NETWORK SIMULATION FOR ADVANCED HF COMMUNICATIONS ENGINEERING

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Abstract

Harris Corporation and the State University of New York at Buffalo are conducting a collaborative project to develop an HF network simulation framework based on the ns-2 open-source network simulator. The framework will contain models of HF channel characteristics, waveforms, protocols, and typical traffic loads, so as to be useful for analyzing HF radio networks under real-world conditions. This paper presents an overview of the project's objectives and strategy, and discusses an approach to incorporating a model of HF surface wave propagation into the simulation framework.

1 Introduction

HF radio has a venerable history in both military and civil communications, based on its ability to provide long-range connectivity at low cost and without a fixed infrastructure. Recent advances in HF radio communications technology promise to expand the range of applications HF can support. The benefits of advances in waveforms and modems, Automatic Link Establishment (ALE) protocols, and data link protocols can be demonstrated to some extent over a single point-to-point link: increased throughput and reliability from the modem waveforms and data link protocols, and faster and more reliable linking from ALE. However, with the increasing prevalence of network-centric operations in both military and civil domains, it is becoming important to evaluate HF communications techniques in terms of the performance of an entire network rather than just of a single link. This becomes especially important as we focus on the application to HF of network-aware and globally-aware techniques such as those of cognitive radio.

Network simulation has proved to be of great value in analyzing the performance of both wired and wireless communication networks. In such simulations, one typically prepares and executes a network model composed of three component models: a *traffic model* describing the attributes and service requirements of the traffic to be delivered; a *bearer model* describing the waveforms, protocol stack, and other functions used to deliver the traffic; and a *channel model* describing the propagation of communications signals through the physical medium over which traffic is to be delivered. For an HF network simulation, each of these component models must take into account the distinctive features of the HF communications environment and technology. The channel model must reflect the characteristics of the sky wave and surface wave propagation modes prevalent at HF, in contrast to the line-of-sight propagation typically assumed in wireless network simulations. The bearer model must reflect the relevant characteristics of the waveforms and protocols used at HF, and the traffic model must represent the traffic characteristics of the most desired and most feasible applications for HF communications.

Network simulations have typically used a simulation framework such as the commercial products OPNET Modeler® and QualNet® and the open-source systems ns-2 and ns-3. In this paper we present a simulation approach for HF networks that is based on an open-source simulation framework and includes traffic, bearer, and channel models addressing at least some of the distinctive features of HF communications. In addition, we report our progress in realizing HF network simulations based on this approach.

2 Simulation objectives and requirements

2.1 Investigation topics

Even after the many years HF radio has been in use, it continues to have critical applications and remains an area of technological innovation. Advances in HF waveforms, protocols, and other techniques have made HF a potentially viable medium for new modes of communication such as those of the worldwide Internet. As these new possibilities are explored, it becomes necessary to evaluate new technologies under conditions reflecting the distinctive challenges of HF radio and the scale and complexity of the envisioned new applications. In particular:

1. The propagation modes used for HF communications, surface wave and sky wave, create special challenges [4]. Surface wave propagation, the simpler of the two cases, can still exhibit variable communications range and

reliability. However, HF communications more typically rely on ionospheric (sky wave) propagation, which limits the range of frequencies that can be used depending on the link distance and ionosphere characteristics. The latter characteristics vary over time due to both predictable (time of day, season, sunspot cycle, station locations, path distance) and unpredictable factors (ionospheric motion, solar events). The predictable factors can be addressed through intelligent communications planning. The unpredictable ones, however, must be taken into account in the design of the waveforms, protocols, and other techniques used for HF communications [2]. To analyze and validate the design of such techniques requires simulation environments reproducing them with sufficient fidelity, and this is as true of network-level simulations (albeit with some inevitable simplifications) as of simulations at the level of an individual link.

