processes as discussed and it became clear from the outset that realistic emulation would require generation of custom code. It would, however, be convenient if a set of basic simulation tools would be available to provide basic functions, such as:

(a) Integration

(b) Digital components

(c) Timing and display functions.

Fortunately, these facilities were available in the Pascal based, pseudo - real-time, Digusim simulation package, developed by the University of Stellenbosch Department of Electronic and Electrical Engineering.

The Digusim package is completely open, with accessible source code.

It was, therefore, relatively easy to integrate the custom code with the basic package, providing a very flexible and powerful simulation tool.

The individual system components and their associated modelling, are dealt with in subsequent paragraphs.

4.2 Hardware Emulation

4.2.1 Block diagram

A typical hardware block diagram for the kind of system under consideration, is shown in Fig 4.1. The configuration is by no means the only possible one, but is a representation of commonly available commercial/industrial hardware. The diagram is self explanatory, but the emulation of each subcomponent, will be discussed in detail.

4.2.2 Transmitter

(a) Modulation
Data encoding/decoding is based on standard FSK, with a 1200 baud transfer rate. The latter is very standard where RF equipment is based on commercial mobile radio gear, for economical reasons. The transmitter contains a master clock, operating at 1200 Hz. All other signals are derived from this clock. The entire overall time resolution is set at $10\mu s$, providing a reasonable accuracy taking the overall bittime of 0.833 ms into account. In accordance with available components, (eg. CML FX 469, viz. References, Addendum A), a logical 1 and 0 are generated by the 1200 Hz and 1800 Hz signals respectively, providing a continuous FSK signal.

The FSK signal is pre- and postceded by a ± 200 and 150 mS carrier signal respectively. This is to take into account typical transmitter/receiver rise times. Where more than one repeater is involved in real life systems, these times may even have to be increased.

The FSK signal, pre- and postambles, are sequentially timed by a timer, with the RMS channel noise and burst noise added, before transmission.

(b) Modulating sequence and message length.

The modulating binary sequence is generated by a random number generator, but ensuring that start and stop bits correspond to logical 1, as per normal. A parity bit is also generated, in accordance with the randomly generated bit sequence. This random sequence is generated using the internal Pascal random function. This sequence does not require a particular distribution, and any good random function will do.

Some of the widely used industrial protocols typically contain a 128 bit message header, plus approximately 2 bytes per I/O point. A small outstation, such as would be used to monitor a water reservoir, or small pumpstation, commonly provides a maximum of 16 I/O connections, rendering a maximum message length of 384 bits, but not less than the 128 bit header. Medium sized stations are often configured for 32 I/O points and larger stations for 64 I/O's, translating into 640 and 1152 bit message lengths respectively. Where variable message length strategies are emulated, the message length is randomized between the minimum and maximum values, co-incidentally with the random sequence generation.

A copy from the VDU display demonstrating the various modulating- and demodulated signals signals and sequences, is shown in Fig. 4.2.

A typical Tx/Rx sequence with the pre- and postambles and control signals is shown in Fig. 4.6.

(c) Noise generation

The spectral characteristic emanating from the first stage of a typical receiver, is, in practice, not flat i.e., not typical white noise. This noise is generated by a combination of several noise sources, i.e.:

- Transmitter noise
- Transmission path noise
- Receiver input stage noise

This resultant noise output was measured for a few very commonly used, typical commercial receivers and is reproduced in Fig. 4.3. It is clear that this characteristic exhibits a decided bias towards the higher frequencies, which was emulated in the model.

Noise is generated in low- mid- and highband components which are individually scaled and added to create the required model characteristic, as shown on Fig. 4.4.

The main white noise source, individual noise components and corresponding RMS values, are shown in Fig. 4.5. Channel noise is randomly allocated between the ranges of 19 and 60 dB SNR, upon initialisation of any master/outstation (or vice versa) comms sequence. The motivation for selecting this particular lower limit, is presented in a later paragraph.

Data links are generally not designed or implemented to possess marginal SNR's, which would consequently result in higher than desired bit error rates and comms retries. More often than not the latter is caused by transient, high level, burst noise phenomena from sources of external electromagnetic pollution. Typical examples are rogue, or poorly installed RF equipment, products of intermod interference, or high energy switching transients. Such burst noise is generated in the model by transmitting a 1mS sequence of noise with characteristic as per Fig. 4.4, but at a low SNR of app. 0 dB. This time period will ensure disturbance of 2 message bits, forcing a comms error and retry. The burst noise occurrence is random, but in accordance with a pre-selected mean percentage of the overall number of signal transmissions.

The randomly assigned channel noise as well as the effect of random burst noise, is evident from the simulation runs depicted in Fig. 4.18 and Fig. 4.22.

4.2.3 Receiver

(a) General

The block diagram for the receiver is included in Fig. 4.1. The receiver configuration is based on popular components commonly used in the design of telemetry hardware, in order to present a realistic a model as possible. The various receiver sub-components will be discussed in the following paragraphs.

(b) Input filter

In keeping with all receivers for this type of application, a bandpass input filter is required to minimise noise. The low-end and high-end cut-off frequencies were set at 600 Hz and 2,7 kHz respectively, in order to match the pass characteristic of typical available commercial equipment and to ensure a realistic bit error vs. SNR rate.

The filter circuit is modelled in accordance with the block diagrams of Fig. 4.7. The transfer function of Fig. 4.7a can be written as:

$$G_1(s) = \frac{s^2}{s^2 + 2\xi\omega s + \omega^2} \tag{4.1}$$

and the transfer function of Fig 4.7b are:

$$G_2(s) = \frac{\omega^2}{s^2 + 2\xi\omega s + \omega^2} \tag{4.2}$$

The theoretical frequency response of (4.2) is plotted in Fig 4.8 and the actual measured response is given in Fig. 4.9. Typical filter input/output signals obtained from simulations, are given in Fig. 4.10.

(c) Bit-error rate and filter response

The required filter response does not only have to comply with the characteristics of actual hardware, but must also ensure that the resultant received bit error rate (BER) is in keeping with what can be expected from standard demodulating circuitry, for a given range of SNR's. The BER's used as a norm, was obtained from data supplied by from Consumer Micro Circuits. The device in question, is the CML-FX469, which has been used as a building block by a number of telemetry OEM's. It is also not unique, but typical of the type of device commonly utilised. Full product data is included under the references, but for convenience, the device's SNR/BER characteristic is reproduced in Fig. 4.11.

During extensive simulations, the actual BER was measured for a range of SNR's, while iteratively adjusting the relevant filter- and other demodulator parameters. It was found that a BER/SNR characteristic approaching the actual response to a reasonable degree, could be found by implementing the following:

(i) Eliminating the initial high-pass filter section, carried very little penalty. This is not so surprising if the noise characteristic of Fig. 4.3 is taken into account. The bias is towards high frequency noise components, relatively unaffected by the HP filter . Eliminating the HP filter has the added bonus of reducing the already high processor load, which is welcome, provided accuracy is not compromised.

(ii) The cut-off corner frequency of the low-pass section was set at 2,7 kHZ with $\xi = 0.6$. This cut-off point is somewhat higher than normally found in FM receivers operating in the telemetry band (440 - 450

MHz), but reducing the cut-off point resulted in an over optimistic BER. The measured BER/Bandwidth characteristic, is given in Fig. 4.13.

The actual measured BER/SNR characteristic, is given in Fig 4.12. It will be seen that the BER increases markedly with a decrease in SNR from 14 dB and exibits a steeper characteristic than the actual device BER. This is primarily due to the characteristics of the Schmitt trigger following the input filter and is difficult to eliminate without fairly extensive signal processing. Whether such effort would be worthwhile, is doubtful. It has already been stated that by far the most interference is caused by either faulty equipment, or burst noise disturbances.

No responsible system designer will knowingly accept a channel SNR below 18 - 20 dB for telemetry applications and this figure was set as the lower limit when randomly allocating individual channel SNR's, in keeping with normal practice.

(iii) Some of the other demodulator parameters were also fine tuned to obtain the correct SNR. This is dealt with somewhat later.

(d) Demodulator

The rest of the demodulation process is relatively straight forward. The filtered signal is first passed through a saturating Schmitt type switch, to obtain a binary type signal. This signal is used to trigger a monostable and also serves as input to a normal D-type flip-flop circuit. The monostable pulse is utilised as clock input to the flip-flop. The flip-flop output is a copy of the original transmitter encoding signal and can be decoded into the original binary data string using the system master clock, together with a collection of timers and control flags.

The BER can clearly also be influenced by the switching characteristic of the Schmitt circuit and the pulse length of the monostable. The latter, naturally, has to be somewhere in between the half-cycle periods of the 1200 and 1800 Hz FSK frequencies. It was finally chosen to be approximately 5% longer than the shorter half-period.

The hysteresis and switching point of the Schmitt, required extensive tuning to establish the correct BER. The switching point and hysteresis were finally selected as approximately 15% and 19% of maximum, respectively. The measured BER vs Hysteresis characteristic of the Schmitt, is given in Fig. 4.14. The rather pronounced knee, resulting in the properties as seen from Fig. 4.12, is also evident in this case.

(e) Error detection

A straightforward parity check was implemented on the received data string, to partially check Rx data integrity.

In actual hardware systems, this basic check is not sufficient and is normally supplemented by CRC and related checks. The parity check was basically implemented to prove it's viability as part of the simulation. After proving the routine, it was eliminated to reduce CPU overhead and replaced by straight Tx buffer / Rx buffer, image comparison.

During such a simulation, one has the advantage of prior knowledge regarding received data content. This comparison check was used to set/reset error flags in order to force retransmits, if necessary.

The complete receiver emulation functions very satisfactory and in accordance with actual systems implemented in hardware.

4.3 Protocol Emulation

4.3.1 Centrally Scheduled (RRP)

A centrally scheduled polling scheme could be implemented in a number of different ways as previously discussed, but any possible merit of a particular variation would be dependent upon the characteristics of the relevant application. There is no all-round best solution and very frequently there is nothing to be gained over a straightforward cyclical poll. It was therefore, decided to emulate this basic format. Any variation is easily implemented anyway, once the core model has been generated.

The RRP poll is simple and generally easy to implement. This plus it's inherent deterministic nature, accounts for the growing popularity of standards such as IEC 870-5-101, which are based on the RRP principle.

A block schematic diagram of a typical RRP scheme is shown in Fig. 4.15. The RRP implementation under discussion, was done according to the strategy depicted in Fig. 4.16. The process operates as follows:

(a) Assume N to be the maximum number of outstations. Outstations are repetitively polled sequentially from $1 - N$. The poll request length is 128 bits, in keeping with a number of real life implementations.

(b) The data file size from each station is randomly chosen between a minimum and maximum value prior to each poll response. The motivation for selecting the particular limits, have been provided earlier.

(c) A data Rx OK check timer is set at the master, coinciding with the time of poll. If the timer times out before receiving sensible data, the station is re-polled. The timer window is set to be slightly longer than the maximum expected message length. The maximum number of poll retries can be preset.

(d) The master-outstation data link burst noise occurrence is randomly varied around a chosen mean, at the time of poll. The channel RMS noise level is also varied, as previously discussed.

(e) System statistics, such as time of station poll, time of successful station data transmission and number of data bits transmitted, are logged to disk for later analysis.

(f) System parameters, such as no. of outstations, maximum poll retry value, minimum/maximum/fixed outstation data bits, average link burst noise content, timeout values and number of simulation cycles, are selectable for each simulation run.

(g) The functioning of the strategy model with and without burst noise disturbance, is shown in Fig. 4.17 and Fig. 4.18, respectively. The simulation was set up for no. of outstations $N = 10$, burst noise $V_{nb} = 10\%$ and one cycle only.

4.3.2 CSMA or Contention Protocol

The CSMA model was implemented in accordance with typical industry examples of the scheme and is schematically shown in Fig. 4.19. General operation follows the process according to Fig. 4.20, and can be summarised as follows:

(a) A global, average outstation event occurrence is set, together with the number of outstations, N.

(b) In accordance with this preset average rate, events are randomly generated between outstations. Event generation follows a Poisson distribution. Some care was taken to ensure that the generation is indeed Poisson distributed. The Pascal compiler's own random number generator was checked and found to be inadequate for this purpose. A published routine known and tested for compliance, was utilised instead.

(c) Upon having had an event generated, resulting in data being contained in the transmission buffer, the particular outstation senses the communication channel. Should the channel be free, data is transmitted to the master and an ACK check timer set.

The number of data bits are randomly varied between minimum/maximum values upon each event generation, as for the RRP case.

(d) The channel burst noise %, V_{nb}, is randomly allocated as before, spanning a preset average. RMS channel noise is also treated identically to the RRP case.

(e) Should the channel be occupied, a backoff timer is started. The backoff time is again Poisson distributed over a preset mean. Upon expiry of the backoff timer, the station tries again.

(f) If data was transmitted, but a valid ACK is not transmitted from the master within the maximum allowable time, the above process is repeated, up to a preset maximum number of retries.

(g) The same procedure as set out for any outstation, equally applies to the master station, except that an ACK is only sent out once, in response to receipt of valid outstation data. ACK message length is fixed and presetable, but normally chosen to be 128 bits, in keeping with common industry practice.

(h) Note that upon an outstation detecting a free channel, data is sent straight away, as opposed to some, but uncommon strategies, where a poll request is first sent. (See the description of the Prodesign protocol in Chapter 2.)

(i) As previously mentioned for the RRP protocol, all system and simulation parameters are prior selectable.

(j) Other refinements, such as system overhead, were also subsequently added to the emulation, to further enhance the authenticity of the model. This is discussed in a subsequent Chapter.

(k) The functioning of the protocol is shown in Fig. 4.21 and Fig. 4.22, again with and without burst noise influence, respectively. The emulation was set up for $N = 10$ and $V_{nb} = 10\%$. Mean event occurrence was set at 15 mS. The various data transmissions and handshake signals, are also shown on Fig.'s 4.21 & 4.22.

(l) Simulation statistics, such as event generation time, data transmitted OK time, data message length and overall event queue length, are logged to disk for record purposes and later analysis.

4.4 Summary

The initial purpose was to create a simulation vehicle with characteristics approximating implementations in hardware, as close as reasonably possible. This facility would then serve as a further tool for determining and predicting the performance of intended systems. Although the emulation was based on general specifications of widely used hardware and software, it is totally accessible and adaptable for individual parameter variations and specific adaptations, as may be required.

Although not absolutely 100% identical in performance to actual systems hardware, it is felt that the characteristics exhibited by the resultant model is still acceptably close enough in order to be very useful. The most significant area of deviation, is in the BER/SNR characteristic. With enough effort, it will be possible to eliminate this difference, but with little or no practical gain. In the area where the emulated result is more optimistic than the actual, the expected BER is extremely low anyway. The end result should not be influenced. Where the emulation is more pessimistic, this falls into the region normally avoided by design and where burst noise plays a bigger part. The end result should again not be influenced.

In keeping with many other simulation tools, it is intended for fairly general use and it's characteristics must be borne in mind, where the system to be emulated is very specific. In a case like that, the model offers the convenience of being readily adaptable.

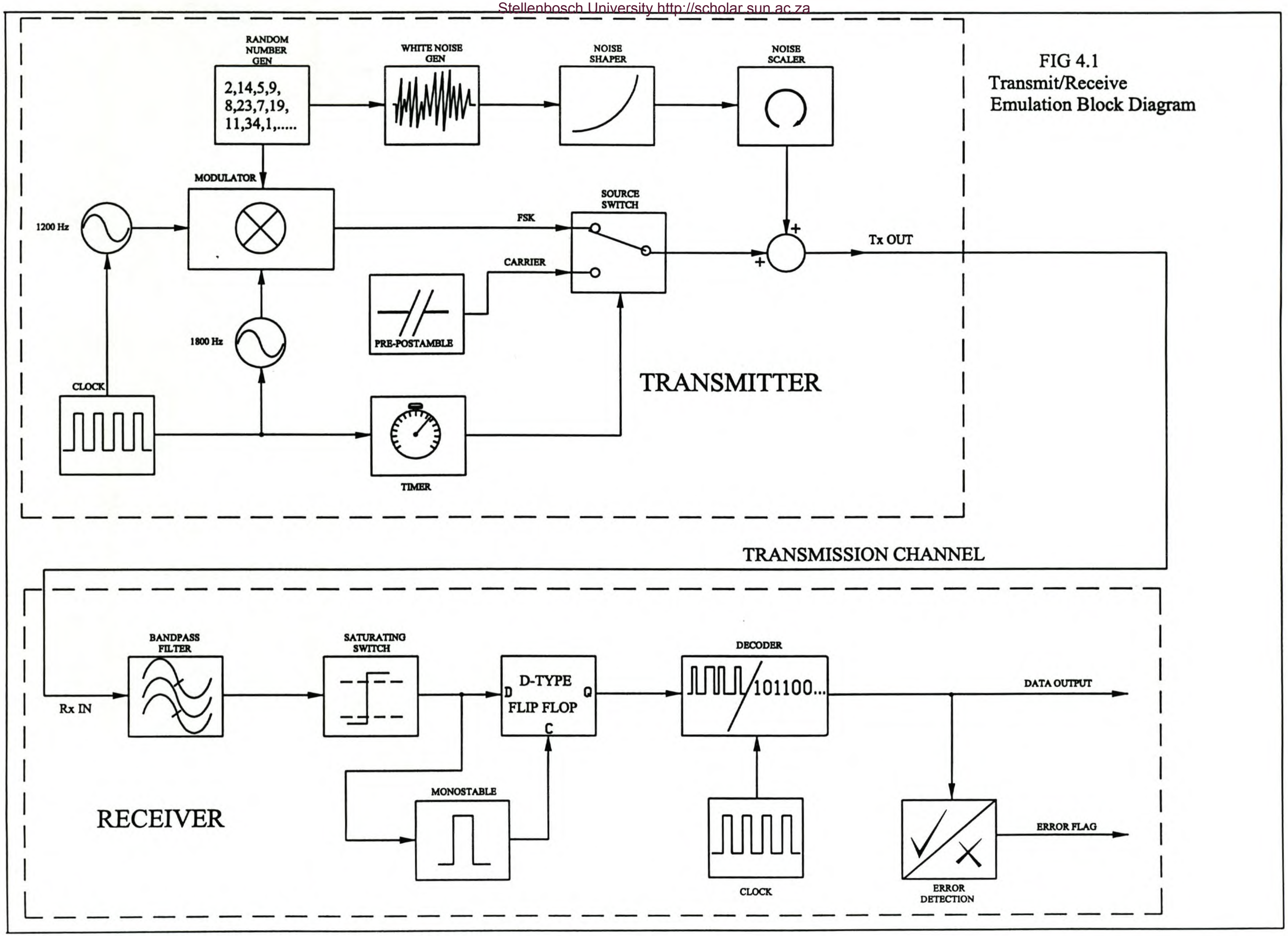

FIG 4.1
Transmit/Receive
Emulation Block Diagram

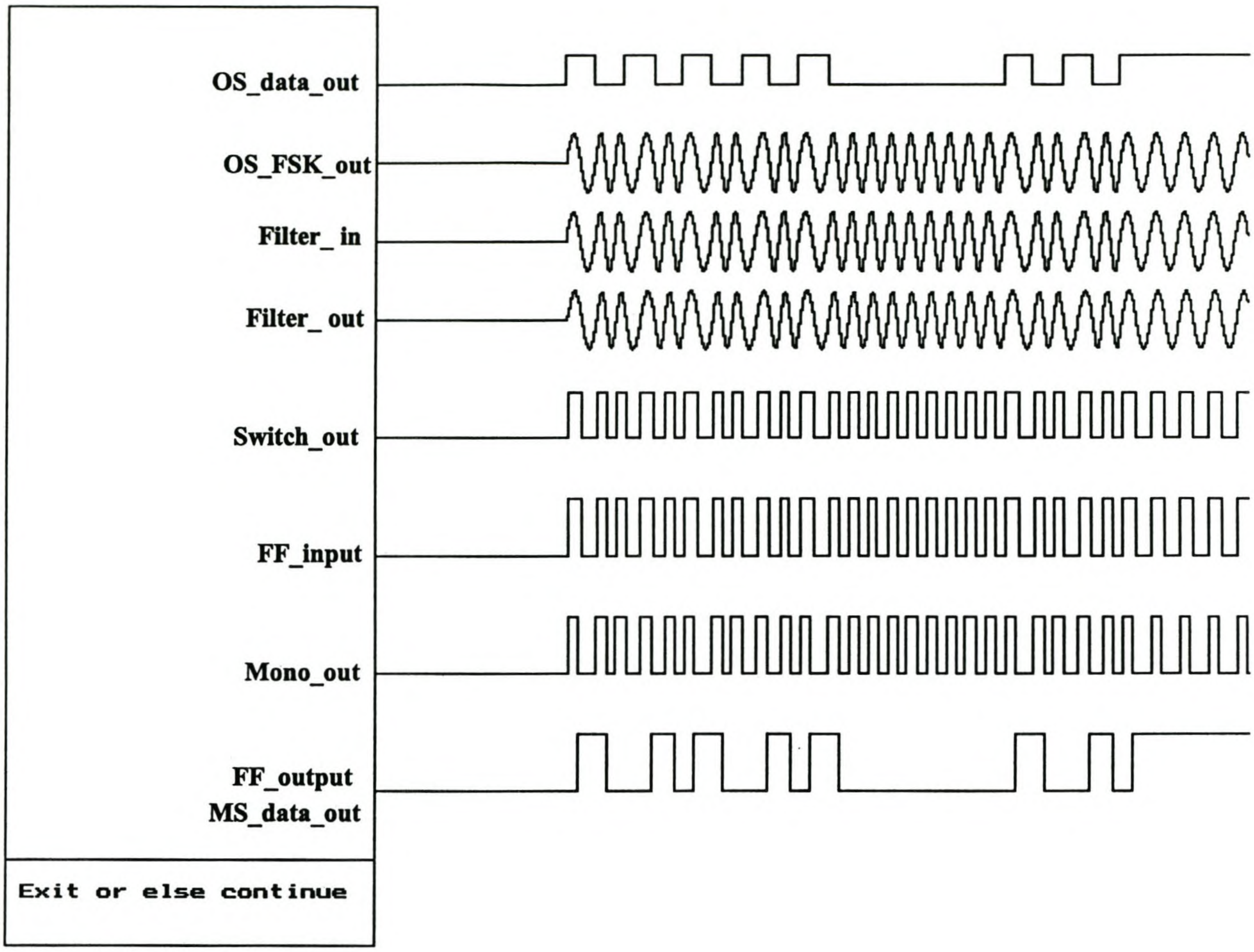

Fig. 4.2
Modulating / Demodulating Signals & Sequences

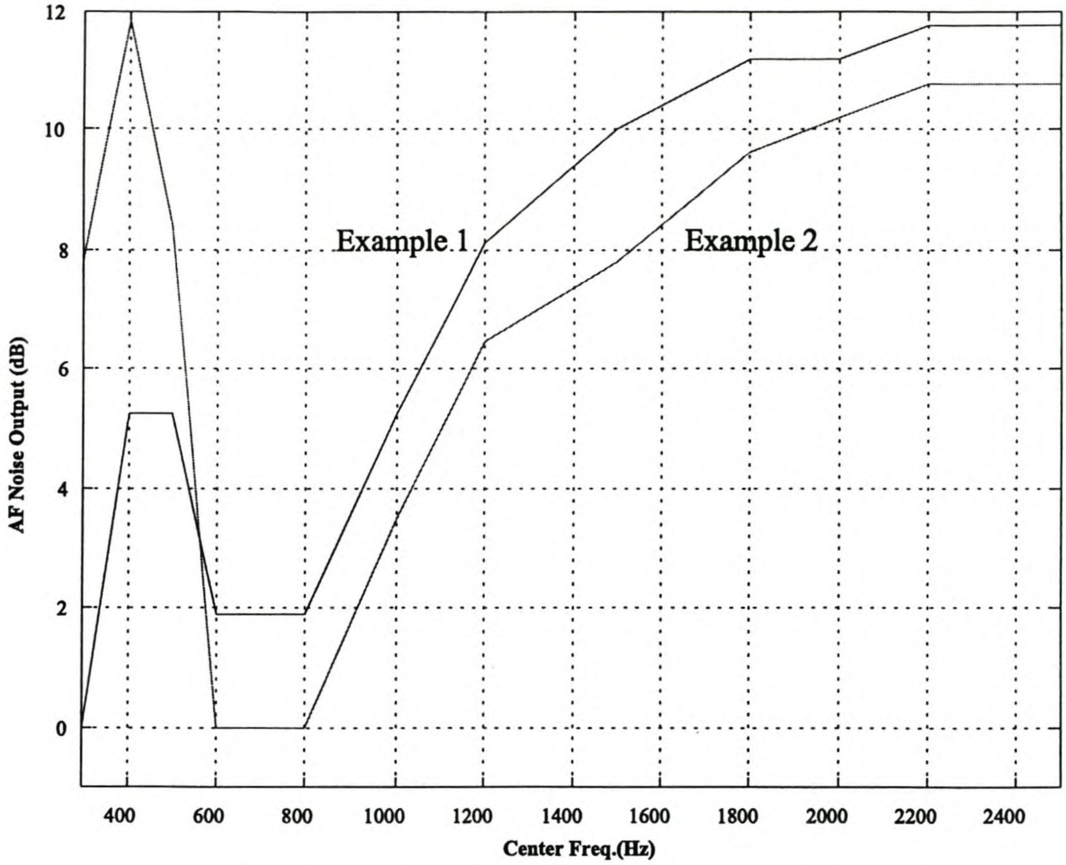

Fig. 4.3 - Actual Receiver AF Noise Response for Constant 20% Bandwidth of Center Freq.

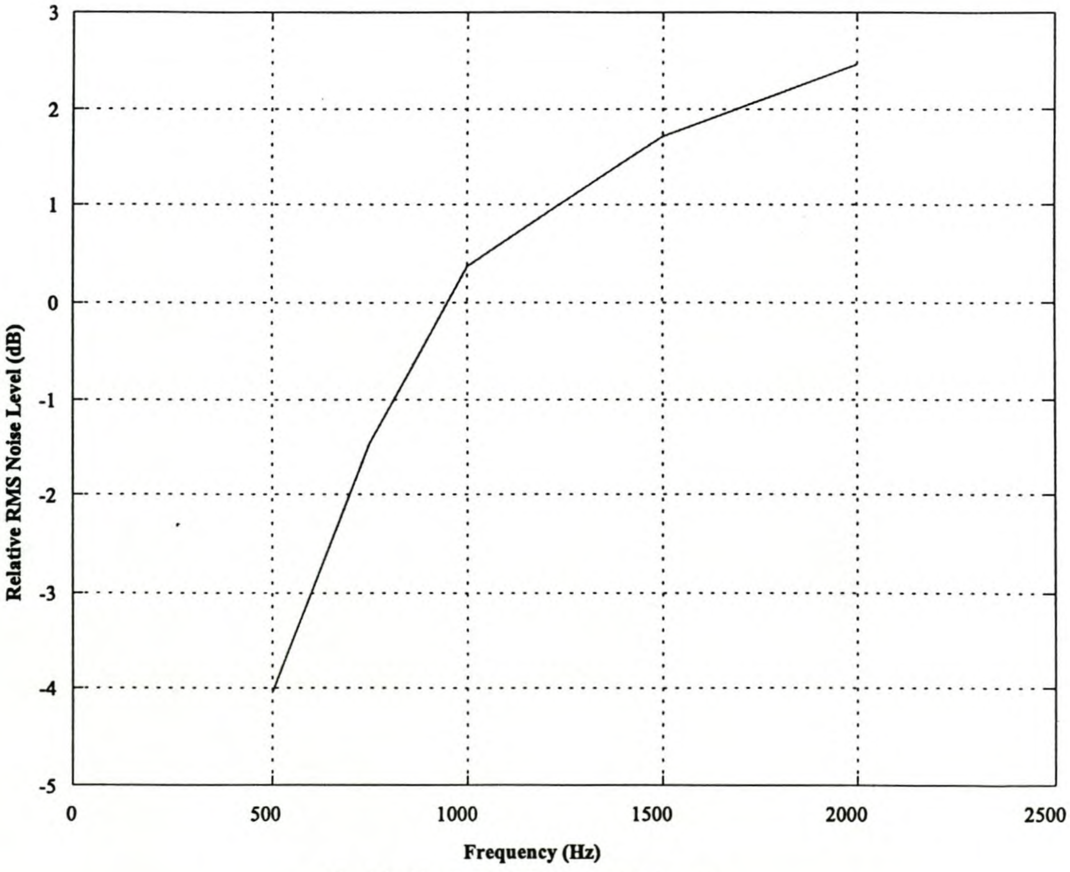

Fig. 4.4 - Simulated Noise Spectral Response

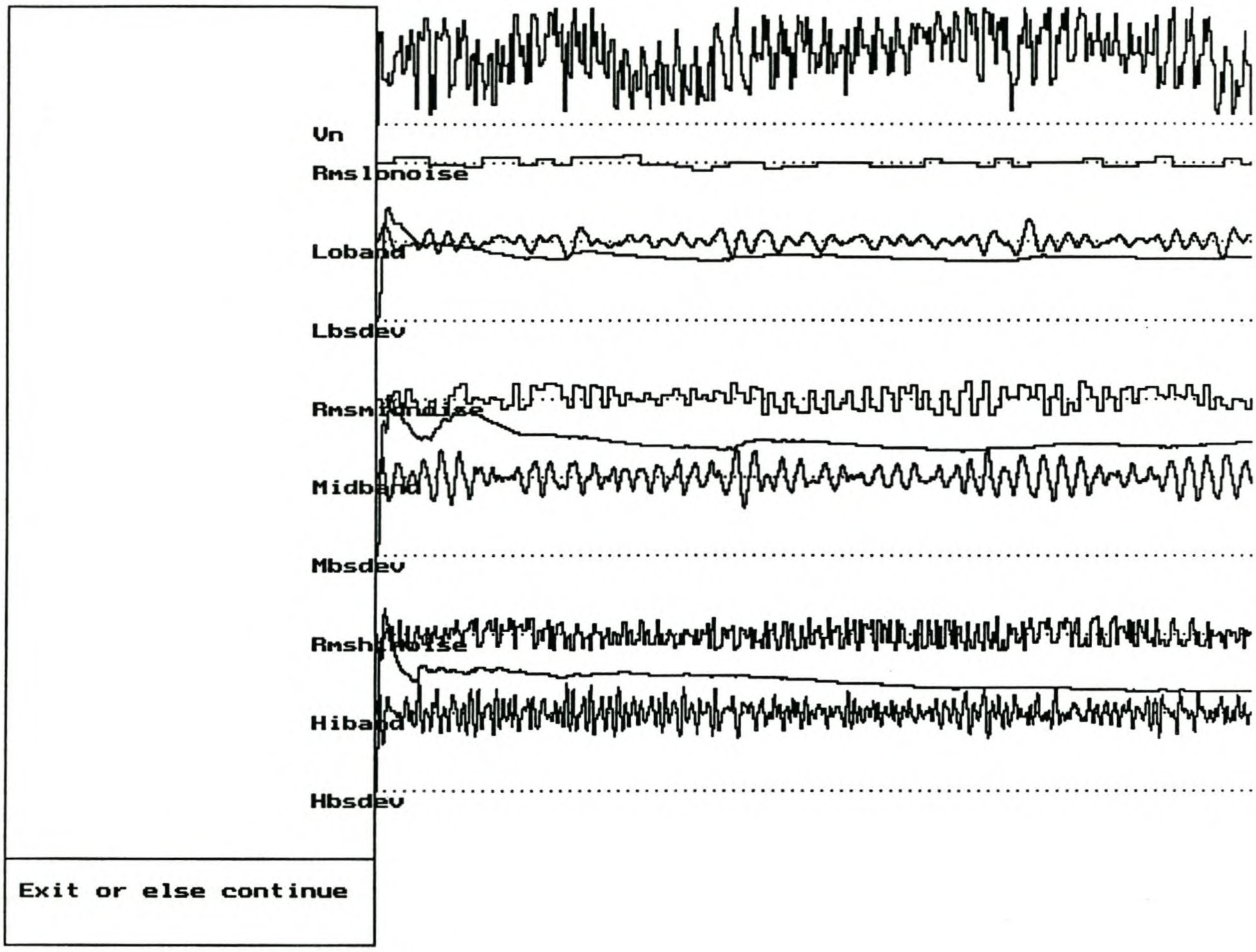

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Fig. 4.5

Random noise signal and relative spectral components with standard deviations

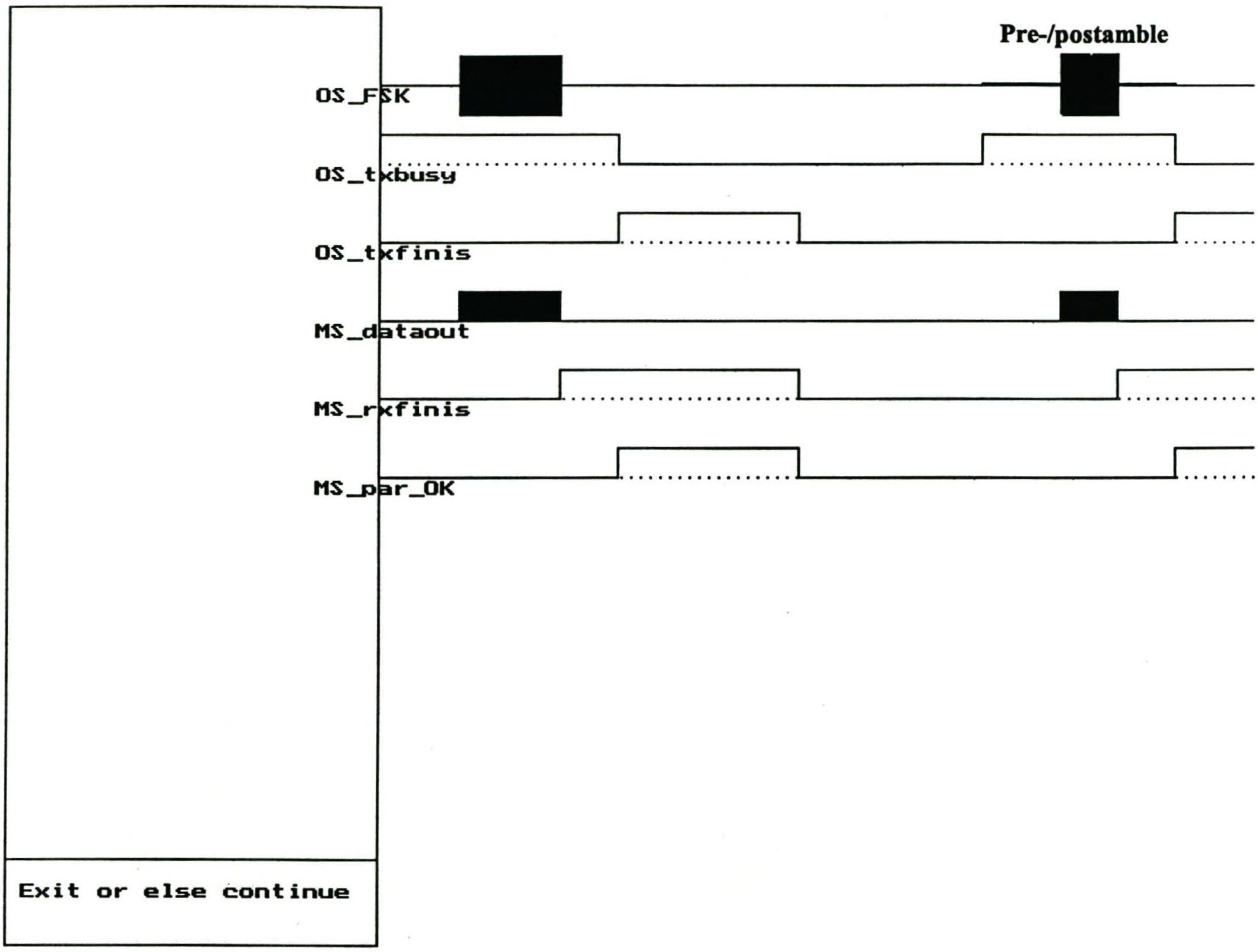

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Fig. 4.6

Tx/Rx Sequences with Pre-/Postambles & Control Signals

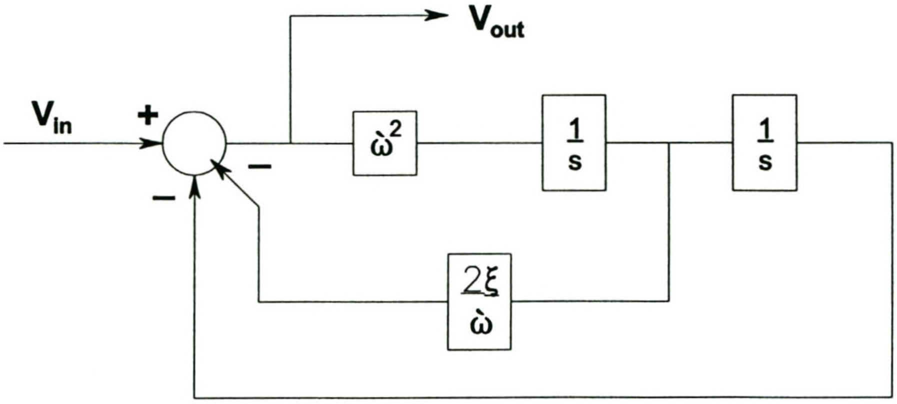


Fig. 4.7a
High-pass filter block diagram

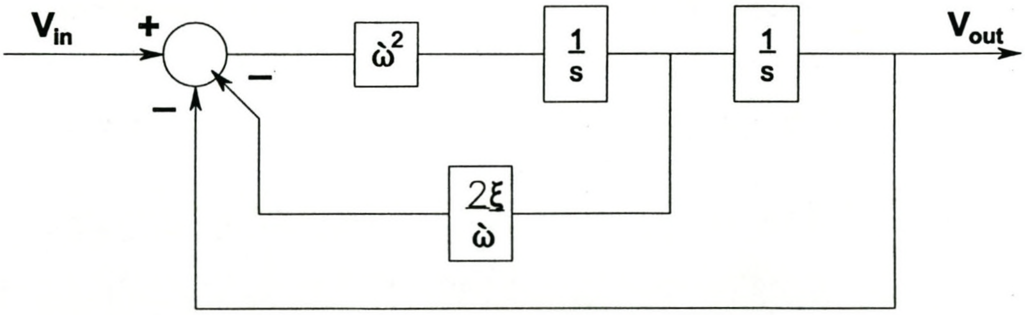
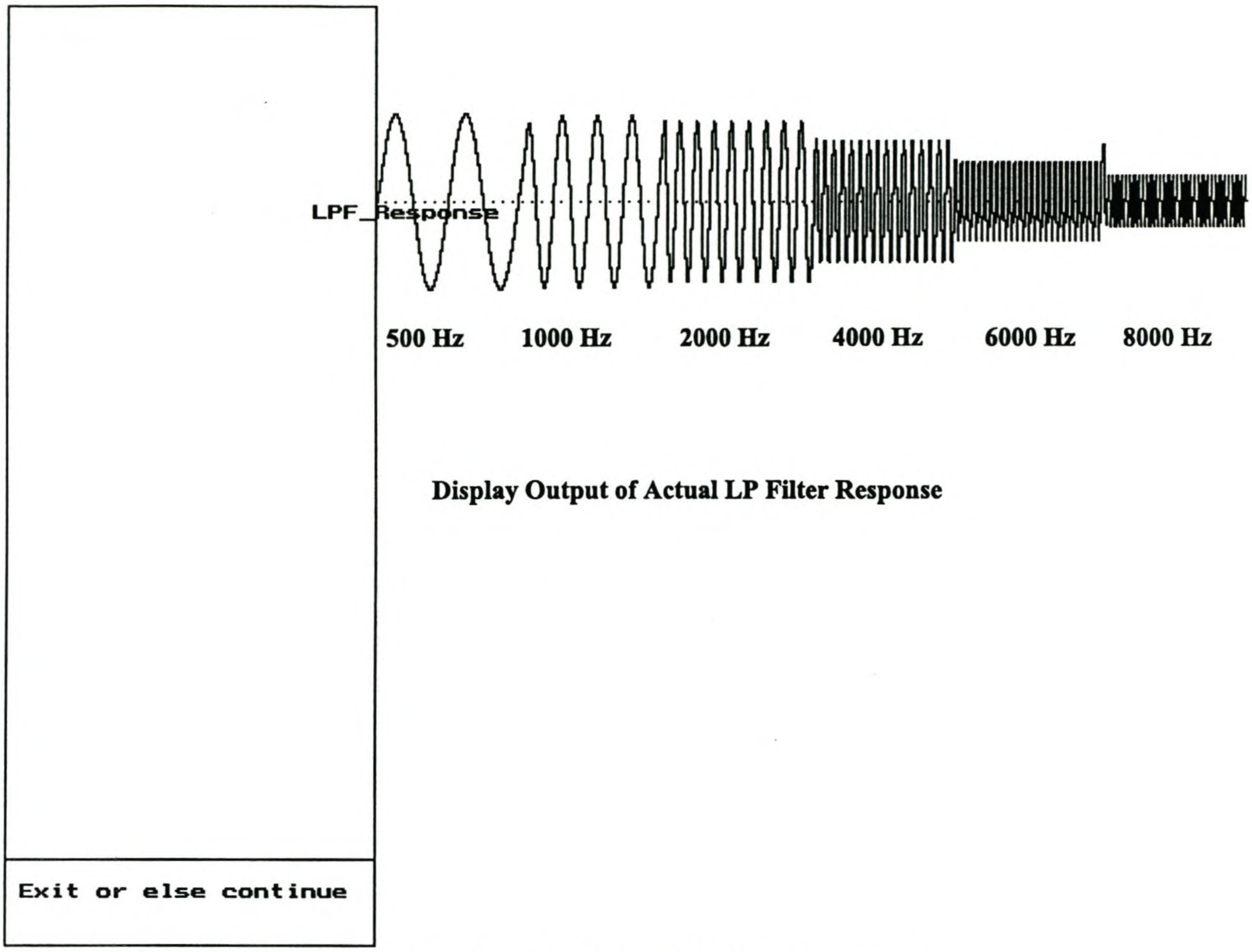
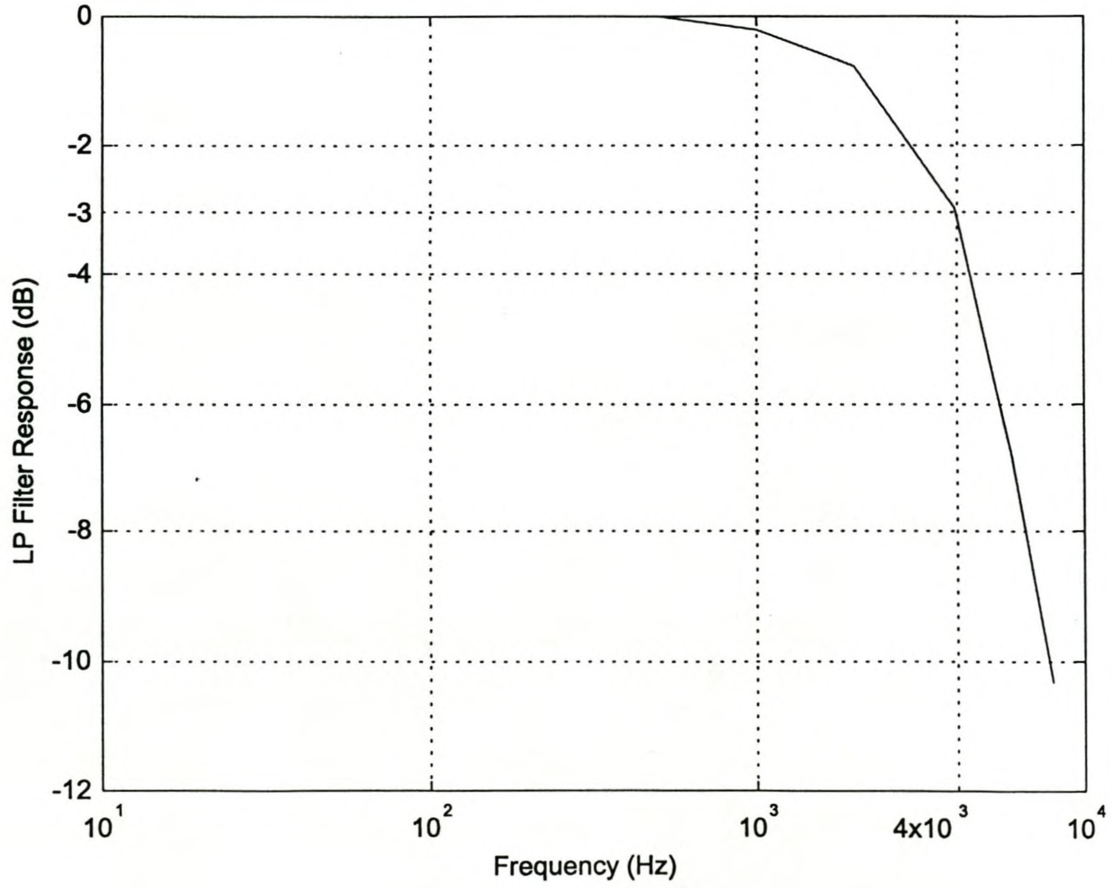


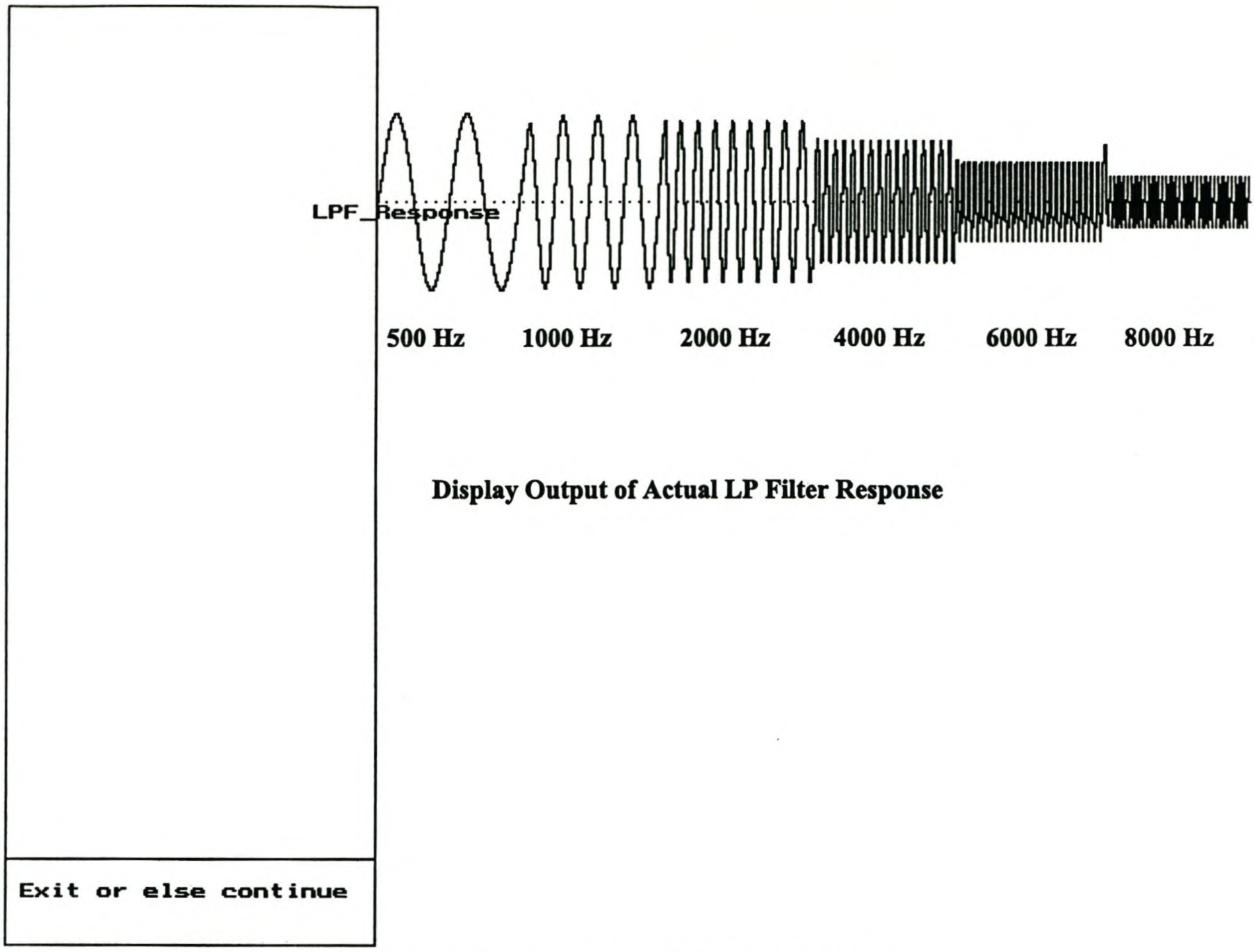
Fig. 4.7b
Low-pass filter block diagram



Display Output of Actual LP Filter Response

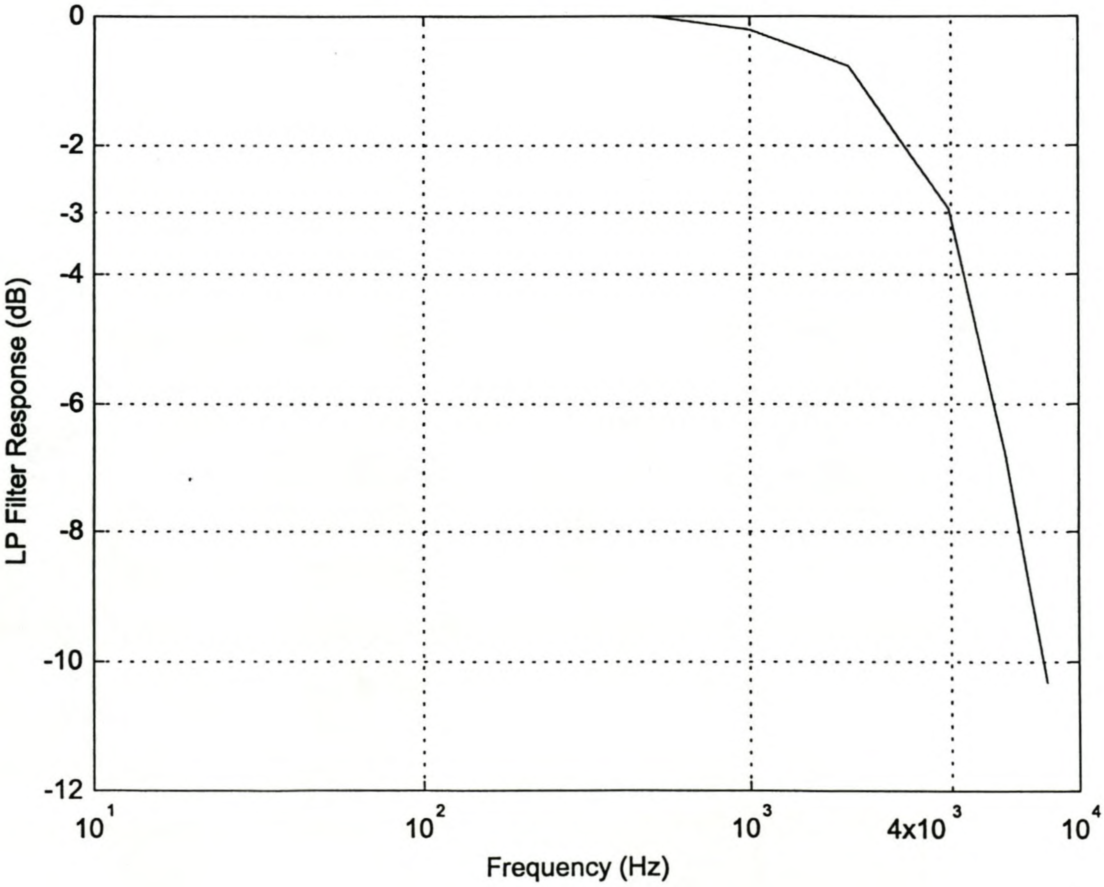
Fig. 4.8 - Plot of Actual LP Filter Response

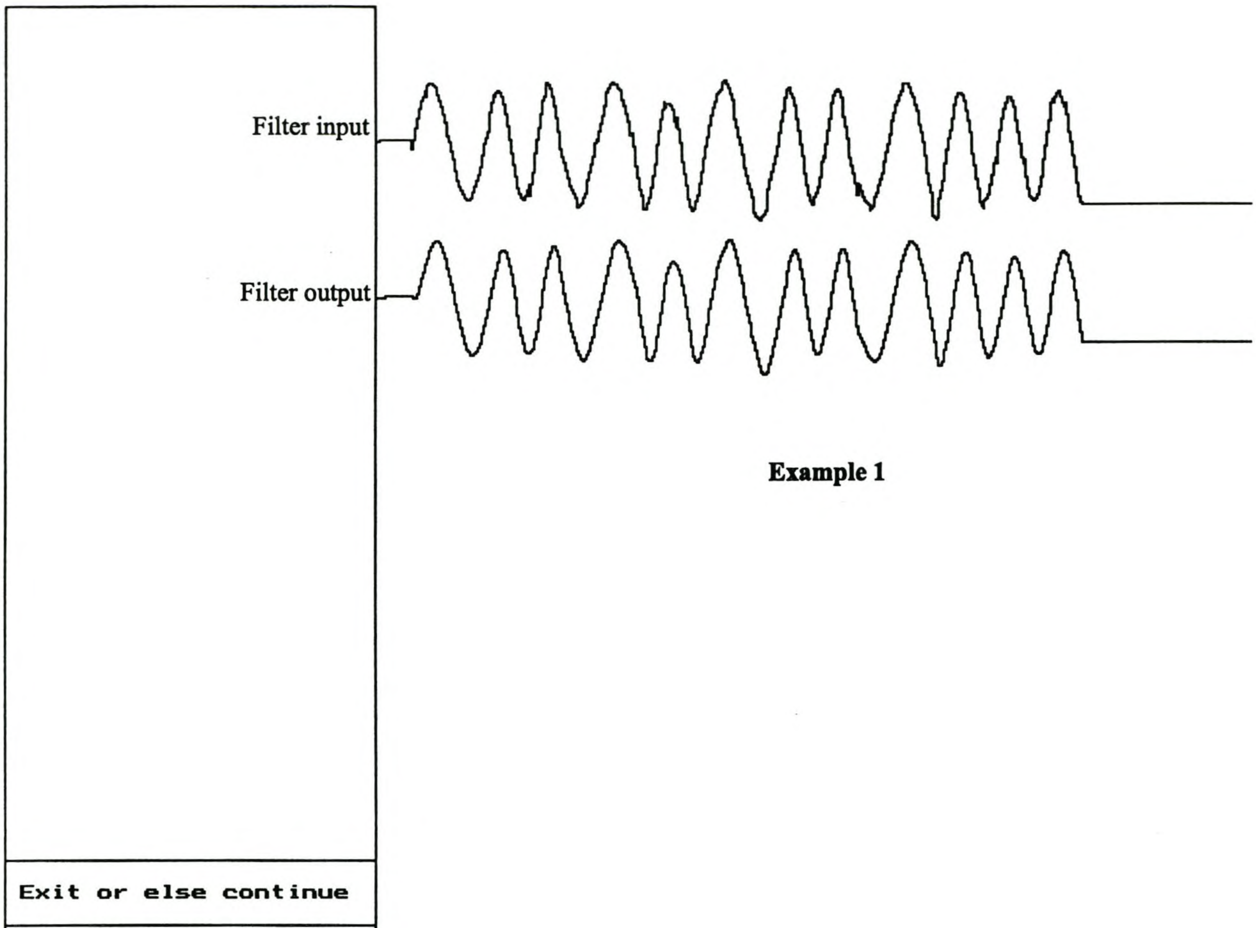




Display Output of Actual LP Filter Response

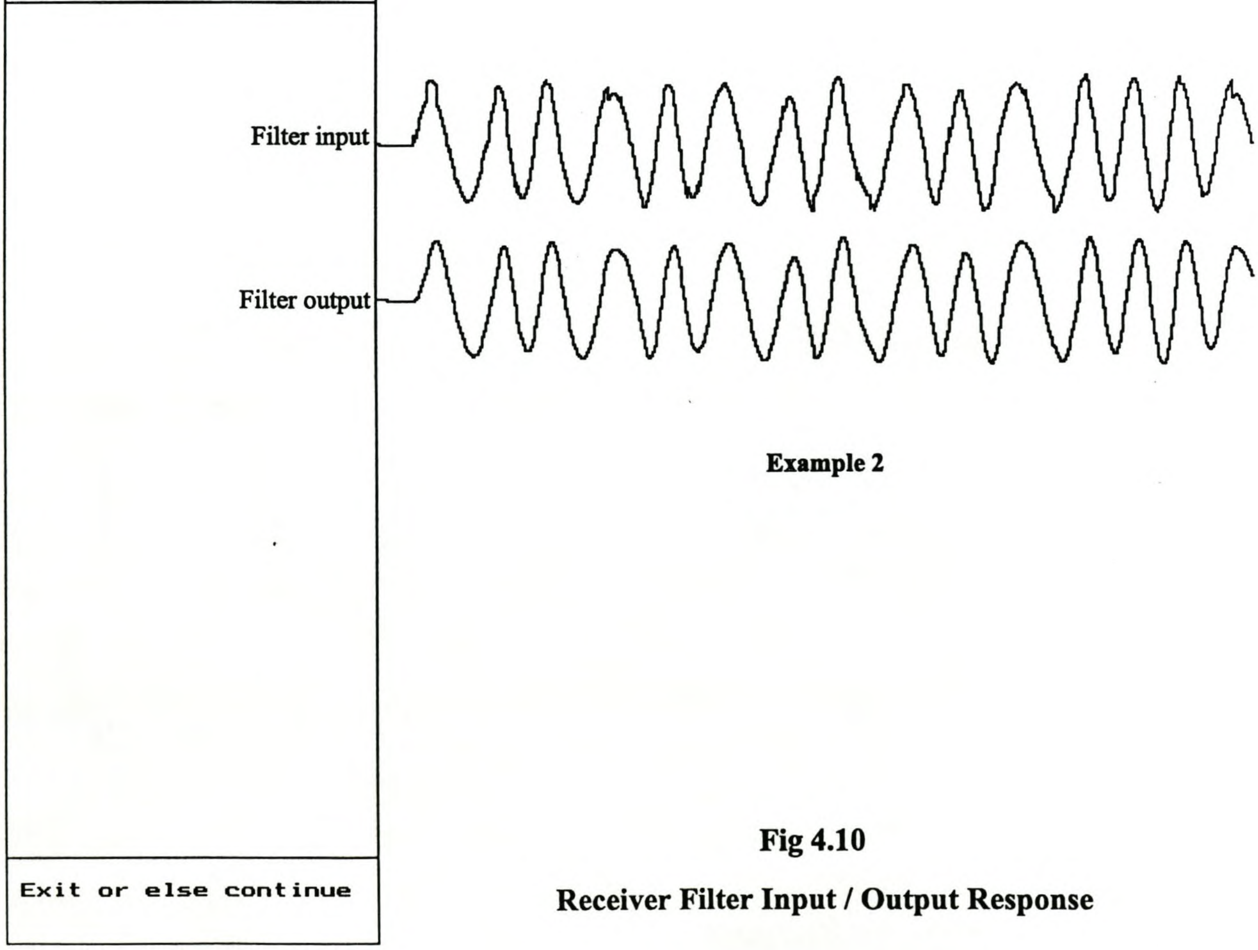
Fig. 4.9 - Plot of Actual LP Filter Response





