DESIGN CONSIDERATIONS FOR ERROR CONTROL PROTOCOLS IN METEOR BURST COMMUNICATION SYSTEMS

by

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ABSTRACT

Meteor burst communication techniques are used to establish secure, over the horizon, radio communication links at VHF frequencies.

A variety of techniques are available for predicting the performance of meteor burst communication systems. These techniques range in complexity from "rule of thumb" analytical estimates to sophisticated computer simulations. Only a few of the most recently published models extend their analysis to include the error profile of the channel and the techniques used to control the errors.

The primary focus of this thesis was to create a model of the meteor burst communication channel and to use it to predict the effect various error control protocols would have on the performance of communications systems using the meteor burst channel. The resulting predictions indicate that significant performance gains can be achieved using Hybrid II ARQ/FEC error control techniques. They also confirm recently published results of system tests which indicate the use of Hybrid I ARQ/FEC protocols would not result in significant improvements in performance.

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DEDICATION

To

Dianne, Emily and Brian

1.0
INTRODUCTION

1.1 Meteor Burst Communication Systems

Meteor burst communication techniques are used to establish secure, over the horizon, radio communication links at VHF frequencies. These links are established by causing transmitted signals to be reflected back to earth by the ionization trails created when meteorites enter the earth's ionosphere and disintegrate.

Systems utilizing meteor burst communication techniques have found wide usage as robust, back up links in long range communication networks. Their mode and frequency of operation permit them to sustain viable communications throughout ionospheric conditions that blank out normal HF nets. For example, a meteor burst communications network can sustain operation through high levels of auroral activity and the very high levels of ionization associated with polar cap absorbtion events. When operated in parallel to an HF system they can also serve as dedicated supervisory and control channel for the network that does not have to constantly vary its frequency of operation to compensate for ionospheric conditions.

Meteor burst communications systems are also used extensively in data acquisition networks. Their chief advantage in this area is their ability to operate over a wide geographical range using a single frequency and the bi-directional nature of the communications link.

1.1.1 Channel Description

The signal received over a meteor burst communication channel is best described as short bursts of rapidly decaying signal followed by long periods of no signal. On a typical channel, the bursts of signal have durations of 100 to 500 milliseconds, decay time constants of 50 to 250 milliseconds and an occurrence rate of one every two to three minutes.

The vast majority of meteor trails used for communication are referred to as underdense. A trail is considered to be underdense if it has an electron line density of less than 10^{14} electrons per square meter. The signal reflected from an underdense trail exhibits a very rapid rise in signal strength to a sharp peak followed by an exponential decay.

Meteor trails with electron lines densities greater than 10^{14} electrons per square meter are referred to as overdense. The signal reflected from these trails exhibits a rounded pulse characteristic of relatively long duration but with deep fades. The fades are the result of the reflective nature of the overdense trail and the multi-pathing which occurs as the electrons in the trail diffuse into the surrounding ionosphere and the physical diameter of the trail changes.

Although overdense trails contribute significantly to the overall throughput of a meteor burst communications system, their contribution is not modeled separately from that of the underdense but is included as part of the underdense model. This approach is valid as the channel control protocols deal with the rapidly fading signals in the same manner as it deals with the loss of signal between underdense meteors. i.e. the protocol treats a fading overdense trail as a sequence of underdense trails that occur in rapid succession.

1.1.2 Communications System Structures

Meteor burst communication systems are generally designed to operate in one of three distinct modes; broadcast networks, point to point communication systems, and wide area networks.

A broadcast network will consist of a small number of transmit only stations broadcasting a continuous stream of messages to a large number of receive only stations. Each message being sent to the receiving stations is transmitted on a repetitive basis and is repeated often enough to ensure its correct reception at the receiving stations.

Point to point communication systems consist of a small number of powerful stations designed to carry symmetric traffic loads. Such stations typically operate in a full duplex manner and may be equipped with multiple transmitters and receivers.

Wide area networks are used primarily for data acquisition and remote monitoring and control applications. These networks will consist of one or two "master" stations communicating with a large number of "remote" stations. The master stations are similar to the stations used in the point to point systems. The remotes are small, low power stations suitable for use in locations where solar panels are the only available power source. The master stations transmit continuously, the remote stations transmit only when they detect the presence of a suitable meteor trail (by correctly receiving the master stations transmissions).

The majority of operational meteor burst communication systems in use today are configured as wide area networks but contain many of the elements of the point to point systems communication protocols. The channel protocols used to model the systems performance in this thesis are patterned after those used in such a system.

1.1.3 Establishing Communications on a Meteor Burst Channel

The protocols used to control the operation of a communication system utilizing the meteor burst channel must be capable of detecting the presence of a trail, establishing a link between the terminals and transferring information over it quickly and efficiently for as long as it is available.

To detect the presence of a meteor burst trail the master station within a wide area network or all the stations within a point to point system transmit a continuous signal referred to as the probing signal. As meteor trails are formed this signal will be reflected back to earth. When a trail at a location and with suitable orientation occurs such that the signal reflected from it can be detected and decoded correctly by a receiving station, the protocol assumes that a viable link can be established.

To establish the communications link the remote station detecting the master station's probe transmits a reply to it. This reply includes information that identifies the remote responding to the master station. If the master station receives the response correctly, the link is established and information is transferred over it.

Information transfer over the link is controlled by a handshake protocol referred to as the channel control protocol. The handshake protocol transfers information over the link while monitoring the validity of the information received. When the number of errors in the transmitted block rises above a pre-defined level at the receiving station, the link is assumed to be lost, i.e. the trail no longer exists, and the master station resumes probing.

When the next probe is detected the procedure is repeated.

1.1.4 Quantifying the Performance of a Meteor Burst Communication System

Two figures of merit are commonly used to describe the performance of a meteor burst communication system; waiting time and throughput.

Waiting time is defined as the expected value for the elapsed time between a message (of predefined length and format) becoming available for transmission and its valid reception at its destination. Two values of waiting time are often quoted. The difference between them is a function of the point in the protocol at which the message is defined to have been received correctly. For example it can be defined as either the point in time at which the receiver has a valid copy of the message ready for delivery to the data sink or the point in time at which the transmitter has received an acknowledgement of correct reception of the block from the receiver.

Long run throughput is a measure of the realized average rate at which information can be passed through the system. It is analogous to the information throughput values stated for conventional communication systems where information throughput is the modulation rate times the protocol efficiency.

A variety of techniques are available for analyzing the performance of a meteor burst communication system and predicting values of waiting time and throughput. These techniques range in complexity from "rule of thumb" estimates to sophisticated computer simulations that take into account factors such a meteoric orbit distribution, geographic location, orientation of the link, etc.

1.2 Organization of this Thesis

This thesis is divided into six chapters including the Introduction and Conclusions.

The second chapter (the first chapter after the Introduction) describes the characteristics of the meteor burst channel and presents the basic equations used to model it.

The third chapter presents a tutorial description of a meteor burst communications system protocol similar to that used in commercially available equipment.

The fourth chapter presents a discussion of error control protocols and error control coding. That discussion focuses on the protocols that have traditionally been used for the meteor burst channel, those that have been suggested for use on the meteor burst channel in the recent literature, and those which this author considers the most likely to provide performance gains on the channel.

The fifth chapter presents the results obtained by modeling the meteor burst channel and applying the various error control protocols presented in the third chapter to it.

The sixth chapter is a short summary of the results of the work presented in the thesis.

2.0
THE METEOR BURST CHANNEL

Communication paths can be established when transmitted radio signals are reflected back to earth by meteoric ionization trails in the ionosphere. These links are used for establishing secure, over the horizon communication links.

2.1 Phenomenological Description

As meteorites enter the earth's ionosphere they dis-integrate leaving behind them a trail of ionized particles. These trails are typically a few meters in diameter and many thousands of meters long. As the trails are formed the ionized particles diffuse into the surrounding ionosphere. The ionization density of the trail is a function of the mass of the meteorite that formed it and its velocity relative to the earth.

Electromagnetic radiation impinging upon these trails is reflected by the ions. The resulting reflection occurs in a specular fashion. At ionization densities greater than approximately 10^{10} electrons/meter, enough signal will be reflected for a receiver located on the earth to detect.

2.1.1 Operational Geometry

The operational geometry is similar to that of other ionoscatter communication techniques. The reflection from the trails is specular and occurs at altitudes of approximately 80 to 100 kilometers. This provides an operational range of approximately 200 to 2000 kilometers. At ranges of less than 200 kilometers other forms of propagation such as direct ground wave and obstructed path diffraction tend to mask any meteor burst propagation that may occur.

To act as a suitable signal reflector, the meteor trail must be tangent to one of a family of ellipsoids of revolution whose foci are the transmitter and receiver locations (Brown [5]). As the geographic distribution of the meteor trails in the ionosphere is random a trail capable of supporting a specular reflection may occur anywhere within the radiation patterns of the two stations as long as it meets the above criteria.

The radiants of the meteor trails, the point on the celestial sphere from which they appear to emanate, observed on a given link between a transmitter and a receiver tend to be distributed directly over the great circle path joining the two stations (Eshleman [10]). This results in a concentration of suitably oriented trails in two "hot spots" located a few degrees to either side of the great circle path. These hot spots will move along the great circle path towards one station or the other as a function of geographic location and orientation of the stations and the distance between them. They will also move both diurnally and annually.

At very short ranges (less than 400 Km) these hot spots tend to move above and behind the two stations creating some interesting propagating scenarios. The author has witnessed excellent performance between two short range systems, one of which had its directional antenna pointed the "wrong" way.

2.1.2 Meteorite Distributions

The majority of meteorites striking the earth's ionosphere are members of the solar system with their orbits clustered near the plane of the ecliptic (Brown [5]). They are fairly evenly distributed throughout space and as such their arrivals are considered random events.

2.1.3 Weight Distribution

The mass distribution of the meteorites has been shown to be inversely proportional to their incidence i.e. the number of meteors **n**, of mass **m** or greater is inversely proportional to $\mathbf{m}^{k}$, where $\mathbf{k} \cong \mathbf{1}$ (Brown [5]). Table 2.1 presents order of magnitude estimates of the size and incidence distribution of the meteorites relevant to the operation of a meteor burst communications system (Spezio [26]). The table includes figures for the approximate electron density of the trail created by the meteorite.

Mass (g)	Radius (mm)	Quantity per Day	Electron Line Density
10	8	10^4	10^{18}
1	4	10^5	10^{17}
10^{-1}	2	10^6	10^{16}
10^{-2}	0.8	10^7	10^{15}
10^{-3}	0.4	10^8	10^{14}
10^{-4}	0.2	10^9	10^{13}
10^{-5}	0.08	10^{10}	10^{12}
10^{-6}	0.04	10^{11}	10^{11}
10^{-7}	0.02	10^{12}	10^{10}
10^{-8}	0.008	?	?

Table 2.1 Size and Quantity Estimates of Sporadic Meteors

2.1.4 Ionization Density

The ionization density (or electron line density) of the trail created by a meteor entering the earth's ionosphere is proportional to the size of the meteor and its velocity profile (initial velocity, angle of entry into the ionosphere and rate of deceleration). The electron line density as a function of the size of the meteor is presented in Table 2.1.

As is evident in the values presented in Table 2.1, the electron line density is directly proportional to the size of the meteor and can be seen to vary from a minimum of less than 10^{10} electrons/meter for the smallest meteors of interest to a maximum of 10^{18} electrons/meter for the largest.

The electron line density of the trail determines the mechanism by which the propagating signal impinging on the trail is returned to earth. For trails with less than 10^{14} electrons/meter the propagating signal is reflected or re-radiated by the individual electrons within the trail. At densities greater than 10^{14} electrons/meter the signal cannot penetrate the trail and is reflected from its surface. This difference in the propagation mechanism has a significant effect on the characteristics of the reflected signal. Trails with electron line densities greater than 10^{14} electrons/meter are referred to as overdense and those with densities less than 10^{14} electrons/meter are referred to as underdense.

2.1.5 Annual Distribution

Meteorites are not distributed evenly throughout the earth's orbit about the sun. This results in an seasonal variation of the order of 3:1 with the peak incidence occurring in June and the minimum incidence occurring in February. The distribution is approximately sinusoidal. Coincident with this distribution is a variation in incidence due to the seasonal change in the tilt of the earth's axis. Thus the annual variation observed in the northern hemisphere will not have the same function as that observed in the southern hemisphere.

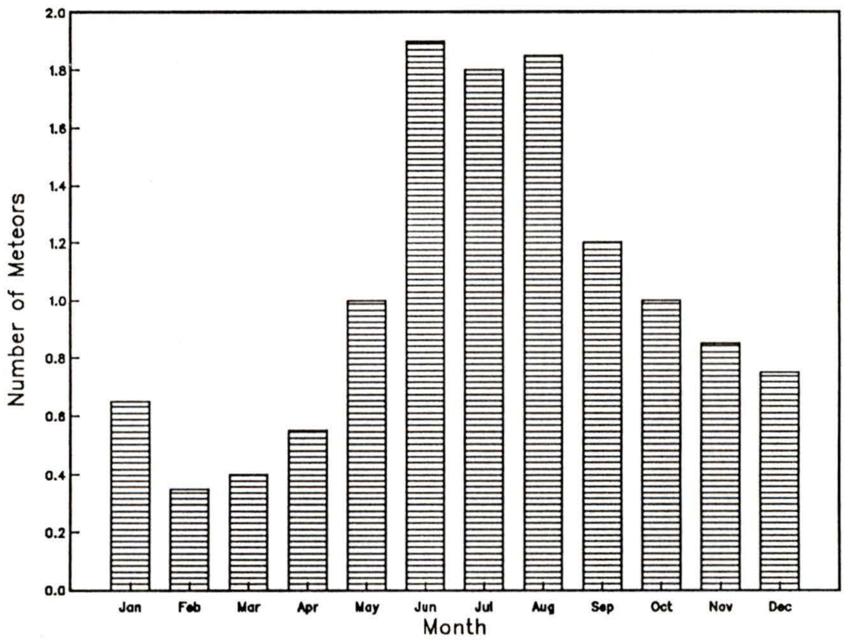

Figure 2.1.1 Annual Variation of the Observed Meteor Rate on a Meteor Burst Communications Link

A plot of the ratios of the monthly meteor rate as measured on a 600 Km link situated on the West Coast of Canada and oriented NE-SW is presented in Figure 2.1.1

2.1.6 Diurnal Distribution

The observed meteor rate also exhibits a diurnal variation. This variation is a result of the morning side of the earth sweeping up meteorites as the earth travels through its orbit and the afternoon side running away from them. The observed variation will be a maximum at the equator and a minimum at the poles. It will also exhibit a seasonal variation.

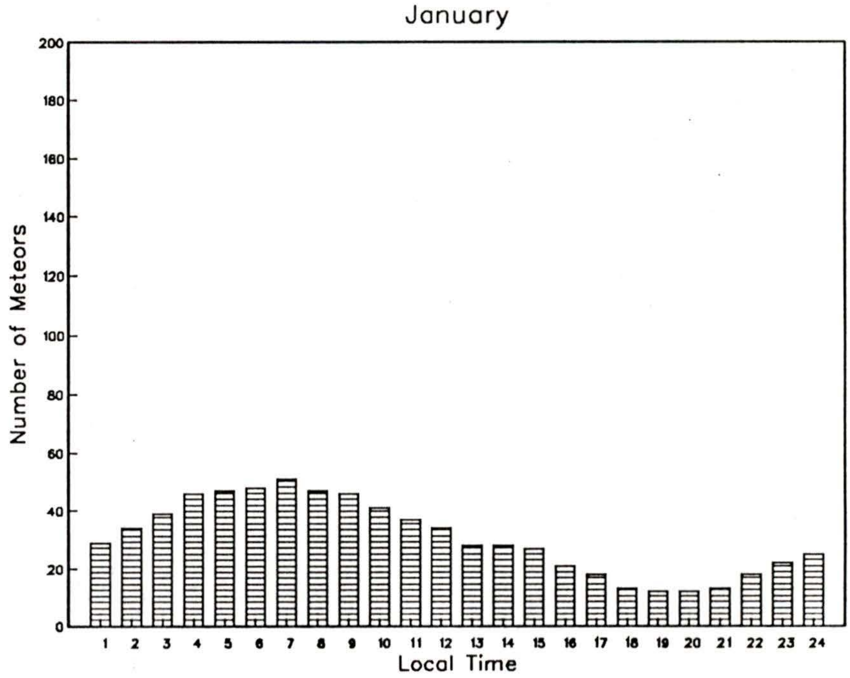

Figure 2.1.2(a) Diurnal Variation in Observed Meteor Rate for January. Meteor Rates are the Monthly Average of the Hourly Reading.

Plots of the observed meteor rate for January and for July on a 600 Km link oriented NE-SW at a Latitude of 50 degrees N are presented in Figures 2.1.2(a) & (b).

2.2 Received Signal Characteristics

The received signal characteristics of a meteor burst communication system are primarily a function of the electron line density of the trail and its orientation with respect to the signal path between the transmitter and receiver. As discussed in Section 2.1.4, the electron line density is a function of the mass of the meteor. The orientation of the trail is a function of the meteor radiant.

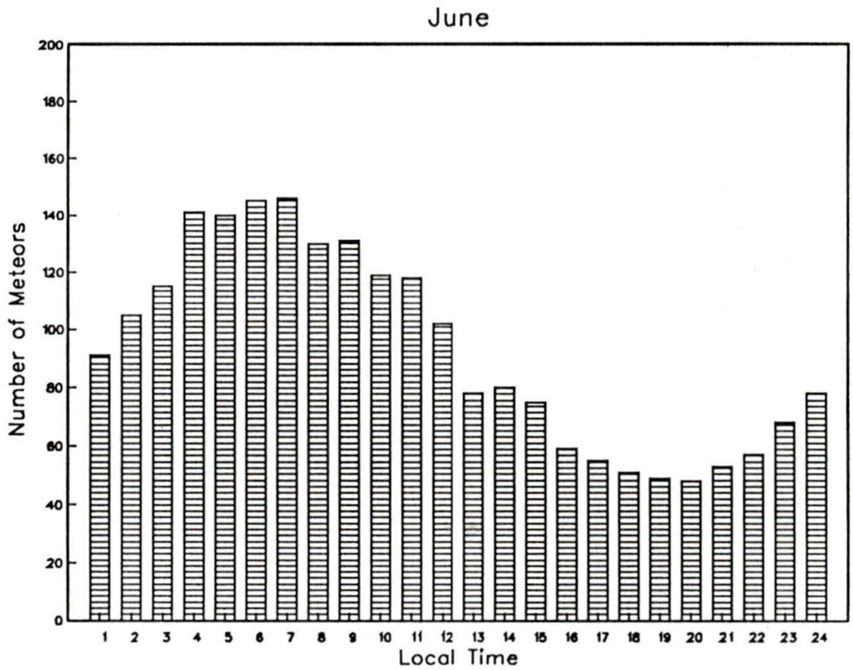

Figure 2.1.2(b) Diurnal Variation in Observed Meteor Rate for July. Meteor Rates are the Monthly Average of the Hourly Reading.

