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Simulated Effects of Sounding on Automatic Link Establishment HF Radio Network Performance

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CONTENTS

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NTIA REPORT 93-291/NCS TECHNICAL INFORMATION BULLETIN 92-21
SIMULATED EFFECTS OF SOUNDING ON AUTOMATIC LINK ESTABLISHMENT HF RADIO NETWORK PERFORMANCE

Page 50. Paragraph 5, Line 3. "… 1 minute(s)." should read "… 1.5 minutes".

Page 118. Paragraph 5, Lines 2-3. "…, and 1 minute(s)." should read "…, and 1.5 minutes."

Page 168. Paragraph 2, Lines 5-6. "…, and 1 minute(s)." should read "…, and 1.5 minutes."

Page 190. "Figure D-20" should read "Figure D-21".

In figures B-11, B-12, B-23, B-24, B-35, B-36, B-47, B-48, B-59, B-60, C-11, C-12, C-23, C-24, C-35, C-36, C-47, C-48, D-7, D-14, D-21, and D-28 "sounds every minute" should read "sounds every 1.5 minutes."

Page 8, Table 3. Some information is presented that can by misinterpreted and thus could cause confusion. Time between sounds, in the table, is listed both for the individual radio station and for the entire network. Time between sounds for a radio station is the time between scheduled sounds for that station only. Thus the smallest increment of time that will pass before the beginning of the next scheduled sound for a single radio is 15 minutes. This means that a radio station is scheduled to sound on every HF frequency once every 15 minutes, in this case.

For the network, the combination of all individual station sounds results in an interval of 1.5 minutes between sounds. So, a receiver monitoring the 10 operating frequencies on the network, would hear sounds beginning 1.5 minutes apart if the sounds from all stations occurred at the scheduled time. Note, that these scheduled sounding times are staggered for the stations so that stations are not scheduled to sound at the same time.

In the appendices, the graphs are presented from the point of view of the network. The statement in Figure B-45 on page 96, for example, that sounds occur every 2 minutes means that a sound is scheduled to occur on the network every 2 minutes, which implies that each individual radio station is scheduled to sound every 20 minutes.

Comments received indicate that readers oriented toward network considerations had no problem distinguishing between the two ways of looking at sounding frequency. However, those readers oriented toward a single radio station might draw the incorrect conclusion that an individual radio was sounding, for example, every 3 minutes when scheduled sounds for that radio station, in the simulation, were actually 30 minutes apart.

SIMULATED EFFECTS OF SOUNDING ON AUTOMATIC LINK ESTABLISHMENT HF RADIO NETWORK PERFORMANCE

David A. Sutherland Jr.*

A discrete event simulation model for an HF Automatic Link Establishment (ALE) radio network is described. The simulation model is based on Federal Standard 1045 "Telecommunications: HF Radio Automatic Link Establishment." The simulation is used to study the effects of sounding on the simulated network. Sounding is the periodic broadcast transmission of identification information by a radio station that may be monitored by other stations. Sounding is used to evaluate the propagation quality of the available HF radio channels (frequencies). The station and channel overhead associated with sounding is indicated by this simulation to be generally detrimental to network performance. The exception is that in poor propagation conditions, at low traffic rates, sounding may significantly enhance some aspects of network performance.

Keywords: automatic link establishment (ALE); Federal Standard 1045; HF radio; modeling; network; simulation; sounding

1. INTRODUCTION

The purpose of this report is to describe a discrete event simulation model for an ALE HF radio network and to report results of a simulation study which used the model. The purpose of the study was to determine the effects on network operation caused by periodic sounding to gain information on the propagation states of the available HF channels. These effects were determined by the simulation study for combinations of

six sounding schemes,

seven message traffic rates, and

eight propagation conditions.

This report also demonstrates the utility of simulation modeling to analyze ALE HF radio networking features proposed for the series of ALE HF radio Federal standards under development.

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This report details the performance of a simulated ALE network which uses sounding. This performance information will be useful to ALE HF radio users, network designers, radio manufacturers and vendors, as well as to those involved in standards development. In particular, this report concludes that sounding is generally detrimental to the performance of the simulated network, with the exception that in poor propagation conditions, at low traffic rates, sounding may significantly enhance some aspects of network performance. The study results indicate, at least, that sounding does not enhance network performance except in the case mentioned.

1.1 Measures of Network Performance

This simulation study was undertaken to determine the effects on the performance of an ALE HF radio network caused by the use of periodic sounding to acquire information on the propagation states of the HF radio channels used by the network. The network performance criteria examined in this study are: average message delay, call success rate, and link success rate. The difference, in each criteria, between the baseline case (no sounds) and each of the various sounding schemes was also determined.

Message delay is defined in this study as the delay imparted by the simulated network to a transmitted message. The delay for a particular message is the difference between the arrival time of the message to the network and the time the message begins to be transmitted after establishment of a link between the transmitting station and the receiving station. The length of the message (the time it takes to transmit the message) is not included in the measured message delay.

Call success rate is the ratio of the number of successful calls to the number of attempted calls. A call is an attempt by a station to handshake with and transmit to another station on a particular channel (HF frequency).

Link success rate is the ratio of the number of successful links to the number of link attempts. A link attempt is an attempt by a station to handshake with (link with) another station. A link attempt consists of 1 to 10 call attempts. In the simulation, a station will continue to attempt calls until either a successful call is made (which implies a successful link) or until every available channel has been tried once without success (a shutout). Once a link has been established the stations may pass traffic (messages).

The definitions of the terms call and link (as well as call attempt and link attempt) are not necessarily standardized or widely accepted. The terms are often used interchangeably in the HF ALE literature. The terms are defined here so as to distinguish between attempts to handshake on a single channel and attempts to handshake using all available channels one at a time. This allows performance measures based on attempts to handshake over individual channels and measures based on the ability of a station to link with another station at all.

After each hour of simulation time, the simulation program determines and records the statistics that determine the call success ratio, the link success ratio, and the average message delay for the previous hour. Average message delay is the sum of the message delays measured in the hour divided by the number of messages for which delay was measured.

The simulation study determined the approximate effects on performance of a network caused by the additional overhead due to sounding. Sounding provides additional channel propagation information to the radio stations to support the movement of traffic and should enhance the ability of a station to automatically select the best available channel; however, since sounding occupies station time and channel time, it could also interfere with other network traffic.

1.2 Brief Description of HF ALE Radio

The basic principles and details of High Frequency (HF) Automatic Link Establishment (ALE) radio are described in Federal Standard 1045 "Telecommunications: HF Radio Automatic Link Establishment" [FS-1045]. Advanced features, including networking features, are being developed for the forthcoming proposed Federal standards on ALE, pFS-1046 **--** pFS-1049. What follows here is a short and simplified outline of the important features of HF ALE radio. More details, as well as discussion of the forthcoming standards, are given by Adair (1991), Adair and Bodson (1992), and McMillian (1991).

The basic tenet of ALE is that the radio system is capable of routine operation without the need for intervention or constant monitoring by an operator; however, the radio operator may take active control of the ALE radio if desired. The data transfer rate of a basic ALE HF radio system is 375 bits per second. The effective data transfer rate is approximately 54 bits per second, or approximately 8 ASCII characters per second.

The basic ALE radio system is capable of scanning up to 100 HF radio frequencies (channels) and selecting one of the frequencies for operation. For this simulation study there are 10 frequencies. As a listening ALE radio scans each frequency, in turn, it pauses at each channel to listen for incoming traffic or sounds. If traffic is not identified for the listening station, the scan continues to the next channel. For this simulation study the scan rate was two channels per second. Scan rates of 5 and 10 channels per second are also specified by FS-1045.

1.2.1 Coding

The ALE waveform features an encoding technique which uses forward error correction (FEC), interleaving, and redundancy to reduce the detrimental effects of noise, fading, and interference in the HF band (3-30 MHz). A text or data message is encoded by a Golay (FEC) scheme. The basic ALE word consists of a 3-bit command word plus three 7-bit ASCII characters. Each half of the 24-bit ALE word is Golay (24,12) encoded, the second half is inverted and the two resulting 24-bit halves are interleaved, and an additional "stuff" bit is added. The final 49-bit words are transmitted redundantly (3 times).

At the receiver, the three words, which have passed through the HF medium, first go through a bit by bit, two out of three, majority vote to determine the received 49-bit word. The resulting 49-bit word is stripped of the extra bit and deinterleaved. The two 24-bit words are then passed through a Golay decoder which returns a 24-bit ALE word.

Several other coding methods are available for longer messages which feature deeper interleaving and cyclic redundancy checking (CRC). These methods may increase the effective data transfer rate. Also, once the ALE link is established, other equipment, such as robust modems, which provide additional FEC coding and an increased data transfer rate, may be added to the HF link.