Exit or else continue

Example 1



Exit or else continue

Example 2

Fig 4.10

Receiver Filter Input / Output Response

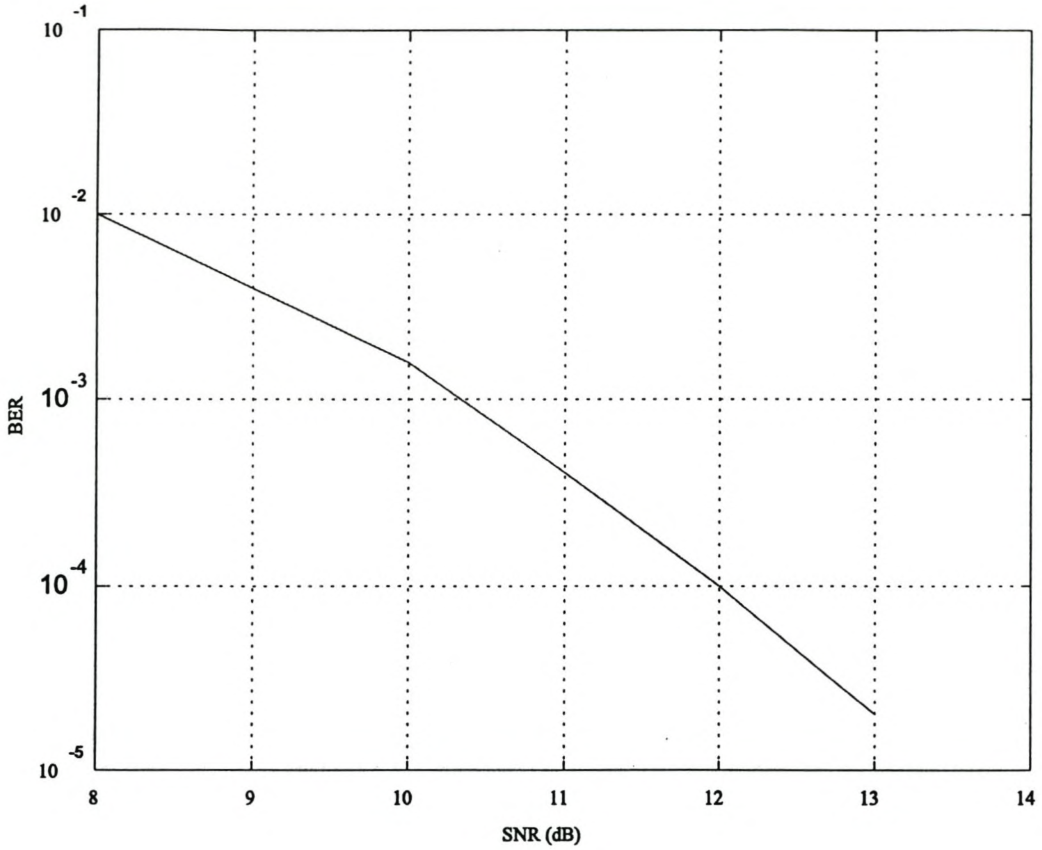


Fig. 4.11 : BER vs SNR of typical hardware

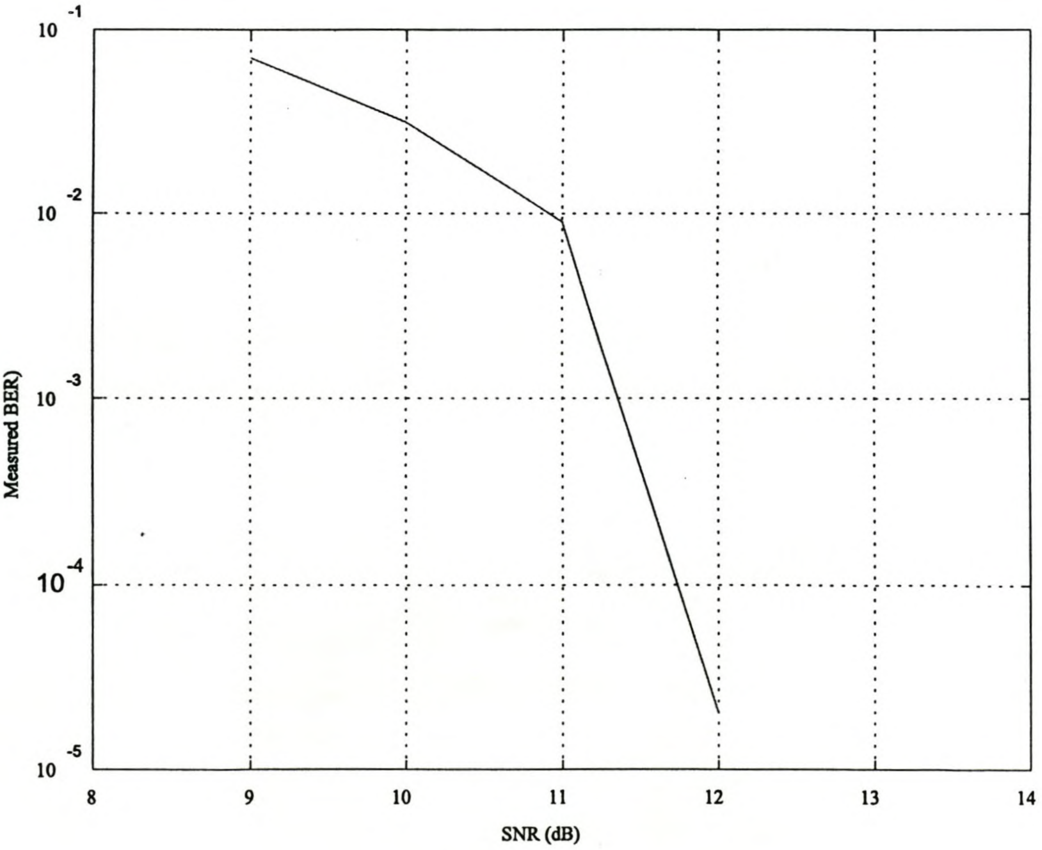


Fig. 4.12 : Measured BER vs SNR of Model

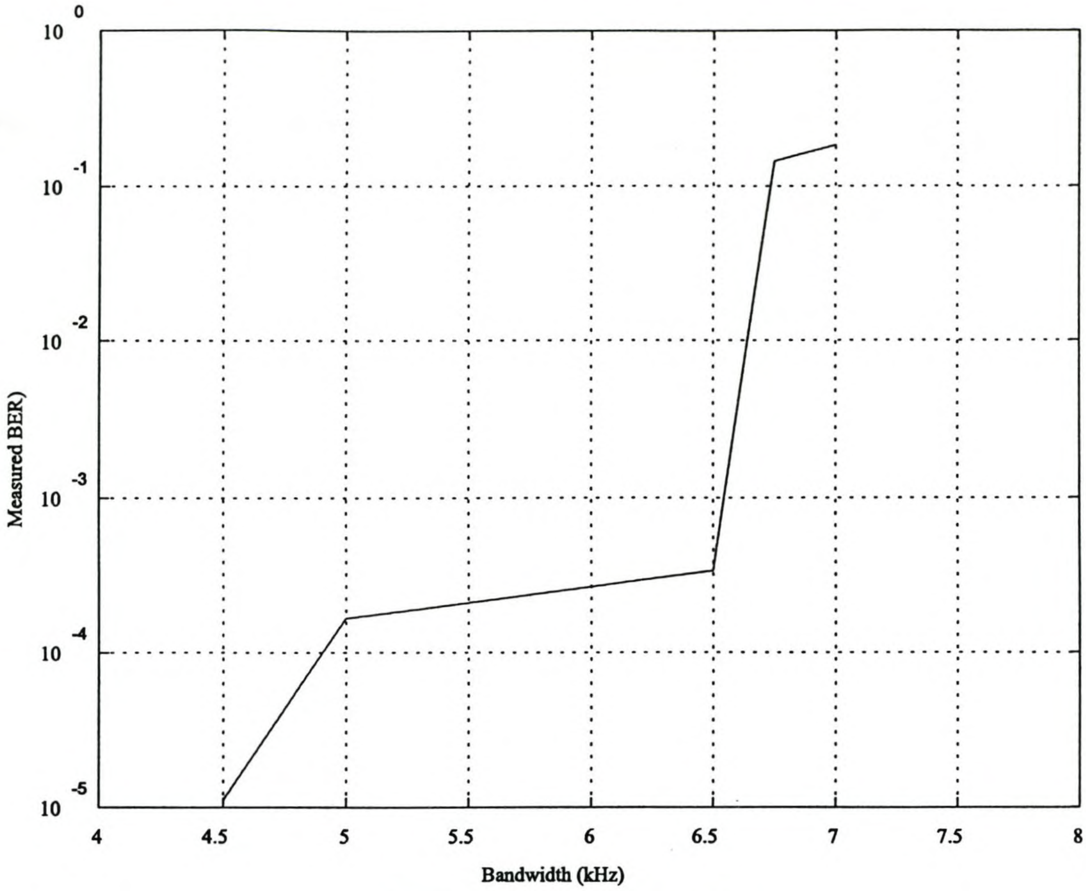
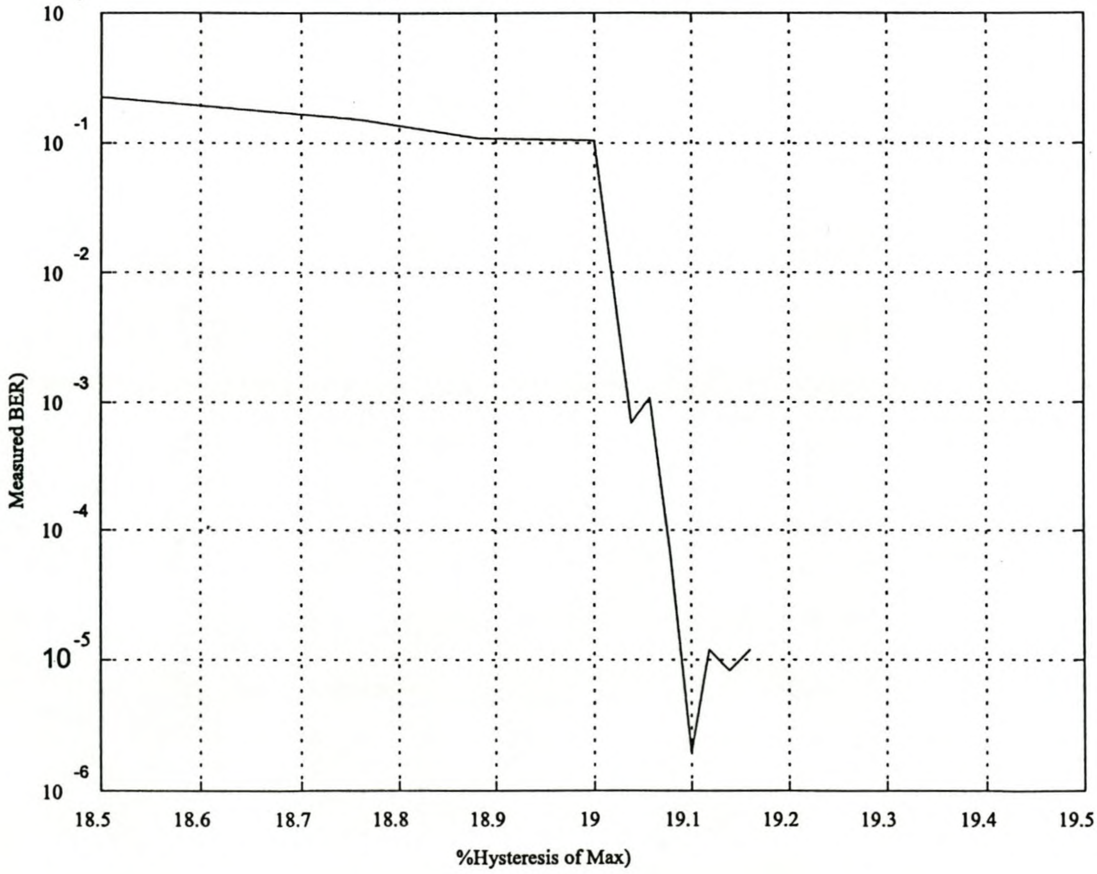


Fig. 4.13 : BER vs Input Filter Bandwidth

Fig. 4.14 : BER vs Switching Hysteresis



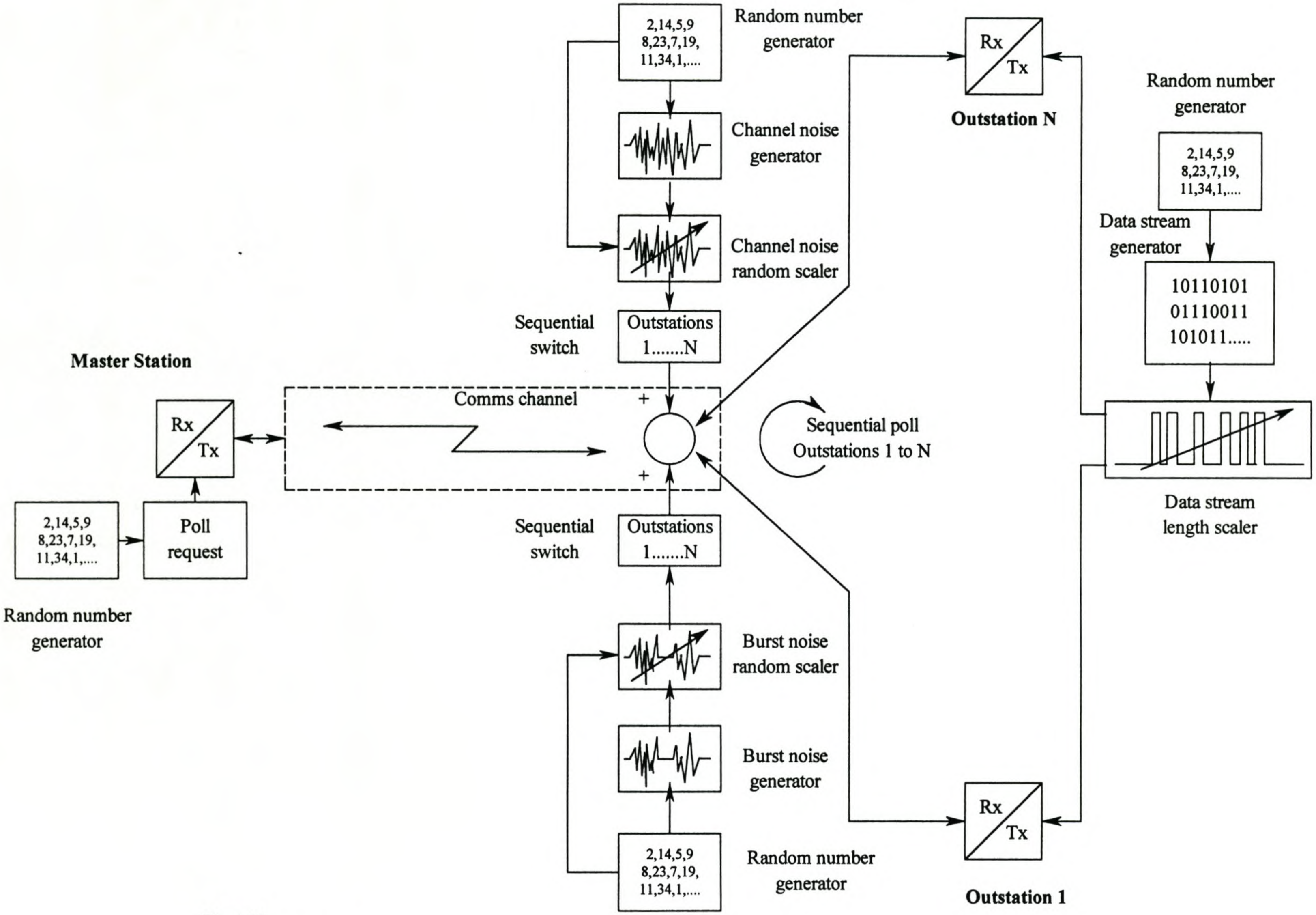


Fig 4.15
Round - Robin Poll Block Schematic Diagram

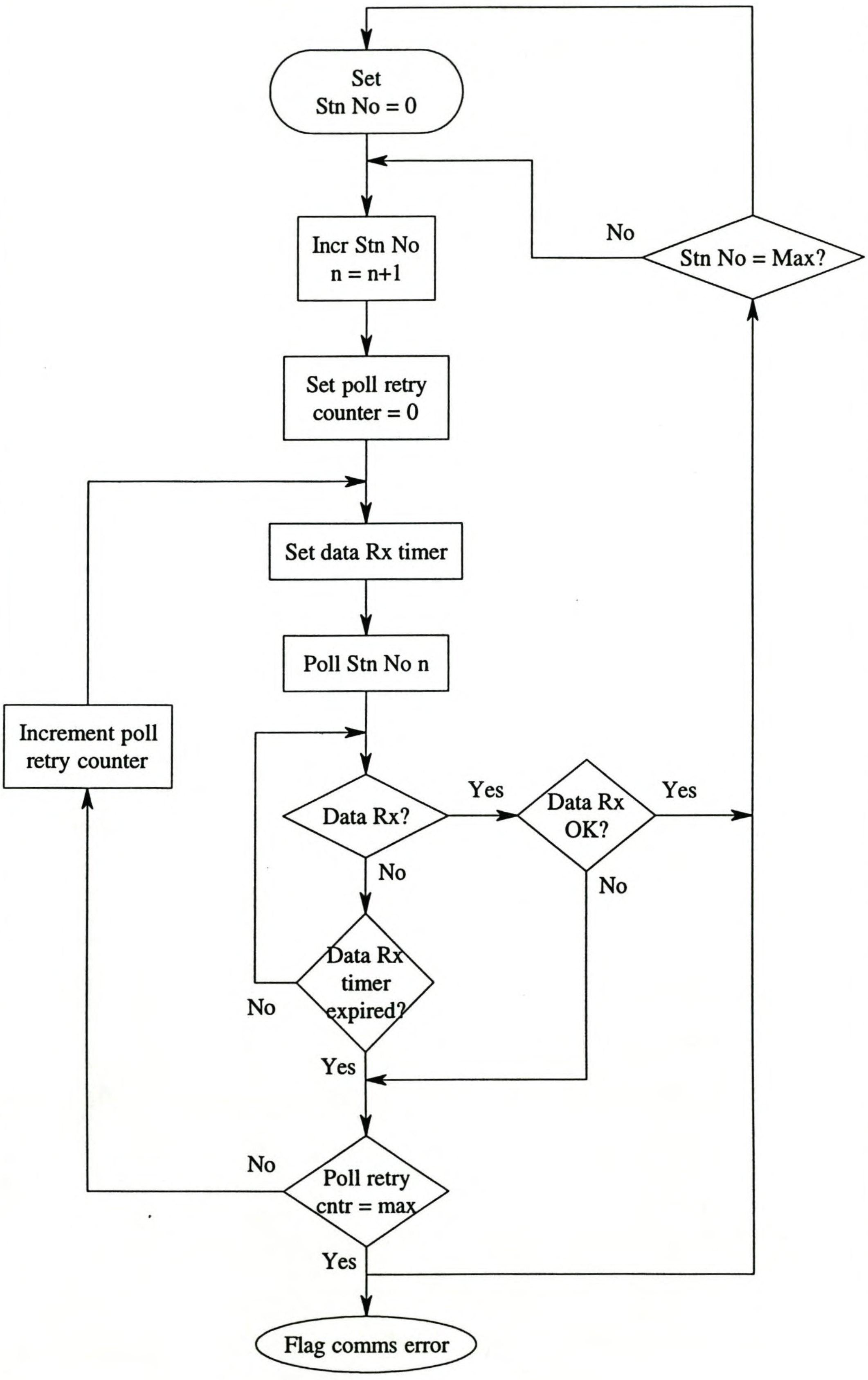
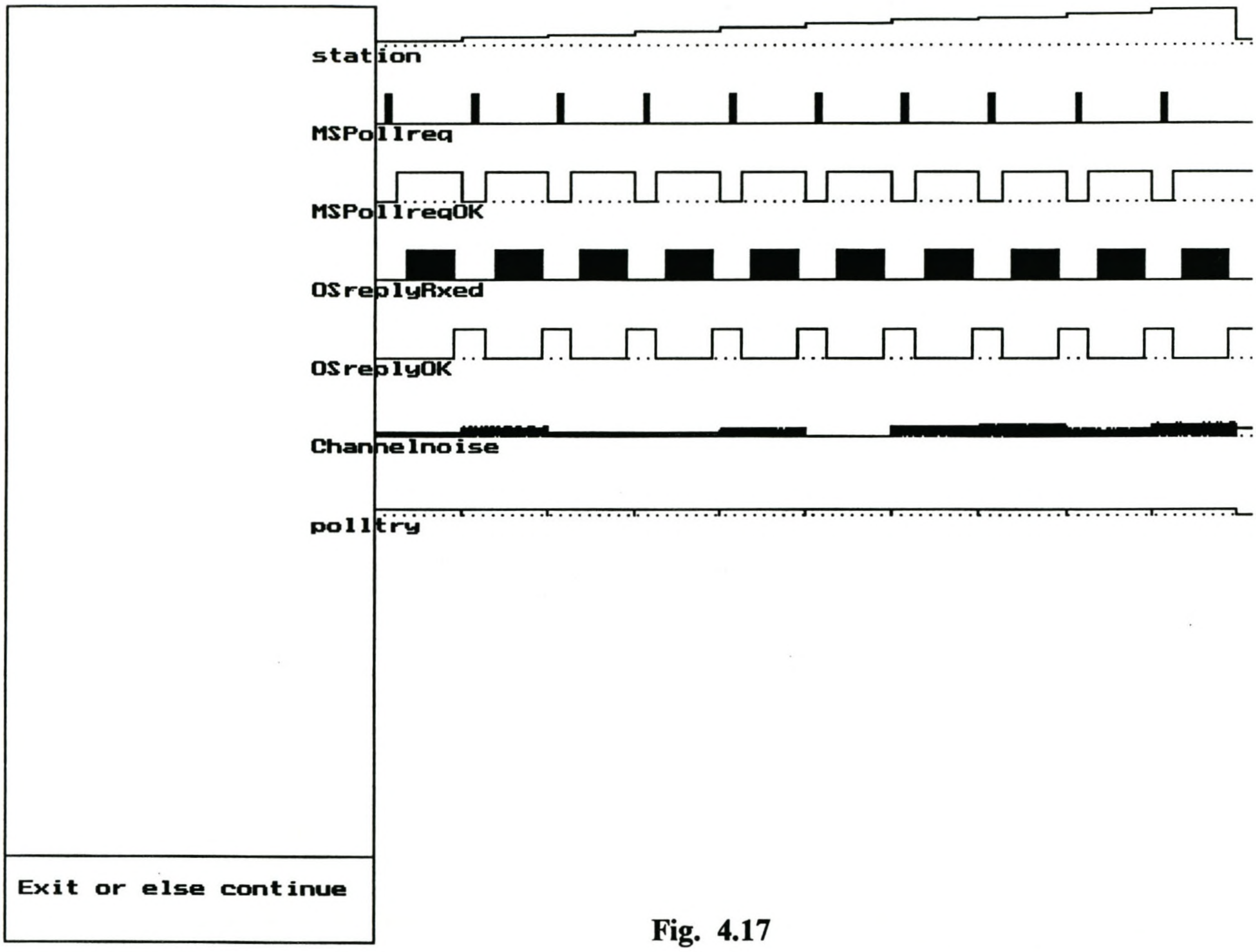


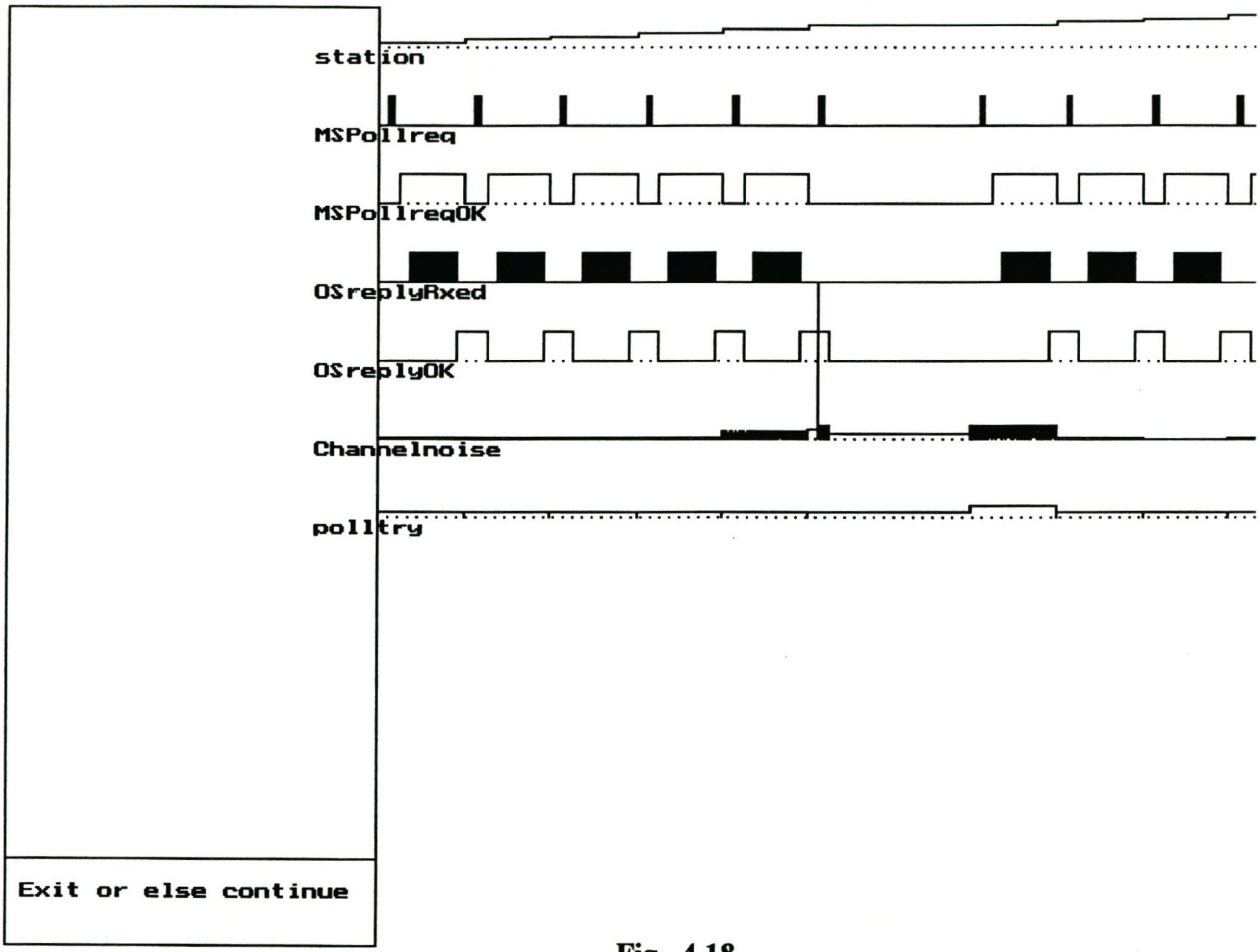
Fig 4.16
Flow Diagram of Round-Robin Polling Strategy



Exit or else continue

Fig. 4.17

Simulation output display of R-R polling sequence without burst noise



Exit or else continue

Fig. 4.18

Simulation output display of R-R polling sequence with burst noise disturbance

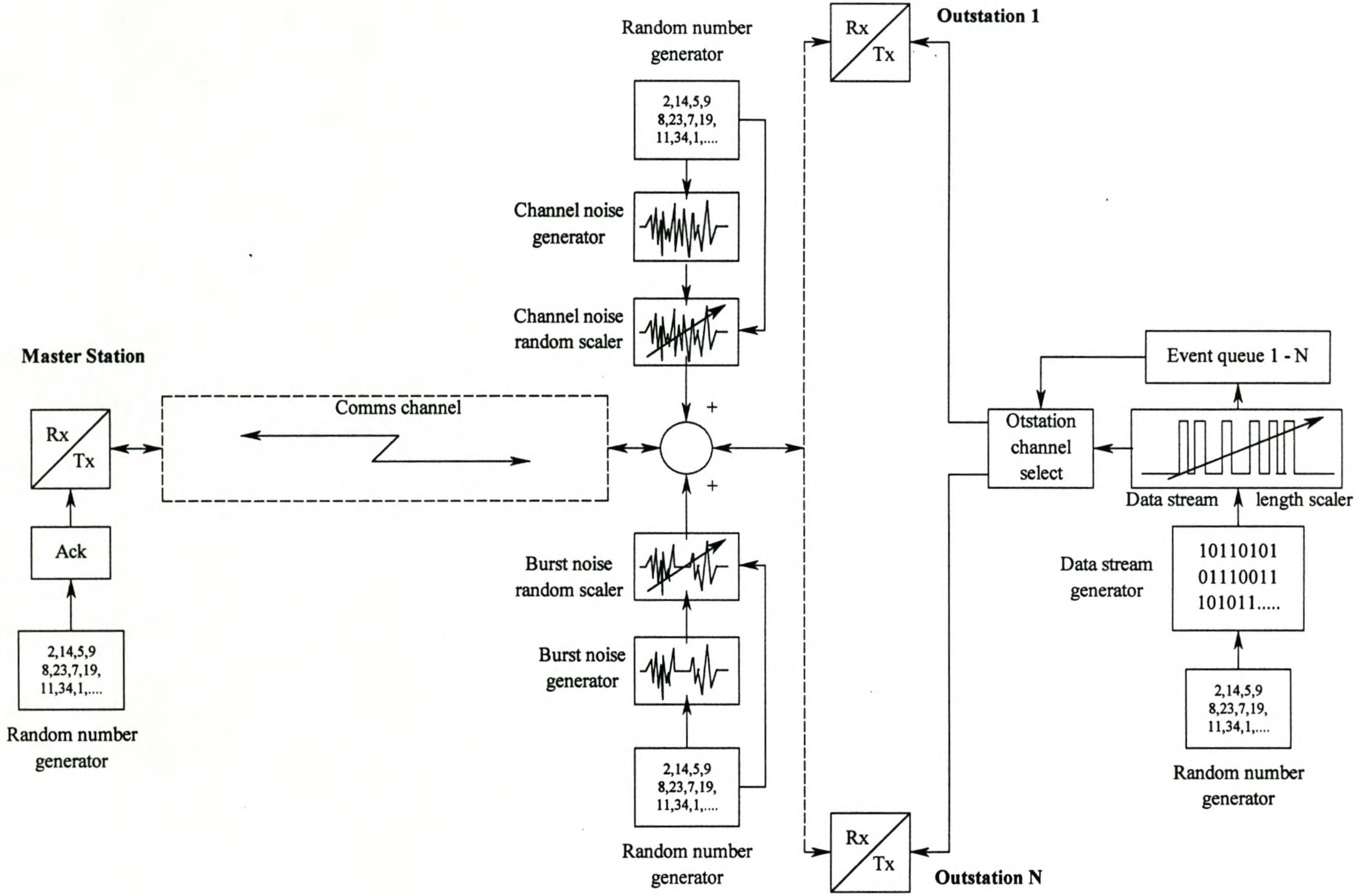


Fig 4.19
CSMA Strategy Block Schematic Diagram

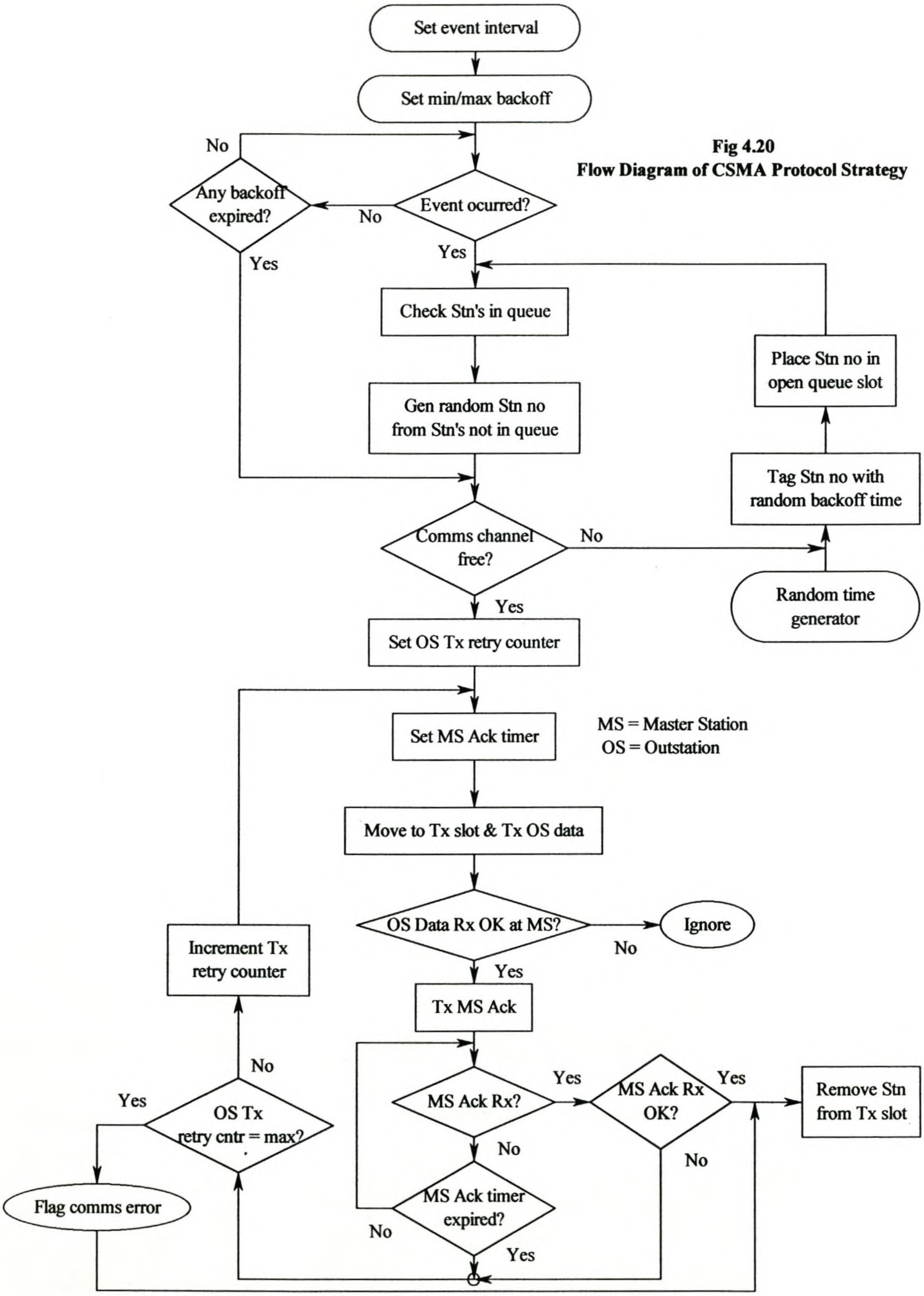
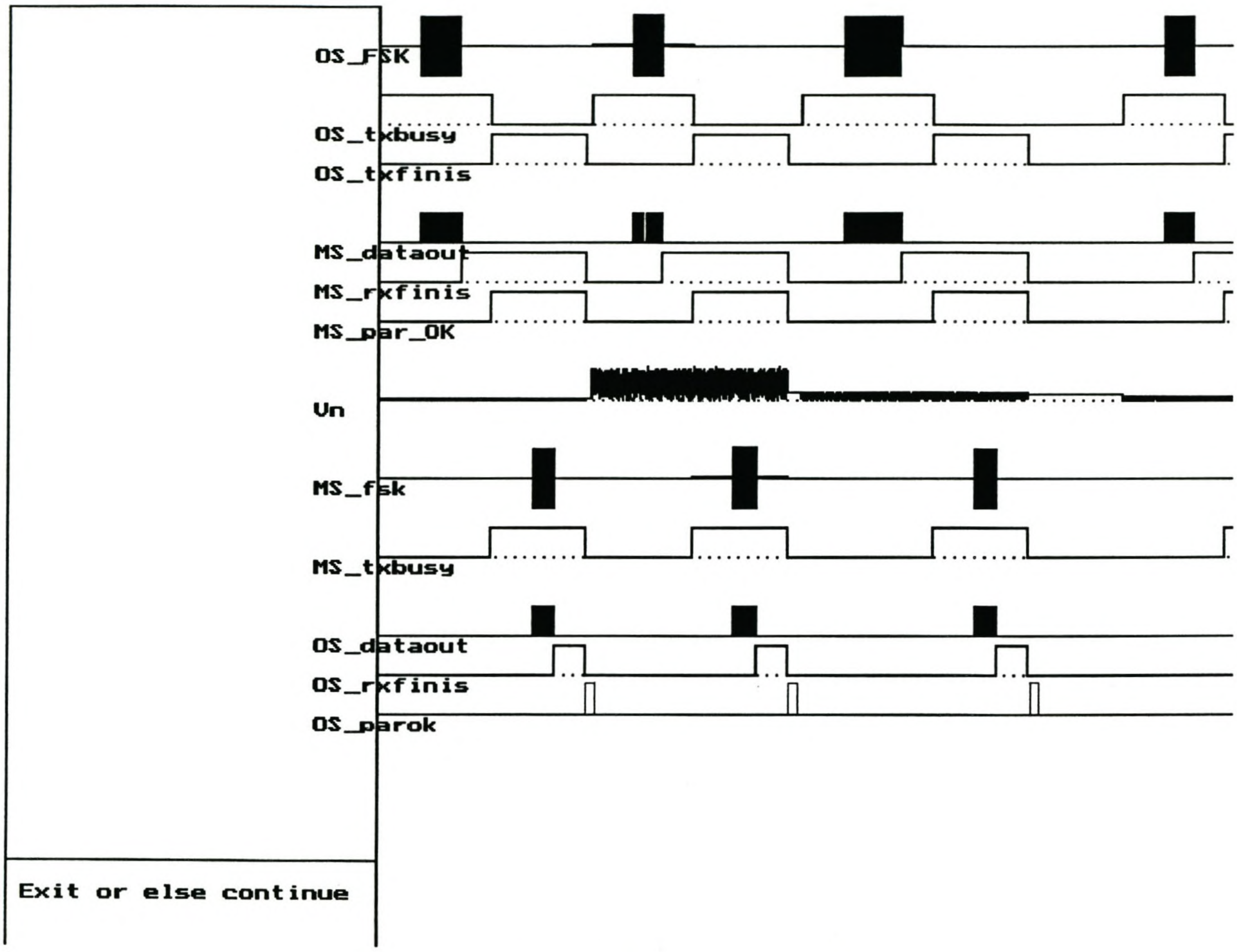


Fig 4.20
Flow Diagram of CSMA Protocol Strategy



Exit or else continue

Fig. 4.21

Simulation output display of CSMA functioning without Burst Noise

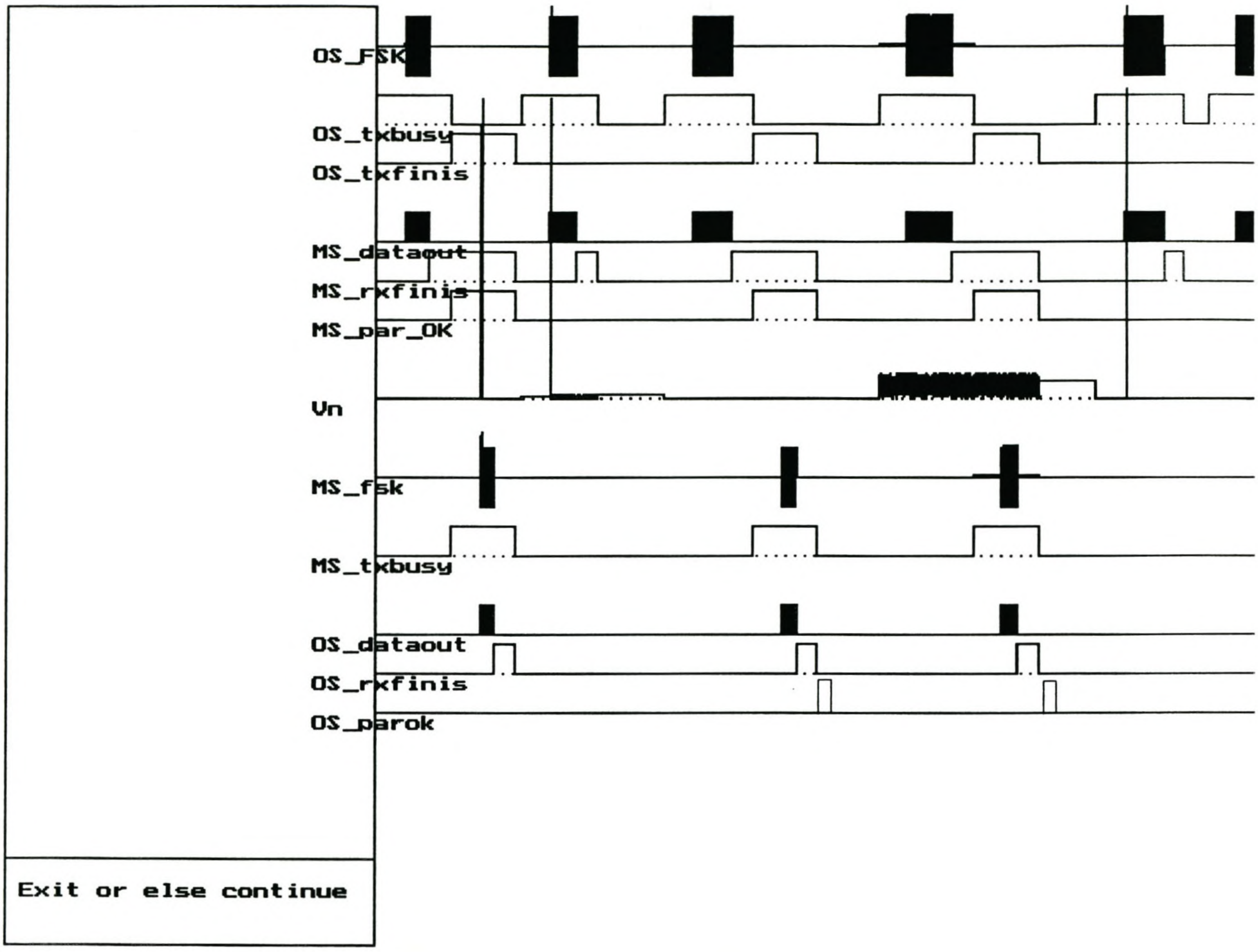


Fig. 4.22

Simulation output display of CSMA functioning with Burst Noise

Chapter 5

Model Simulations

5.1 Background of Approach

Having verified the validity of emulation of the two mainstream strategies, i.e. Round-Robin and CSMA, as set out in Chapter 4, extensive simulations were completed for both model types. In order to establish some reference performance data, to serve as a basis for the various contention type options, the RRP simulations were completed first. The deterministic nature of the strategy is well suited to this purpose and, being slightly simpler to implement, provided a good and less time consuming opportunity to ensure that all basic routines are properly debugged.

5.2 Types of Simulation

5.2.1 Basic parameters

It is clear that in order to be able to make valid and meaningful comparisons between the relative performance of the various strategies, the baseline parameters should be common to all, as far as possible and applicable. The underlying assumptions can be summarised as follows:

(a) **Baud rate**

All data transmission was set to take place at 1200 baud, async. The background to this was discussed in Chapter 4, but is in line with the attempt to simulate commonly utilised equipment in the low, to mid portion of the market. Licenced bandwidth allocation is also a consideration, as previously mentioned.

(b) Pre- and postamble times

If commercial voice comms type radios are utilised, a fairly long carrier key time is required to open the squelch circuitry of the receiver. If a repeater is utilised, as is very often the case, this clearly extends the minimum pre- and postamble times even more. These have been set at 200 mS and 150 mS respectively, throughout.

(c) Header block size and content

In keeping once again, with popular industry standards, the block size of the Poll command and Data Ack message, has been set at a constant 128 bits. As discussed in Chapter 3, this header normally contains start stop and error control bits, as well as source-, destination- and routing address information. In the simulations, provision was made for start- stop- and error checking bits, while the rest of the content was randomly allocated. Addressing was done implicitly in the software and not explicitly, having no specific influence over performance and in order to reduce unnecessary CPU overhead.

(d) Outstation I/O Count and Data Block Size

The decision regarding the selection of outstation data block size is somewhat arbitrary, but was based on practical experience with many functioning installations. After some consideration, it was decided to emulate 3 different sizes of outstation, i.e.

- Small basic outstation with a max I/O count of 16, such as would be applied to a single water reservoir site, very small pumpstation, or electrical metering point.
- Small to medium size outstation with max I/O count of 32, such as would be suitable for a bigger pumpstation, or small electrical substation.
- Medium to large size outstation with a max I/O count of 64, as may be utilised at a small purification works, or bigger substation.

The method and efficiency of I/O data encoding varies significantly between suppliers and is dependent upon a number of factors, such as A/D resolution, binary packing of status/control I/O's and use of local time tagging, or not. As a fair average, however, it is reasonable to assume a 2 byte/ I/O point data encoding. Together with a 128 bit header block, the expected maximum data block sizes for the 3 different outstation types, are as follows:

- 16 I/O point station : 384 bits
- 32 I/O point station : 640 bits
- 64 I/O point station : 1152 bits

It was also decided that the simulations should allow for variable outstation data block size and in the simulation, the data bit count was randomly varied between 128 to maximum, prior to each poll or event generation. It was felt that with simulation results in hand for the above configurations, it should not be too difficult to extrapolate predictions for different station sizes.

(e) Channel noise and burst noise

The SNR for continuous, time averaged channel noise is randomly allocated between 20 - 60 dB for each master station- outstation channel, prior to each data transmission. The channel noise generation process, has been described in Chapter 4. The percentage transmission disturbances caused by random, short burst noise sequences, is set prior to each simulation run. The selected values for the RRP case were: 0%, 5%, 10%, 15% and 20%, while the 5% and 15% options were omitted from the CSMA set of simulations, in order to render the whole process somewhat less tedious.

(f) Parameter allocation

Each type of simulation is provided with a constant declaration header field, where all parameters as abovementioned and others specific to the particular type of strategy, can be conveniently set. In order to prevent confusion between individual sets of results in the rather large overall collection, file name allocation is unique according to the selected parameter values and also automatic.

(g) Iteration count

It is clear that data from a simulation run should be based on a sufficiently large statistical sample, in order to be used with confidence. To this end, a balance had to be found between a short run consisting of a relatively low number of iterations, but producing data with a low level of confidence and the opposite, which may be unnecessarily time consuming. In an attempt to determine an acceptable optimum for both the RRP and contention groups, a long simulation run was initially completed for a representative version of both and the standard deviation for the minimum wait time calculated at fairly large increments along the way. The results are reproduced in Table 5.1. Based on these initial trails, the iteration count for the RRP and contention groups was chosen to be app. 1400 and 3600 respectively, as a reasonable compromise.

Table 5.1
Mean, std. deviation and deviation from mean against no. of iterations for CSMA and RRP Trials

CSMA Trial				RRP Trial		
No of Samples	Avg. wait time	Std Deviation	% Dev from avg.	Avg. wait time	Std Deviation	% Dev from avg.
200	5.891	5.725	5.792	1.024	0.060	0.286
400	5.877	5.913	5.530	1.024	0.063	0.247
600	5.814	5.764	4.404	1.024	0.063	0.313
800	5.727	5.665	2.848	1.022	0.063	0.047
1000	5.681	5.759	2.018	1.022	0.063	0.073
1200	5.635	5.692	1.196	1.022	0.063	0.044
1400	5.621	5.835	0.936	1.022	0.062	0.094
1600	5.610	5.900	0.742	1.022	0.062	0.086
1800	5.600	5.873	0.571	1.022	0.062	0.039
2000	5.594	5.883	0.457	1.021	0.062	0.006
2200	5.592	5.868	0.416	1.021	0.062	-0.016
2400	5.587	5.827	0.337	1.022	0.062	0.058
2600	5.585	5.872	0.297	1.022	0.062	0.069
2800	5.585	5.888	0.297	1.022	0.062	0.028
3000	5.581	5.854	0.229	1.022	0.062	0.042
3200	5.580	5.852	0.198	1.022	0.062	0.083
3400	5.578	5.880	0.172	1.022	0.062	0.043
3600	5.578	5.912	0.159	1.022	0.062	0.047
3800	5.576	5.821	0.136	1.022	0.062	0.068
4000	5.576	5.777	0.128	1.022	0.062	0.037
4200	5.576	5.741	0.125	1.022	0.062	0.045
4400	5.575	5.678	0.108	1.021	0.062	-0.001
4600	5.574	5.634	0.098	1.021	0.062	-0.025
4800	5.573	5.593	0.085	1.021	0.062	-0.015
5000	5.573	5.547	0.071	1.021	0.062	0.000
5200	5.572	5.532	0.060			
5400	5.571	5.493	0.043			
5600	5.571	5.469	0.043			
5800	5.570	5.431	0.032			
6000	5.570	5.408	0.023			
6200	5.569	5.386	0.012			
6400	5.569	5.378	0.008			
6600	5.569	5.360	0.006			
6800	5.569	5.326	0.005			
7000	5.569	5.308	0.001			
7200	5.569	5.294	0.000			

(h) **Implementation**

Although dependent upon CPU type and speed, some of the strategy variations are still very time consuming to run, stretching over app. 8 hrs individually. To reduce this overhead, many variations were run in parallel on multiple machines, whenever possible. Many simulations were still run sequentially on single PC's though, where parallel processing was not possible, or gaps required filling.

5.3 Round-Robin Strategies

The RRP strategy implemented, is a straightforward sequential, cyclical
Master Station - Outstation poll, with timeouts, re-polls and data Rx OK ACK facilities, as set out in Chapter 3.

The different variations regarding outstation data block size, no of stations and burst noise content, are shown in Table 5.2.

Table 5.2

Simulation Options for RRP

Data length No of bits	Station Count	Burst Noise %				
384	10	0	5	10	15	20
	20					
	40					
	60					
	80					
640	10	0	5	10	15	20
	20					
	40					
	60					
	80					
1152	10	0	5	10	15	20
	20					
	40					
	60					
	80					

The critical aspects of performance in type of application under investigation, are the minimum, average and maximum wait times for any outstation event, to be serviced and forwarded to the master station.

Processing of the results have, therefore, concentrated on these times, as well as effective channel bit rate.

5.3.1 Results for 384 bit max outstation data block size.

The processed minimum, average and maximum wait times for the abovementioned collection of simulations, are plotted in Figures 5.1 - 5.5. Due to the nature of these strategy, the min. wait time would be the same irrespective of the number of stations in the system. Average- and maximum wait times are, obviously, dependent on the number of stations, with average wait time equal to 50% of the total polling cycle time.

From the plotted results, it is also clear that each 5% increment in burst noise, results in an approximate 20% increase in wait times.

The effective overall bit throughput rates, as plotted in Fig 5.6, were calculated taken in all aspects of link overhead, such as pre-. postambles and ACK sequences into account.

5.3.2 Results for 640 bit maximum outstation data block size

The results for this set of data, are plotted in Fig's 5.7-5.12. The minimum wait time obtained for this case is 1.1251 S, for 0% burst noise. Other ratios are similar as for the 384 bit option. The increase of the 640 bit minimum wait time over the 384 bit time is approximately 10%, while the increase in actual transmitted data bits, is a much bigger 50%. This is of course, due to the considerable link overhead (pre-postambles and ACK routine) common to both.

Effective transmission bit rates are subsequently also higher than for the 384 bit case. The reduction in bit rate is approximately 16 - 17 % with each 5% increase in burst noise.

5.3.3 Results for 1152 bit maximum outstation data block size

The results for this subset of simulations, are plotted in Figure's 5.13 - 5.18.

The resultant minimum wait time obtained for the 0% burst noise case, is 1.3455 S.

The effective bit rates, as plotted in Fig 5.18, are also the highest of the three sets, due to the more favourable ratio of overhead vs. data bits.

5.3.4 Round-Robin Conclusions

The results from the RRP simulations are mostly self-evident and do not require too much comment. The differences in performance between the various outstation data types and burst noise levels, are expected and predictable.

The real value of the exercise was to throughly test the simulation software and to establish a deterministic performance base against which subsequent strategies can be measured and compared with. It is also a very popular protocol type in widespread use in many commercial and industrial applications. This is to a large extent due to it's deterministic nature and where firm master/slave control is required.

5.4 CSMA, or Contention Based Simulations

5.4.1 General

Overall parameters for the CSMA set of simulations, were the same as for the RRP case, with the exception of the Event Generation Interval (EGI) and Backoff Period (BP) which are, of course, specific to the CSMA strategy.

The choice of EGI is arbitrary and can only be based on practical, to be expected, values. Even here, an enormous variation is to be found, dependent upon the particular system application. Electrical networks, as an example, normally exhibit a far higher event rate than water reticulation systems. An enormous variation is also found in industrial, plant monitoring and control applications.

Some comparison base between the different strategies is, however, required and it was decided to use the minimum RRP poll/wait time for each outstation data block size, as a point of departure and as a set parameter for the initial group of simulations. To provide further insight in the performance of the scheme, additional sets of simulations were run with different EGI's, but where the particular EGI was still a fixed factor (albeit longer or shorter) of the base, RRP derived, EGI.

An initial value for the BP had to be selected as well. The BP was defined as a factor of the maximum comms timeout, or turnaround time. This is the time period $t - 0\ max$ allowed between outstation event transmission and ACK received back by the outstation. The actual BP was, of course, a randomized value, somewhere between approximately 0 and this maximum value.

After completion of the initial set with this BP, additional runs were completed with both shorter, and longer BP's, respectively.

The different CSMA variations regarding outstation data block size no of stations, burst noise content, EGI and BP, are shown in Table 5.3.

Table 5.3

Simulation Options for CSMA

Data length No of bits	**Backoff Period Factor of Max Timeout**	**EGI = RRP min wait time**	**Station Count**	**Burst Noise %**		
384	Sets for ×3.5 max timeout & ×0.375 max timeout	Sets for ×1 RRP EGI & ×1.5 RRP EGI & selected ×0.67 RRP EGI	10	0	10	20
			20	0	10	20
			40	0	10	20
			80	0	10	20
640	Sets for ×3.5 max timeout & 0.375 max	Sets for ×1 RRP EGI & ×1.5 RRP EGI	10	0	10	20
			20	0	10	20
			40	0	10	20
1152	Sets for ×3.5 max timeout & 0.375 max timeout	Sets for ×1 RRP EGI & ×1.5 RRP EGI	10	0	10	20
			20	0	10	20
			40	0	10	20
			80	0	10	20

5.4.2 Results from simulations with 384 bit data block length maximum $BP = 3,5 \times t - 0\ max$ and $EGI = 1.0 \times RRPt_{w-min}$ (Min. wait period for RRP).

The results from the above, have again been processed for wait times and plotted in Figures 5.19, for the 3 burst noise percentages.

A maximum wait time on the basis of a single, statistically very high occurrence may present a distorted presentation and a minimum wait time is not really significant in this case, as it could, and would, be close to the RRP$t_{w-\mathrm{min}}$, provided that a large enough sample base is generated. To provide further insight into the scheme's behaviour, the mean, standard deviation and variance are also presented for the 0% burst noise case, in Fig. 5.21. The results are mostly self evident, but a few comments may be useful:

(a) The increase in mean wait times with each 10% increase in burst noise content, is approximately 20-23%.

(b) The effective throughput bitrates as plotted in Fig 5.20, show a marked decrease with the increase in no of outstations. The % influence by burst noise on effective throughput, is also higher with the increase in station count.

(c) The standard deviation and variance for the 0% burst noise case, is plotted out in Fig. 5.21. It is clear that a significant standard deviation and consequently, even bigger variance is evident. This is to be expected, due to the large statistical variation of the process and should be kept in mind during design when system performance has to be kept within tight limits. The mean value, may very well be misleading.

The results of Fig. 5.20 and 5.21, are typical for a contention type strategy and will be discussed in more detail in a subsequent paragraph.

5.4.3 Results from simulations with 640 bit data block length max, $BP = 3.5 \times t - 0\ max$ and $EGI = 1,0 \times RRPt_{w\min}$.

Processed results from these simulations are presented in Fig's 5.22 - 5.24. The same comments are applicable as for the 384 bit set, except that:

(a) Wait times are slightly longer throughout. This is clearly due to the increased transmission times.

(b) Effective data throughput rates are higher due to the increased efficiency and reduced overhead resulting from longer block length, containing more data for the same overhead structure.

(c) Standard deviation and variance results follow suit, in accordance with the longer data set length.

5.4.4 Results from simulations with 1152 bit data block length max, $BP = 3.5 \times t - 0\ max$ and $EGI = 1,0 \times RRPt_{w\min}$.

The processed results from this set of simulations are shown in Fig's. 5.25 - 5.27.

The results are self evident and the main difference is the significant increase in data throughput rates, over the cases with shorter block lengths, again due to better efficiency. Other comments are similar, as for the two previous sets.

5.4.5 Results from simulations with $EGI = 1.0 \times RRPt_{wmin}$ and $BP = 0.375 \times t - 0\ max$.

The 3 groups of simulations (384, 640 and 1152 data bits) were wholly repeated, but with drastically shortened backoff time. The processed results are presented in Fig's. 5.28-5.36. Comments on these results, are as follows:

(a) Ratios between the respective wait times are not significantly different than those for the longer BP.

(b) Wait times are generally similar, or slightly shorter, than for the set with the longer BP.

(c) Due to (b) above, it is tempting to conclude that general performance with this BP should be equal or better than with the longer BP. In such a case, where a station would check more frequently for comms channel availability, giving it a better chance for access. However, all the other stations do the same and the increased competition results in increased system overhead due to an increased collision rate. This is, however, not proved by the above simulation results and the anomaly is investigated in depth in a subsequent Chapter.

5.4.6 CSMA simulations with $EGI = 1.5 \times RRPt_{w-min}$ and $BP = 3.5 \times t - 0\ max$.

The results from this set of simulations are presented in Fig.'s 5.37-5.39:

Note that the 384 bit case only is presented. There is no reason to expect the tendency to higher efficiencies for the longer data set length, not to be similar as seen for the previous options. The possibility for extrapolation, is further discussed in Chapter 7. Comments on the results, are as follows:

(a) Wait times are generally approximately 10% shorter, than for the $EGI = 1.0 \times RRPt_{wmin}$ case. This is to be expected, due to the reduced channel loading.

Wait time % increments with corresponding burst noise increments, are comparable with the corresponding set of results for the lesser EGI case.

(b) Data throughput, as per Fig. 5.38, is significantly better. This would be a consequence of the reduced wait times.

(c) Standard deviation and variance are also reduced, as would be expected.

5.4.7 CSMA simulations with $EGI = 0.67 \times RRPt_{w-min}$ and $BP = 3.5 \times t - 0\ max$.

A complete set of simulations for this variation, was only run for the 384 bit data block case with 0% burst noise. Results are plotted in Fig 5.40. Comments are as follows:

(a) Wait times are significantly longer, as would be expected, from the increased competition for resources.

(b) Data throughput, as presented in Fig. 5.41, is much reduced.

Further comments on this type of scenario, are discussed in Chapter 7.

5.4.8 CSMA Results for BP's between $0.5 - 16 \times t - 0\ max$.

Upon presentation of the results from simulations based on the shortened BP $= 0.375 \times t - 0$ max case, it was decided to produce a more complete set of results, based on an increased range of BP, varying from BP $= 0.5 - 16 \times t - 0\ max$. It was deemed adequate to implement this for the 384 bit case only. The results from this investigation is plotted in Fig. 5.43 and clearly show a constant increase in performance with decrease in BP. The explanation for this apparent anomaly, is twofold:

(a) No allowance was made in the initial simulation software for the increased channel competition caused by receiver/transmitter risetimes and propagation delays. A more self-centered backoff strategy would, therefore, tend to produce improve results. This point is more comprehensively discussed under Chapter 7 and will not be further elaborated upon at present.

(b) Increasing the BP to ridiculous lengths and investigating the time/performance data logging procedure in detail, led to evidence that the simulation and data logging time cycles selected, exhibited a saturation characteristic under conditions of very high loading, resulting in over-optimistic wait times. This situation was easily remedied and more realistic results subsequently obtained. These are more appropriately discussed under Chapter 7. It should be mentioned that in view of this investigation, the CSMA results for the BP $= 3.5 \times t - 0\ max$, are well below the saturation point and still completely valid. This result was welcomed, due to the very time-consuming nature of the simulation process.