The number of meteors **n** relevant to the performance of a meteor burst communication system is inversely proportional to the mass $\mathbf{m^k}$ of the meteors (Brown [5]).

$$n \cong \frac{1}{m^k} \qquad k \cong 1 \qquad \{2.1\}$$

The actual mass distribution and resulting electron line densities have been presented in Table 2.1.

For the purposes of analysis meteor trails are described as being either overdense or underdense depending on their electron line density. The transition from underdense to overdense occurs at an electron line density of 10^{14} electrons/meter.

2.2.1 Underdense Trails

Underdense meteor trails are those in which the electron line density is less than 10^{14} electrons per meter. When an electromagnetic wave impinges upon a trail of this density or less it tends to pass through the trail essentially unchanged (Forsyth [13]). When this occurs each ionized particle within the trail acts as an independent reflector or scattering source. The signal returned to earth is thus the sum of the signals reflected from the independent scatterers.

When a trail is formed it is very long and thin. At this point the scattering sources can be modeled as a line. As the ions diffuse into the surrounding ionosphere, the diameter of the trail increases and phase interference between the individual signals results in a rapid decrease in the strength of the reflected signal. This process is specular.

Eshlemann [10], gives the following expression for the received power of a signal reflected from an underdense meteor trail.

$$P_R = P_T \frac{1}{32\pi^4} \frac{(\mu_o \varepsilon^2)^2}{(4m)^2} \frac{2\lambda^3 G_R G_T q^2 \sin^2\alpha}{R_1 R_2 (R_1+R_2)(1-\cos^2\beta \sin^2\phi)} \exp\left(\frac{-t}{\tau}\right) \qquad \{2.2\}$$

where:

P_R, P_T = received and transmitted powers

$\left(\frac{\mu_0 \varepsilon^2}{4m}\right)$ = 0.8852 x 10^{-14} meters where μ_o is the permeability of free space and ε and **m** are the electronic charge and the mass respectively

λ = wavelength
R_1, R_2 = ranges of the meteor trail from the transmitter and receiver
G_T, G_R = transmitter and receiver antenna gains
q = electron line density (electrons per meter)
α = angle between the electric vector of the incident wave and the line R_2
2ϕ = interior angle between R_1 and R_2, i.e. the forward scattering angle

β = angle between the axis of the column and the plane containing the transmitter, the receiver, and the center of the principal Fresnel zone

τ = the burst time constant

The burst time constant τ is equal to:

$$\tau = \left(\frac{\lambda^2 \sec^2\phi}{32\, \pi^2 D} \right) \qquad \{2.3\}$$

where:

D = ambipolar diffusion coefficient of the ionosphere

It should be noted that τ is independent of **q** the electron line density. A plot of this equation as a function of time is presented in Figure 2.2.1.

The purpose of this thesis is to model the effect different error control protocols have on the performance of a meteor burst communications link. As a consequence equation 2.2 can be dealt with in the form:

$$P_R = K_P\, q^2 \exp\left(\frac{-t}{\tau} \right) \qquad \{2.4\}$$

where:

K_p = the link power budget and is assumed constant

The link power budget constant K_p can be used without loss of generality as the protocol comparisons are independent of the parameters that make up the link power budget as long as those comparisons are made on a relative basis.

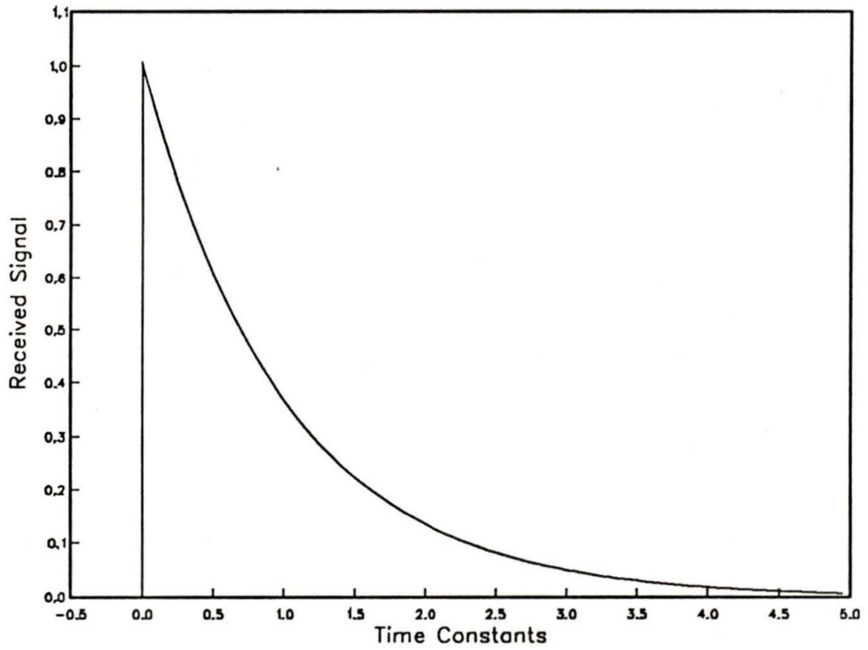

Figure 2.2.1 Plot of the Received Signal Characteristic for an Underdense Meteor Trail

2.2.2 Overdense

Overdense meteor trails are those in which the electron line density is greater than 10^{14} electrons per meter. When a radio wave impinges upon a trail of this density or greater it tends to be reflected from the surface of the trail (Forsythe [13]). The received signal power equation for the overdense case is derived assuming the trail takes the form of a cylinder with a reflective surface and that this cylinder expands at a rate commensurate with the ambipolar diffusion constant.

Forsythe gives the following expression for the received power of a signal reflected from an overdense meteor trail.

$$P_R = \frac{P_T\ G_R\ G_T\ \lambda^2 \cos\phi \sin^2\alpha}{16\pi^2 R_1 R_2 (R_1+R_2)\ (1 - \cos^2\beta \sin^2\phi)} \left(Dt \ln\left(\frac{t}{\tau}\right)\right)^{\frac{1}{2}} \qquad \{2.5\}$$

where the variables are as defined previously for the underdense case. For the overdense trail the time constant takes the form:

$$\tau = \frac{\mu_o \, \varepsilon^2 \, q \, \lambda^2 \sec^2\phi}{16 \, m \, \pi^3 \, D} \qquad \{2.6\}$$

As the ions in the overdense trail diffuse into the ionosphere high level winds tend to distort the cylinder. Although the burst time constant of the overdense trail is much longer than that for the underdense trail the resultant fading and multi-path distortion degrade the received signal.

2.2.3 Overdense/Underdense Distribution

As discussed previously the electron line density of a trail is proportional to the mass of the meteor that created it. The mass distribution of the meteors striking the earth's ionosphere is inversely proportional to their rate of occurrence. As a result the majority of the trails available to a meteor burst communication system are underdense. As a consequence of their very long time constants, overdense trails have the potential to contribute significantly to the long run throughput of a meteor burst communications system however their contribution to a reduced waiting time is minimal as they are relatively few in number.

When the waiting time of a meteor burst communications system is being analyzed or modeled the contribution of the overdense trails is ignored. When modeling long run throughput, they are modeled as a series of rapidly occurring underdense trails. This is justified on the basis that the multi-path fading prevents full exploitation of the long time constant and that in actual operation the protocol has no mechanism to differentiate an overdense fade from an underdense decay and must re-acquire the link after each fade. In operational systems overdense trails have been shown to make a significant contribution to the long run throughput of a meteor burst communications system. This is especially true in systems with low power budgets (low antenna gain, low power transmitters, etc.) or in systems operating in the presence of high levels of interference (which has an equivalent effect to reducing the receiver sensitivity).

2.3 Signal Duration for an Underdense Trail

The time constant of the decay of the signal received from an underdense meteor is given by equation 2.3. From 2.3 it can be seen that this time constant is a function of the wavelength of the signal, the included angle ϕ of the reflection path between the transmitter and receiver, and the ambipolar diffusion coefficient **D**.

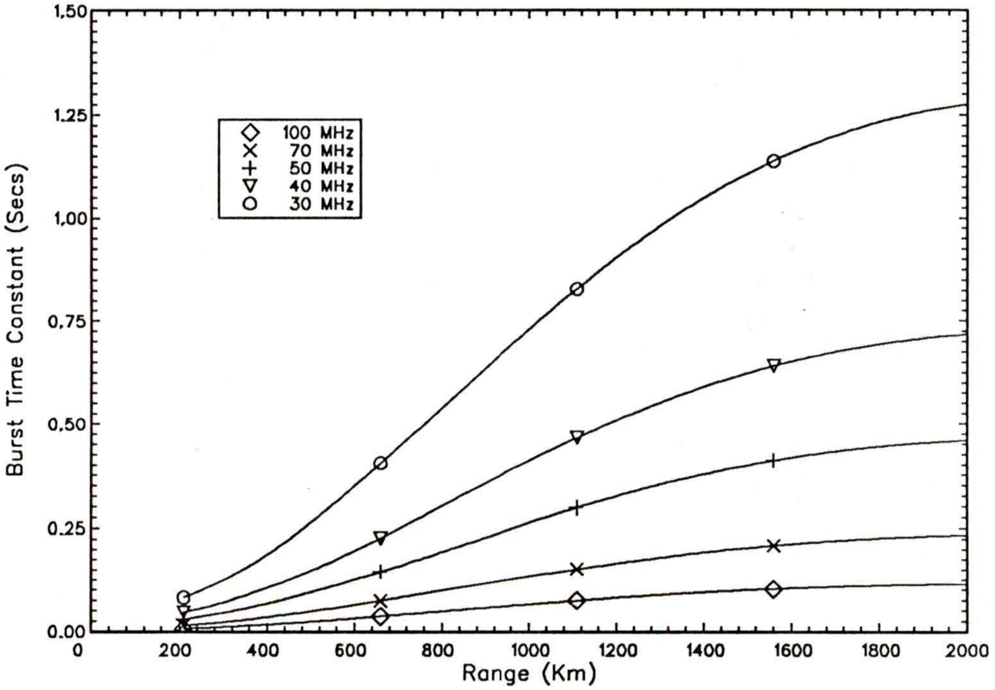

Figure 2.3.1 Plot of the Burst Time Constant as a Function of the Operating Frequency and the Range between the Transmitter and Receiver

A significant amount of confusion exists regarding the values of **D** that are most appropriate when modeling a meteor burst channel. Sugar [27] states that **D** will vary from 1 m^2/sec at an altitude of 85 km to

140 m^2/sec at an altitude of 115 km without offering a distribution or mean value to be used. Most other authors consider it to be a fixed value however some inconsistency exists as to what value is the most appropriate. Eshelmann [11] suggests 3 m^2/sec, Spezio [26] 8 m^2/sec, etc. Donich [8] recommends a value of 8 m^2/sec based on experimental evidence and operational experience. It should be noted that the range of values suggested for this parameter will effect the calculated throughput of a meteor burst link by a factor of over 2:1.

A plot of the burst time constant as a function of wavelength and range is presented in Figure 2.3.1.

2.4 Mean Burst Duration

The burst duration is defined as the length of time the amplitude of a received signal is above a given level. This level is referred to as the threshold of the receiver and is the level below which the demodulated error rate rise to unacceptable values.

The burst durations observed on a link exhibit a probability density distribution that is a function of the distribution of the initial signal amplitudes received from each trail and the burst time constant for the link. The signal amplitudes are a function of the electron line densities of the individual meteors which are in turn a function of the mass of the meteor that created the trail.

The time constant of the decay of the received signal has been shown to be a function of the wavelength of the signal and of the distance between the transmitter and the receiver and not of the electron line density of the trail. Therefore for an operational link with fixed geographical position and operating frequency the observed time constant will also be a constant.

Thus the probability density distribution of the burst durations will be a function of the density function of the mass distribution of the meteors. This concept is presented graphically in Figure 2.4.

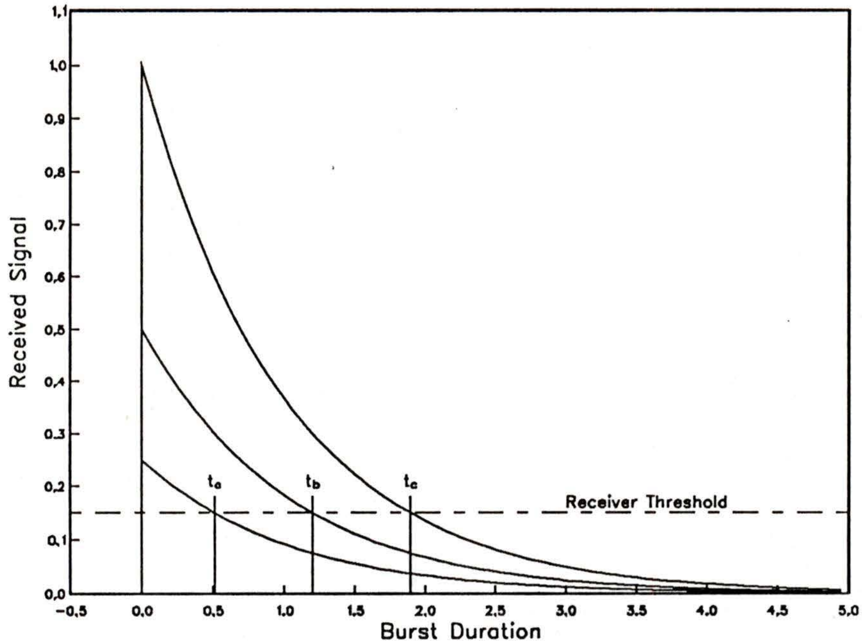

Figure 2.4 Graphical representation of the relationship between the burst time constant, burst duration, operational threshold, and received signal strength distribution.

2.4.1 Development of an Expression for the Mean Burst Duration Density Distribution

From equation 2.4 it can be seen that the amplitude of the signal received from a meteor trail will vary inversely as a function of $\mathbf{q^2}$ where $\mathbf{q}$ is the electron line density of the trail. To develop and expression for the duration distribution for an operational link the threshold $\mathbf{P_{Rth}}$ of the link is defined as follows:

$$\mathbf{P_{R_{th}} = K_p\, q^2 \exp\left(\frac{-t_b}{\tau}\right)} \qquad \{2.7\}$$

where:

$\mathbf{P_{R_{th}}}$	= the operational threshold of the receiver
$\mathbf{t_b}$	= the burst duration
$\mathbf{K_p}$	= link amplitude constant
$\mathbf{q^2}$	= electron line density
τ	= burst time constant

The burst duration is the time the received signal is above this threshold and is therefore:

$$t_b = \tau \ \ln \left(K_p \ \frac{q^2}{P_{R_{th}}} \right) \qquad \{2.8\}$$

The mass density distribution of meteors, significant to the operation of a meteor burst communication link, has been shown to be $\frac{1}{m^n}$ where **n** is generally taken to be equal to 1 (Brown[5]). The electron line density distribution and thus the signal strength density distributions are proportional to $\frac{1}{q^2}$.

Combining this distribution with equation 2.8 the following relationship can be developed:

$$P(t > t_0) = \exp \left(\frac{-t_0}{\tau_b} \right) \qquad \{2.9\}$$

where:

$P(t > t_0)$	= the probability that **t** will exceed some value t_0
t	= the burst duration of a meteor
τ	= the mean of the burst duration density distribution

The mean of this distribution τ_b is often referred to as the mean burst time constant. However, this term is mis-leading as it is not the mean of the burst time constant τ but is instead the mean of the burst duration distribution.

For the reader interested in the derivation of this relationship it is presented by Campbell and Hines [6]. It has subsequently been modified into various forms by others (Miller & Milstein [21], Spezio [26], Sugar [27]). Caution is advised when utilizing this equation as many of the indicated authors have developed it for the amplitude version of the burst time constant, τ_a where $\tau_a = 2\,\tau$.

2.4.2 Link Power Budget Effects on the Burst Duration Density Distribution

From the above discussion regarding the development of the burst duration density distribution, and the contribution the chosen operational threshold has on that development, one would expect the mean burst duration to vary as a function of the link power budget. This is indeed what happens as Brown's [5] model illustrates.

If the power budget $\mathbf{K_p}$ on a link is increased (greater antenna gain, higher power transmitters, etc.) the burst duration will increase at a rate proportional to the natural logarithm of the power {2.8}. However the increased power budget also serves to raise a new group of short duration meteor returns above the noise level. The number of new meteors that become available will be inversely proportional to the increase in the power budget. Although the two effects counter balance each other, the increase in the number of short duration meteors will predominate resulting in a net decrease in the mean burst duration observed on the link.

As the link power budget is not expected to vary with time on a given link, the magnitude of this variance is not relevant to the protocol development discussed in the remainder of this thesis. The interested reader will find extensive discussions of this relationship and development of the relevant equations in the general meteor burst literature.

2.4.3 Diurnal Variation in the Burst Duration Density Distribution

The burst duration density distribution exhibits a diurnal variation. This variation is due to the difference in the relative velocity of the meteors entering the ionosphere over the period of a day. In the morning the earth tends to sweep up meteors as it moves through its orbit, thus the relative velocities will be higher in the morning than in the afternoon. The lower velocity meteors penetrate the ionosphere further than the high velocity ones before burning up. Morning meteor trails will therefore be formed at higher altitudes than afternoon meteor trails. The ambipolar diffusion time constant is higher at higher altitudes thus the time constant of the morning meteor trails will be shorter than that of the afternoon meteor trails. For this reason the meteor burst duration distribution is considered to be a non-stationary random process.

A plot of the diurnal variation of the observed burst durations on an operational link is presented in Figure 2.4.1.

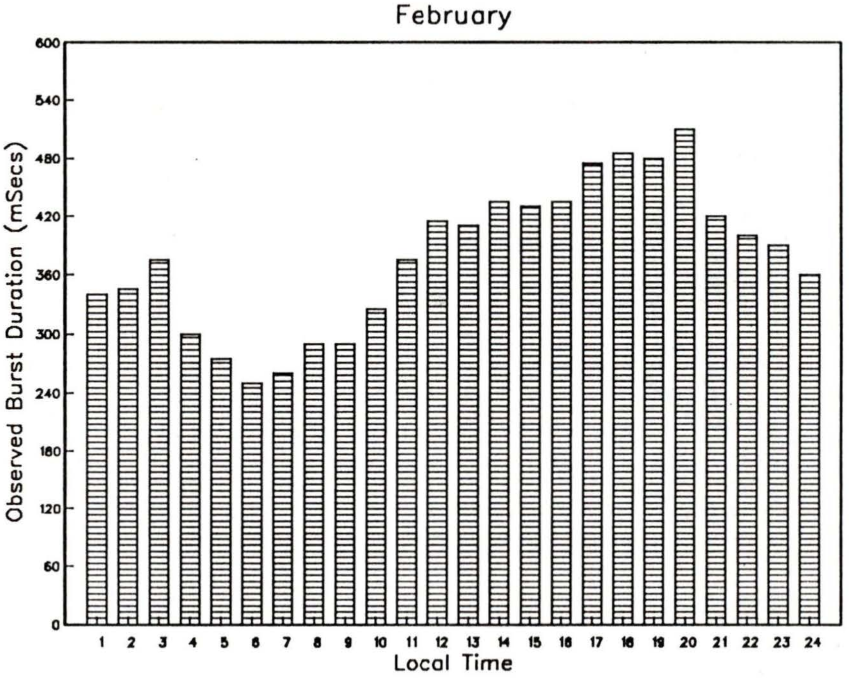

Figure 2.4.1 Diurnal Variation in the Observed Burst Durations for an Operational Meteor Burst Communications Link.

