Fast Propagation Predictions for HF Network Simulations

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Abstract

The complexity of current HF radio networks (such as the SCOPE Command HF Global Communications System) has renewed interest in techniques for efficiently simulating long-haul HF radio networks. Because the dynamic propagation effects of skywave paths are the distinguishing characteristic of HF network simulations, we need to accurately simulate the connectivity among HF stations. Predictions of ionospheric propagation are typically very costly in either time or memory or both. There is a clear need for accurate, efficient techniques to predict the path losses between pairs of HF stations.

This paper describes a suite of techniques that has been developed and applied to simulations of large networks of fixed and mobile radios. These techniques approximate the accuracy of the best propagation prediction programs while minimizing both the memory and CPU time used during a simulation. The paper discusses the accuracy of the predictions along with the memory requirements and running time of the new propagation prediction techniques.

Introduction

In any HF radio simulation, the model used for the channels is of critical importance. This is especially true for HF *network* simulations, because many of the interesting effects result from the differences in propagation among the stations. For example, station A may be transmitting to station B on a frequency that propagates between B and C, but not between A and C. As a result, if C wishes to link with B, C may listen on the channel and, not hearing the transmissions from A, begin transmitting to B and interfere with the transmission from A. Thus, it is critical to accurately model the dependence of link propagation on the time of day, sunspot activity, the frequency chosen, the types, locations, and orientations of the sending and receiving antennas, and the other equipment and protocols in use.

The overall performance of an HF network is a result of how effectively it uses the links and stations available. Due to the complexities of skywave propagation, HF radio networks are less amenable to analytical modeling than other networking technologies, and usually require simulation for accurate performance prediction.

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Hierarchical HF Networking Simulator

This section presents an overview of a hierarchical simulation suite for automated HF radio networks. A layered view of the functions of an automated HF network is shown in Figure 1 (from [1]).

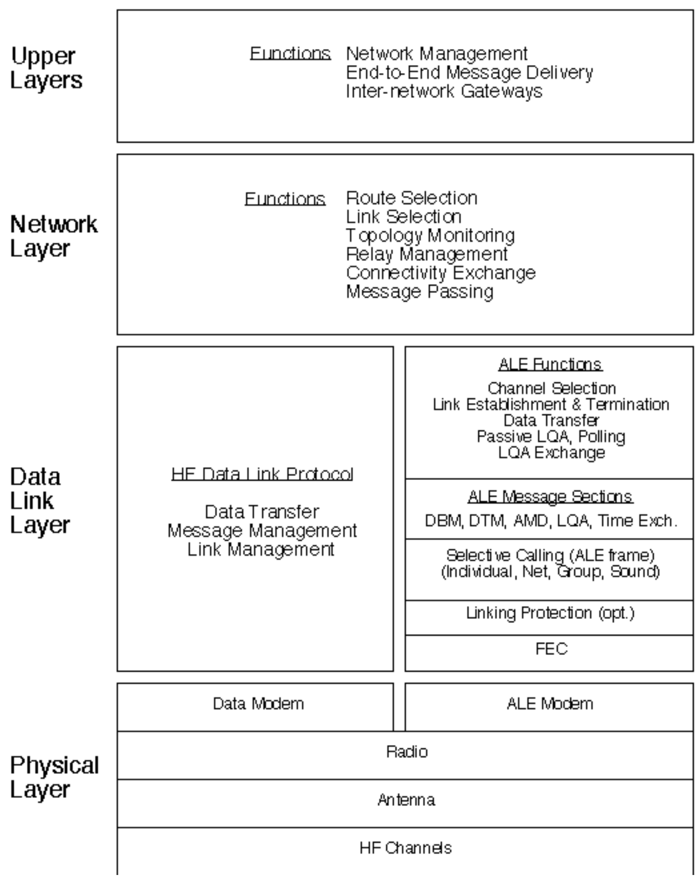

Figure 1: HF Automation Functions

The simulation suite, shown in Figure 2, is structured similarly. All of the modules are independent, and communicate with each other (and with multiple instances of themselves) using "events." For example, each instance of a Traffic Source (a message generator) sends itself events to prompt future messages, and also uses events to post messages to the node controller (HFNC) for delivery to other stations.