5.4.9 Comments on CSMA Results.

The following comments are applicable on the CSMA results, as a group:

(a) CSMA wait times and data throughput as a consequence, are greatly influenced by the EGI. This is, of course, not unknown or unexpected, as discussed in Chapter 2. What is valuable, is the availability of a realistic simulation tool in this regard.

(b) Performance is obviously affected by the addition of burst noise. The deterioration is relatively constant for the various options, with the stepped increments in noise disturbance.

(c) Performance is definitely and significantly affected by a change in backoff strategy. No deterministic approach to predefine and predict a suitable value for this parameter could be obtained from literature, including the key references listed elsewhere. Although this aspect is discussed in Chapter 7 from a theoretical point of view, it is also very useful to have access to a simulation tool to predetermine the effect of intended parameter selection.

(d) The anomalous results initially obtained with varying BP's, is an excellent reminder of the care required when carrying out supposedly realistic simulations of real life systems. Apart from attempting to achieve exact system and hardware modeling, it is also vitally important to consider the method, and point in time, of data recording. This is in confirmation of the principles underlying sound, measurement techniques.

5.5 Comparison between RRP and CSMA Results.

It is very useful to compare the simulation results obtained for the two main strategies. With regards to the processed data as presented and referred to in the preceding paragraphs, the following comments are relevant:

5.5.1 For the $EGI = 1.0 \times RRP\,tw - min$, the CSMA performance is consistently better in terms of mean wait time, over the entire station count spread and burst noise range. Data throughput is also enhanced, as is to be expected from the wait times.

This statement must be taken with care, in view of the large standard deviation exibited by the performance data sets. If performance is to be guaranteed, an investigation would be required for limits sensitivity.

5.5.2 Where the EGI is increased to $1.5 \times RRPtw - min$, the performance margin over RRP is even higher, as is normal for a contention strategy.

5.5.3 For the reduced EGI, eg. $EGI = 0.67 \times RRPtw - min$, the situation is different, with RRP being consistently close to CSMA performance.

It is clear that the expected EGI, would have a definite influence on the selection of a particular strategy,

5.5.4 The decision regarding the mean BP, is an important one. It is clear that a non-optimum choice of BP will put CSMA at a disadvantage to a comparative RRP strategy.

5.5.5 The longer data block lengths are the most efficient, as would be expected. This also applies to the best-case short (384 bit - 0% noise) vs. worst case, long data length (1152 bit - 20% noise) where the latter still has a 65% throughput advantage over the shorter block length, as applicable to CSMA.

5.5.5 It should again be emphasized that the RRP/CSMA performance comparisons as discussed above, are relevant only to the set of test conditions applicable. All practical assessments should be done on a per case basis, with due cognisance to the expected EGI in particular.

5.6 Summary

The detailed aspects discussed above, could be summarised as follows:

5.6.1 A valuable set of deterministic baseline data was obtained by implementing the RRP simulations, for the various options as set out. This process also served to ensure calibration of the simulation model and to establish the necessary level of confidence in it's functioning.

5.6.2 The results obtained from the RRP group, are predictable and within expectations.

5.6.3 A comprehensive set of CSMA based simulations were subsequently run, using each respective RRP minimum wait time as a reference parameter. This is admittedly open to question, but is felt to be reasonably justified in the absence of any strictly definable alternative.

5.6.4 The efficiency increase offered by longer data string lengths, is clear and to be expected. Even with a 20% burst noise occurrence, the longer length is still advantageous, due to the very onerous system overhead imposed by use of the type of equipment concerned.

5.6.5 Due note should be taken of the large variance exhibited by the CSMA strategy, when defining hardware specifications to comply with performance requirements.

5.6.6 The performance penalty paid due to increased event arrival rates, is obvious and to be expected. Being a finite source system, as later discussed in Chapter 7, the strategy will not be unstable, but very long delays will certainly occur with excessive EGI.

5.6.7 Under conditions of low to medium loading, CSMA consistently outperforms the RRP option, for the type of configuration under investigation. This is particularly and expectantly true, when station count is increased.

5.6.8 The anomalous results initially obtained for the different BP's simulated, indicates the amount of care required to ensure realistic and correct measurement of system performance.

5.6.9 Variation in BP strategy, will certainly iinfluence system performance. The desirability to enable quantification of this influence by formal means, is once more confirmed.

5.6.10 The results indicate the usefulness of the simulation tool, to predict and compare system performance when subjected to different operational parameters.

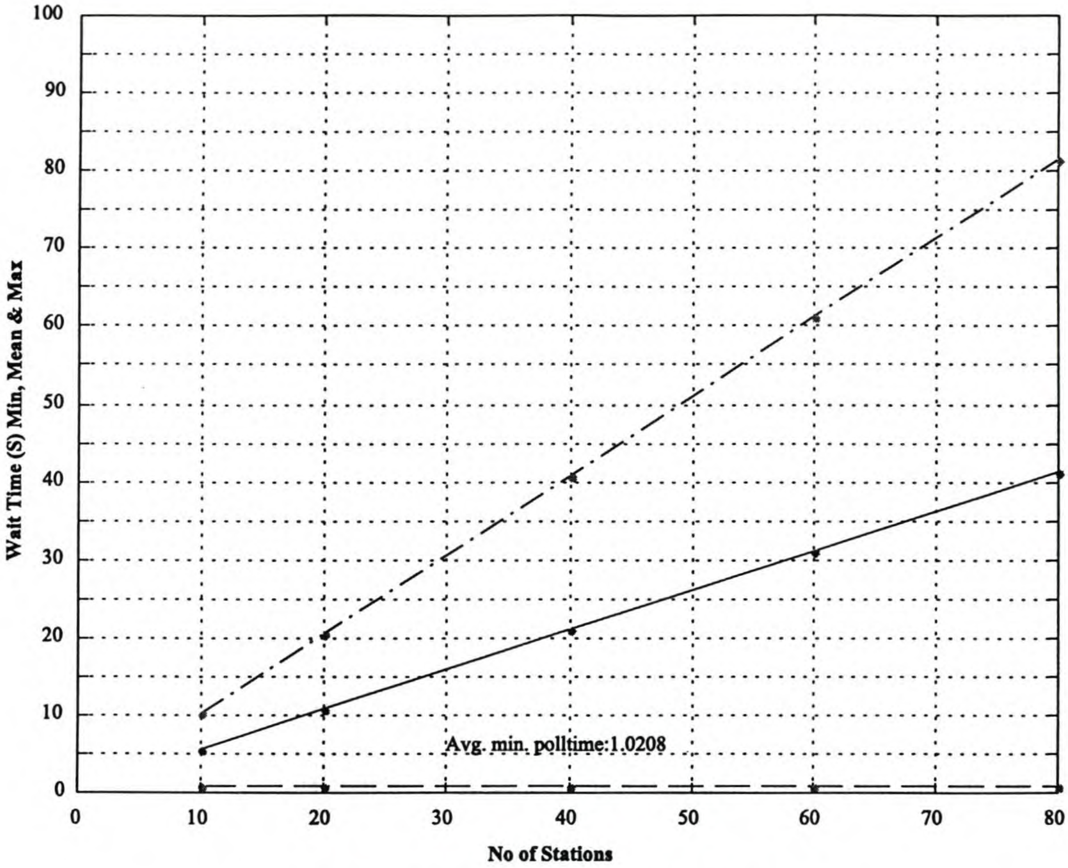


Fig.5.1 : Wait times - R-R Poll, 384 Data bits, 0% Burst noise

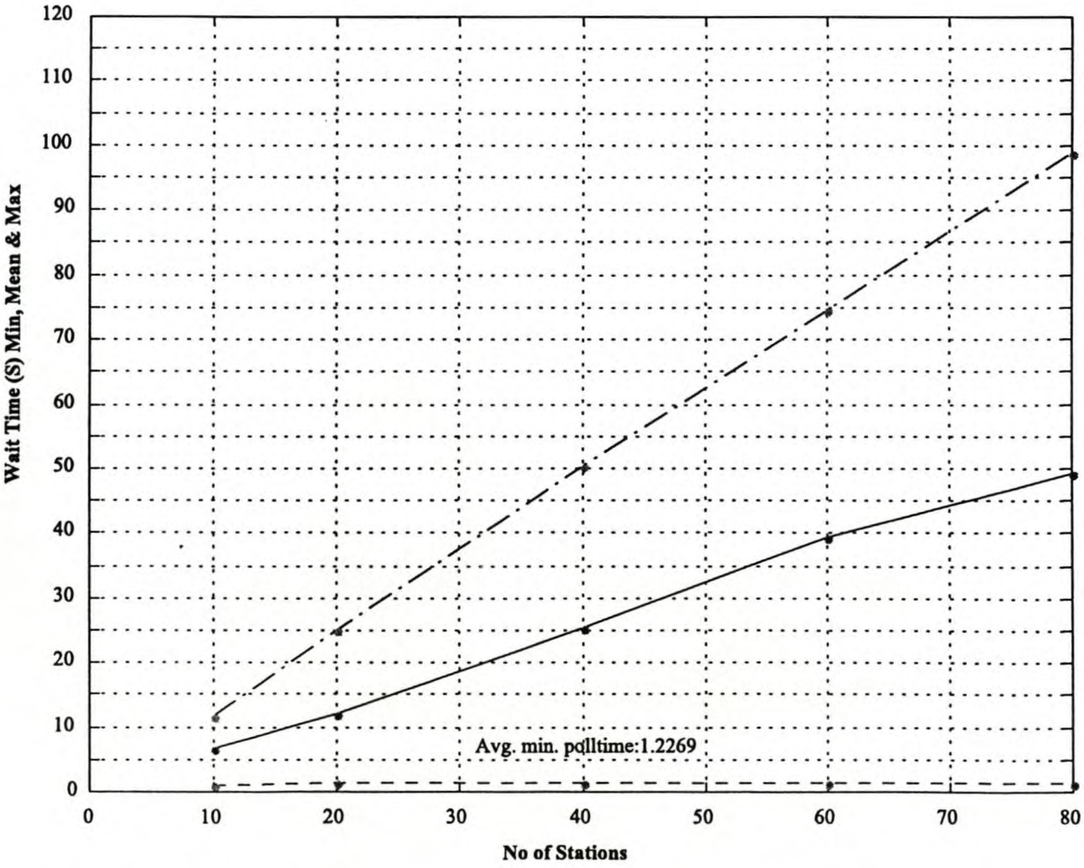


Fig. 5.2 : Wait times - R-R Poll, 384 Data bits, 5% Burst noise

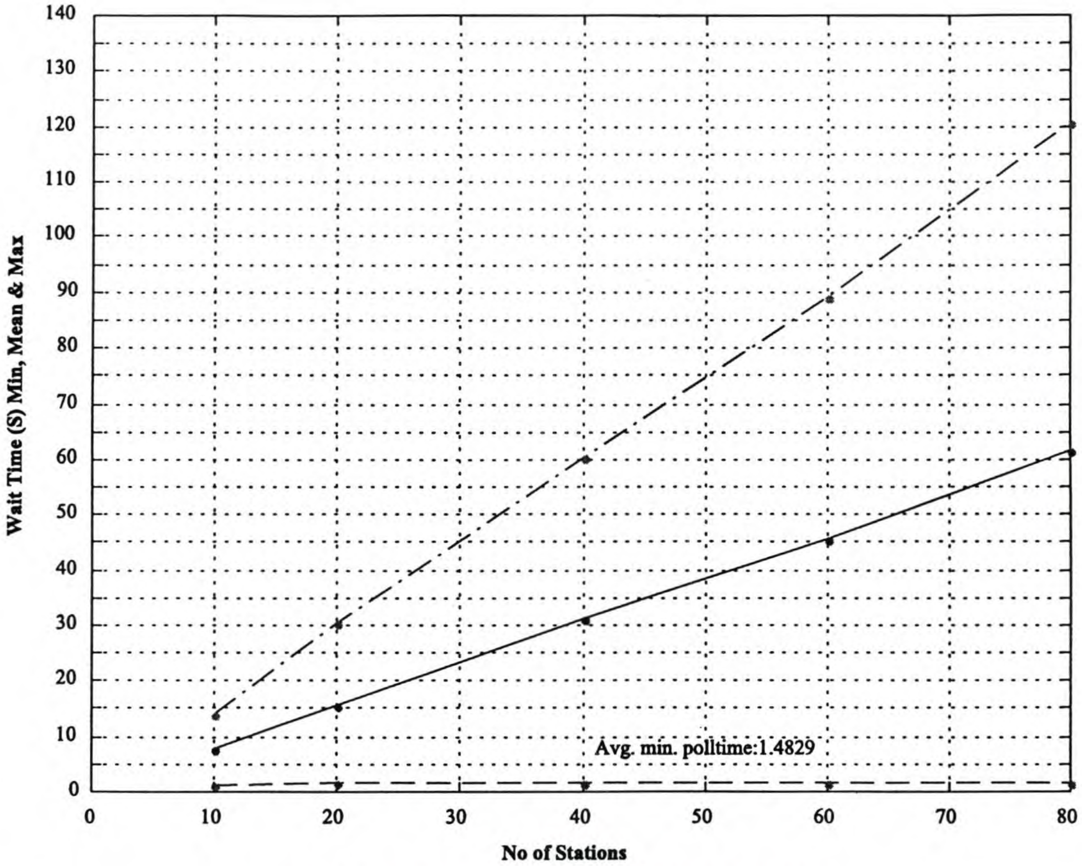


Fig.5.3 : Wait times - RRP, 384 Data bits, 10% Burst Noise

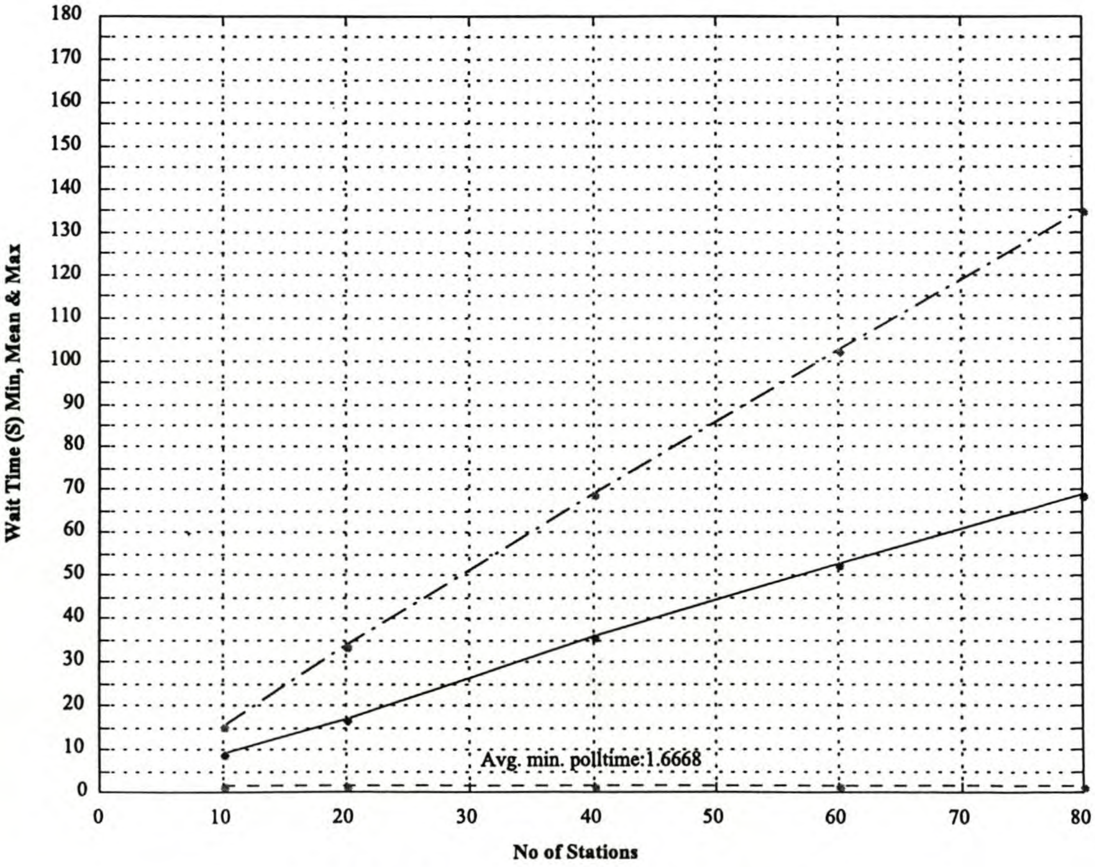


Fig.5.4 : Wait times - R-R Poll, 384 Data bits,15% Burst noise

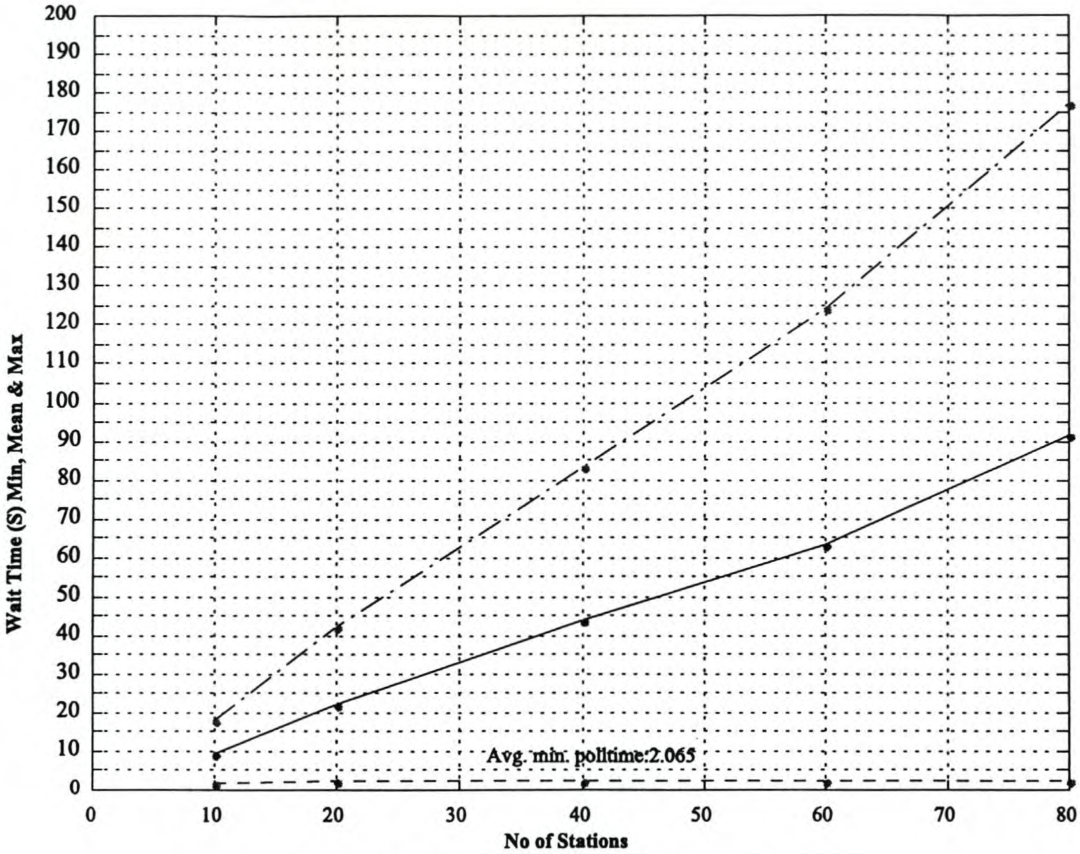


Fig.5.5 : Wait times - RRP, 384 Data bits, 20% Burst Noise

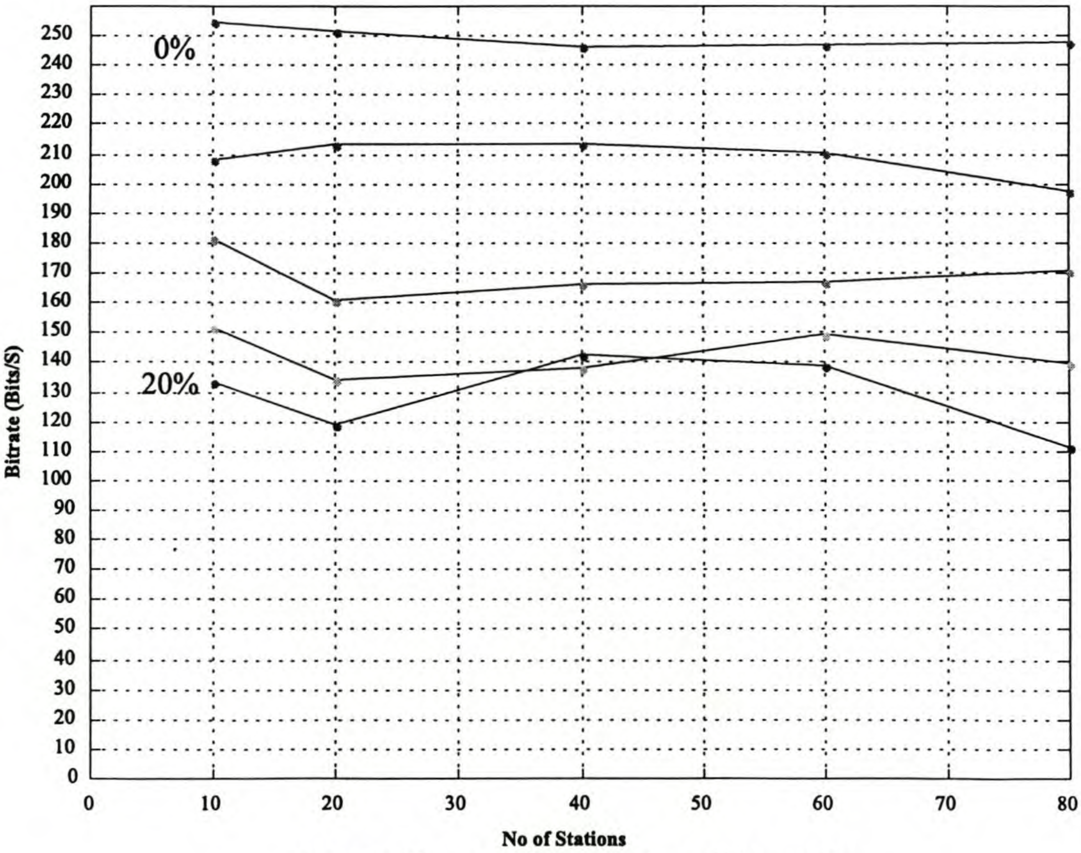


Fig.5.6 : Eff. Bitrates - RRP, 384 Data bits, 0 - 20% Burst Noise

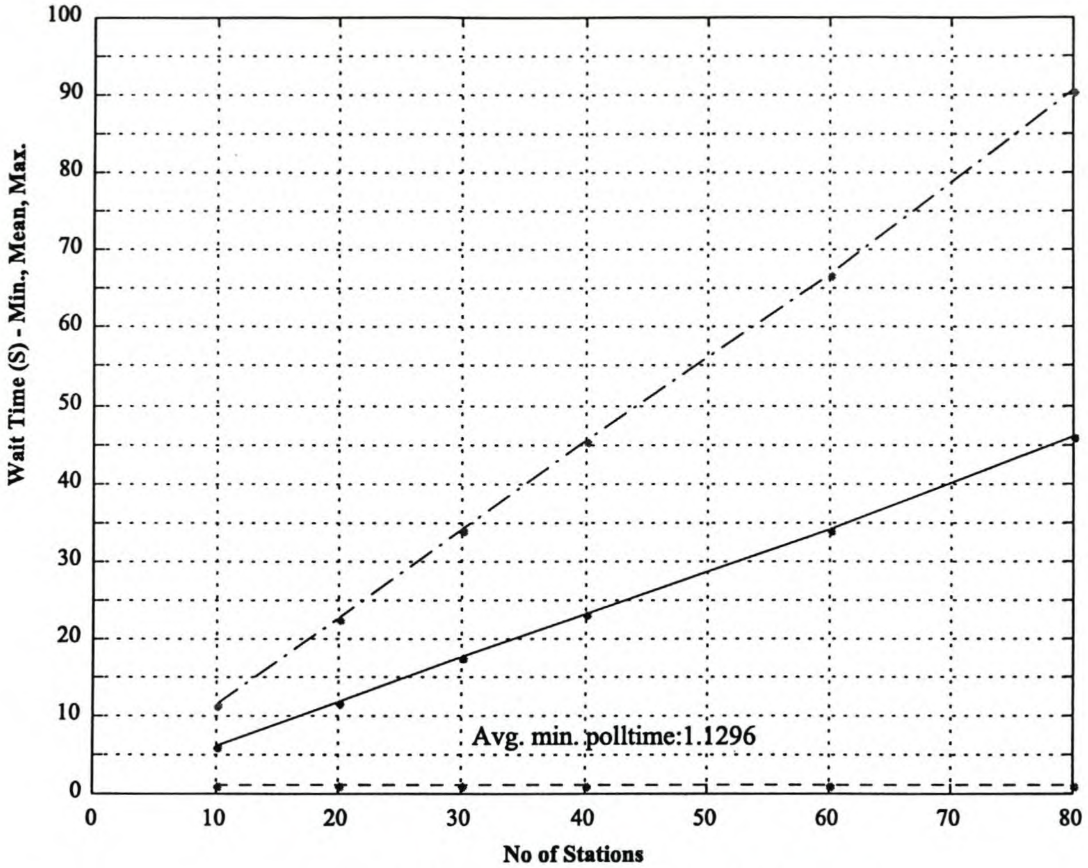


Fig. 5.7 : Wait times - R-R Poll, 640 Data bits, 0% Burst noise

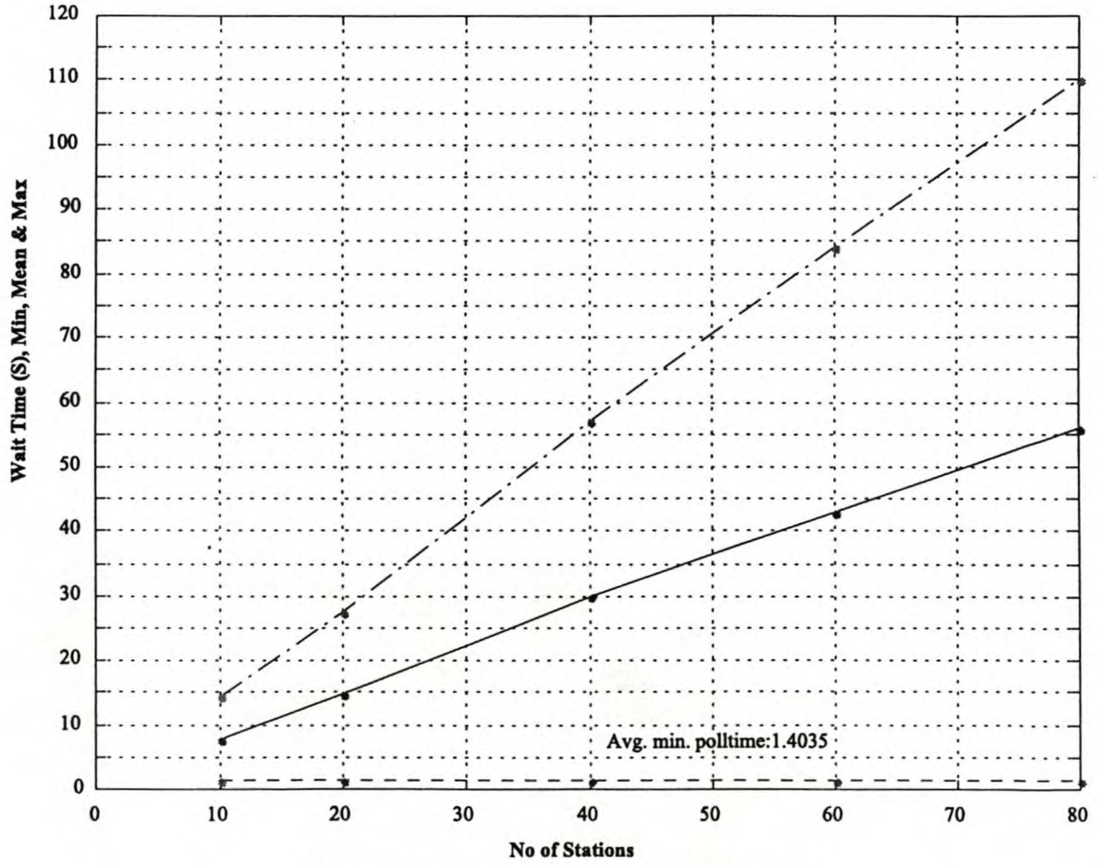


Fig. 5.8 : Wait times - RRP, 640 Data bits, 5% Burst Noise

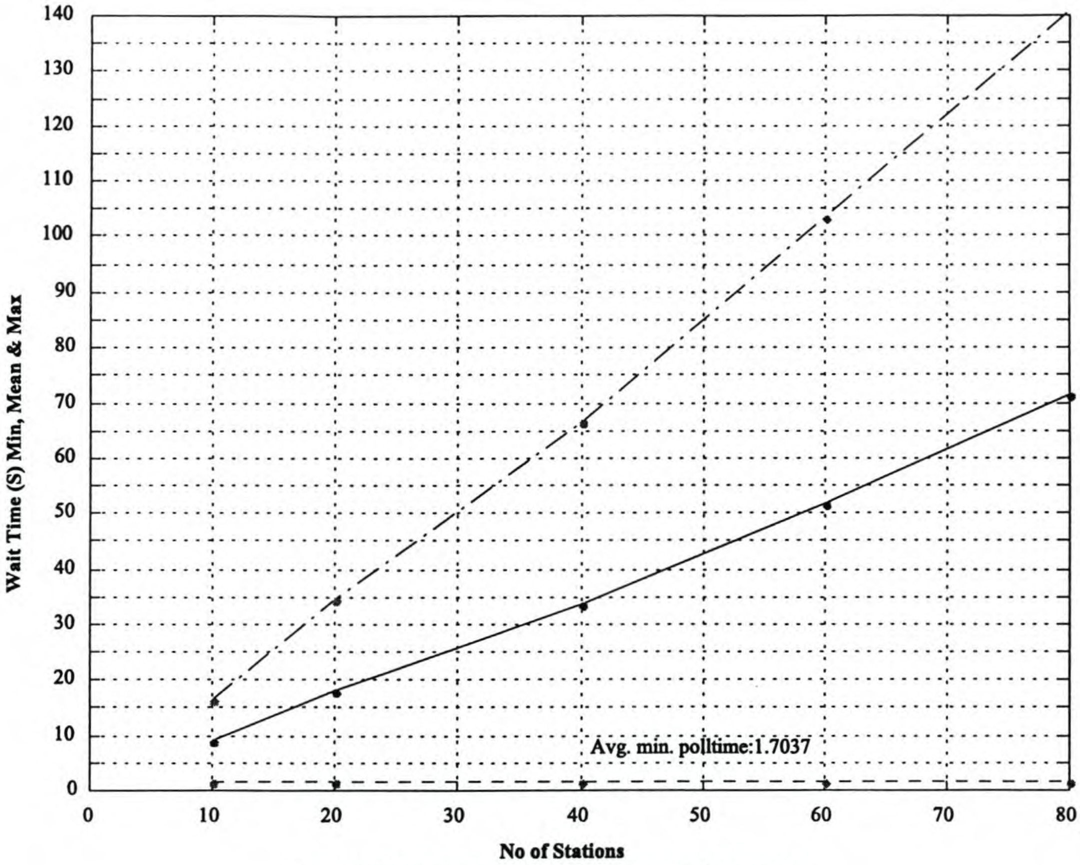


Fig. 5.9 : Wait times - RRP, 640 Data bits, 10% Burst Noise

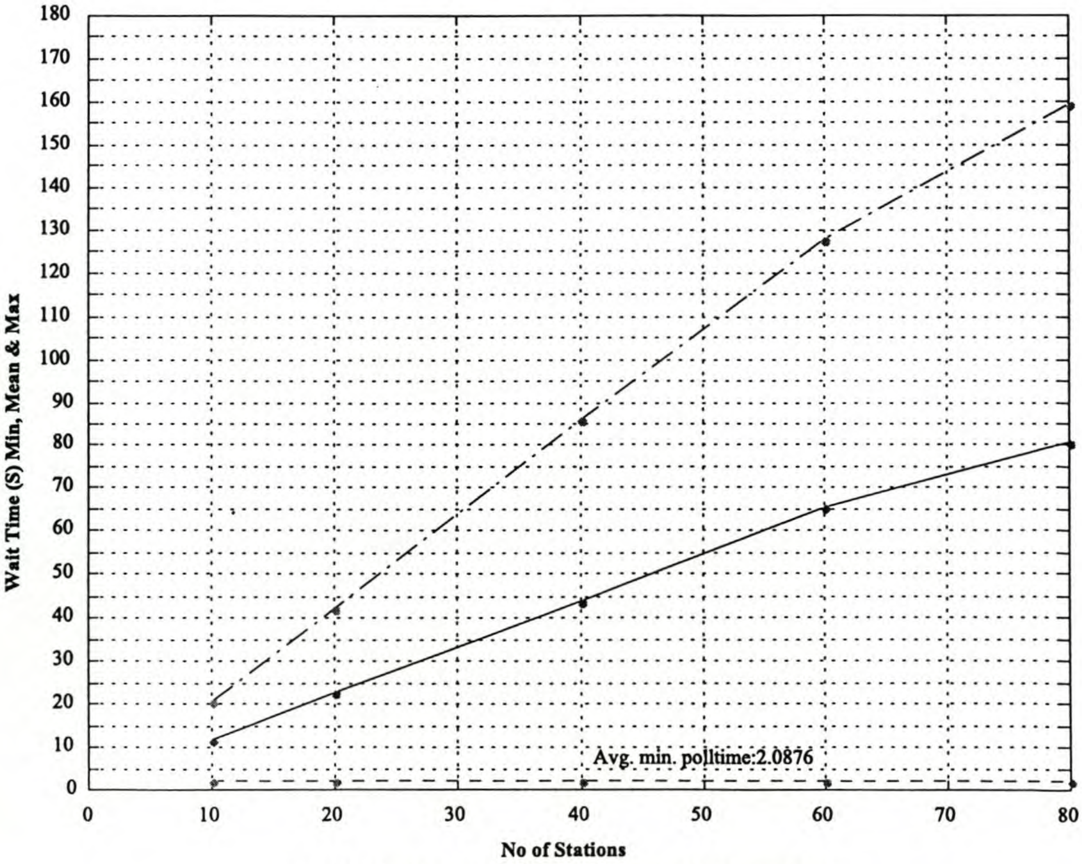


Fig. 5.10 : Wait times - RRP, 640 Data bits, 15% Burst Noise

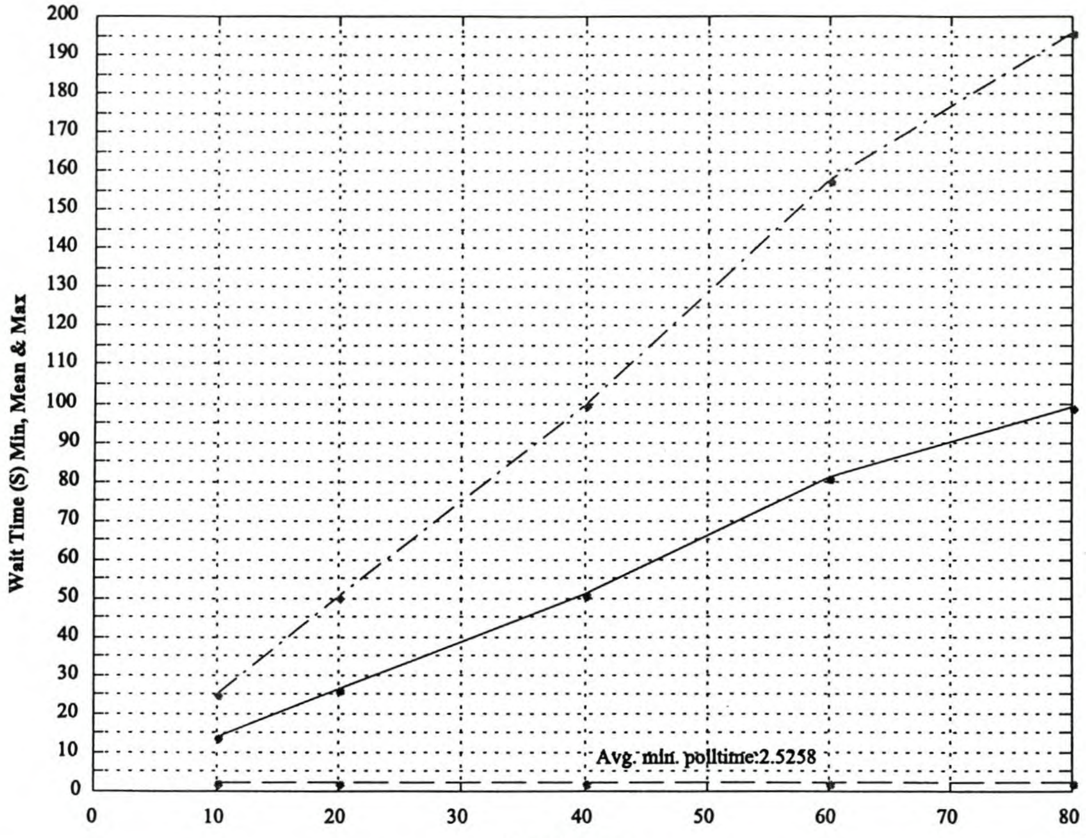


Fig. 5.11 : Wait times - RRP, 640 Data bits, 20% Burst Noise

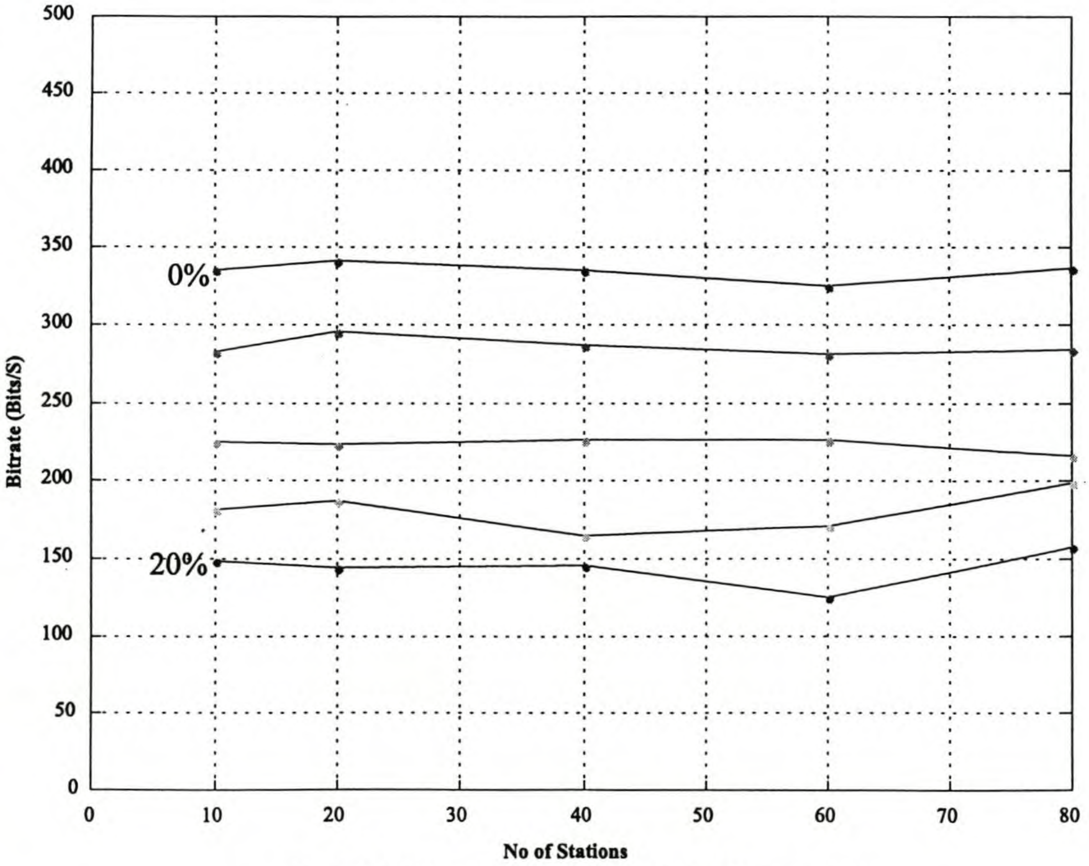


Fig. 5.12 : Eff. Bitrates - RRP, 640 Data bits, 0 - 20% Burst Noise

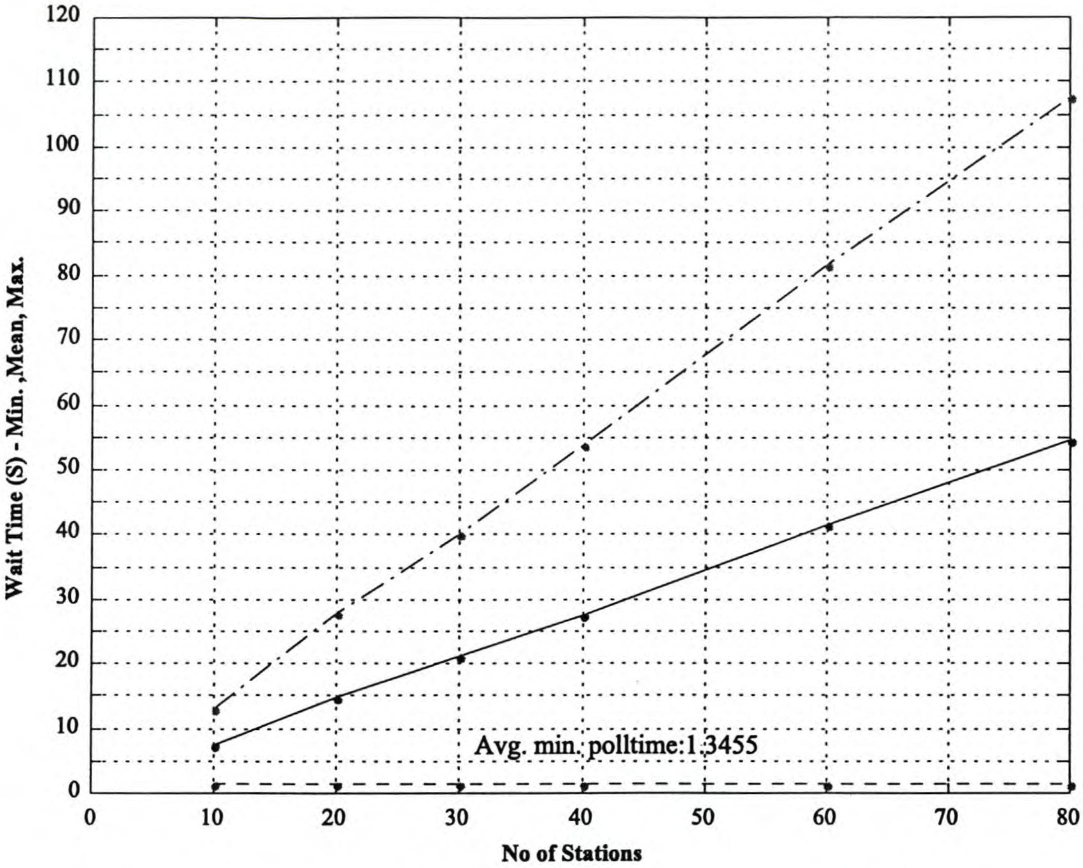


Fig. 5.13 : Wait times - R-R Poll, 1152 Data bits, 0% Burst noise

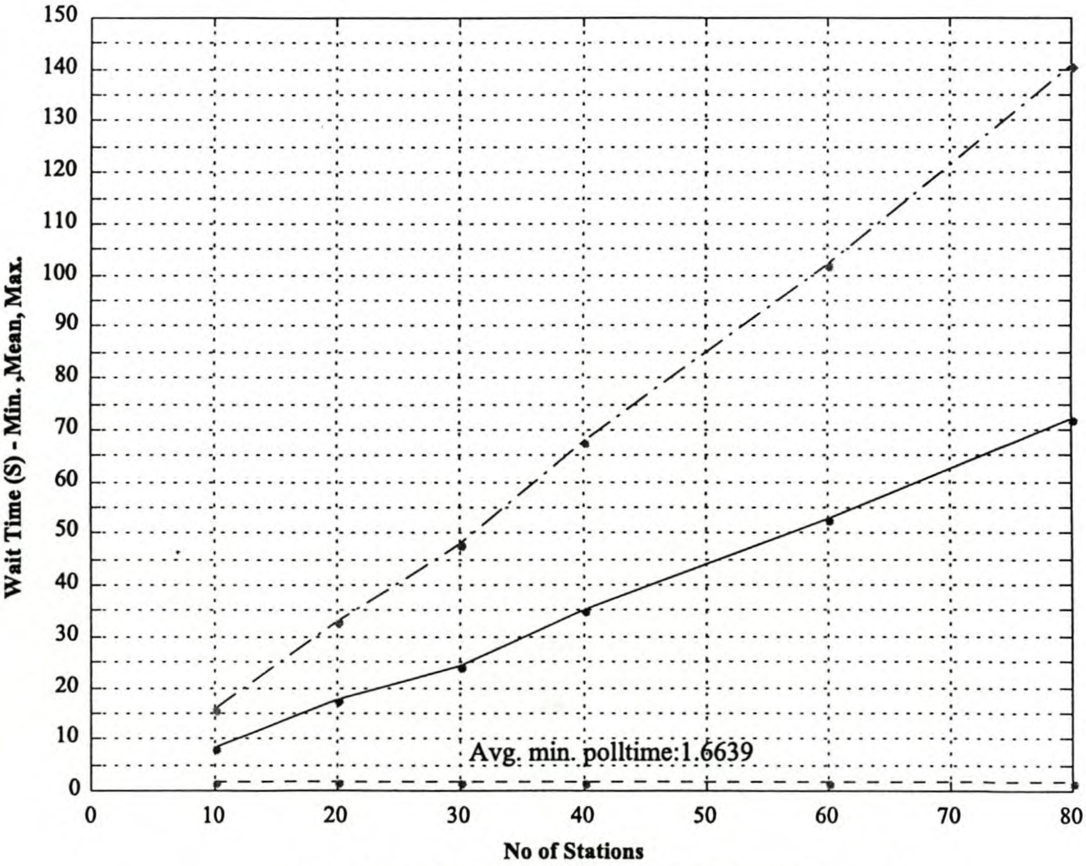


Fig. 5.14 : Wait times - R-R Poll, 1152 Data bits, 5% Burst noise

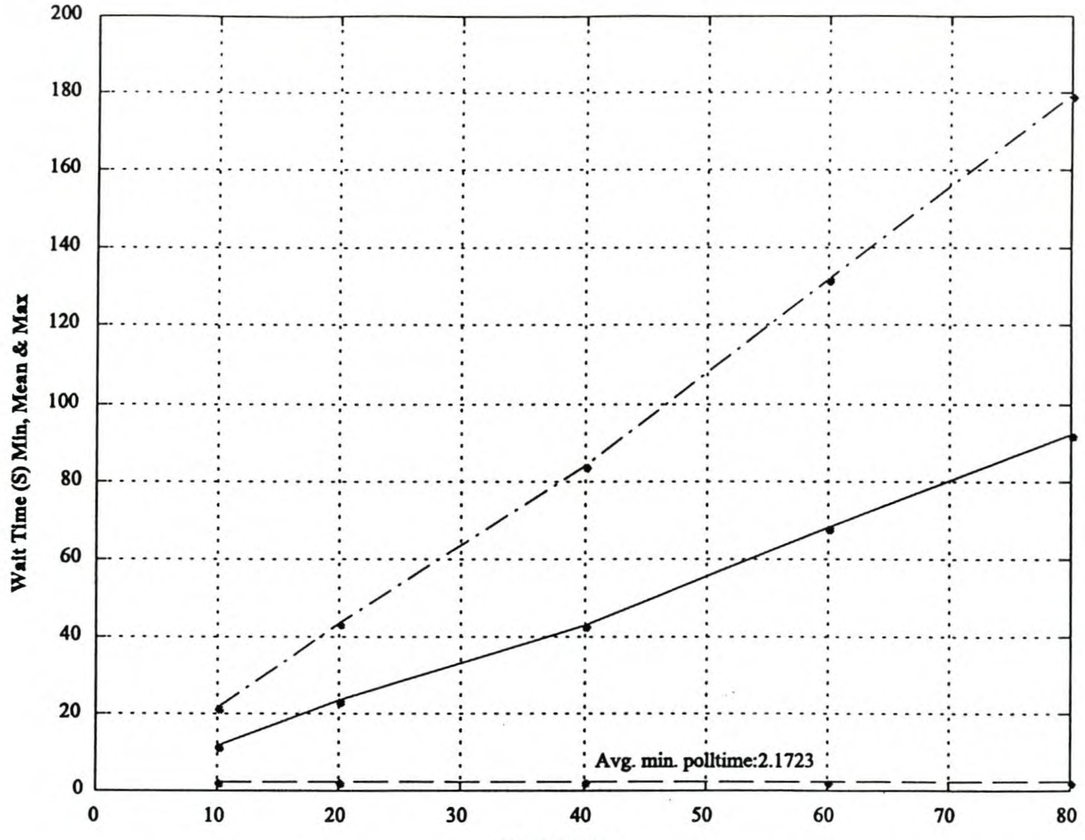


Fig. 5.15 : Wait times - RRP, 1152 Data bits,10% Burst Noise

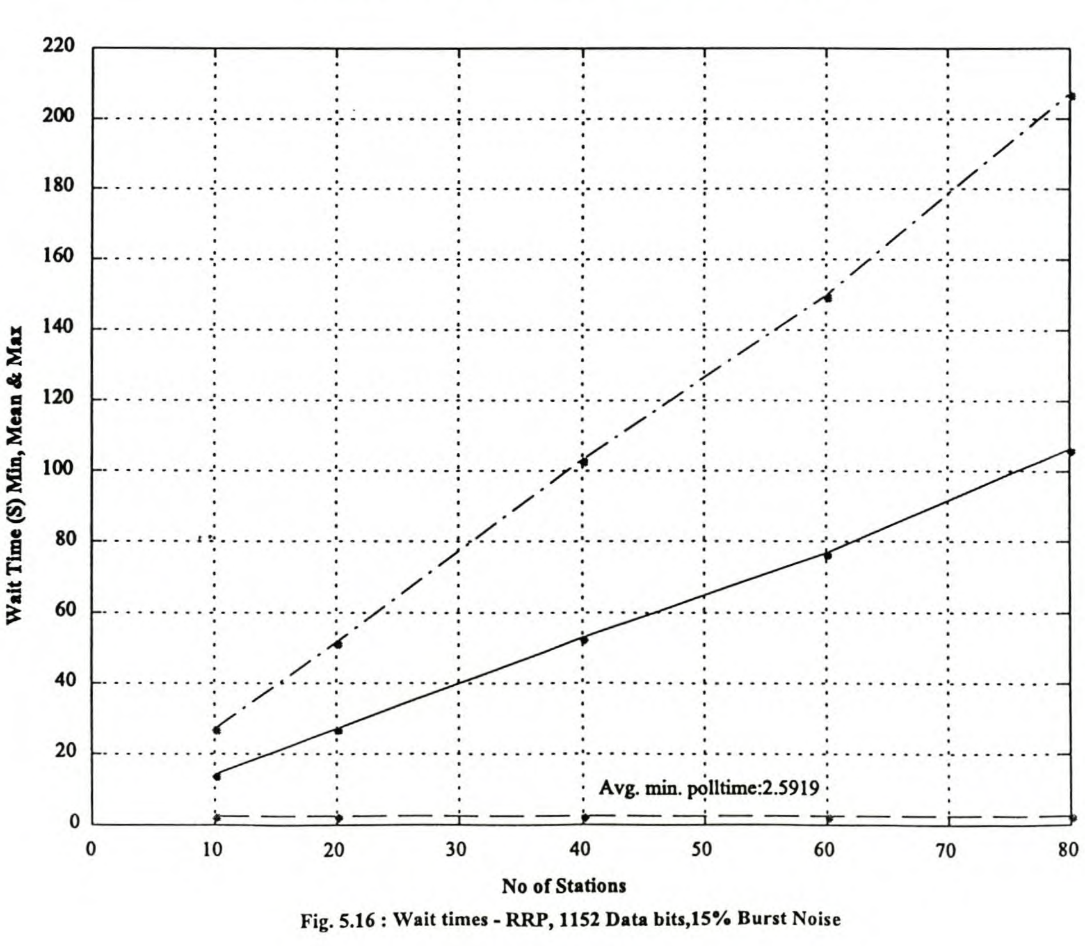


Fig. 5.16 : Wait times - RRP, 1152 Data bits,15% Burst Noise

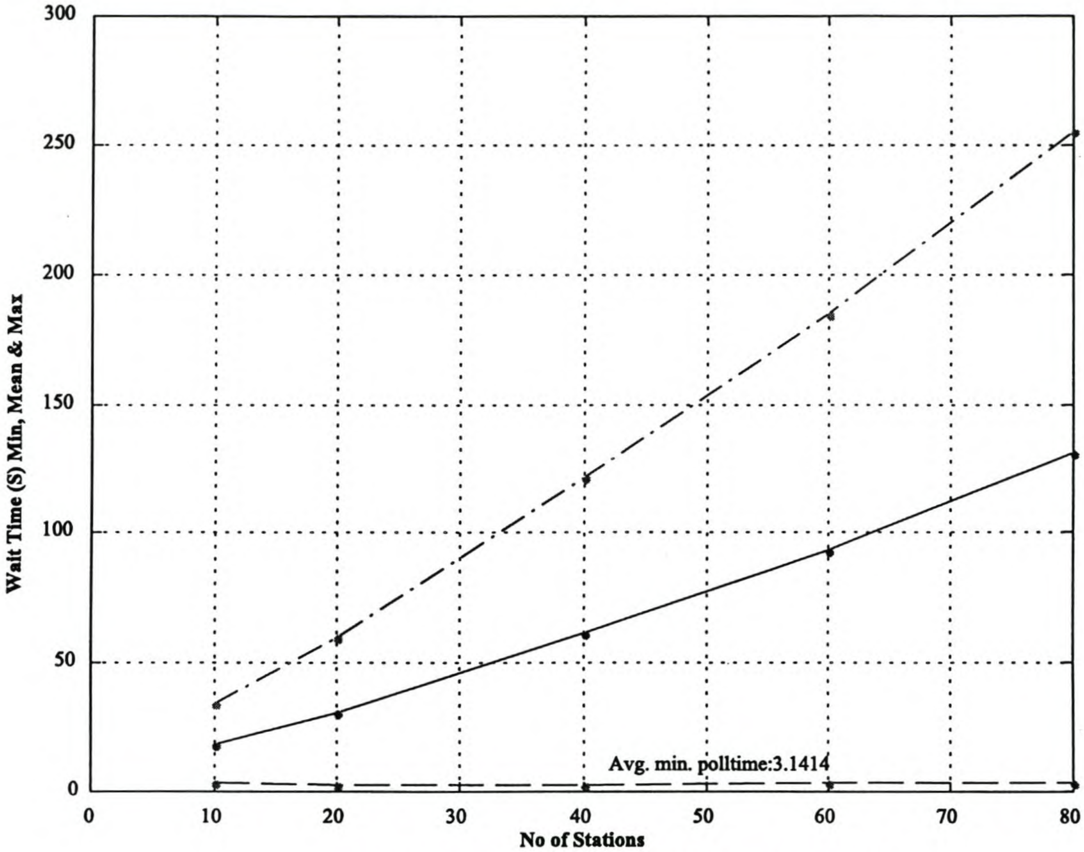


Fig. 5.17 : Wait times - RRP, 1152 Data bits, 20% Burst Noise

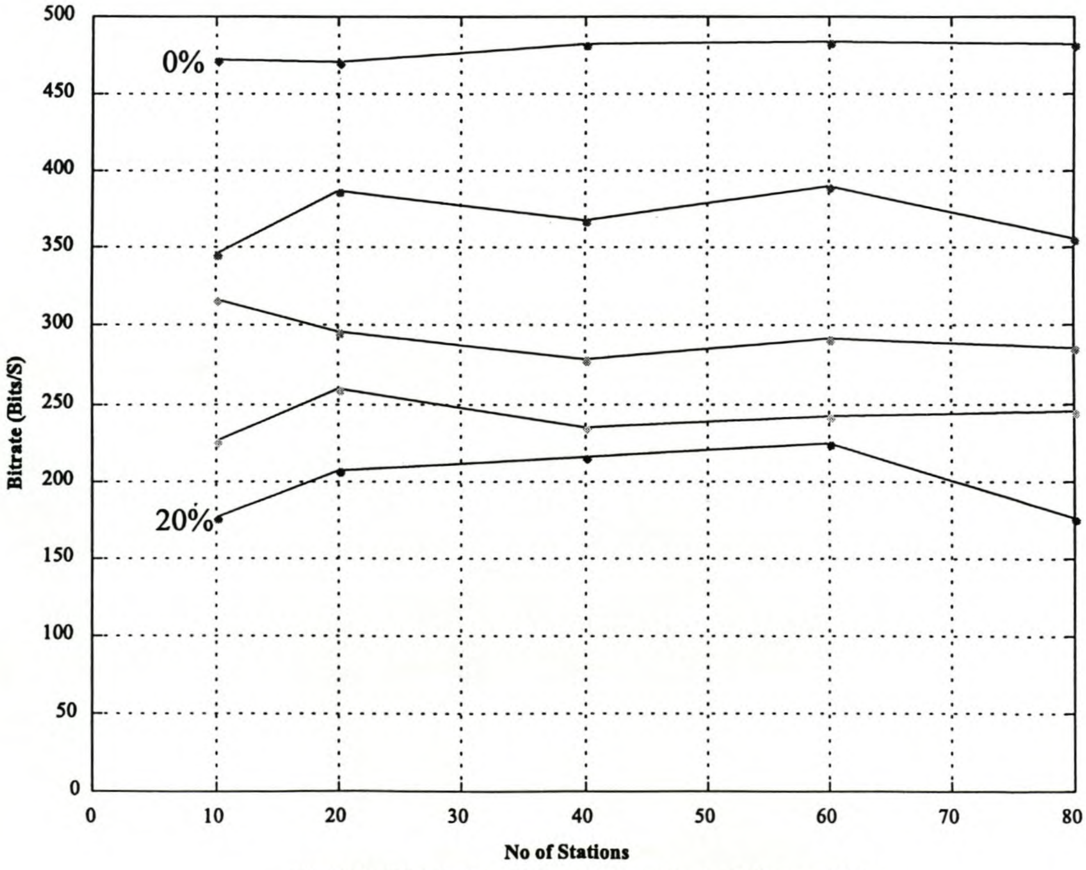


Fig. 5.18 : Eff. Bitrates - RRP, 1152 Data bits, 0 - 20% Burst Noise

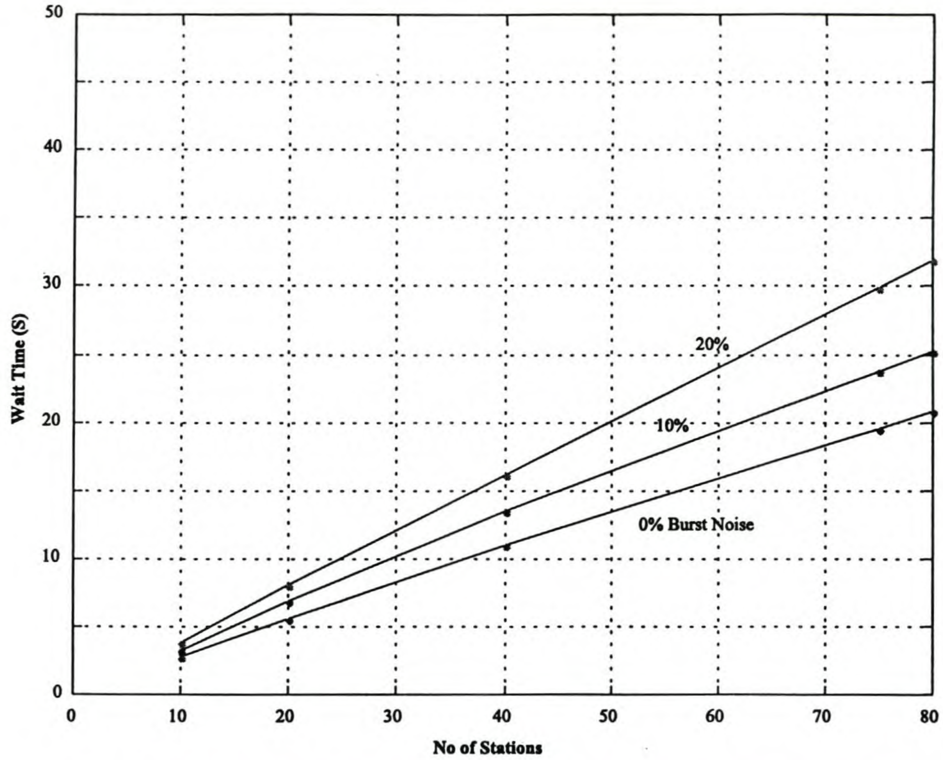


Fig.5.19 : Mean Wait Times - CSMA, 384 Data bits, 0 - 20% Burst Noise, Backoff = 3,5x t-o max

