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A MODELING PERSPECTIVE FOR METEOR BURST COMMUNICATION

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ABSTRACT

This paper describes the design and development of a methodology to analyze Meteor Burst Communication (MBC) networks. A decision support system was developed that provides a simulation model for any single or multiple-link MBC network. This model runs on a microcomputer and consists of two distinct components. The first component uses engineering parameters to compute intermediate queueing characteristics used by a discrete event simulation component. The simulation component provides point estimates for throughput, message delay, and resource utilization in tabular and graphical form. The MBC process is shown to be a M/G/1 queue with server vacations. Analytical equations and empirical data were both used to validate the MBC performance model. The modeling perspective presented in this research represents a new and robust method for analyzing MBC networks. Adaptive message routing, flood routing, and priority message traffic are discussed. By separating the engineering parameters of the MBC network from the simulation code, portability, ease of use, and conceptual simplicity was achieved. This research demonstrates the successful marriage of complex communication system engineering with queueing theory and simulation models to produce a highly productive analysis tool.

1. INTRODUCTION

The earth is constantly bombarded by billions of meteors each day. Most of these meteors burn up when they enter the earth's atmosphere and create meteor trails. These trails usually disappear after a few seconds but last long enough to reflect radio waves. These radio waves are reflected 80 to 120 kilometers above the earth's surface at frequencies ranging from 30 to 120 MHz. Communication systems that use these trails are known as meteor burst networks.

MBC does, however, suffer two major drawbacks: low throughput and long message waiting time. In order for MBC to be utilized effectively, methods need to be developed to optimize performance. Simulation is a cost-effective technique which can be used to effectively evaluate MBC networks. Effects on throughput and message waiting time caused by changes in network topology, message transmission protocol, routing algorithms, and variations in network operating parameters can be readily studied with simulation models. Simulation models can be used to develop methods to improve network throughput and message waiting time necessary to make MBC a viable communication medium.

1.1 Problem

The problem addressed in this research was to develop a design tool that could be used to accept engineering design specifications for single or multiple-link MBC networks. The model was designed to run on personal computers by keeping the model conceptually and computationally simple without unnecessary loss of accuracy. This approach provides MBC network designers with a modeling tool which maximizes usefulness and flexibility.

This computer model consists of a Pascal front-end module, a SLAM II single-link module, and several SLAM II network model examples. The Pascal front-end module uses analytical equations for network specific engineering parameters to generate values for the SLAM II single-link module. The Pascal module generates values of meteor trail interarrival rate, meteor trail duration, and message duration required by the SLAM II single-link module. The SLAM II single-link module then provides values of average message buffer size, message buffer delay, message waiting time, message transmission time, the number of meteor trails required per message, and throughput.

1.2 Assumptions

The following general assumptions were made in this research project:

- fixed length messages,
- two message transmission protocols,
- constant transmitter bit rates,
- exponential meteor trail arrivals,
- exponential meteor trail durations,
- poisson message arrivals,
- static message routing,
- no message retransmissions,
- no message transmission errors,
- middle-latitude networks,
- normal environmental and propagational effects,
- half-duplex transmission links,
- no priority classes between messages, and
- underdense meteor trails (electron density $< 2 \times 10^{14}$ electrons/meter).

These assumptions, however, were not a limitation. They were selected to keep the models as simple and generic as possible. Current simulation technology allows the models to be more detailed and user specific.

2. METEOR TRAIL PHENOMENON

Sugar's (1964) work in the field of MBC forms the foundation for today's research. His paper, *Propagation Via Meteor Trails*, provides an excellent overview of meteor burst theory. He describes meteoric particles, meteor trail parameters, overdense and underdense meteor trails, and variations in meteor arrival rate. Morin (1985) describes ionospheric scattering effects on MBC in the report, *Meteor Burst Communications for Military Applications*.

2.1 Meteoric Particles

Meteors that are used for communication can be classified as either shower meteors or sporadic meteors. Shower meteors are groups of particles that move together at the same velocity and enter the atmosphere at the same time each year. Sporadic meteors, on the other hand, do not move together and appear randomly. The shower meteors are not as common as the sporadic meteors and, therefore, not as useful. The sporadic meteors make up the majority of the ionized trails used for meteor burst systems.