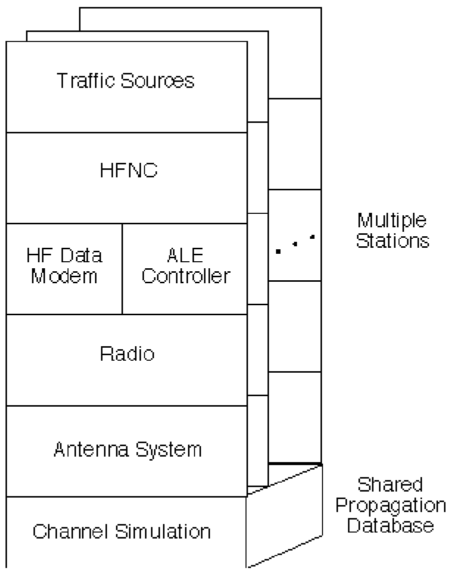

Figure 2: Simulator Structure

Each module simulates corresponding entities to the degree of detail appropriate for an investigation. For example, channel occupancy and the utilization of Automatic Link Establishment (ALE) assets are of primary interest in the system engineering of ALE networks. In this case, the ALE controller is simulated in full detail while the upper layers are simulated only to the extent necessary for realistic traffic loading. Similarly, the modem simulation needs only produce the correct effects of channel conditions on the integrity of ALE frames, and the channel simulation must accurately model propagation effects that affect the modem simulation, principally narrowband signal-to-noise ratio (SNR).

SNR Prediction

For the ALE modem [1] and the serial-tone HF data modem [2], performance over skywave channels is almost entirely a function of SNR [3, 4], although severe multipath effects will affect the ALE modem when the multipath spread exceeds about 4 ms. SNR on an HF link is a function of the following variables:

- Transmit antenna location
- Receive antenna location, and gain in the direction of propagation
- Transmit effective radiated power
- Receiver effective noise
- Frequency
- Time of day
- Day of year
- Sunspot number

For the purposes of network simulations, useful SNR predictions for each link can be derived from IONCAP [4] or one of its descendants (e.g., VOACAP or ICEPAC). Such prediction programs use a combination of measured data and generally-respected algorithms to make statistical predictions of signal strength for arbitrary links. When combined with noise estimates, the programs produce estimates of median SNR over a link as well as estimates of the first and ninth deciles of SNR. These can be used to generate representative random processes for the SNR values on the links of interest.

Of course, when a radio is tuned to a particular frequency, it will receive a composite signal that includes the effects of all transmissions worldwide that are in progress on that frequency. To compute the effective SNR of the composite signal (for receivers that lock onto the strongest arriving signal), it is sufficient to compute the ratio of the strength of the strongest arriving signal to the (noncoherent) sum of natural noise plus all other signals. When SNR processes are computed for each link as described herein, the strength of each arriving signal can be readily extracted since all SNRs are computed relative to the same local noise.

Channel Simulation in Static Networks

In the simplest case, all stations in a network are stationary. The SNR deciles for all of the possible links can be computed once, and reused throughout the simulation. The size of such a table grows linearly with the number of frequencies and as the square of the number of stations in the network, but should not consume more than one megabyte for networks of practical size.