2.5 Meteor Arrival Rates and Distributions

The meteor arrival rate observed on a communications link will be a function of both system hardware design parameters such as the link power budget and a function of natural phenomena such as time of day, geographic location and day of the year. On a short term basis, for example a one hour period, meteor arrivals will be a random process. Therefore the burst occurrence density function is well approximated by the Poison distribution (Oetting [23]) as presented in equation 2.10.

$$P(n,\mu) = \frac{(\mu t)^n \exp(-\mu t)}{n!} \qquad \{2.10\}$$

where:

μ	= the average arrival rate of meteors with thresholds above that necessary to establish communications
P(n,μ)	= the probability that **n** bursts with thresholds above that necessary to establish communications will occur in time **t** given the average rate μ

As described previously μ will vary as a function of natural phenomena such as the time of day, day of the year, etc. For this reason the meteor burst incidence is considered to be a non-stationary random process.

2.6 Summary

This chapter has presented a tutorial description of the meteor burst channel and the equations used to model it.

Of the equations and relationships presented special note should be made of equation 2.3, the received signal strength as a function of time, and equation 2.9, the burst duration density function. These relationships form the basis of the channel model used to evaluate the various error control protocols discussed in the following chapters. Although significant to a system designer, it is not necessary to include the other relationships in the model for the comparison to be valid.

The next chapter presents a simple block oriented protocol as an example of the communication protocols that are used on a meteor burst channel.

3.0
BASIC PROTOCOL STRUCTURES

3.1 System Structures

Meteor burst communication systems can be used in a variety of network configurations. Standard configurations include point to point bi-directional communications links, wide area data acquisition networks, and broadcast networks. Each has its own unique protocol requirements over and above the standard meteor burst protocol formats.

3.1.1 Point to Point Communications Systems

Point to point meteor burst communications systems are used to establish links between two fixed sites. The equipment used to establish these links is usually designed to maximize long run system throughput.

The RF circuit is designed with very high link power budgets, i.e. powerful transmitters, high gain antennas, etc., are used, and for full duplex operation, i.e. simultaneous transmission and reception. Variable rate modulation techniques are often used to maximize the data transfer rate (Abel[1], Davidovici & Kanterakis[7]). The network protocols are designed to control the modulation rates and to take advantage of the full duplex communication link available.

3.1.2 Data Acquisition Networks

Meteor burst data acquisition networks are used to collect data from a large number of remote sites spread over a wide geographical area. These networks typically consist of a large, powerful central station, referred to as the Master Station, communicating with a large number of Remote Stations. The Remote Stations are designed for low cost and low power operation.

The design of the RF link will often be asymmetric with a powerful transmitter at the master station making up for reduced sensitivity receivers in the Remote Stations and very sensitive receivers at the master making up for less powerful transmitters at the remotes. The antennas used at the master will be designed to cover a wide area and will therefore have relatively low gain relative to those used in point to point systems. The antennas used at the remote will range from low cost, low gain configurations to high gain, higher cost configurations when necessary. The RF link power budget will be substantially lower than that used in point to point systems. As a further cost saving measure the remote stations are restricted to half-duplex or simplex operation.

The protocols used in a data acquisition network are designed to operate on the half-duplex, simplex link and to minimize the power consumption at the remote stations by minimizing the number and duration of transmissions from the remotes.

3.1.3 Broadcast

Broadcast systems are used to transfer information from a central location out to a large number of independent receivers. Their structure is similar to that of a data acquisition network however the remote sites will be receive only, thus no return communication path exists from the remote stations to the master station.

Pure broadcast networks are not widely used however broadcast techniques are used in point to point and data acquisition networks to transfer network management information such as real time clock synchronization.

3.2 Basic Protocols

An example of the protocol structures used in a data acquisition network is presented in the following sections. Point to point and broadcast protocols are discussed from the perspective of their differences with respect to the data acquisition protocol.

3.2.1 Data Acquisition Network Protocol

The data acquisition network protocol is based on three sequential functions; acquisition of the link, transfer of information over the link, and release of the link.

3.2.1.1 Link Acquisition

The process by which the master station and a remote station establish a viable communication path between themselves is referred to as link acquisition.

The first step in acquiring a link is for the two stations to determine when a suitably oriented meteor trail exists. To do this the master station transmits a probing signal on a continuous basis. The remote stations listen for this probe. When a remote station detects the probe it knows a suitable trail exists.

When the remote detects the probe it responds by transmitting an acknowledging signal to the master station. This signal is referred to as a No Text (NTXT). Upon receiving the NTXT, the master is also aware that a trail exists and the link is established.

The format of a typical probe signal is presented in Figure 3.2.1.

Preamble	Sync	PCI	MID	Data	Parity

Figure 3.2.1 Typical Probe Format for a Meteor Burst Data Acquisition Network

The preamble field is a stream of continuous ones or zeros used by the remote receiver to acquire carrier lock and bit synchronization. The sync field is a maximal length sequence used by the remote station decoding software to acquire symbol synchronization and to resolve any phase ambiguities inherent in the demodulation process. It is selected to provide a maximum correlation distance between a noisy preamble pattern and the correct symbol alignment.

The Probe Content Indicator (PCI) field is used to define the contents of the data field in the probe. The Master Identification (MID) field contains a numerical identifier of the master station transmitting the probe. It is only relevant in networks containing multiple masters.

The data field in the probe is used to transfer broadcast information such as network time of day messages, system status messages, etc. to all other stations within the network. A remote will not necessarily acknowledge correct reception of a broadcast probe.

The parity field contains parity bits calculated using the contents of the previous fields. It is used to check the validity of the bit pattern received.

The format of the probing sequence transmitted by the master station in a simplex or half-duplex network is presented in Figure 3.2.2.

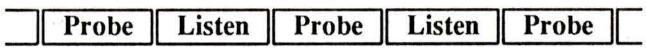

Figure 3.2.2 Probing Sequence for a Meteor Burst Data Acquisition Network

The probing sequence for a half-duplex or simplex system consists of alternating probe transmissions and listening periods. The listening period is long enough for the master station to receive and correctly decode the preamble and header information of a remote station transmission. The length of the probe and the listening period has a direct bearing on how quickly the system can acquire the link and establish communications once a suitable meteor trail has formed.

The format of the NTXT sent by the remote is similar to that of the probe. It is presented in Figure 3.2.3.

Preamble	**Sync**	**MCI**	**MID**	**RID**	**Parity**

Figure 3.2.3 NTXT Format as used in a Meteor Burst Data Acquisition Network

The format and purpose of the preamble and sync fields are identical to those used in the probe signal.

The Message Content Indicator (MCI) field is used to indicate that this transmission is a NTXT, i.e. it is an acknowledgement to a correctly received probe.

The Remote Identification (RID) field contains the identification number of the remote terminal transmitting the NTXT and the Master ID (MID) field contains the identification number of the master station it is intended for.

The parity field is as described previously for the probe signal.

Correct reception of the NTXT by the master station is considered the point at which a communications link has been established.

3.2.1.2 Information Transfer

As soon as the link has been established the transfer of information commences. The information will be transferred in the form of blocks, each block being very similar in format to the NTXT described in the previous section. The information is transferred in blocks as a block structure fits easily and naturally into the bursty nature of the meteor burst channel.

The format of an information block is presented in Figure 3.2.4.

Preamble	Sync	MCI	MID	RID	Data	Parity

Figure 3.2.4 Transmit Segment Format as used in a Meteor Burst Data Acquisition Network

The format and purpose of the preamble, sync, RID, MID, and parity fields are identical to the definitions provided for the NTXT.

The Message Content Indicator (MCI) field is used to indicate the type of information contained in the data field of the block and its position in the message being transmitted.

The data field contains the segment or block of information being transmitted.

If the master station receives the transmitted block correctly it responds by transmitting an acknowledgement (NTXT) to the remote. If the master station did not receive the block correctly it resumes probing, i.e. it transmits a probe. If the meteor trail still exists the reception of this probe will be interpreted by the remote as an implicit negative acknowledgement. Thus the protocol is similar to a conventional ARQ protocol as described in Chapter 4.0.

By modifying the above noted procedure slightly, bi-directional transfers of information can be accomplished, i.e. information blocks will be transferred from the master station to the remote in between transfers from the remote to the master. If the master station has received a block of information from a remote correctly and has information destined for that particular remote, it will transmit that block of information instead of transmitting an acknowledgement. If the remote receives the header of that information block correctly it will interpret it as an implicit acknowledgement of its block. It will then proceed to decode the information transmitted to it by the master.

The format of the master information transfer block is the same as that presented for the remote in Figure 3.2.4.

To make more efficient use of the communication link the technique of implicit acknowledgement of correct reception is used whenever possible thus eliminating sequences of explicit acknowledgements. For example, assume a remote has information ready for transmission to the master station and coincident with this the master station has information ready for transfer to the remote station. When the remote station detects the presence of the master stations probe signal it responds by transmitting an information segment to the master. If the master receives this information segment correctly, it responds with a segment of the information for the remote. In this situation the reception of an information segment in response to the transmission of an information segment is interpreted as an implicit acknowledgement of that segment.

3.2.1.3 Loss of link, Termination and Restart Mechanisms

The meteor burst communication link is expected to disappear within a few hundred milliseconds of its formation. As a consequence the protocol must be capable of dealing efficiently with the continuous loss and re-acquisition of the link.

A master station will assume no link exists if it does not start receiving a valid block in response to a transmission within the prescribed listening period. When this occurs it will either continue probing if that is what it was doing or will resume probing if it transmitted a block of information or an acknowledgement. A problem arises in this situation as the master station has no way of knowing if the remote received the transmission correctly.

If the transmission was an acknowledgement to an information block but the remote did not receive the acknowledgement the remote will repeat the information block the next time it communicates with the master. The master station will therefore retain a copy of the information block and will reject subsequent receptions of that particular block. It will however continue to transmit an acknowledgement to them. This mechanism is referred to as identical segment rejection and is also present in the remote.

If the transmission was a block of information that the remote received correctly but the master did not receive the acknowledgement for, the master would retransmit this block the next time it established communications with that remote. To prevent this, the MCI field in the transmissions from the remote to the master station indicates the last block received correctly. Thus a remote station responding to a probe on a new meteor will effectively re-acknowledge the last good reception it had from the master. This will help prevent the re-transmission of blocks that have been correctly received.

Ifa remote does not receive a reply from the master station when it is expecting one it assumes the link is lost and remains silent. If the master was in turn expecting a reply to its transmission, and doesn't receive one within the normal listening period, it will resume its probing sequence. In this manner the master can establish communications with another remote in the network within a probe cycle of loosing the link with the first. If the remote is transferring information into the master it will not remove information segments from its transmit queue until it has received an acknowledgement from the master indicating that it has received the segment correctly.

Not Acknowledgements (NAK) are not used by the protocol as it is assumed that in the majority of cases the lack of response is due to a loss of the link and there is no point trying to confirm it over a link that doesn't exist.

To terminate communications when all information has been transferred successfully two slightly different strategies are used. If the remote was the last station to transmit an information block and it received the acknowledgement correctly it will remain silent thus forcing the master to drop into a probing sequence. If the master transmitted a block, received the acknowledgement correctly, and has no more information to send, it will resume probing.

3.3 Conclusions

A brief explanation of a typical communications protocol as used in a meteor burst communication system has been presented.

The purpose of this presentation is to illustrate the block structure of the protocols and the manner in which ARQ error control techniques are used as a mechanism for establishing, maintaining, and re-establishing the communications link on the intermittent channel.

The next chapter presents the various protocols that could be used to control the errors on the channel. It includes a description of the simple ARQ protocol presented here.

4.0
ERROR CONTROL PROTOCOL CONSIDERATIONS

4.1 Introduction

All data telemetry systems experience errors in the transfer of information from one terminal to another. Various techniques have evolved for detecting and correcting these errors. By using these techniques, a communications system designer can guarantee a maximum level of undetected error in the received information.

To operate reliably the meteor burst communications system requires the application of some form error detection and correction algorithm. A well designed error detection and correction protocol can be used to provide both channel quality information and to maintain an acceptable error rate. The channel quality information provided is used by the communications protocol to control the flow of information over the channel.

This chapter presents a review of some of the error detection and control techniques applicable to the meteor burst channel.

4.2 Error Control Codes

Error control codes are capable of detecting the presence of errors in a block of information and correcting them.

An error control code operates by attaching redundancy in the form of parity symbols to an information block prior to its transfer through a communications system. Upon reception the contents of the information block are mathematically compared to the contents of the parity symbols. If an error has occurred in transmission in either the information block or parity symbols, this comparison will detect its presence.

Error control code structures are divided into two general categories referred to as convolutional codes and block codes. Block codes are based on mathematical structures of finite length. To encode a continuous stream of information using block codes it must be divided into blocks of appropriate length. The encoding of each block is independent of the encoding of every other block. Convolutional codes are based on mathematical structures that can encode a stream of data by modifying it and adding redundancy in a continuous manner.

As the intermittent nature of the meteor burst channel is best suited to block protocols, the error control codes and error correction techniques considered in this thesis will be restricted to block codes.

4.2.1 Encoder/Decoder

The implementation of the algorithm that computes the parity symbols is referred to as the encoder. The resultant block of combined information and parity symbols is referred to as a codeword. This codeword is transmitted through the communications channel in its entirety. The implementation of the algorithm that checks the received codeword to determine if errors are present is referred to as the decoder. When combined they are referred to as the codec.

When error control codes that are capable of error correction as well as error detection are being used, the decoder may use the mathematical structure of the received codeword to produce an estimate of the location and magnitude of the errors in it. With this information the received codeword can be "corrected". The corrected codeword is then rechecked to see if a valid codeword has resulted.

4.2.2 Decoder Failure Mechanisms

Error control codes can fail in two distinct ways. If the transmitted codeword has been corrupted in such a manner that the received word is a valid codeword, albeit the wrong one, the decoder has no way of recognizing this and will declare the information valid. Such an error is referred to as an undetectable error and a decoder failure is said to have been committed. The rate at which this will occur for a given error control code is referred to as the probability of undetected error. It will be a function of the error control code and the error patterns that occur on the communications channel.

The second type of failure occurs when an error correcting decoder changes a received word into a valid codeword which is not the same codeword as that originally transmitted. This is referred to as a decoder error. It will occur if the error pattern present in the received word has modified it such that its Hamming distance from a valid but incorrect codeword is within the error correcting capability of the error control code.

4.2.3 Hamming distance

The Hamming distance $\mathbf{d}$ between any two codewords is defined as the number of positions in which the codewords differ. The minimum Hamming distance $\mathbf{d}_{min}$ of an error control code is the distance that separates the two valid codewords that have the most positions in common.

Error control code structures are designed to maximize the Hamming distance for the codewords produced by the encoding process. The greater the minimum distance $\mathbf{d}_{min}$ of the code, the better the probability the decoder will detect the presence of an error in a received codeword.

4.2.4 Code Rate

The rate of an error control code is the ratio of the number of information symbols to the number of information plus parity symbols contained in the codewords. It is also referred to as the code rate and is abbreviated $\mathbf{r}$.

The minimum distance of most error control codes cannot be determined precisely however upper bounds are defined for the more common codes. The exception to this are codes referred to as Maximum Distance Separable (MDS) codes.

4.2.5 Error Detection/Correction Bounds

The number of random erroneous symbols t_d that can be detected in a codeword is bounded by the minimum distance of the code and is given by the relationship

$$t_d \leq d_{min} - 1 \qquad \{4.1\}$$

The number of random erroneous symbols t_c that can be detected and corrected in a codeword is bounded by the minimum distance of the code and is given by the relationship

$$t_c \leq \frac{d_{min} - 1}{2} \qquad \{4.2\}$$

4.2.6 Detecting the Presence of Errors

To detect the presence of errors in a received codeword, the decoder re-applies the coding rule to it. For cyclic block codes the decoder divides the received codeword by the roots of the polynomial used to generate the transmitted codeword.

If the received word is a valid codeword the remainder symbols of each of these divisions, referred to as the syndromes, will be zero. If any of the syndromes are non-zero, the received word is not a valid codeword and error detection is declared.

4.2.7 Correcting the Errors

When an erroneous codeword has been detected, a number of techniques are available to correct it. These techniques fall into two categories: Automatic Repeat Request (ARQ) techniques and Forward Error Correction (FEC) techniques.

As implied by its name, an ARQ protocol will automatically inform the transmitter of the error and request that a repeat transmission of the codeword be made. Forward Error Correction (FEC) techniques utilize the mathematical relationships used to create the codeword as the basis for estimating the error pattern that is present in the received codeword. This estimate is used to modify the received codeword. If the estimate is correct the codeword can be corrected.

When FEC techniques are used in conjunction with ARQ techniques the resultant protocols are referred to as Hybrid FEC/ARQ protocols.

A more extensive discussion of some specific error control codes and error detection and correction techniques is presented in the following sections.

4.3 Automatic Repeat Request (ARQ) Protocols

The simplest and most commonly used form of error correction is referred to as Automatic Repeat Request (ARQ). As the name implies, an ARQ protocol corrects errors by requesting a repeat of a block of information if it contains detectable errors. ARQ protocols are block protocols.

To implement an ARQ protocol, a mechanism for detecting the presence of errors in a received block and a bi-directional communications channel are required. Error control codes are used to detect the presence of errors in the information block.

Three variations of the ARQ protocols have been defined. They are: Stop and Wait ARQ, Go Back N ARQ and Selective Repeat ARQ.

4.3.1 Stop and Wait ARQ

The Stop and Wait ARQ protocol is the simplest of the ARQ protocols and the most straight forward to implement. It operates as follows.