2.2 Meteor Trail Parameters

Meteor trails are formed when meteoric particles collide with air molecules in the atmosphere. These collisions produce heat, light, and ionization streams. The collision with air molecules causing ionization does not occur until about 120 km from Earth. Ionization is complete about 80 km from Earth at which point the meteors are completely vaporized. The lengths of the trails are a function of mass and the angle at which the meteors enter the atmosphere [Brown and Williams, 1978]. The time it takes for the meteor trail to dissipate is a function of meteor size and atmospheric wind [Manning, 1954]. Most of the trails that are detected are from small particles which cause trails that last only tenths of a second. Larger particles can cause trails that last for minutes or longer.

2.3 Meteor Arrival Rate Variations

The occurrence of sporadic meteors is determined by several factors. The variation in meteor arrival rate is influenced by diurnal, monthly, and geographic dependencies. Because of diurnal variation, the maximum meteor rate occurs around 0400 and a minimum rate occurs around 1800. The concentrations of meteor orbits around the Earth's ecliptic plane cause more sporadic meteors to occur in the summer than in the winter. Latitude also affects the number of sporadic meteors. Polar Cap Absorption (PCA) is the result of low-energy cosmic rays caused by solar flares. Because of PCA, the number of useful meteor trails is diminished. This phenomenon is most pronounced at latitudes greater than 64 degrees [Ost85].

3. METEOR BURST COMMUNICATION NETWORKS

The principle of MBC is not new. In fact, this form of communication has been studied for the last 30 to 40 years. MBC, however, has recently become popular because of its antijamming (AJ) features and its low probability of interception (LPI). The advances in microcomputer technology and inexpensive solid-state memories are also responsible for making MBC desirable [Oetting, 1979]. The microcomputer revolution has made it possible to provide the inexpensive transmitters necessary to use the short meteor trail lifetime for communication [Kokjer and Roberts, 1986]. MBC is simple to implement, inexpensive, and highly reliable. In addition, MBC has a range from about 400 km to 2000 km. The nuclear survivability is superior to other beyond line-of-sight (BLOS) transmission media such as satellite and HF radio.

3.1 History

Kokjer and Roberts (1986) present a description of the first two meteor burst networks that laid the framework for current MBC. The Canadian JANET system was developed in the 1950s for teletype communications between Toronto and Port Arthur. It is the forerunner of current meteor burst networks. The JANET system used full duplex transmission with VHF frequency of 50 MHz and duty cycles around 0.1. The COMET system was a meteor burst network established between the Netherlands and Southern France during the 1960s and 1970s. Worst case message delays for the COMET system were 3 to 4 minutes.

Three current MBC networks include the RADC test link, SNOTEL (SNOw TELemetry), and the Alaska Meteor Burst Communications System (AMBCS). The RADC test link is composed of a transmitter located at Sondrestrom Air Base and a receiver located at Thule Air Base in northern Greenland. This test link is designed to study the effects of high-latitude on MBC.

3.2 Performance Characteristics

MBC links can average 100 words per minute with over 90 percent reliability at ranges up to 2000 km [KoR86]. This communication medium can transmit data at about 2.5 kbps but averages 75 bps due to the low average duty cycle. The maximum distance a transmitter can send is 2000 km. This limitation is a result of the curvature of the Earth and not of the transmission system [Day, 1982]. In addition to the variations produced by diurnal, monthly, and geographic effects, the number of meteor trails useable for communication is a function of transmitter power, transmitter and receiver antenna gain, transmitter frequency, range, and transmitter bit rate. The effect these parameters have on detected meteor trails is described by Healy (1988). The location of "hot spots" between a transmitter and receiver also has a major impact on network performance.