1.2.2 Link Quality Assessment (LQA)

Each ALE radio maintains an LQA matrix in which information on the measured propagation path quality of the HF channels between stations on the network is stored. The stored information is acquired by the station either actively, by linking with other radio stations and evaluating the traffic received, or passively, by listening to sounds, which are transmissions broadcast by a station so other stations may acquire channel quality information. Each analyzed channel is assigned a score automatically determined from the measured signal-to-noise ratio (SNR), bit-error ratio (BER), and multipath delay.

The LQA score is then stored in the matrix and will be used to automatically select the channel over which the transmitting station is most likely to successfully link with the desired receiver. This implies that the selected channel is most likely to provide the clearest HF path for message transmission. If the selected channel is occupied by other traffic, or if the channel is closed (handshake is not possible due to adverse propagation path conditions), or the desired receiving station is busy (cannot respond) then the transmitting station automatically chooses the next best channel to try according to the LQA matrix and so on.

1.2.3 Linking (Handshake)

A station attempting to link with another station repeatedly transmits a call message with the desired receiving station's identification. The length of this transmission is at least as long as it takes the receiving station to scan all available channels in the network. Once the receiver listens on the channel being used and hears its identification, it stops scanning and waits until the sending station stops transmitting. The receiving station then transmits a response. The original transmitting station will transmit an acknowledgement of the receipt of the receiver's response. The response and acknowledgement along with the original transmission is a "three-way handshake." Once this link is achieved, then traffic may be transmitted between the two stations or possibly among more if more than two stations are included in the link (this group operation is not addressed in this report). If the three-way handshake is not completed after a set time, the stations will return to scan, or other operation.

1.3 The Simulated Network

1.3.1 Description

The simulated HF ALE radio network is made up of the 10 radio station locations listed in Table 1. Real locations are used to obtain propagation reliability information from the Ionospheric

Table 1. Network Station Locations with Simulation Indices

INDEX	STATION
1	Boulder, Colorado *
2	Cedar Rapids, Iowa *
3	East St. Louis, Illinois
4	Ft. Lauderdale, Florida *
5	Frederick, Maryland *
6	Kansas City, Kansas
7	New Orleans, Louisiana
8	Raleigh, North Carolina *
9	Rochester, New York *
10	Schaumburg, Illinois *

Communications Analysis and Prediction Program (IONCAP) [Teters]. Seven of these locations (*) are sites where HF ALE radio is being tested or developed. The three others are added to bring the total to ten and to distribute the network more widely. The model simulates a fully connected network operating without a net control station (NCS). Each station is able to call, link with, and transmit messages to any other station on the network.

The 10 HF frequencies used in the simulation, with channel indices, are given in Table 2.

Only the identifying indices of both the station locations and the available HF frequencies are used in the simulation. The actual stations and frequencies are transparent to the simulation program. It is then easy to alter simulation input or network configuration.

1.3.2 Operation

Each station, when otherwise idle, must listen for calls and always scans all 10 channels in turn. Each station separately receives digital messages to transmit to another station in the network. If the station is sounding, transmitting another message, attempting to transmit another message, or is receiving a message, the new message is placed in the message queue at that station. Otherwise, the radio sorts the available channels by information in the Link

Table 2. HF Channels

INDEX	FREQUENCY (Channel)
1	3 MHz
2	5 MHz
3	7 MHz
4	9 MHz
5	11 MHz
6	13 MHz
7	15 MHz
8	17 MHz
9	19 MHz
10	21 MHz

Quality Assessment (LQA) Table. The idea is to select and try the channel providing the greatest probability of handshaking with the other station. If the selected channel is occupied (by other traffic), then the station tries the next channel on the sorted list.

If the selected channel is not occupied, the calling station transmits a call to the intended receiving station. If the channel is open in that direction and the receiving station is not busy, the receiving station will hear the call and transmit a response. If the channel is also open in the reverse direction, the calling station will hear the response and transmit an acknowledgement to the receiving station. A link (handshake) has been established and traffic (messages) can now be passed. Each station measures the propagation state of the channel and enters the data into the LQA table along with a time stamp.

At various pre-programmed times the stations sound. Sounding is an operation by which idle stations can assess the quality of the channels without a handshake and by so doing update their LQA Tables. The sounding station broadcasts self-identification information on each unoccupied channel in turn (occupied channels are skipped). The length of the transmission on each channel is greater than or equal to the time it takes a station to scan all ten channels. If an idle scanning station detects a sound from another station, the listening station stops scanning and automatically assesses the quality of that channel and records the assigned score in its LQA Table with a time stamp.

There are six sound schemes used in the simulation study which are summarized in Table 3 with respect to an individual station and with respect to the network. The time between sounds refers to scheduling of sounds by the simulation program. The sounds are added to the station message queues. The station will sound when it reaches the sound message in its queue.

2. VALIDATION

Validation of the simulation model is difficult since, at present, there are no active HF ALE networks that are available for testing and comparison. Thus, there is no way to obtain direct performance data of a particular ALE network for comparison with the model. With or without comparison data, any network simulation is still an approximation of the network being modeled.

Validation thus rests on implementing the procedures of FS-1045 as closely as possible. Any departures from FS-1045 are specifically pointed out in the assumptions of the simulation model. In FS-1045, there are several criteria for which a range of values is

Table 3. Sound Schemes

NETWORK		STATION	
Time Between Sounds (Min)	Sounds per Hour	Time Between Sounds (Min)	Sounds per Hour
15	4	150	-
10	6	100	-
6	10	60	1
3	20	30	2
2	30	20	3
1.5	40	15	4

given. In these cases it was necessary to choose reasonable values without the aid of field data. These values are pointed out in Section 3.1.

3. THE SIMULATION PROGRAM

3.1 Assumptions and Limitations

The limitations and assumptions imposed on the simulation model are intended to simplify and speed up both the executing simulation program and the development of the model. The intent is to not simulate the aspects of an ALE HF radio network that do not directly affect the questions being considered. Since the questions of interest have to do with calling, linking and message delay, several aspects of ALE radio are simplified or not simulated in this model.

3.1.1 Limitations

Each run of the simulation is for 24 hours of HF ALE network operation. The network begins from the idle state for each run of the simulation. Since the propagation path quality varies over the 24-hour period for each HF channel, the network does not achieve a steady state; hence, a warm-up period is not necessary.

The station message queues are limited to a total of 250 messages. This limitation is necessitated by limits on available computer memory for the dynamic variables heap. The number of shutouts in any hour is limited to 400. This limit precludes some network overload cases in which the queues continually grow larger and most transmission attempts are shut out. The network does not recover or reach a steady state in the 24-hour simulation period in these cases. When either of these limits is reached the program prints an error message and halts execution.

Only one scheduled sound is allowed in any station message queue at one time. This precludes the situations in which the station message queues are filled with upcoming sounds. The network frequencies will not be cluttered up by unnecessary repetition of sounds. This limitation guarantees that if the 250-messages-in-queue limit is reached, the simulation will be halted due to message backup and not to sound overload.

There is no priority among messages. This limitation helps minimize both the code and the simulation complexity. All station queues are essentially first-in, first-out (FIFO) stacks. All linkage in the queues is one directional, i.e., the message records contain only one pointer which points to the next message in the queue.

Radio traffic is limited to digital data messages. No voice traffic is modeled. Messages are characterized by the length of time it takes to transmit the message (once the transmitting station and the receiving station are linked), by the arrival time of the message, and by the indices of the originating (transmitting) station and destination (receiving) station.

Procedures and processes of the ALE radio stations and the network are modeled by the length of time they take to be accomplished.

If a station cannot transmit a message due to failure to link on any of the channels (each channel tried once) then, if the station message queue is empty, that message is held by the station for five minutes before trying to transmit the message again. If there are other messages in the station message queue, the message which was shutout is placed on the end of the queue. If a new message arrives while a message is being held, the held message is placed on the end of the message queue after the arrival. Holding the shutout message precludes the station from continually attempting to link with another station when it might be impossible at the moment. The receiving station may be busy or all useable channels might be occupied. Interference with other traffic is avoided.

3.1.2 Assumptions

If an HF channel is open, transmitted messages are assumed to be received at the destination station with no errors. That is, all bits transmitted are received exactly as sent. Likewise, if the channel is closed then no bits are passed at all. This assumption makes it possible to model messages in terms of the length of time it takes to transmit the individual messages. The content of the message is not considered. The ALE method of encoding is transparent to the simulation.

If the signal-to-noise ratio (SNR) over an HF frequency is 5 dB or greater for the transmitted power (either 100 W or 1,000 W), then that channel is assumed to be open. This is used to generate channel reliability information from IONCAP.

An ALE radio can always detect if a channel is occupied (busy). This perfect detection assumption means that contention for a channel is not allowed; hence, a station can never begin operation on a channel that is already being used. This is reasonable since we are only interested, at this time, in the effects of sounding; however, in actual operation this may be a significant issue particularly in low power networks.