The station in the communication system originating a block of information, referred to as the source, encodes the block of information creating a codeword which is then transmitted through the communications channel to the intended recipient station, referred to as the destination. Upon receipt of the codeword, the receiver decodes it to determine if detectable errors are present. If no errors are present the destination station transmits an acknowledgement of correct reception (ACK) to the source station. If errors are detected the destination station transmits a Not Acknowledgement (NACK) to the source station. Upon receipt of a NACK the source station will retransmit the erroneous codeword. Upon receipt of an ACK the source station will send the next codeword in its transmit queue. This mechanism will be repeated until the block is received correctly.

Stop and Wait ARQ protocols are most commonly implemented in simplex communication networks or in systems where channel turnaround times are minimal relative to the channel data rate. A simplex communication network is one in which a common channel is used for both the forward and return messages. Channel turnaround time refers to the cumulative time delays associated with the stopping and restarting of the flow of information on the channel such that a bi-directional or multi-directional flow of information is realized.

After some additional channel delay time, the receive status of the codeword is received at the source station. If the codeword was received correctly it is removed from the transmitted codeword buffer. If it was received incorrectly it is re-transmitted with its original identification number. It is at this point the two protocols diverge.

If a Go Back N protocol is being used, the source transmitter will step back into its transmitted codeword buffer to the point where the erroneously received codeword is located and resume transmissions at this point. All the codewords that were transmitted after the erroneous codeword are re-transmitted regardless of their status at the receiver.

When the re-transmitted codeword is received at the destination it is again checked for errors. If no errors are detected in the codeword the reception process then carries on receiving, decoding, and releasing codewords until another error is detected.

If a Selective Repeat protocol is being used the source transmitter will step back into its transmitted codeword buffer to the point where the erroneously received codeword is located and insert it into its transmit queue at the next available slot. The codewords that were transmitted after the erroneous codeword are not re-transmitted.

All the codewords received correctly at the destination station after the detection of the erroneous codeword and prior to the reception of the re-transmitted codeword are placed in a temporary receive buffer. When the re-transmitted codeword is received, it is again decoded and checked for errors. If it is correct it is released to the data sink along with any of the received codewords in the buffer that have also been received correctly. The receiver in a system utilizing a Selective Repeat Protocol must therefore have buffers large enough to hold as many codewords as can be expected to be backed up waiting for a particular codeword to be received correctly.

4.3.2 Go Back N ARQ and Selective Repeat ARQ Protocols

In many communication systems channel turnaround times become significant relative to other operational parameters. For example on channels using very high data rates even short turnaround times can represent a significant amount of information throughput. Other communication links such as satellite links have unavoidably long channel turnaround times where the lost channel time becomes significant regardless of the data rate on the channel.

To overcome the delays associated with long channel turnaround times, two extensions of the basic Stop and Wait ARQ protocol have been developed. These extensions are referred to as Go Back N ARQ and Selective Repeat ARQ. Two channels must be available between the source station and destination station for these protocols to operate. The channel that carries information from the source to destination is referred to as the forward channel. The channel that carries the protocol responses from the destination to the source is referred to as the reverse, or back, channel.

A description of the operation of the two protocols is presented in the following paragraphs. As their operation is very similar they are described concurrently with the differences between them indicated where appropriate.

The source station transmits a continuous stream of codewords to the destination station over the forward channel. Before transmission, it applies a unique identification number to each codeword. After transmission it temporarily places each transmitted codeword and its identification number in a buffer.

After some channel delay time the transmitted codeword arrives at the destination station. The destination station receives it, decodes it, and checks it for the presence of errors. If no errors are detected the information contained in the codeword is removed and released to the data sink and the identification number of the received codeword is transmitted to the source station over the reverse channel with an ACK status associated with it. If errors are detected a NACK status is transmitted instead.

Intuitively we can see that the Selective Repeat ARQ Protocol is the most efficient and the Stop and Wait ARQ protocol the simplest to implement. Expressions for the relative efficiencies of the protocols are developed in the following section.

4.3.3 Throughput Efficiency of the ARQ Protocols

To determine the throughput efficiencies of the ARQ protocols we first of all consider Selective Repeat ARQ. This development follows that presented by Lin and Costello[16].

The probability that a received codeword will be accepted by the receiver is defined as:

$$P = P_c + P_e \qquad \{4.3\}$$

where

P_c = the probability that the codeword is received correctly
P_e = the probability that the codeword contains an undetectable error

The probability that a codeword will be retransmitted, P_r, is therefore

$$P_r = 1 - P \qquad \{4.4\}$$

The average number of times a codeword will be transmitted as the result of an error in the received codeword will then be

$$T_{sr} = P + 2P(1 - P) + 3P(1 - P)^2 + \cdots + n\,P(1 - P)^{n-1} \cong \frac{1}{P} \qquad \{4.5\}$$

The throughput efficiency of the Selective Repeat protocol will then be

$$\nu_{sr} = \frac{k}{T\,n} \qquad \{4.6\}$$

where $\frac{k}{n}$ is the rate of the error detection code used. The throughput efficiencies of the Stop and Wait ARQ protocol and Go Back N ARQ protocol are determined by modifying this expression to take into account the delay times associated with the repeat process.

For the Stop and Wait protocol the time delay associated with the channel turn around time needs to be incorporated into the expression. We define **Dt** as the number of bits that could be transmitted during the channel turn around time where **D** represents the signalling rate on the channel and **t** represents the channel turn around time.

If the turn around time on the channel did not exist the total number of bits that could be transmitted would be **n + Dt** where **n** is the number of bits in a codeword. The average number of re-transmissions would therefore be

$$T_{sw} = (n + Dt)\,P + 2(n + Dt)\,P\,(1 - P) + \cdots \cong \frac{n + Dt}{P} \qquad \{4.7\}$$

The efficiency of the Stop and Wait ARQ is thus

$$\nu_{sw} = \frac{P}{1 + \frac{Dt}{n}}\;\frac{k}{n} \qquad \{4.8\}$$

To determine the efficiency of the Go Back N ARQ protocol the number of additional blocks that are retransmitted each time an erroneous block is retransmitted has to be factored into the throughput. The number of blocks that are retransmitted is **N - 1** therefore the average number of retransmissions required is

$$T_{gbn} = P + (N + 1) P (1 - P) + (2N + 1) P (1 - P)^2 + \cdots \cong 1 + \frac{N (1 - P)}{P} \qquad \{4.9\}$$

The throughput efficiency is therefore

$$n_{gbn} = \frac{P \frac{k}{n}}{P + (1 - P) N} \qquad \{4.10\}$$

As expected the Selective Repeat is the most efficient protocol and the Stop and Wait the most inefficient.

4.3.4 Reliability of an ARQ Protocol

Lin and Costello[16] show that the reliability of a communication system utilizing an ARQ protocol is

$$P(E) = \frac{P_e}{P_c + P_e} \qquad \{4.11\}$$

where:

P(E)	= probability of an error event, i.e. the probability that an erroneous codeword is accepted as correct
P_e	= probability that the received codeword contains an undetectable error
P_c	= probability that the received codeword does not contain an error

It will be shown in the following sections that high rate error control codes are capable of achieving very low values of P_e. For example, using a Reed-Solomon (255,253) code (defined in Section 4.4.2) will result in a $P_e < 2^{-16}$ in a received codeword. Codewords produced using this code contain 2 eight bit parity symbols (16 bits). The information block to be encoded can contain up to 253 eight bit symbols (2024 bits) with a resultant code rate > 0.99.

Transmitting the codeword over a binary symmetric channel (BSC) with a crossover probability of $p = 1 \times 10^{-3}$ would result in a P_c of 0.13 ($P_c = (1 - p)^n$). Using the Reed-Solomon error control code to detect the presence of errors and the ARQ protocol to cause the retransmission of the erroneously received codewords until correct would result in a probability of undetected error **P(E)** of $< 1.2 \times 10^{-4}$.

4.4 Forward Error Correction (FEC)

Forward Error Correction (FEC) techniques can be used to correct errors in codewords using only the information contained in the received codeword. As a consequence FEC techniques are the only technique available for correcting errors in communication systems where a return path is not available between the data source and destination.

All error control codes can be used to detect and correct errors within the constraints implied by equations 4.1 and 4.2. They can therefore be used for error detection only or for combined error detection and correction.

In the following sections two Error Control Codes suitable for use on the meteor burst channel are presented. Both are cyclic block codes and are closely related mathematically. The first to be presented, the BCH codes, are binary codes. The second, the Reed-Solomon codes, are a non-binary extension of the BCH codes based on symbols with dimension **m**. It should be noted that some authors prefer to consider the BCH codes a sub-class of the Reed-Solomon codes.

4.4.1 BCH Error Control Codes

The **Bose-Chaudhuri-Hocquenghem (BCH)** codes are a class of cyclic block codes that are capable of detecting and correcting multiple errors in a codeword.

An (n,k,t) BCH code will have the following parameters:

Block Size

$$\mathbf{n = 2^m - 1} \tag{4.12}$$

where

$$\mathbf{k \geq n - mt} \tag{4.13}$$

and minimum distance

$$\mathbf{d \geq 2t + 1} \tag{4.14}$$

BCH codes therefore have no more than **mt** parity bits and are capable of correcting up to **t** random errors or detecting bursts of up to **2t** errors.

BCH codes are cyclic codes defined in terms of a generator polynomial **g(x)**. Given α, a primitive element of the extension field $\mathbf{GF(2^m)}$, the generator polynomial of a **t**-error correcting BCH code is chosen so that **2t** consecutive powers of α ($\alpha, \alpha^2, \alpha^3, \ldots, \alpha^{2t}$) are roots of the generator polynomial and thus of the codeword generated by it. These are not necessarily the only roots, others may exist.

4.4.1.1 Encoding Binary BCH Codes

Cyclic codes are encoded by multiplying the information polynomial by the generator polynomial to produce the codeword polynomial as per

$$\mathbf{c(x) = i(x)\, g(x)} \tag{4.15}$$

where

$$i(x) = i_1 + i_2 x + i_3 x^2 + \cdots + i_k x^{k-1} \qquad \{4.16\}$$

represents the information polynomial of degree **k - 1** with the coefficients i_l representing the values of the information bits and

$$g(x) = g_1 + g_2 x + g_3 x^2 + \cdots + g_k x^{n-k} \qquad \{4.17\}$$

represents the generator polynomial of degree **n - k** and

$$g(x) = c_1 + c_2 x + c_3 x^2 + \cdots + c_k x^{n-k} \qquad \{4.18\}$$

represents the resulting codeword polynomial of degree **n - 1.**

The codeword that is generated by the above manipulation will not be in systematic form. To generate a systematic codeword the equation is re-written in the following manner

$$c(x) = [\, x^{n-k}\, i(x) \bmod g(x)] + x^{n-k}\, i(x) \qquad \{4.19\}$$

The first term of the equation generates the parity bits as the low order coefficients of the codeword which are then added to the information bits which have been multiplied by x^{n-k}. Multiplying a cyclic polynomial by x^m has the same effect as shifting the coefficients of the polynomial **m** locations to the right. As a consequence the original **k** information polynomial coefficients become the high order **k** coefficients of the codeword.

A systematic codeword thus has the form

$$c(x) = p_1 + p_2 x + \cdots + p_{n-k} x^{n-k-1} + i_1 x^{n-k} + \cdots + i_k x^{n-1} \qquad \{4.20\}$$

where the p_i represent the parity bits and the i_j represent the original information bits.

Feedback shift registers of the form presented in Lin and Costello [16] can be used to encode (and decode) BCH codes. These shift registers may be implemented in either hardware or software.

4.4.1.2 Decoding Binary BCH Codes

The first step in decoding a BCH code is determining if the received codeword is a valid codeword.

To determine if the received codeword is a valid codeword, the decoder calculates a set of values referred to as the syndromes of the received codeword. A total of $n - k$ syndrome values are calculated. The calculation of the syndromes is developed as follows.

The received codeword is defined as

$$r(x) = c(x) + e(x) \qquad \{4.21\}$$

where

$r(x)$	= the received codeword
$c(x)$	= the codeword transmitted into the channel
$e(x)$	= an error polynomial

The error polynomial represents the error pattern that is present in the received codeword. If no errors are present the coefficients of this polynomial are all equal to zero and $r(x)$ will be equal to $c(x)$.

The $n - k$ syndrome values $\{S_k\}$ are computed by evaluating the received codeword at the roots of the generator polynomial. These roots are referred to as the prescribed roots. Thus

$$S_k = r(\alpha^k) \qquad \{4.22\}$$

where the α^k are the **k** roots used to form the generator polynomial and the S_k the resulting syndrome values. If the syndrome values are all equal to zero the received word is a valid codeword. To see this we combine {4.22} and {4.21} to form

$$S_k = c(\alpha^k) + e(\alpha^k) \qquad \{4.23\}$$

which (because the α^k are roots of **c(x)**) is the equivalent to

$$S_k = e(\alpha^k) \qquad k = 1, 3, \ldots, 2t-1 \qquad \{4.24\}$$

If errors are present in the received codeword, the S_k will be non-zero as the α^k will not be its roots.

If the syndromes are non-zero, error detection can be announced. If error correction is to be attempted the information contained in the non-zero syndromes has to be processed to locate and correct the errors present.

The first step in the process is to locate the errors. The second is to determine the magnitude of the error and apply it to the erroneous symbol. For a binary code such as the BCH codes this is straight forward as the error magnitude must be equal to 1.

To locate the errors in the received codeword polynomial a parameter X_l referred to as the error locator is defined as follows

$$X_l = \alpha^J \qquad \{4.25\}$$

where X_i represents the i^{th} $(1 \le i \le t)$ error which has occurred in the j^{th} $(0 \le j \le n\text{-}1)$ location in the received codeword. A polynomial referred to as the error polynomial is written based on the relationship between the errors that are present in the codeword and the error locators as follows

$$e(\alpha^k) = \sum_{i=1}^{t} x_i^k \qquad \{4.26\}$$

where the magnitude of the error is implied to be equal to 1 or 0 for a binary code.

Combining {4.24} and {4.26} we get

$$S_k = \sum_{i=1}^{t} x_i^k \qquad \{4.27\}$$

Thus we have a relationship between the syndrome values calculated for the received codeword and the location of the errors in it. Unfortunately {4.27} represents **t** nonlinear, coupled, algebraic equations defined over the finite field GF(2^m).

The solution to this system of equations is not straight forward and must be performed in a round about way. To this end a second polynomial referred to as the error locator polynomial is defined as follows

$$\sigma(x) = \prod_{i=1}^{t} (x + X_i) \qquad \{4.28\}$$

$$= x^t + \sigma_1 x^{t-1} + \cdots + \sigma_t \qquad \{4.29\}$$

The roots of this polynomial are, by definition, the error locators. The coefficients of this polynomial, the σ_i's, are known as elementary symmetric functions. They are related to the syndrome values by the following Newton's identities

$$S_1 + \sigma_1 = 0$$
$$S_3 + S_2\sigma_1 + S_1\sigma_2 + \sigma_3 = 0$$
$$S_5 + S_4\sigma_1 + S_3\sigma_2 + S_2\sigma_3 + S_1\sigma_4 + \sigma_5 = 0$$

{4.30}

The solution to this system of equations are the coefficients of the error locator polynomial. Various techniques have been developed for solving them. For high rate codes Peterson's direct solution method (Michelson & Levesque [20]) provides a straight forward and efficient technique. For lower rate codes the Massey-Berlekamp algorithm is a better choice.

Peterson's direct solution method is based on techniques used in ordinary linear algebra. The Massey-Berlekamp algorithm uses a feedback shift register synthesis technique. This shift register determines the coefficients of the minimum degree, reciprocal, error locator polynomial whose coefficients, taken together with the syndrome values, satisfy {4.30}.

Once the coefficients of the error locator polynomial have been found, its roots the error locators, are found using a Chien search. A Chien search is simply an iterative procedure that involves solving the equation for each value in the number field over which the error control code is defined. Each number in that field for which the solution is zero will be a root of the polynomial.

Given the error locations the received codeword is corrected by inverting the bit at each of the error locations.

4.4.2 Reed-Solomon Error Control Codes

Reed-Solomon (RS) error control codes are non-binary, cyclic codes defined over a finite field **GF(q)**. Reed-Solomon codes are used extensively in applications where burst error detection and correction is required.

An (n,k,t) RS code will have the following parameters:

Block Size

$$\mathbf{n = q - 1} \qquad \{4.31\}$$

and minimum distance

$$\mathbf{d = n - k + 1} \qquad \{4.32\}$$

where **n**, **k**, and **t** represent non-binary symbols. In practice RS codes are usually defined on a finite field of characteristic 2 thus $q = 2^m$ where **m** is the dimension of the code symbols. For example, A RS code defined on $GF(2^5)$ will have 5 bit symbols and a block length **n** of 31 symbols (155 bits).

RS codes are maximum distance separable (MDS) codes therefore the design distance of the code is equal to its true minimum distance.

RS codes may be encoded and decoded using either a time domain, syndrome based approach or a frequency domain, transform based approach. The syndrome approach is identical to that presented for the BCH codes except that it is extended to cover the non-binary symbols (Michelson and Levesque[20]).

The transform approach is based on a transform pair similar in structure to the Fourier transform pair (thus the term frequency domain). The message word and parity symbols are transformed prior to transmission over the communication link. At the receiver the codeword is reconstructed using the inverse transform and the message word extracted (assuming errors have occurred) using recursion and root finding techniques (Blahut [4]).

The following discussion will extend the time domain approach already presented for the BCH codes. The frequency domain approach is not dealt with in this thesis.

4.4.2.1 Encoding Reed Solomon Error Control Codes

The generator polynomial for RS codes is defined as follows:

$$g(x) = (x - a^{m})(x - a^{m+1}) \cdots (x - a^{m+2t-1}) \qquad \{4.33\}$$

$$= x^{2t} + g_{m+2t-1} x^{2t-1} + \cdots + g_{m+1} x + g_{m} \qquad \{4.34\}$$

where **m** is an arbitrary integer usually set equal to 1 or 0 and the coefficients g_i are elements from the field **GF(q)**.

The encoding process for the Reed Solomon code is the same as described for the BCH code. The information polynomial is multiplied by the generator polynomial to produce the codeword polynomial using {4.15}. The difference is that the coefficients of the polynomials involved in the computations are now elements from the non-binary field **GF(q)**. As with the BCH code this encoding process can be performed by a feedback shift register of dimension **m**.

4.4.2.2 Decoding Reed Solomon Error Control Codes

As with encoding, the decoding techniques and considerations for Reed-Solomon codes are similar to those of the BCH codes.

The error locator X_l is defined in the same manner as for the BCH codes but now the error polynomial {4.26} is written in the following form:

$$S_k = \sum_{l=1}^{t} X_l^k Y_l \qquad \{4.35\}$$

where Y_l is the magnitude of the error at location X_l.

Once again the error locator polynomial is defined and Newton's identities are used to relate the elementary symmetric functions to the syndrome values. For the RS codes these identities take the form

$$S_{t+j} + \sigma_1 S_{t+j-1} + \cdots + \sigma_t S_j = 0 \qquad \{4.36\}$$

where **j** ranges from **1** to **t**. Peterson's direct solution method is once again good for finding the solution to this set of equations for high rate codes and the Massey Berlekamp method good for lower rate codes.