3.3 Transmission Protocols

This research considered two simple protocols. In Protocol 1, a receiving station continually broadcasts a probe signal. A transmitting station begins transmitting when a probe signal is received. The probe response delay for Protocol 1 is at most equal to the one-way propagation delay between the transmitter and receiver [Milstein 1986, and 1987]. Protocol 1 is known as message piecing [Haakinson, 1983]. Every meteor trail long enough to complete the probe response delay and transmit at least part of the message is used. Protocol 2 is simpler to implement than Protocol 1 and decreases transmission requirements. In Protocol 2, a transmitting station broadcasts a probe signal when it has a message to transmit. A communication link is established when the transmitter receives a response from the desired receiving station. The worst case probe response delay is equal to the two-way propagation delay from the transmitter to the receiver. In this protocol, only meteor trails long enough to complete the probe response delay and deliver the entire message are used for communication. If a message is not completed before the end of the trail, the entire message must be retransmitted. This protocol is referred to as single burst transfer.

4. EXISTING METEOR BURST COMMUNICATION MODELS

Modeling can be a powerful tool for studying existing meteor burst networks and for the design of new networks. Several simulation and analytical models have been developed to study the performance characteristics of MBC. These models were designed to study single MBC links or networks of transmitters and receivers. Most of these models can be classified as either reference models or physical propagation models.

4.1 Reference and Physical Propagation Models

Reference models use experimental data from existing meteor burst links to extrapolate performance characteristics for an arbitrary link. The reference model concept is the result of work by IBM, (1985). Manning (1954) theorized that the meteor arrival rate for an arbitrary link could be determined from a known arrival rate on an existing link. He determined that the unknown arrival rate was proportional to the:

- transmitter power,
- transmitter antenna gain,
- receiver antenna gain,
- receiver detection threshold, and
- frequency

between the arbitrary link and the known link. This relationship, however, assumes that meteors arrive uniformly over the transmitter/receiver common volume [IBM, 1986].

Table 1. Summary of Meteor Burst Communication Models

SIMULATION MODEL	PREDICTION TECHNIQUE	MAX NODES	PROGRAM LANGUAGE	COMPUTER REQUIREMENT
Single-Link Models				
CSC: Brown (1988)	physical	2	Fortran	PC & VAX 8650
Conklin (1986)	physical	2	Pascal	VAX 11/785
Hampton (1985)	reference	N/A	N/A	N/A
BLINK: IBM (1986)	reference	2	Pascal PL/1	PC IBM 4341
MITRE Link: Hirst (1985)	reference	2	Fortran	VAX 11/780
Network Models				
BURST: Haakinson (1983)	reference	4	Fortran	HP 1000
RESQ: IBM (1985)	N/A	30	PL/1	IBM 4341
MITRE Network: Hirst (1985)	N/A	50	Pascal	VAX 11/780

Scale factors are used to compensate for differences between the known link and the arbitrary link. Additional meteor trail properties can be included in the model by adding scale factors. The reference model is conceptually and computationally simple, easy to use, and relatively accurate. The reference model, however, is only as accurate as the scale factors used. As the scale factors become more complex, the reference model becomes less useful.

Currently available meteor burst models are summarized in Table 1. Max nodes refers to the maximum number of nodes in the network. Single-link models have a maximum of two nodes. MITRE link refers to the MITRE link model, and MITRE ntwk refers to the MITRE network model. The Hampton model is not a computer model; therefore, it has no computer requirements. Further detailed information comparing these models is found in Healy (1988).

5. MODELING PERSPECTIVE

The major objective of this research effort was to design an integrated design tool to predict MBC performance. This computer tool was designed for portability, ease of use, and conceptual simplicity to provide maximum usefulness to the network designer. The tool consists of several sub-modules and two main modules. The sub-modules are designed to provide an interface between the two main modules and the user. A description of the sub-modules is provided by Healy (1988). The first main module is a revision of the BLINK model written in Pascal. This revision is called BLINK2. BLINK2 is designed to provide values of meteor trail interarrival time, meteor trail duration, and message duration to be used by the second main module. The second main module is written in the SLAM II simulation language [Pritsker, 1986]. This module simulates a single MBC link. Conceptual simplicity is achieved by decoupling the engineering parameters from the queueing module. For network simulation, the single-link module is replicated for each node in the network. This modeling perspective is described in Figure 1.