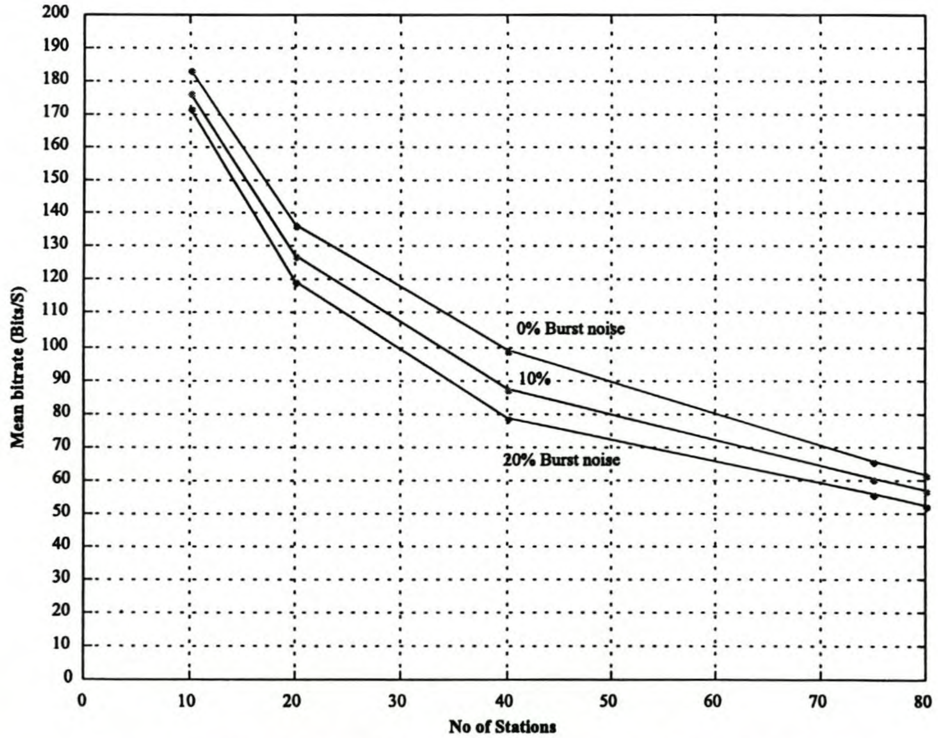


Fig.5.20 : Eff. Bitrate - CSMA, 384 Data bits, 0-20% Burst Noise, Backoff = 3,5x t-o max

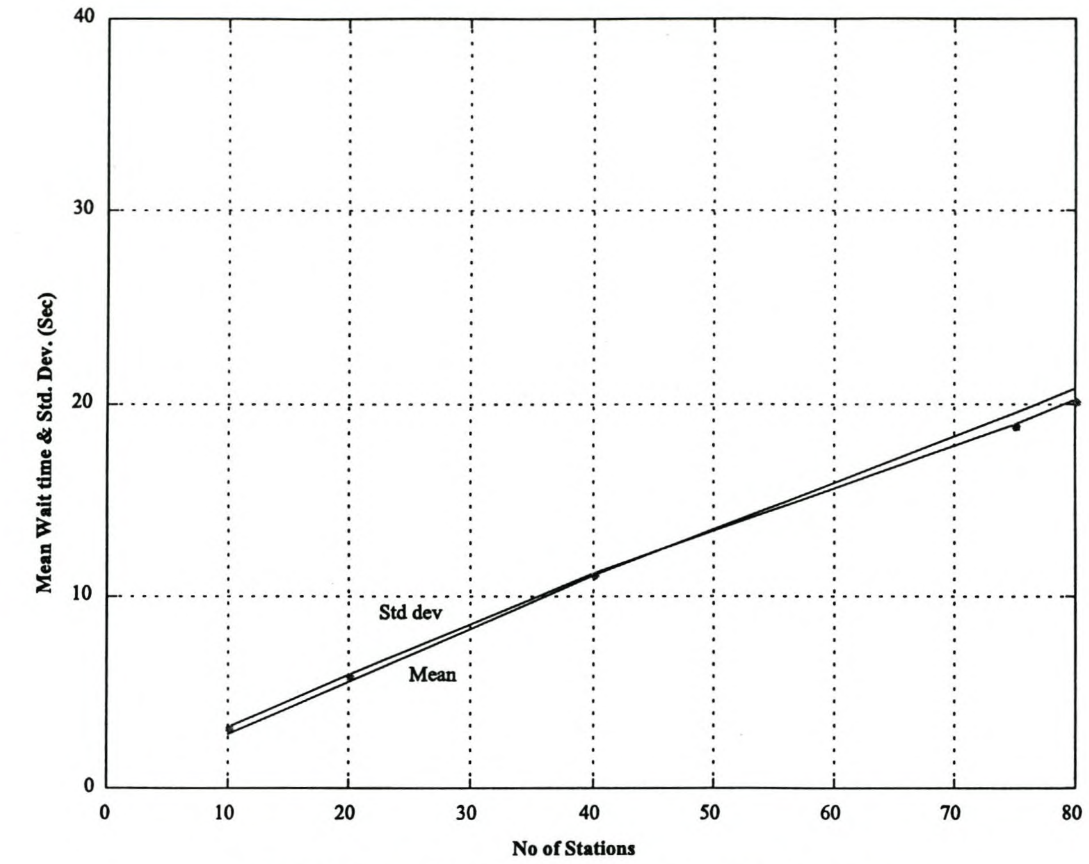


Fig. 5.21a : Mean, & Std Dev - CSMA, 384 Data bits,Backoff = 3,5x t-o max

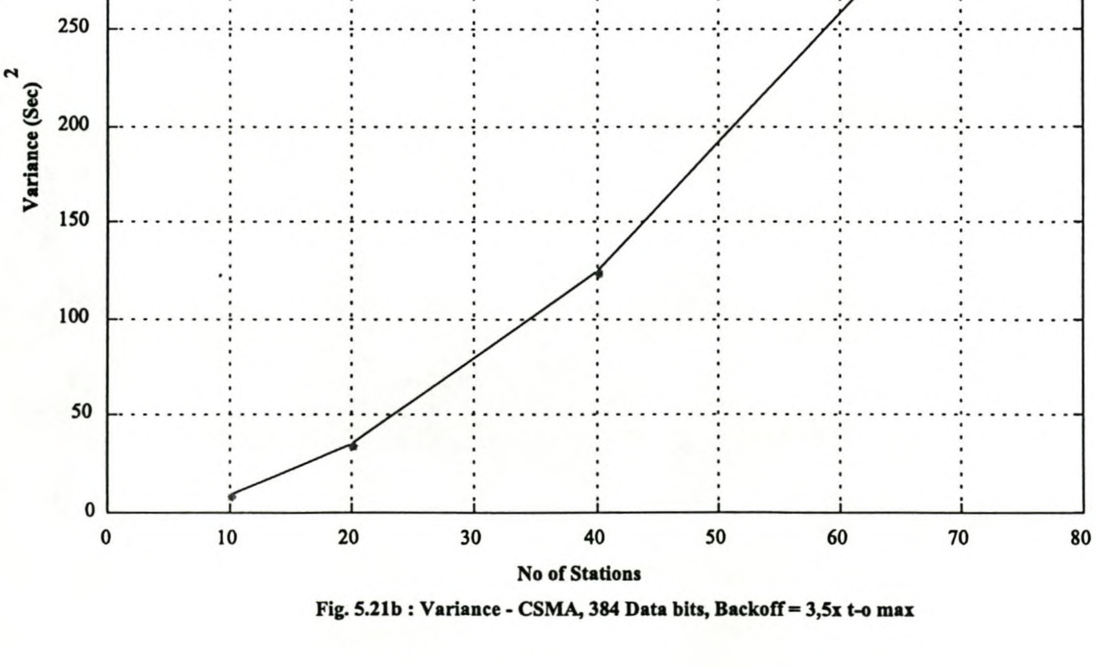


Fig. 5.21b : Variance - CSMA, 384 Data bits, Backoff = 3,5x t-o max

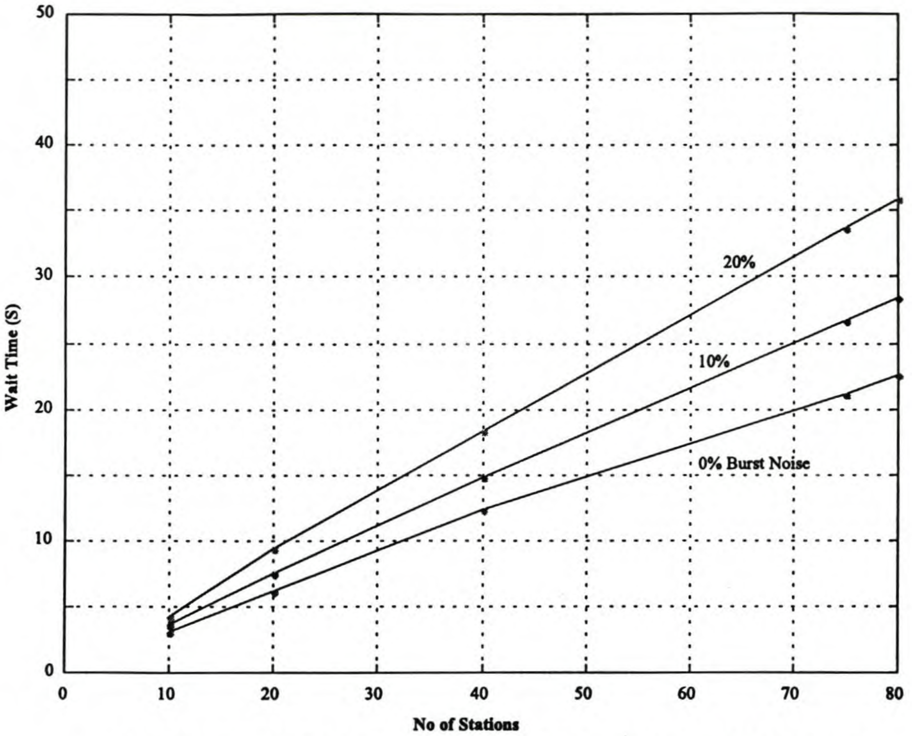


Fig.5.22 : Mean Wait Times - CSMA, 640 Data bits, 0 - 20% Burst Noise, Backoff = 3,5x max t-out

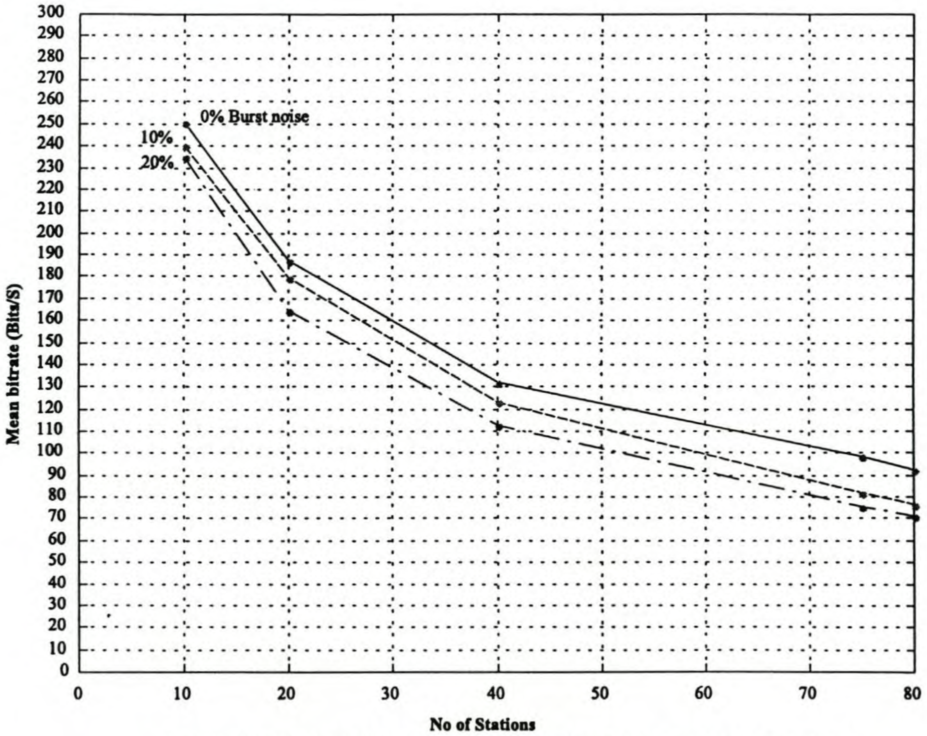


Fig.5.23 : Eff. Bitrate - CSMA, 640 Data bits, 0-20% Burst Noise, Backoff = 3,5x max t-out

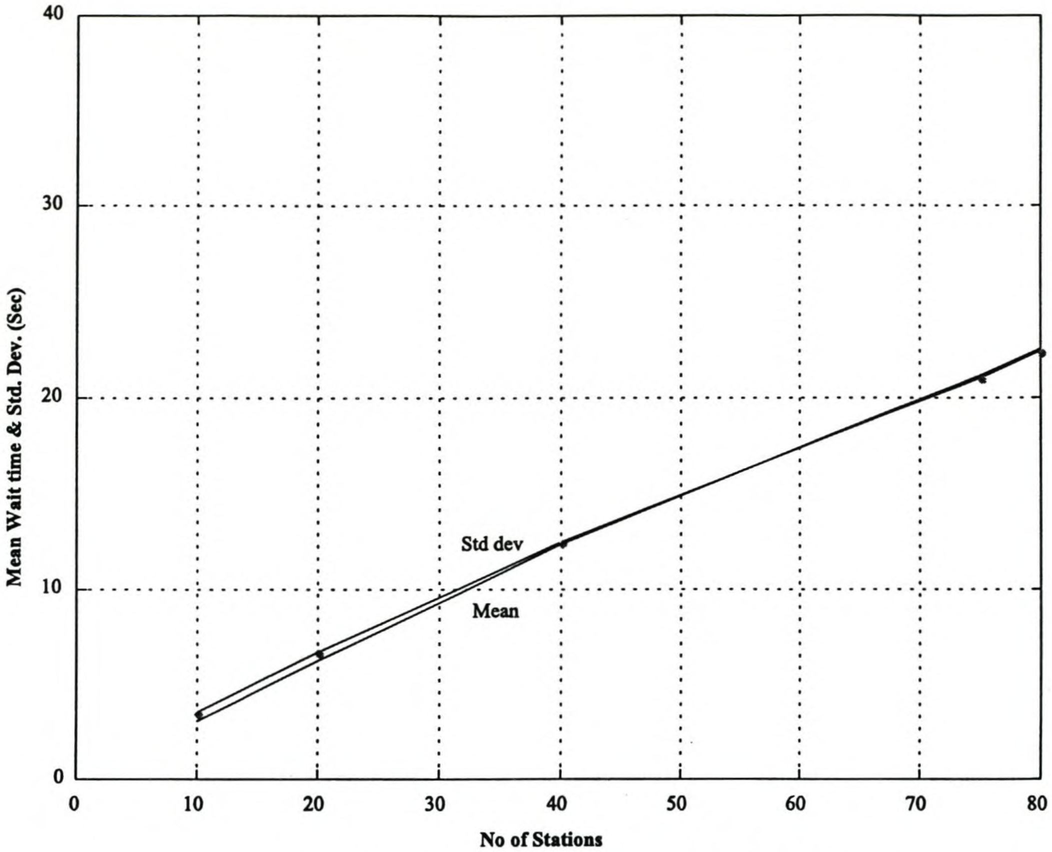


Fig.5.24a : Mean, & Std Dev - CSMA, 640 Data bits, Backoff = 3,5x t-o max

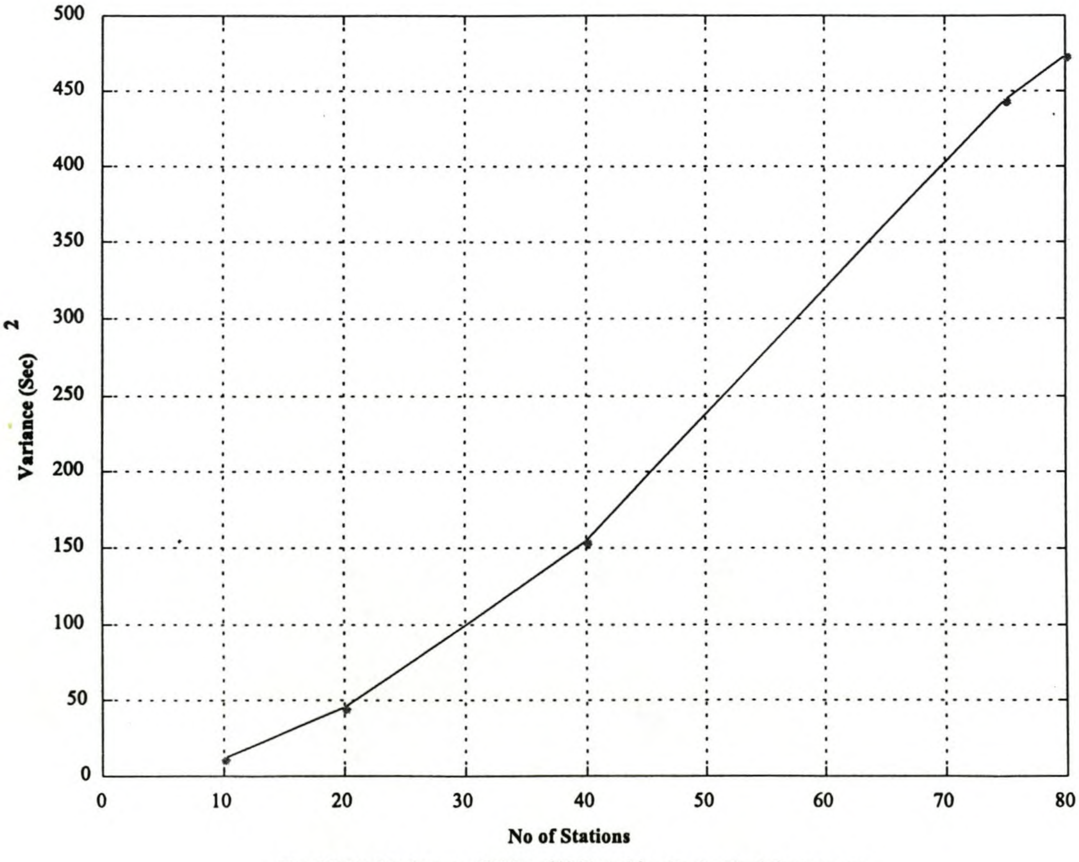


Fig.5.24b : Variance - CSMA, 640 Data bits, Backoff = 3,5x t-o max

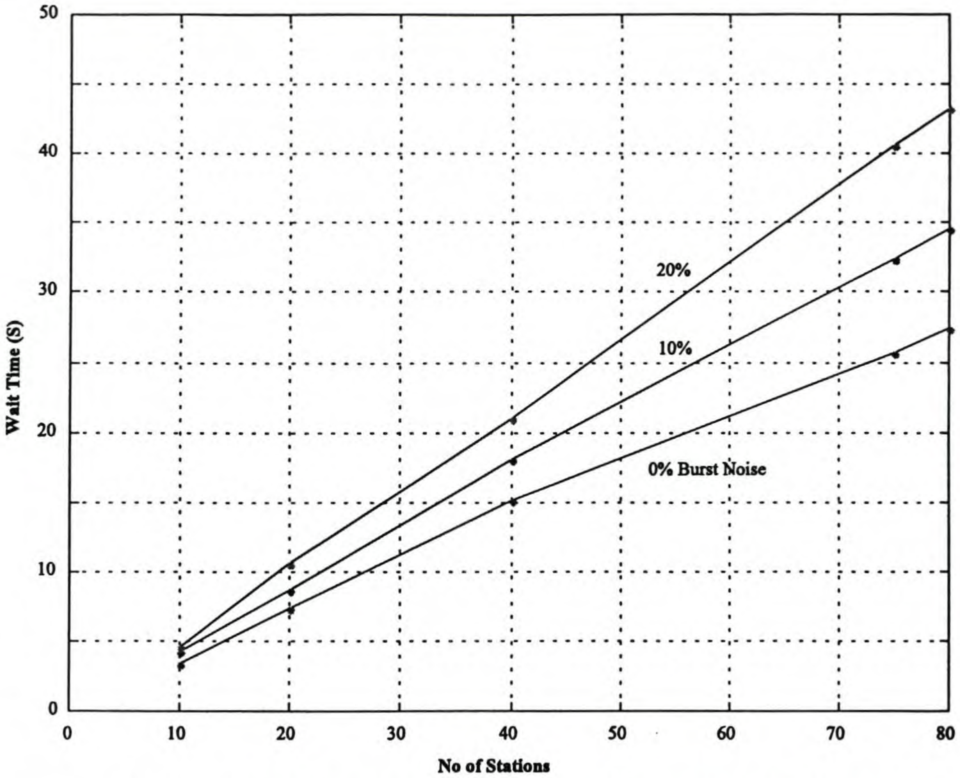


Fig. 5.25 : Mean Wait Times - CSMA, 1152 Data bits, 0 - 20% Burst Noise, Backoff = 3,5x t-o max

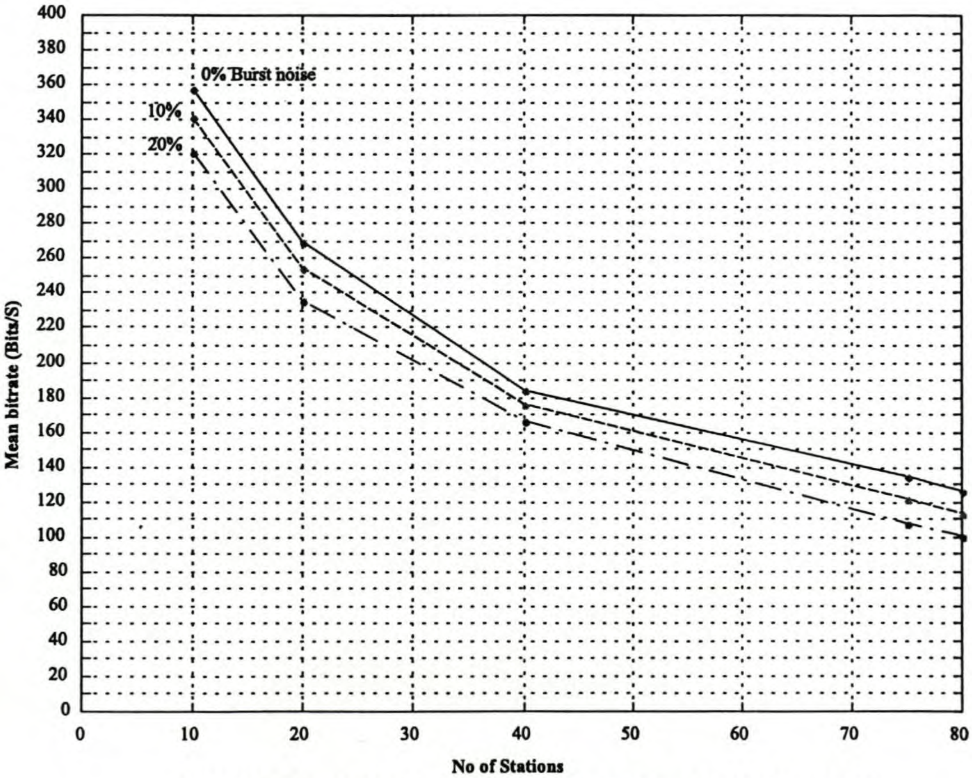


Fig.5.26 : Eff. Bitrate - CSMA, 1152 Data bits, 20% Burst noise, Backoff = 3,5x t-o max

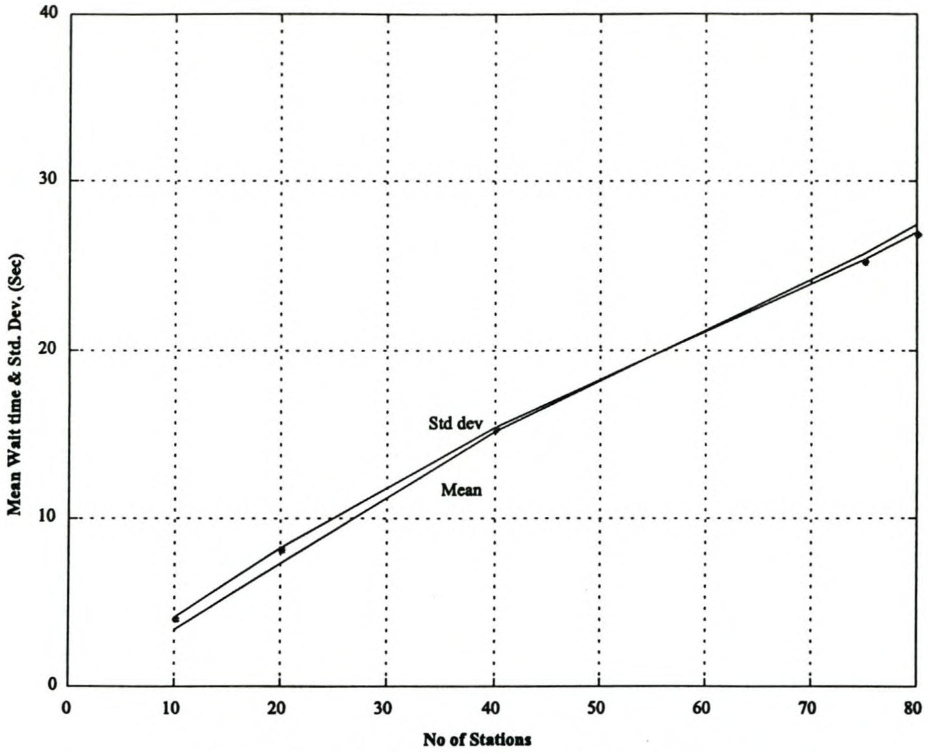


Fig.5.27a : Mean, & Std Dev - CSMA, 1152 Data bits,Backoff = 3,5x t-o max

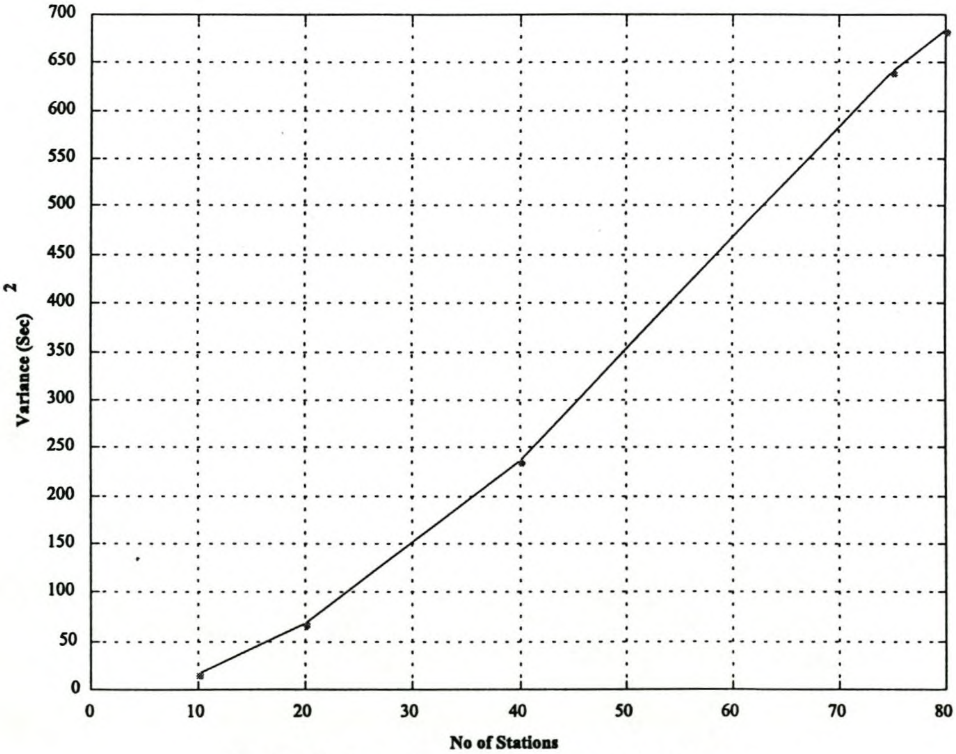


Fig. 5.27b : Variance - CSMA, 1152 Data bits, Backoff = 3,5x t-o max

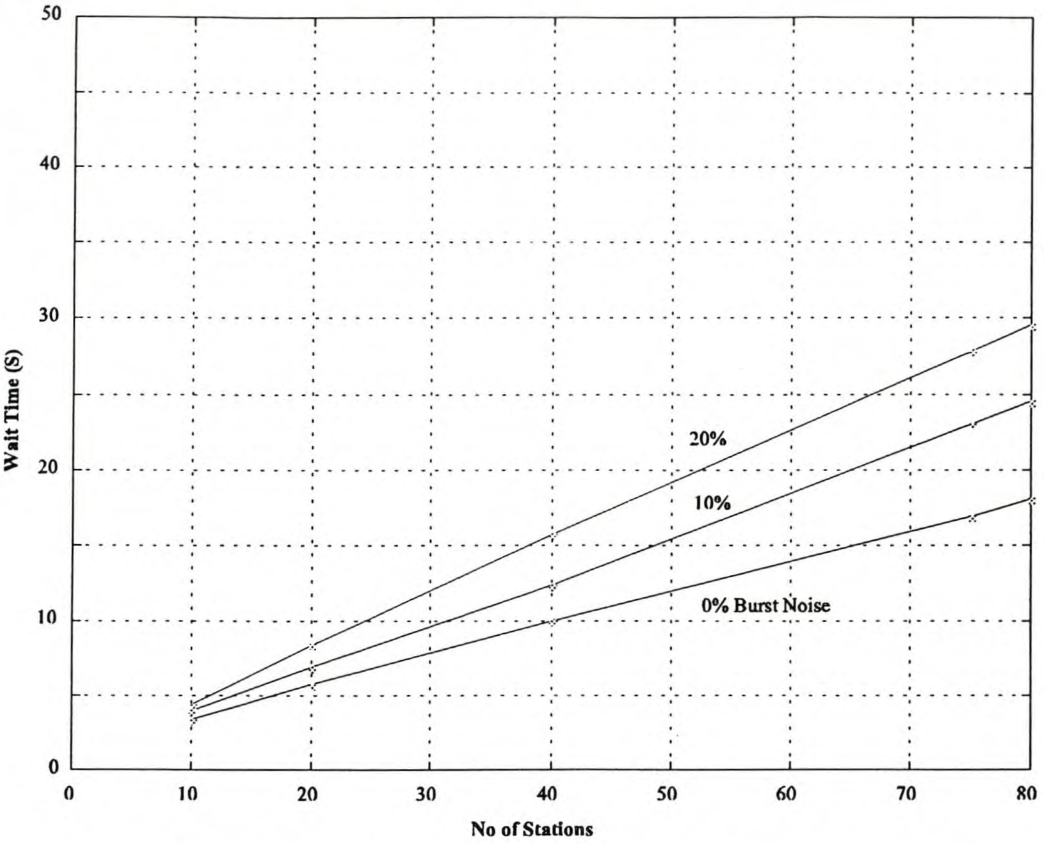


Fig.5.28 : Mean Wait Times - CSMA, 384 Data bits, 0 - 20% Burst Noise, Backoff = 0,5x max t-out

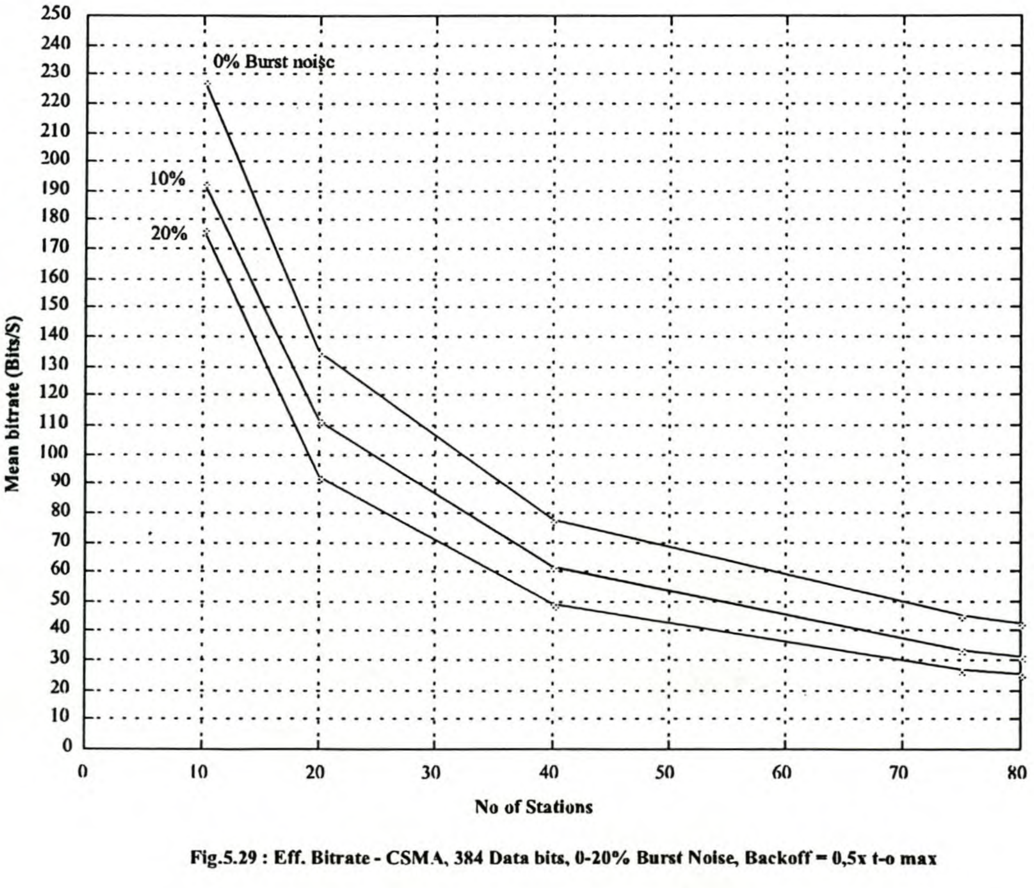


Fig.5.29 : Eff. Bitrate - CSMA, 384 Data bits, 0-20% Burst Noise, Backoff = 0,5x t-o max

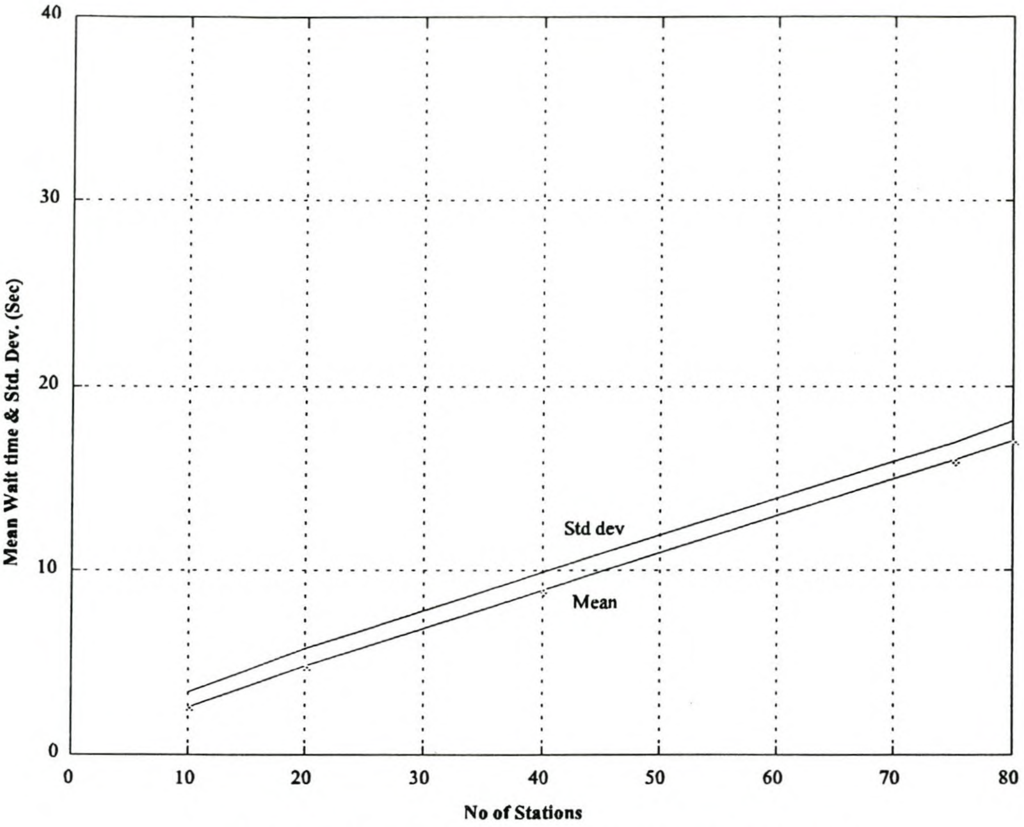


Fig.5.30a : Mean, & Std Dev - CSMA, 384 Data bits,Backoff = 0,5x t-o max

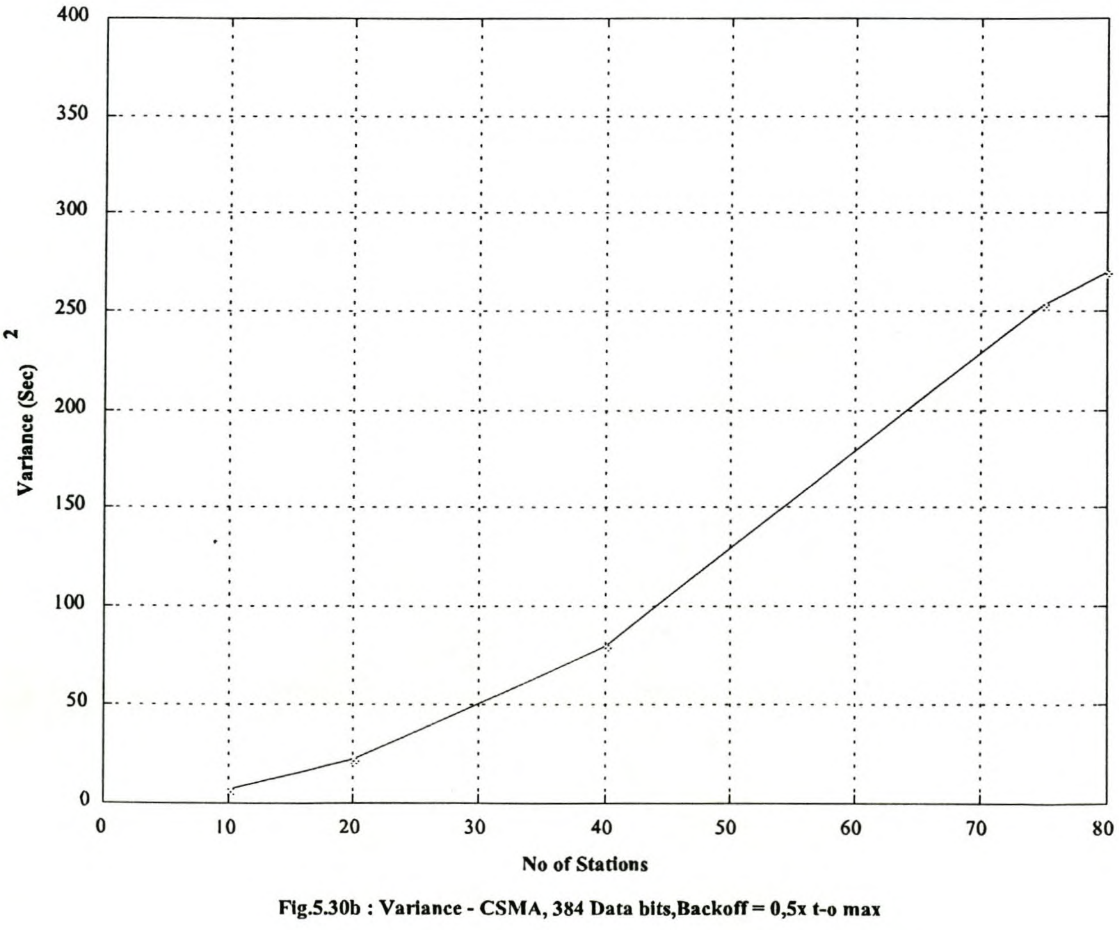


Fig.5.30b : Variance - CSMA, 384 Data bits,Backoff = 0,5x t-o max

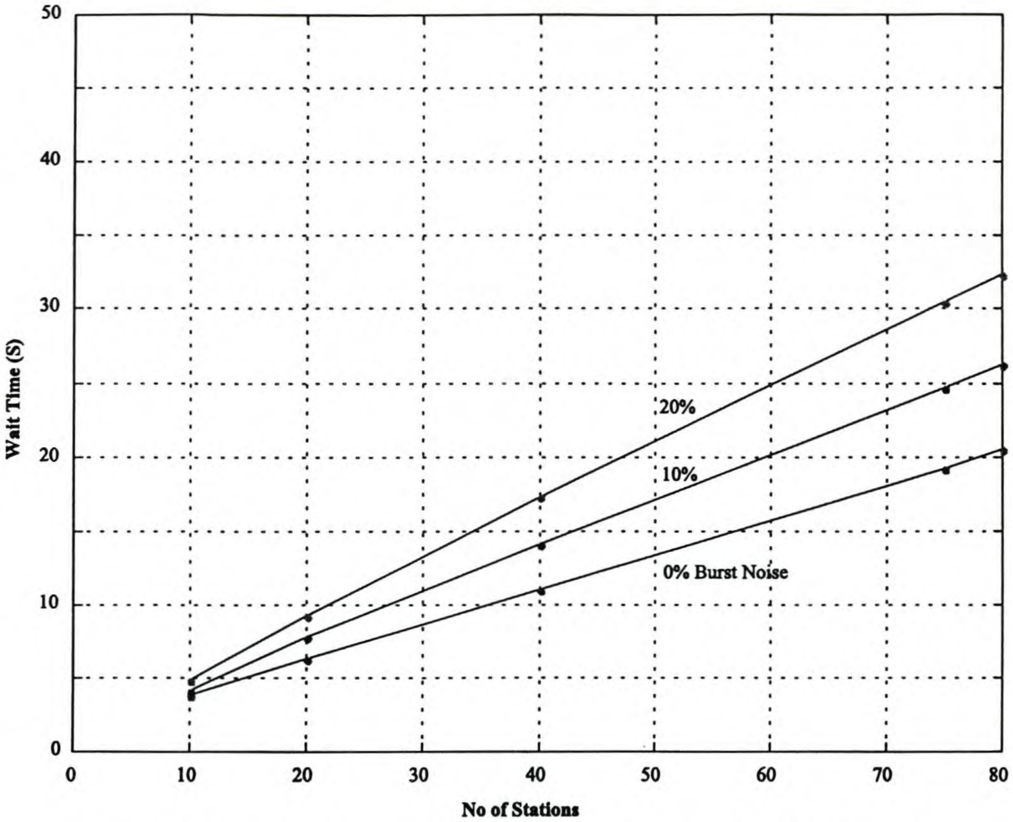


Fig.5.31 : Mean Wait Times - CSMA, 640 Data bits, 0 - 20% Burst Noise, Backoff = 0,5x max t-out

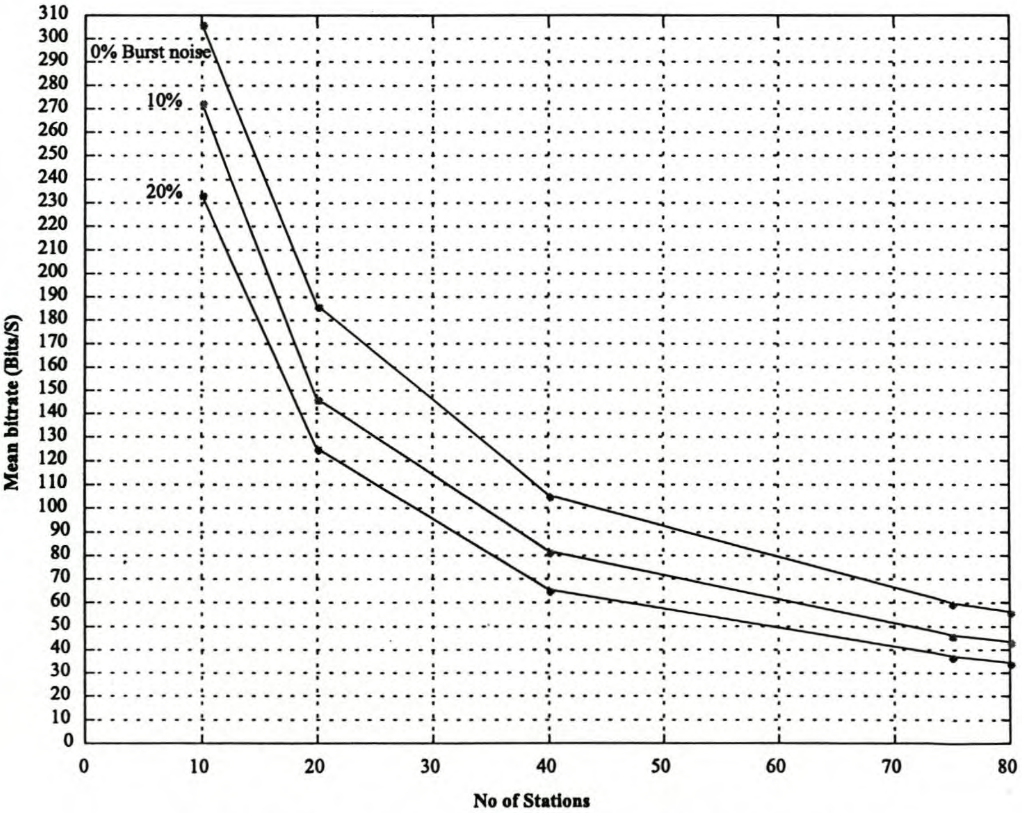


Fig. 5.32: Eff. Bitrate - CSMA, 640 Data bits,0-20% Burst Noise, Backoff = 0,5x t-o max

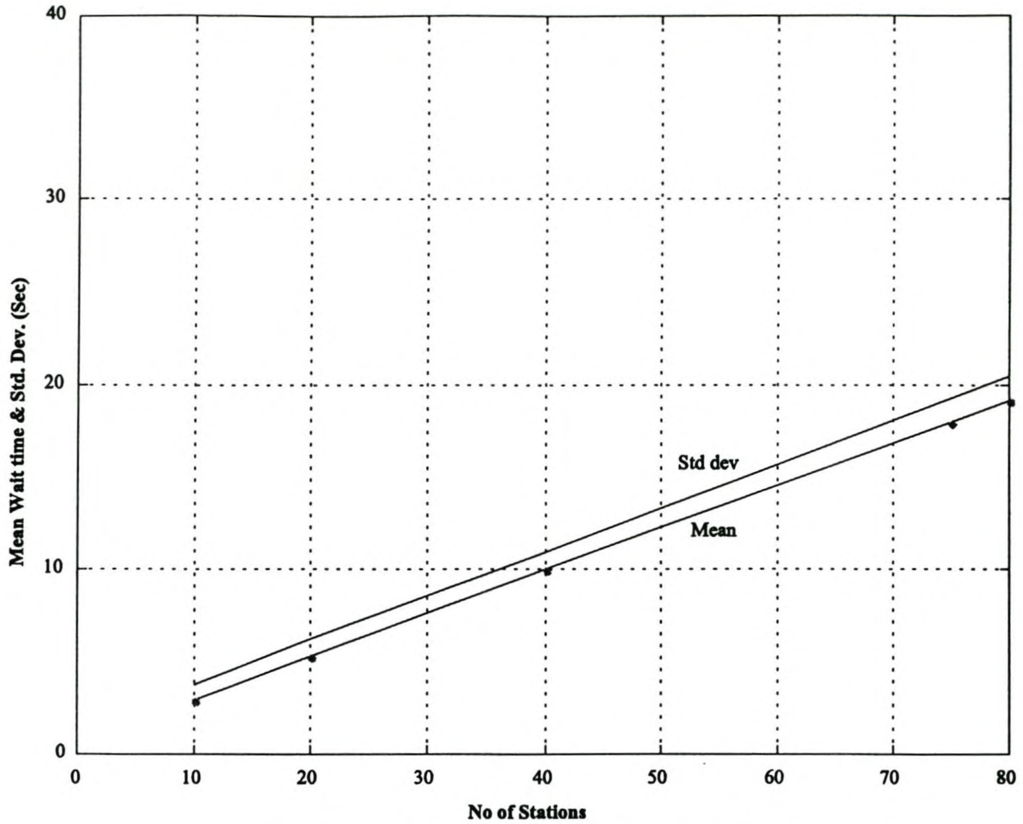


Fig.5.33a : Mean, & Std Dev - CSMA, 640 Data bits, Backoff = 0,5x t-o max

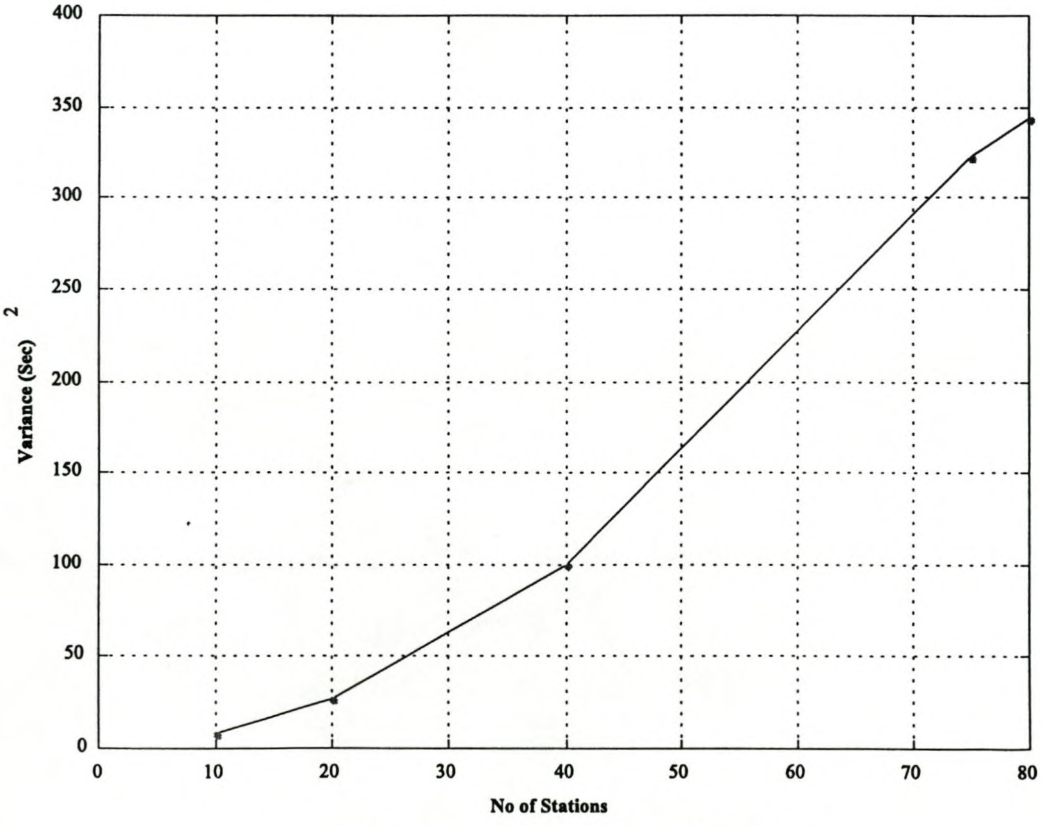


Fig.5.33b : Variance - CSMA, 640 Data bits, Backoff = 0,5x t-o max

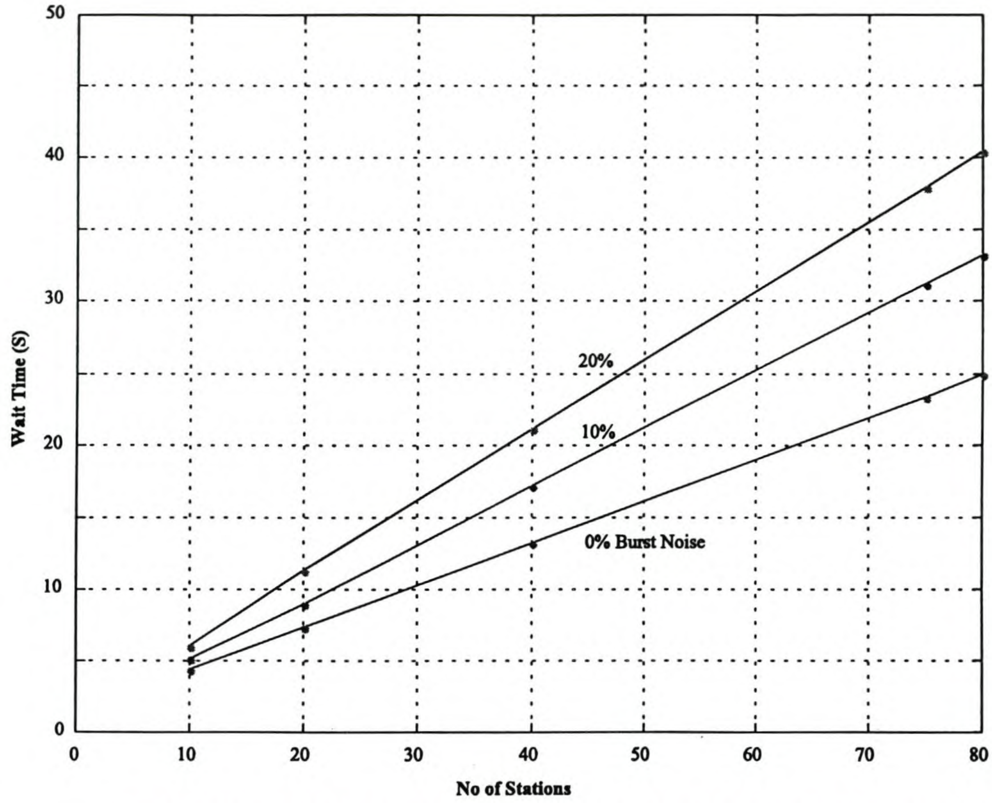


Fig.5.34 : Mean Wait Times - CSMA, 1152 Data bits, 0 - 20% Burst Noise, Backoff = 0,5x max t-out

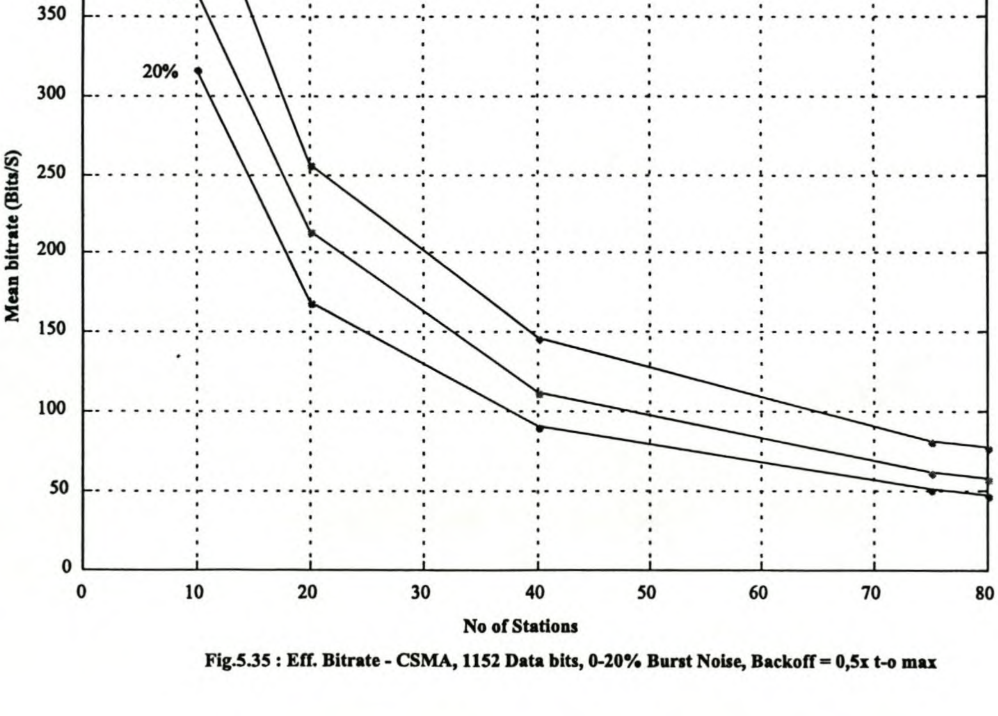


Fig.5.35 : Eff. Bitrate - CSMA, 1152 Data bits, 0-20% Burst Noise, Backoff = 0,5x t-o max