2. HF communications typically involve potential contention for access to a shared medium, and hence have requirements for media access control (MAC) capabilities. However, for HF, media access has typically been provided as an additional aspect of an Automatic Link Establishment (ALE) capability having the primary function of finding a usable frequency for a link. To accomplish these multiple objectives within a single facility can give rise to considerable complexity and some difficult trade-off decisions. To properly analyze and validate such an ALE/media access solution requires a simulation environment modelling the variable and unpredictable aspects of the communications environment (sketched in #1 above) with sufficient fidelity.
3. Recent years have seen growing interest in the potential benefits of adding intelligence to radio systems, under the banner of “cognitive radio”. The cognitive radio technique receiving the greatest attention is dynamic spectrum access (DSA), in which radios intelligently sense the presence or absence of other transmissions on communications frequencies and infer opportunities for spectral reuse. Successful spectral reuse relies upon some form of diversity: *frequency* diversity (different users transmit on different frequencies), *time* diversity (different users transmit at different times), or *spatial* diversity (even while transmitting simultaneously on the same frequency, different users do not interfere because they are sufficiently separated in space) [20]. Of these, it is spatial diversity that may have the greatest potential benefit, since the other two are already in use at HF to some extent. However, the applicability of spatial diversity to HF communications is questionable: when ionospheric propagation makes signal propagation possible over long distances but with limited predictability, how can we be confident that two (or more) HF links are separated sufficiently in space so as to be able to communicate on a reused frequency without interference? Cooperative techniques (in which users share information as to spectral occupancy) may help but carry a cost in overhead as well as questions as to the reliability and timeliness of the information shared. Here again, there is a need for simulation studies, performed in a simulation environment accurately reflecting the distinctive aspects of HF communications, to illuminate these questions.

2.2 Model components

2.2.1 Channel model

It is HF sky wave propagation that is most commonly used in HF communications, because it is the ionosphere’s refraction of HF radio waves that makes possible the low-cost long-distance communications that are HF’s distinctive niche. Sky wave channels are dispersive channels characterized by Doppler spreads (fading bandwidths) of typically up to roughly 5 Hz and multipath spreads of up to 6 ms in mid-latitude circuits [15]. For network simulation, a practical compromise is to assume that the Doppler and multipath spreads will remain toward the lower ends of these ranges, as it then becomes reasonable to represent the performance impact of these modest Doppler and multipath spreads to be equivalent to a downward biasing of the SNR.

SNR estimates for sky-wave HF links are most commonly obtained from an automated propagation prediction program such as VOACAP. The underlying model used in these programs is a statistical model; the SNR predictions provided are estimates at the median or other percentile of a probability distribution. The distributions result from not only uncertainty but also the real-time variability of ionospheric propagation, which causes the received signal strength and hence SNR to continuously vary [2]. This being the case, it can be recommended that network simulations use an estimated SNR with similar real-time variation characteristics; Johnson [11] describes one approach.

Surface wave, the other common mode of terrestrial HF propagation, can in some scenarios be the principal mode relied upon for communication. Even when ionospheric propagation is expected, on relatively short Near Vertically Incident Skywave (NVIS) links, the received signal can also contain a significant surface wave component giving rise to multipath. In this project we have chosen to focus first on incorporating a surface wave propagation model into a network simulation; section 4 of the paper will describe this further.

2.2.2 Bearer model

The definition of a bearer model for an HF network simulation is complicated by the diversity of techniques that are used – often simultaneously – in HF networks. Packetized voice techniques such as VoIP have been slow to find applications in HF radio, because the limited communications bandwidth (3 kHz, traditionally) has made the packet overhead unaffordable. Instead, ALE techniques have been used to reserve a channel for digital voice traffic in the form of continuous bit-stream transmissions of variable length. The modem waveforms used are typically the 3 kHz waveforms of MIL-STD-188-110C [13] at 2400 or 600 bps; the digital voice coding is typically that of LPC-10 or MELP. Even in networks whose traffic is limited to digital voice of this sort, interesting network capacity problems can arise that lend themselves to investigation through network simulation; Koski [12] describes one example.