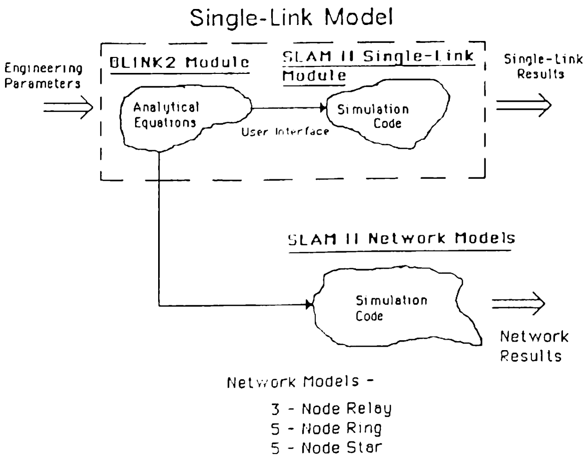

Figure 1. Modeling Perspective

5.1 M/G/1 Queue with Server Vacations

The Meteor Burst Communication process can be visualized as a M/G/1 queue with server vacations. A M/G/1 queue has exponentially distributed interarrival times, a general service time distribution, and one server. Server vacations refer to the process of a disappearing server at a random time for a random duration. Messages are assumed to arrive randomly (exponential interarrival time) to a transmitter. The server in the MBC scenario is the meteor trail used for transmission. The service time is a function of meteor mass, trail altitude, message size, transmission protocol, and engineering parameters. The service time is assumed to have a general distribution. The meteor trail duration is greater than or equal to the service time and is assumed to have an exponential distribution [Sugar 1964, Oetting 1979, Ostergaard 1985, Milstein 1987].

Some analytical results exist for the M/G/1 queue with server vacations. The current state of the art is summarized in articles written by Fuhrmann and Cooper (1985), Keilson and Servi (1987), Harris and Marchal (1988), and Shanthikumar (1988). Adapting their results to the MBC scenario, expressions for the number of messages in a transmitter buffer, meteor trail duration, meteor trail interarrival time, and message waiting time can be derived [Hea88]. These results can be used to calculate meteor trail duration, meteor trail interarrival time, and message waiting time. However, these results are based on the following assumptions:

1) Poisson arrivals,
2) infinite queueing capacity,
3) first-in-first-out (FIFO) service discipline,
4) server vacations independent of customer arrivals, and
5) nonpreemptive service [Sha88].

Assumptions 1, 3, and 4 are compatible with the MBC scenario. However, assumptions 2 and 5 are violated. Assumption 2 is not as significant as assumption 5. Message buffers could be simulated as infinite queues provided the system was ergodic. However, the server (i.e. the meteor trail) can clearly preempt the transmission of a message when it disappears. Fuhrmann and Cooper propose that preemptive service can be modeled as nonpreemptive by using appropriately longer service times.

Results for Protocol 2 delay are described in [IBM 1986]. These results use the Pollaczek-Khinchin equation for waiting time assuming a M/G/1 queue without server vacations. An effective service rate is determined from obtaining moments of the distribution for message transmission time.

The analytical results become much more complex when additional assumptions are made. If arrivals are not Poisson (i.e. general, Gamma, or deterministic distributions), if multiple servers are present (i.e. using multiple meteor bursts), or priority service disciplines are used than results are not easy to derive analytically. These modifications, however, can easily be simulated. Once a simulation model is created and validated, modeling any modification to the system is much simpler. Simulation can also be used to gain insight to the problem and help extend the analytical results.

5.2 BLINK2 Single-Link Module

The BLINK model developed by IBM was used as a baseline for BLINK2. BLINK2 is the result of numerous modifications and additional calculations. BLINK2 is written in Pascal and is used as the front-end module for this computer model. The BLINK model was chosen as a baseline because it is conceptually and computationally simple without unnecessary loss of accuracy. A version of the BLINK model is also compatible with the IBM XT/AT which increases its usefulness for this modeling perspective.

BLINK2 uses a number of engineering parameters to generate meteor trail interarrival time, meteor trail duration, and message duration. BLINK2 uses both overdense and underdense trails to calculate meteor trail interarrival time. However, overdense trails are modeled as underdense to calculate meteor trail duration. The message duration is a function of message size, transmitter bit rate, and propagation delay. The engineering parameters are input to BLINK2 through the use of an input data file. A detailed description of these parameters is provided by Healy [Hea88] and summarized in Figure 2.