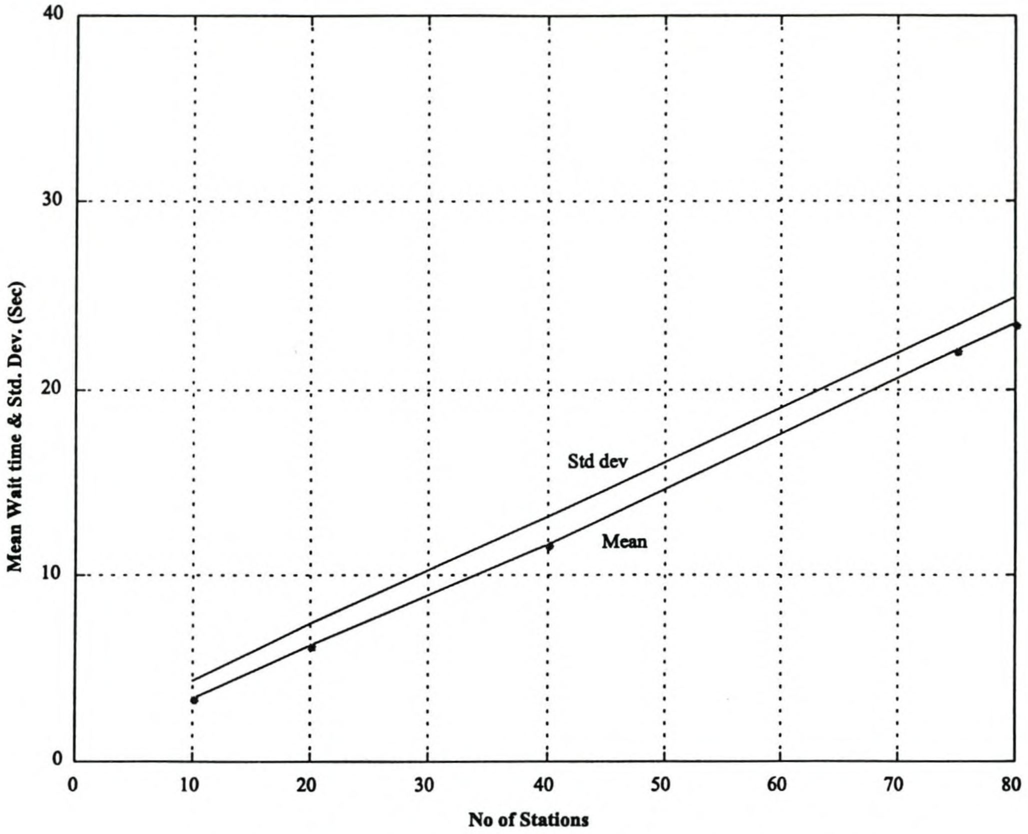


Fig.5.36a : Mean, & Std Dev - CSMA, 1152 Data bits, Backoff = 0,5x t-o max

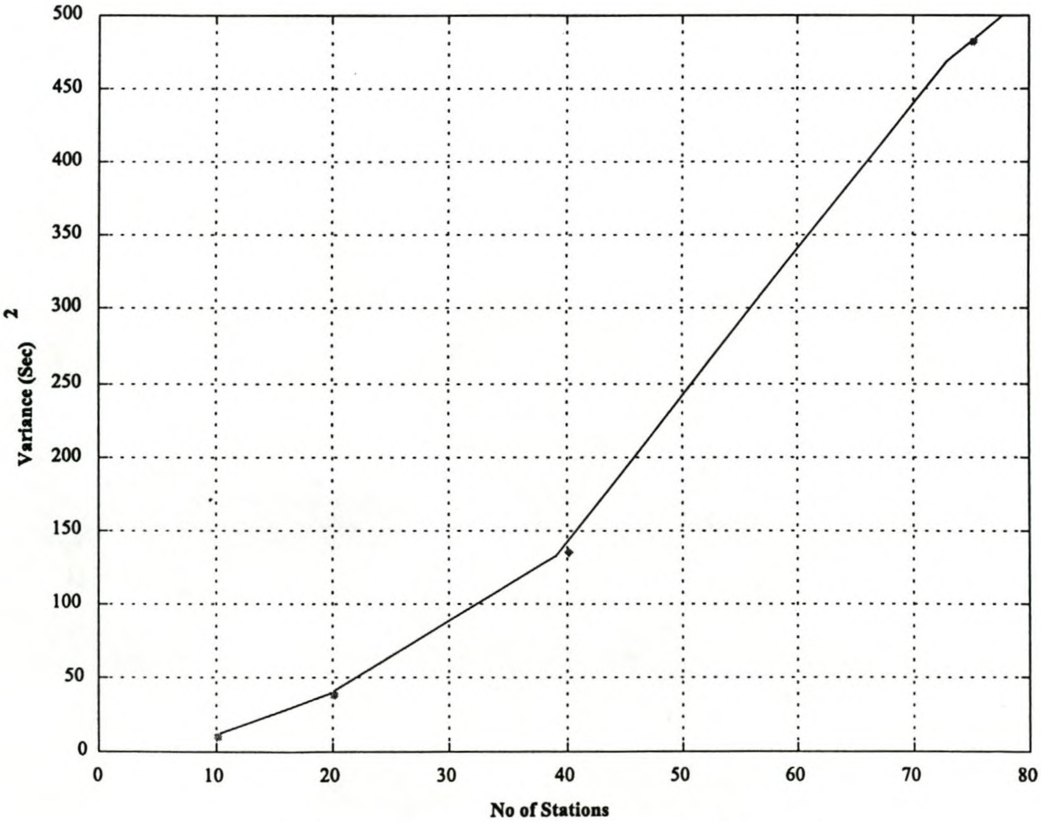


Fig.5.36b : Variance - CSMA, 1152 Data bits,Backoff = 0,5x t-o max

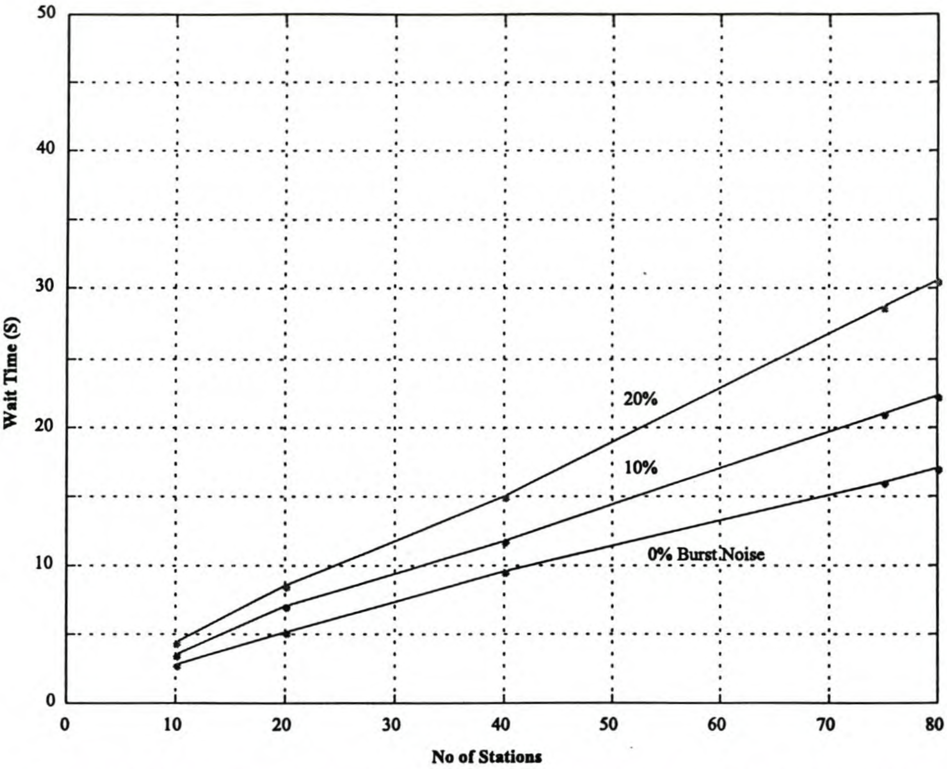


Fig.5.37 : Mean Wait Times - CSMA, 384 Data bits,0 - 20% Burst Noise, BP = 3,5x t-o max, EGI = 1,5x RRP tw-min

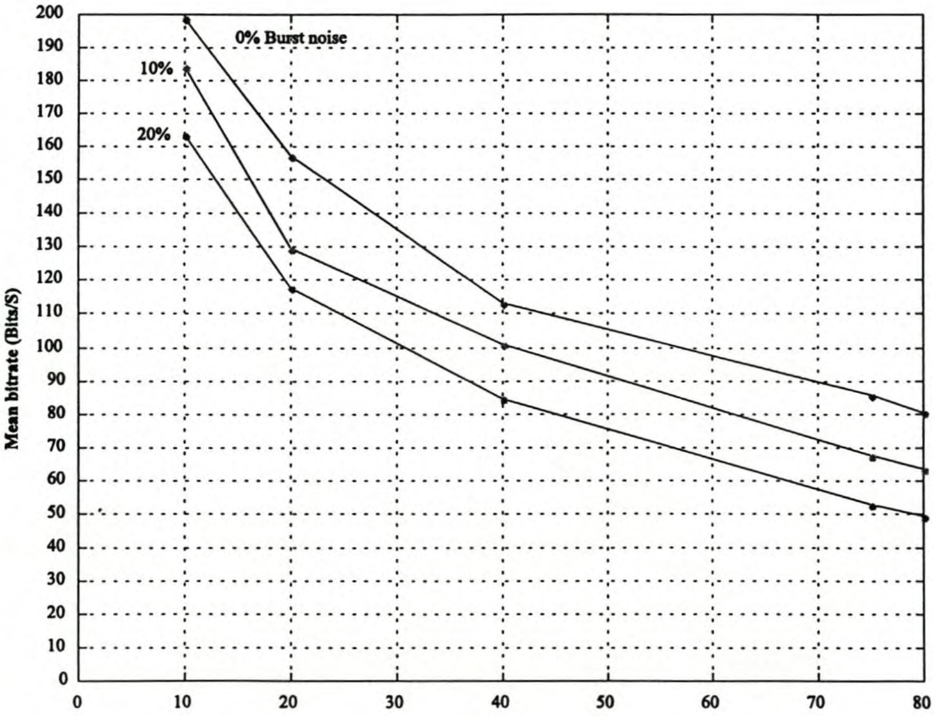


Fig.5.38 : Eff. Bitrate - CSMA, 384 Data bits,0-20% Burst Noise, BP = 3,5x t-o max, EGI = 1,5x RRP tw-min

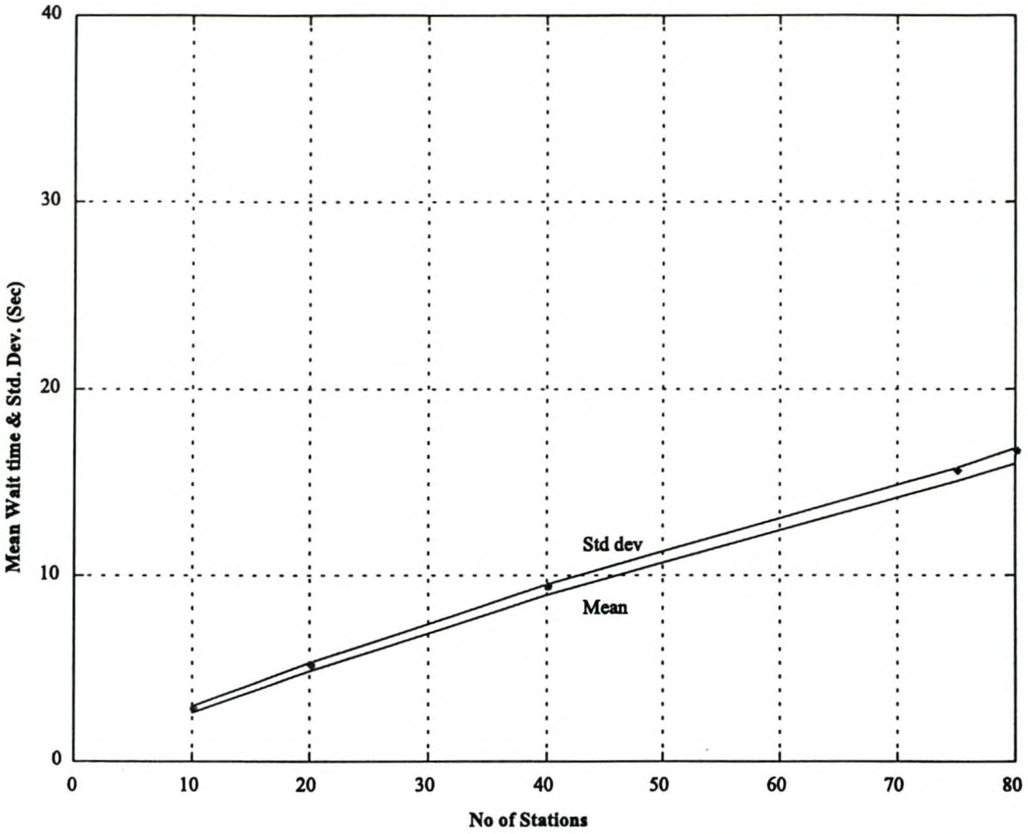


Fig.5.39a : Mean, & Std Dev - CSMA, 384 Data bits,BP = 3,5x t-o max, EGI = 1,5x RRP tw-min

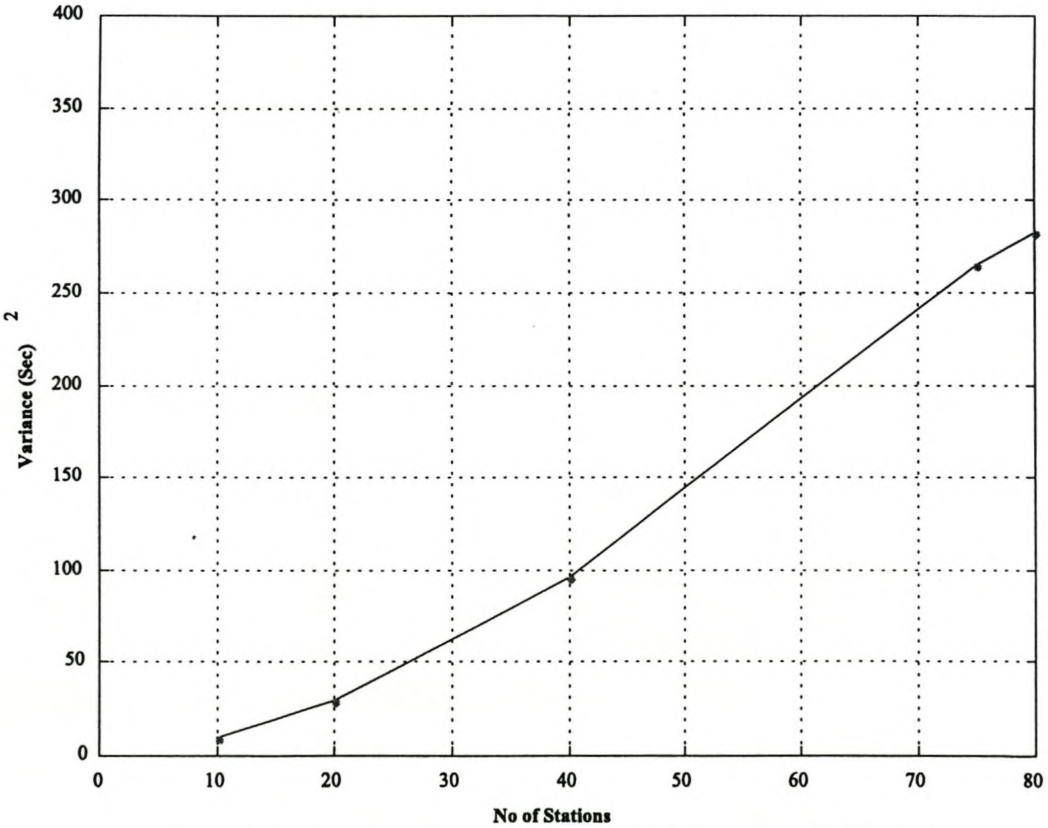


Fig.5.39b : Variance - CSMA, 384 Data bits,Backoff = 3,5x t-o max, EGI = 1,5x RRP tw-min

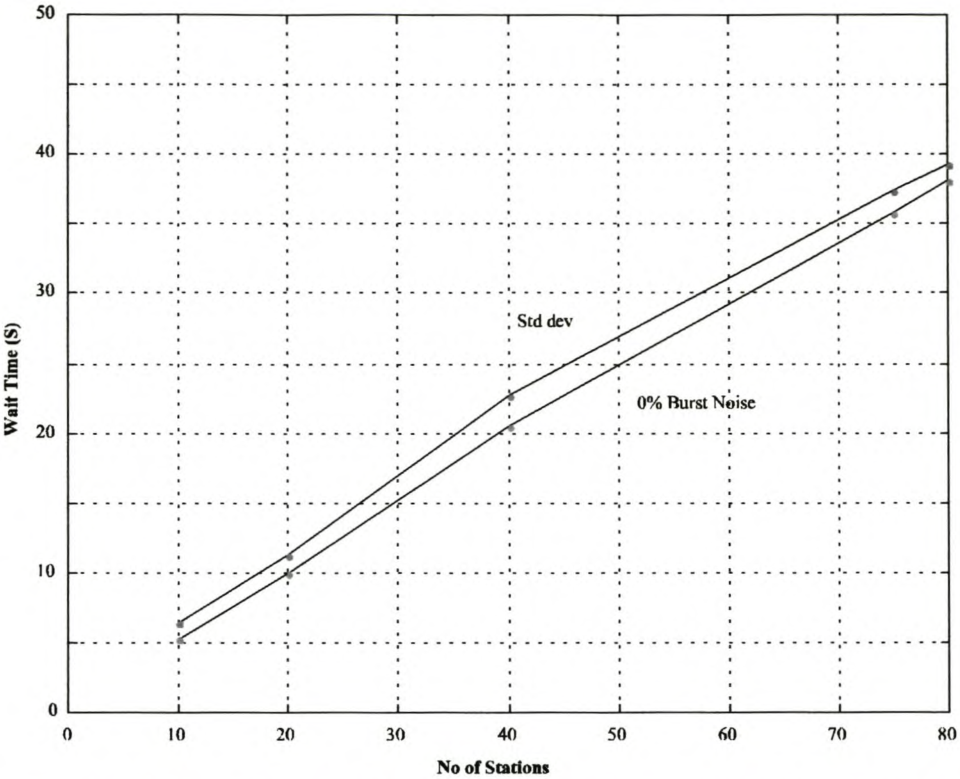


Fig. 5.40 : Mean Wait Times - CSMA, 384 Data bits,0% Burst Noise, EGI = 0.67x RRP tw-min, Backoff = 3,5x max t-out

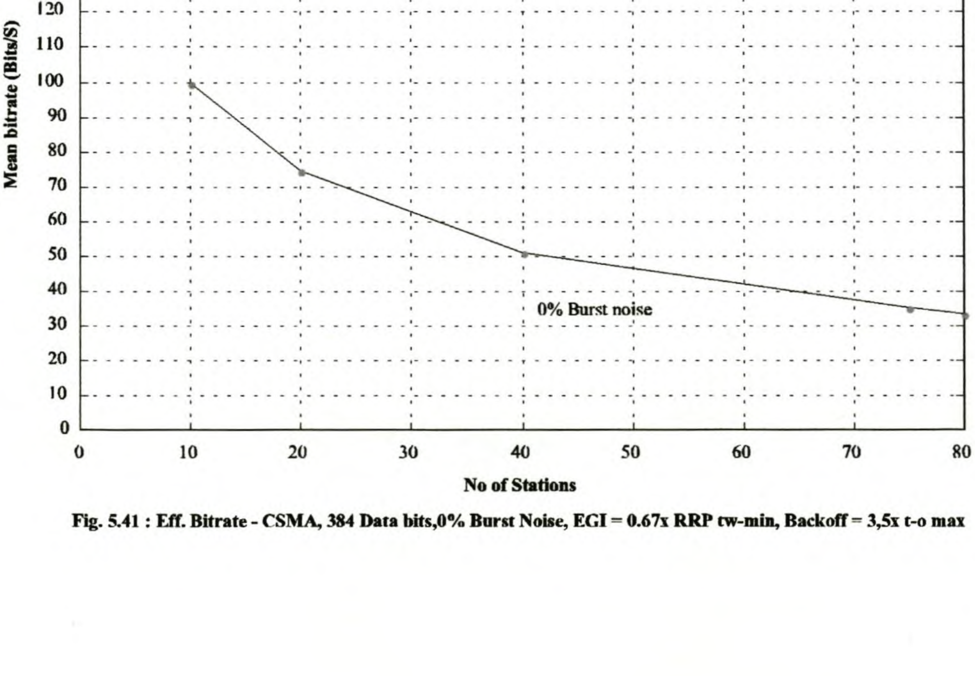


Fig. 5.41 : Eff. Bitrate - CSMA, 384 Data bits,0% Burst Noise, EGI = 0.67x RRP tw-min, Backoff = 3,5x t-o max

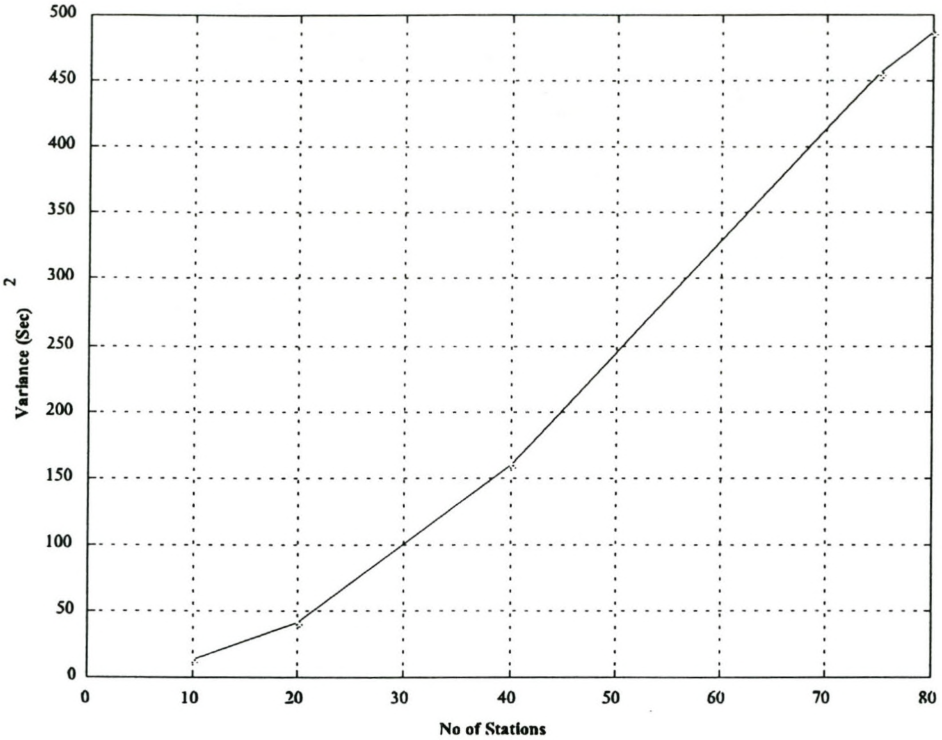


Fig.5.42 : Variance - CSMA, 384 Data bits, EGI = 0.67x RRP tw-max, Backoff = 3,5x t-o max

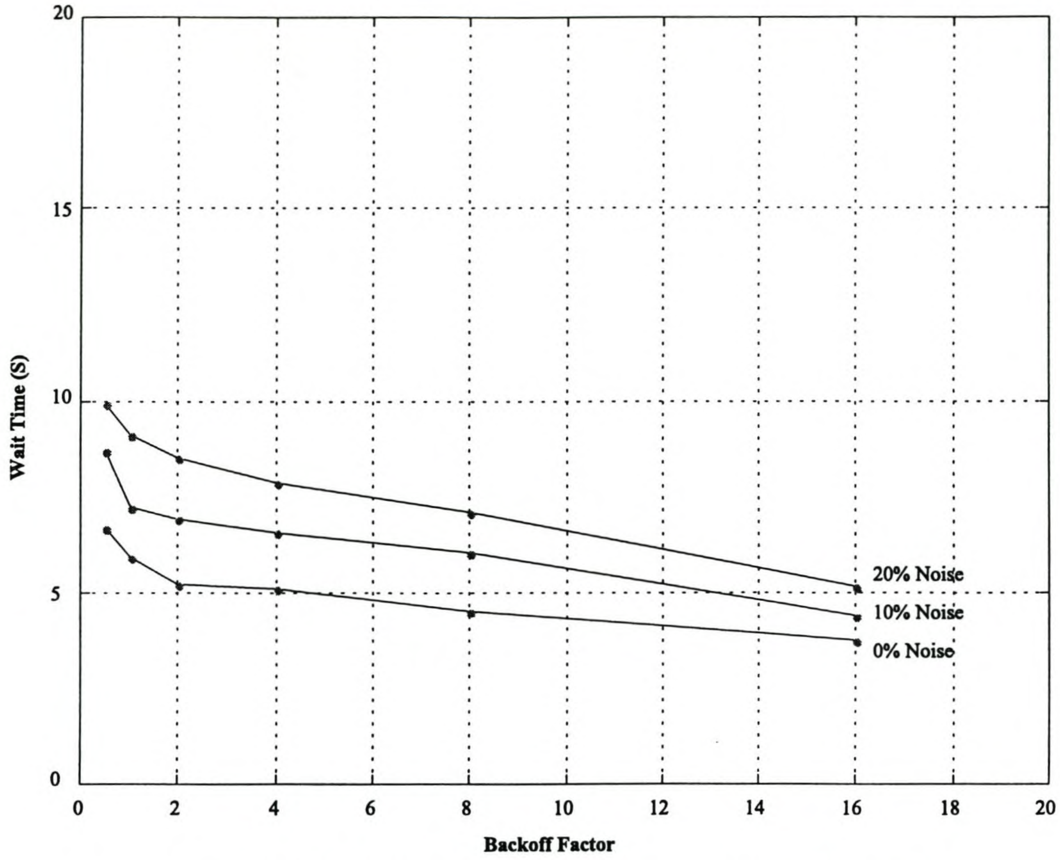


Fig. 5.43 (a): Wait times - CSMA, 20 Stations, 384 bits with Var. Backoff Times (Initial insufficiently short cycle times)

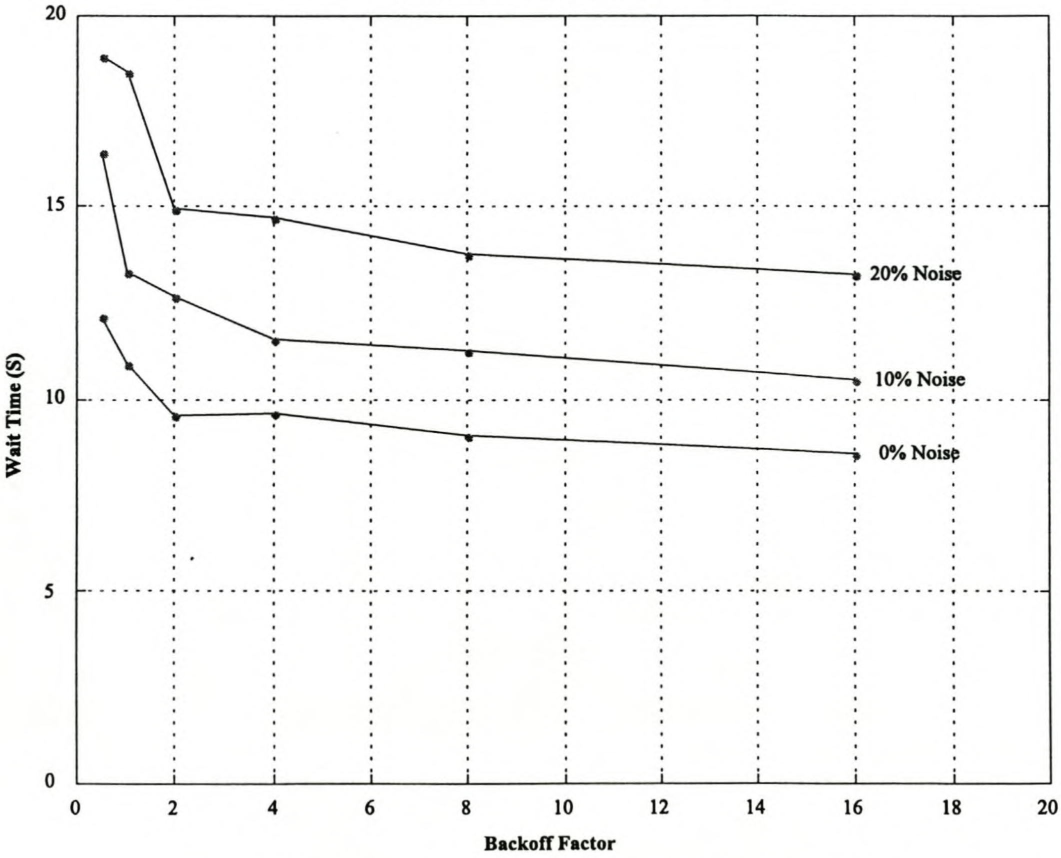


Fig. 5.43 (b): Wait times - CSMA, 40 Stations, 384 bits with Var. Backoff Times (Initial insufficiently short cycle times)

Chapter 6

Simplified Simulation Models

6.1 General

It was attempted to render the simulation models discussed in prior Chapters, as realistical as possible, emulating actual hardware and operational conditions down to component and fundamental signal level. While it is felt that this approach provides a very flexible means of performance prediction to within an acceptable degree of confidence, the actual process is very time consuming, with high CPU overhead.

For many applications, it is quite sufficient for this process to be simplified, eg. under conditions of known SNR and associated BER. There may be a further requirement to check even more basic system fundamentals, without the entire Tx/Rx modulating/demodulating process. Queue length, or buffer size, and wait time prediction for simple configurations, are possible examples.

To this end, an attempt was made to simplify the original model, while retaining it's validity under a reduced set of operating parameters.

6.2 CSMA Simplified Model

In order to simplify the software model as previously discussed, the following assumptions and procedures were implemented:

6.2.1 Individual link SNR's would be kept constant and high, eliminating individual probabilistic bit-errors.

6.2.2 Noise spectrum shaping is eliminated, due to 6.2.1 above.

6.2.3 Burst noise occurrence, would be retained as before, this being considered of some importance in practical systems.

6.2.4 The modulation/demodulation sequences would be simplified.

6.2.5 Input signal filtering is ignored. This a particular bonus, as the associated integration routines are quite slow in execution.

6.2.6 Rx error checking is not done on a bit by bit basis. The transmitted sequence is known and used to match the received sequence.

6.2.7 All other conditions of strategy and parameters, such as event generation, time setup and backoff, are retained unchanged.

6.3 Results from Simplified CSMA Model

Particular modulation and handshake sequences for the simplified CSMA model, with and without burst noise occurrence, are shown in Fig's 6.1 and 6.2 respectively. The differences in actual waveform conditioning, as opposed to the approach set out in Chapter 4, are obvious.

The model was tested for the 384 bit data string case, for the same burst noise occurrences as before and a BP $= 3.5 \times t - 0\,\mathrm{max}$. The results of these simulation runs are presented in Fig. 6.3. The results compare favourably with those of the comprehensive model, as depicted in Fig. 5.19, and are sufficiently close. For convenience, the two sets of data are reproduced together. In view of the small differences in measured performance, it was not deemed necessary to repeat the trial for other data string lengths. There is no reason to expect any significant deviation.

6.4 Basic Queue Simulation

As stated above it was considered convenient to create a basic routine which could be used to check fundamental system performance with a given set of basic parameters, such as station count, event generation rate, service time and event arrival/service time distribution.

The model was set up as a finite source queue system, the particulars of which are more fully discussed in Chapter 7. The station count could be set and the event arrival - and service rates varied in accordance with a required mean, in each case. Care was taken to ensure that the event generating routine generated events in accordance with a Poisson distribution. The service times were varied in accordance with the same distribution by varying the string length of individual transactions.

The process was left to run for an extended number of iterations, ie. 100 000. Being not very CPU power dependent, this was not a particularly time consuming operation. During the process, the arrival/service times are recorded, as well as the queue buffer occupation at each event arrival point.

Subsequent to each simulation run, the results were analysed and compared with a figure theoretically calculated by means of a Matlab routine. The comparative results from some typical simulations and the associated Matlab routines are shown in Table 6.1 and plotted in Fig.6.4.

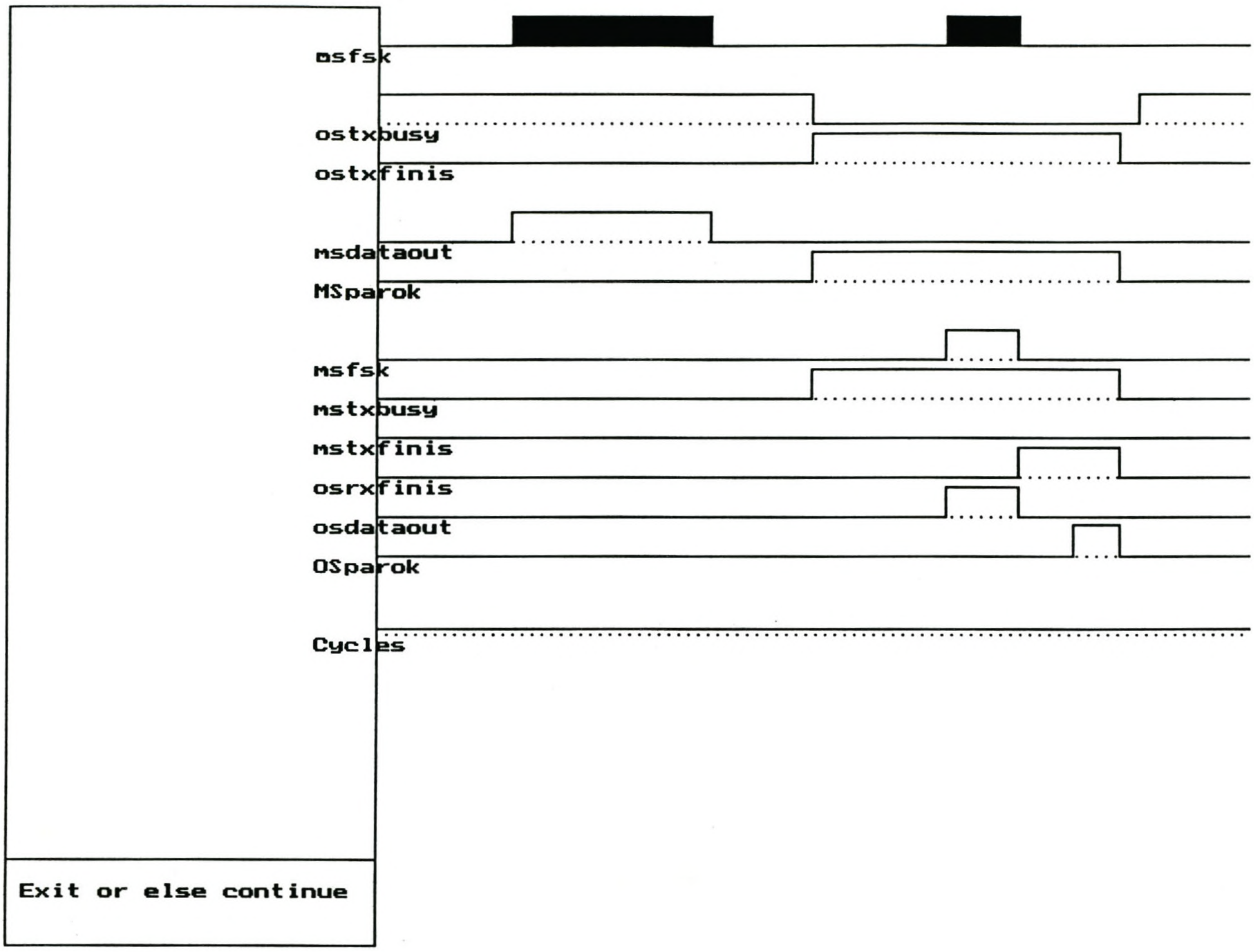
No. of stations	Traffic Int. Rho	Calculated Queue length	Simulated Queue length
20	0.60	8.12	7.68
	0.80	5.03	4.03
	1.00	3.10	2.27
	1.20	2.17	1.24
40	0.60	16.00	15.59
	0.80	8.86	7.58
	1.00	4.56	3.80
	1.20	2.77	1.32
80	0.60	32.00	30.31
	0.80	16.46	15.29
	1.00	6.73	6.48
	1.20	3.37	1.54

It is clear that correspondence between the two sets, is good. The basic queue simulation also served to confirm the validity of the Poisson distribution routine used in the other simulation versions.

6.5 Summary

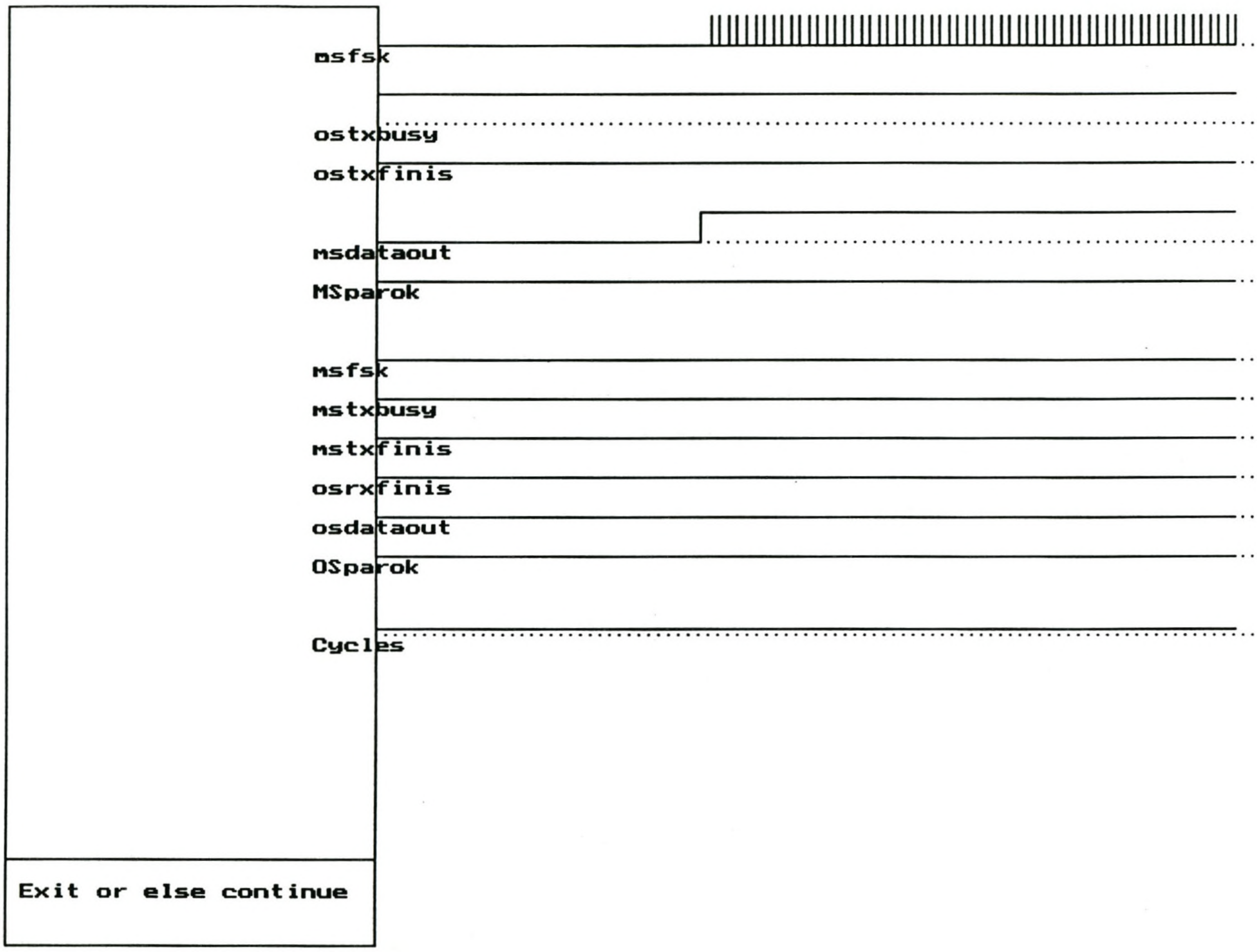
The simplified simulation routine's main advantage, is the app. 30% reduction in run-time. It has possible application in all cases except where links are subject to marginal, or reasonably close to marginal, SNR's. It is clear that in cases other than these, it could be used with a reasonable degree of confidence.

Although not as clearly advantageous as the simplified emulation set out in 6.2 above, a result complementary to the outcome of the theoretical process is provided, establishing confidence and confirming the validity of both.



Exit or else continue

Fig. 6.1: Simplified Tx/Rx Sequences with Control Signals



Exit or else continue

Fig 6.2 Display of Simplified Modulation Signal

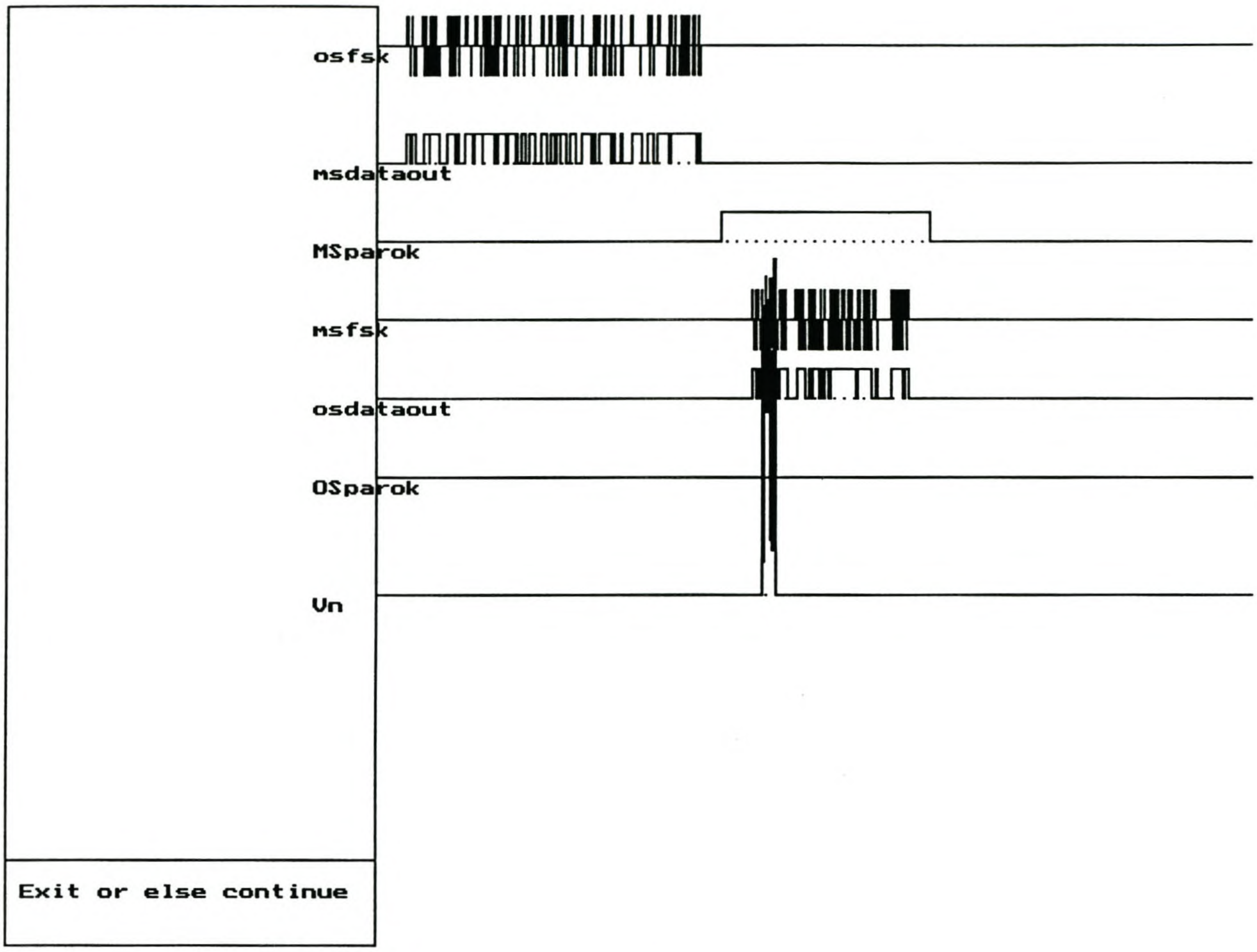


Fig 6.3: Simplified Simulation with Burst Noise

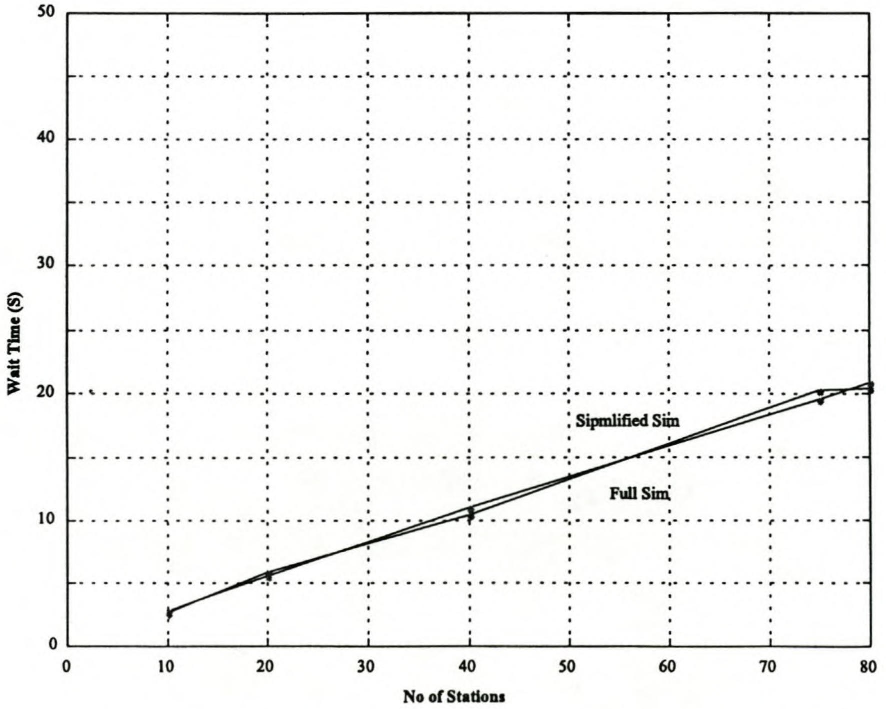
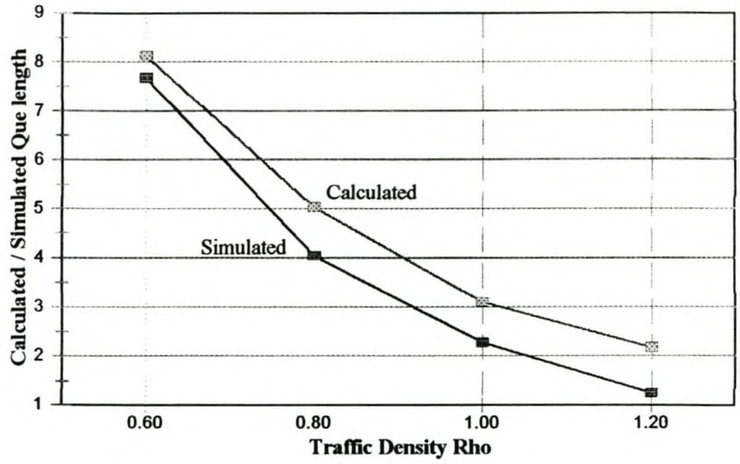


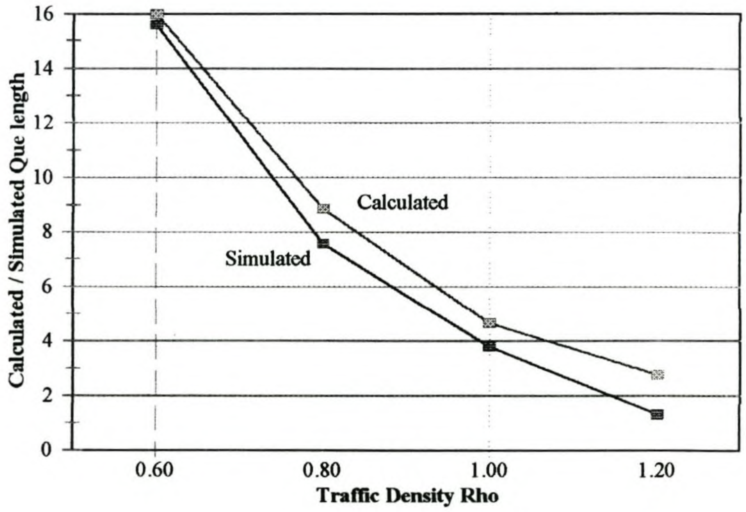
Fig. 6.4 : Mean Wait Times - CSMA, 384 Data bits, 0 % Burst Noise, Backoff = 3,5x max t-out
Full vs Simplified Simulation

Fig 6.5: Calculated vs Simulated Finite Source Queue Lengths Comparison

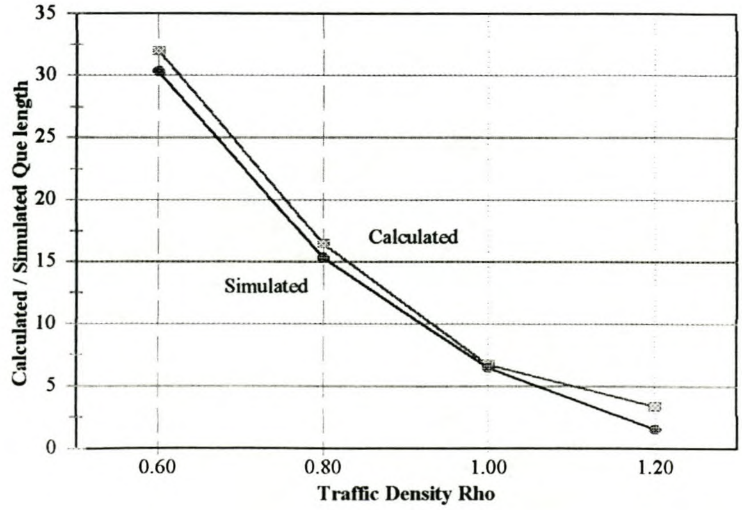
Simple finite 20 station process
No back-off



Simple finite 40 station process
No back-off



Simple finite 80 station process
No back-off



Chapter 7

Theoretical Modeling

7.1 General

In this Chapter, the possible theoretical modeling of the two main strategy types, i.e. Round Robin and Contention, will be discussed.

Of the two, the round-robin model is clearly the simplest to formulate, and will be dealt with first. The more problematic contention strategy, will be approached subsequently.

7.2 Round-Robin Modeling

The total round-robin per station poll time, in an error free environment, can be stated as:

$$t_{ps} = t_{pr} + t_d \tag{7.2.1}$$

If:

t_{ps} = Total poll time/station
t_{pr} = Poll request time/station
t_d = Data transmit time/station

and:

t_{pre} = Transmission pre-amble time
t_{poa} = Transmission postamble time
t_b = Bit time
t_r = Retry time delay
n_h = No. of header bits
$n_{d\max}$ = Max. no. of data bits
$n_{d\min}$ = Min. no. of data bits
n_p = No. of poll request bits, additional to the header (if implemented)

Eq. (7.2.1) can subsequently be written as:

$$t_{ps} = 2t_{pre} + 2t_{poa} + t_b(n_h + n_b) + t_b[n_h + (n_{d\max} - n_{d\min})/2] \tag{7.2.2}$$

It should be noted that no purpose is served by the master station replying with an ACK message, subsequent to the receipt of valid data from an outstation. Such an ACK sequence would be subject to the same possible noise disruption as any other sequence. It is adequate for the master merely to persist in requesting valid data until such is received. Any further handshaking does not improve data security. (See also: The Two Army scenario as set out in [Tanen-96]).

To take burst noise induced errors into account, it must be borne in mind that disturbances can take place either during the poll request (PR) transmission (master-outstation) or during the data reply (DR) transmission (outstation-master). Disturbance during the PR sequence will result in a delay constituted of another PR sequence plus a retry time delay t_r.

Disturbance during the DR sequence will result in a delay constituted by an additional PR sequence t_{pr}, plus another retry time delay t_r, and DR sequence, t_d.

Both occurrences are equally likely.

If:

v_{nb} = Transmission sequence percentage disrupted by burst noise, and:

t_{psn} = Mean poll time/station with burst noise accounted for, then:

$$\begin{aligned} t_{psn} &= t_{pr} + t_d + \frac{V_{nb/2}}{100}.(t_{pr} + t_r + t_d) \\ &= 2.t_{pre} + 2.t_{poa} + t_b(n_h + n_p) + t_b[n_h + (n_{d\max} - n_{d\min})/2] \\ &\quad + \frac{V_{nb/2}}{100}\{t_b(n_h + n_p) + t_r + t_b\left[(n_h + n_p) + n_h + (n_{d\max} - n_{d\min})/2\right]\} \end{aligned} \tag{7.2.3}$$

The maximum cycle time for N station is simply

$$t_{cyc-\max} = N.t_{psn}, \tag{7.2.4}$$

which is clearly also the worst case wait time to obtain data. The mean wait time is then:

$$t_{cyc-av} = \tfrac{N}{2}.t_{psn}. \tag{7.2.5}$$

The correlation between the relationships (7.2.3), (7.2.4) and (7.2.5), and results from simulations as presented in Chapter 5, are given in Table 7.1 below. As is to be expected from a fairly simple deterministic process such as round-robin, the modeling thereof is straight forward with predictable results.

Table 7.1

Comparison of RRP Simulation and Theoretical Results

		Mean Wait times from Simulations			Mean Theoretical Wait Times			% Difference		
Data length No of bits	**Station Count**	**Burst Noise %**			**Burst Noise %**			**Burst Noise %**		
		0	10	20	0	10	20	0	10	20
384	10	5.7	8	10.0	5.1	7.4	9.7	-11.8%	-8.1%	-3.1%
	20	10.1	15	21.5	10.2	14.8	19.4	1.5%	-1.4%	-10.8%
	40	21.5	30.1	42.0	20.4	29.6	38.8	-5.4%	-1.7%	-8.2%
	80	41.0	61.5	82.5	40.8	59.2	77.6	-0.5%	-3.9%	-6.3%
640	10	6.3	9.15	11.9	5.63	8.41	11.2	-11.9%	-8.8%	-6.3%
	20	11.5	17.5	24.7	11.3	16.8	22.4	-2.1%	-4.2%	-10.3%
	40	23.5	34	48.2	22.5	33.6	44.8	-4.4%	-1.2%	-7.6%
	80	46.0	71.5	98.5	45.1	67.3	89.6	-2.0%	-6.2%	-9.9%
1152	10	7.5	11	13.5	6.7	10.4	14.2	-11.9%	-5.8%	4.9%
	20	14.5	21.5	26.0	13.4	20.9	28.3	-8.2%	-2.9%	8.1%
	40	26.5	41	60.0	26.8	41.8	56.7	1.1%	1.9%	-5.8%
	80	55.0	90	115.0	53.6	83.5	113.5	-2.6%	-7.7%	-1.3%

7.3 Contention Protocol Modeling

7.3.1 Comments on Available Analyses of Contention Type Protocols

As stated in Chapter 2, the simplest of all contention protocols, is the basic, unslotted Aloha. The functioning of the strategy as well as that of some of the other more complicated related variants, has been discussed in Chapter 2. All contributors acknowledge that definite and generally valid analysis of this group of protocols, is very difficult. Major contributions in this regard has been made by Kleinrock, Tobagi, Lam and others. See [Klein-75a], [Molle-75], [Klein-75b], and [Tobag-80b], in particular.

A comprehensive review of this work will not be given, but it is useful to take note of the common, underlying relevant principles. Those, of particular interest to the attempt at hand, can be summarised as follows:

(a) It is assumed that the event source population is infinite. Each arrival is unique. (Sidi and Rom [Rom-90] offered an analysis for finite source Aloha which is a development of the Kleinrock & Lam model [Klein-75b]).

(b) The event arrival process is a Poisson process. This is not necessarily the case, but any other assumption renders the whole modeling approach mathematically intractable. The existence of a process with a general distribution, i.e. bursty data, is entirely possible, but can frequently only be treated by approximation, or empirically by simulation.

The assumption of a Poisson process may, therefore, have it's limitations, but does at least provide a reasonable point of departure.

(c) The event arrival rate of, say g events per sec., is constituted of two components, i.e.: New arrivals and;

Arrivals from the backoff retry process.

In the standard models, this ratio is not defined and the particulars of the backoff process is not taken into account.

(d) If the event-, or packet transmission time is τ, then a vulnerable period of 2τ exists (overlapping between packets may occur) during which period a collision will occur if another transmission is to take place. This particular situation is clearly not exactly the same between all the contention variants, particularly not when a slotted timebase is used, but the underlying principles still apply where the channel throughput depends on:

The event-, or packet arrival probability

Channel being idle probability

Slot time (if applicable)
Propagation delay time.

(e) The process is memoryless, i.e. the service to be expected by a new arrival does not depend on previous arrivals, or their treatment.

(f) For long term stability, it is required that the throughput $S = \lambda T$, i.e. long term arrival rate must be less or equal to long term rate of throughput.

(g) For slotted Aloha, the vulnerable period is reduced to one slot period.

(h) For NP-CSMA the vulnerable period is reduced to the channel end-to-end propagation delay τ. The probability of successful transmission depends on the probability that a new arrival, or retry, will occur during this vulnerable period.

Although never taken into account explicitly in the standard analysis, there are timing considerations, other than τ, viewed to be more onerous, particularly in some applications. This is dealt with in a subsequent paragraph. NP-CSMA is a slotted protocol and not directly relevant to this investigation.

(i) For 1-Persistent CSMA, the analysis is based on the following fundamental probabilities:

  (i) If a new arrival finds the channel idle, a transmission is successful only if no other arrivals occur during the vulnerable period τ.

  (ii) If a packet arrives during the first τ seconds of a transmission period, its probability of success is 0.

  (iii) If a packet arrives during the channel busy period (excluding period τ), then it will be successfully transmitted during the next transmission period, if and only if it is the only packet to arrive during this period, and if no other events occur (packets arrive) during it's own first τ sec.

  (iv) The process can be viewed as a sequence of channel idle and channel busy periods, the latter consisting of successful and unsuccessful transmission periods. The throughput equation for the process as stated in Chapter 2.3.3 eq. 2.2 is subsequently derived [Klein-75a], [Klein-75c]. and it is restated for convenience:

$$S = \frac{G[1+G+aG(1+G+aG/2)]e^{-G(1+2a)}}{G(1+2a)-(1-e^{-aG})+(1+aG)e^{-G(1+a)}} \qquad (7.3.1)$$

For short distances and ideal sensing, $a \approx o$, so that:

$$S = \frac{G[1+G]e^{-G}}{G+e^{-G}} \qquad (7.3.2)$$

Where:
G = Attempted channel traffic
S = Channel throughput
a = Normalised propagation delay

(v) The average packet throughput delay, i.e. time between generation/arrival and successful reception, is derived by Kleinrock and Tobagi [Klein-75c] as:

$$D = \left(\frac{G}{S} - 1\right) R + 1 + a, \text{ where} \tag{7.3.3}$$

$$R = 1 + 2a + \alpha + \delta \quad \text{(Parameters normalized per packet length)}$$

$$R = T + \tau + T_a + \tau + \overline{\times} \tag{7.3.4}$$

R consists of the packet transmission time, packet retransmission interval (δ) (backoff), transmission acknowledgment time (α) and round-trip propagation delay, ($2a$). No optimum value for the backoff period is derived in [Klein-75c] and the authors suggest that the problem is best solved by simulation. A very small δ will result in increased interference (or system overhead) and resultant increase in offered traffic. A very large δ on the other hand, will clearly result in very long and unacceptable delays.

(vi) An in-depth analysis of the family of persitent CSMA systems, is to be found in [Takag-85]. The throughput models derived, are all based on either full-duplex channels, and/or slotted timebases. Although providing a useful indication, the system type subjected to the present investigation, is not fully analysed.

The inclusion of channel noise is dealt with by [Huang-92]. While the contribution is clearly of a very high standard, it assumes a slotted timebase for the CSMA case. The second instance treated under the abovementioned publication, is a Busy Tone CSMA variant, which cannot be considered for the applications under investigation, due to practical channel and bandwidth considerations.

(vii) A further very interesting approach to the solution of the BP optimisation problem is found in [Raych-92], where the channel access discipline is adjusted in accordance with observed successful and unsuccessful traffic. In practice, this method cannot really be considered without a full-duplex channel being available.

In the absence of such, the sensing mechanism is subject to excessive time delay and further conflict. The solution provided is, therefore, not directly applicable.

7.3.2 The Utilisation of Queueing Theory for Throughput Modeling

The utilisation of queueing theory in performance modeling of telecomms applications, is common practice. The throughput/stability analysis of data networks and switched circuit networks, is a case in point and the subject of a number of excellent works of reference. [Daigl-92], [Tanen-89], [Winst-91].

In the relevant key publications in this regard, the throughput equations for the various types of contention protocols discussed under Chapter 2 and paragraph 7.3.2 above, are, however, derived differently.

It has already been mentioned that the backoff strategy for 1- Persistent CSMA operation in particular, is not taken into account adequately in the expressions for channel throughput and forwarding delay. Neither are system overhead conditions, such as noise and equipment rise times.

The application of queueing theory to the modeling and performance prediction of data transmission links and networks, is considered very elegant.

It was, therefore, decided to investigate whether the type of telemetry protocols under consideration, could be satisfactorily modeled using this approach.

Such a model should then ideally:

- Be as general as possible for the particular protocol
- Make provision for the backoff strategy as abovementioned
- Accommodate system overhead as discussed in a subsequent paragraph
- Make provision for additive channel noise.

In the type of application under consideration, the time delay between event generation and successfully received ACK, time delay, is viewed as being of prime importance, in performance evaluation of this type of strategy. This round trip delay time can be readily determined by **Little's Result**, once the message queue length has been established, in accordance with an appropriate, valid queueing model for the overall system.

This will be addressed in subsequent paragraphs, once some general queueing principles and related applications have been briefly reviewed, as useful background material.