Most present-day HF networks are used for data traffic in place of or in addition to voice (digital or analogue), and these are the kinds of networks that will be of the greatest interest for simulation. The waveforms and protocols used most often for HF belong to either of two profiles, a '2G profile' and a '3G profile'. In the 2G profile, the 3 kHz serial tone modem waveforms of MIL-STD-188-110C are used for data transfer at rates of typically 75 to 9600 bps; a network simulation will also need to take into account the latencies resulting from preambles and interleaving. The NATO standard STANAG 5066 [19] defines a widely-used data link protocol for HF, which has the capability to adaptively select from among the data rate and interleaver settings provided by the MIL-STD-188-110C waveforms in response to channel conditions. STANAG 5066 defines its own MAC layer techniques suitable for single-channel operation; for operation on multiple channels, it is typically married with the second-generation ALE technique defined by MIL-STD-188-141C. STANAG 5066 data link traffic is inherently packet-oriented, which indicates that a simulation can straightforwardly model the success or failure of packet delivery based on known frame error rates of the modem waveforms.

The '3G profile' contains the suite of protocols and waveforms defined by NATO standard STANAG 4538 [18], including ALE techniques, Type II Hybrid-ARQ protocols, and specialized burst waveforms having specific uses in the protocol framework. Various aspects of these protocols will complicate the task of modelling them in a simulation framework; this is an area that will require further study.

2.2.3 Traffic model

The traffic model component of an HF network simulation needs to include not only the forms of traffic most commonly used in present HF networks, but also the kinds of traffic resulting from the new applications made possible by next-generation HF technologies such as the wideband HF waveforms of MIL-STD-188-110C Appendix D. Voice will play a significant role, often in the context of mixed voice/data networks. Data will take the form not only of E-mail and other similar message formats, but increasingly, IP traffic generated by network-centric applications such as situational awareness.

3 Simulation approach

For this project, we have chosen to develop an HF network simulation framework based on the public-domain network simulation framework known as Network Simulator 2, or ns-2, an object-oriented discrete event simulator targeted at networking research. ns-2 is written in C++ and OTcl, where C++ is used to implement code that needs fast execution, such as specific protocol actions, and OTcl is used for less time-critical functions and to bind the C++ blocks together. Entire networks can be modeled by putting together new and existing C++ and OTcl components.

A distinctive advantage of ns-2 is its modularity, which allows a user to modify and test just one single component without having to be concerned with other components. Commonly used network protocols are already implemented, including transport layer protocols, routing protocols, queue management, and an accurate IEEE 802.11 implementation, among others. In addition, ns-2 is widely used in the academic community and many studies have been performed verifying its accuracy. For this project, this leads us to prefer ns-2 to ns-3, which, while similar in concept and having some attractive features, lacks the extensive research track record and validation history of ns-2.

4 Channel model investigation

4.1 GRWAVE

GRWAVE is a numerical ground wave propagation prediction model for MF and HF frequencies that is recommended by The International Telecommunication Union (ITU) [8][17]. Specifically, this model predicts the electrical-field strength and transmission loss over a curved, homogeneous, smooth earth [5]. GRWAVE takes as input parameters the height and polarization of the transmit and receive antennas, the electrical properties of the ground (conductivity and permittivity), the frequency, and the troposphere refractivity. GRWAVE employs four different algorithms to estimate field strength and path loss: the flat earth model, the method of geometrical optics, numerical integration techniques, and a residue series solution. For more information, the reader is directed to the useful overview by Bash [1].

4.2 Millington method

The estimation of the ground wave field strength depends on both the distance between the sender and receiver as well as the *specific path* between them. For a single homogenous path, the GRWAVE model can be implemented directly. However, most paths will include multiple types of terrain constants. In this case, we need to use the Millington Method, described in the ITU Recommendation (ITU-R P. 368.9) [8].