Once the coefficients of the error locator polynomial have been found, the error locators are found using the Chien search. With the locations of the errors known the problem now becomes one of finding the magnitude of the error so that the erroneous symbol can be corrected.

An efficient technique, originally developed by Forney, for finding the error magnitudes is as follows. Given the error locators X_l $i = 1, 2, \ldots, t,$ a series of new error locator polynomials ${}_l\sigma(x)$ are formed, each of which has as roots all of the error locators except X_l. These polynomials will each have the form

$${}_l\sigma(x) = {}_l\sigma_0\, x^{t-1} + {}_l\sigma_1\, x^{t-2} + \cdots + {}_l\sigma^{t-l} \qquad \{4.37\}$$

The magnitude of the error Y_l at location X_l is then

$$Y_l = \frac{\sum_{k=0}^{t-1} {}_l\sigma_k \, S_{t-k}}{\sum_{j=0}^{t-1} {}_l\sigma_j \, S_{t-k}} \qquad \{4.38\}$$

As each error magnitude is found it is added to the erroneous symbol at the appropriate location in the codeword.

When all the detected errors have been corrected the codeword is once again checked for errors by recalculating the syndromes.

4.4.2.3 Lengthening and Shortening RS Codes

The length of a cyclic block code can be extended by one or two symbols or shortened to any desired length. The techniques used for lengthening codewords are not dealt with in this thesis due to the limited change in length achievable.

To shorten a code the appropriate number of high order information symbols are defined as zero. They are then not transmitted or stored in the communication system. During the decoding process the decoder makes the assumption that it has received the appropriate number of leading symbols, that they were set equal to zero, and that they were received correctly.

When the block length of a code has been shortened, the number of parity symbols remains the same thus the number of errors that can be detected and corrected remains the same.

For MDS codes such as Reed Solomon Codes where $\mathbf{d}$ is equal to $\mathbf{n - k + 1}$, the minimum distance of the shortened codewords is the same as for the full length codewords. As a consequence code shortening is an effective technique for varying the coding rate in response to error conditions on the channel. The problem with using code shortening to vary the coding rate is that the length of the resultant codeword will vary as a function of the rate. This can create implementation problems in block protocols.

4.4.2.4 Errors and Erasures Decoding

Forney [12] introduced a procedure for correcting both errors and erasures using cyclic block codes, specifically BCH codes. These techniques apply equally well to Reed Solomon codes. In this situation an error is defined as an erroneous symbol in a codeword for which neither the location nor the magnitude is known. An erasure is defined as an erroneous symbol for which the location is known but not the magnitude of the error.

For a RS code with distance **d,** it is possible to correct **t** errors plus **s** erasures where **d** > 2t + s. For a communication system that is capable of providing the decoder with the necessary a priori knowledge of the location of some of the errors in the codeword, a significant increase in the error correcting capability of the decoder can therefore be realized.

The procedure for correcting both errors and erasures as presented by Michelson & Levesque[20] follows. It is in turn based on that originally presented by Forney. This procedure assumes a primitive code with **m** = **1** in a field of characteristic 2.

An erasure locator polynomial **σ'(x)** of degree **s** with the erasure locators as roots is defined.

$$\sigma'(x) = \prod_{i=1}^{s} (z + Z_i) \tag{4.39}$$

$$= \sigma_0' z^s + \sigma_1' z^{s-1} + \cdots + \sigma_S' \tag{4.40}$$

For combined errors and erasures decoding the first step is to calculate the **n - k** syndromes as for the errors only situation. These syndromes are then transformed to produce **d - s - 2** modified syndromes. The transform process has the effect of including the erasure location information in the original syndromes. That transform is

$$T_i = \sum_{j=0}^{s} \sigma_j' \, S_{i+s+1-j} , \qquad 0 \le i \le d-1 \qquad \{4.41\}$$

There will be **s** fewer modified syndromes than original syndromes and the total number of modified syndromes will depend on the number of erasures declared.

We first develop a relationship between the erasure and error locators, the magnitude of the errors in the symbols and the syndromes. Assuming **t** errors with magnitudes $Y_1, Y_2, ..., Y_t$ at locations $X_1, X_2, ..., X_t$ and s erasures with error magnitudes of $D_1, D_2, ..., D_s$ at locations $Z_1, Z_2, ..., Z_s$ the original syndromes can be expressed as

$$S_k = \sum_{m=1}^{t} Y_m X_m^k + \sum_{n=1}^{s} D_n Z_n^k , \qquad 1 \le k \le d-1 \qquad \{4.42\}$$

combining this with the expression for the modified syndromes {4.41} results in

$$T_i = \sum_{j=0}^{s} \sigma_i' \left(\sum_{m=1}^{t} Y_m X_m^{i+s+1-j} + \sum_{n=1}^{s} D_n Z_n^{i+s+1-j} \right) \qquad 1 \le k \le d-s-2 \qquad \{4.43\}$$

which is the same as

$$T_l = \left(\sum_{m=1}^{t} Y_m X_m^{l+1} \sum_{j=0}^{s} \sigma_l' X_m^{s-j} \right) + \left(\sum_{n=1}^{s} D_n Z_n^{l+1} \sum_{j=0}^{s} \sigma_l' Z_n^{s-j} \right) \qquad \{4.44\}$$

The second summation of the last term is the erasure locator polynomial {4.40} evaluated at Z_n, which is one of its roots. It will therefore be equal to zero. The second summation of the first term is also the erasure locator polynomial but this time evaluated at the error location X_m. It can therefore be written as $\sigma'(X_m)$. If we then define the quantity

$$E_m = Y_m X_m \sigma'(X_m) \qquad \{4.45\}$$

{4.44} can be re-written in the form

$$T_l = \sum_{m=1}^{t} E_m X_m^l \qquad 0 \le i \le d - s - 2 \qquad \{4.46\}$$

This equation represents the definition of **t** modified syndromes. These modified syndromes include the known erasure locations in the received codeword. Equation {4.46} can now be solved in the conventional manner to determine the coefficients of the error locator polynomial. The roots of the error locator polynomial are now found using a Chien search. With both the error locators and erasure locators known the error magnitudes are calculated using {4.38} and the codeword corrected.

4.4.2.5 Inversion of a Half Rate RS Code

Code inversion is a technique for recovering the original information symbols of a codeword given the parity symbols. As will be seen in subsequent sections this technique is important to the operation of a modified ARQ protocol referred to as Hybrid II ARQ/FEC.

The development of code inversion is presented here. It closely follows that introduced by Lin and Yu [17] with slight modifications to include shortened (to half-rate or less) Reed-Solomon Codes.

Let C be an **(n,k)** shortened cyclic code with $n - k \leq k$. The generator polynomial **g(x)** for C will have the form

$$g(x) = g_0 + g_1 x + g_2 x^2 + \cdots + g_{n-k-1} x^{n-k-1} + x^{n-k} \qquad \{4.47\}$$

The shortened cyclic codes considered here are those for which the $n - 2(n - k)$ leading high order coefficients have been set equal to zero (assuming systematic codewords). These codes retain the same error correcting capability as the original code and in the case of the Reed-Solomon codes they also retain the same minimum distance. Given

$$u(x) = u_0 + u_1 x + \cdots + u_{n-k-1} x^{n-k-1} \qquad \{4.48\}$$

an information word to be encoded.

Using the generator polynomial **g(x)** to encode the information word we divide $x^{n-k}\, u(x)$ by g(x) we get

$$x^{n-k}\, u(x) = a(x)\, g(x) + p(x) \qquad \{4.49\}$$

which results in the codeword

$$w(x) = p(x) + x^{n-k}\, u(x) \qquad \{4.50\}$$

which is in systematic form and which is half rate.

For the code to be invertible the parity symbols generated by the above division must be unique to the information word. This is proven in the following theorem.

Theorem 3.1 No two code words in a half-rate shortened cyclic code C will have the same parity symbols.

Proof:

Let $\mathbf{u}_1(x)$ and $\mathbf{u}_2(x)$ be two distinct information words. Encoding each in systematic form using the generator polynomial $\mathbf{g}(x)$ as follows

$$\begin{aligned} x^{n-k}\,u_1(x) &= a_1(x)\,g(x) + p_1(x) \\ x^{n-k}\,u_2(x) &= a_2(x)\,g(x) + p_2(x) \end{aligned} \tag{4.51}$$

we obtain the codewords

$$\begin{aligned} w_1(x) &= p_1(x) + x^{n-k}\,u_1(x) \\ w_2(x) &= p_2(x) + x^{n-k}\,u_2(x) \end{aligned} \tag{4.52}$$

then if

$$p_1(x) = p_2(x) = p(x) \tag{4.53}$$

using {4.53} we can add {4.51} to obtain

$$(u_1(x) + u_2(x))\,x^{n-k} = (a_1(x) + a_2(x))\,g(x) \tag{4.54}$$

Since $\mathbf{x^{n-k}}$ and $\mathbf{g(x)}$ are relatively prime, $\mathbf{u_1(x) + u_2(x)}$ must be divisible by $\mathbf{g(x)}$. However this is impossible as $\mathbf{u_1(x) + u_2(x)}$ does not equal 0 and its degree is less than $\mathbf{n - k}$ by definition whereas the degree of $\mathbf{g(x)}$ is $\mathbf{n - k}$ also by definition. Therefore $\mathbf{p_1(x)}$ cannot equal $\mathbf{p_2(x)}$.

Q.E.D.

Given the parity symbols $\mathbf{p(x)}$ of a codeword the problem now is to recover the information word symbols $\mathbf{u(x)}$ used to generate $\mathbf{p(x)}$. Working from {4.49}, the original expression for the systematic encoding process, and multiplying both sides by $\mathbf{x^k}$, we obtain

$$\mathbf{x^n\,u(x) = a(x)\,g(x)\,x^k + p(x)\,x^k} \qquad \{4.55\}$$

which can be re-arranged to give

$$\mathbf{(x^n + 1)\,u(x) + u(x) = a(x)\,g(x)\,x^k + p(x)\,x^k} \qquad \{4.56\}$$

and since $\mathbf{g(x)}$ is a factor of $\mathbf{(x^n + 1)}$, this can be re-written to give

$$\mathbf{p(x)\,x^k = (u(x)\,h(x) + a(x)\,x^k)\,g(x) + u(x)} \qquad \{4.57\}$$

where

$$\mathbf{h(x) = \frac{x^n + 1}{g(x)}} \qquad \{4.58\}$$

Therefore if we divide $\mathbf{p(x)\,x^k}$ by the generator polynomial $\mathbf{g(x)}$ we will obtain the original information word $\mathbf{u(x)}$.

Lin and Costello also present a more efficient technique for recovering the original information word **u(x)**.

Dividing $\mathbf{x^k}$ by **g(x)** we obtain

$$\mathbf{x^k = c(x)\, g(x) + r(x)} \qquad \{4.59\}$$

Multiplying both sides of this equation by **p(x)** and using the equality of {4.57} we obtain

$$\mathbf{p(x)\, r(x) = \{ u(x)\, h(x) + a(x)\, x^k + p(x)\, c(x)\}\, g(x) + u(x)} \qquad \{4.60\}$$

This expression indicates that **u(x)** can be recovered by multiplying **p(x)** by **r(x)** and dividing the result by g(x).

4.4.2.6 Probability of Undetected Error for RS Codes

The probability of undetected error $\mathbf{P_{ud}(C,\varepsilon)}$ for a code **C**, where ε is the probability that a symbol has been received incorrectly, is the probability that the decoder fails to detect the presence of the error in the received codeword. It is used as a measure of the error detection performance of a code. For a code to be considered good for error detection $\mathbf{P_{ud}(C,\varepsilon)}$ should be small for all ε.

Kasami and Lin [14] have shown that Reed Solomon codes are effective for both pure error detection and simultaneous error correction and detection and have developed expressions for the upper bounds of $\mathbf{P_{ud}(C,\varepsilon)}$. The following development is an abbreviated version of their original development.

Assume that a Maximum Distance Separable (MDS) code, such as a Reed Solomon code, with symbols from **GF(q)** has been transmitted over a channel with a bit error probability of ε. The probability of a symbol being received correctly is therefore $1 - \varepsilon$ and the probability that it is received incorrectly is $\frac{\varepsilon}{1 - q}$.

The probability of undetected error for this code operating in this channel will then be

$$P_{ud}(C,\varepsilon) = \sum_{i=1}^{n} A_i) \left(\frac{\varepsilon}{q - 1}\right)^i (1 - \varepsilon)^{n-i} \qquad \{4.61\}$$

where A_i is the weight distribution of the code which for Reed Solomon codes is

$$A_i = \binom{n}{i} (q - 1) \sum_{j=0}^{1-d} (-1)^j \;) \binom{i-1}{j} q^{i-d-j} \qquad \{4.62\}$$

Kasami and Lin present the argument that for a code to be considered good for error detection its probability of undetected error must satisfy the following bound

$$P_{ud}(C,\varepsilon) < q^{-(n-k)} \qquad \{4.63\}$$

and that $P_{ud}(C,\varepsilon)$ must decrease monotonically as ε decreases from $\frac{q-1}{q}$ to 0. Their argument is based on the proof that codes satisfying this bound exist but that only a few known codes have actually been proven to satisfy it.

Kasami and Lin then show that for pure error detection on a worst case channel, i.e. a channel where $\varepsilon = \frac{q-1}{q}$,

$$P_{ud}(C,\varepsilon) = q^{-(n-k)} - q^{-n} < q^{-(n-k)} \qquad \{4.64\}$$

and that it decreases monotonically as ε decreases.

For error detection after correction this bound becomes

$$P_{ud}(C,t,\varepsilon) = q^{-(n-k)} - q^{-n} \sum_{h=0}^{t} \binom{n}{h} (q-1)^h < q^{-(n-k)} \sum_{h=0}^{t} \binom{n}{h} (q-1)^h \qquad \{4.65\}$$

where $\varepsilon = \frac{q-1}{q}$ and t is the number of symbols corrected by the code. It also decreases monotonically as ε decreases.

This expression indicates that MDS codes satisfy the Kasami and Lin criteria for good codes and that they can be considered good codes for both error detection only and combined error detection and correction.

As an example, assume a Reed Solomon code with distance 7 defined on $GF(2^8)$ is being used on a channel. This code is capable of correcting 0, 1, 2 or 3 errors. The bounds on $P_{ud}(C,t,\varepsilon)$ for $t = 0, 1, 2,$ and 3 can be calculated to be 3.6×10^{-15}, 2.3×10^{-10}, 7.5×10^{-6} and 0.16 respectively.

MDS codes thus provide a system designer with the option of using a single code (i.e. CODEC software and/or hardware) for a variety of error detection and error detection and correction functions within a system. The reliability of the information present in a corrected codeword, as required by an individual function, can be achieved by constraining the number of errors the decoder will correct.

4.5 Hybrid ARQ/FEC Error Control Protocols

Both Automatic Request for Repeat protocols and Forward Error Correction protocols have a number of advantages and disadvantages.

The advantages of ARQ are:

- high reliabilities can be achieved with very low levels of redundancy
- operate effectively and efficiently over a wide range of channel conditions such as periodic bursts of noise or fading
- relatively straightforward and inexpensive to implement

and the disadvantages are:

- a return communications channel is required
- errors cause an interruption in the flow of information
- throughput drops rapidly to zero if a low, but constant error rate is experienced on the channel

The advantages of FEC are:

- they operate well on channels that experience low, but constant error rates
- a return communications channel is not required
- a constant flow of information can be maintained

and the disadvantages are:

- efficient, reliable operation is only achieved when the channel error rate is equal to that which the code is designed for
- no mechanism is available to recover information lost if the channel fades or a burst of errors occurs
- the CODEC's are complex and often expensive

It is evident that many of the advantages and disadvantages of each form of error control are complimentary.

When the two protocols are properly combined into a single protocol, it is possible to realize some of the advantages of each thus overcoming some of the disadvantages. The resultant error control protocol is referred to as Hybrid ARQ/FEC.

4.5.1 Hybrid I ARQ/FEC

A Hybrid I ARQ/FEC error control protocol is structured as a concatenated error control protocol. The Forward Error Correction protocol forms the inner code and an Automatic Request Repeat protocol forms the outer code.

The FEC protocol is designed to correct those error patterns that occur on the channel continuously. The ARQ protocol is designed to detect and correct those error patterns that the FEC cannot detect or correct properly. By selecting the respective coding rates appropriately the communications system will now be able to operate reliably and efficiently over a much wider range of channel conditions.

By correcting the steady state error patterns the FEC code can significantly reduce the number of repeat transmissions generated by the ARQ protocol. By using an ARQ protocol to correct those error patterns that the FEC cannot detect or has corrected erroneously a very high reliability can be achieved with little additional overhead. The FEC need only have enough redundancy to correct the most common error patterns. It need not be designed to correct those error patterns that only occur sporadically. To achieve the same reliability with an FEC only code would require the use of a much lower rate codes which would reduce the overall efficiency of the system. The resulting code will also operate reliably over a much wider range of channel conditions.

Hybrid I ARQ/FEC protocols can be designed to use either separate codes for the FEC and ARQ protocols or to use a single code. If a single code is used, the FEC decoder will only correct a portion of the detected errors. It will use the remainder of its error detection/correction capability for error detection only. The error detection function will then be used to drive the ARQ protocol. The results presented in section 4.4.2.6 indicate that Reed-Solomon error control codes are suitable for this purpose.

Although superior to pure ARQ or FEC protocols, Hybrid I FEC/ARQ protocols still suffer from a significant drawback. The rate of the forward error correcting code must be low enough to accommodate the highest number of bit errors expected to occur on the channel on a continuous basis. For a channel experiencing less than this maximum number of errors the throughput will be reduced from that which could be achieved.

One technique for dealing with this is to use a variable rate CODEC and to have the error control protocol adjust the coding rate in response to the number of repeat requests being generated by the ARQ protocol. Unfortunately variable rate CODEC's are complex and thus difficult and expensive to implement.

4.5.2 Hybrid II FEC/ARQ

Hybrid II FEC/ARQ is a protocol that can overcome some of the inefficiency of the Hybrid I ARQ/FEC protocol and that extends the range of operable channel conditions even further. This protocol, first presented by Lin and Yu [17], is referred to as the Hybrid II ARQ/FEC protocol. The concept of a Hybrid II protocol is to transmit the FEC parity symbols to the receiver only when they are required. The explanation presented follows that of Lin and Yu.

Two codes are used in a Hybrid II protocol. A high rate code $\mathbf{C_0}$ designed to check for errors in the received codeword and a half-rate, invertible code $\mathbf{C_1}$ designed for simultaneous error detection and correction. The code $\mathbf{C_0}$ is used to drive the ARQ protocol, the code $\mathbf{C_1}$ to perform the FEC protocol functions.