7.3.3 Basic Queueing Principles

Comprehensive treatment of queueing theory is to be found in many excellent works of reference, i.e. [Altio-97], [Giffi-78] and [Winst-91] and the basic principles will merely be summarised for convenience.

(a) **Basic Description of Queues**

Queues are characterised by the following parameters:

1. The characteristics of the source population (finite or infinite).
2. The probability density function (PDF) of the arrival process.
3. The PDF of the service process.
4. The number of servers.
5. Queueing discipline (i.e. first come, first served, or prioritising).
6. Queueing buffer space. This is not necessarily infinite. When full, some arrivals may be lost.

The basic elements of a queueing system are shown in Fig. 7.1.

(b) **Kendall's Notation**

The shorthand notation most commonly used for queueing processes, is the Kendall notation of **A/B/m**, where:

A = Arrival probability density
B = Service probability density
m = No. of servers.

(A further extension is sometimes added for subclass description).

The arrival/service characteristics are either Markovian, General (arbitrary), Erlang or Deterministic, denoted by **M, G, E or D**. The Deterministic case implies that all intervals (arrival or service) are exactly the same. The Erlang case can be viewed as a subgroup under the general distribution.

The general distribution is analytically very difficult to handle and does not submit to exact modeling.

The most common case, is the Markov, or Poisson process, where interarrival times have an exponential PDF. If at all possible, all processes are simplified, or broken up into sub-processes, with Markovian characteristics.

(c) **Markov or Poisson Processes**

Modeling of queues is commonly, but not always, based on Markov chain theory, which enables a mathematically tractable approach.

Simply stated, a Markov process is *memoryless*, i.e. the amount of future service you can expect is *independent of the amount of service already* *obtained.* The probability distribution for future system states can be developed from knowledge of the existing system state, with *disregard to history.*

(d) **Arrival PDF**

It is useful to briefly review the Poisson arrival process:

An absolutely constant arrival rate, is contrasted by a completely random one. This implies that there is a constant probability of an arrival event, occurring between t and $t + \delta t$. Furthermore, what happens in $(t, t + \delta t)$ is statistically independent of the arrival, or non-arrival of customers (or events) in any other overlapping interval. This type of pattern is described by the Poisson law:

$$P_n(t) = \frac{(\lambda t)^n}{n!} e^{-\lambda t} \qquad (7.3.5)$$

Where λ = mean arrival rate and $P_n(t)$ = the probability that exactly n arrivals occur in an interval of length t.

It can be shown ([Daigl-92] and [Walpo-78]) that in order for (7.3.5) to be satisfied, the inter-arrival times must be exponentially distributed so that

$$A(t) = \lambda e^{-\lambda t} \qquad (7.3.6)$$

The justification that the event arrival process is a Poisson one, is not always easy. It is certainly not true in the case of bursty traffic. It is, however, mathematically convenient, and known to be valid for many communications applications.

[Daigl-92]. It is generally a very good point of departure at least.

(e) **Service PDF**

To regard the service PDF as a Poisson process as well, is the most convenient approach, and generally valid. There are, however, cases where it is not, such as regularly timed processing of fixed length data, which is clearly a deterministic process.

The basic queueing analyses are, however, carried out under the assumption that it is indeed a Poisson process. This is further motivated in a subsequent paragraph.

(f) **System State and the Birth-Death Process**

If we assume that at a particular time, the system is in equilibrium i.e. the number of customers in the system, is constant, then the state of the system describes the no. of customers in the system, both in the queue and being serviced. Generally P_k is the equilibrium state, with k customers, or events, on board.

The arrival of a new event moves the system from k to $k+1$ and a service competition similarly moves the system from k to $k-1$. This is the well known birth-death process.

(g) **Arrival Rate**

If the *arrival rate* is λ events/sec., then the mean no. of transactions to move the state between state k and $k+1$, is $\lambda\rho_k$. It is important to note, that an infinitely sized event source is assumed.

(h) **Service rate**

In similar fashion, if the *service rate* is μ customers/sec., then the transition rate from state $k+1$ to k is $\mu\rho_{k+1}$.

It should be noted that in order to work out the transition rate, you only need to know the probability of the *initial* state and not the state to which the system proceeds. This is a characteristic of the Markov memoryless property.

(i) **Length of Queue for the M/M/1 Model**

In order to have a stable system, the transition rate from state k to $k+1$ must equal the rate from $k+1$ to k. Using this principle, we can solve for the state probabilities. It should also be borne in mind that the sum of the total probabilities in the system, must be 1.

It does not serve any particular purpose to supply the complete proof for the expected queue length of the system. This can conveniently be found in [Tanen-89], [Giffi-78], amongst others, but can be stated as:

$$N = \frac{\rho}{1-\rho} \tag{7.3.7}$$

where $\rho = \frac{\lambda}{\mu}$, known as the traffic intensity.

It is clear that when $\lambda = \mu$, the queue will grow boundlessly and be unstable.

(j) **Waiting Time**

Another key question to be answered, is the value of the mean waiting time. If a particular customer spends T sec. in the queue and is eventually in front, everybody arriving after him have arrived during the time T. If the arrival rate is λ/sec. then:

$$N = \lambda T \tag{7.3.8}$$

This is the well known and important **Little's Result**. [Tanen-89]

From (7.3.7) and (7.3.8):

$$T = \frac{1}{\mu-\lambda} \tag{7.3.9}$$

Note that T includes both the waiting and service times, i.e. the total time in the system.

(k) Arrival- and Service Distributions for Non-Poisson Processes

1. General Distribution

When arrival or service distributions are not exponentially distributed, i.e. a non-Poisson process, the queueing model is more difficult to formalise. In the case of the G/G/M model, no definitive mathematical identity has been found and practical problems are solved either by approximation or simulation. The general distribution applies when arrival- or service intervals are arbitrary and do not exhibit a particular PDF, such irregular or bursty traffic, as already mentioned. The requirement for different types of service, is another example.

The M/G/1 case has been modeled and queue length is given by the Pollaczek-Khintchine expression [Tanen-89] as:

$$N = \rho + \rho^2 \frac{1 + C_b 2}{2(1 - \rho)} \tag{7.3.10}$$

where C_b = ratio of:

Standard deviation/Mean of the service time PDF

This is a very useful result.

The G/M/1 case can also be solved but with more difficulty, normally using numerical methods.

See [Daigl-92] and [Winst-91]

2. Erlang-k Distribution

The Erlang-k distribution is particularly useful in modeling batch processing of data, or products. Events/parts will arrive in Poisson fashion, but processing does not take place until a certain minimum has been accumulated in the feeding buffer. When $k = 1$, the process reverts to the more common one with exponential interarrival times. [Daigl-92]

7.3.4 Publications and Examples on Queueing Theory and Industrial Optimisation

1. **General**

   During the investigations regarding a suitable model for the contention protocol under investigation, various publications on queueing theory and industrial planning and optimisation were consulted. Some of the sources are regarded as very interesting and associated comments and examples there from, analogous to the investigation at hand, can be summarised as follows:

   A. Queueing Theory in Manufacturing Systems Analysis and Design
   H.T. Papadopolous, C. Heavy, J. Browne [Papad-93]
   - Good background on general queueing theory
   - Discussion of applicability of different arrival/service distributions. Particularly complete discussion of phase type, or Erlang-k distributions.
   - Principles of open and closed queueing networks.
   - Production line modeling with queuing networks
   - Production lines with blocking
   - Production line modeling with holding points
   - Unreliable production lines
   - Introduction to the state matrix approach.

   B. Stochastic Service Systems
   John Riordan [Riord-62]
   - Queueing theory concepts
   - Arrival/service time interval characteristics
   - Development of various queueing models for different PDF's

   C. Operations Research; Applications and Algorithms
   W.L. Winston [Winst-91]
   Comments:
   - Queueing terminology
   - Arrival/Service distributions
   - Principles of birth-death processes
   - Very good summarised treatment of the different queueing models, i.e. single server, multiserver, Markovian, General, Deterministic, with individual variations.

- Somewhat more practical than some of the other references, but still with a fair amount of theory.
- Excellent general work of reference on the subject.

D. Probability, Statistics and Queueing Theory
A.O. Allen [Allen-78]
Comments:

- General background on queueing theory
- Analysis of multiple server system
- Good treatment of finite source systems

E. Queueing : Basic Theory and Applications
Walter C. Giffin [Giffi-78]

- Introduction to Markov claims
- Poisson type arrival/service processes
- Birth-death processes
- Full theoretical treatment of queueing models
- Basic queueing networks
- Non-Poisson PDF's and bulk arrival/service
- Emphirical modeling
- Advanced mathematical techniques
- Excellent general work of reference on queues.

F. Queueing Theory for Telecommunications
J.N. Daigle [Daigl-92]
Comments:

- Introduction to basic computer networks
- Development of queueing theory using imbedded Markov claims, birth-death processes and Poisson PDF's
- Very complete treatment of General type distributions, with various queueing disciplines
- Useful reference, provided it is not the only one available.

G. Performance Analysis of Manufacturing Systems
Tayfur Altiok [Altio-97]
Comments:

- Overview of random variable distributions and stochastic processes
- Single work station models, including basic queueing theory

- Machine repair modeling
- Modeling of complete production lines
- Full treatment of the state matrix analysis method
- Analysis of synchronous production and transfer production lines
- Assembly systems and modeling of manufacturing systems with more than one product
- An outstanding work in the field of production optimisation, and covering methodology with very real application in our particular field of interest.

2. **Example from Production Optimisation: The Machine-Repair Model**

This example certainly does not exactly resemble the operation of the protocol under discussion, but is useful background material, in particular for providing a simplified point of departure for further subsequent development. For this reason, it is worthwhile discussing.

Assume we have a plant with N identical production machines. A corporate environment with a like no. of photocopiers, will also do.

There is one repairman servicing the machines in case of breakdown. The service interval is $^1/_\mu$ and exponentially distributed, i.e. a Poisson process. The machines break down at interval $^1/_\lambda$, which is similarly exponentially distributed.

The object is to determine the mean no. of machines out of service and the mean downtime to be expected, per machine.

With reference to Fig. 7.2 below:

Let $P_{o1}, P_1 \ldots P_k$ be the probabilities that $1, 2, \ldots k$ machines are in repair, which we can refer to as states $0, 1, \ldots k$.

For state o : $\lambda_o = N\lambda$

For state 1: $\lambda_1 = (N-1)\lambda$

For state 2: $\lambda_2 = (N-2)\lambda$

For state k: $\lambda_k = (N-k)\lambda$

For the queue to be in equilibrium at a particular moment in time, an arrival to the workshop, must correspond to a departure from the workshop.

$$\lambda_o P_o = \mu P_1$$

$$N\lambda P_o = \mu P_1 \quad ; \quad P_1 = N\frac{\lambda}{\mu}P_o$$

If $\rho = \frac{\lambda}{u}$, then $P_1 = N\rho P_o$ (7.3.11)

$$\begin{aligned}\lambda P_1 &= \mu P_2 \\ (N-1)\lambda P_1 &= \mu P_2 \\ P_2 &= (N-1)\rho P_1\end{aligned}$$

Substituting from (7.3.11)

$$P_2 = N(N-1)\rho^2 P_o \qquad (7.3.12)$$

and similarly

$$P_k = N[(N-1)(N-2)\dots(N-k)]\rho^k P_o \qquad (7.3.13)$$

If the state probabilities have to sum to 1, then

$$P_o\left[\sum_{r=0}^{k}\frac{N!}{(N-r)!}\rho^r\right] = 1 \qquad (7.3.14)$$

There is no closed form solution for this expression and P_o has to be determined numerically. The queue occupation can be stated as:

$$Lq = 0.P_o + 1.P_1 + \dots\dots\dots + k.P_k \qquad (7.3.15)$$

From the above, it is clear that if P_o is known, $P_1 \dots P_k$ can also be found and, therefore, Lq.

The out of service delay T, is simply found from Little's Result, which holds generally, for a large no. of queueing disciplines. Note that in this case, the *effective* λ must be used, depending on the queue length.

The machine repair model will be revisited in a subsequent paragraph.

7.3.5 Queueing Approach for Non - Persistent Contention Model

With the above in mind, it was decided to attempt modeling the protocol under consideration, using a queueing approach. To this end, it is necessary to establish the queueing parameters applicable to the protocol.

(a) Arrival Distribution

The most convenient arrival PDF to utilise, would clearly be an exponentially distributed one. It is important to establish whether this is valid or not and it is useful to briefly examine the expected event arrival characteristics of a typical system. It should also be remembered that we are dealing with telemetry applications in particular, and not generalised systems.

A specific Western Cape sewerage pumpstation network consists of app. 70 pumpstations, each containing 2, or 3 pumps. On average, 3 analogue values and 12 digital inputs are monitored at each station. An analogue value (i.e. sump level and flow rate) is logged upon each 10% change in value, relevant to the particular full scale range. Pumping cycles vary greatly, depending on drainage area, industrial vs. domestic effluent station design, and so on. A 15 min. cycle has, however, been observed to be fairly typical over the total sump level variation. This would result in an analogue event being generated at a rate of 1 per 90 sec. resulting from the sump level variation. Flow rate varies as well, but less so; not more than at 50% of the level event input rate.

Pump motor current varies even less under normal conditions. It would be reasonable to expect a maximum of two motor current related events per pump cycle. Each cycle would also be accompanied by a motor stop, motor start signal. There would be further inputs of an exception nature, over the entire network, such as alarms. If no distinction is made between the character of an analogue and digital events, the total event rate/station would be in the order of 0,02/sec. For the total network, the overall event rate would be app. 1,4/sec.

As the stations are unco-ordinated and spread out over a large area and subject to a significant variety of operational conditions, *this arrival pattern can be regarded as random with typical Poisson behaviour.* Sufficient proof exists, that such a characteristic is to be expected from systems subject to similar random input conditions. [Altio-97], [Daigl-92].

The mean arrival rate over the entire system, will definitely increase and decrease in line with effluent load, but without affecting the nature of the PDF. Where networks of a different type, - i.e. electrical distribution systems, are monitored, a similar argument should be valid. Load profile and other distribution characteristics vary between substations, depending on the area, the surrounding network topology and related factors. Such a PDF would not be arbitrary (G-type) but is highly likely to exhibit a Poisson characteristic (M-type).

(b) Service distribution

The expected service PDF is, perhaps, harder to justify as being Poisson. The following arguments should, however, be considered:

(i) The majority of practical installations of this nature, do not employ fixed length protocol structures, for clear reasons of efficiency. The variation in min./max. length data fields is dependent upon event occurrence and is certainly random, i.e. following a Poisson characteristic, although the range is somewhat restricted.

(ii) Channel interference phenomena, such as additive white noise, or burst noise, is certainly random and will affect the service times in like manner.

(iii) The ACK message transmitted by the server, is subject to the same competition for channel access as all the other data strings to be transmitted from outstations. This is also a random process and while the message length in this case is mostly fixed, the channel access time is not.

(c) No. of Servers

Although not of fundamental importance, a single server/master station configuration can be accepted as valid for general modeling. In systems such as under investigation, it is normally essential that overall supervision and control is exercised from one point only, for reasons of organisation and co-ordination. Secondary servers are frequently installed, but these are always utilised for management information only, not requiring time critical communication.

(d) Finite Source System

The fact that this type of network should be regarded as a finite source system, has already been discussed under Chapter 4, but restatement of the argument may be useful at this stage:

In typical outstation design, for the type of application under consideration, any status/analogue value change at the outstation, is entered into the transmit buffer queue. Any subsequent change occurring on any input, does not result in a separate transmission. This is too wasteful of valuable comms channel resources. Such an event is added to the event buffer and the entire buffer is emptied as a single transmission to the server, once the channel is accessed. There is a permitted limit on the maximum length of the data string, for reasons of noise and error detection, but this is normally generous and seldom exceeded.

Once a station has put an event in the overall system queue, it does not generate another queue arrival until the previous one has been dealt with. This is typical of a finite source system and could validly be treated as such.

(e) Summary

From the above, it is clear that the fundamental queueing discipline for the protocol would be the M/M/1/K/K type, but with the necessary expansions to accommodate the particular protocol parameters, such as backoff strategy, noise influence and general system overhead, as later more fully defined.

7.3.6 State Transition Matrix Approach

From a computational point of view, it is very convenient to represent the state transitions in a queueing system, in a matrix format. The matrix is constructed from the flow balance equations and will represent one equation for each system state. This, of course, is a normal application of linear algebra. To illustrate the methodology for the particular class of applications under consideration, observe the state transition flow diagram of the Machine Repair Model of 7.3.4, as per Fig 7.2.

For a queue in equilibrium, the balance equation for each possible state, can be produced. If the notation $P(n, m)$ indicates the probability that n machines are up and m units in repair, then:

$$P(N,0)N\lambda = P(N-1,1)\mu, \quad \text{or}$$

$$P(N,0)N\lambda - P(N-1,1)\mu = 0 \tag{7.3.16}$$

$$P(N-1,1)[(N-1)\lambda + \mu] = P(N,0)N\lambda + P(N-2,2)\mu, \quad \text{or}$$

$$P(N-1,1)[(N-1)\lambda + \mu] - P(N,0)N\lambda - P(N-2,2)\mu = 0 \tag{7.3.17}$$

$$\vdots$$

$$P(k, N-k)[(N-k)\lambda + \mu] = P(k-1, N-k+1)(N-k+1)\lambda + P(k, N-k)\mu,$$

or

$$P(k, N-k)[(N-k)\lambda+\mu] - P(k-1, N-k+1).(N-k+1)\lambda - P(k, N-k)\mu = 0 \tag{7.3.18}$$

$$\vdots$$

$$P(0,N)\mu = P(1, N-1)\lambda$$

$$P(0,N)\mu - P(1, N-1)\lambda = 0 \tag{7.3.19}$$

Equations (7.3.16 - 19) can be written as:

$$\begin{array}{ccccccc}
N\lambda & -\mu\cdots & & \cdots & 0 & = & 0 \\
-N\lambda & (N-1)\lambda+\mu\cdots & & \cdots & 0 & = & 0 \\
\cdots & \cdots & \cdots & \cdots & \cdots & = & \vdots \\
\cdots & \cdots & \cdots & \cdots & \cdots & = & \vdots \\
 & & & -\lambda & \mu & = & 0
\end{array}$$

This can be expressed in matrix format as:

$$A = \begin{bmatrix} N\lambda & -\mu & \cdots\cdots & 0 \\ -N\lambda & (N-1)\lambda + \mu & \cdots\cdots & 0 \\ \cdots & & & \\ \cdots & & & \\ \cdots & & & \\ & \cdots & \cdots\cdots\lambda & \mu \end{bmatrix} \tag{7.3.20}$$

$$B = \begin{bmatrix} P(N,0) \\ P(N-1,1) \\ \vdots \\ P(0,N) \end{bmatrix} \tag{7.3.21}$$

$$C = \begin{bmatrix} 0 \\ 0 \\ 0\cdot\cdot \\ \cdot\cdot \\ 0 \end{bmatrix} \tag{7.3.22}$$

(7.3.20 - 22) is equivalent to:

$$AB = C \tag{7.3.23}$$

and solving for B:

$$B = A^{-1}C \tag{7.3.24}$$

The solution for the matrix B is readily obtained by utilising numerical methods, such as are available in a mathematical software utility, eg. Matlab, once the set of state equations have been defined.

7.3.7 Pseudo-Queue Approach for Non-Persistent Contention Protocol

As a first attempt to model the particular protocol using queueing theory, it was reasoned as follows:

The protocol operation resembles a finite source single server queueing system with all new arrivals ending up in a main queue for service. Should the server be occupied, the new arrival leaves the main queue and joins a second 'pseudoqueue' during the backoff time. It is assumed that the backoff time interval $^1/_\gamma$ is exponentially distributed, as well.

Upon expiring of the residence time in the backoff 'pseudoqueue' the occupant, or event, attempts to re-join the main queue. It seemed that the effective arrival rate to the main queue could be considered as coexisting of two components, i.e. the new arrival rate λ plus a rate γ from the pseudoqueue. Clearly, not all new arrivals end up in the pseudoqueue and it was attempted to scale this rate by the probability $1 - e^{-t_b/t_e}$ of service taking place, or the possibility of service taking place, where

t_b = mean backoff time and

t_e = mean interarrival.

Applying this principle to the basic finite source model, then:

$$\lambda_0 = N\lambda$$

$$\lambda_1 = (N-1)\lambda + \gamma^1$$

$$\lambda_0 P_0 = \mu P_1$$

$$P_1 = P_0 \frac{N\lambda}{\mu} = P_0 N\rho$$

where $\rho = \frac{\lambda}{\mu}$, as before.

$$\lambda_1 P_1 = \mu P_2$$

If $\rho' = \frac{\gamma}{\mu}$ then

$$P_2 = [N\rho((N-1)\rho + \rho')]P_0$$

$$P_k = N\rho[(N-1)\rho + \rho'] \ldots [(N-k-1)\rho + (k-1)\rho']P_0 \tag{7.3.25}$$

And also as before

$$P_0 + P_1 + \cdots + P_k = 1$$

Again, solve numerically for P_0 and calculate queue length as

$$L_q = 0.P_0 + 1P + \cdots + kP_k$$

The approach was tested with a realistic selection of values for the $\rho' = \frac{\gamma}{\mu}$ ratio. The results were promising initially, but was found to provide values for the expected L_q and T, in too narrow a range of ρ' when compared with the simulation results. Although some progress were made, it was felt to be inadequate for general application.

7.3.8 State Matrix Approach for Non-Persistent CSMA Protocol Model.

In order to overcome the shortcomings of the pseudoqueue algorithm as above-mentioned, it was decided to investigate whether more realistic results could not be obtained by using an expansion of the state-matrix form for the finite source model.

To this end, the flow-balance diagram of Fig 7.3, can be referred to, as the basis for the following discussion:

The probability for each possible state in the process is defined as $P(n,m)$, where:

$n =$ No. of stations without any events to be forwarded, or in queueing terminology,

the number of "up" machines not "in repair".

$m = 1$ When the server (or repairman) is occupied and

$m = 0$ When the server is free.

The arrival rate per station is λ and the service rate μ, as before. Define the backoff interval as $\frac{1}{\gamma}$ and exponentially distributed. The backoff rate, therefore, is γ, which is the rate at which stations leave the backoff process to attempt another transmission. The total no. of stations (or machines) is N.

(a) When no station has an event to be sent, any change of state from $P(N, 0)$ to $P(N-1, 1)$, will occur in accordance with a possible arrival rate of $N\lambda$. Should another station have events available, a further change of state from
$P(N-1, 1)$ to $P(N-2, 1)$ will take place at arrival rate $(N-1)\lambda$.

(b) It is also possible that the server might not be busy, but a station has generated an event, in which case the station will sit in the backoff state, $P(N-1, 0)$. Any arrival from the backoff state, in this case, from $P(N-1, 0)$ to state $P(N-1, 1)$ (server busy) will take place at rate γ.

(c) Service completion, that is, reverting from $P(N-1, 1)$ to $P(N, 0)$ takes place at the service rate μ.

(d) It is also possible that service completion can take place *without* an event immediately waiting, because all stations are in backoff mode. In such a case the change of state will be from $P(N-2, 1)$ to $P(N-1, 0)$.

(e) There is further possibility that a new arrival may take place while the server is not busy and all contending stations in backoff mode. In such a case the change from $P(N-1, 0)$ to $P(N-2, 1)$ will take place at an arrival rate of $(N-1)\lambda$

(f) The process is followed through until $P(0, 1)$, when all stations have events for transmission and the server is busy. It is also possible to have state $P(1, 0)$ when only one station remains without events, the server is unoccupied and all contending events are in backoff mode.

(g) It should be noted that state $P(0, 0)$ is not possible. Should all stations have events and the server busy, i.e. $P(0, 1)$, a new station is available immediately upon event completion, i.e. state $P(1, 0)$ and not $P(0, 0)$.

(h) The flow balance equations can now be set up for each state, as follows:

$$P(N, 0)N\lambda = P(N-1, 1)\mu \qquad (7.3.26)$$

$$P(N-1,1)[(N-1)\lambda+\mu] = P(N,0)N\lambda + P(N-1,0)\gamma \tag{7.3.27}$$

$$P(N-1,0)[(N-1)\lambda+\gamma] = P(N-2,1)\mu \tag{7.3.28}$$

......

......

......

$$P(N-k,1)[(N-k)\lambda+\mu] = (N-k+1)\lambda[P(N-k+1,1)+P(N-k+1,0)] + P(N-k,0)k\gamma \tag{7.3.29}$$

$$P(N-k,0)[(N-k)\lambda+k\gamma] = P(N-k-1,1)\mu \tag{7.3.30}$$

......

......

......

$$P(1,1)[\lambda+\mu] = P(2,1)2\lambda + P(2,0)2\lambda + P(1,0)[(N-1)\gamma] \tag{7.3.31}$$

$$P(1,0)[\lambda+(N-1)\gamma] = P(0,1)\mu \tag{7.3.32}$$

$$P(0,1)\mu = P(1,1)\lambda + P(1,0)\lambda \tag{7.3.33}$$

Equations (7.3.26) to (7.3.33) can, as before, be expressed in matrix format, where:

$$A = \begin{bmatrix}
N\lambda & -\mu & & & \cdots & & & & & & \cdots & & & & & \\
-N\lambda & (N-1)\lambda+\mu & & -\gamma & \cdots & & & & & & \cdots & & & & & \\
 & & -\mu & (N-1)\lambda+\gamma & \cdots & & & & & & \cdots & & & & & \\
\vdots & \vdots & \cdots & \cdots & \cdots & & & & & & & & & & & \\
 & & & & \cdots & & (N-K)\lambda+\mu & -(N-K+1)\lambda & -K\gamma & -(N-K+1)\lambda & \cdots & & & & & \\
 & & & & \cdots & -\mu & & & (N-K)\lambda+K\gamma & & \cdots & & & & & \\
\cdots & & & & \cdots & & & & & & & & & & & \\
 & & & & \cdots & & & & & & \cdots & -2\lambda & \lambda+\mu & & -2\lambda & -(N-1)\gamma \\
 & & & & \cdots & & & & & & \cdots & & & -\mu & & \lambda+(N-1)\gamma \\
 & & & & \cdots & & & & & & \cdots & & -\lambda & \mu & & -\lambda
\end{bmatrix} \tag{7.3.34}$$

$$B = \begin{bmatrix} P(N,0) \\ P(N-1,1) \\ P(N-2,1) \\ P(N-1,0) \\ \vdots \\ P(N-k-1,1) \\ P(N-k,1) \\ P(N-k+1,1) \\ P(N-k,0) \\ P(N-k+1,0) \\ \vdots \\ P(2,1) \\ P(1,1) \\ P(0,1) \\ P(2,0) \\ P(1,0) \end{bmatrix} \tag{7.3.35}$$

$$C = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ \vdots \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ \vdots \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} \tag{7.3.36}$$

$A = B.C$ with $B = A^{-1}.C$, to be solved numerically, as set out before.

7.3.9 Results for the State Matrix Theoretical Model

A numerical representation of the model as discussed above, was implemented in Matlab and solved for wait times and effective throughput, in keeping with processing of simulation results. In order to make reasonable comparisons between the simulations and the model, the latter was fed with the same basic parameters, i.e. event arrival - processing rates, data string lengths and mean backoff times. The results obtained from the model, are shown in Fig's 7.4 to 7.6. It should be noted that the influence of system overhead other than burst noise has been ignored in these initial calculations.

Perusal of this set of results, lead to the following observations and further developments.

(a) The calculted results emanating from the model track the simulation results fairly closely, with the mean difference in respective wait times being in the order of 5%. The same applies to the comparison between the throughput rates.

(b) In order to accommodate the disturbance by burst noise into the model, the following approach was used:
Occurrence of burst noise during a transmission, will result in a data transmission failure, given a sufficiently high noise level. Failures would take place on either the outstation data forwarding leg, or the master station ACK response leg. In both cases, the entire data transmission process has to be re-initialised from the beginning. This can clearly only take place, once the outstation timer set upon data transmission has timed out. The data transmission failure could be viewed as similar to a production line failure due to machine breakdown, or similar
The failure process clearly reduces the overall system throughput and has the same effect as a reduction in the processing speed, μ, would have. The failure rate is independent of the processing time and if the total error retry cycle time is t_{er}, the burst noise failure rate δ_n, the processing time without noise $t_s = \frac{1}{\mu}$, then t_s would be increased to t_{s-eff_1} by a fraction of t_s which is a function of t_{er} and δ_n. Therefore:

$$t_{s-eff_1} = \frac{1}{\mu_{eff_1}} = t_s(1 + \delta_n t_{er}) \qquad (7.3.37)$$

This is similar to the approach followed for production line breakdowns [Altio-97]
The state matrix model discussed earlier was modified to incorporate the relationship (7.3.37) directly (See Fig. 7.7) and the results plotted out for the same burst noise percentages as used in the CSMA simluations. This particular set of theoretical results are also included in Fig's 7.4 - 7.6. When compared with Fig's. 5.19, 5.22 and 5.25, it will be seen that the performance of the model again tracks the simulations within a $5 - 7,5\%$ margin, which appears to be acceptably close and realistic.

(c) The results from both the simulations and the model exhibit the same paradox regarding wait times vs. mean backoff intervals, indicating a slight improvement in wait times with decrease in the backoff interval. This is not in keeping with actual applications, where the increased competition between new arrivals and returns from the backoff queue would result in more collisions and, therefore reduced throughput.

This aspect of the simulation results can be explained by the method of communications channel occupancy sensing, as implemented in the CSMA simulation.

Sensing is done virtually instantaneously in a maximum period of $\delta t = 10\mu s$, which is the maximum time resolution of the simulation time base. Carrier sense risetimes and propagation delays, have not been built into the original simulation. It is granted that propagation delays are small over short distances, but carrier sense, or receiver squelch opening delays, are not and have a typical value ranging between 0.1 and 0.15 sec., if no repeater is utilised. With a repeater in place, the above mentioned times could easily be extended by a factor 3, or more.

The sensing risetime and the propagation delay, constitute periods of uncertainty, during which collisions could take place, resulting in longer delays. This is paramount to experiencing additional disruption and consequently, longer throughput times, due to additional burst noise over and above the prevalent level.

It was, therefore, considered justified to follow the same basic approach for inclusion of burst noise is set out above. The relevant assumptions, are as follows:

i. In order for transmissions from two stations not to collide i.e. overlap, a channel-free period of 2τ is required, where τ is the end-to-end propagation delay.

ii. A station leaving the backoff state has a probability of collision with a new-arrival during the transition period, or risetime, of the new arrival attempting to grab the channel. Clearly, the higher the backoff retry rate and the longer the risetime, the higher the probability of collision.

iii. A station leaving the backoff state will not collide if it's attempted channel entry takes place while another transmission is in progress, but only during the channel-unoccupied portion of total channel utilisation, i.e., as a function of the traffic density ρ. The processing time t_{s-eff_1} of (7.3.37), could again be extended by a fraction of t_s, based on an interrelationship of the above mentioned factors, to be expressed as follows:

$$\begin{aligned} t_{s-eff_2} &= \frac{1}{\mu_{eff_2}} \\ &= t_s(1+\delta_n t_{er}) + 2\tau + n\gamma t_r \rho t_{er} \end{aligned} \tag{7.3.38}$$

where:

$n\gamma$ = backoff retry rate and

t_r = channel sense rise time

The state-matrix model was adjusted to accommodate (7.3.38) and the predicted performance plotted out in Fig's. 7.8 and 7.9 for different backoff retry rates. It should be noted that the fourth term of (7.3.38) is not constant, but requires dynamic variation in accordance with each possible model state. This requirement was incorporated in the model.

The results depicted in Fig's. 7.8 and 7.9 indicate the type of fall-off in performance to be expected with increased system overhead, as a result of increased competition for channel occupation.

It should also be noted that a short, propagation distance (30 km) was used in the model. This is, arguably, an arbitrary figure, but was deliberately chosen not to have too significant an influence, in order to evaluate the influence of risetime and backoff retry rate, unobscured.

The CMSA simulation software was somewhat modified to incorporate the risetime and propagation delay and a set of simulations re-run for the 384 data bit length, 20 station case. The results are plotted out in Fig. 7.13. It should be noted that the simulation results were not influenced by the introduction of a simple, constant factor, but were made to experience a realistic system overhead due to probabalistic outcome of the risetime/backoff rate/propagation delay interaction.

It is clear that the simulation results exhibit the same tendency as the model and within similar tolerance as before.

In order to enable convenient comparison of simulation and theoretical results, they are presented in combined fashion in Fig's 7.10 - 7.12, for the case without risetime and propagation system overhead.

7.3.10 Implications for System Configuration

Further to the above, the following additional comments may be appropriate

(a) Within reasonable limits, the model appears to be in agreement with the simulations. It, therefore, seems to be convenient and justified to use the theoretical approach as a valid means to predict system performance, in terms of the particular set of operational parameters.

(b) Fairly drastic increase in the propagation distance, does not have a proportional effect on the wait times. (See Fig. 7.14 (a)/(b)) This is to be expected, where the propagation delay constitutes a relatively small fraction of the total message transmission time. The latter, of course, is primarily a result of the low communications baud rate.

(c) Increase in risetime, coupled with a decrease in backoff time, certainly result in a marked increase in wait times, as is evidenced by Fig's. 7.15 - 7.17. This is also to be expected, as the probability for confict is increased proportionately with the increase of both these two parameters.

(d) For the reference arrival rate used in both the simulations and initial modeling, the optimum backoff period is found to be within 2-4 times the "normalised" unit backoff period, the latter being the total data message length, plus ACK message length, plus a 3 bit safety margin for each string. Utilisation of multiples of each unit backoff period, eliminates the influence of different data string lengths and simplifies simulation and model bookkeeping.

(e) At reduced arrival rate λ, the optimum backoff period shifts towards the shorter unit lengths, and vice versa for increased λ, as can be seen from Fig's 7.18 and 7.19. This is again to be expected, as unnecessary long backoff periods under conditions of reduced λ, would cause underutilisation of the comms medium. Too large a reduction in backoff times, coupled with increased λ, will result in increased competition and conflict.

7.4 Summary

7.4.1 In keeping with the simulation results from Chapter 5, the theoretical calculations once more clearly indicates the superiority of CSMA over RRP, for conditions of medium low to medium loading. However, the large standard deviation of CSMA behaviour, must be kept in mind.

7.4.2 The occurrence of noise has a deterious effect on the performance of both strategies, but in a pro-rata fashion. It does not change the relative effectiveness of the two methods.

7.4.3 The performance indications provided by simulations and theoretical modeling respectively, are substantially similar and either will suffice as a prognostic means. The model is clearly more convenient and less time consuming.

7.4.4 Channel noise, as well as futher system overhead imposing parameters, such as propagation delay and Rx/Tx rise times, could be accurately included in both the simulation and theoretical approaches.

7.4.5 The performance of the model appears to be quite satisfactory and the ability to allow for the inclusion of system overhead, backoff, noise and other relevant system parameters in a single theoretical framework, is viewed as very convenient. It should present the system designer with a useful means towards optimum system design.

7.4.6 The model succeeded in providing a formal base for inclusion of system parameters into analysis of a typical half-duplex narrow band CSMA protocol.

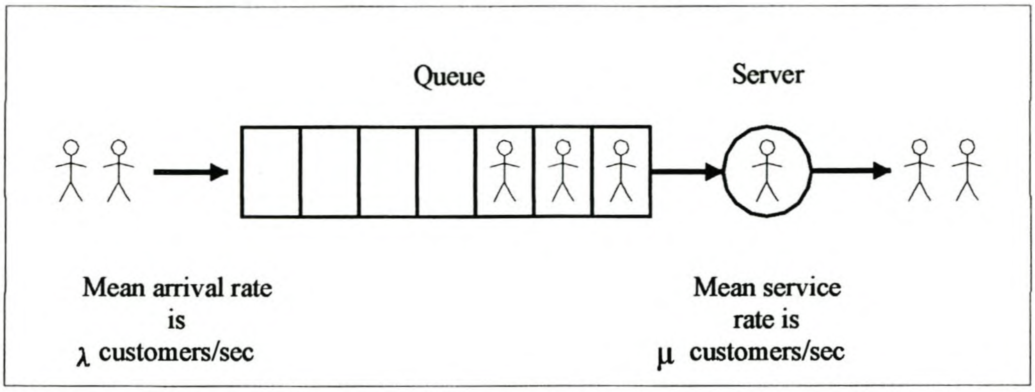


Fig 7.1

Single Server Queueing System with Four Customers, One in Service, Three in Queue

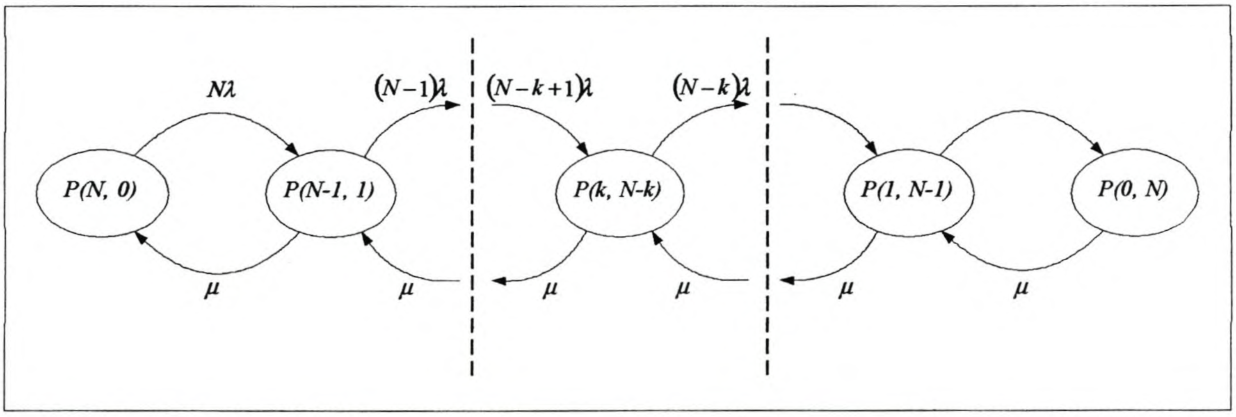


Fig. 7.2 Machine Repair State Transition Diagram

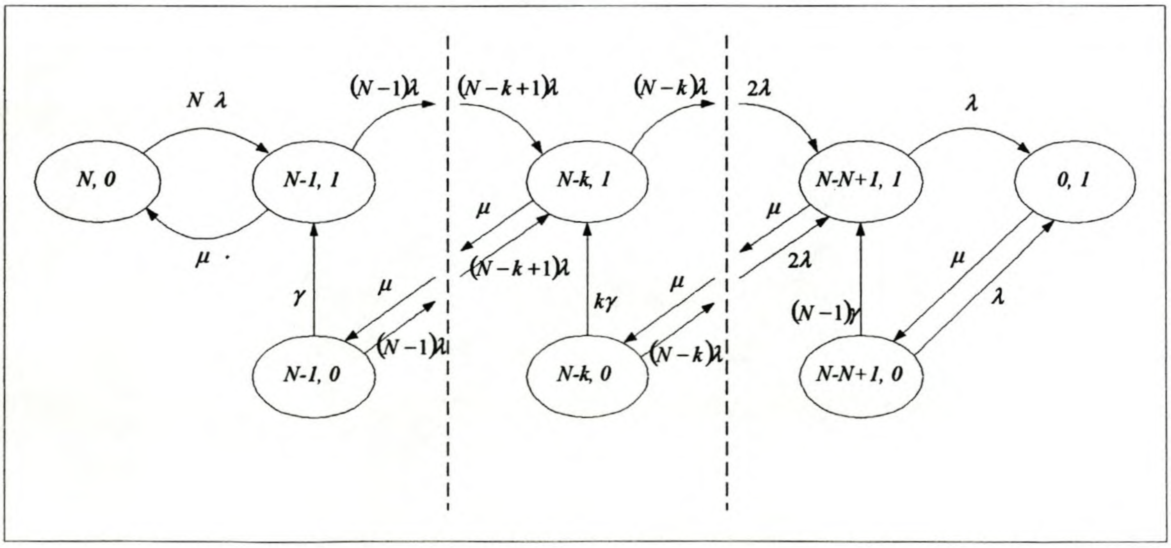


Fig. 7.3 CSMA State Probability Diagram

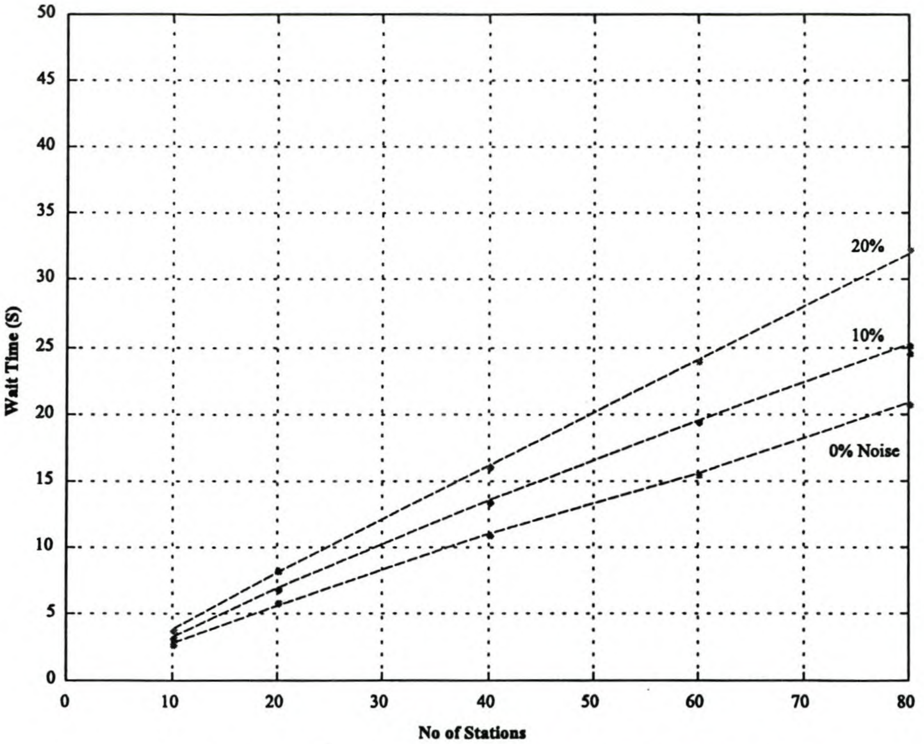


Fig.7.4 : Theoretical Mean Wait times - CSMA, 384 Data Bits, 0 -20 % Burst Noise,
Backoff = Serv. time x 4, EGI = 1x RRP tw-min

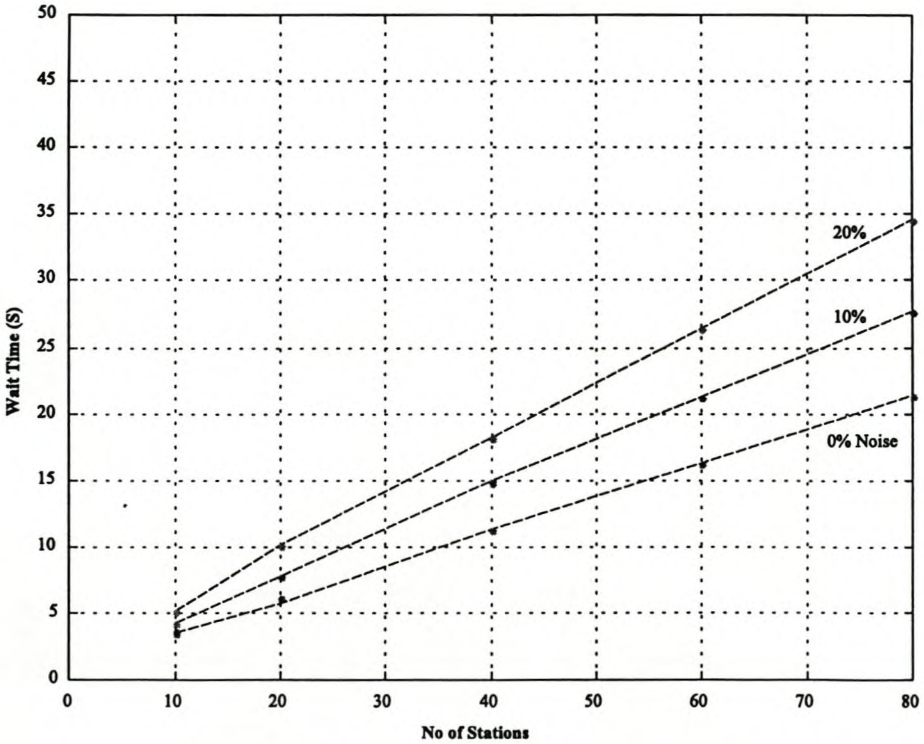


Fig.7.5 : Theoretical Mean Wait times - CSMA, 640 Data Bits, 0 -20 % Burst Noise,
Backoff = Serv. time x 4, EGI = 1x RRP tw-min

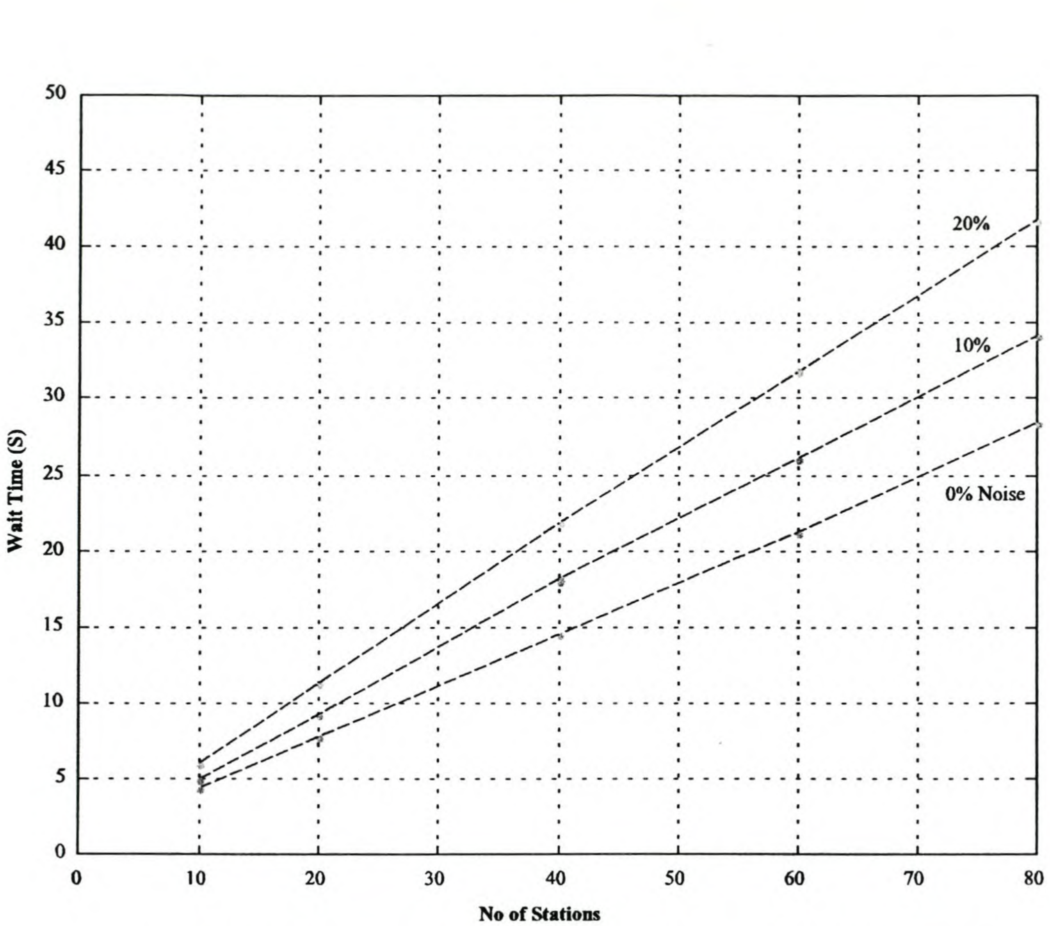


Fig. 7.6 : Theoretical Mean Wait times - CSMA, 1152 Data Bits, 0 -20 % Burst Noise
Backoff = Serv. time x 4, EGI = 1x RRP tw-min

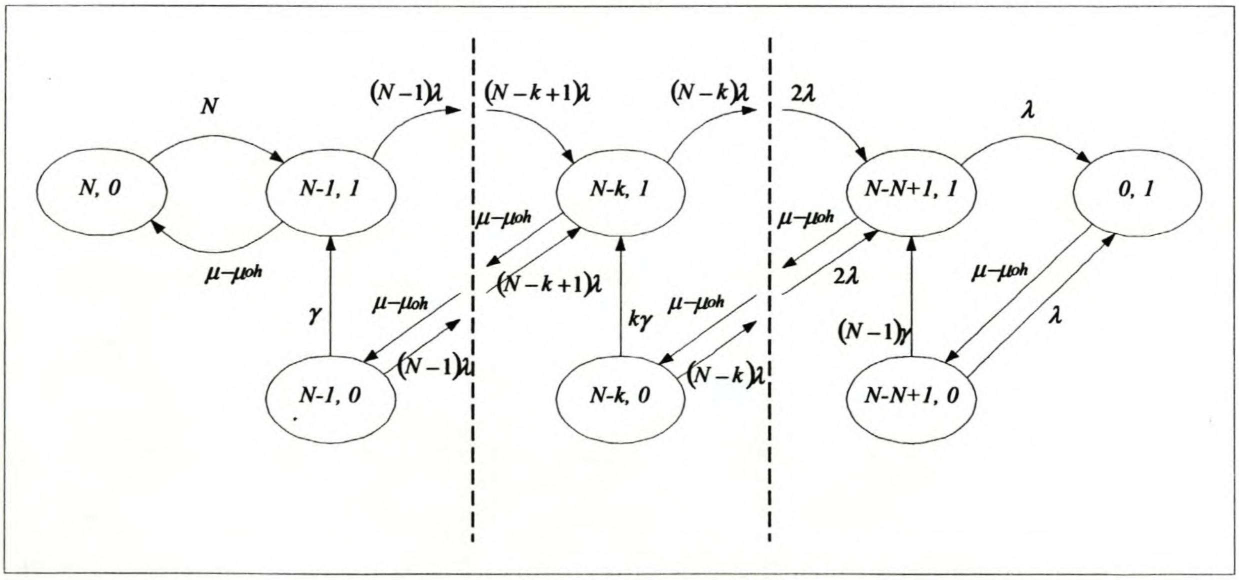


Fig. 7.7 CSMA State Probability Diagram with System Overhead

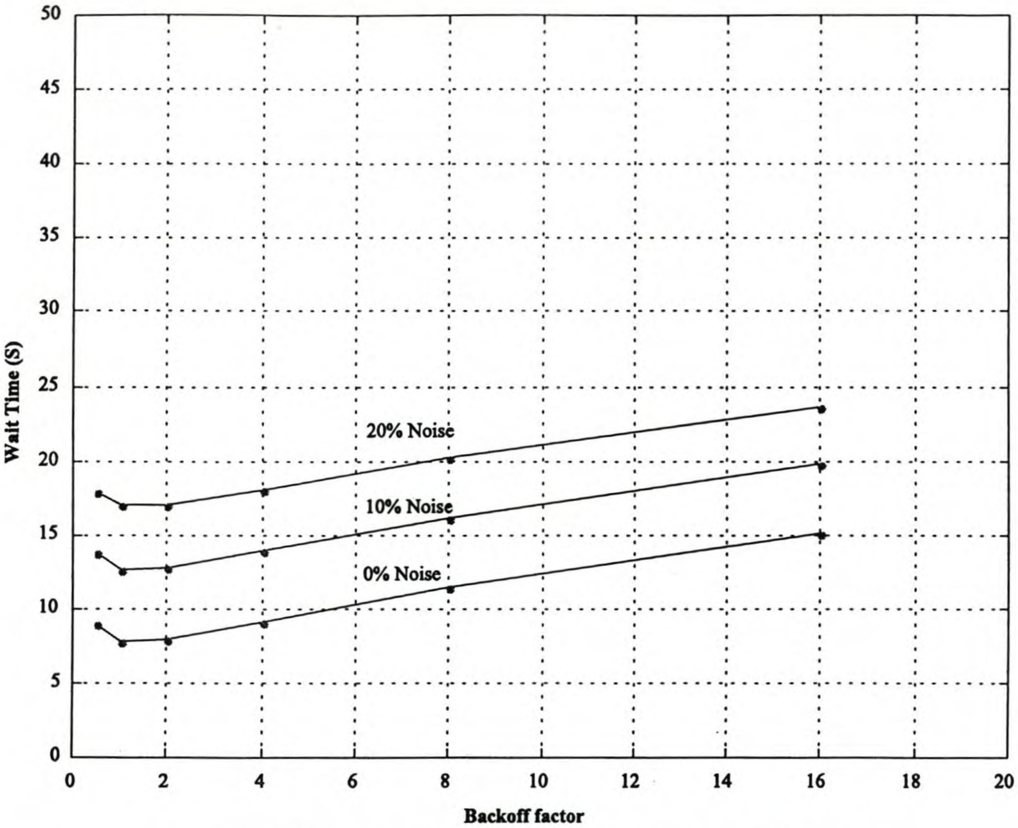


Fig.7.8 (a) : Theoretical Mean Wait times - CSMA, 384 bits, var. Backoff & Noise
20 Stations, EGI = 1x RRP tw-min, Distance 30 km

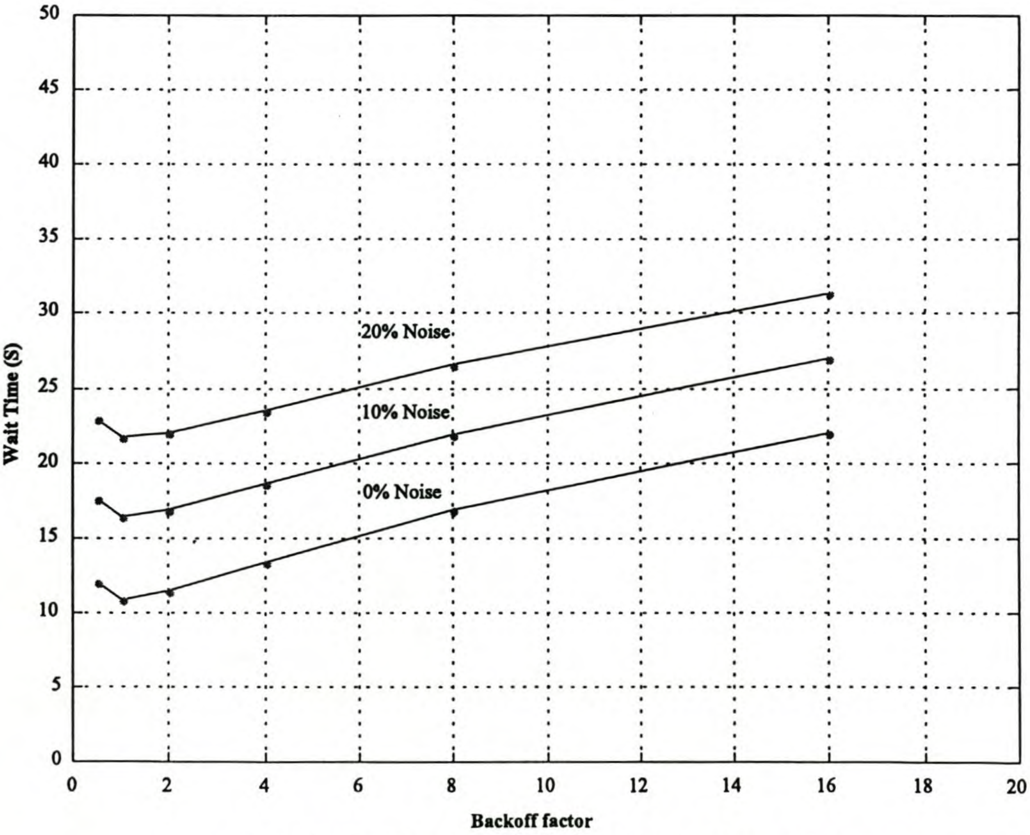


Fig.7.8 (b): Theoretical Mean Wait times - CSMA, 384 bits, var Backoff & Noise
40 Stations, EGI = 1x RRP tw-min, Distance 30 km

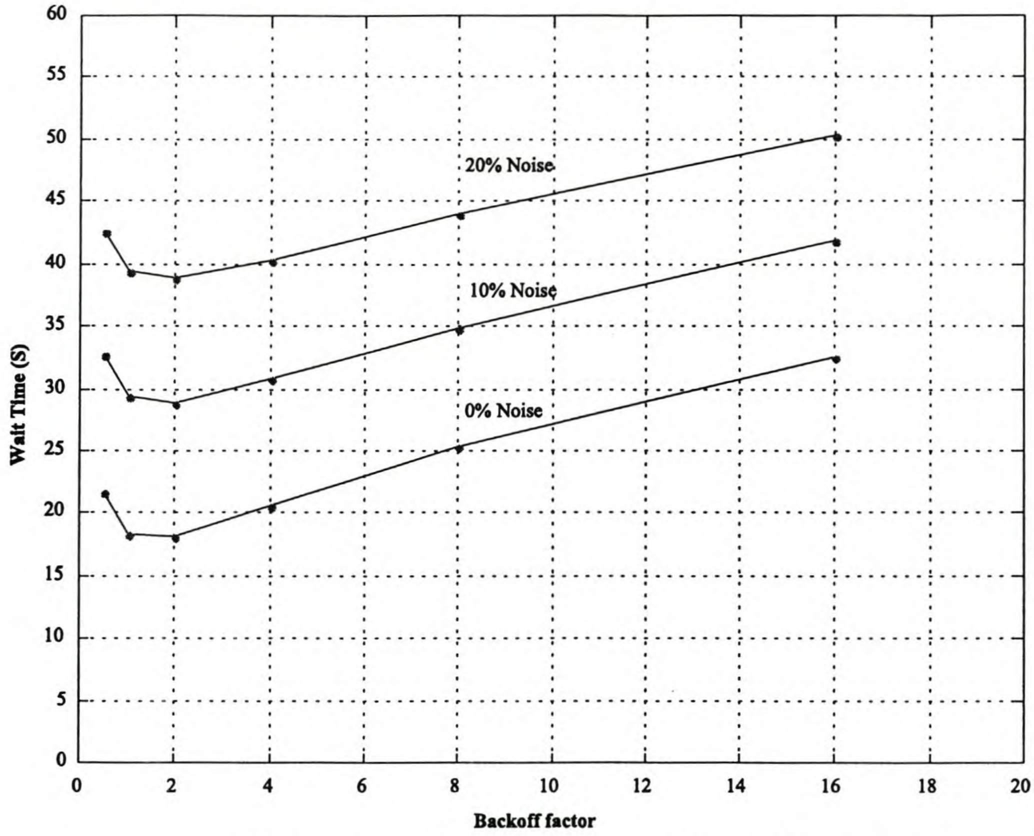


Fig.7.8 (c): Theoretical Mean Wait times - CSMA, 384 bits, var. Backoff & Noise 80 Stations, EGI = 1x RRP tw-min, Distance 30 km, tr = 0.1s