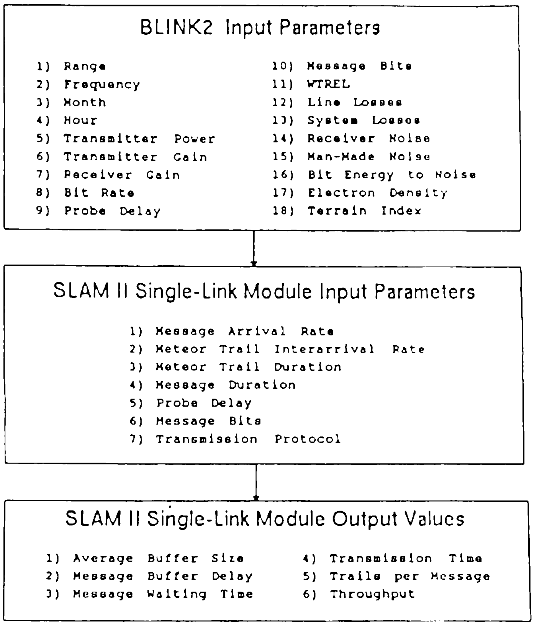

Figure 2. Single-Link Model Parameters

5.3 SLAM II Single-Link Module

A SLAM II single-link model was created which uses the values of meteor trail interarrival time, meteor trail duration, and message duration calculated by BLINK2. The SLAM II module also requires values for message arrival rate, probe response delay, the number of message bits, and the desired transmission protocol. Two versions of the single-link module were created. The first version simulates Protocol 1 transmission. The second version simulates Protocol 2 transmission. The SLAM II single-link module provides output values for:

- average buffer size,
- message buffer delay,
- message waiting time,
- message transmission time,
- the number of meteor trails required per message, and
- throughput.

Average buffer size is a measure of the number of messages waiting to be transmitted as a function of time. Message buffer delay is the time a message waits in the buffer until it begins transmission. Message transmission time is the time required to transmit a message. Message waiting time is the total time a message spends in the system which includes buffer delay and transmission time. The number of meteor trails per message is calculated as the ratio of the total number of meteor trails required to transmit a fixed number of messages. The throughput values are for long-term average throughput. Throughput is calculated as the total number of bits divided by total time. Throughput calculations take into consideration the time between message arrivals and the time between meteor trail arrivals.

5.4 SLAM II Network Models

Each transmitter-receiver link in the SLAM II network models was implemented using the single-link module. In addition to the single-link input parameters, a network topology and message routing algorithm must be specified for the network. Four network topologies were simulated [Hea88]:

- 3-node relay network,
- 5-node ring network,
- 5-node star network, and
- 7-node hybrid network.

To achieve message routing, a routing table was designed in SLAM II to implement each network topology. The routing table determines which links are used to transmit a message from one node to another. The message routing table is implemented as a NxN table where N is the number of nodes in the network. The BLINK2 module is run for each link in the network to provide meteor trail interarrival time, meteor trail duration, and message duration. In addition, the desired transmission protocol and probe response delay are required for each link in the network. Message size and message arrival rate is required for each transmitter.

A separate meteor trail arrival process exists for each link in the network. Each meteor trail arrival process is initialized with the meteor trail interarrival and duration times calculated by BLINK2. The probe response delay in the meteor trail arrival process is initialized to the link probe response delay when Protocol 1 is used. When Protocol 2 is used for message transmission, the probe response delay in the meteor trail arrival process is null. The node preemption capability of SLAM was used to preempt messages traversing a link where the preemption entity is controlled by the link parameters supplied by the preliminary BLINK2 analysis.

5.5 An Example Network.

An example network is shown here to show the type analysis which is possible. Other network results are available in Healy's original work (1988). A relay network consisting of three nodes is shown here. Figure 3 describes the network topology and message routing table for the network. In this network, only nodes 1 and 3 create messages. Node 2 is a relay which receives messages from node 1 and transmits them to node 3. Messages created at node 3 are transmitted directly to node 1. The topology is represented by arrows and boxes. Link numbers are indicated beside the arrows. Node numbers are inside the box. In this example, messages created at node 1 with node 3 as final destination must first go to node 2 via link 1. The message is then transmitted from node 2 via link 2 to node 3.