Denoting the hour by subscript h, the frequency by subscript f, the sending station by subscript s, and the receiving station by subscript r, we can precompute the first, fifth, and ninth deciles of the SNR, $S1_{hfsr}$, $S5_{hfsr}$, and $S9_{hfsr}$ using a prediction program. When the SNR on a link is required during simulation, the appropriate set of three channel parameters is retrieved, two uniformly-distributed random numbers u_1 and u_2 are drawn, and an estimate of SNR_{hfsr} is computed as follows. First, a normally distributed random variable z is computed from u_1 and u_2:

$$z = \cos(2\pi u_1)\sqrt{-2\ln(u_2)}$$

Then the sign of z is used to determine whether the SNR value will be above or below the median:

$$SNR_{hfsr} = \begin{cases} S_{5hfsr} + z\left(\dfrac{S_{5hfsr} - S_{1hfsr}}{1.28}\right) & z < 0 \\ S_{5hfsr} + z\left(\dfrac{S_{9hfsr} - S_{5hfsr}}{1.28}\right) & z \geq 0 \end{cases}$$

The time required for computing the parameters was measured on an IBM RS/6000 model 580 using Method 23 of VOACAP 96.0213. For eleven frequencies, 24 hourly parameter sets are computed in 1.1 s. This equates to about 4 ms per set. Computation of SNR samples on the same machine takes about 7 µs per sample after the parameters are precomputed.

An example application of this static approach to channel simulation may be found in [6], which describes an HF radio network that links a number of nuclear power plants within the Russian Federation.

Channel Simulation in Dynamic Networks

Many applications of HF radio involve mobile platforms. For these networks the static approach described above is clearly untenable (unless the mobile platforms can send and receive calls only at locations for which propagation constants have been precomputed!).

The straightforward solution for links to and among mobile stations would simply use calls to the prediction program during the execution of the simulation. From the measurements cited above, though, it appears that this would result in nearly a 1000-fold slowdown in the channel simulation. In absolute terms, a network simulation can easily call the channel simulation routine 10,000,000 times as it simulates a moderate-size network through a few hours of simulated time. This would mean that 40,000 s (over 11 hours) would be consumed for the channel simulation alone.

It is clear that a more efficient approach to channel simulation in networks of mobile stations is required. The next section describes such an approach.

Interpolated Propagation Prediction

The high speed of using tables of precomputed propagation parameters can be achieved to great extent for mixed static/dynamic networks by computing a table of parameters for links from each fixed station to grid points located throughout the world. The storage requirements for these tables grows only linearly with the number of fixed stations and the number of frequencies, but as the square of the grid density (e.g., the number of points on the equator).

When the SNR is required for any link that involves one of the fixed stations, we simply retrieve the parameters from the corresponding table for the corners of the grid square that encloses the other station (fixed or mobile) and interpolate among those sets of parameters to estimate the parameters for the interior point.

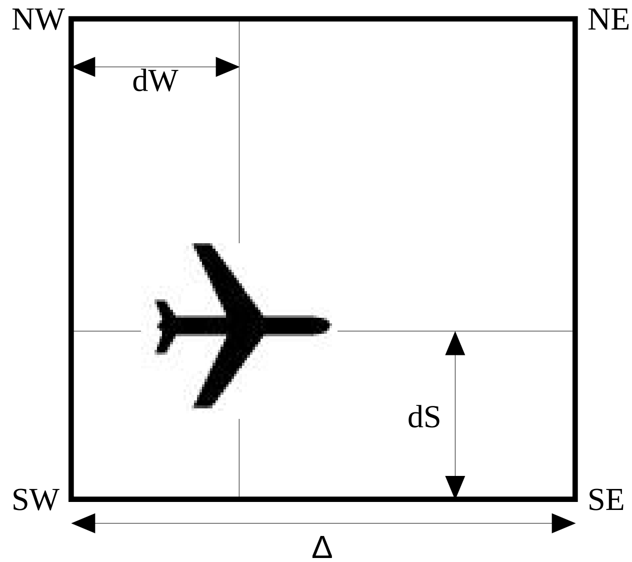

Figure 3: Interpolation Example

For example, an arbitrary propagation parameter X would be computed as follows for the position of the aircraft shown in Figure 3:

1. Retrieve parameter values X_{SW}, X_{SE}, X_{NW}, and X_{NE} from the table of precomputed values for the fixed station at the other end of the link.