In normal operation only the parity symbols generated by the code $\mathbf{C_0}$ are included in the transmitted codeword. The parity symbols generated by the code $\mathbf{C_1}$ are retained in a buffer in the transmitter. At the receiver, the parity symbols generated by $\mathbf{C_0}$ are used to determine if any errors are present in the codeword. If no errors are present the receiver ACK's the codeword and the next one is transmitted as would happen with a conventional ARQ protocol.

If the C_0 decoder detects the presence of errors, the erroneous information codeword is placed in a buffer and a NACK returned to the transmitter. Upon receiving the NACK the transmitter places the buffered C_1 parity symbols in the repeat codeword instead of the original information symbols. It then passes this parity codeword through the C_0 encoder and transmits it.

Upon receipt, the parity codeword is checked for errors using code C_0. If no errors are present, the codeword is ACK'd and the C_1 parity symbols inverted to recover the original information.

If errors are present, the erroneous parity symbols are combined with the erroneous information symbols to form a complete, half rate C_1 codeword. The C_1 decoder then attempts to locate and correct the errors in the information symbols and their associated C_0 parity symbols. The resulting codeword is then rechecked for errors using C_0 which will in turn generate the ACK or NACK response to the parity codeword.

The Hybrid II ARQ/FEC protocol will thus have a throughput equivalent to that of a pure ARQ protocol when the error rate on the channel is low. As the error rate increases the throughput of the Hybrid II drops very quickly to slightly less than that of a Hybrid I scheme using a half rate code. It then sustains this level of throughput beyond the point where the Hybrid I throughput falls to zero.

The Hybrid II ARQ/FEC protocol has received considerable interest in the literature. Techniques for combining the repeated information codewords and parity codewords such that an improvement in the robustness of the error correction process have been presented by authors such as Metzner and Chang [19]. Separable error control codes suitable for use in Hybrid II ARQ/FEC protocols have been investigated by Du, Kasahara, and Namekawa [9].

Lin and Yu [17] present an analysis of the throughput efficiency of the Hybrid II protocol based on the binary symmetric channel. This analysis is not repeated here as it is a lower bound and is not directly applicable to the meteor burst channel. It does however indicate that the Hybrid II ARQ/FEC protocol is the most efficient and robust of the various error control protocols discussed except for a small region of the performance envelope where the Hybrid I is more efficient.

5.0
MODELING THE PERFORMANCE OF A METEOR BURST COMMUNICATION SYSTEM

5.1 Introduction

This chapter starts with a subjective discussion of the meteor burst channel and the equations used to describe it. The discussion focuses on information throughput as opposed to waiting time.

A detailed analysis of the error patterns that would be expected on an operational channel is then presented.

Using the information presented in these first two sub-sections and chapters 2.0 and 3.0 of this thesis, a model of the meteor burst channel was constructed. This model simulates the meteor burst channel as a series of sequential signal bursts such as would occur over a period of time on an operational channel. The signal amplitude characteristic is modeled as an underdense, exponentially decaying signal. The amplitude distribution, and thus the "observed" burst durations are exponentially distributed.

This model was used to characterize the longrun throughput of a meteor burst channel using the error control protocols presented in chapter 4.0. The effect these protocols would have on the observed waiting time was not considered and the model as it is currently implemented does not deal with the time distribution of the signal bursts.

A Stop and Wait ARQ protocol similar to that presented in the chapter 3.0 is used as the basis protocol for the channel model. The model calculates the total expected throughput in bits **b** for a given number of meteors. If these meteors are assumed to have occurred within a span of time **t** the throughput can then be defined to be $\frac{\mathbf{b}}{\mathbf{t}}$.

The model first calculates the expected throughput for the basic protocol and then calculates it for each of the more sophisticated protocols using the same signal burst series. The relative throughputs are plotted to determine if any improvement was realized.

The results of these comparisons for the various protocols presented in the previous chapter are then presented followed by a discussion of the results.

5.2 Quantifying a Systems Performance

The performance of a meteor burst communication system is quantified by two parameters; long run throughput and waiting time. Long run throughput is a measure of the maximum amount of information that can be transmitted over a link on a long term basis. It is usually expressed as equivalent bits per second and may be quoted as an hourly average for different times of the day or as a daily average for different times of the year. Waiting time is the elapsed time from when a message of a given length becomes available for transmission over the link until it has been successfully received at its destination. Waiting time will normally be expressed in either seconds or minutes as appropriate to the link in question.

5.2.1 Long Run Throughput

Long run throughput, Θ **bits/sec**, of a communications system is defined as the average number of information bits that will be transmitted over the channel per unit time. An expression for Θ can be developed as follows:

$$\Theta = \frac{E\{N_b(t)\}}{t} \qquad \{5.1\}$$

where $N_b(t)$ is the number of information bits transmitted over the channel in time t and $E[x]$ is the mathematical expectation function.

The expected number of bits that can be transmitted over the channel in a given period of time will be the product of the expected number of meteors in that time period and the expected number of bits that can be transmitted on each meteor. This can be expressed as follows:

$$\mathbf{E[N_b(t)] = E[m(t)]\ E[N_{bm}]} \qquad \{5.2\}$$

or as:

$$\mathbf{E[N_b(t)] = \mu\ t\ b \sum_{k=1} k\ Q_k} \qquad \{5.3\}$$

where:

b	the number of information bits in a transmit segment
μ	the meteor rate per unit time
t	time
k	the number of transmit segments
Q_k	the probability that **k** segments can be transmitted on the meteor

therefore the long run or average throughput for the meteor channel is:

$$\Theta = \mathbf{b}\ \mu \sum_{k=1} \mathbf{k\ Q_k} \qquad \{5.4\}$$

Q_k is defined as the probability that **k** segments of information can be transferred successfully on a meteor. This value is required to determine the average number (statistical mean or expected value) of segments that can be transmitted per meteor on a given link.

An expression for calculating the Q_k, the probabilities that **k** segments can be transmitted on a meteor, has been developed by Miller and Milstein {21}. That development is repeated here in an abbreviated form as it presents insight into the operation of a model of the meteor burst channel.

The probability of **k** segments being transmitted successfully on a given meteor will be a function of the length of time available for communication on the meteor and the probability that each segment k that is transmitted is received correctly. The probability that each transmitted segment k is received correctly is a function of the probability that each bit in the segment is received correctly which is in turn a function of the modulation format, the transmit bit rate and the signal to noise ratio at the receiver. Expressions for the probability of a bit error occurring in a transmit block are developed in following section.

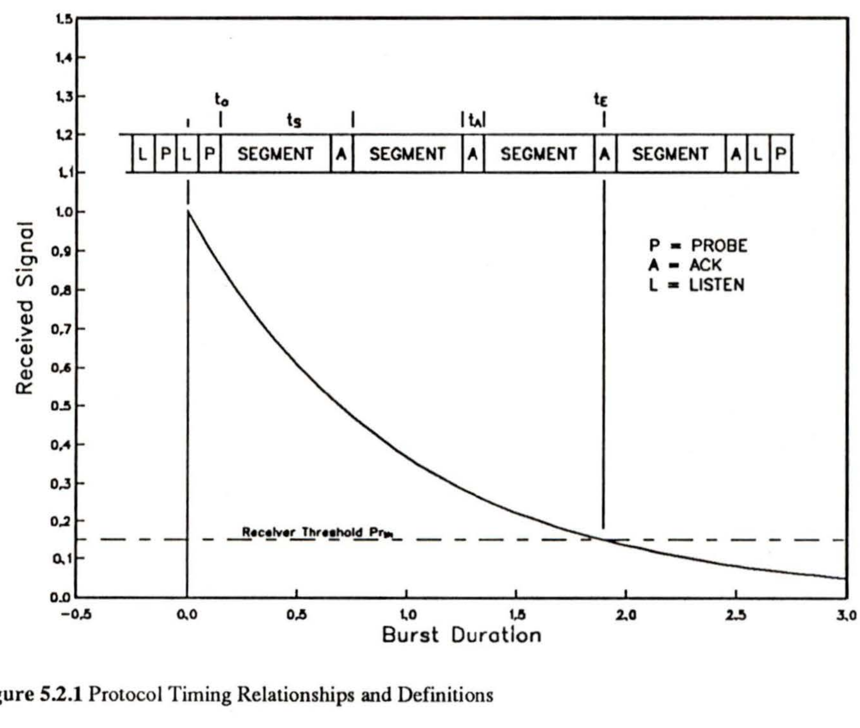

Figure 5.2.1 Protocol Timing Relationships and Definitions

To start the development we first define some relationships between the length of the transmit segment, the burst duration and the time requirements of the communications protocol. These timing relationships and definitions are illustrated in Figure 5.2.1.

As shown in Figure 5.2.1 the meteor burst is defined to start at time $t = 0$ and to end at time $t = t_E$ which is the point at which the signal strength drops below the threshold value P_{Rth}. The time t_0 is equivalent to the time lag between the formation of the meteor trail and the time the transmission of the first information segment commences. The time required to complete the transmission of a segment is defined as t_S and the time required to acknowledge it is t_A.

The maximum number of information segments that can be transmitted on a burst, assuming successful transmissions will only occur when the signal is above the threshold, is represented by the parameter N_s which is defined as follows:

$$N_s = \left\lfloor \frac{t_E - t_o}{t_s} \right\rfloor \qquad \{5.5\}$$

where $\lfloor t \rfloor$ represents the greatest integer $\leq t$.

To develop an expression for N_s the form $N_s(x)$ will be used where $x = t_E - t_o$. $N_s(x)$ is thus N_s conditioned on x where x represents the burst duration of a given meteor.

In their development of these relationships, Miller and Milstein have included the value t_a, the time required for the protocol to acknowledge the received segment, in the calculation of N_s and then drop it in their final segment transfer. It is dropped on the assumption that the last acknowledgement will be received error free as it is a much shorter block than the segment and will therefore have a lower probability of error. In the author's experience this is not a valid assumption. The reason is that this acknowledgement will be transmitted on the tail end of the burst where the signal level is decaying rapidly and the highest probability of a bit error occurring exists. Dropping this value also results in an unbalanced protocol. With it included the protocol will be balanced for both master to remote and remote to master information transfers where a single probing master station is used.

We next define the parameter $P_k(x)$ which is defined as the probability the k^{th} segment is successfully transmitted given **x**. This parameter is simply the probability that all the bits in a transmitted segment will be received correctly conditioned to represent the k^{th} segment in the transmit data stream given a burst duration **x**.

Using $P_k(x)$ we can define $Q_0(x)$, the probability that zero segments will be transmitted correctly on a burst of duration **x** as:

$$Q_o(x) = \prod_{k=1}^{N_S(x)} (1 - P_k(x)) \qquad \{5.6\}$$

Miller and Milstein have shown that the $Q_k(x)$ can then be determined using the relationship:

$$Q_k(x) = Q_o(x)\ S_k, N_s(x) \qquad \{5.7\}$$

where

$$\begin{aligned} S_k,N_s(x) &= S_k,N_{s-1}(x) + S_{k-1},N_{s-1}(x)\ \{S_1,N_s(x) - S_1,N_{s-1}(x)\} && \text{for } k \leq N \\ &= 0 && \text{for } k > N_s \quad \{5.8\} \end{aligned}$$

This is a recursive relationship with

$$S_1,N_s(x) = \sum_{k=1}^{N_S} \frac{P_k(x)}{1 - P_k(x)} \qquad \{5.9\}$$

To determine Q_k the probability that k segments can be transmitted on any burst, the mean of the $Q_k(x)$ has to be found using the distribution of the **x**. This distribution will be the burst duration density distribution developed in section 2.4 corrected for the channel acquisition time t_0. To do so $Q_k(x)$ is multiplied by the density distribution function of **x** and then integrated using the following relationship:

$$Q_k = \int \frac{Q_k(x)}{2\tau} \exp\left[\frac{-(x + t_o)}{2\tau}\right] dx \qquad \{5.10\}$$

where $Q_k(x)$ is Q_k conditioned on **x** and the remainder of the right hand side is the density function of **x** for a Stop and Wait ARQ protocol. $Q_k(x)$ is the function that brings the variable signal levels and thus the variable probability of bit error into the calculation of the throughput.

Miller and Milstein have used this relationship to model the operational characteristics of a meteor burst communication system. Where appropriate their results will be referred to in the following sections.

5.2.2 Waiting Time

The waiting time is defined as the elapsed time between a message becoming available for transmission over the link and its successful reception at its destination. Waiting time will normally be expressed in either seconds or minutes as appropriate to the link in question.

For long messages that must be broken into segments and transferred over a large number of meteors, a valid approximation of the waiting time is obtained by dividing the message length by the long run throughput value.

For messages equal to the mean burst duration in length, the expected waiting time will be the inverse of the meteor arrival rate.

Many authors have developed complex expressions for waiting time that take into account such factors as reducing the block length to the minimum required, broadcast protocols, etc. For the purposes of this thesis the above definitions of waiting time are adequate. The interested reader is referred to Oetting[23] or Miller and Milstein[16] for a more in depth analysis of waiting time.

5.3 Expected Error Patterns

To create a valid model of a meteor burst channel, expressions for the probability of one or more bit errors occurring in a received segment have to be developed.

The probability of a bit being in error, P_e is a function of the modulation rate of the transmitted signal and the signal to noise ratio at the input to the receiver. These two factors are combined into a single ratio referred to as

$$\frac{E_b}{N_o} \tag{5.11}$$

where:

E_b = bit energy (integral of the signal magnitude over the bit period)
N_o = noise spectral density of additive white Gaussian noise

As it is a ratio of powers it is usually converted to decibels (dB) for discussion. P_e is thus a function of the $\frac{E_b}{N_o}$ at the input to the modulator. This statement assumes the operation of the demodulator circuitry is perfect, i.e. it does not introduce error mechanisms of its own to the demodulation process. The assumption of an ideal receiver and demodulator implementation is used through the remainder of this thesis. An actual system would be expected to experience a 1 - 2 dB degradation relative to the ideal.

Different modulation techniques result in different probabilities of error for a given $\frac{E_b}{N_o}$. As most meteor burst communication systems in operation today utilize either Binary Phase Shift Keying (BPSK) or Quadrature Phase Shift Keying (QPSK) modulation, the use of BPSK modulation will be assumed for the remainder of this thesis.

The probability of a bit being in error for BPSK modulation is:

$$P_e = \frac{1}{2}\,\mathrm{erfc}\left(\sqrt{\frac{E_b}{N_o}}\right) \qquad \{5.12\}$$

Block protocols are used for the channel control protocols and error detection and correction protocols in a meteor burst communication system. We are therefore interested in the probability of t or more bits in a block being in error, where $t = 0, 1, 2, \ldots, n$ or conversely the probability that all the bits in the block are correct.

The expression for the probability of t or more errors in a block given a constant $\frac{E_b}{N_o}$ for the block is well known. The goal here is to develop an expression for the probability of t or more errors in a block transmitted on a meteor burst channel where $\frac{E_b}{N_o}$ is not a constant. To do so we will start by developing the expression for t or more errors on a block from first principles and diverging it from the classic approach at the appropriate point.

Consider a block of n bits b_i, $i = n-1, n-2, \ldots, 0$. The probability that bit b_j is in error is:

$$P_e = \frac{1}{2}\,\mathrm{erfc}\left(\sqrt{\frac{E_{bj}}{N_o}}\right) \qquad \{5.13\}$$

where E_{bj} is the bit energy of b_j. The probability that b_j is correct is therefore $1 - P_j$ and the probability that all the bits in the block are correct is:

$$P_{e0} = \prod_{j=0}^{n-1} 1 - P_j \qquad \{5.14\}$$

The probability that b_j is in error and the remaining bits correct is:

$$P_{ej} = p_j \prod_{\substack{i=0 \\ i \neq j}}^{n-1} 1 - P_i \qquad \{5.15\}$$

It follows that the expression for the probability that any single bit in the block is in error is:

$$P_e(1) = \sum_{j=0}^{n-1} p_j \prod_{\substack{i=0 \\ i \neq j}}^{n-1} 1 - P_i \qquad \{5.16\}$$

and that any two bits are in error is:

$$P_e(2) = \sum_{k=0}^{n-2} p_k \sum_{j=k+1}^{n-1} p_j \prod_{\substack{i=0 \\ i \neq j \\ i \neq k}}^{n-1} 1 - P_i \qquad \{5.17\}$$

In general the probability of t errors occurring in a block of length n is:

$$P_e(t) = \sum_{k_1=0}^{n-t} p_{k_1} \sum_{k_2=k_1+1}^{n-t+1} p_{k_2} \cdots \sum_{k_t=k_{t-1}+1}^{n-1} p_{k_t} \prod_{\substack{i=0 \\ i \neq k_1,k_2,\ldots,k_t}}^{n-1} 1 - P_i \qquad \{5.18\}$$

The probability of receiving the block with the number of erroneous bits $\leq t$ is therefore:

$$P_{blk}(t) = P_e(0) + P_e(1) + P_e(2) + \cdots + P_e(t) \qquad \{5.19\}$$

and the probability of receiving the block with the number of erroneous bits > t is:

$$P_{blk}(>t) = 1 - P_{blk}(t) \qquad \{5.20\}$$

For the conventional (flat amplitude) binary symmetric channel the bit error probabilities $P_k, P_j, P_l, \ldots, P_n = P$ are all equal thus {5.19} would become (Bhargava, et al [3]):

$$P_e(t \leq 2) = \sum_{i=0}^{n} \binom{n}{i} p^i (1 - p)^{n-i} \qquad n = 2 \qquad \{5.21\}$$

For the meteor burst channel the individual bit error probabilities have to be assessed independently therefore the general form of the equation is not valid.

To illustrate the meaning of these relationships, the individual probabilities of bit error that would be expected at the receiver of an operational meteor burst communication link have been calculated and are presented graphically in Figure 5.3.1. The calculations were performed assuming a 1000 bit block was being received at 4kbps using BPSK modulation over meteors with a burst time constant of 0.25 Secs.

The vertical axis is the probability that the individual bit is in error, the horizontal axis is the bit number. The curves represent the bit error probability for each received bit in the block. The bit error probabilities were calculated for three meteors with starting signal to noise ratios of 12, 9, and 6 dB respectively. The bit error probabilities for a block transmitted over a channel with constant received amplitude equivalent to the initial meteor signal amplitude would be a horizontal line that intersected the vertical axis at the same location as bit 0 in the block.