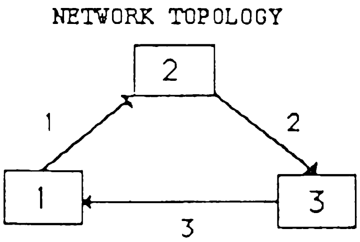

Figure 3. Simple Relay Network

5.6 Additional Modeling Techniques

The modeling perspectives used to create these network models can be used to simulate many other more complex MBC networks. Several additional modeling techniques are discussed to illustrate the possibilities.

To demonstrate how overdense meteor trails could be simulated, a single-link example which models overdense and underdense meteor trails was completed [Hea88]. Meteor trail interarrival time was chosen to be the interarrival time of an underdense meteor trail. Meteor trail duration was simulated as overdense 10 percent of the time and underdense 90 percent of the time. An exponential distribution for overdense trail duration was used.

Adaptive routing dynamically updates the message routing table based on the state of the network. To implement adaptive routing, the link numbers in the message routing table would be changed dynamically as a function of a selected model variable such as the number of messages currently in a queue.

In basic flood routing, every incoming message is retransmitted on every outgoing link except the link the message arrived on. To implement flood routing, an additional table could be created with a row for each node. Each row would contain all links a node could use for transmission. When a message is received, it would be retransmitted on all links in the row except for the link the message arrived on.

Priority message traffic can be easily simulated using SLAM II. A PRIORITY statement specifies the service discipline for messages waiting in a transmission buffer. The value used for determining priority would be assigned as a message attribute.

6. MODELING RESULTS

This section compares empirical data for meteor arrival rate with results from BLINK and BLINK2 and also validates the delay and throughput results of the SLAM II single-link module. The SLAM II single-link module was validated by comparing the simulation results for Protocols 1 and 2 with analytical results produced by BLINK2.

6.1 Empirical Results for Meteor Arrival Rate

Empirical data for meteor arrival rate is compared to predicted results from BLINK and BLINK2 in Figure 4. The empirical data is from the RADC high-latitude MBC link in Greenland [IBM85, IBM86]. RSL is the received signal level in dBm, and it is a measure of the minimum receiver detection threshold. The number of detected meteor trails decreases as RSL increases.

Figure 4 presents results for a transmitter frequency of 45 MHz. For RSL levels less than -110 dBm, BLINK predictions are closer to empirical data than BLINK2. Both BLINK and BLINK2 predictions are very close to empirical data for RSL levels greater than -110 dBm. Since the transmitter freqeuncy is crucial other freqeuncies were also tested. For example, using a transmitter frequency of 104 MHz, BLINK2 predictions were closer to empirical data than BLINK. BLINK2 provides optimistic results for RSL levels greater than -110 dBm. In general, both BLINK and BLINK2 were quite good predictors of RSL.

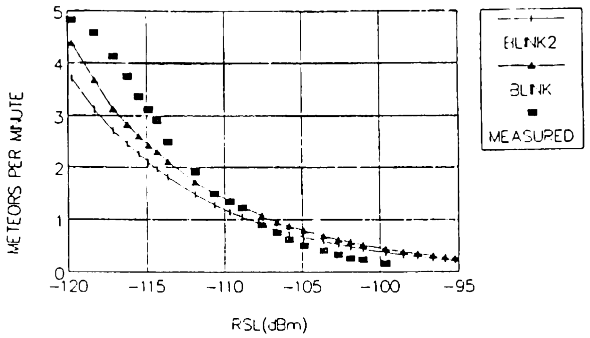

Figure 4. Meteor Arrival Rate at a Frequency of 45 MHz

6.2 Delay and Throughput Validation

Throughput calculated by BLINK2 for Protocol 1 and a modification of Protocol 2 were used to validate the simulation throughput results. Only the modified Protocol 2 was used to validate the simulation delay results. Milstein (1986, 1987) derived equations describing throughput for Protocol 1 and the modified Protocol 2. These equations included the effects of message arrival rate and modeled the message transmission process as a M/G/1 queue. Time between meteor trails was modeled as exponential. The Laplace transform of the distribution of message transmission time was used to calculate delay. Results for Protocol 1 delay were derived by Oetting (1979).