2. $$\begin{aligned} X &= X_{SW}\left(1 - \frac{dS}{\Delta}\right)\left(1 - \frac{dW}{\Delta}\right) \\ &+ X_{SE}\left(1 - \frac{dS}{\Delta}\right)\left(\frac{dW}{\Delta}\right) \\ &+ X_{NW}\left(\frac{dS}{\Delta}\right)\left(1 - \frac{dW}{\Delta}\right) \\ &+ X_{NE}\left(\frac{dS}{\Delta}\right)\left(\frac{dW}{\Delta}\right) \end{aligned}$$

On the RS/6000 used for the timing experiments, this interpolation adds only 2 µs to the 7 µs required to compute a sample SNR. The speed of this technique is therefore quite attractive. We must now evaluate the *accuracy* of the interpolated SNR estimates compared to direct estimates from the prediction program.

Accuracy of Interpolated Estimates

This section presents the results of an evaluation of the degree to which link SNR estimates that use interpolated parameters differ from those that use directly-computed parameters.

Methodology

For the experiment, five stations were selected from the fourteen fixed stations in the SCOPE Command network: Andersen (Guam), Ascension, Croughton (UK), McClellan AFB (CA), and Thule (Greenland). For each fixed station, a destination 15° grid square was selected in such a fashion that the experiment contained a mixture of polar, temperate, and equatorial links of varying distances and with both north-south and east-west links (see Table 1). SSN was 10 and the month was June.

Each of the destination 15° grid squares was subdivided first into a 5° subgrid. The center square of this grid was then further subdivided into a 1° grid as illustrated in Figure 4. Two series of comparisons were then performed for each propagation path over 24 hours and 11 frequencies (3 to 21 MHz):

1. Predict the median SNR at each 5° grid point using interpolation from the corners of the 15° grid square. Compare this value to that predicted using direct execution of VOACAP.
2. Predict the median SNR at each 1° grid point using interpolation from the corners of the 5° grid square and compare to direct predictions as above.

Because the uncertainty in the VOACAP predictions varies widely with time and geography, the method used for comparisons was made relative to the standard deviations of the direct predictions. The difference in the median predictions was normalized by dividing by the standard deviation of the direct prediction.

Table 1: Paths Used in Accuracy Experiment

Fixed Station			Destination			Link	Great Circle
Base	Lat	Lon	Vicinity	Lat	Lon	Orientation	Distance (km)
Guam	14N	145E	N Guinea	8S	142E	N-S	2360
Ascension	8S	14W	Brazil	8S	52W	E-W	4200
Croughton	52N	0E	Warsaw	52N	22E	E-W	1538
McClellan	39N	121W	E Pacific	22N	128W	N-S	1888
Thule	77N	69W	N Atlantic	52N	38S	N-S	3060