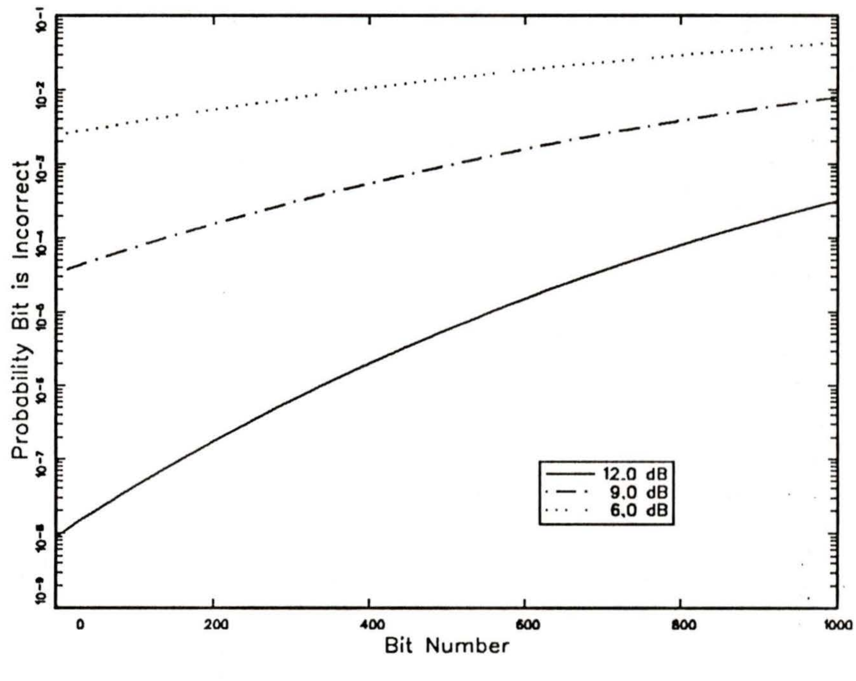

Figure 5.3.1 Plot of the bit error probabilities for a block of 1000 bits received over three meteors with different initial amplitudes.

From the curves presented in the plot we should expect the probability of bit error in a received block to vary at least one order of magnitude and probably several orders of magnitude from the start of the block to the end.

5.4 Modeling the Meteor Burst Channel

The goal of this thesis is to determine the effect variations in the communication channel control protocol and error control protocol will have on the performance of a meteor burst communication system. These effects are difficult to determine analytically due primarily to the time varying and sporadic nature of the received signal. Instead of attempting to construct an analytical model, a simulation model of the meteor burst communication channel has been constructed.

The meteor burst communication model constructed is based on a time series of meteor trail formations as would occur on an operational link. The meteor trails are simulated as sequential blocks of signal presence. The amplitude and duration characteristics of these blocks of signal simulate the characteristics that would be observed on actual meteor trail reflections. They are therefore based on the decaying signal amplitude characteristics and probability distributions presented in Chapter 2.0. The time series is constructed for the model using a random number generation technique.

The basic model makes the following assumptions which are derived from the design specifications of a commercial meteor burst communications system.

- 0.25 second burst time constant
- 4 kbps, BPSK modulation
- half-duplex/simplex operation
- 10 millisecond link turnaround time between transmissions
- uni-directional information transfer from the non-probing station to the probing station
- Stop and Wait ARQ error control protocol driven by a 16 bit CRCC

The probability of errors occurring in the protocol overhead transmissions such as the ACK/NACK replies sent back to the transmitter are included in the calculation of the probability of a successful information block transfer.

In the following sections, the channel control protocol and error control protocols are applied to this basic model to determine the effect variations in the protocol parameters would have on system performance. In this context performance is considered to be the long run information throughput. Waiting times are not considered and in all cases protocol overhead is removed from the information throughput figures.

5.5 Modeling the Channel Control Protocol

5.5.1 Throughput as a Function of Block Length

The throughput of a meteor burst communication link will vary as a function of the ratio of the information block length to the mean burst duration (assuming the block transfer overhead is constant).

To determine the effect the transmit block length has on the throughput the model was run sequentially for different information block lengths. The same signal series was used for each block length to remove any simulation related differences in the computed throughputs.

A plot of the normalized throughput as a function of the ratio of information block length to mean burst duration is presented in Figure 5.5.1. The data in this and subsequent plots is presented as normalized values and ratios to generalize the results and to remove the focus from the specific values obtained.

From this plot it can be seen that system throughput will be sensitive to the ratio of the information block length to the mean burst duration observed on the link. The peak throughput will occur at a block length to burst duration ratio of 0.15 to 0.2. That is, the length of the transmit block in time should be equal to 0.175 of the mean burst duration observed on the channel for maximum throughput to be obtained.

From the plot it is also evident that the peak is fairly sharp. For example, the realized throughput will drop to half of its peak value if the block to burst ratio is less than 0.05 or greater than 0.5. If the block length to burst duration ratio exceeds 0.7, the throughput will drop essentially to zero.

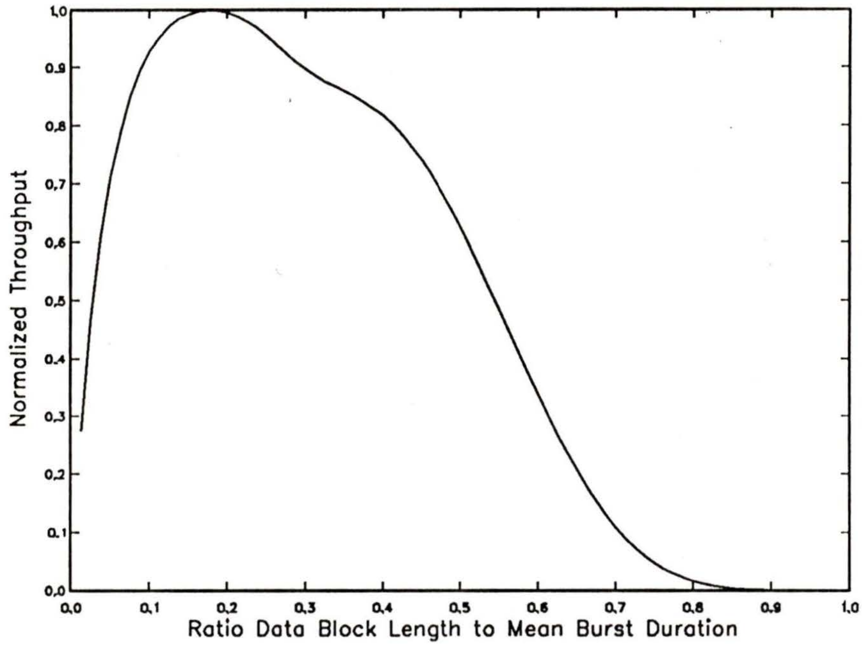

Figure 5.5.1 Plot of the Normalized Throughput as a Function of the Ratio of Block Length to Mean Burst Duration.

The selection of the transmit block length for an operational system is critical for acceptable performance to be realized. The statistical distribution of the mean burst duration, its diurnal variation and its variation as a function of distance between the communicating stations are all factors that must be taken into consideration when choosing a value for the block length. For example, a large network operating over a wide geographical area will have to ensure that the information block length is short enough that operation between short range systems is not severely reduced. A network with stations located throughout the 2000 Km operational range of the technology could experience a variation in mean burst duration of up to 5:1. Significant improvements in throughput could be obtained on such a network if the channel control protocol was capable of varying the information block length in response to the observed mean burst duration.

5.5.2 Signal Acquisition Threshold

The distribution of the burst durations observed on an operational link is heavily weighted towards the shorter durations. Therefore, a large percentage of the probes received at a remote station are expected to be reflected by meteor trails that are too short (i.e. are of too low an initial amplitude) for an information block transfer to be completed successfully. In many operational situations it is important that the stations detecting a probe restrict their responses to those occasions when the probability of a successful transfer is high. For example, in networks with a large number of stations spread over a wide geographical area the probability of signal collisions occurring at the master station becomes fairly high (Bartholome [2]). By restricting the transmissions at the remote stations the probability of collision is reduced. A second consideration is the reduction of the power consumption of the remote station. For example, a solar powered remote data acquisition station having limited battery capacity will want to conserve power.

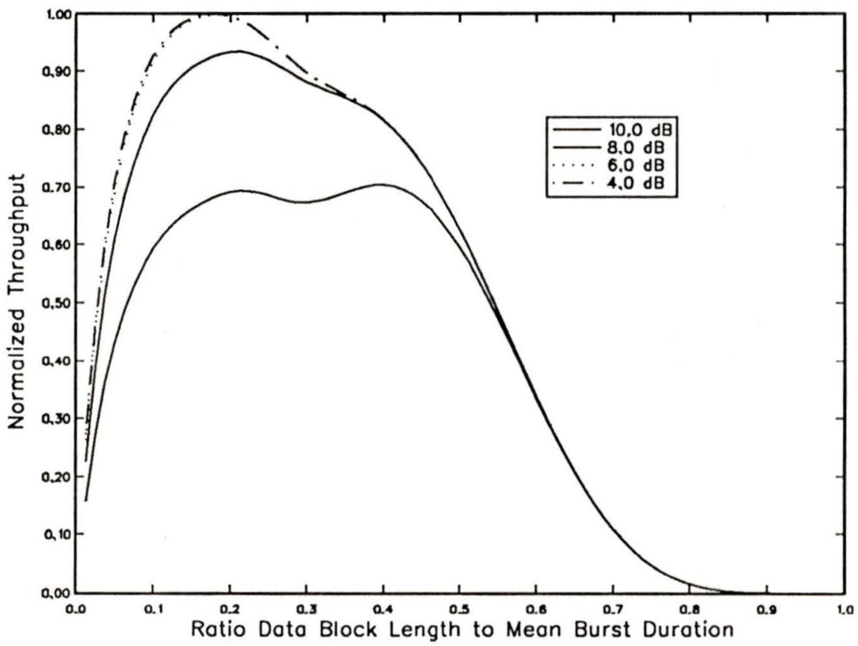

Figure 5.5.2(a) Plot of the Normalized Throughput as a Function of the Ratio of Information Block Length to Mean Burst Duration for Different Initial Signal Amplitudes.

To restrict the transmissions in an operational system, the remote station measures the initial amplitude of the received signal each time a new meteor is detected and holds off the transmission if that amplitude is below a pre-defined threshold. Once the initial amplitude of the meteor has exceeded the threshold, the transfer of information continues for as long as the protocol is able to sustain it, even when the amplitude drops below the threshold.

To determine the sensitivity of the system throughput to the threshold level, the block length model was re-run for different threshold levels. The results of that simulation are presented in Figure 5.5.2. The signal amplitudes indicated in these plots are the initial amplitudes the received signal must exceed for a transmission to be considered to have taken place.

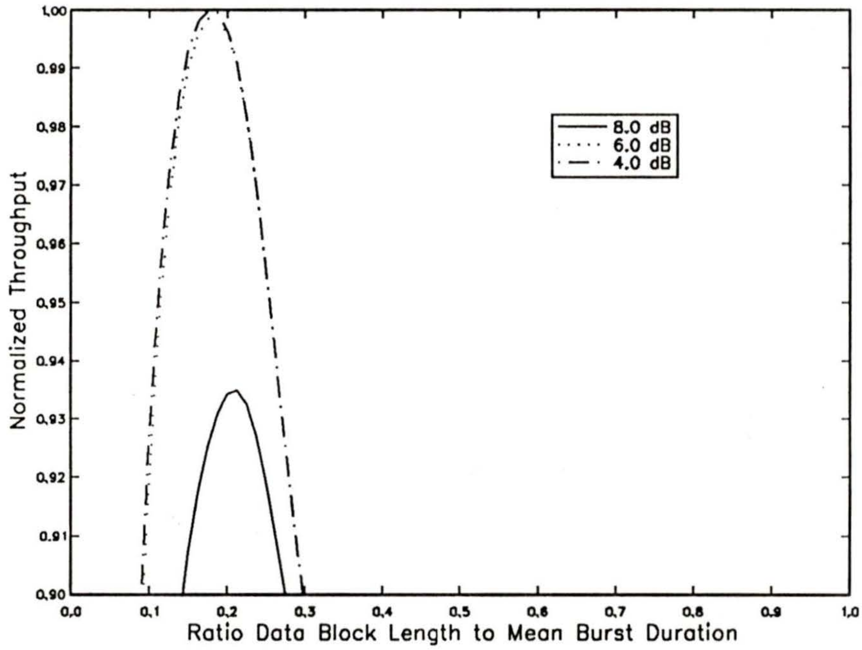

Figure 5.5.2(b) An expansion of the top portion of the plot presented in Figure 5.5.2(a).

From these plots it is evident that an optimum level for the transmission hold-off threshold exists and that it occurs between 6 and 8 dB. To express it a different way, a unit receiving a probe signal should only transmit a response to that probe if the initial amplitude of the received signal is at least 6 dB above the quiescent noise level. In this application, the quiescent noise level is considered to be the rms amplitude of the noise as measured in the receivers bandwidth immediately prior to the signals reception.

The 6 - 8 dB level obtained here is slightly lower than the 9 dB level obtained by Miller and Milstein[16]. The difference is most likely due to their model suspending communications when the received signal dropped back below the threshold where as this model continues to calculate throughput for as long as the protocol can sustain it.

5.5.3 Effect of Modulation Rate on Throughput

Increasing modulation rates on a conventional communication channel does not necessarily result in an increase in information throughput. For example, if the bit rate on a communications link is doubled, a 3 dB reduction in $\frac{E_b}{N_o}$ at the de-modulator will occur. This will result in a higher probability of bit error which will in turn result in a corresponding reduction in throughput. The magnitude and significance of this reduction will depend on the $\frac{E_b}{N_o}$ levels present in the receiver.

As indicated in Chapter 2.0, the signal reflected from the meteor trail is specular. Therefore it should be possible to select the operational bandwidth of the transmitter as required. For the BPSK modulation format considered throughout this thesis, increasing the baseband data rate will result in a 1:1 increase in the bandwidth of the transmitted signal if the same modulation format is used. To determine the effect an increase in the modulation rate will have on the throughput of a meteor burst communications link, the throughput model was run for a series of modulation rates. The results of these simulations are presented in Figure 5.5.3.

From the information presented in the plot it can be seen that an increase in the modulation rate results in an increase in the throughput and that this increase in throughput has a 1:1 correspondence with the modulation rate at the optimum block to burst ratio. As the block length increases with respect to the burst time constant the magnitude of the increase in throughput with modulation rate becomes less pronounced and for a small portion of the simulated range actually reverses itself.

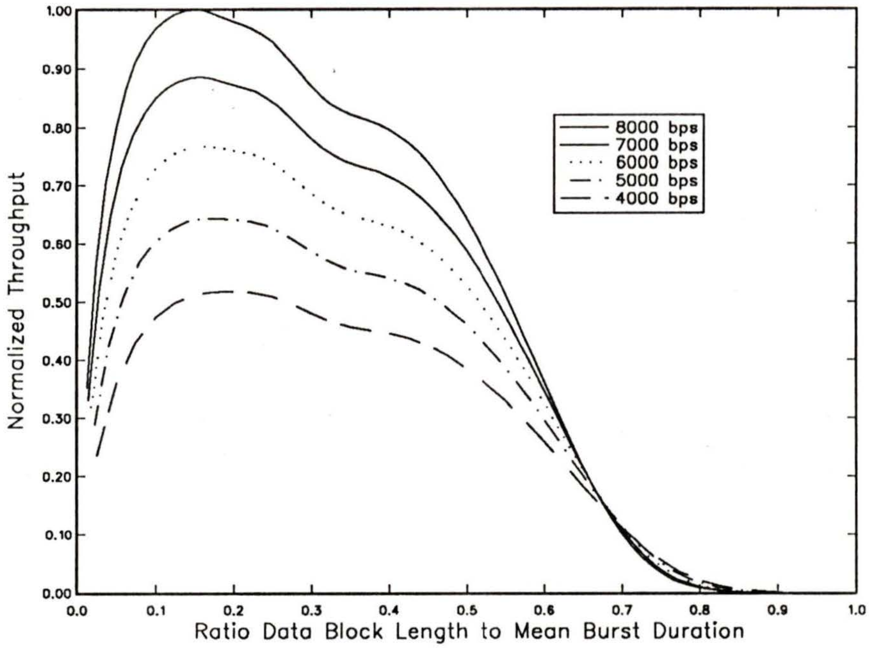

Figure 5.5.3 Normalized throughput vs. Block length of a Stop and Wait ARQ protocol at different modulation rates

The conclusion here is that as long as the amplitude of the received signal exceeds the operational threshold of the receiver/demodulator, the throughput of the system will be a directly dependent on the baseband data rate and that once the signal drops below that threshold, very little information is going to get through regardless of the modulation rate, or more accurately, the $\frac{E_b}{N_o}$ of the received signal relative to the $\frac{E_b}{N_o}$ at the threshold level.

5.6 Modeling the Error Control Protocols

When modeling the performance of a meteor communications system, the most common practice to date has been to consider the signal to noise ratio constant over the entire received block. In these models the probability of bit error occurring at the end of the block was used as the probability of bit error over the entire block. The resulting conservative estimate was considered valid for a system using a simple Stop and Wait ARQ protocol for error control and it permitted the use of conventional analysis techniques.

The first published account of this practice creating unexpected results was discussed by Milstein et. al.[22]. They used this approach to design an error control protocol for an operational link that utilized a Reed-Solomon Forward Error Correction code. When the performance of the link was evaluated the expected improvement in performance was not realized.

The most interesting point regarding this application of an error control code to the link is the fact that even though the throughput did not increase when the code was applied, it didn't decrease significantly either. This means the link that was previously transferring **k** bits of information successfully was now transferring **k** bits of information plus the **n - k** bits of parity associated with the error control code. This fact leads to the expectation that if a mechanism could be found that would apply the error control code to the channel only when it was needed, an improvement in performance could be realized.

A number of potential techniques for doing this are available. One technique that has been discussed in the literature (Abel[1], Davidovici and Kanterakis[7]) is to vary the modulation rate at the transmitter such that a constant $\frac{E_b}{N_o}$ is realized at the receiver. This results in a constant probability of bit error over the full extent of the received block thus permitting the use of conventional error control code analysis and application techniques.

A second technique is to vary the coding rate in response to the signal to noise ratio of the received signal. A third technique is to use Hybrid II ARQ/FEC techniques. Neither technique has received much attention in the literature with respect to meteor burst communication systems. This thesis deals with the application of Hybrid II techniques to the channel. Coincident with the completion of this thesis, a paper was published (Pursley and Sandberg [24]) that deals with the application of a variable rate code to the channel.

In the following sections Hybrid I and II ARQ/FEC protocols are modeled to determine the effect their use would have on the throughput of an operational meteor burst communication system.

5.6.1 ARQ Protocols on the Meteor Burst Channel

The basic protocol assumed in the meteor burst channel model is a Stop and Wait ARQ protocol using a 16 bit CRC for error checking. This protocol was used throughout the previous section. In this section Forward Error Correction protocols are combined with this base protocol thus the resulting protocols are Hybrid ARQ/FEC protocols. In each case the ARQ aspect of the Hybrid protocol is a Stop and Wait implementation.