The arrival of messages to the simulation network is a Poisson process. This implies that interarrival time is an independent and identically distributed exponential random variable. The arrival of messages is not affected by the configuration of the simulation. That is, the use of a particular sound scheme or a particular propagation condition does not affect the arrival of messages. The average interarrival time and hence the arrival rate of messages is the same throughout the 24-hour period. The average hourly arrival rates studied in this simulation are: 5, 10, 15, 30, 45, and 60 messages per hour. This corresponds to the respective average interarrival times of: 12.0, 6.0, 4.0, 2.0, 1.33, and 1.0 minutes.

Failure to handshake implies a closed channel between the stations. The channel is either closed (no propagation possible) or the receiving station is busy. The transmitting station cannot distinguish between the two cases, although the simulation can. The LQA matrix will indicate the channel is closed.

Length of time a listening station takes to determine if a channel is occupied is 0.0131 minutes, 784 milliseconds, or 2 TRW, where a TRW is a triply redundant word period, i.e., the length of time it takes to transmit one ALE word three times [FS-1045].

The length of time for a handshake (response and acknowledgement) is 0.0392 minutes, 2,352 ms, or 6 TRW. Turnaround time (time it takes a station to respond) is zero. Time to process (set up) a message for first call is 0.01 minutes. Length of full scanning call (also time to determine if a channel is closed) is 0.111 minutes, 6,664 ms, or 17 TRW. Scan length (time to scan all 10 channels) is 0.083 minutes, at 2 channels per second. [FS-1045]

Propagation time between radio stations is zero. With this simplifying assumption differences in radio wave propagation times due to distances between stations and the presence of various reflecting and absorbing ionospheric layers can be ignored.

Modeling propagation times is an unnecessary level of complexity for the purposes of this simulation study.

The measured output criteria, link success rate, call success rate and average message delay, are normally distributed random variables. This assumption allows for the use of standard, simple statistical analysis tools.

Message length is an identically distributed gamma random variable. The average message length is 2 minutes. This corresponds to an average message text of approximately 960 ASCII characters. The variance is two minutes. This choice of the variance results in a reasonable computer algorithm for generating message length.

3.2 Simulation Input

3.2.1 Randomly Generated Input Data

Pseudorandom Number Generation

To use the mean, variance and distribution to generate input data, it is necessary to generate pseudorandom numbers uniformly distributed on (0,1). The pseudorandom-number generator used to create random variates is a prime multiplicative modulus linear congruential generator (PMMLCG), [Law, with further reference to Marse and Roberts]. Pseudorandom numbers are referred to as random numbers in the remainder of this report.

The integer sequence generator is defined by the recursive equation

$$Z_i = a\ Z_{i-1} \bmod m\ , \qquad \textbf{(1)}$$

where a is 630,360,016, m is 2,147,483,647 or (2^{31}-1). The random numbers, U_i, on the interval (0,1) are obtained by dividing the integers Z_i by m where i=1, ..., 2,147,483,646. This PMMLCG is widely used in applications requiring uniformly distributed, random numbers [Law], [Fox], and [Fishman].

Law also gives an algorithm to generate integer seeds of this PMMLCG that are 100,000 apart. This provides separate random number streams that are useful in generating random variates, and in particular provides the necessary synchronization for the common random numbers (CRN) technique of variance reduction described below. There are 21,474 separate, non-overlapping random number streams of 100,000 numbers available.

Generating Messages

The messages that comprise the network radio traffic are characterized by length, arrival time, transmitting station index, and receiving station index. Length is the time it takes for the transmitting station to transmit a message to the receiving station once a link has been established. Arrival time is the time that a message arrives at the originating station ready for transmission. The transmitting station index is the integer identifier of the originating station. The receiving station index is the integer identifier of the destination station. (See Table 1.) These parameters are contained in data records called message records in the simulation.

Interarrival times, time between successive message arrivals, are generated by using the exponential probability distribution, with density given by

$$f(x) = \frac{1}{\beta}e^{-\frac{x}{\beta}}, \quad x \geq 0, \tag{2}$$

where β (the scale factor) is the mean, see Figure 1. The variance is given by β^2. The exponential distribution function is

$$F(x) = 1 - e^{-\frac{x}{\beta}} \ . \tag{3}$$

The exponential distribution is used to model interarrival times in simulations when the arrival of messages is a Poisson process. The interarrival times are obtained from the inverse of the exponential distribution function by

$$X_i = -\beta \ln U_i \ , \tag{4}$$

where U_i is a uniformly distributed random variable on (0,1). The arrival time, which is the parameter in the message record, is determined by keeping a running total of the interarrival times.

The message length is generated by using the gamma distribution function with density function given by

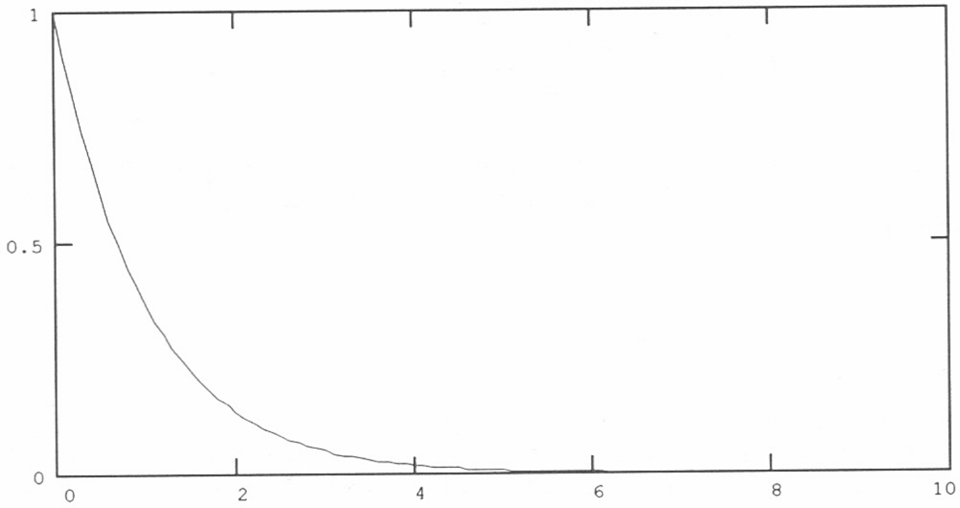

Figure 1. The exponential density function.

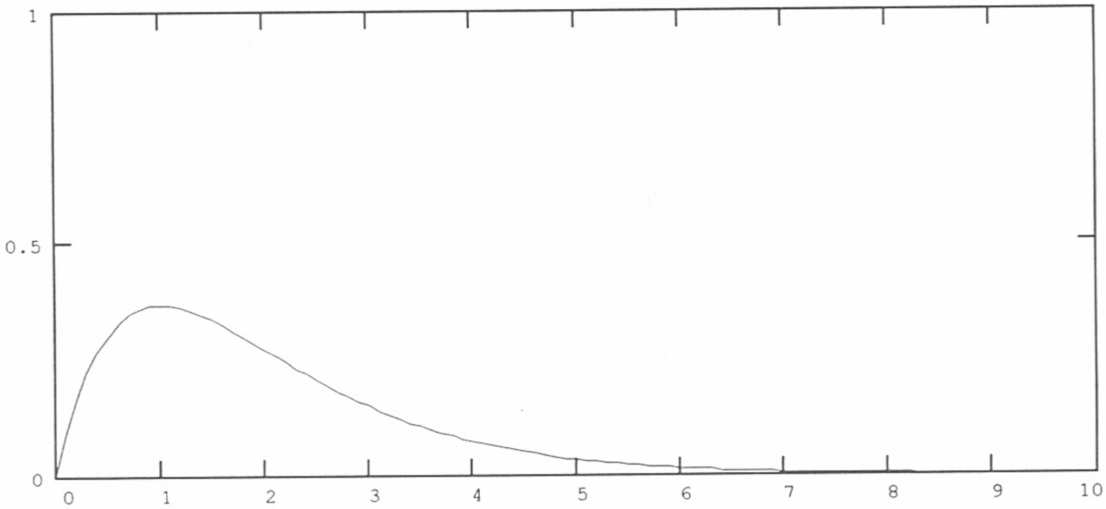

Figure 2. The gamma density function.

$$f(x) = \frac{\beta^{-\alpha} x^{\alpha-1} e^{-\frac{x}{\beta}}}{\Gamma(\alpha)} , \quad x > 0 , \tag{5}$$

where β is the scale parameter, and α is the shape parameter, see Figure 2. The mean is αβ and the variance is given by $\alpha\beta^2$. Γ() is the gamma function,

$$\Gamma(n) = \int_{t=0}^{\infty} t^{n-1} e^{-t} dt , \quad n > 0 . \tag{6}$$

The desired mean for message length in this simulation is 2 minutes. An integer shape parameter is needed to obtain the distribution function in a closed form. The shape parameter, α, is set to 2 to obtain a reasonable algorithm for generating the random variate length; hence, β is set to 1. The Gamma distribution function, when α is an integer, is given by

$$F(x) = 1 - e^{-\frac{x}{\beta}} \sum_{j=0}^{\alpha-1} \frac{\left(\frac{x}{\beta}\right)^j}{j!} , \quad x > 0 . \tag{7}$$

The length of a message is generated by an acceptance/rejection method algorithm [Law, with further reference to Cheng].