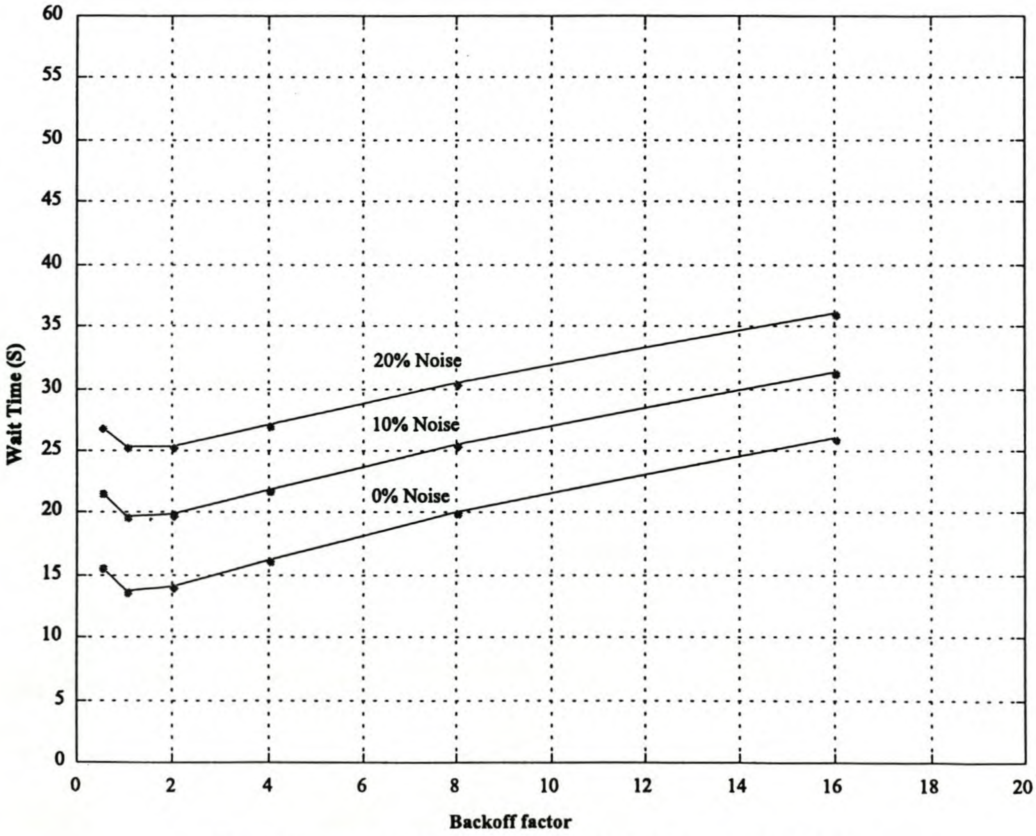


Fig.7.9 : Theoretical Mean Wait times - CSMA, 640 bits,var Backoff & Noise 40 Stations, EGI = 1x RRP tw-min, Distance 30 km, tr = 0.1s

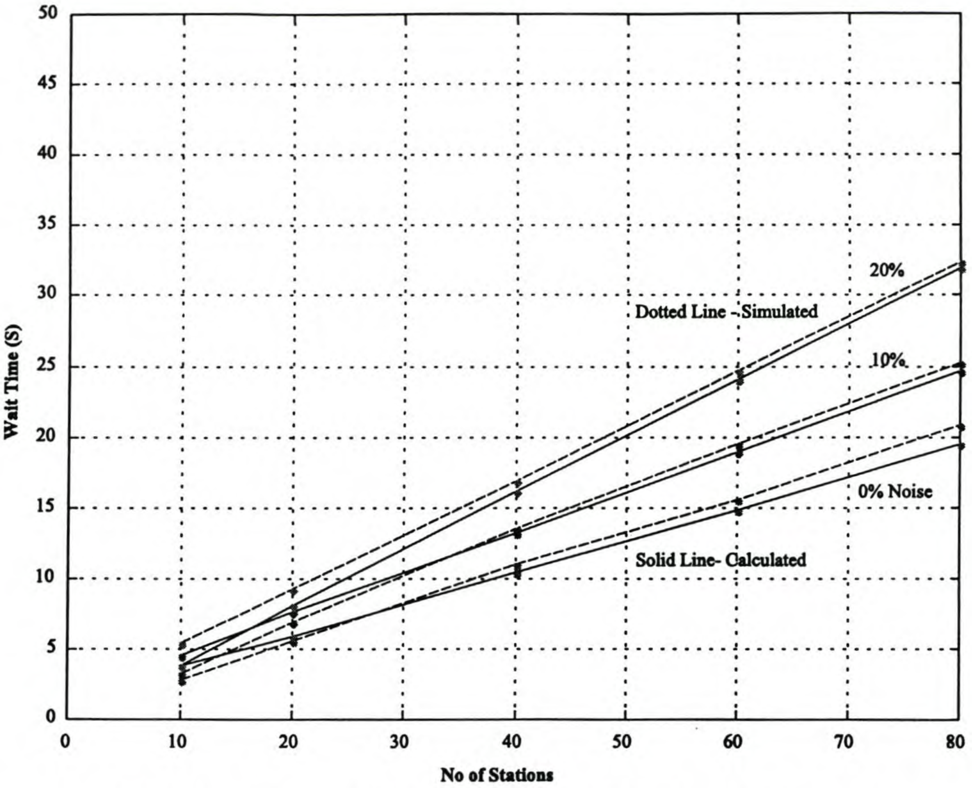


Fig. 7.10 : Theoretical vs Simulated Mean Wait times - CSMA, 384 Data Bits, 0 -20 % Burst Noise, Equal Backoff & EGI

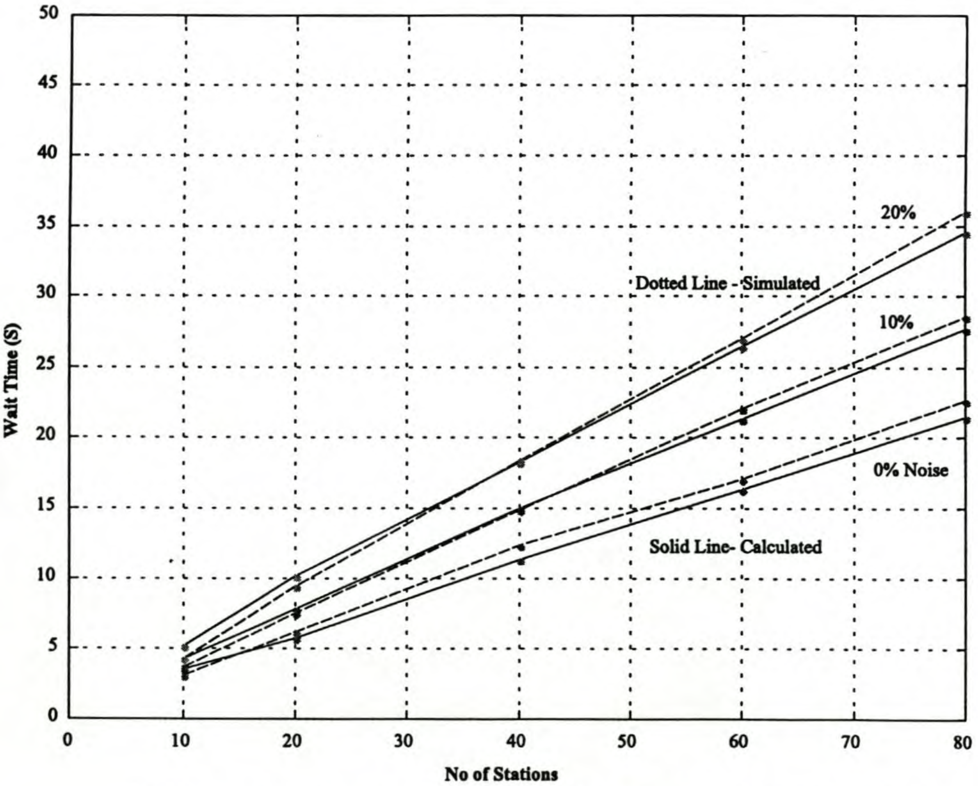


Fig.7.11 : Theoretical vs Simulated Mean Wait times - CSMA, 640 Data Bits, 0 -20 % Burst Noise Equal Backoff & EGI

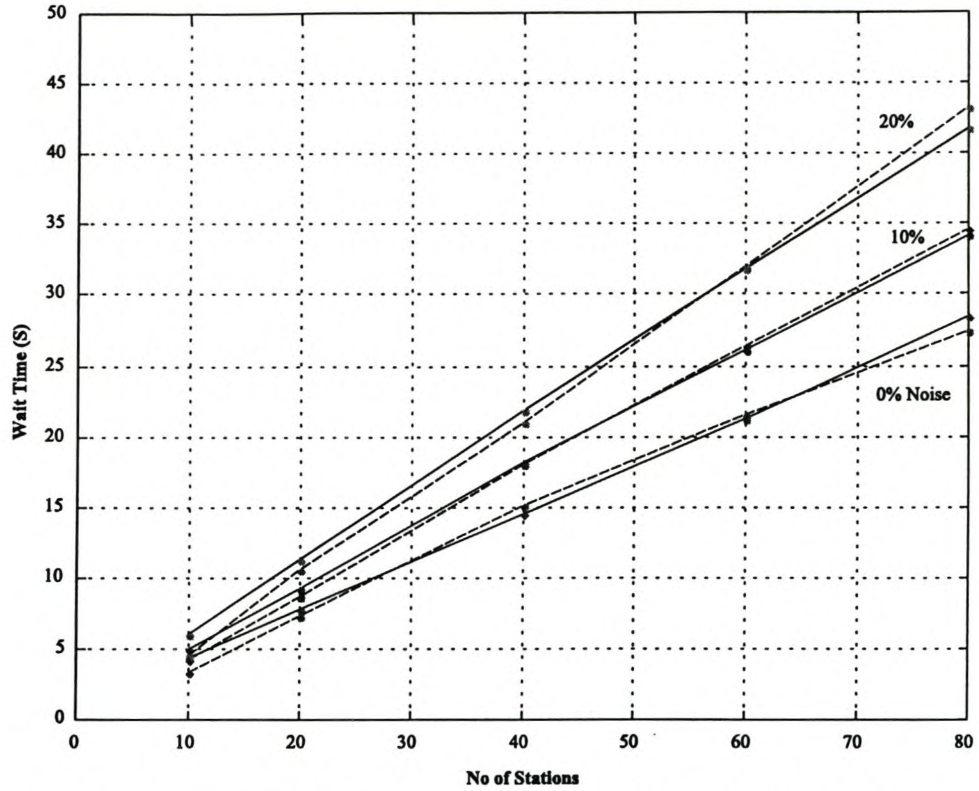


Fig. 7.12 : Theoretical vs Simulated Mean Wait times - CSMA, 1152 Data Bits, 0 -20 % Burst Noise, Equal Backoff & EGI

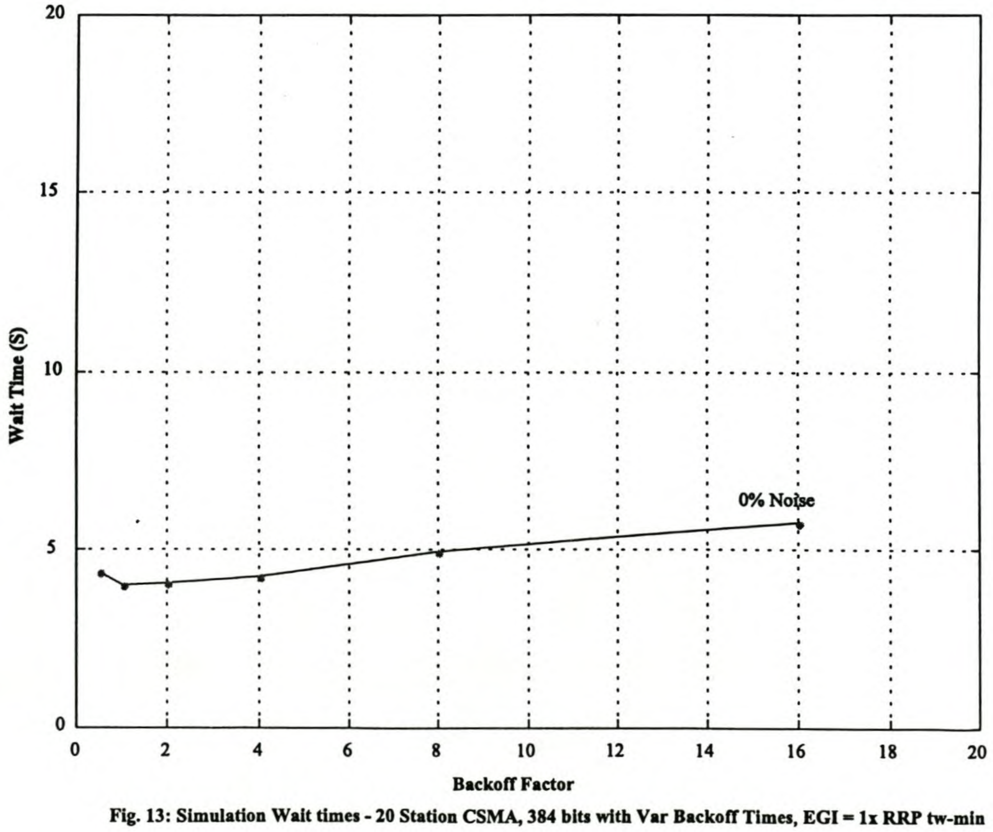


Fig. 13: Simulation Wait times - 20 Station CSMA, 384 bits with Var Backoff Times, EGI = 1x RRP tw-min

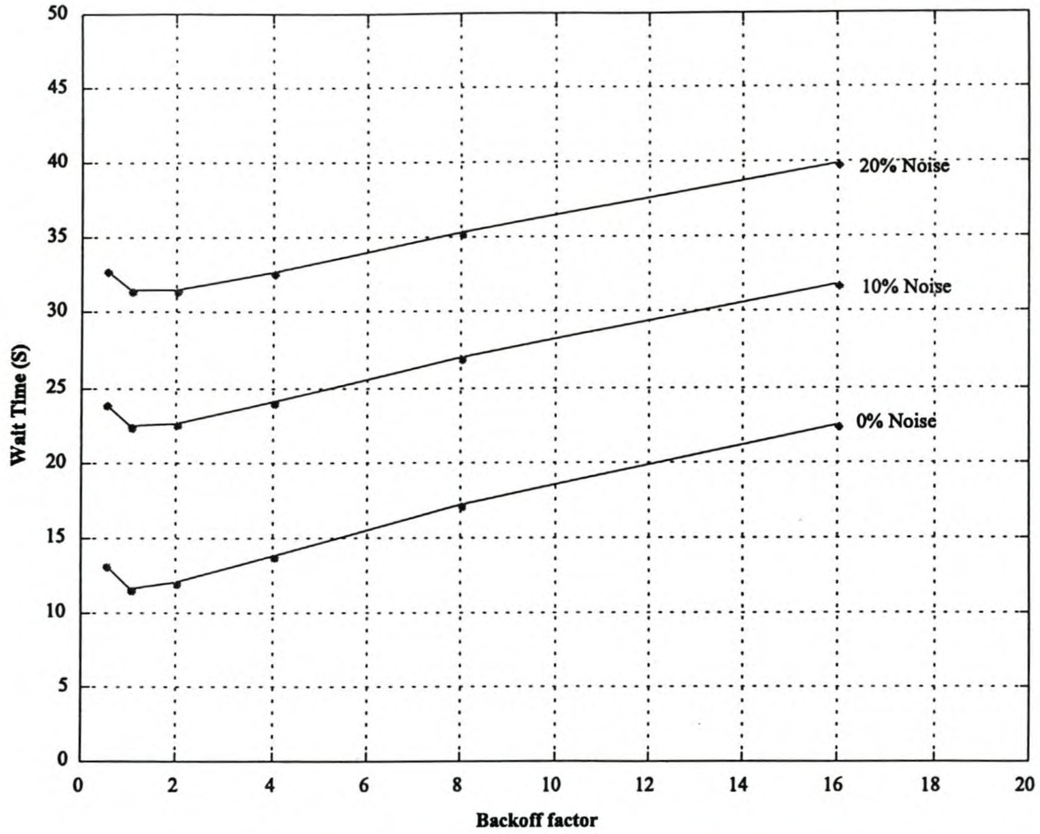


Fig.7.14 (a) : Theoretical Mean Wait times - CSMA, 384 bits, var. Backoff & Noise
Propagation Distance 30 km

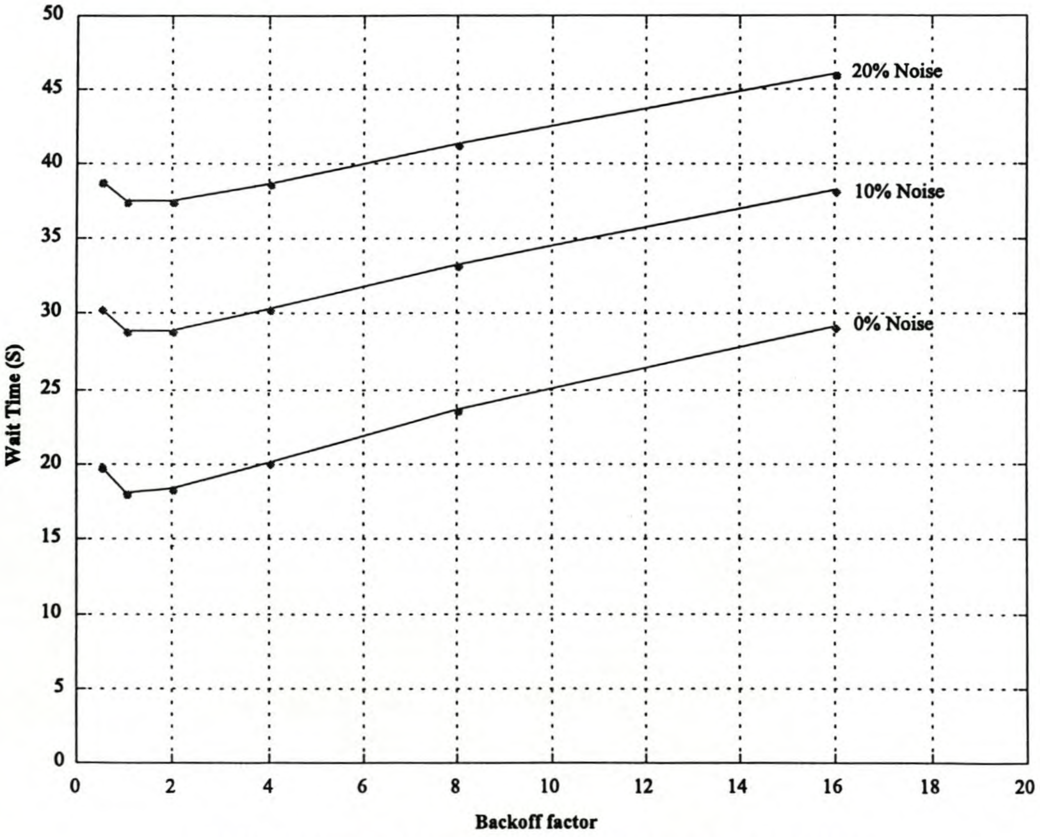


Fig. 7.14(b) : Theoretical Mean Wait times - CSMA, 384 bits,var Backoff & Noise
Propagation distance increased to 30 000 km

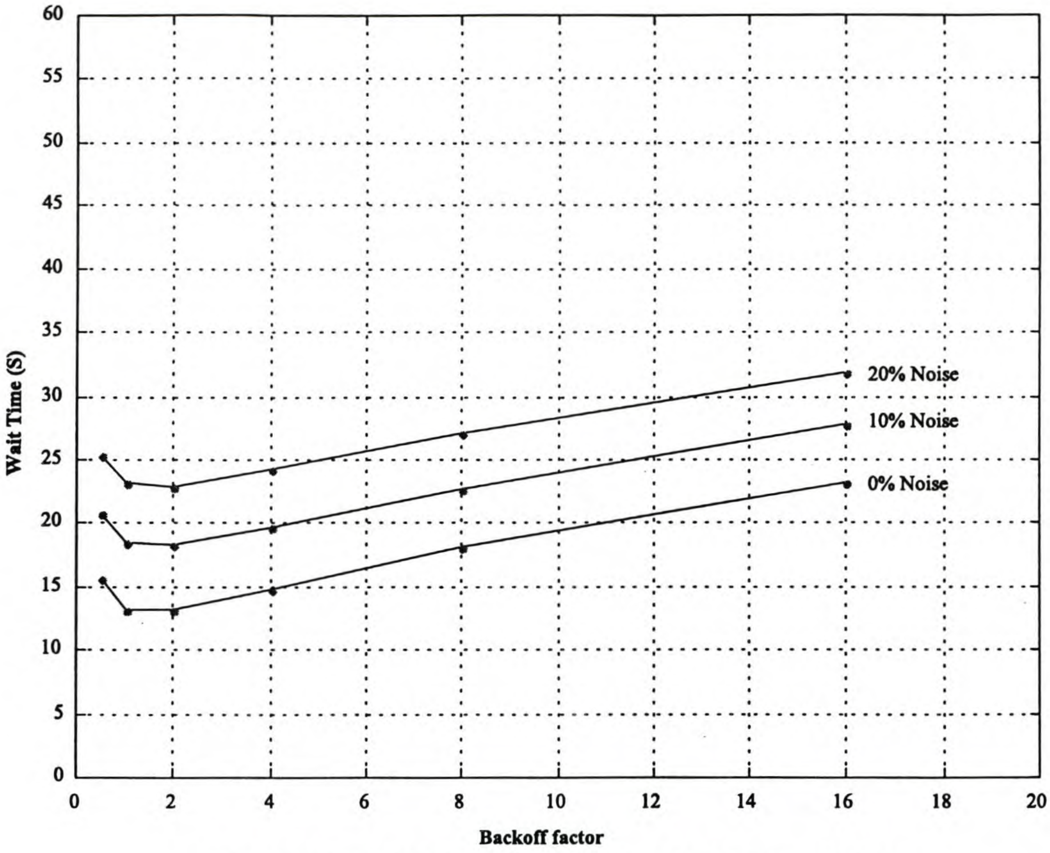


Fig. 7.15 : Theoretical Mean Wait times - CSMA, 384 bits, Var Backoff & Noise
Risetime = 0.1 sec., EGI = 1x RRP tw-min

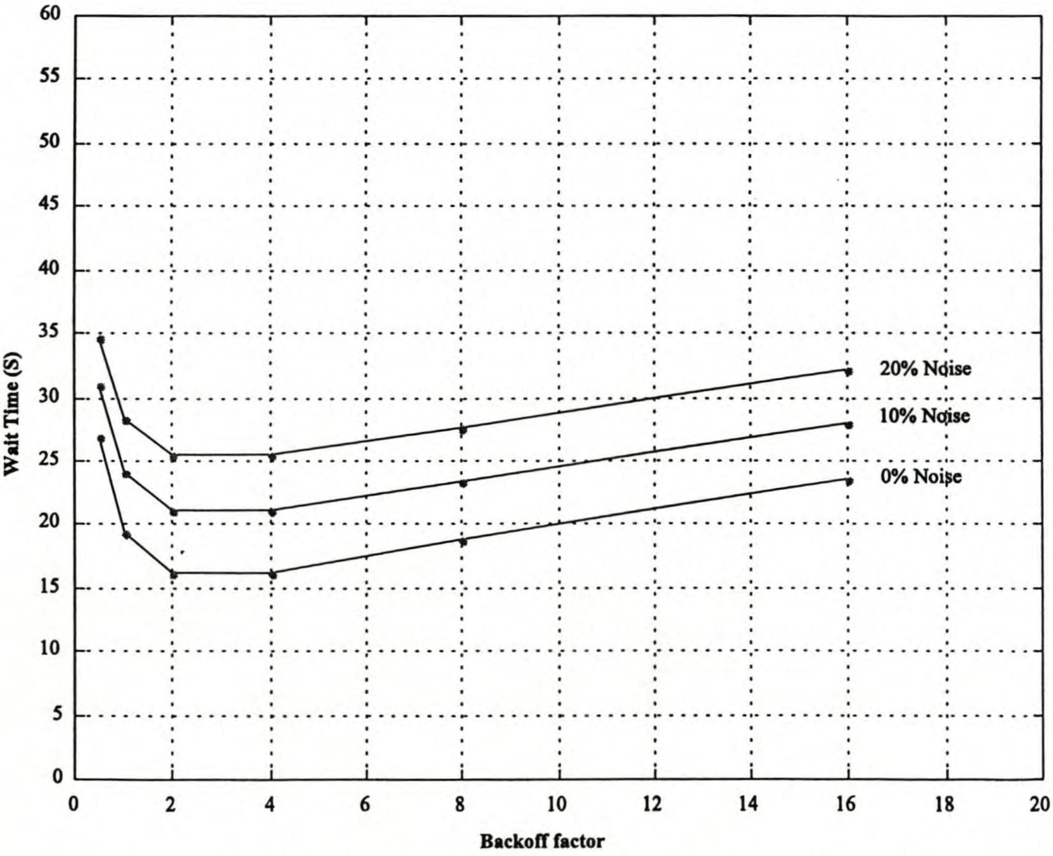


Fig. 7.16 : Theoretical Mean Wait times - CSMA, 384 bits, Var Backoff & Noise
Risetime = 0.3 sec. EGI = 1x RRP tw-min

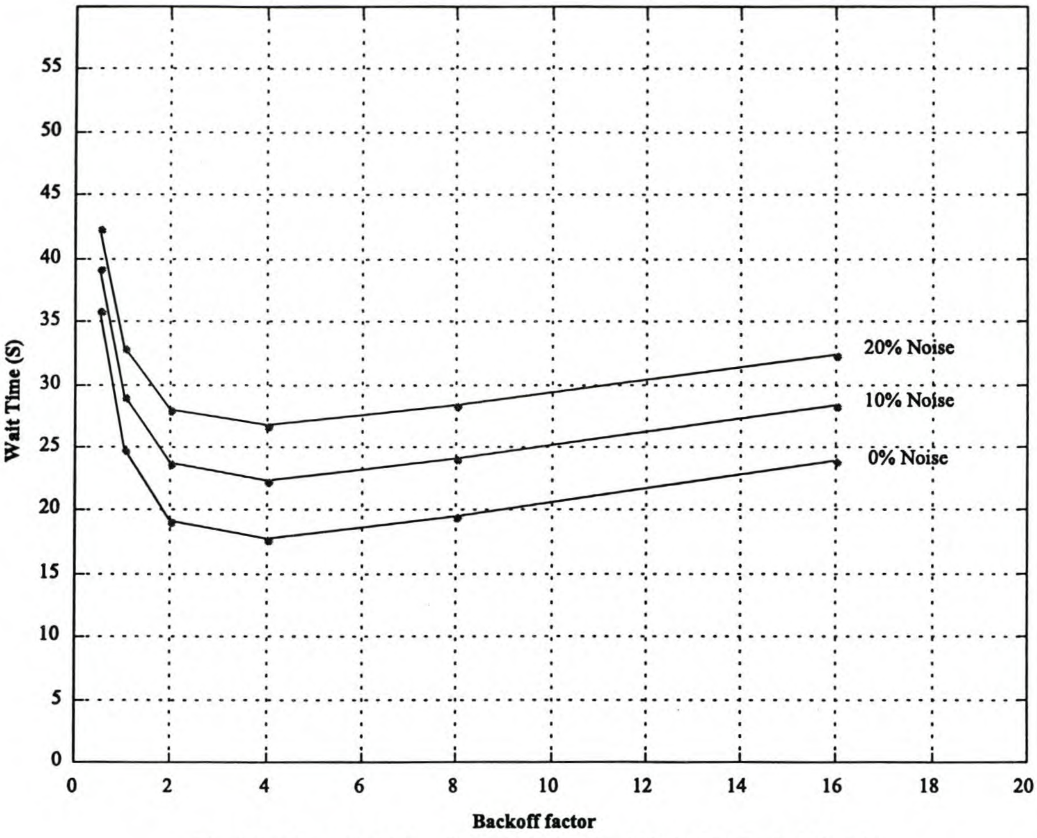


Fig. 7.17 : Theoretical Mean Wait times - CSMA, 384 bits, Var Backoff & Noise
Increased Risetime = 0.5 sec.

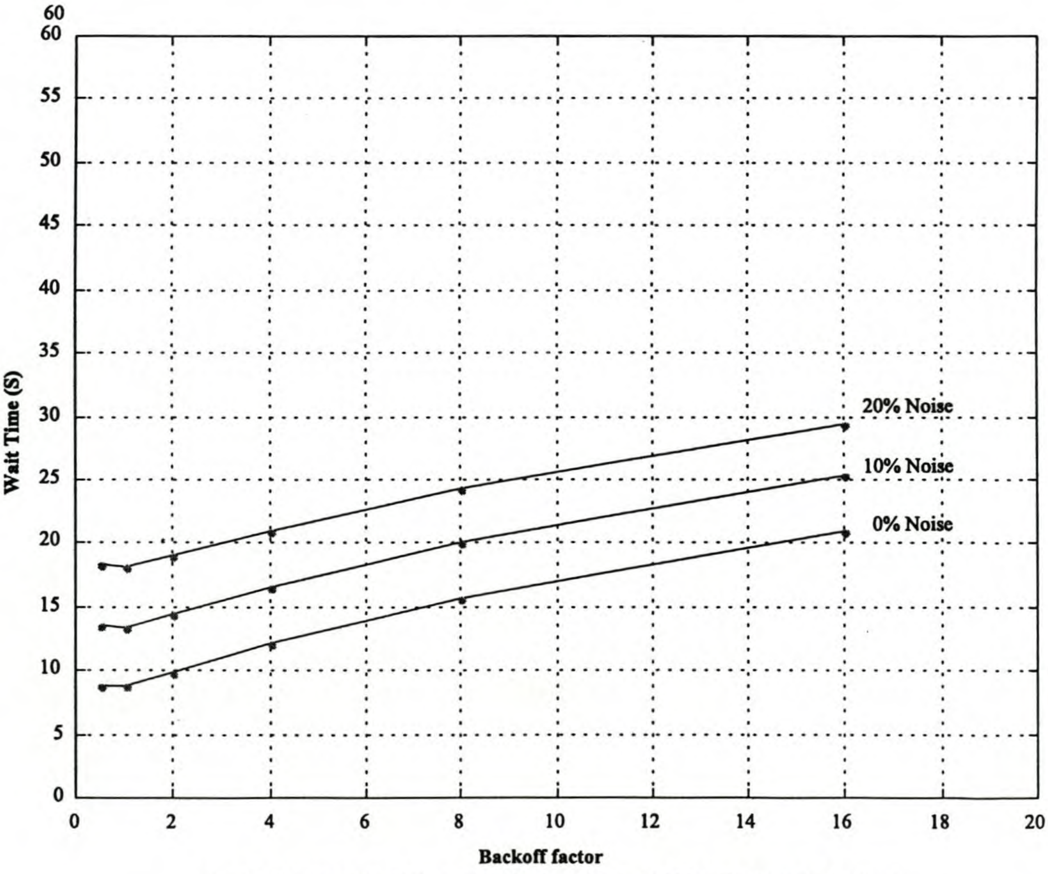


Fig. 7.18 : Theoretical Mean Wait times - CSMA, 384 bits, Var Backoff & Noise
Risetime = 0.1 sec., but with 10% Reduction in Arrival Rate

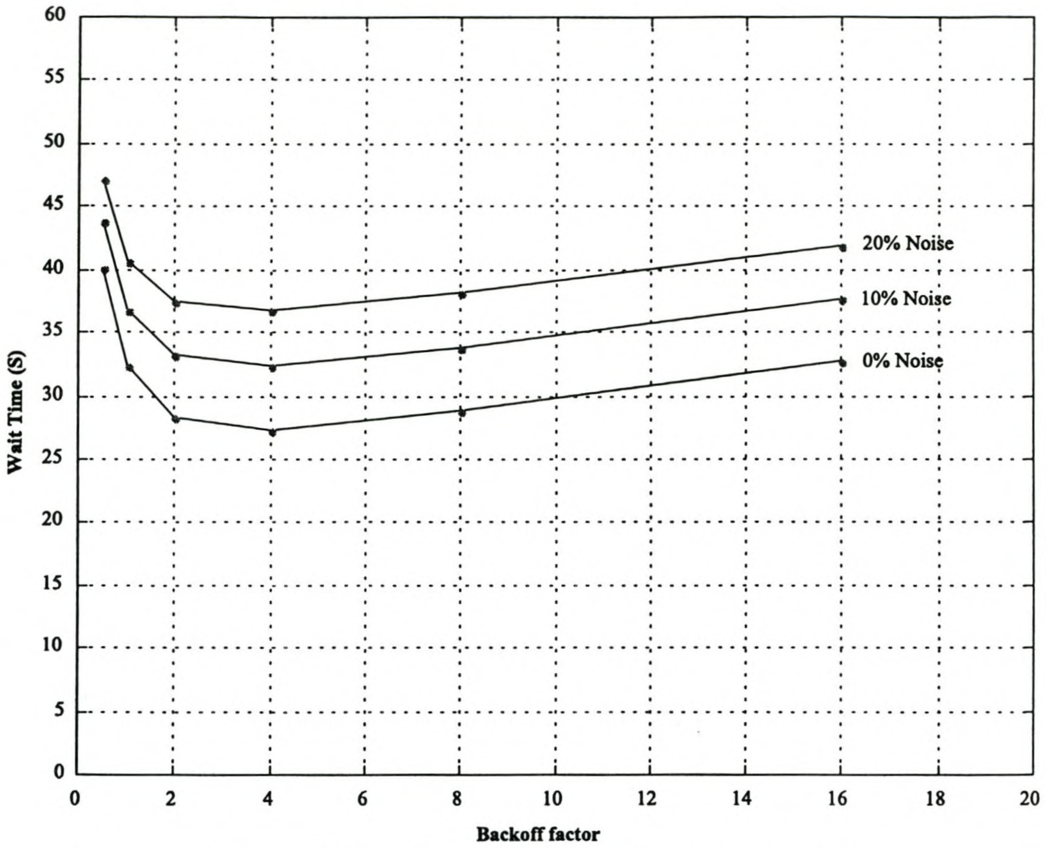


Fig.7.19 : Theoretical Mean Wait times - CSMA, 384 bits, Var Backoff & Noise 50% Increase in Arrival Rate, Risetime = 0.1 sec.

Chapter 8

Strategy Selection and Contributions

8.1 Comments on Strategy Selection

8.1.1 For the set of conditions where the $EGI = 1 \times RRPt_{w-\min}$, CSMA consistently outperforms RRP by a wide margin (typically 70-80%), when judged against to be expected, mean values. The large standard deviation associated with that performance, must certainly be taken into account. This is particularly important when systems design is undertaken on networks where one abnormal condition rapidly results in a subsequent series of similar events. Telemetry systems for electrical distribution networks, are typical cases.

8.1.2 Channel noise does not influence the strategy decision materially. It has a very similar degenerative effect on both.

8.1.3 The comments submitted under 8.1.1, may appear to suggest that RRP has a very inferior role to play. This is not the case at all, which is proved by it's continuing popularity in industrial applications, in particular. The deterministic and inherently stable behaviour of RRP are significant positive factors.

Further advantages are compactness of code and ease of implementation, which are important considerations in the cost effective application of bottom-end hardware, eg. small PLC's.

8.1.4 Propagation delay has little influence in system performance in the terrestrial type of application investigated.

8.1.5 Receiver sensing- and transmitter rise times have a significant effect, not only on throughput, but also on the selection of a backoff strategy.

8.1.6 The expected EGI has a definite influence on backoff strategy selection for optimum throughput.

8.1.7 Protocols with a slotted time base offer a clear performance advantage in other types of application, but not in this case. The conditions imposed by low baud rate, slow rise times, long pre- and postamble times and problems of synchronisation, render them unsuitable.

8.1.8 Similar arguments can be brought against Busy Tone and Collision Detect variants. These all require additional channels and/or bandwidth. Neither is available in the area of investigation.

8.2 Contributions

The contributions of the work contained in this dissertation, are as follows:

8.2.1 Existing and generally recognised work in the field of CSMA type protocol modeling concentrated on full-duplex, slotted and unslotted, infinite source types.

8.2.2 Although forming part of the abovementioned group of protocols, the type of strategy under investigation, ie., narrow-band half-duplex type, is not fully described by published analyses. Backoff strategy and system overhead components such as noise and sense/transmit activation rise times, are not included as formal parameters. In the case of backoff strategy, it has been suggested that an optimum be established by simulation, for a particular case. The effect of noise has been investigated for the Busy Tone protocol only and no evidence could be found for analytical work providing for rise times.

8.2.3 In order to establish a valid theoretical model, not only including event arrival- and service rates, but propagation delay, backoff strategy and the system overhead parameters as discussed under 8.2.2 as well, an approach differing from the previously published methods, was followed.

The relevant protocol was modeled as a finite source, state transition probability matrix derived from queueing theory. All variables as abovementioned, can be formally included and the model conveniently solved by straightforward numerical methods. The approach is essentially uncomplicated, lends itself to practical application and provides predictive results of acceptable accuracy.

8.2.4 Parallel and complementary to the theoretical model, a software emulation of a typical system, was developed. The simulation is adaptable to cater for various strategies and system parameters and closely tracks the performance of actual hardware.

8.2.5 As a result of the above, a dual set of system design tools are obtained, which could be used interactively and complementary, for the prediction of system performance and to facilitate optimum protocol- and parameter selection.

Chapter 9

Summary and Conclusions

Upon completion of this dissertation, the following remarks and conclusions may be appropriate.

9.1 Motivation

9.1.1 Although much emphasis is being placed towards the development of wireless based high speed links and networks, cost and bandwidth considerations still ensure extensive use of low-end equipment and systems, for a wide range of data link and telemetry applications

9.1.2 Practical experience and observation has also indicated that protocol selection and implementation for these systems are, more often than not, done on the basis of engineering instinct and not via more formalised system analysis. The existence of a requirement for the latter, is viewed as definite.

9.1.3 Initial, prelimenary investigations indicated that of the many deterministic and non-deterministic protocols available and published, only a few are practical and suitable for implementation in the type of system under investigation.

9.2 Summary of Objectives

Further to the above, the ensuing objectives can be summarised as follows:

9.2.1 It appeared essential to carry out a thorough investigation regarding the type- and characteristics of protocols generally utilised for the type of application concerned.

9.2.2 It was also necessary to investigate the availability and applicability of existing analytical work in this field.

9.2.3 The development of a software simulation tool, not only to obtain typical baseline performance data from different strategies, but also to subsequently be utilised in system design, was seen as a requirement.

9.2.4 Although initially suspected during the investigation abovementioned in 9.1.3, it became clear that in comparision with existing analyses, the development of an encompassing model more representative of the type of strategy concerned, would be a positive contribution.

9.2.5 The dual theoretical and simulation approach could subsequently be used in the strategy selection and performance prediction process.

9.3 Summary of Dissertation

9.3.1 After defining the motivation and objectives of the investigation the applicability of existing published, definitive, theoretical work, was reviewed. While the theoretical work carried out to date on the analysis of this broad class of protocols, by a relatively small number of authors is enlightening and very valuable, the particular type of protocol of interest, with all it's associated parameters is not specifically addressed, although it does fall under a wider group of CSMA strategies. The exact modeling with inclusion of all relevant parameters of these strategies, is acknowledged to be very difficult.

9.3.2 The procedures to be followed to achieve the required end result, were subsequently set out. These mainly concentrate on intentions for simulation and extended theoretical modeling. The accuracy of both should ideally be such as to be utilised for mutual confirmation, in order to enable reliable prediction of system performance and to assist with strategy selection.

9.3.3 A description of the software emulation of typical hardware is provided, with procedures followed for model calibration to ensure realistic representation of real life installations. The two main strategies to be simulated and their variant parameters, are set out.

9.3.4 Sets of simulations were subsequently carried out for basically two main protocol types, ie RRP and CSMA, as applicable to this type of application. A number of permutations were applied to both sets, in order to obtain a sufficiently complete set of reference data. The simulation model allows for adaptation to emulate different hardware specifications, in addition to a variable set of operational system parameters. The results from the two main groups are compared for performance and discussed.

9.3.5 Complementary to the simulation software implementation, a theoretical model of the relevant system type was defined, using a state-transition probability approach, based on a finite source, single server queueing discipline.

The theoretical model allows for incorporation of system parameters, such as event arrival rate, service rate, message format, backoff strategy and system overhead. The latter includes receiver/transmitter risetimes, propagation delay and communications channel disruption, with associated retry delays, due to noise intrusion.

The results from the model are compared with those from prior simulations and the two sets found to be within reasonable tolerances of one another. The theoretical approach is seen to be realistic and very flexible. Evidence is provided of the differences to be obtained in predicted system performance, by variation of key system overhead and backoff parameters.

9.3.6 The original contributions by this dissertation and their relevance to the selection of optimum protocol strategies, are presented in Chapter 8. The emphasis is on the formal inclusion of system overhead parameters and backoff strategy into a finite source model for half-duplex, narrow-band, CSMA type protocols. These, with the exception of propagation delay, are not accounted for in recognised benchmark analyses of similar protocols.

9.4 Future work

In retrospect, it is clear that significant and interesting opportunities exist for refinement and further research and development. The following aspects may be considered in this regard:

9.4.1 The present simulation software is very flexible, but decidedly user-unfriendly. It also runs under the DOS operating system, resulting in inconvenience and lack of compatibility with the latest PC software. The conversion, therefore, to a high level language allowing for more general use, should be considered.

9.4.2 Although significant obstacles will be encountered, primarily due to possible system topography and throughput limitations, the investigation into real-time, adaptive backoff strategies, will be very interesting and may prove rewarding. The exponential backoff procedure utilised for the Ethernet protocol is, obviously, a step in this direction.

9.4.3 The further adaptation and refinement of this model for different system characteristics, appear to be of additional interest. In this regard, the investigation of the incorporation of bursty traffic, may be considered in particular. Such a PDF will render the present model invalid, but an approach along the lines of Pollaczek-Khintchiné comes to mind and may be rewarding.

9.4.4 With the recent advent of relatively low cost digital data radio equipment, capable of 4800 and 9600 baud operation with some relaxation of bandwidth restraints, the possibility of slotted operation could be revisisted. The conditions are still onerous, but for some selected telemetry applications, this type of strategy may just be suitable. The implementation of this will have to be accompanied by significant development by hardware and software suppliers alike, as none of the industry standard, popular SCADA packages and outstation equipment currently make allowance for such operation.

9.5 Final Comment

In closing summary, it is felt that the availability of a complementary simulation and readily applicable theoretical tool should prove valuable to the system designer for the analysis and prediction of system performance. At the same time, some further progress and contribution have been made towards the theoretical modeling of this type of communications strategy.

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ADDENDUM A

DATA SHEETS : CML FX 469

The CML FX 469 is a typical example of a single chip FSK modem, such as is available from several manufacturers. This type of device has found widespread and convenient application in the design of narrow band telemetry hardware. The software Rx/Tx routines emulate the characteristics of the FX 469.

The full device datasheet is herewith included.

CML Semiconductor Products

PRODUCT INFORMATION

FX469 1200/2400/4800 Baud FFSK Modem

Publication D/469/6 April 1998

Features

- **Selectable Data Rates**
  1200, 2400 and 4800 Baud
- **Full-Duplex FFSK**
- **Rx and Tx Bandpass Filters**
- **Clock Recovery and Carrier Detect Facilities**
- **Rx and Tx Enable Functions**
- **Pin Selected Xtal/Clock Inputs**
  1.008MHz or 4.032MHz
- **Radio and General Applications**
  - **Data-Over-Radio**
  - **PMR and Cellular Signalling**
  - **Portable Data Terminals**
  - **Personal/Cordless Telephone**

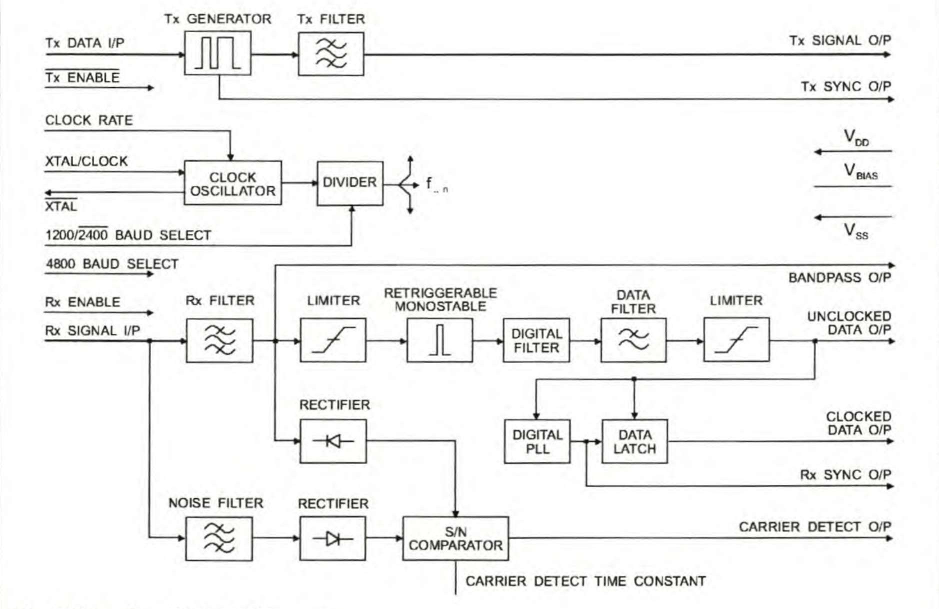


Fig.1 Functional Block Diagram

FX469

Brief Description

The FX469 is a single-chip CMOS LSI circuit which operates as a full-duplex pin-selectable 1200, 2400 or 4800 baud FFSK Modem. The mark and space frequencies are 1200/1800, 1200/2400 and 2400/4800 Hz respectively. Tone frequencies are phase continuous; transitions occur at the zero crossing point.

Employing a common Xtal oscillator with a choice of two clock frequencies (1.008MHz or 4.032MHz) to provide baud-rate, transmit frequencies, and Rx and Tx synchronization, the transmitter and receiver operate entirely independently including individual section powersave functions.

The FX469 includes on chip circuitry for Carrier Detect and Rx Clock recovery, both of which are made available as output pins.

Rx, Tx and Carrier Detect paths each contain a bandpass filter to ensure the provision of optimum signal conditions both in the modem and for the Tx modulation circuitry.

The FX469 demonstrates a high sensitivity and good bit-error-rate under adverse signal conditions; the carrier detect time constant is set by an external capacitor, whose value should be arranged as required to further enhance this product's performance in high noise environments.

This low-power device requires few external components and is available in small outline plastic (S.O.I.C) and cerdip DIL packages.

Pin Number			Function
	FX469		
DW	LG/LS	J/P6	
1	1	1	**Xtal/Clock :** The input to the on-chip inverter, for use with either a 1.008MHz or a 4.032MHz Xtal or external clock. Clock frequency selection is by the “Clock Rate” input pin. The selection of this frequency will affect the operational Data Rate of this device. Refer to Baud Selection information on the next page. Operation of any CML microcircuit without a Xtal or clock input may cause device damage. To minimise damage in the event of a Xtal/drive failure. it is recommended that the power rail (V_{DD}) is fitted with a current limiting device (resistor or fast-reaction fuse).
2	2	2	**XtalN :** Output of the on-chip inverter.
3	3	3	**Tx Sync O/P :** A squarewave, produced on-chip, to synchronize the input of logic data and transmission of the FFSK signal (See Figure 4).
4	5	5	**Tx Signal O/P :** When the transmitter is enabled, this pin outputs the (140-step pseudo sinewave) FFSK signal (See Figure 4). With the transmitter disabled, this output is set to a high-impedance state.
5	7	6	**Tx Data I/P :** Serial logic data to be transmitted is input to this pin.
6	8	7	**Tx EnableN :** A logic ‘0’ will enable the transmitter (See Figure 4). A logic ‘1’ at this input will put the transmitter into powersave whilst forcing “Tx Sync Out” to a logic ‘1’ and “Tx Signal Out” to a high-impedance state. This pin is internally pulled to V_{DD}.
7	9	8	**Bandpass O/P :** The output of the Rx Bandpass Filter. This output impedance is typically 10kW and may require buffering prior to use.
8	10	9	**Rx Enable :** The control of the Rx function. The control of other outputs is given below.

Rx Enable	=	Rx Function	Clock Data O/P	Carrier Detect	Rx Sync Out
“1”	=	Enabled	Enabled	Enabled	Enabled
“0”	=	Powersave	“0”	“0”	1” or “0”

DW	LG/LS	J/P6	Function
9	11	10	**V_{BIAS}:** The output of the on-chip analogue bias circuitry. Held internally at $V_{DD}/2$, this pin should be decoupled to V_{SS} by a capacitor (C_2). (See Figure 2. This bias voltage is maintained under all powersave conditions.
10	12	11	**V_{SS}:** Negative supply rail (GND).

Pin Number Function

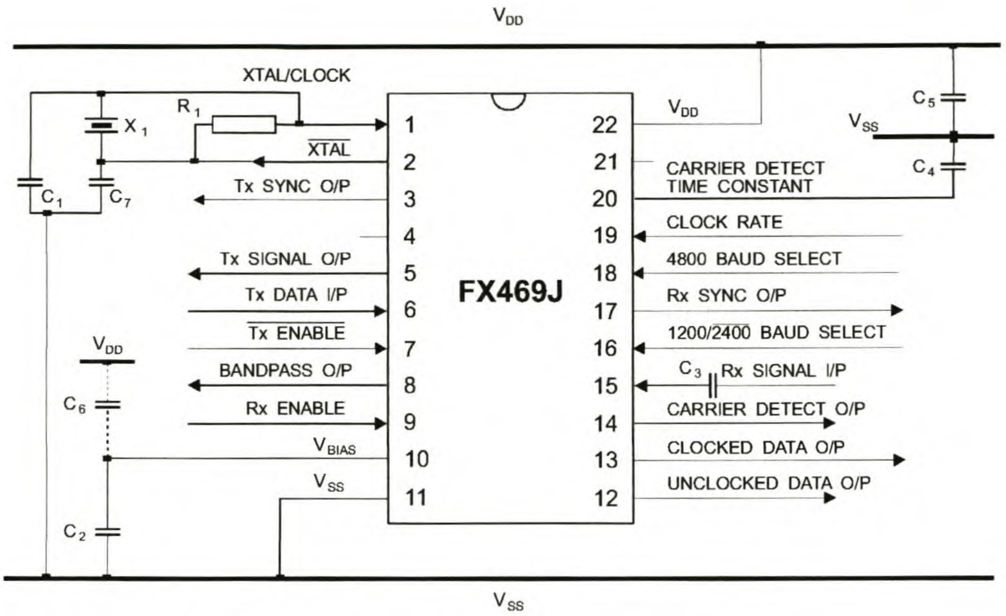
FX469 DW	FX469 LG/LS	FX469 J/P6	Function
11	13	12	**Unclocked Data O/P:** The recovered asynchronous serial data output from the receiver.
12	14	13	**Clocked Data O/P:** The recovered synchronous serial data output from the receiver. Data is latched out by the recovered clock, available at the "Rx Sync O/P," (See Figure 5).
13	15	14	**Carrier Detect O/P:** When an FFSK signal is being received this output is a logic '1.'
14	16	15	**Rx Signal I/P:** The FFSK signal input for the receiver. This input should be coupled via a capacitor, C_3.
15	18	17	**Rx Sync O/P:** A flywheel squarewave output. This clock will synchronize to incoming Rx FFSK data (See Figure 5).
16	19	16	**1200/2400 Baud Select:** A logic '1' on this pin selects the 1200 baud option. Tone frequencies are: one cycle of 1200Hz represents a logic '1,' one-and-a-half cycles of 1800Hz represents a logic '0.' A logic '0' on this pin selects the 2400 baud option. Tone frequencies are: one-half cycle of 1200Hz represents a logic '1,' one cycle of 2400Hz represents a logic '0.' This function is also used, in part, to select the 4800 baud option. This pin has an internal 1MW pullup resistor.

Operational Data Rate Configurations are illustrated in the table below.

Xtal/Clock Frequency	**1.008MHz**		**4.032MHz**		
Clock Rate pin	0	0	1	1	1
1200/2400 Select pin	1	0	1	0	0
4800 Select pin	0	0	0	0	1
Baud Rate	**1200**	**2400**	**1200**	**2400**	**4800**

FX469 DW	FX469 LG/LS	FX469 J/P6	Function
17	20	18	**4800 Baud Select:** A logic '1' on this pin combined with a logic '0' on the 1200/2400 Baud Select pin will select the 4800 option (1MW pulldown resistor). Tone frequencies are: one-half cycle of 2400Hz represents a logic '1,' one cycle of 4800Hz represents a logic '0.' This state can only be achieved using a 4.032MHz Xtal input.
18	21	19	**Clock Rate:** A logic input to select and allow the use of either a 1.008MHz or 4.032MHz Xtal/clock. Logic '1' = 4.032MHz, logic '0' = 1.008MHz. This input has an internal pulldown resistor (1.008MHz).
19	22	20	**Carrier Detect Time Constant :** Part of the carrier detect integration function. The value of C_4 connected to this pin will affect the carrier detect response time and hence noise performance (See Figure 2, Note 3).
20	24	22	**V_{DD}:** Positive supply rail. A single 5-volt supply is required.
	4, 6, 17, 23	4, 21	No internal connection, do not use.

Application Information



Component	Value	Tolerance
R_1	1.0MW	±10%
C_1	33.0pF	
C_2	1.0µF	±20%
C_3	0.1µF	
C_4	0.1µF	±10%
C_5	1.0µF	±20%
C_6	1.0µF	
C_7	33.0pF	
X_1	1.008MHz or 4.032MHz	See 'Clock-Rate' Pin

Notes

1. V_{BIAS} may be decoupled to V_{SS} and V_{DD} using C_2 and C_6 when input signals are referenced to the V_{BIAS} pin. For input signals referenced to V_{SS}, decouple V_{BIAS} to V_{SS} using C_2 only.
2. Use C_5 when input signals are referenced to V_{SS}, to decouple V_{DD}.
3. The value of C_4 determines the Carrier Detect time constant. A long time constant results in improved noise immunity but increased response time. C_4 may be varied to trade-off response time for noise immunity.
4. C_7 reduces Xtal voltage overshoot. Refer to CML Xtal Application Note D/XT/2 December 1991.

Fig.2 External Components

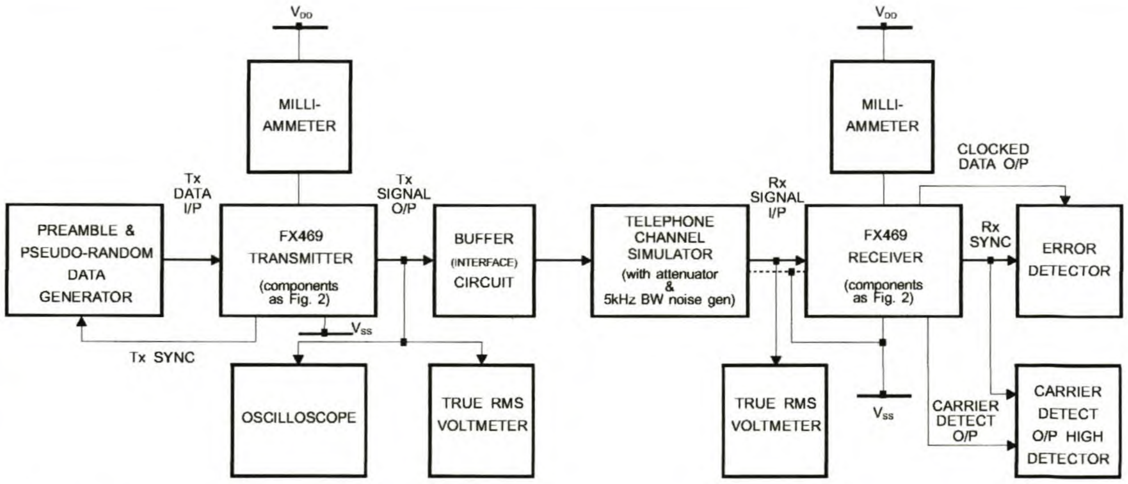


Fig.3 Suggested FX469 Test Set-Up

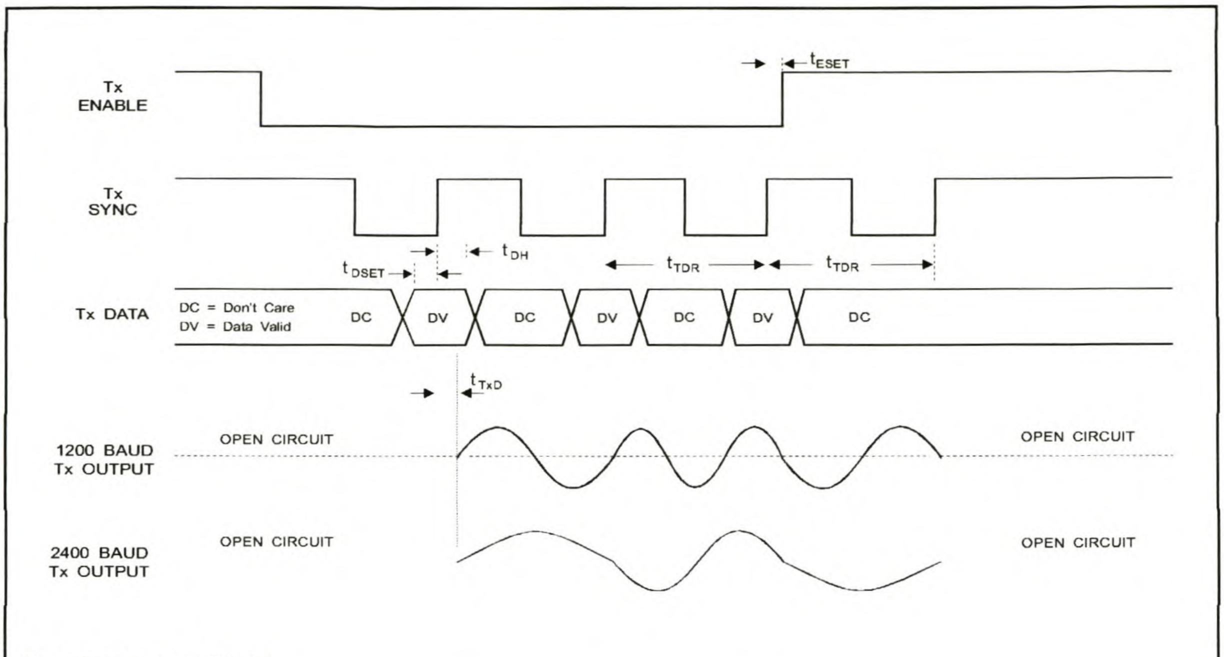


Fig.4 Transmitter Timing

Characteristics		Note	Min.	Typ.	Max.	Unit
Tx Delay, Signal to Disable Time	t_{ESET}	3	2.0	-	800	µs
Data Set-Up Time	t_{DSET}	1	2.0	-	-	µs
Data Hold Time	t_{DH}		2.0	-	-	µs
Tx Delay to O/P Time	t_{TxD}		-	1.2	-	µs
Tx Data Rate Period	t_{TDR}	3	-	833	-	µs
Rx Data Rate Period	t_{RDR}	3	800	-	865	µs
Undetermined State			-	-	2.0	µs
Internal Rx Delay	t_{ID}		-	1.5	-	ms

1. Consider the Xtal/Clock tolerance.
2. All Tx timings are related to the Tx Sync Output.
3. 1200 baud example.

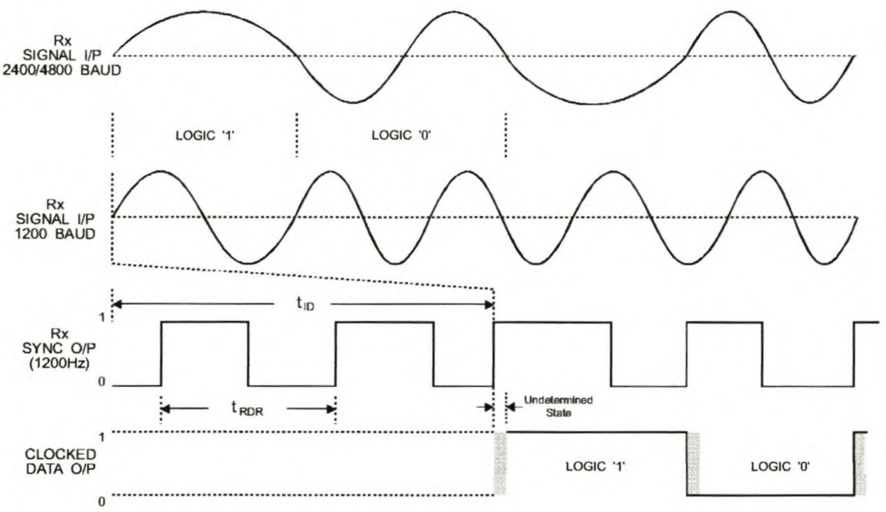


Fig.5 Rx Timing Diagram

Specification

Absolute Maximum Ratings

Exceeding the maximum rating can result in device damage. Operation of the device outside the operating limits is not implied.