Protocol 1 Validation. There are two methods of modeling message transmission using Protocol 1. The first method considers messages as distinct groups of bits with an associated message duration. The second method removes the distinction between messages, and considers messages as one single collection of bits. When the second method is used, the trail duration is substituted for the message duration in the throughput equation. Comparison of analytical and simulation results indicated that method 1 is more accurate than method 2 when the ratio of meteor trail duration to message duration exceeds a value of six.

Protocol 2 Validation. Analytical results for Protocol 2 assume only one meteor trail is used for message transmission. If a message completes transmission before the meteor trail disappears, a new meteor trail must be acquired for the next message. This represents an artificial constraint on the message transmission process. In reality, an existing meteor trail could be re-acquired after transmitting a message and considered a new trail. The SLAM II single-link module models the process in this manner. Deviations from the simulation and analytical results become larger as the ratio of meteor trail duration to message duration becomes larger.

Figure 5 includes a graph of throughput for Protocols 1 and 2. For Protocol 1, messages are considered as distinct entities with an associated message duration. Figure 6 includes a graph of message delay for Protocols 1 and 2. The dashed vertical lines indicate maximum transmitter capability. As the message arrival rate approaches the maximum transmitter capability, infinite message delay results which the simulation model can not accurately predict. These points are circled in Figure 6. Throughput and delay values were averaged from two sets of antithetic simulation runs. The simulation input values were the same as noted above. The simulation results closely map to asymptotic bounds described by analytic equations.

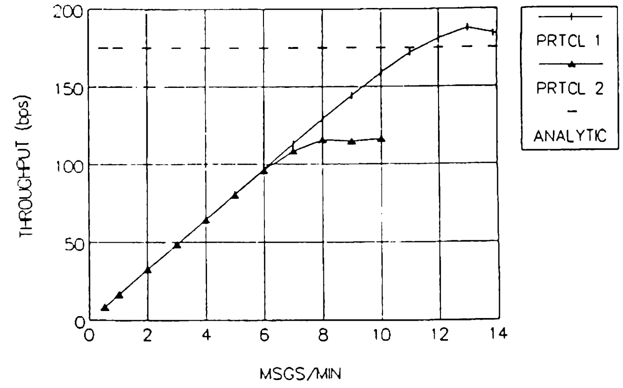

Figure 5. Throughput for Protocols 1 and 2

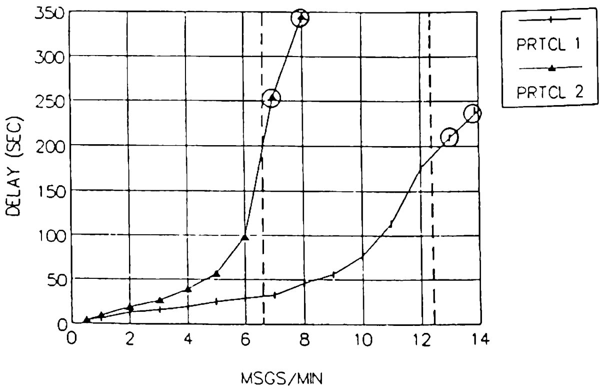

Figure 6. Message Delay for Protocols 1 and 2

6.3 SLAM II Network Model Results

Results for only the example relay network model are given here; the entire set of results is available in Healy

(1988). Engineering and the SLAM II network input parameters were specified for each link. However, only output for designated links is provided.

Example Relay Network. Input values for the relay network were chosen to illustrate the effect range has on MBC performance. Two antithetic simulation runs were made to calculate the output values. All design parameters for each link were identical except link 3 was 300 km versus 1000 km for links 1 and 2. Table 2 includes the SLAM II network input parameters, and Table 4 lists selected output values.