The indexes of the transmitting and receiving stations, 1-10, for the message record are generated from the uniformly distributed random numbers U_i by multiplying a random number by 10, truncating to a single digit integer and adding 1.

Twenty random integers for each message are also generated from U_i by multiplying a random number by 100 and truncating to two digit integers. These numbers are attached to the message record and are used to determine if a channel is open. The two digit integers are compared to the IONCAP generated probabilities that the SNR on a channel is at least 5 dB. If the random integer value is less than or equal to the IONCAP probabilities then the channel is open. There is one number for each direction of each channel between the transmitting and receiving station.

The message records are generated by a separate program prior to simulation and read from files by the simulation program. This approach allowed for easier debugging of the program and for predicting the state of the simulation at a particular time. The simulation code is reduced since it does not contain random number or data generators.

To create a message record, the message generating program reads a random number, generates the interarrival time, and then determines the arrival time of the message. Then two random numbers are read and if the length algorithm does not achieve a result (rejected), it will read two more random numbers until the result is accepted. A random number is read to determine the transmitting station index and another to fix the receiving station index. Of course, the two station numbers are not allowed to be identical. Finally, 20 random numbers are read to create the channel probability integers.

Twenty-four hours of message records are created for each pass of the simulation. Twenty-five different sets of message records were created for each message arrival rate. The average arrival rates studied in this simulation are 5, 10, 15, 30, 45, and 60 messages per hour. This corresponds to average interarrival times of 12.0, 6.0, 4.0, 2.0, 1.33, and 1.0 minutes respectively.

Additional Random Numbers

If a message is shutout (no link established) after trying all 10 channels, then the 20 random 2-digit integers attached to the message record for comparison with channel propagation probabilities are replaced by 20 new integers. The new random integers are read by the simulation program from a file into the message record.

The 2-digit integers in the file are created prior to simulation by reading a random number, multiplying by 100 and truncating to an integer value. Eight-thousand 2-digit integers are created which allows for reloading 400 shutout messages, the maximum allowed in one hour. If the number of shutout messages is less than 400, the program will read additional random numbers up to the 8,000 available for that hour. This supports the common random numbers technique of variance reduction.

3.2.2 IONCAP

IONCAP [Teters] is used to provide probability of linking over the HF ALE network channels. Prior to the simulation, method 24 of IONCAP is run twice for every pair of stations, once for each propagation direction. The output of each run gives reliabilities for a propagation path (one direction only) by channel (frequency in MHz) and by hour (24 hours UT) for a particular month. Representative IONCAP output for the longest and shortest links in the simulated network is shown in Appendix A.

From the IONCAP output, a file of linking probabilities for every channel for each pair of stations is prepared for each hour of the simulation by a separate program. These files are read into a three dimensional array by the simulation program. The array is indexed by the transmitting station index, the receiving station index, and the channel index. The probabilities are stored as integers, 0 to 100, to save storage space in memory. The integers represent the probability that the SNR is 5 dB or better for one particular hour on that channel at the specified power.

When a station is attempting to link with another station and a channel is found that is not occupied, the appropriate probabilities (one for each direction) are compared to 2 numbers from the list of 20 random integers in the message record. If each of the random integers is less than its respective channel probability, the channel is open; otherwise, the channel is closed.

The fixed settings for the IONCAP program are as follows. All network antennas are horizontal dipoles. Background noise at each site is -125.0 dBW which corresponds to industrial area background. Required signal to noise ratio is 5.0 dB.

3.2.3 Propagation Conditions

The variable settings for IONCAP characterize the eight propagation conditions. Sunspot number (SSN), radiated power, in watts, and month of the year are the parameters varied. The settings for each propagation condition used in the simulation study are given in Table 4.

The variation is necessary to study simulation results under different propagation conditions. Of particular interest are results from conditions using 100 watts of power since many applications of ALE radio are expected to use power in this range.

The complete simulation study is done for each of these conditions. ALE testing is currently being accomplished in the part of the sunspot cycle with relatively high SSN. ALE is too young a technology to have been tested in the low end of the sunspot cycle.

3.2.4 Common Random Numbers (CRN)

For each of the 6 message rates, 25 separate randomly generated message streams are created. The message streams are created from separate random number streams.

For each run of the simulation, the message rate, the propagation condition and the sounding scheme are fixed. The simulation is run without sounding for the 25 separate passes of 25 data sets under the same propagation conditions. Thus, there are 25 nonconsecutive days of simulation for each run. Data is recorded every hour, on the hour, covering the previous hour of simulation.

Table 4. Propagation Conditions

CONDITION	SUNSPOT NUMBER	POWER (WATTS)	MONTH
1	130	1,000	JAN
2	130	1,000	JUL
3	30	1,000	JAN
4	30	1,000	JUL
5	30	100	JUL
6	30	100	JAN
7	130	100	JAN
8	130	100	JUL

A sounding scheme is then added to the program to make another run of the simulation against the same 25 message streams under the same propagation condition. The two sets of output data are analyzed separately and are also used to create a third set of data: the difference between the two data sets,

$$Z_{i,j} = X_{i,j} - Y_{i,j} \ , \qquad \textbf{(8)}$$

where X is the set of hourly output parameters measured from the initial run of the simulation without sounding, Y is the set of hourly output parameters measured from the run with a sounding scheme, and Z is the difference between the two. The subscript i indicates the input data set (one of the 25 message streams), and j indicates the hour of the measured output data. The third set of output data is also analyzed.

Using the same data streams with different configurations of the simulation program is a variance reduction technique called common random numbers (CRN) [Law] and [Brately]. The propagation condition and the sounding scheme are assumed not to affect the arrival of messages for transmission. The arrival of messages is fully synchronized regardless of the choice of propagation condition or sounding scheme.

The CRN technique allows for direct comparison between alternative propagation conditions and thus, will illustrate differences in performance of the simulation caused by differing propagation conditions. Similarly, alternative sounding schemes can be compared. In this initial simulation study the sounding schemes are only compared with the baseline scheme (no sounds), within each propagation condition.

The additional randomly generated sets of integers for reloading the 20 random numbers in each message after a shutout are synchronized by the hour. The limitation that only 400 shutouts are allowed means that in one hour a maximum of 8,000 numbers are required. Hence, the simulation program draws 8,000 random numbers every hour whether they are used or not. This guarantees that in each hour the random numbers used for reload are the same for the runs to be compared. It is not possible to achieve complete synchronization since the choice of sounding scheme does affect the occurrence of shutouts and the necessary random number reloads. The randomly generated sets of integers used in generating sounds are similarly synchronized.

3.3 Simulation Description

This section describes the basic procedures of the program and the basic data structures. It is not intended to be exhaustive in describing the algorithms and variables, or the procedures and functions used in the simulation program. The important data structures will be described as they occur in the descriptions of the important procedures or algorithms. The description is given in terms of the simulation events which cause state changes and the subroutines associated with the events.

3.3.1 Initialization

Each of the 25 passes of one run of the simulation program begins with initialization of the data structures.

IONCAP generated probabilities of channel SNR of 5 dB or better, for the initial hour, are read into the IONCAP array. This array is a three dimensional matrix with indexes indicating calling station, receiving station, and channel (frequency). The order of station indexes indicates the direction of propagation.

Pointers to dynamic data structures are initialized. These dynamic structures are message records and event records. The structures only exist (take up memory) when they contain an active message or a scheduled event. They are created as needed. Once the simulation has accomplished the event or a successful transmission has occurred, the memory used by the message or event record is returned to the available memory heap. This maximizes available memory and avoids long arrays of records most of which would be inactive or empty.

The content of the message records includes the previously described messages and a pointer to the next message. These pointers are used to link messages into a separate queue at each station.

The event records contain an event index type, station index, event start time, and an event record pointer. The pointers serve to link the event records into a queue. The events in the queue are arranged in sorted order of event start time. The individual event records are popped from the top of the event queue. The event type is read from the record and the appropriate subroutine is identified and called. The events are: call, departure, arrival, sound preparation, time-in, shutout-return, and hourly.

Call events are either attempts by a station to handshake with another station and then pass traffic or they are sounds. A sound record is the same as a message record except that sound records have a "0" value for the receiving station index. Departures occur when a message transmission ends; the two stations and the channel involved are returned to an idle state. Arrivals indicate the arrival of messages into the simulated network. Sound preparation schedules sounds. Shutout-returns indicate the return of a previously shutout message to the station queue. After a shutout, the station will not attempt to retransmit the message for at least five minutes. After this time the message is returned to the queue. Time-in events return stations to a fully active condition after a period of one full scan during which the station is only allowed to receive incoming message traffic. Hourlies are the housekeeping procedures which load new IONCAP data into the IONCAP array and synchronize the extra random numbers for the next hour.