5.6.2 Hybrid I ARQ/FEC Protocols

Hybrid I ARQ/FEC protocols were described in the previous chapter. The throughput of a meteor burst communications system using Hybrid I ARQ/FEC error control protocols has been simulated and the results presented in this section.

Binary BCH and Reed Solomon Forward Error Correcting codes were used at rates of 7/8, 3/4, 5/8, and 1/2. As in the previous section, the simulations were run for different block lengths. For each block length the code that produced the greatest distance at the desired coding rate for that block length was chosen. In some cases this resulted in the use of shortened codes.

An equal level of both error correction and erasure correction was assumed for each of the codes. That is, the assumption was made that the decoder was capable of correcting $\mathbf{t} = \frac{\mathbf{d}}{3}$ errors and $s = \frac{\mathbf{d}}{3}$ erasures, where $\mathbf{d} = 2t + s$, and that the demodulator was capable of providing the necessary erasure information reliably. Errors were corrected on the basis of the bits (or where appropriate - symbols) that were calculated to be most likely in error. For the exponentially decreasing meteor burst signal these symbols would in fact be the final s symbols in the information block. In an operational system this would not necessarily be the case.

The calculations for each block length and coding rate were performed assuming both a fixed modulation rate and a fixed information rate. For the fixed information rate, the modulation rate was increased relative to the non-coded rate as a function of the level of redundancy required by the error correcting code. Therefore the information rate, i.e. the number of information bits that could be transmitted per unit channel time, remained constant.

The results for binary BCH codes with a fixed modulation rate are presented in Figure 5.6.1 (a) and for a fixed information rate in Figure 5.6.1 (b). The comparable results for a Reed-Solomon code are presented in Figures 5.6.2 (a) and (b). The simulations were truncated at the block length that was considered to be the maximum practical for the code concerned. The maximum length BCH code used was a (1000,500) code, and the maximum RS code used was a (250,125) defined on $GF(2^8)$.

From these plots we can see that using a Hybrid I ARQ/FEC protocol at a fixed modulation rate will result in a reduction in the system throughput. This reduction is in 1:1 correspondence with the coding rate for the BCH codes and a little less so for the Reed-Solomon codes.

If the modulation rate is increased such that the information rate remains constant, the throughput using the BCH binary code remains relatively constant as the coding rate is increased. Increasing the modulation rate for the Reed-Solomon codes results in some improvement in the long run throughput.

This slightly better performance of the Reed-Solomon Codes over the BCH codes is probably due to the better distance properties of Reed-Solomon codes (Michelson and Levesque [20]).

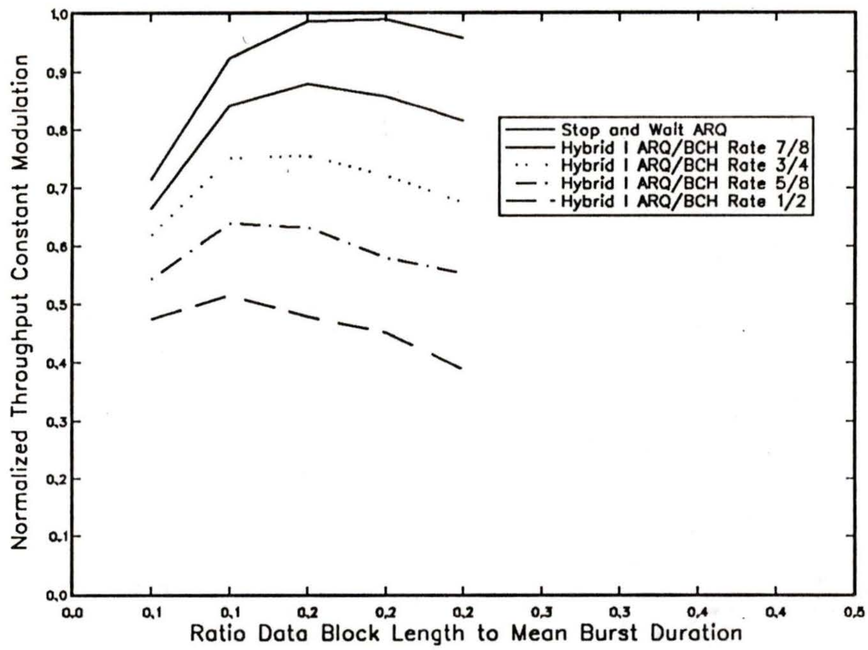

Figure 5.6.1 (a) Normalized throughput vs. block length for a Hybrid I ARQ/FEC protocol using binary BCH Codes at a constant modulation rate.

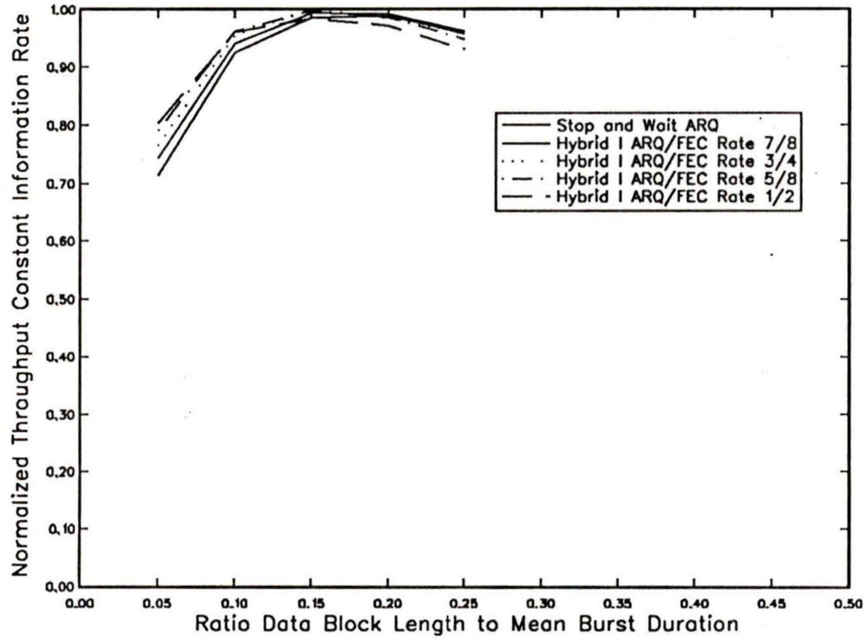

Figure 5.6.1 (b) Normalized throughput vs. block length for a Hybrid I ARQ/FEC protocol using binary BCH codes at a constant information rate.

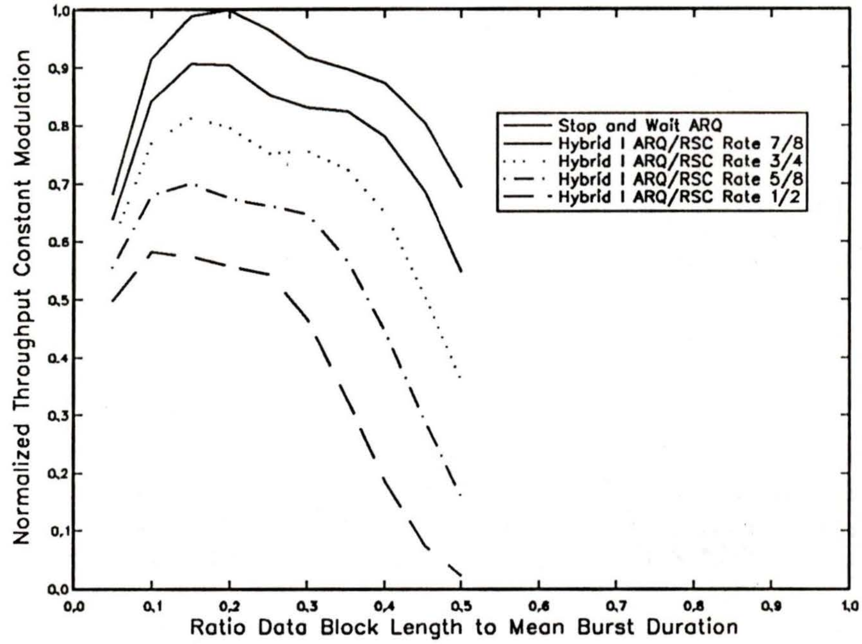

Figure 5.6.2 (a) Normalized throughput vs. block length for a Hybrid I ARQ/FEC protocol using Reed-Solomon Code at a constant modulation rate.

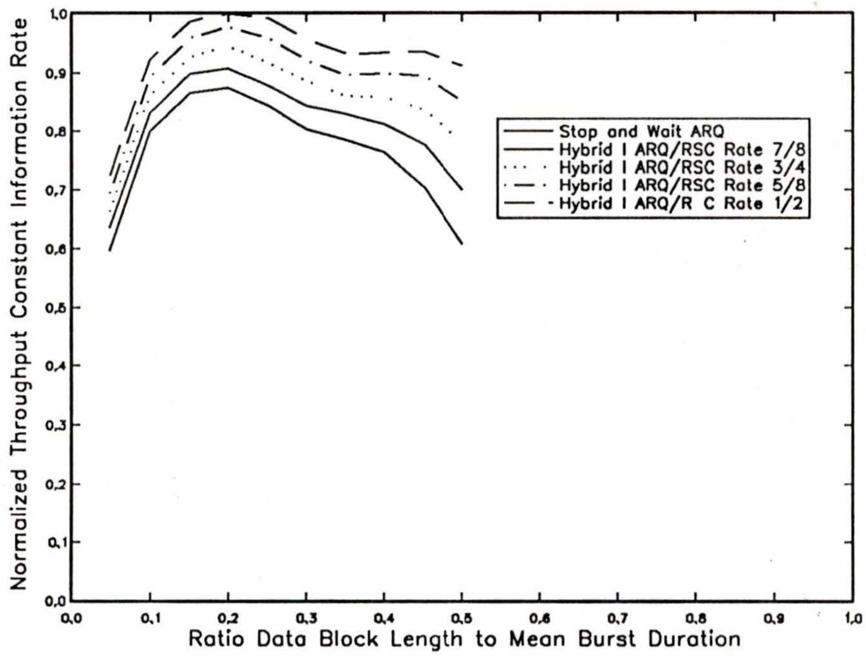

Figure 5.6.2 (b) Normalized throughput vs. block length for a Hybrid I ARQ/FEC protocol using a Reed-Solomon code at a constant information rate.

5.6.3 Hybrid II ARQ/FEC Protocols

A Hybrid II ARQ/FEC protocol will only transmit parity symbols in the communications channel when they are needed. These protocols therefore have the potential of overcoming the problems encountered with the Hybrid I ARQ/FEC protocol.

To determine if this was the case, the throughput of a meteor burst communication system was modeled using a Hybrid II ARQ/FEC protocol. The results of that simulation are presented in Figure 5.6.3. The simulated protocol consisted of the base Stop and Wait ARQ protocol and used a Reed-Solomon Forward Error Control to provide additional error detection and correction.

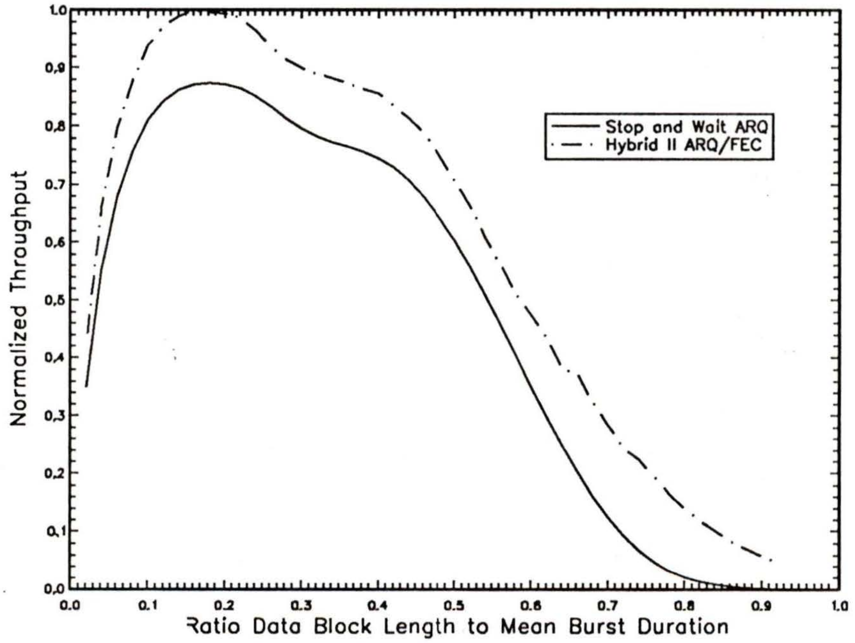

Figure 5.6.3 Normalized throughput vs. block length for a Hybrid II ARQ/FEC protocol.

The Reed Solomon error control code was assumed to be correcting an equal number of errors and erasures each time a parity block was transmitted. That is the assumption was made that the receiver was capable of correcting $\mathbf{t} = \frac{\mathbf{d}}{3}$ errors and $\mathbf{s} = \frac{\mathbf{d}}{3}$ erasures, where $\mathbf{d} = \mathbf{2t} + \mathbf{s}$, and that the demodulator could provide the erasure information reliably. The use of code inversion was also assumed as the model does take into account the probability of block error on the return channel.

From the plot we can see that the use of a Hybrid II ARQ/FEC protocol would result in a 10% - 15% increase in throughput for the system. This is a significant improvement over the results obtained for the Hybrid I ARQ/FEC protocol.

This improvement can be explained by considering the protocols ability to combine two sequential, but erroneous, block transfers into a good transfer. For example, consider two meteors occurring in succession, the second of which has too short a duration to successfully transfer a block completely. At the termination of the first meteor, the receiver will be left with some portion of a transmitted block that contains errors. The transmitter will be aware of the fact that the receiver has not acknowledged receipt of this block and therefore will transmit a parity block to the receiver the next time it hears from it. When the second, short duration meteor occurs, the receiver only needs to receive a portion of that parity block to reconstruct the original transmitted block. The system will therefore have successfully transferred a block of information in a situation in which it could not have previously done so.

5.7 Conclusions

5.7.1 Channel Protocol Effects

The channel control protocol modeling indicated that the transmit block length to mean burst duration ratio is an important factor in the performance of a meteor burst communications system. The statistical distribution of the mean burst duration, its diurnal variation and its variation as a function of distance between the communicating stations are all factors that must be taken into consideration when choosing a value for the block length. Optimum performance can only be achieved over a small range of ratios.

This information leads to the conclusion that for a network operating over a wide geographical area, a channel control protocol capable of optimizing the transmit block length / observed mean burst duration ratio on a link by link basis is desirable.

The simulation of the operational threshold effects and baseband data modulation rate effects indicate that a narrow region exists in the $\frac{E_b}{N_o}$ curve of the received signal above which the reception of the transmitted information is reliable and below which it is not. This finding is in accordance with that presented by Milstein, et al [22].

The establishment and setting of this operational threshold is a critical parameter in the design of an operational meteor burst network. If the threshold is set above this level, the throughput will be adversely affected. If it is set below this level, no significant increase in throughput will result but the number of un-successful transmissions made by the remote station will increase as will the probability of collision on the network.

The simulation of the effects a variation in the baseband data modulation rate would have on the system throughput indicates that the throughput is a linear function of the modulation rate when the system is operating within the vicinity of its optimum block length to mean burst duration ratio. If operation within this region can be established, it is worth the designers effort to increase the modulation bandwidth if that option is open.

5.7.2 Hybrid I ARQ/FEC

The simulation results indicate that the use of Hybrid I ARQ/FEC Error Control protocols will result in a reduction in throughput in the presence of Additive White Gaussian Noise (AWGN). This reduction is directly proportional to the coding rate used.

This result reinforces that obtained when higher data modulation rates and operational thresholds were simulated. The narrow "boundary" range in the received $\frac{E_b}{N_o}$ separating good performance from no performance and the 1:1 increase in throughput (in the presence of AWGN) with respect to the data modulation rate corresponds to a similar 1:1 reduction in throughput with respect to code rate.These observations are in accordance with those presented by Milstein, et al.[22].

This does not however lead to the conclusion that Hybrid I ARQ/FEC protocols do not have potential benefits when applied to the meteor burst channel. The signal present at the input of a meteor burst receiver contains noise from both man made sources and natural sources. The man made noise very often contains large quantities of periodic, impulse components such as would be created by the commutator brushes in rotating electric machinery or vehicle engines.

Periodic impulse noise will quickly reduce the throughput of an ARQ protocol to zero even if the rms noise level is relatively low. For example, noise spikes created in rotating machinery drawing power from a 60 Hz source will exhibit a period between pulses of 16 milliseconds. At a modulation symbol rate of 4000 bits per second, any transmit block longer than 64 bits will probably contain one or more erroneous bits. If type of noise is present at the receiver, a Stop and Wait ARQ protocol would have to request a repeat of this block, which would in turn probably contain errors resulting in a throughput of zero.

Hybrid I ARQ/FEC protocols capable of correcting burst errors resulting from non AWGN noise would improve the robustness and functionality of a meteor burst communications protocol even though a reduction in the maximum obtainable throughput relative to the ideal was realized. In this context, robustness is considered to be a protocols ability to operate reliably over a wide range of external interference conditions. The system designer would have to be careful to select the highest rate code capable of providing the robustness required so as to not unduly reduce the throughput of the system.

5.7.3 Hybrid II ARQ/FEC

The throughput simulation for the system using a Hybrid II ARQ/FEC protocol indicates that about a 10% - 15% improvement in throughput across the entire performance envelope would be realized. This finding is significant as it indicates that an improvement in throughput can be achieved purely on the basis of an error control protocol and that the robustness of a Hybrid ARQ/FEC protocol can be obtained without incurring the reduction in throughput that would occur with Hybrid I ARQ/FEC protocols.

6.0
SUMMARY

This thesis has presented a review of meteor burst communication techniques and an analysis of the effect variations in the channel access and error control protocols would have on the performance of an operational system. New expressions were developed for the probability of bit error on the meteor burst channel.

A model of the meteor burst communication channel, based on the information presented, has been constructed. This model was used to simulate the effects variations in the channel control protocols and error control protocols would have on the performance of a meteor burst communications system. Particular attention was paid to the use of Hybrid I and Hybrid II ARQ/FEC protocols.

With respect to the channel control protocols and the Hybrid I ARQ/FEC error control protocols, these simulations confirmed results previously published by other authors using different models and also showed good correspondence with previously published experimental results.

The simulations of the Hybrid II ARQ/FEC error control protocols indicated that improvements in both system throughput and robustness could be obtained by the use of a properly designed error control protocol. An analysis or simulation of the performance of Hybrid II ARQ/FEC protocols on the meteor burst channel has not been previously published.

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DESIGN CONSIDERATIONS OF ERROR CONTROL PROTOCOLS
FOR METEOR BURST COMMUNICATION SYSTEMS

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[redacted]

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