The Millington Method applies the reciprocity condition by simply averaging the forward and reverse field strength values, and is defined by

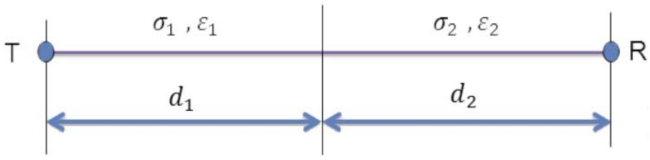

Figure 1. Non-Homogeneous Path

$$E_f = E_1(d_1) - E_2(d_1) + E_2(d_1 + d_2), \quad (4.2.1)$$

$$E_b = E_2(d_2) - E_1(d_2) + E_1(d_1 + d_2), \quad (4.2.2)$$

$$E_t = \frac{E_f + E_b}{2}, \qquad (4.2.3)$$

where $E_1(d)$ is the field at distance d computed using conductivity and permittivity values σ_1 and ε_1 (and likewise for $E_2(d)$), E_f is the *Forward Field* from the transmitter to the receiver and E_b is the *Back Field* in the opposite direction, Receiver to Transmitter. Both of them must be calculated to obtain the reciprocal total field E_t [3].

4.3 Terrain information

The Millington method considers smooth non-homogeneous spherical Earth terrain profiles, recognizing that different sections of a propagation path may have different conductivity and permittivity values. To simulate communications in a particular region of interest, it may be desirable to use measured values where these are available. Currently, there is no digital high-resolution conductivity database available. However, ITU-R provides a detailed atlas of ground conductivity in its Recommendation P.832-2 [9], which could be used as a basis for groundwave predictions.

4.4 Model integration

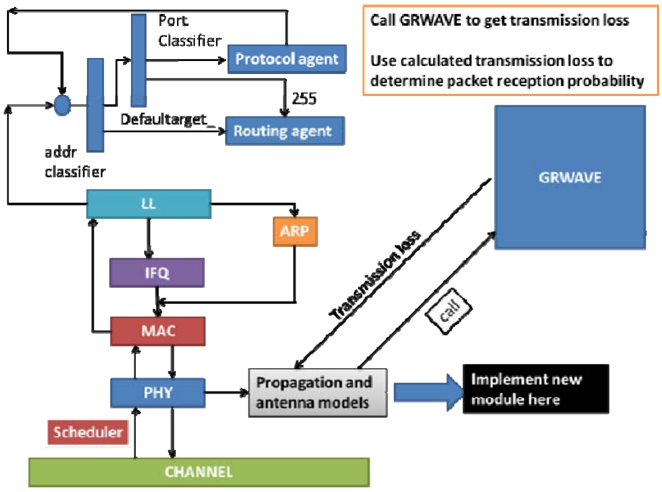

Figure 2. Embedding GRWAVE within ns-2

In this project, we are incorporating GRWAVE into the ns-2 model framework as an extension of the PHY layer model (see Fig. 2). The receiver, based on location of both the sender and receiver and the terrain between the two, will calculate the ground wave path loss for each section of the terrain (see Fig. 3).

After employing Millington's method, we will be able to determine the basic path loss and field strength values within a specific simulation scenario. This field strength will then be incorporated into the ns-2 shadowing model.

The shadowing model consists of two parts. The first one is the path loss model, which provides the ground wave path loss as calculated by GRWAVE. We can represent this loss as the ratio of the received power at distance d, with respect to the receive power at some “close” distance d_0, shown as