The LQA matrix is initialized to "4" for all entry values and "0" for the time stamps. The possible entries are:

1 - Channel Open - A successful link has been accomplished on this channel.

2 - Heard Sound - station has heard a sound from the other station on this channel.

3 - Channel Busy - station attempting to call detected other radio traffic on this channel.

4 - Channel Untried.

5 - Channel Closed - Attempt to call on this channel was unsuccessful.

The data input files containing the messages and additional random number files are initialized and opened for reading. The message files and the additional random number files for both reloading message records and creating sound records are each indexed by run. There are 25 of each of these files. The program opens the appropriate files for the current pass.

The output files are also initialized and opened for writing. There is an output file for each pass.

The first hourly event is scheduled by creating an hourly event record and placing it in the event queue. The first message is read from the message input file. An arrival event is created for the first message and placed in the event queue. The first sound (if sounding is used) is scheduled by creating a call event (receive station index is 0) and placing it in the event queue.

With the variable "clock" set at zero, the program then proceeds through a loop taking the event from the top of the queue and calling the appropriate subroutine for each pass of the loop. The loop will continue until the clock reaches 1440 minutes (24-hours), the length of one pass of the simulation. The simulation clock is driven by the occurrence of the simulation events. As events occur, the clock is advanced to the time of the event.

3.3.2 Message Arrival

The arrival subroutine begins by advancing the simulation clock to the arrival time of the next message (or sound) to the network. The transmitting station is read from the message record. If the message record queue at that station is not empty, the message record is attached to the end of that queue. If the queue is empty, but the station is busy transmitting a sound, transmitting or receiving a message, or attempting to handshake with another station, the new record is held at the front of the queue.

If the station is not busy, the call setup subroutine sorts the channel information in the LQA matrix which determines the order in which the channels between the transmitting and receiving station will be tried. The sorting routine uses an insertion sort algorithm [Horowitz]. The channel indexes are sorted by the stored LQA value in order 1,2,3,4,5. Then the channels with state values 1,2,3 (open channel, heard sound, and busy channel, respectively) are sorted in reverse time order, latest first, within each state. Channels with state value 4 (untried channels) are not time sorted which means they remain sorted by channel index. Channels in state 5 (closed channel) are sorted by regular time order, oldest first, within state 5.

Once the channels are sorted, in a channel index stack, the setup subroutine schedules the first call attempt from the transmitting station to the receiving station over the channel indicated by the first index of the sorted index stack, by creating a call event. The call event is placed in the event queue. The scheduled time for the call event is the current clock time plus 0.1 minute (for processing).

Control is passed back to the arrival subroutine. If a previously shutout message is being held, it is attached to the end of the event queue. The next message is read from the message input file and an event record for the new message's arrival time is created and placed in the event queue. If the arrival was a sound being scheduled, then the next sound event is scheduled and placed in the event queue.

3.3.3 Call

Message

The call subroutine first advances the clock. To accomplish a call the simulation begins by checking which channel to try from the sorted channel list prepared by the call setup subroutine. The simulation then checks the channel state array which holds the state for each station with values 0 (idle) and 1 (busy). If the channel is idle the call subroutine continues.

But, if the channel is busy, the program advances the sorted channel list and schedules the next call attempt by creating a new call event and placing it in the event queue. Counting statistics are updated for a call attempt resulting in a busy channel. Control passes back to the main program.

If this call attempt was on the last channel of the sorted channel list, the message was shutout. The message record will be placed on the end of the station queue or held by the station for 5 minutes before trying to transmit again. Twenty new random numbers are read from file into the message record. A time-in event will be scheduled by creating a time-in event record and placing it in the event queue. Statistics are updated for an unsuccessful link attempt.

The LQA matrix is updated for the calling station with a value of 3 - (channel busy) for the channel to the receiving station at the time of the call attempt if the current value is 3 or 4 (untried channel). The values 1 (channel open), 2 (heard sound), and 5 (channel closed) will not be changed since these conditions are not necessarily canceled by sensing a busy channel. Control will pass back to the main program.

If the channel is idle, the program then checks the state of the receiving station which is either 0 (idle) or 1 (busy). If the receiver is busy the program takes exactly the same action as if the channel was busy (above). Statistics appropriate to a closed channel due to a busy station are updated. A value of 2 (closed channel) is placed in the LQA matrix for the selected channel from the calling station to the receiving station.

If the receiving station is idle (ready to receive traffic), the program checks the channel probability for each direction between the transmitting and receiving station, against the two random numbers contained in the message record for that channel. If the channel probability is greater than or equal to the random number, then the channel in that direction is open. If either or both directions of the channel are closed, then the simulation program advances the sorted channel list and schedules the next call attempt by creating a new call event and placing it in the event queue. Statistics are updated for a closed channel. A value of 2 (closed channel) is entered into the calling station's LQA matrix for the channel to the receiving station. If this call attempt was on the last channel to try, the program runs through the shutout procedure described above.

If both directions of the channel are open, then both station states and the channel states are made busy. The LQA matrix for each station is updated to a value of 1 (channel open) for that channel to the other station. The departure time for the message is set to the current clock time plus the length of the message plus the time its takes for the link to be accomplished. A departure event is scheduled for that time by creating a new departure event and placing it in the event queue. The appropriate statistics for a successful call and a successful link are updated. Control passes back to the main program.

Sound

If the message record indicates a sound (receiving station index is zero), then the call is handled by a slightly different routine. The channels are not sorted in this case but will be tried sequentially by channel index.

If the current channel is busy, then a new call (sound) event is scheduled for the next channel and the call event record is placed in the event queue. If the current channel is the last channel, the program schedules a time-in event for the sounding station and places the event record in the event queue. Control goes back to the main program.

If the channel is idle, then the sound takes place on that channel. For each of the other stations, if that station is idle and if the one way channel to the listening station is open then the listening station hears the sound. The LQA matrix is updated at the listening station for the channel to the sounding station with a 3 (heard sound) only if the current value is not 1 (channel open).

Once the sound is completed on that channel, the program schedules the next call event for the sound on the next channel. The new event record is placed in the event queue. If the sound was on the last channel to be sounded upon, the program schedules a time-in event for the sounding station and places the event in the event queue. Control reverts to the main program.

3.3.4 Departure

Departure is the event that marks the end of a message transmission. The message record is returned to the heap. The program changes the channel state from busy to idle. If the receiving station's message queue is empty, the station state is changed to idle. If the queue is not empty, the queue is advanced and the program runs through the call setup procedure to schedule the first call event for the next message.

A time-in event is scheduled for the transmitting station and the event record is placed in the event queue. Control goes back to the main program.

3.3.5 Shutout-Return

A shutout-return event is the return to queue of a message being held by the station for five minutes after the station fails the attempt to link with the receiving station. If the station is idle, the returned message is handled as a new arrival. If the station is busy, say receiving a message, the returned message is placed in the queue and will be handled when the station returns to idle status.

3.3.6 Time-In

The time-in event is set after a station completes transmission of a message or completes a sound. The time of this event is the same as the departure time of the message plus the time it takes for a full scan of all 10 channels. This event is necessary since a full message queue at a station would be completely handled, successful transmissions or shutouts, without pausing to listen for incoming messages. This could eventually result in lock up of the entire network (in the simulation) as the same state occurs at every station.

During the period prior to the time-in event but after the departure event, the station will accept incoming calls and will listen to sounds. When the time-in event occurs, the station is free to begin handling and transmitting its own message traffic.

3.3.7 Hourly

The hourly event is the bookkeeping routine. After advancing the clock, the hourly routine schedules the next hourly event by creating an hourly event record and placing it in the event queue. The routine then ensures that during the last hour exactly 8,000 random numbers were drawn from the file used to reload random numbers to shutout messages.

The routine next loads the new IONCAP data for the coming hour. And finally it collects and determines statistics, writes the statistics to the output file, and resets all counters.

3.3.8 Sound Preparation

This routine produces sound records (message records with receiving station index zero). It functions exactly as the arrival routine does for regular message records except that the data for the sound records are produced internally, not read from file.

The sounds are scheduled at pre-programmed intervals determined by the sound scheme being used for the current run. The scheduled sounding order is sequential, i.e., station 1 is scheduled to sound first, station 2 is scheduled second, etc., and station 1 follows station 10. If a sound record is already in the message record queue at a station, a new sound record will not be attached to the station queue.

The routine also sets the next sound-preparation event by creating the event record and placing it in the event queue.

3.3.9 Finish

When the simulation clock reaches 1440 minutes the program ends the pass by closing all open files and returning all remaining dynamic variable space to the memory heap. The simulation program then begins another pass using the same propagation condition and sound scheme but using a different randomly generated message data stream with the same arrival rate. The extra random number files for reloading shutout messages and creating sounds are in different files for different runs. There are 25 sets of input data at each data rate.