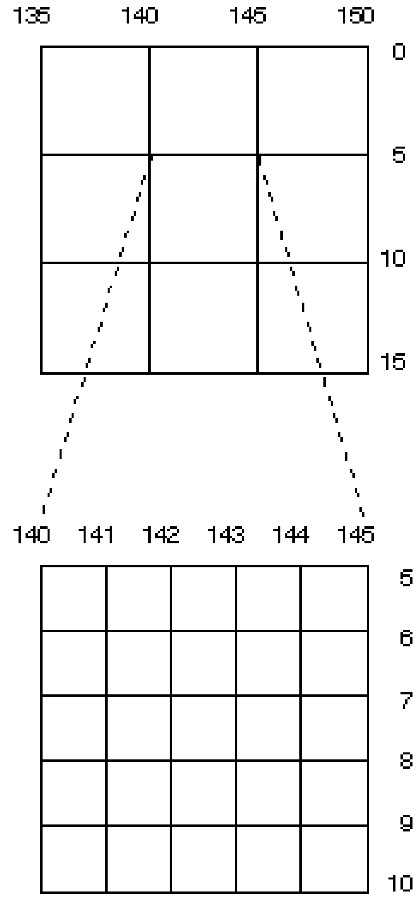

Figure 4: Example Subgrids for Accuracy Comparisons

Results

In evaluating this technique for use in network simulations, the most critical metrics from this experiment are the median and maximum number of gross mispredictions of propagation. The rate of gross mispredictions is defined as the fraction of times the interpolated SNR for a particular hour for a particular destination grid location varied by more than one standard deviation from the presumably more accurate direct prediction. Such errors are noticeable in a simulation when at least one of the interpolated or direct SNR prediction fell in the critical transition region of 0 to 15 dB. (Below this range, channels are unusable for voice and marginal for data; above this range, variations in SNR affect data rate but have only second-order effects on the usability of a link for linking or communication.)

Table 2 summarizes the median and maximum number of gross mispredictions over 24 hours for the full destination grids from each fixed station.

Table 2: Results of Accuracy Experiment

Fixed Station Location	Misprediction Rates (24 hr, 3 - 21 MHz) 15° - 5° Median	Maximum	5° - 1° Median	Maximum
Guam	0.9%	9.1%	0.8%	6.4%
Ascension	3.2%	9.8%	0.6%	1.9%
Croughton	0.0%	7.6%	0.0%	0.0%
McClellan	2.3%	7.6%	0.0%	0.0%
Thule	4.0%	20.1%	0.2%	2.3%
Average	2.1%	10.8%	0.3%	2.1%

As expected, interpolation accuracy improves as the density of grid points increases. A 15° grid spacing produced marginally usable accuracy in some cases, but gross misprediction rates ranged up to 20%. At a 5° grid spacing, however, there were no egregious mispredictions for the mid-latitude links, and the median rate of such mispredictions was always below 1%. This level of accuracy is not ideal, of course, but is of a suitable order of magnitude for use in simulations.

Storage Considerations

The storage required for tables grows inversely with the square of the grid spacing. Thus, 5° tables require 9 times as much storage space as 15° tables. For our purposes, a 3 kHz SNR range of –128 dB to +127 dB is sufficient. Therefore each table entry can be stored as three 8-bit bytes, and a global 5° grid requires about 8kB per station per hour per channel. Tables for 14 stations, 12 channels, and 24 hours consume 30 MB on disk, but can be paged into 2.5 MB.

Mobile-to-Mobile Station Propagation

The interpolation technique requires that at least one end of each path be fixed, so mobile-to-mobile paths are not directly supported. When two aircraft are within line of sight, the direct-wave equation can be used. In other cases, the path loss can be approximated as follows:

- Translate both mobiles so that one is located over a nearby fixed station.
- Interpolate as above using the translated location of the other station.
- Compensate for the translation.

While this latter approach is seldom as accurate as the fixed-to-mobile interpolation technique, it may be sufficiently accurate for computing air-to-air interference.

Conclusions

Prediction of ionospheric propagation is a complex task that allows for tradeoffs among speed, accuracy, and memory requirements. A suite of techniques for quickly predicting ionospheric propagation for HF radio network simulations has been developed that is capable of achieving nearly three orders of magnitude in speedup while losing little of the accuracy of ionospheric prediction programs.

Another possible technique for fast propagation predictions is modification of the prediction programs themselves to reduce execution time. This approach is the subject of current work.

Acknowledgements

In a field as near to religion as ionospheric modeling, one must be careful in naming contributors to a technique that is admittedly less accurate than those that came before! The author takes full blame for all blasphemy, and acknowledges with gratitude the contributions of Greg Hand of NTIA, John Goodman of TCI/BR, Robert Desourdis of CACI, and Robert Couch and Gary Schmieding of SAIC who surely kept this abomination from being worse than it is. Thanks also to Wayne Foemmel and the whole SCOPE Command engineering community for lively and useful discussions.

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