Supply voltage		-0.3 to 7.0V
Input voltage at any pin (ref V_{SS} = 0V)		-0.3 to (V_{DD} + 0.3V)
Sink/source current (supply pins)		+/- 30mA
(other pins)		+/- 20mA
Total device dissipation @ T_{AMB} 25°C		800mW Max.
Derating		10mW/°C
Operating temperature range:	**FX469DW/LG/LS/P6**	-30°C to +70°C (plastic)
	FX469J	-30°C to +85°C (cerdip)
Storage temperature range:	**FX469DW/LG/LS/P6**	-40°C to +85°C (plastic)
	FX469J	-55°C to +125°C (cerdip)

Operating Limits

All device characteristics are measured under the following conditions unless otherwise specified:
V_{DD} = 5.0V, T_{AMB} = 25°C. Audio Level 0dB ref: = 300mVrms. Xtal/Clock = 4.032MHz.
Signal-to-Noise Ratio measured in the Bit-Rate Bandwidth Baud Rate = 1200 baud.

Characteristics		See Note	Min.	Typ.	Max.	Unit
Static Values						
Supply Voltage			4.5	5.0	5.5	V
Supply Current	Rx Enabled Tx Disabled		-	3.6	-	mA
	Rx and Tx Enabled		-	4.5	-	mA
	Rx and Tx Disabled		-	650	-	µA
Logic '1' Level		1	4.0	-	-	V
Logic '0' Level		1	-	-	1.0	V
Digital Output Impedance			-	4.0	-	kW
Analogue and Digital Input Impedance			100	-	-	kW
Tx Output Impedance			-	0.6	1.0	kW
On-Chip Xtal Oscillator						
	R_{IN}		10.0	-	-	MW
	R_{OUT}		5.0	-	15.0	kW
Inverter d.c. Voltage Gain			10.0	-	20.0	V/V
Gain Bandwidth Product			4.1	-	-	MHz
Xtal Frequency		2	-	1.008	-	MHz
Xtal Frequency		2	-	4.032	-	MHz
Dynamic Values						
Receiver						
Signal Input Dynamic Range	SNR = 50dB	3, 4	100	230	1000	mVrms
Bit Error Rate	SNR = 12dB	4				
	1200 Baud		-	2.5	-	10^4
	2400 Baud		-	1.5	-	10^3
	4800 Baud		-	1.5	-	10^3
	SNR = 20dB	4				
	1200/2400/4800 Baud		-	<1.0	-	10^8
Receiver Synchronization	**SNR =12dB**	7				
Probability of Bit 16 Being Correct			-	0.995	-	
Carrier Detect		5, 10				
Sensitivity		7, 8	-	-	150	mVrms
Probabilty of C.D. Being High						
After Bit 16	SNR = 12dB	5, 9		0.995		
0dB Noise	No Signal	9		0.05		

Specification ......

Characteristics		See Note	Min.	Typ.	Max.	Unit
Transmitter Output						
Tx Output Level			-	775	-	mVrms
Output Level Variation						
1200/1800Hz or 1200/2400Hz or 2400/4800Hz			0	-	±1.0	dB
Output Distortion			-	3.0	5.0	%
3rd Harmonic Distortion			-	2.0	3.0	%
Logic '1' Carrier Frequency	1200 Baud	6	-	1200	-	Hz
	2400 Baud	6	-	1200	-	Hz
	4800 Baud	6	-	2400	-	Hz
Logic '0' Carrier Frequency	1200 Baud	6	-	1800	-	Hz
	2400 Baud	6	-	2400	-	Hz
	4800 Baud	6	-	4800	-	Hz
Isochronous Distortion						
1200Hz - 1800Hz/1800Hz - 1200Hz			-	25.0	40.0	μs
1200Hz - 2400Hz/2400Hz - 1200Hz			-	20.0	30.0	μs
2400Hz - 4800Hz/4800Hz - 2400Hz				-	10.0	20 μs

Notes

1. With reference to V_{DD} = 5.0 volts.
2. Xtal frequency, type and tolerance depends upon system requirements.
3. See Figure 5 (variation of BER with Input Signal Level).
4. SNR = Signal-to-Noise Ratio in the Bit-Rate Bandwidth.
5. See Figure 2.
6. Dependent upon Xtal tolerance.
7. 10101010101 ...01 pattern.
8. Measured with a 150mVrms input signal (no noise); 1200/2400 baud operation.
9. Reference (0dB) level for C.D. probability measurements is 230mVrms.
10. For 1200 and 2400 baud operation only; when operating at 4800 baud the Carrier Detect output should be ignored.

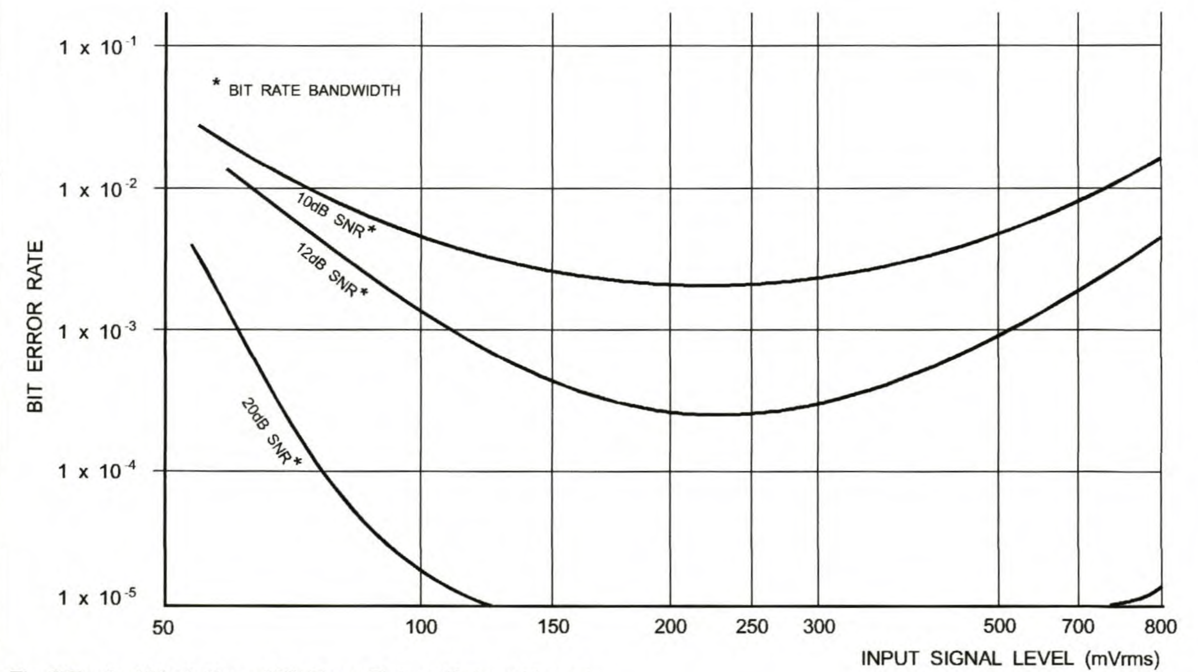


Fig.6 Typical Variation of Bit Error Rate with Input Level

Application Information

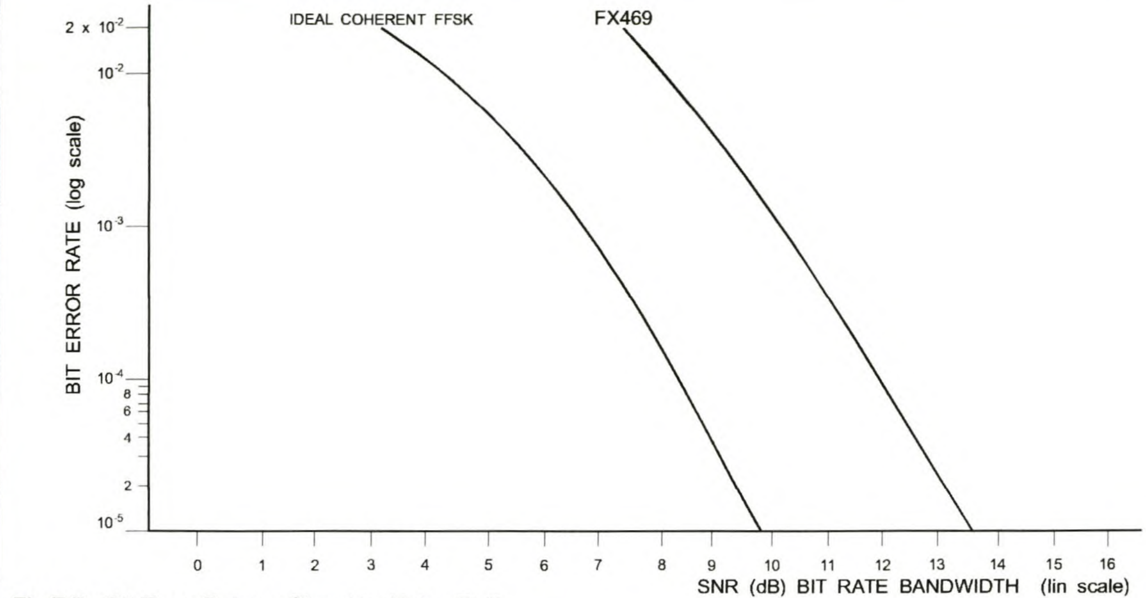


Fig.7 Rx Bit-Error-Rate vs Signal-to-Noise Ratio

Package Outlines

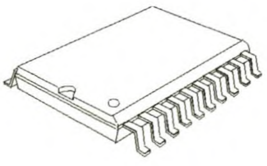
The FX469 is available in the package styles outlined below. Mechanical package diagrams and specifications are detailed in Section 10 of this document.
Pin 1 identification marking is shown on the relevant diagram and pins on all package styles number anti-clockwise when viewed from the top.

Handling Precautions

The FX469 is a CMOS LSI circuit which includes input protection. However precautions should be taken to prevent static discharges which may cause damage.

FX469DW 20-pin plastic S.O.I.C. (D3)

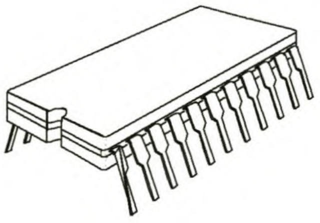
NOT TO SCALE



Max. Body Length	12.95mm
Max. Body Width	7.59mm

FX469J 22-pin cerdip DIL (J3)

NOT TO SCALE

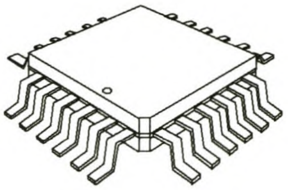


Max. Body Length	27.38mm
Max. Body Width	9.75mm

Package Outlines ......

FX469LG 24-pin quad plastic encapsulated bent and cropped (L1)

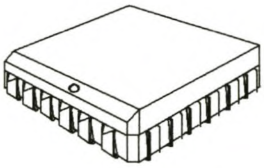
NOT TO SCALE



Max. Body Length 10.25mm
Max. Body Width 10.25mm

FX469LS 24-lead plastic leaded chip carrier (L2)

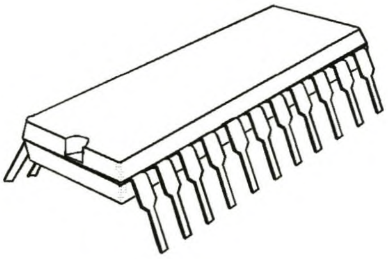
NOT TO SCALE



Max. Body Length 10.40mm
Max. Body Width 10.40mm

FX469P6 22-pin plastic DIL

NOT TO SCALE



Max. Body Length 27.94mm
Max. Body Width 9.14mm

Ordering Information

FX469DW	20-pin surface mount S.O.I.C.
FX469J	22-pin cerdip DIL
FX469LG	24-pin quad plastic encapsulated bent and cropped (L1)
FX469LS	24-lead plastic leaded chip carrier (L2)
FX469P6	22-pin plastic DIL

ADDENDUM B

SIMULATION PROGRAMMES : PASCAL LISTINGS

Two sets of Pascal software listings are included under this Addendum.

The first, *Program Ohsim1*, represents a full contention simulation, but with simplified noise filtering and no continuous channel noise.

Full noise generation and scaling is included for perusal, but not used in this case to expedite simulation time.

Burst noise is, however, supported. Risetime and propagation overheads, are also included. The program allows for exponential PDF event- and service time generation, signal modulation/demodulation, full hardware emulation, error detection, backoff routines, retries and performance logging.

The second, *Program Quetest*, emulates a finite source queueing system, without any overhead or backoff. The program serves to demonstrate and prove the exponentially generated arrival- and service time intervals and to ensure proper correlation with theoretical calculations. All times and queue lengths are logged for later analysis.

(All program listings included on attached CD-ROM)

ADDENDUM C

MATLAB SCRIPT FILES

Two Matlab script files are included in this Addendum.

The first presents one example of a numerical implementation of the state transition matrix approach for the finite source CSMA protocol, as investigated. System overhead and variable backoff is accounted for in the implementation. It is clear that the application of the theoretical model, is relatively straightforward, once design parameters are defined.

The second script file is very similar, but without system overhead.

(All program listings included on attached CD-ROM)

ADDENDUM D

TYPICAL TELEMETRY PRODUCT DATA

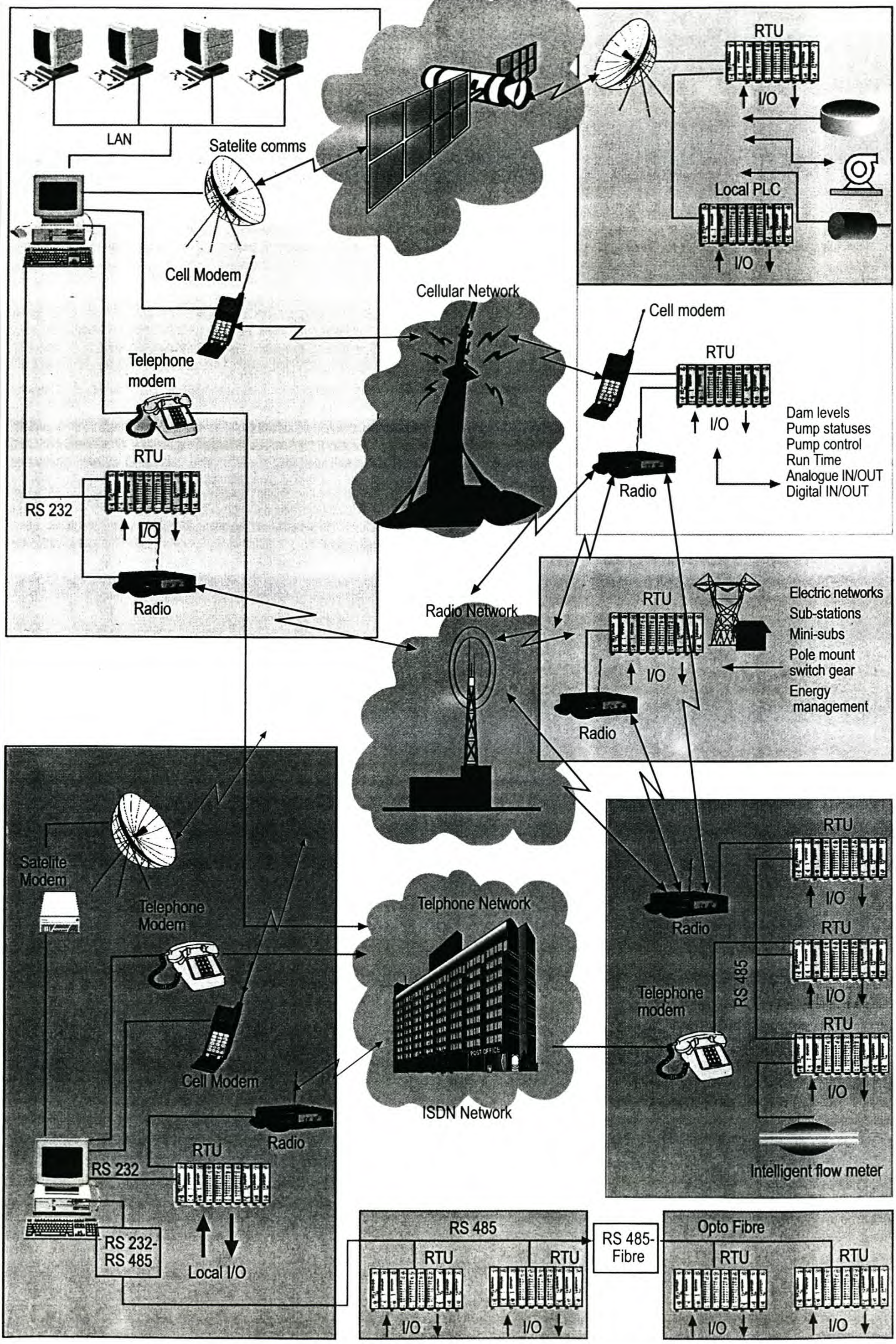
The following typical telemetry hardware data is included:

1. Product data sheet from SSE, a well known South African manufacturer, indicating some of the possible system configurations and characteristics of the various outstation modules.

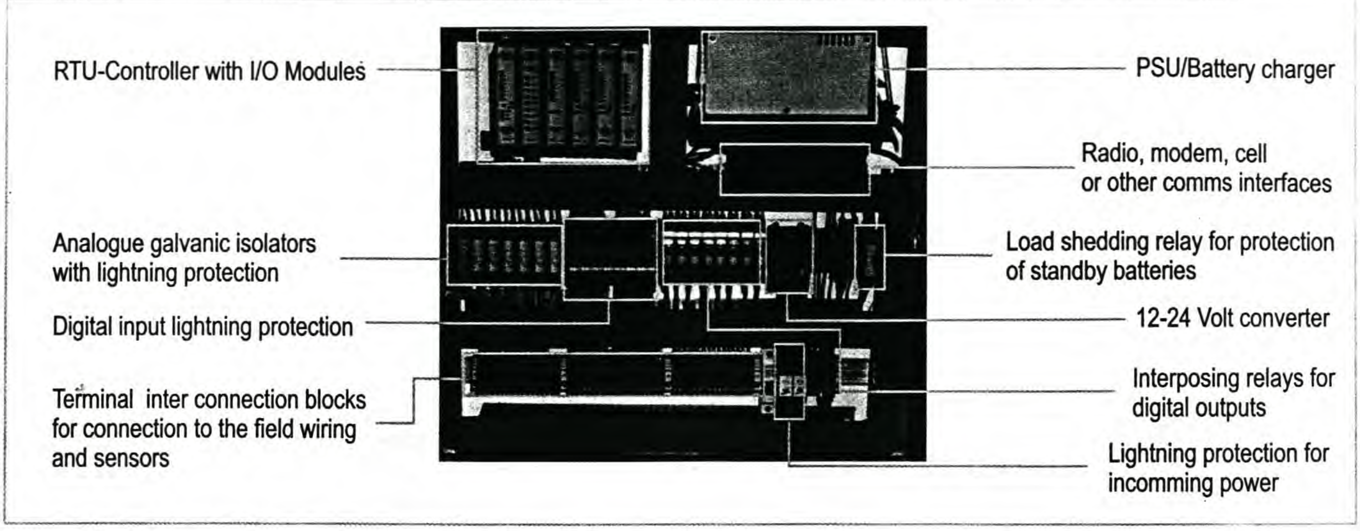
2. A short form user manual on the Teleflex hardware from Spectrum Communications, another big South African supplier, is also included.

   The differences between the two product ranges are more cosmetic than functional and both cater for the same market. Their main characteristics are in line with the descriptions elsewhere in this document.

3. As stated earlier in this dissertation, the use of relatively low cost radio equipment in this type of application, is common. A data sheet reflecting typical characteristics of such equipment, is included.


LAN
Satelite comms
RTU
I/O
Local PLC
I/O
Cell Modem
Cellular Network
Cell modem
RTU
I/O
Dam levels
Pump statuses
Pump control
Run Time
Analogue IN/OUT
Digital IN/OUT
Telephone modem
RTU
RS 232
I/O
Radio
Radio
Radio Network
RTU
I/O
Electric networks
Sub-stations
Mini-subs
Pole mount switch gear
Energy management
Radio
Satelite Modem
Telephone Modem
Telphone Network
Cell Modem
ISDN Network
Radio
RTU
RS 232
RS 232-RS 485
Local I/O
RTU
I/O
Radio
RTU
I/O
RS 485
Telephone modem
RTU
I/O
Intelligent flow meter
RS 485
RTU
RTU
I/O
I/O
RS 485-Fibre
Opto Fibre
RTU
RTU
I/O
I/O

A Typical Tele-Control Station Layout



An Industrial Concept

The PLC philosophy of immunity, reliability and autonomy is inherently designed and build into the SSE telemetry stations. However, SSE telemetry goes further than the standard features found in PLC's. Communication via various communication mediums, the time stamped data logger, time stamp events (Change of State) and numerous other functions are standard features in the SSE-RTU3 system not found in PLC based systems.

A Telemetry outstation consists of a number of functional building blocks, all contained in a robust IP rated steel enclosure. The photo insert shows a typical layout of a telemetry station.

RTU Controller and I/0 Modules

Each station is equipped with at least one RTU Controller with the necessary I/0 modules as prescribed by the application. A station can be expanded to 16 RTU Controller units each with 12 I/0 modules that can bring the I/O count to 5000 per outstation. The units are mounted in such a way to ensure easy installation for future maintenance.

Lightning Protection and Galvanic Isolation

There are some countries where lightning and surges are one of the biggest dangers to telemetry equipment. Telemetry stations are usually installed in high lying areas connected to field sensors with long cables prone to lightning. Comprehensive lightning protection is therefore of the utmost importance. Inherently designed in our system is comprehensive lightning, surge and ground loop protection.

On-board I/0 circuitry has been designed with sufficient surge protection. However, additional lightning protection on antennae system, inputsloutputs and incoming power lines can be added for sites with high lightning occurrences.

It is always a good practise to galvanicaly isolate telemetry in and outputs from the field instrumentation and machinery. This is to isolate the Telemetry equipment from the field to protect it against possible ground loops and incoming surges. Digital I/O modules have galvanic isolation on-board through 5 kVolt Opto-Isolators. Additional 10 kAmp lightning protection circuitry can be connected external to the RTU I/0 modules. See the photo insert.

Analogue Input Modules have comprehensive on-board lightning protection but no galvanic isolation. Galvanic isolators with comprehensive 10 kamp lightning protection can be added as indicated in the photo insert.

All RTU-3 digital outputs are of an open collector design whereby interposing relays can be connected directly to the outputs. When controlling pumps and other machinery in a plant or remote stations, the use of interposing relays is extremely important to isolate the telemetry equipment from the plant to protect it against possible surges and ground loops.

Communication Medium

Reliable communication from master to remote and peer-to-peer is of the utmost importance for any telemetry system- A wide range of communication mediums (as well as combinations there of) is possible on the SSE-RTU telemetry equipment. In the above example, an of-the-shelf two-way analogue radio was used as a communication device. However, the radio can be replaced by any other conununication unit such as: Digital Radios, telephone and cell phone modems, satellite modems, RS 232 to Fibre Opto converters, etc.

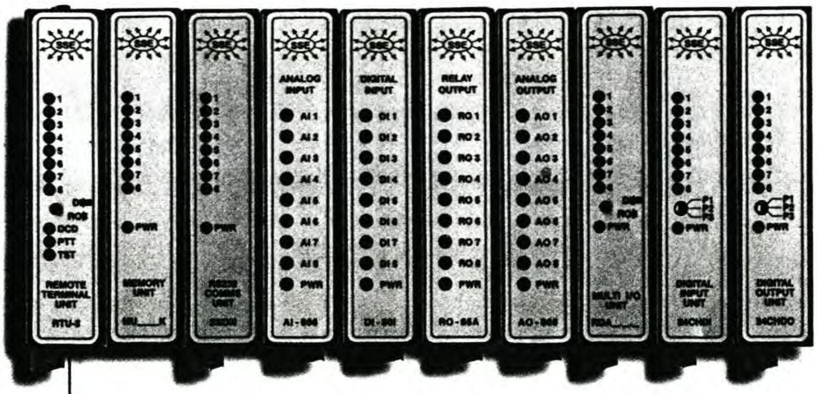
Power Supply Units

A rugged power supply/charger is installed at each station. The power supply will power the outstation at 12 volts and also charge a high quality maintenance free battery. A Battery is normally installed at each station for maintaining the operation of the outstation during long power failures. A station will continuously monitor the incoming power and will notify the master station of power failures.

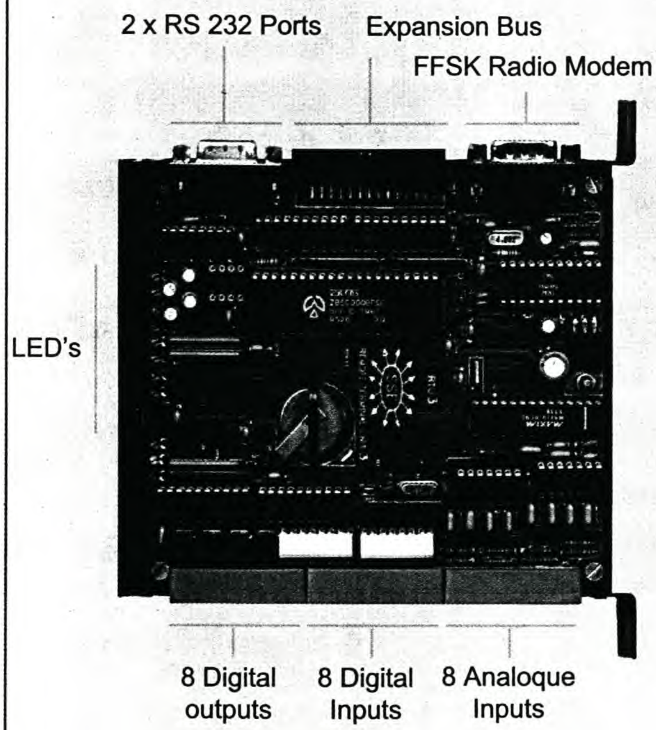
Terminal Blocks

Situated in the bottom of a telemetry station is a number of high quality termination blocks with knife disconnect links. These termination points are extremely important for ease of installation and maintenance. All incoming and outgoing wiring from the field must be terminated on these terminals. A clean break point between the telemetry processing equipment and the sensor field wiring can be established.

RTU-3 TELE-CONTROL WITH I/O MODULES



The RT-3 CPU Processor Module



Each station has to be equipped with a RTU-3 CPU Module which forms the heart of the Tele-Control Stations.

Features

- Extremely Powerful Software.
- A Real-Time I/O device.
- An Intelligent Data Logger.
- Remote time stamping of events and logged data.
- Programmable with a powerful "PLC" type instruction language.
- Totally user configurable and programmable.
- Modular and easy expandable.
- Easy to install and maintain.
- Excellent EMI protection.
- Industrial standard 8051 CPU (Also 16 Bit versions).

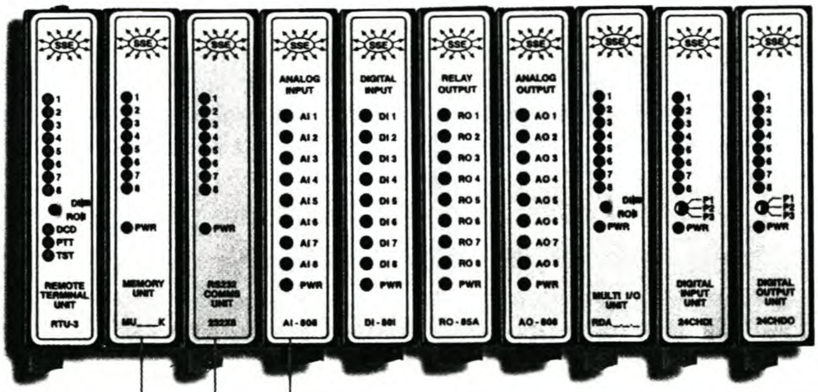
- On-Board 128 K Byte memory (Expandable with external modules).
- On-Board FFSK Radio modem to be connected to virtually any two way radio.
- Controls up to 12 I/O modules per RTU Controller.
- Can be expanded to 16 RTU controllers each with 12 I/O modules per station.
- On-Board real-time clock with watch-dog timer.
- On-Board LED's indicating status of on-board I/O's.
- Two RS 232 ports which can be connected to:
  - A Telephone Modem.
  - A Cellular Modem.
  - A ISDN Modem Interface.
  - A Satellite Modem Interface.
  - A twisted pair Interface.
  - A Fibre Optic Interface.
  - A local PLC or any other intelligent device.
  - A Laptop computer for detail diagnostics.

- **Analogue inputs (On-Board)**
  - 8 Input channels.
  - 12 Bit resolution.
  - 0,1% Accuracy.
  - Single ended.

- **Digital Inputs (On-board)**
  - 8 Input channels.
  - Opto-isolated.
  - 5 KV isolation.

- **Digital Outputs (On-board)**
  - 8 Output channels.
  - Open collector outputs.
  - 250 m A sinking per channel.

RTU-3 I/O MODULES



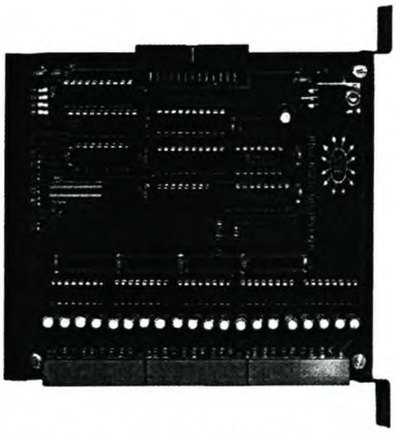
Memory Expansion Module

This module is used for the expansion of memory for the storage of logged and event data

Feature

- Each card can be equipped with 8 x 128 k Byte memory IC's bringing the total memory per module to 1 Mega Byte
- Up to 12 Memory Expansion Modules can be added per RTU bringing the total memory expansion to 12.2 Mega Byte
- Non volatile storage
- 10 year backup of memory in absence of power

8 Channel RS 232 Module



This module is used if the RTU controller RS 232 Port has to be duplexed and expanded.

Features

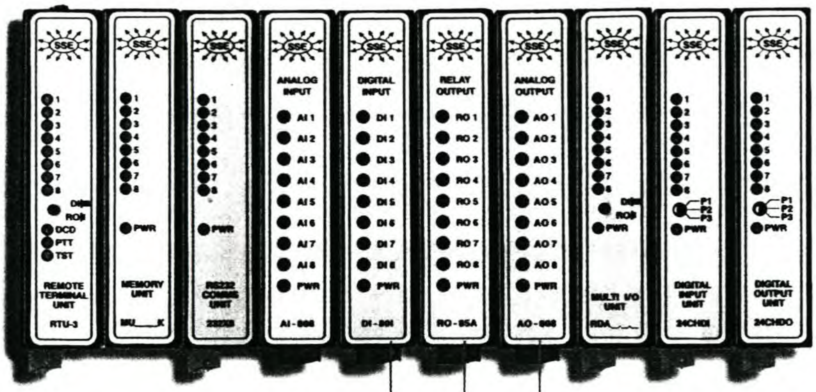
- 8 multiplexed RS 232 ports
- Used to communicate with intelligent devices with the same protocols
- Up to 12 RS 232 modules per RTU controller
- New drivers can be developed on demand

8 Channel Analogue Input Module

Features

- 8 Differential Analogue Inputs
- 8 Bit resolution
- 0,5% accuracy
- Up to 12 modules per RTU Controller
- Led's to indicate 50% of full scale
- Comprehensive 10 K Amp On-board lightning protection (common mode 8/20 micro seconds)

RTU-3 WITH I/O MODULES

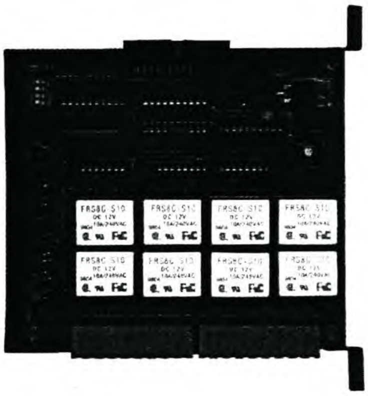


8 Channel Digital Input Module

Features

- 8 Digital input channels
- 5 kVolt Opto isolation on all inputs
- Comprehensive 10k amp lightning protection common mode (8/20 micro seconds)
- Any digital input can be used as a counter input
- Up to 12 Modules per RTU controller
- Inputs 8-32 Volt's
- Inputs individually isolated
- Led's display input status

8 Channel Relay Output Module



Features

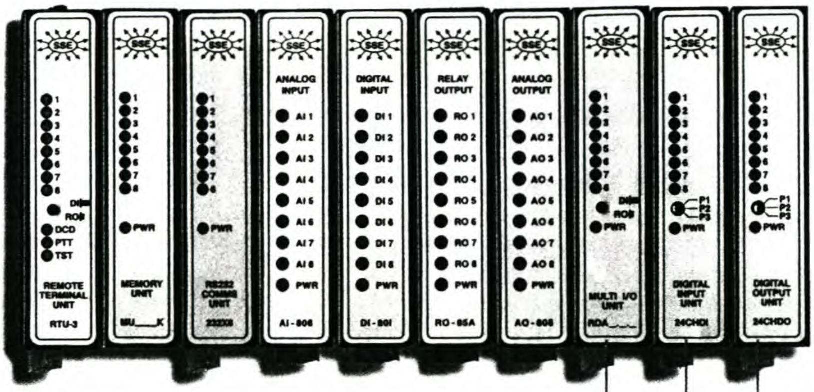
- 8 Relay output channels
- Normally open contacts
- Relay ratings: 10 Amp 250 VAC resistive load
- LED display status of relays
- Up to 12 modules per RTU controller

8 Channel Analogue Output Module

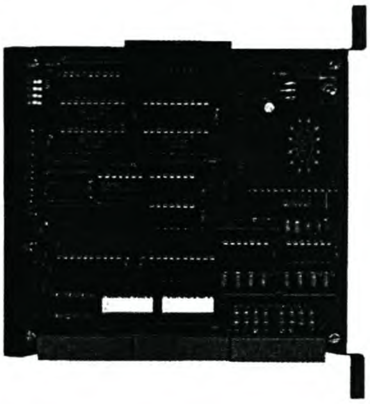
Features

- 8 Channel 4-20 m Amp outputs
- 8 Bit resolution
- Comprehensive 10 k Amp lightning protection on-board common mode (8/20 micro seconds)
- Up to 12 modules per RTU controller
- LED's display 50% of full-scale

RTU-3 WITH I/O MODULES



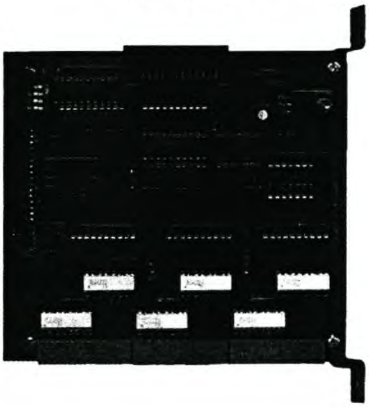
Mixed I/O Module



Features

- **Analogue Inputs**
  - 8 Channels single ended
  - 12 Bit resolution
  - 0,1 % Accuracy
- **Digital Inputs**
  - 8 Channels
  - 5 k Volt Opto-Isolation on each input
  - 8-32 Volt Dc inputs
- **Digital Outputs**
  - 8 Channels
  - Open collector
  - 250 mA sinking
- LED's display I/O statuses
- Up to12 modules per RTU controller module

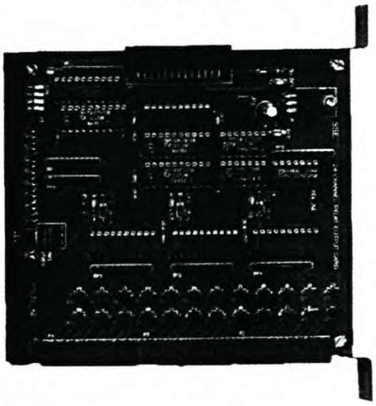
24 Channel Digital Input Module



Features

- 24 Digital input channels
- 5 kVolt Opto-Isolated
- 8-32 Volt DC Inputs
- LED's Displaying input statuses
- Up to 12 input modules per RTU controller

24 Channel Digital Output Module



Features

- 24 Digital output channels
- Open collector output - 250 mA sinking
- LED's display output statuses
- Up to 12 output modules per RTU controller

Tele-Control (Telemetry) Systems

Practical Approach

Telemetry systems are important tools for operational, financial and technical personnel for the effective management of water, electricity utilities in municipal and city councils. The system enables the effective management, the control of losses and proper future planning for the upgrading and expansion of plants and networks.

Technology changes and innovative designs are driving down costs while pumping up the functionality. The SSE Telemetry (Tele-Control) system is ideal whenever and wherever a client needs to monitor and control infrastructure, networks, equipment and machinery remotely over long distances.

With all the possibilities of local and remote communication, and the various possible types of interconnections, the SSE RTU solution adapts itself to all topologies. Even on faraway sites you keep control of your application in terms of development and set-up.

System Architecture

A Telemetry system consists of a combination of technologies integrated to establish a working system. It is therefore critical that reliable and well-proven equipment be used. The various technologies rely on each other for a workable solution. Telemetry combines technologies such as front end instrumentation (a wide variety), micro controllers, lightning protection, earthing systems, radio technologies, antenna systems, modems, computers, communication protocols, internet, PC software, etc.

Master Stations

Master stations can be any SCADA package (or other third party software) for the display of valuable information, data capturing, trending, alarming and control of remote stations. SSE has developed a number of protocol drivers for various SCADA packages. However, our OPC server protocol driver makes the system truly accessible to any software package with OLE or OPC client software.

Communication Networks

For a Tele-Control system to operate effectively, proper communication mediums are essential for Master station to remote and/or peer-to-peer communication. The SSE RTU Tele-Control equipment can communicate via any one or a combination of the following communication mediums:

- A private radio network system with or without repeater stations
- The telephone network through dial-up telephone modems
- The cellular phone network through dial-up cell phone modems.
- The cellular phone network through the Short Message Service (SMS).
- A satellite communication network.
- Through ISDN communication network.
- Through leased lines.
- Through a RS 485 communication network.
- Through Fibre Opto communication.

A standard feature is the **store and foreword (Digipeating)** capability of the RTU which forms an integral part of the protocols for radio and landline communication mediums. This enables any remote station equipped with the SSE RTU equipment to be used as a digital repeater (Digipeater) for the transmission of data to remote stations. The system can use three intermediate remote stations as digipeaters to reach its destined station.

Remote Stations

The design philosophy of the remote stations is inspired by a PLC concept where the SSE RTU system rests on three fundamentals: immunity, reliability and autonomy. Due to its enclosure design, comprehensive lightning and surge protection on antenna, I/O's and power lines, in conjunction to its electronic concepts that uses the latest technology, the SSE RTU can be installed in remote regions with little or no maintenance.

Due to its solar/battery charger, it's low power consumption and its long–life memory backup, the RTU carries on with its programmed tasks. With its unique features such as real-time data monitoring, data logging capabilities, "PLC" like control programmes and extensive communication abilities, the RTU stations can be configured and programmed to execute almost any task, from the simplest to the most extensive control functions.

Field Sensors

Field sensors makes up an integral and extremely important part of a telemetry system. Field sensors such as pressure, level, ultra sonic, flow, turbidity, amps, volts, KWA, temperature, gas, etc, can be installed and connected to the remote stations for measurement, processing and transmission to a master or other remote stations.

A Truly OPEN Distributed Control System

The unique, powerful and configurable communication (Network) and I/O mapping of the RTU telemetry system gives you full control of the communication and control strategies. Any RTU station can be controlled by any other master control computer or by any other remote RTU station.

For Example: A master remote RTU station can have four or five (or more) other remote slave RTU stations under its control. However, these RTU stations can also be controlled by any other remote station or master control SCADA computer. A slave remote RTU station, under the control of another master control station, can again act as a master controlling station of its own set of remote slave stations under its control. This unique versatility enables any remote station to act as a controller of any other remote station via any communication networks available.

The type of control and communication strategies that may be implemented is only limited to that of its configurator.

RTU Controller Software

To complement the high quality hardware design of the SSE RTU Telemetry equipment, is the RTU software packed with powerful functions and features. The fact that the software has been modularly designed ensures that expansions and extensions on the system can be done without sacrificing backward compatibility.

Totally Configurable

All functions and features in the RTU are user configurable. These configurations can be done locally at a remote station or on a master station. These configuration data can then be downloaded via the radio, modem or any other communication medium available. All configuration and programming functions of a RTU are done with a poweful Windows based configuration tool. The tool is menu driven with comprehensive help functions.

I/O Configurations

Each and every I/0 in the RTU can be configured individually. These I/0 configurations are important so that the RTU can be instructed on the way data logging, event logging, event reporting, change of state time stamping and other I/0 functions must be executed.

An Analopue Example: An analogue input can be configured where the number of samples, the integration times, the delta changes, the logging, the High-High, High, Low and Low-Low alarms can be configured.

A Digital Input Example:. A digital inputs dead times, alarm, event and logging functions can be configured.

Intelligent Data Logging

All data logging parameters are user configurable. The RTU can be instructed to log selected inputs at regular intervals, on specific times of the day or on specific or combined triggers and events. The RTU can gather and store data for weeks or months. All logged data can then be downloaded from the station by using a laptop computer on site or remotely via the available communication network.

Change Of States (EventsI

The RTU can be programmed that Change of States (for digitals and Change of Value for analogues) on all or selected I/0's, will be time stamped and immediately reported to a master and/or other remote stations.

Remote Time stamping

The RTU is equipped with a real-titne clock, normally synchronised with a master station computer. All events, change of states, change of values and logged data are remotely time stamped at the outstation. These data are transmitted to a master, or to another remote station with the related time stamping information. This is extremely useful to determine the actual time of occurrence and not the time of arrival of I/0 value at the master computer. This is a powerful feature for times when real-time communication is not available. Data can then be extracted at times when communication is available with a SCADA computer. Historical trending and replays will then represent the actual sequence and time of events.

"PLC" Control Programs

Powerful control programmes can be developed on a master station computer and then downloaded to the outstation either at site or remotely via the available communication medium. The program is a "PLC" type instruction set: ALL RTU configurable functions and features are accessible and can be programmed by the programming language, The programming language allows you to directly control functions, features and I/0's in other remote stations. Comprehensive and powerful distributed control strategies can be developed and implemented.

Alarming

Various types and intelligent alarms can be configured in the RTU.

For analogue inputs, the following four alarm levels can be set: High High, High, Low and Low Low. For digital inputs a status level can be defined as an alarm condition.

RTU SYSTEM alarms can also be configured. If, for example, a RTU program goes into an infinitive loop or, if parts of the RTU program are corrupted, then the RTU will generate an alarm and notify the master station.

Intelligent alarm conditions can also be programmed in the RTU.

Communication Protocol

The communication protocols are designed to optimise the transmission of data between stations. Comprehensive CRC error checking is done on all data messages through the various communication networks to ensure absolute correct data retrieval on the receiving side.

tele-FLEX User's Manual

(version 1.82)

Index

1. Overview

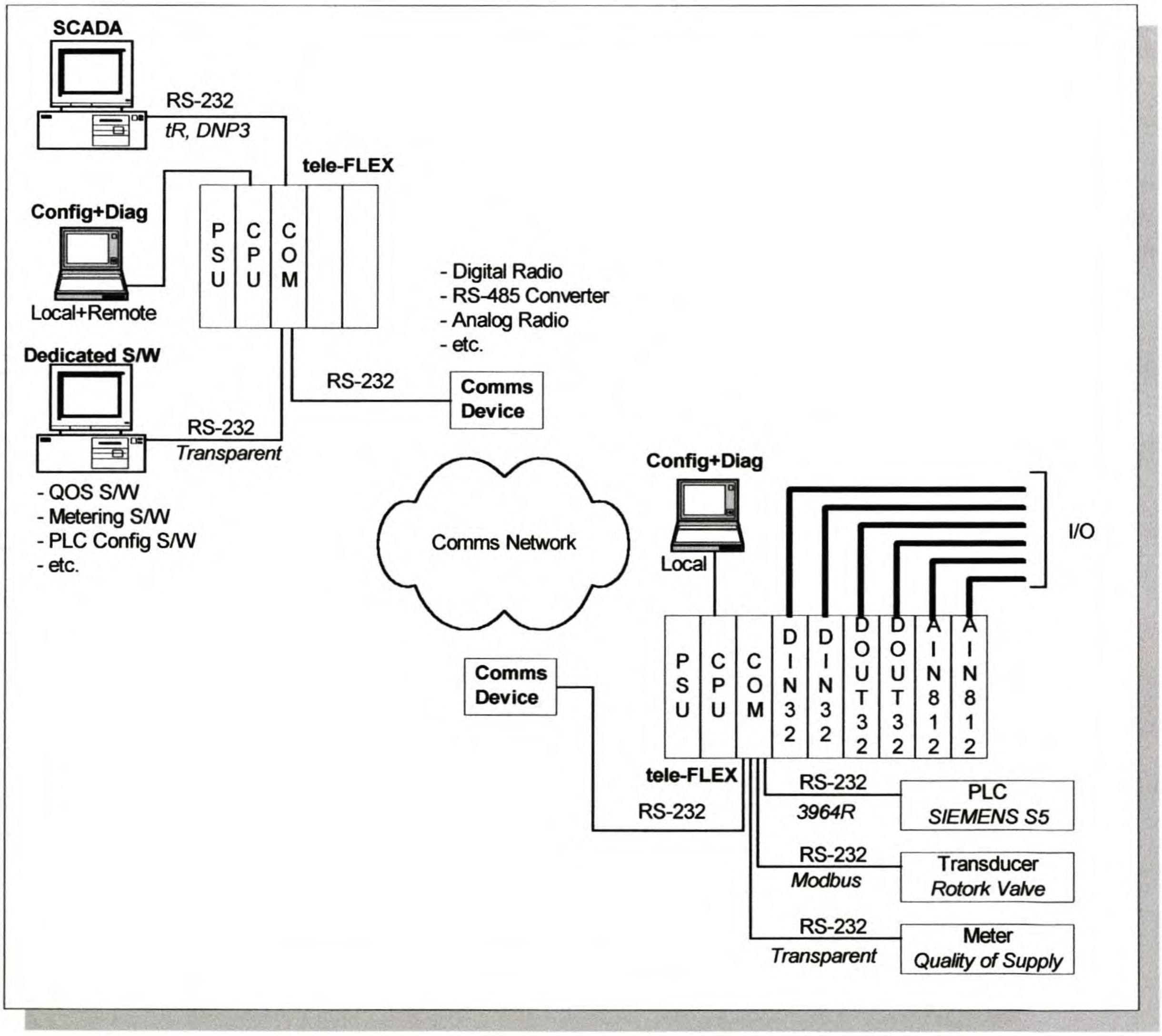
tele-FLEX is an advanced telemetry system, designed to provide flexible communications solutions for a variety of applications.

Multiple serial ports and device drivers enable connectivity with a large number of Intelligent Electronic Devices (PLCs, meters, transducers, data loggers, UPS's, etc.)

Digital and Analog I/O cards provide local I/O capabilities.

High and low speed remote communication between tele-FLEX nodes is accomplished via digital radio, analog radio, RS-485 or Ethernet and TCP/IP using various communications protocols.

A block diagram of a typical tele-FLEX system is shown below:



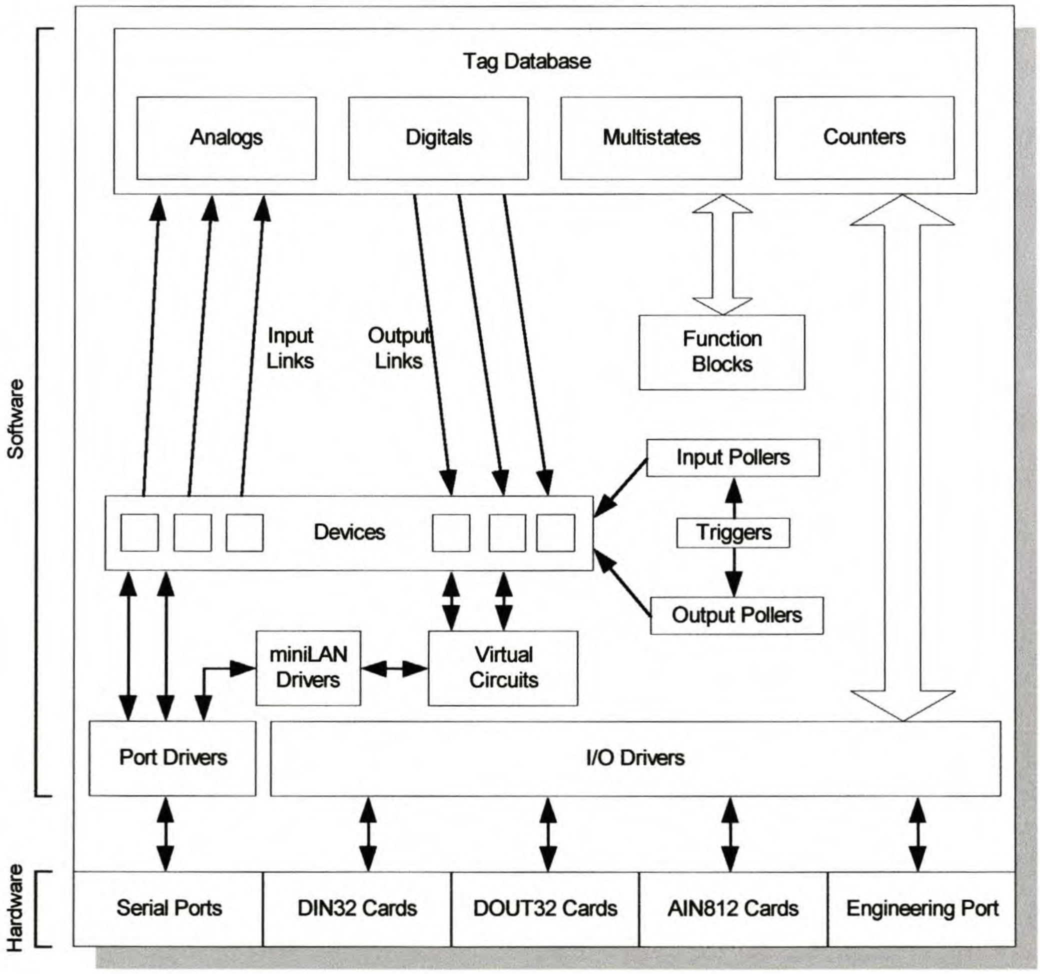
The remote tele-FLEX gathers digital and analog I/O data from the field and compiles it into a tag database. The tele-FLEX also extracts data from IEDs such as PLCs and transducers using device specific communications protocols, and adds this data to the tag database.

Data in the tag database is then sent via the communications network to the SCADA computer using a protocol such as tele-RANGER or DNP3.

Similarly, data originating at the SCADA computer such as control outputs and setpoints is sent to the remote tele-FLEX to control output relays or update values in the IEDs.

In modern SCADA systems there is often an additional requirement for a transparent data link between a second PC at the central and a remote IED. The central tele-FLEX multiplexes requests from the two PCs onto a single multiplexed channel which is then de-multiplexed by the remote tele-FLEX.

A simplified block diagram of the basic elements of a tele-FLEX node is shown below:



The *Serial Ports*, *DIN32 Cards*, *DOUT32 Cards*, *AIN812 Cards* and the *Engineering Port* are the hardware resources available for the transfer of data in or out of a tele-FLEX node.

The *Port Drivers* and *I/O Drivers* communicate with the physical hardware via a backplane. *Device Drivers* communicate with physical devices connected to the serial ports using device specific communications protocols.

The *miniLAN Driver* provides a means of transporting multiple protocols through a single serial port. This means that multiple communications sessions can be maintained through a single radio channel or over a single RS-485 link. *Device Drivers* can either connect directly to a *Serial Port* or to a *Virtual Circuit.*

The *Tag Database* contains *Analog, Digital, Counter* and *Multistate Tags. Device Drivers* update and query the *Tag Database* via *Input Links* and *Output Links*, which map device specific addresses into and out of the *Tag Database*.

I/O Drivers update and query the *Tag Database* directly at regular intervals.

Input Pollers and *Output Pollers* perform block reads and block writes from and to connected physical devices. *Triggers* initiate the block reads / writes at regular intervals.

Function Blocks are pre-defined blocks of code which perform a specific function on one or more input tags and write the result into one or more output tags.

Each tag has various attributes associated with it. For example an analog tag has *raw min, raw max, eng min, eng max, deadband, noise rejection* and *control word* attributes in addition to it's *value* attribute. *Input Links* and *Output Links* can link to any tag attribute to allow remote configuration of a tag's attributes.

Motorola GM340

Specifications

General Specifications
Portable Military Standards 810 C, D & E
Transmitter
Receiver

GENERAL SPECIFICATIONS	
Channel Capacity	6
Power Supply	13.2Vdc (10.8-15.6 Vdc) negative vehicle ground
Dimensions H x W x D	177 x 176 x 56 mm (add 8 mm for volume knob)
Weight:	1400g
Operating temperature:	-30 to +60 ºC
Sealing	Withstands rain testing per MIL STD 810 C/D/E and IP54
Shock and Vibration	Protection provided via impact resistant housing exceeding MIL STD 810-C/D/E and TIA/EIA 603
Dust and Humidity	Protection provided via environment resistant housing exceeding MIL STD 810 C/D/E and TIA/EIA 603

MOBILE MILITARY STANDARDS 810 C, D, & E (Back to top)

	810C		**810D**		**810E**	
Applicable MIL-STD	Methods	Procedures	Methods	Procedures	Methods	Procedures
Low Pressure	500.1	1	500.2	2	500.3	2
High Temperature	501.1	1,2	501.2	1,2	501.3	1,2
Low Temperature	502.1	2	502.2	1,2	502.3	1,2
Temp. Shock	503.1	1	503.2	1	503.3	1
Solar Radiation	505.1	1	505.2	1	505.3	1
Rain	506.1	2	506.2	2	506.3	2
Humidity	507.1	2	507.2	2,3	507.3	3
Salt Fog	509.1	1	509.2	1	509.3	1
Dust	510.1	1	510.2	1	510.3	1
Vibration	514.2	8,10	514.3	1	514.4	1
Shock	516.2	1,2,5	516.3	1	516.4	1

TRANSMITTER (Back to top)

Frequencies - Full Bandsplit *(Availability subject to individual country's law and regulations)*	VHF: 136-174 MHz UHF: 403-470 MHz
Channel Spacing	12.5/20/25 kHz
Frequency Stability (-30°C to +60°C, +25° Ref.)	±2.5 ppm (VHF) ±2 ppm (UHF)
Power	1-25 W

Modulation Limiting	±2.5 kHz @ 12.5 kHz ±4.0 kHz @ 20 kHz ±5.0 kHz @ 25 kHz
FM Hum & Noise	-40 dB @ 12.5 kHz -45 dB @ 20/25 kHz
Conducted/Radiated Emission	-36 dBm <1 GHz -30 dBm >1 GHz
Adjacent Channel Power	-60 dB @ 12.5 kHz -70 dB @ 20/25 kHz
Audio Response (300 - 3000 Hz)	+1 to -3 dB
Audio Distortion	3% typical

RECEIVER (Back to top)	
Frequencies - Full Bandsplit *(Availability subject to individual country's law and regulations)*	VHF: 136-174 MHz UHF: 403-470 MHz
Channel Spacing	12.5/20/25 kHz
Frequency Stability (-30°C to +60°C, +25° Ref.)	±2.5 ppm (VHF) ±2 ppm (UHF)
Sensitivity (12 dB SINAD) EIA	.30 µV (.22 µV typical)
Intermodulation (ETS)	>65 dB; >70 dB in Base Mode
Adjacent Channel Selectivity(ETS)	VHF: 65 dB @ 12.5 kHz 75 dB @ 20 kHz 80 dB @ 25 kHz UHF: 65 dB @ 12.5 kHz 70 dB @ 20 kHz 75 dB @ 25 kHz
Spurious Rejection	VHF: 75 dB @ 12.5 kHz 80 dB @ 20/25 kHz UHF: 70 dB @ 12.5 kHz 75 dB @ 20/25 kHz
Rated Audio	3 W internal; 7.5 & 13 W external
Audio Distortion @ Rated Audio	3% typical
Hum & Noise	-40 dB @ 12.5 kHz -50 dB @ 20/25 kHz
Audio Response (300 - 3000 Hz)	+1 to -3 dB
Conducted Spurious Emission	-57 dBm <1 GHz -47 dBm >1 GHz ETS 300 086
Data for +25°C unless otherwise specified	

Specifications are subject to change without notice and are issued for guidance purposes only.
All specifications listed are typical. Radios meet applicable regulatory requirements.
Conforms to EC directive 89/336/EEC.
Complies with ETS 300 113.

VX-4000 Series Specifications

General Specifications	**VX-4000L**	**VX-4000V**	**VX-4000U**
Frequency Range	29.7-37 MHz	134-1 60 MHz	400-430 MHz
	37-50 MHz	148-174 MHz	450-490 MHz
			480-512 MHz
Number of Channels	250 Channels		
Channel Spacing	20 kHz	12.5/25/30 kHz	
PLL Steps	5/6.25kHz	2.5/5/6.25 kHz	2.5/5/6.25 kHz
Power Supply Voltage	13.8 VDC ± 20%		
Current Consumption STBY	400 mA		
RX	2.1 A		
TX	12 A		
Operating Temperature Range	-22F to +140F (-30C to +60C)		
Frequency Stability	Better than ±5 ppm	Better than ±2.5 ppm	
RF Input-Output Impedance	50 Ohms		
Audio Output Impedance	4 Ohms		
Dimensions	7"(W) x 2.4"(H) x 7.7"(D) (178 x 60 x 195 mm)		
Weight	4.9 lb. (2.2 kg)		
Receiver Specifications	Measurements made per EIA standard TIA/EIA-603		
Circuit Type	Double-conversion Super-heterodyne		
Sensitivity(EIA 12 dB SINAD)	0.25uV	0.25 uV	
Adjacent Channel Selectivity	85dB	85dB/75dB	80dB/70dB
		(25 kHz/2.5 kHz)	(25 kHz/12.5 kHz)
Intermodulation	75dB	76dB	
Spurious and Image Rejection	85 dB	90 dB	
Audio Output	5W @ 4 Ohms w/ 3% THD		
	10W @ 4 Ohms w/3%THD (Optional MLS-100)		
Transmitter Specifications	Measurements made per EIA standard TIA/EIA-603		
Power Output	70 W Adjustable to 30 W	50 W Adjustable to 5 W	40 W Adjustable to 5 W
Modulation	16K0F3E	16K0F3E , 11K0F3E	
Maximum Deviation	5 kHz	5.0 / 2.5 kHz	
Conducted Spurious Emissions	70 dB Below Carrier		
Audio Distortion (@1 kHz)	<3%		

INTRODUCTION	CONFIGURATION	FEATURES	ACCESSORIES
GO	GO	GO	GO

ADDENDUM E

TELEMETRY SYSTEM LAYOUTS

Several system layouts of typical, existing telemetry networks are included, as an example of the extent of some of these systems.

1. The South Peninsula Sewerage Telemetry Network form part of the overall Cape Town Unicity infrastructure and the difficulty in ensuring adequate signal strengths to all stations could, to some extent, be seen from the geographical presentation. The fact that more than one repeater is required, is of particular relevance to considerations of system overhead.

   It could be mentioned that the entire Unicity network has a total of app. 70 000 Input/Output points connected in individual networks, such as the above. An integration study to interconnect the subsystems, is currently underway.

2. The West Coast District Council manages a very extensive water supply network along the West Coast of South Africa. The total North-South distance of the network is in the order of 400 km. The entire network is monitored and controlled by a telemetry system exactly conforming to the type investigated in this dissertation. The use of multiple repeaters are unavoidable and impose significant throughput delays and overhead. The network consists of three subsystems, of which three are schematically shown in the Addendum. Although configured with relatively low cost equipment, the required level of sophistication is considerable and demands careful and thorough systems analysis and design.