3.4 Output

The output files written by the hourly routine contain two types of data. The first is data which relates to development and debugging of the program. This includes current information about message and event queue sizes, current station status as well as the number of active message and event records.

The second set are statistics from which performance data will be determined. The link statistics are link attempts, link successes and link failures. The call statistics are call attempts, call successes, call failures due to closed channel, and call failures due to busy channel. The delay statistics are average delay and maximum delay. These statistics will be read and tabulated by the statistical analysis programs and used to obtain the desired measures of performance: average hourly delay, call success rate, and link success rate.

4. ANALYSIS

4.1 Analysis Program

The analysis program is separate from the main simulation program. This is done to keep the code for the simulation program as small as possible. Also, additional analyses or different analysis techniques on the same output data do not require an additional run of the simulation. The analysis program is a Pascal program consisting of about 150 lines of source code.

The analysis program reads the 25 output files for a run of the simulation. It compiles, for each separate pass, link attempts, link successes, call attempts, call successes, and average delay and computes the link success rate and the call success rate for each hour. The program then does a simple statistical analysis of the three hourly performance parameters: link-success rate, call-success rate and average delay. The mean and variance are computed using standard statistical formulae.

A second analysis program creates comparison (difference) data for two separate runs of the simulation according to equation 8. Comparison data is created for the baseline case (no sounds) and each of the sounding schemes over the same randomly generated traffic data and IONCAP generated propagation conditions. Mean, variance, and a 90% confidence interval (t-distribution) are computed for the three comparisons of measures of performance.

4.2 Results

The simulation study resulted in many megabytes of output data. Hence, the results of the simulation runs are reported here graphically. Since the propagation conditions (from IONCAP input) vary hour by hour and traffic arrival is random, I do not report composite results for 24-hour periods. The simulated performance often varies dramatically over a 24-hour period and to note this without wading through reams of numerical data I have graphed the performance data hourly.

The graphical data is still many pages long. So, I have presented the major results for the best and worst propagation conditions, 1 and 5. (See Table 4.) For additional results which report performance as functions of traffic rate and scheduled sound frequency at two representative hours, I have presented graphs for the best and worst propagation conditions at both 100 and 1,000 watts of power, that is, for propagation conditions 1, 3, 5 and 8.

The reduced graphical presentation is meant to limit redundancy and saves space in the appendices while still illustrating the major results of the simulation study.

4.2.1 Description and Interpretation of Graphs

Four different styles of graphs are presented in this report. Each of the data points plotted represents the mean (average) of the particular measured criteria for the 25 passes at that hour. The data presented is discrete (measured hourly). The lines connecting the data points are not intended to imply approximation of continuous data or to represent fitted curves. The connecting lines are intended for display purposes particularly in that some of the graphs are "busy."

The first style is a trace of each of the baseline (no sounds) performance criteria for a particular data rate and propagation condition along with the trace of the same performance criteria for a particular sounding scheme, see the left hand facing pages in Appendices B and C. The sounding scheme trace is for the same data rate and propagation condition as the baseline (no sounds) case. The baseline data points are indicated by x's and are connected by a dotted line. The sounding scheme data points are indicated by squares and are connected by a dashed line. For each of the performance graphs the horizontal axis represents a 24-hour time period in universal time (UT). For the link-success rate and call-success rate graphs, the vertical scale reflects the performance as a rate between zero and one. For average message delays the vertical scale measures message delay in minutes.

The first set of graphs indicates differences in the sound scheme and the baseline case. The emphasis here is on visual difference of traces over the 24-hour period. Note the difference in scales. The presentation software was allowed to use default settings for each graph, to better emphasize the changes in performance over the 24-hour period.

The first and second styles of graphs are presented on facing pages for the same message rate, propagation condition and sound scheme. The two pages are different presentations of the same information.

The second style of graphs is a presentation of the difference of the measured network performance criteria between the baseline case and a sound scheme for the same propagation condition and data rate, see the right facing pages in Appendices B and C. These graphs present the hourly mean of the difference as the midpoint of the 90 percent confidence interval indicated by error bars. The mean for each hour is connected by a dotted line. The vertical axes for these graphs are the same as for the first set of graphs except that the vertical scales may now include negative values.

The second set of graphs emphasize the difference in performance between the two cases. The 90 percent confidence interval is used to present a range of plausible values for the true mean of the difference. A 90 percent confidence interval that contains zero indicates that the difference in performance between the two measured cases may not be significant, while a confidence interval not containing zero indicates that the difference between the two cases may be statistically significant.

Caution should be exercised in interpreting confidence intervals. A common erroneous interpretation is that the true mean is contained in any given 90 percent confidence interval with a probability of 0.9. A correct interpretation is that if many runs of an experiment (simulation) are done and the confidence interval computed for each replication, then the true mean is contained in the computed confidence intervals 90 percent of the time. [Devore]

A positive mean value of the difference in the call success rates (or link success rates) in these graphs indicates that the mean value obtained for the baseline case (no sounds) is greater than the mean value obtained for the specific sounding scheme case being compared. That is, the performance (call success or link success) of the baseline case (no sounds), is better than the performance when a sound scheme is used. A negative mean value indicates that the measured performance for the sounding scheme case is better than the performance for the baseline (no sounds) case.

In the average delay graphs, a positive mean value of the difference indicates that the average delay for that hour is greater for the baseline case (no sounds) than the average delay for the sounding scheme case being compared. That is, the performance (average message delays) is better when a sound scheme is used than the performance for the baseline case (no sounds). A negative mean value means that the performance of the baseline case is better, as measured by the average hourly delays.

For the first two sets of graphs, by the CRN technique, the input data is the same for the two cases being compared, the baseline case and a case with a specific sounding scheme. Since the propagation condition and the randomly generated traffic are the same for both cases, the differences between the two cases are due to the effects of sounding on network performance.

Each graph for the three performance criteria is displayed on the same page for each simulation run. It is important to note that although the individual confidence intervals are at the 90% confidence level, if the three confidence intervals (for the same hour) are considered simultaneously, the confidence level may be less. This is illustrated by Bonferroni's inequality

$$P(\mu_s \in I_s \text{ for all } s=1,2,\ldots,k) \geq 1 - \sum_{s=1}^{k} \alpha_s \quad , \tag{9}$$

where μ_s is the mean associated with the confidence interval I_s, and $1-\alpha_s$ is the associated confidence level. Bonferroni's inequality illustrates a lower bound for the simultaneous confidence level. Since $\alpha = 0.1$ for the confidence level of each performance criteria, the simultaneous confidence level is greater than 70% for this simulation. Various strategies are available to mitigate this situation, including making the confidence level higher, taking more runs of the simulation, and studying fewer performance measures simultaneously [LAW].

The third set of graphs is a presentation of the three network performance criteria measured for the sixth and eighteenth hours (0600 and 1800 UT) as the traffic rates increase, see Appendix D. Performance criteria are plotted for 5, 10, 15, 30, 45 and 60 messages per hour for propagation conditions 1, 3, 5, and 8 for each sound scheme, including the baseline case (no sounds).

The fourth set of graphs is a presentation of the three network performance criteria measured at the sixth and eighteenth hours (0600 and 1800 UT) as the frequency of scheduled sounds increases, see Appendix E. Each performance criteria is plotted for 4, 6, 10, 20, 30, and 40 sounds per hour (with respect to the network) for propagation conditions 1, 3, 5, and 8 at each of the traffic rates.

In the third and fourth sets of graphs, if a data point is missing then that simulation run failed against the stopping conditions for total queue size or number of shutouts. (See section 3.1.1.) For both sets of graphs the data points are measurements for that hour only and do not represent composites of the previous hours.

4.3 Analysis And Conclusions

In general, simulated network performance is better without sounding. The degree of difference depends on the frequency of scheduled sounds and on the traffic load. The significance of the difference will depend on the requirements of each specific network application of ALE HF radio. For example, the users of an operational, law enforcement network may not be able to tolerate average delays of more than one minute, while much larger delays are acceptable to the users of a radio network handling ordinary, low priority traffic, provided that a certain throughput is maintained.

The first major observation of this simulation study is that sounding generally hinders performance of the network, since sounding occupies station and channel time, for two examples, see Figures B-55, B-56 and C-45, C-46. No calls are possible to a station which is sounding and no calls are possible on a channel which is currently being sounded upon. The reduced call and link success rates and the increased message delays caused by the overhead of sounding may not be acceptable in some applications.

The second major observation, and exception to the first, is that for low traffic rates in poor propagation conditions, particularly during the poor part of the diurnal propagation variation, sounding improved network performance with at least statistical significance in the call success rate, see Figures B-1 and B-2, for example.