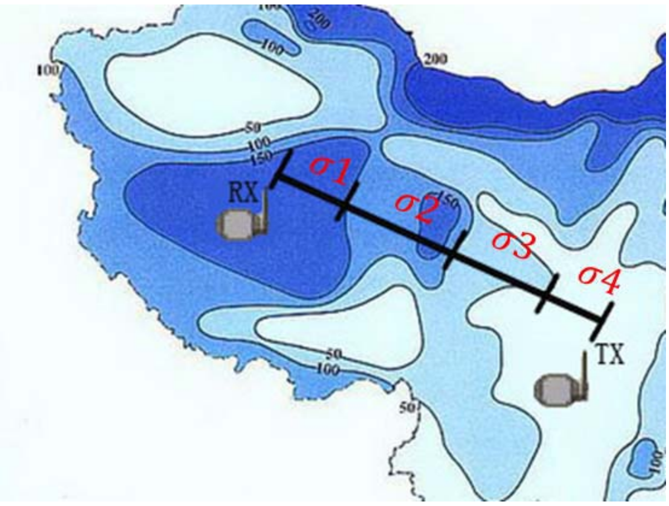

Figure 3. Path with sections having different conductivity

$$\frac{P_r(d_0)}{P_r(d)} = L_{GR}, \qquad (4.4.1)$$

where L_{GR} is the mean path loss determined by GRWAVE in conjunction with Millington’s method.

The second part of the shadowing model estimates the variation in the received power, and is modeled by

$$\left[\frac{P_r(d)}{P_r(d_0)}\right]_{dB} = -10\log(L_{GR}) + X_{dB}, \qquad (4.4.2)$$

where X_{dB} is a Gaussian random variable with zero mean and standard deviation (σ). This relationship in (4.4.2) gives us an accurate estimate of the path loss along an HF channel, and can be used to determine a realistic bit error rate.

Since ns-2 is primarily designed to model higher layer (layer 2 and above) network performance, it uses a simple SNR threshold to determine whether the receiver receives a frame correctly – an oversimplified approach not taking interference into account. To solve this problem, Xiuchao [22] developed a method to calculate SNR and BER within the ns-2 environment to simulate an 802.11b channel. In [22], the author claims that in ns-2, it is the MAC module which knows the interference caused by other transmitted frames; hence, the SNR should be calculated in the MAC module (rather than the PHY module). In this project, we will modify the MAC module to calculate the SNR.

If only one frame is being received by the receiver, the SNR is calculated by the following formula:

$$SNR = 10log\left(\frac{P_{Rx}}{G_{noise}}\right) \qquad (4.4.3)$$

P_{Rx} is the frame signal strength at the receiver, which is calculated using the propagation model and G_{noise} is the noise level at the receiver. Here it is important to understand that the performance of HF systems is usually limited primarily by environmental noise (atmospheric, galactic, or man-made) and not by thermal or platform noise in the receiver. For simulation purposes, it is necessary to model the environmental noise; suitable models are provided in [7].

If other frames arrive to the receiver when it is receiving one frame, the SNR of the initial received frame is effectively reduced as shown here:

$$SNR = 10 log\left(\frac{P_{Rx}}{G_{noise} + \sum_{i=1}^{i-1} P_{Rxi}}\right) \qquad (4.4.4)$$

Once the SNR is known, the next step is to determine its impact on traffic delivery progress, success, or failure. Precisely how this is done may depend on the traffic being delivered and the communications techniques being used. For an uncoded modulation, the BER can be determined analytically from a constant SNR once that is known. This can still be true if coding and interleaving are added; however, the burstiness of the resulting residual error process can have a significant impact on system performance that we may need to capture in the model. To determine packet delivery success or failure, frame error rates can be obtained directly from modem simulations using channel models as described by [6]. For varying packet sizes, a more flexible approach may be to obtain bit error sequences having the desired statistical properties (burstiness) from Markov models similar to those of [16], and use them to generate packet errors for the packet size of interest. Further subtleties arise from the use of Type II Hybrid-ARQ protocols [21] in STANAG 4538, where modeling delivery progress and success may require treating packet retransmissions as increasing the SNR through symbol combining or increased coding gain.

5 Conclusions and future work

This paper has provided an overview of an effort to develop an HF network simulation based on ns-2, providing facilities for the analysis and evaluation of existing and new HF communications techniques, and a description in greater detail of an approach for incorporating the GRWAVE surface wave propagation model into such a network simulation. In future work we hope to incorporate a sky wave propagation model alongside the GRWAVE model, to further elaborate the bearer and network model components of the simulation framework, and to begin using this framework to investigate the behaviour of present and future HF communications networks.

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