Table 2. SLAM II Relay Network Input Parameters

Node Feature	**NODE 1**	**NODE 2**	**NODE 3**
Message Arrival Rate (msgs/min)	3	0	3
Link Feature	**LINK 1**	**LINK 2**	**LINK 3**
Trail Interarrival Rate (sec)	6.446	6.446	14.967
Trail Duration (sec)	0.949	0.949	0.348
Message Duration (sec)	0.210	0.210	0.205
Probe Response Delay (sec)	0.020	0.020	0.020
Message Bits	406	406	406
Transmission Protocol	1	1	1

Table 3. SLAM II Relay Network Output Values

	LINK 1	**LINK 2**	**LINK 3**
Transmission Time (sec)	5.7	5.1	14.2
Message Waiting Time (sec)	15.8	15.8	43.9
Throughput (bps)	19.5	19.5	22.3

Throughput results for link 3 and links 1&2 are nearly the same. However, message delay for link 3 is more than twice the delay experienced by transmitting over both link 1 and link 2. This result demonstrates the importance of network topology on message waiting time and confirms that performance is maximized at ranges around 1000 km. Shorter or longer links are less efficient and experience greater message delay. Adding relays to a MBC network to achieve links of 1000 km may improve performance. Other considerations, however, include the increased system overhead and queueing delay caused by adding additional relay transmitters. Simulation can be used to analyze all of these effects on network performance.

Results for the other MBC networks are available in Healy [Hea88]. Generally, the simulations reveal predictable delay and throughput charactersitcs. The use of simulation allows the system designer to quickly assess the impact of engineering speciations and topological variations of the network. We show the simple relay as an example of the type of analysis attained with a simulator and the fascinating results which are <u>not</u> so predictable.

7. CONCLUSIONS AND RECOMMENDATIONS

7.1 Research Conclusions

The ultimate objective of this research effort was to develop a simulation methodology which could be used to evaluate any single or multiple-link MBC network. The significant conclusions which can be drawn from this effort include:

1. The MBC process can be accurately modeled with simulation technology where the complexities due to engineering design are condensed into queueing network parameteres and used to drive a discrete event model.

2. The general analytical equations for M/G/1 can be used to a degree to describe this queueing behavior. However, these analytical equations are complex and are based on assumptions which limit their capability to model the MBC process.

3. Simulation can be validated with analytical results within the constraints of existing analytical equations and empirical observation.

4. The use of distinct design modules to separate the engineering specification form the simulaiton allowed an analyst to rapidly determine the impact of design changes without extensive knowledge of simulaiton code. In fact we were able to completely automate the construction of single-link SLAM model code.

5. Finally, simulation can be used to extend analytical results for the M/G/1 queue with server vacations and to investigate complex network design tradeoffs. The simulation approach is readily extendable to include alternative routing strategies and transmission protocols.

7.2 Recommendations for Future Research

Because this research was focused on a high level modeling perspective, several enhancements and alternative approaches were not completed. Several possibilities for future research are possible:

1. Extend the analytical results describing the M/G/1 queue with server vacations for the MBC scenario. Most existing results assume nonpreeptive service. However, Fuhrmann and Cooper (1985) claim these results can be applied to preemptive service if appropriately longer service times are used.

2. Test the SLAM II single-link module using actual meteor trail data. Middle-latitude meteor trail data is available from the Shape Technical Center. High-latitude meteor trail data is available from the RADC test link in Greenland.

3. Model the effects of overdense meteor trails with the SLAM II single-link module and determine the impact on network performance.

4. Implement adaptive and flood routing in a SLAM II network model and compare the results to static routing.

5. Model variable bit rates and compare the results to the constant bit rate approach used in the single-link model.

7. Model priority messages and compare the message waiting times to a network without priority messages.

8. Automate the creation of network models. The automatic creation of the single-link module accomplished in this modeling perspective establishes the feasibility of this idea.

The results generated by this research effort and additional results which can be obtained by pursuing these recommendations will help the network designer improve the performance of MBC. Additional insight into the complexities of the M/G/1 queue with server vacations may be a further benefit. In closing, this research has produced a highly productive tool for MBC network simulation. The modeling perspective used in this research is extendable to many operational environments. This research has also introduced a rich source of additional research issues.

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