A third observation is that as the frequency of scheduled sounding increased, link success rate and call success rate decreased while delays increased, for example, see Figure E-4. As scheduled sounding frequency increases, the link success and call success rates decrease and message delays increase. In some cases there is improvement in performance in going from no sounds to low numbers of sounds per hour. This is seen particularly for the eighteenth hour, for instance, see Figure E-2. The is due to the updated information in the LQA table, acquired by the increased sounding frequency, allowing stations to identify the useable channels more quickly. After this peak there is generally a drop off in performance as the scheduled soundings increase. This is another way of illustrating the second observation above.

A fourth observation is that as the traffic loading increases while keeping the propagation condition and the sounding scheme the same, the measured network performance decreases, for example, see Figure D-1 or Figure D-6. This is due to traffic interfering with other traffic. This appears to be a more serious detriment to network performance than sounding is.

For certain cases in the better propagation conditions, there is an increase in performance as the traffic rate increases at the lower data rates. This is most likely due to the increased channel propagation quality information, acquired by increased linking. Each link provides a good channel quality assessment. In most of these cases there is a falloff in measured performance after a peak in the lower traffic rates.

4.3.1 Link Success Rate

Link success rate is, generally, slightly higher without using a sounding scheme, for example, see Figure C-29. This is due to channels becoming increasingly occupied by sounding stations as the sounding frequency increases which, in turn, results in more shutouts.

The link success rate decreases as the traffic level increases with the sound scheme fixed at the sixth and the eighteenth hours, see Figure D-1. This is due to stations transmitting or receiving message traffic occupying channels more frequently and making the channels unavailable for other traffic.

If a sound is in queue then another sound will not be added to the queue. So as the traffic load increases and station queues back up, scheduled sounds are precluded (or canceled) since they have less priority than messages. On the other hand, the sounds which are done by the stations can have more effect interfering with other message traffic at higher traffic rates. The link success rate generally decreases slightly as the frequency of sounding increases at both the sixth and eighteenth hours, see Figure E-8, for example.

There is little evidence in these results that the link success rate improves with sounding. The link success rate gets somewhat worse as the frequency of sounding increases. However the differences are generally not significant at the 90% confidence level, except at the higher sounding rates under the higher traffic loads, see Figures B-60 and C-46. Significant deterioration in the link success rate seems to be associated with increasing traffic loads.

4.3.2 Call Success Rate

Analysis of call success rate shows some surprising results. First, I note a diurnal variation at the lower traffic rates, which I believe is due to propagation conditions affecting the number of available, useable channels (out of 10), for example, see Figures B-17 and B-18. The call success rate is generally better in the first 10 to 12 hours of the period. Then there is a 2 to 4 hour transition to a call success rate noticeably worse for the second half of the day, followed by a transition to better conditions at the end of the period. This is not surprising since call success rate is related more to the propagation conditions on the individual channels. Link success rate, which does not appear to have much of a diurnal variation, is related more to the availability of any useable channels.

The surprising result here is that, with sounding, at the lower traffic rates, the call success rate is generally significantly worse in the first part of the period but is generally significantly better during the second part than the baseline case without sounding. This is seen for 5, 10, 15, and 30 messages per hour at the best propagation conditions (Condition 1) with the differences becoming less pronounced (but still significant) as the traffic load increases.

The diurnal variation is not seen, at all, at 45 or 60 messages per hour at propagation condition 1, see Figures B-59 and B-60. This is because traffic loading has become the dominant drawback to network performance.

The diurnal variation is also seen at the worst propagation conditions in the study (Condition 5), see Figures C-9, C-10, for example. The change in call success rate caused by sounding in the first part of the period is generally not so pronounced but still generally significant for a shorter period than that for propagation condition 1. In the second 12 hours the change is even more slight and is generally significant only at 5 and 10 messages per hour for just a few hours. As the traffic load increases to 15 messages per hour the sounding effect disappears, although the diurnal variation is still seen at 30 messages per hour, see Figures C-45 and C-46.

In both the best and worst propagation conditions, once the diurnal variation disappears (at higher traffic rates) the call success is slightly better without sounding in the first part of the period and hardly different with or without sounding in the second part of the period.

The conclusion here is that in low traffic conditions sounding may significantly degrade the call success rate when propagation conditions are relatively good. And as the propagation conditions get generally worse the presence of sounding can improve the call success rate. This implies that sounding as a feature to improve network operation should be variable and switchable. Sounding should be used only when it can improve the call success rate. Sounding improves the call success rate by providing information for the LQA matrix which allows the radio set to find the best channel more quickly. Sounding degrades call success rate when there are already sufficient useable channels. Sounding interferes with the traffic and does not provide enough information to the LQA matrix to make a difference in choosing good channels.

Call success rate decreases as traffic loading increases, with propagation conditions and sounding scheme remaining the same, see Figure D-7. Call success rate generally decreases as scheduled sounding frequency increases. In Figure E-1, the effect of sounding in the second half of the period is noted in the immediate improvement of call success at the eighteenth hour over the call success in the no sounds case. In the same Figure, note the corresponding decrease in call success rate at the sixth hour.

4.3.3 Average Message Delay

Average delay results exhibit a diurnal effect similar to that for call success rate. Generally the delays are greater for the cases using sounding than for the no sounds case.

An increase in delays is seen in the first part of the period at the lower traffic rates in propagation condition 1 with any sounding scheme. And the decrease in average delays is apparent during the second part of the period. The variation in performance measured by average message delay is similar to that measured by call success rate, see Figures B-5 and B-6.

For propagation condition 5, the average delays increase over the first part of the period and become even larger beginning at about the fifteenth hour and then decrease at the end of the period as the propagation conditions get better. With sounding the delays are slightly longer but the difference between sounding and no sounding does not appear significant at the 90% confidence level. In the second half of the period, the delays are not as great with sounding for the lower traffic rates as the delays for the baseline case; however, the difference is again generally not significant at the 90% confidence level, see Figures C-31, C-32.

For propagation condition 5, at 15 messages per hour there is a spike at the 20th hour, see Figures C-25 to C-38. This is due to one particular message (in one of the input data sets) from the Boulder, Colorado station destined for the station in Ft. Lauderdale, Florida. Because of poor propagation conditions (this is the longest link), this message could not be transmitted during the several previous hours. This single message colored the statistics for all three measurement criteria for the eighteenth through twentieth hours. I left this data in the report to indicate the possible effect of a single message on the network performance. I discovered this as I was doing a line-by-line verification of the program. This type of large delay is the cause of the wide variations in the 90% confidence intervals in the second half of the period, due to the large variance.

At 30 messages per hour the average delay traces are smoother and the variation in the confidence intervals is not as wide. Even though this is the same propagation condition, there are more messages for the statistics and the effects of one message is more easily absorbed. Note also that late in the period the degradation in the delay is significant for the cases of sounds scheduled every 3 minutes and every minute. This is illustrated by the average message delay graphs in Figures C-43, C-44 and C-47, C-48 which show that the differences in message delay between the sound and no sound case is significant at the 90% confidence interval.

4.3.4 LQA Tables

In doing line-by-line debugging or verification, I found that the LQA tables occasionally contained somewhat false or misleading information. The problem is when a station is attempting to link with another and is shut out because the destination station is busy, a closed channel is recorded for all of the channels except the one being used at the destination station. According to the calling station's LQA table, nine channels to the destination station were closed and one was busy when IONCAP output indicated several channels to be near 100% reliability at 5 dB. This situation would continue until the destination station finished, and the traffic was passed after a link up. The transmitting stations LQA matrix may now record one channel open and the rest closed.

The ALE radio station is robust enough to recover fairly quickly from this "bad" information although the LQA matrix can't possibly provide the radio set with a reasonable channel to try except maybe for one. The LQA table in this case contains a record of results of link and call attempts but not a measurement of channel propagation quality. Closed channels are recorded as closed no matter the cause. ALE radio sets can't detect another station's status or condition without linking up. If the desired destination station is busy the recorded LQA values will not be information on the channel quality.

A further problem could arise when the LQA table information is transmitted to another station by way of connectivity exchange protocols (which are not simulated here). Other stations could now have and act upon information indicating that a particular link was unavailable when one of the stations is merely busy.

A way to mitigate this is with degrading algorithms which will age the LQA data so that false information in the tables does not remain long in the table. Proprietary degrading algorithms are in use in ALE radio systems, but have not been standardized. It is possible that correct and useful information could also be degraded too soon by such algorithms.

Another method of avoiding the false information is for the individual stations to actively poll one another, to actually link up, for the sole purpose of evaluating the channels. This will probably add significant additional overhead to the operation of the network which would further degrade network performance.

4.3.5 A Time-In Protocol

The need for the time-in procedure mentioned in the description of the simulation program was discovered in line-by-line debugging of an unusual problem. The simulated network quickly locked up especially at higher data rates. The stations were sounding and attempting calls and links, but no message traffic was moving.

The problem was that each station would attempt to transmit all the messages and sounds in its own queue and would only be available to receive other traffic when it was idle, that is, the message queue was empty. Message queues become full at each station and no station is available to receive messages since they were all busy continually attempting calls. A simple way around this, without imposing some outside traffic control from a net control station, or using a complicated queuing or slotting discipline, is to have each station wait and scan for at least one full scan period or longer (scan every channel at least once) when that station finishes transmitting a message or sound and before it goes on to handle the next message in the queue. After a station receives a message it would take up the next item in the queue without scanning and attempt transmission. Scanning for one full scan period after transmitting cleared up the problem for the simulation.

It is possible to contrive a message data set that would still cause network lock up. The stations would be calling and sounding synchronously. I believe this condition to be very unlikely in practice. A small random delay added somewhere to the automatic procedures at each station would preclude this possibility.

4.3.6 Useable Channels, Sounding, and Performance

Network performance appears to be associated with the number of available useable channels. The effects of sounding on the performance of the network also appears to be associated with the number of available useable channels. This appears to be more strongly associated with the simulated call success rate than with the link success rate or average message delay. This association is not strong in every case and appears also to be associated with distance between stations. It is not possible to give general guidelines concerning the use of sounding without knowing the configuration of a specific network (distances between stations and frequencies available). The effects of sounding may be specific to each link.

For example, consider Figure A-1 (longest link) and Figure B-1. In the call success rate graph there is a falloff in the baseline performance measure from 1300-1500 UT which corresponds to the disappearance of channels with probability of linking (SNR better than 5 dB) greater than 0.9. After 2000 UT, as these good channels reappear and their number increases, the call success rate increases.

Notice that when sounding is used the simulated call success rate is greatly increased in the period 1500-2000 UT when there are no channels with probability of linking greater than 0.9. This is due to information gained by sounding enabling stations to identify the channels over which a link is most likely to occur. Thus it would seem that network performance is enhanced by sounding when there are a small number of available good channels.

Notice, however, that in Figure A-5, the shortest link, in the same propagation conditions as Figure A-1 that the number of channels with probability of linking greater that 0.9 is greatest when the number of high probability channels is the least over the longest link (Figure A-1), that is, in the period 1500-2000 UT. It would seem in this case that network performance is enhanced by sounding when the number of available good channels is the greatest.

Such contradictions and the number of links in the simulated network (90) naturally forced the analysis of the simulation output to composite network measures of performance. Information on conditions when sounding would enhance (or lower) network performance for a specific network could be determined by simulation of that network or by direct experience.

5. FUTURE SIMULATION OF ALE HF RADIO NETWORKS

5.1 Supporting Federal Standards Development

A current problem in research on ALE networks is that there are no available HF radio networks to conduct active network testing. This is a significant problem in the development of Federal HF Radio Standards. ALE radio features (including networking features and protocols) are not included in the standards until the feature is tested and the feature passes such testing. Such testing must include compatibility testing with other features and other versions of ALE radios, and extensive interoperability testing. This ensures interoperability of the feature between different manufacturer's radio sets. The implementation of the feature may be different in each manufacturer's sets.

It will be difficult to set up a network with a set of ALE radios which have the feature to be tested built-in via either hardware or software. This can be an expense that vendors and researchers as well as users may not wish to pay.

Simulation of the advanced features of ALE HF Radio Networks may provide a partial solution. Advanced networking features may be simulated in lieu of testing. The features may be simulated at the network level as shown by this report and at the radio set level (passing data bit-by-bit) in the laboratory. Successful results may allow standards development to proceed without testing.

I believe that simulation should not be substituted for actual "over-the-air" testing. Even well validated simulations only approximate the performance of a real network. Simulations are known to do a better job at comparing alternatives than in providing reliable performance data [Law].

5.2 Future Modelinq Efforts

One area that could be studied by simulation is the question of interference. A station may attempt to call or sound on a channel that is occupied by one or more other stations. This may happen when the calling station cannot detect traffic on that channel due to adverse propagation conditions, extreme distance, low power, or radio set malfunction. The simulation described in this report assumes that occupied channels can always be detected. If this assumption is dropped, then effects on network operation of such interference can be determined by simulation.

A number of questions concern network routing procedures. If a station is unable to transmit a message to another station, how does the calling station route the message through other stations? One method is to use LQA information that is shared among radio stations. A station could obtain such connectivity information via automatic, scheduled broadcasts or by direct query of other stations or even by polling and collection by a central station which in turn makes the data available to other stations in the net. From this connectivity information a route could be chosen automatically. Stations along this route may be obliged to re-transmit the message as specified by the route. An acknowledgement of receipt of the message may be sent back by the receiving station along the same or another route.

One alternative is to allow intermediate stations to re-transmit the message as if the message originated at that intermediate station. The message might be transmitted on a better (or worse) propagation path than originally intended by the first station.

Another alternative is to use routing tables. The idea is that a station would attempt to transmit along a preset route when a direct path to the destination station is not available. The alternative routes could be based on least distance or some other factor. In these cases, the exchange of connectivity information could be unnecessary although such information may be needed if the routing tables were determined by a dynamic process.

A simulation can determine the effects of each of the methods of exchanging connectivity information. A simulation can also indicate the effects of alternative methods of channel selection other than by using sorted LQA information. For example, select higher frequencies first, lower frequencies first or select at random. Some radio stations may even be able to use maximum useable frequency (MUF) and lowest useable frequency (LUF) provided by IONCAP or other propagation prediction programs.

Other measures of network performance may be studied by simulation. For example: throughput of messages, probability of linking on the first call, or even maximum delay.

6. SUMMARY

I have described a discrete event computer simulation of an ALE HF radio network. The simulation provides evaluation of network performance by measuring call success rate, link success rate, and average message delay.

The simulation was used to study the effects of sounding on network performance. Sounding is the periodic broadcast of identification information on all available idle channels. The stations in the network listen to sounds when not otherwise occupied. The channels can thus be evaluated by the listening stations. The problem is to discover, by simulation, if the additional overhead (station time and channel time) for sounding is detrimental to network performance, or if the additional available evaluation of channels enhances network performance by allowing stations to identify the good channels and avoid the bad channels.

The evaluation of network performance in this study indicates that sounding is generally detrimental to network performance. This is due to the additional overhead and interference of sounding with other traffic. An exception to this is that at low traffic rates, in poor propagation conditions caused by diurnal variation, sounding can significantly improve network performance.

The study also showed that the performance of the ALE HF radio network suffers as the message traffic rate increases. Increasing the traffic rate appears to be more detrimental to network performance than does increasing the frequency at which the individual stations are scheduled to sound. This is partly due to the limitation that only one sound is allowed in the message queue at each station. At higher traffic rates many scheduled sounds are precluded or canceled due to queue sizes.

More detailed results on the effects of sounding on network performance are not possible since network performance is related to the configuration of the network. Specifically the frequencies available and the distances between stations effect the performance of the network with and without sounding. Simulation of a specific network could provide this information.

Link Quality Assessment (LQA) tables at each station contain channel propagation information which is obtained by analysis of active channels during operation. The simulation study indicates that the LQA matrix may contain false or misleading information. If a station is busy, either transmitting or receiving, then for any calls from another station, that calling station will record the channels tried as closed. The channels have not actually been evaluated and the information in the LQA table is a record of the failed link attempts rather than a record of the channel evaluation. The channels may actually be useable, not closed.

The simulation study also emphasized the need for a pause, after transmission of a message or completion of a sound, to scan for incoming traffic. If there is no pause then the stations will handle every message waiting in queue prior to going to scan to listen for incoming traffic. At higher traffic rates with the associated larger queues, the network quickly locked up. Every station was attempting to transmit and no station was scanning. No traffic was moving at all. A pause to scan each channel once for incoming traffic is a reasonable minimum solution. This pause cleared up the problem in the simulation.

I outlined directions for future simulation work for ALE HF radio networks. I also indicated the importance of simulation to the development of Federal standards for ALE HF radio. No feature is included in the standards without being tested. Such over-the-air testing is not always possible. An alternative is to simulate new features in lieu of testing to allow standards development to continue. I believe that simulation should not replace over-the-air testing since, at best, simulation is an approximation of network operation.

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15. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

A discrete event simulation model for an HF Automatic Link Establishment (ALE) radio network is described. The simulation model is based on Federal Standard 1045 "Telecommunications: HF Radio Automatic Link Establishment." The simulation is used to study the effects of sounding on the simulated network. Sounding is the periodic broadcast transmission of identification information by a radio station that may be monitored by other stations. Sounding is used to evaluate the propagation quality of the available HF radio channels (frequencies). The station and channel overhead associated with sounding is indicated by this simulation to be generally detrimental to network performance. The exception is that in poor propagation conditions, at low traffic rates, sounding may significantly enhance some aspects of network performance.

16. Key Words *(Alphabetical order, separated by semicolons)*

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