Simulation Results for Third-Generation HF Automatic Link Establishment

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***Abstract* – The third generation of HF automation technology was designed to efficiently support large, data-intensive networks as well as the traditional voice and smaller network applications of second-generation HF networks. The performance goals for the new generation of technology were order-of-magnitude improvements in network size, traffic throughput, and signal-to-noise ratio (SNR). Third-generation technology has now been standardized in MIL-STD-188-141B Appendix C.**

This paper presents initial results of simulating third-generation HF networks with various network topologies and workloads. The NetSim simulations employ a validated HF propagation module and a detailed implementation of the protocols under study. Analysis of the simulation results indicates that the new technology links faster, carries heavier traffic, and scales better than current generation HF ALE.

I. INTRODUCTION

The second-generation HF automation standardized in MIL-STD-188-141A and FED-STD-1045 provided a robust, reliable, and interoperable ALE technology that led to a resurgence of interest in HF radio for long-haul and mobile voice networks beginning in the 1980s. With the addition of a robust data link protocol (e.g., FED-STD-1052 or, more recently, STANAG 5066), the second generation technology was extended to support data applications over HF. By the mid-1990’s, however, the growth of HF networking revealed the need for more efficient protocols so that the limited HF spectrum could support larger networks and more data traffic.

A cooperative development effort among government, industry, and academia resulted in a third-generation (3G) protocol suite [1, 2, 3] that was recently standardized in MIL-STD-188-141B Appendix C. Some of the key 3G improvements are listed below:

- Faster link establishment
- Linking at lower SNR
- Improved channel efficiency
- Automatic link establishment (ALE) and data traffic use the same family of waveforms
- Higher throughput for short and long data messages
- Better support for Internet protocols and applications

This paper presents the results of an initial investigation of the performance of 3G HF networks. First, the salient characteristics of 3G technology are summarized. This is followed by a discussion of the simulation approach used in this investigation, including the propagation model, network topologies, and workloads that were employed. Presentation and discussion of the results conclude the paper.

II. OVERVIEW OF 3G TECHNOLOGY

Previous papers [1, 2, 3] have discussed many of the novel aspects of 3G technology, and complete details may be found in the standard (MIL-STD-188-141B Appendix C). This section summarizes this literature, including those details important to understanding the results presented later.

A. *Waveforms*

Both linking and data transfer PDUs are conveyed over the channel by a family of PSK waveforms that are derived from the MIL-STD-188-110A serial-tone modem. The new waveforms are optimized for bursts rather than long transmissions, which gives the system improved agility. Measurements of the 3G waveforms indicate 6–9 dB improvement in AWGN and fading channels over 2G waveforms [1].

B. *Automatic Channel Selection*

Third-generation ALE supports separate calling and traffic channels, although calling channels may be used for traffic when necessary. Traffic channels are normally assigned near calling frequencies so that their propagation is correlated. It uses a specialized carrier-sense-multiple-access (CSMA) scheme to share calling channels, and monitors traffic channels prior to using them to avoid interference.

As in second-generation ALE, 3G-ALE receivers scan an assigned list of *calling channels*, listening for 2G or 3G calls. However, 2G-ALE is an asynchronous system in the sense that a calling station makes no assumption about when a destination station will be listening to any particular channel and therefore uses long calls. 3G-ALE includes an asynchronous mode, but it achieves its highest performance under synchronous operation.

When operating in synchronous mode, all scanning receivers in a 3G-ALE network change frequency at the same time (to within a relatively small timing uncertainty). It is not necessary that all stations monitor the same calling channel at the same time, however. By assigning groups of network members to monitor different channels in each scanning dwell, calls directed to network member stations will be distributed in time and/or frequency, which greatly reduces the probability of collisions among 3G-ALE calls. This is especially important under high-traffic conditions. The set of stations that monitor the same channels at the same time is called a *dwell group*.

C. Synchronous Dwell Structure

The nominal duration of each synchronous dwell is 4 seconds. The timing structure within each synchronous dwell time is as follows (see Fig. 1):

Listen Time. At the beginning of each dwell period, every receiver samples a traffic frequency in the vicinity of the new calling channel, attempting to detect traffic. This "listen time" has a duration of 800 ms. It precedes the calling slots so that stations have recent traffic channel status for use during a handshake.

Calling Slots. The remainder of the dwell time is divided into 4 equal-length slots. These slots are used for the synchronous exchange of PDUs on calling channels. 800 ms per slot allows for a 600 ms PDU, 70 ms of propagation, 100 ms for network time uncertainty, plus transmit level control and automatic gain control settling time.

Prioritized Slot Selection. The probability of selecting a slot for sending a call is randomized over all usable slots, but the slot selection probabilities for higher-priority calls are skewed toward the early slots while low-priority calls are skewed toward the later slots. Such a scheme will operate reasonably well in all situations, whereas hard partitioning of early slots for high priority calls and late slots for low priorities would exhibit inordinate congestion in crisis and/or routine times.

Sounding. If sounding is needed to support adaptive routing, stations send a single burst in the final slot of a dwell.

D. Synchronous Calling

3G ALE employs a carrier-sense multiple access with collision avoidance (CSMA/CA) channel access scheme. When a *calling* station is directed to establish a link to a prospective *called* station, the calling station will compute the frequency to be scanned by the called station during the next dwell and select a calling slot within that dwell time. During Slot 0 of that dwell, the calling station will listen to a nearby traffic channel that has recently been free of traffic to evaluate its current occupancy. If not calling in Slot 1, the calling station will listen on the calling channel for other calls during the slot that precedes its call. If it detects a handshake that will extend into its chosen slot, it will defer its call for one or more slots. Otherwise, the calling station will send a call in its slot and listen for a response in the next slot (see Fig. 2).

3G ALE calls identify the stations and indicate the type of traffic to be carried on a link. When a station receives a call addressed to it, it will respond in the next slot with a Handshake PDU. The Handshake PDU may

- reject ("Abort") the call, returning the caller to scan;
- indicate lack of a suitable channel for the announced type of traffic ("Continue handshake");
- accept the call and designate a good traffic channel for transmissions to that responding station ("Commence traffic").

In the latter case, both stations will tune to that traffic channel and commence the traffic setup protocol to establish the timing, waveform, protocol, and other settings to be used for the traffic described in the call.

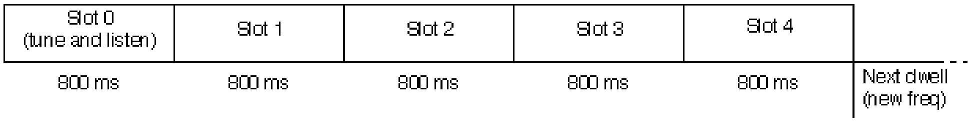

Fig. 1. Synchronous Dwell Structure

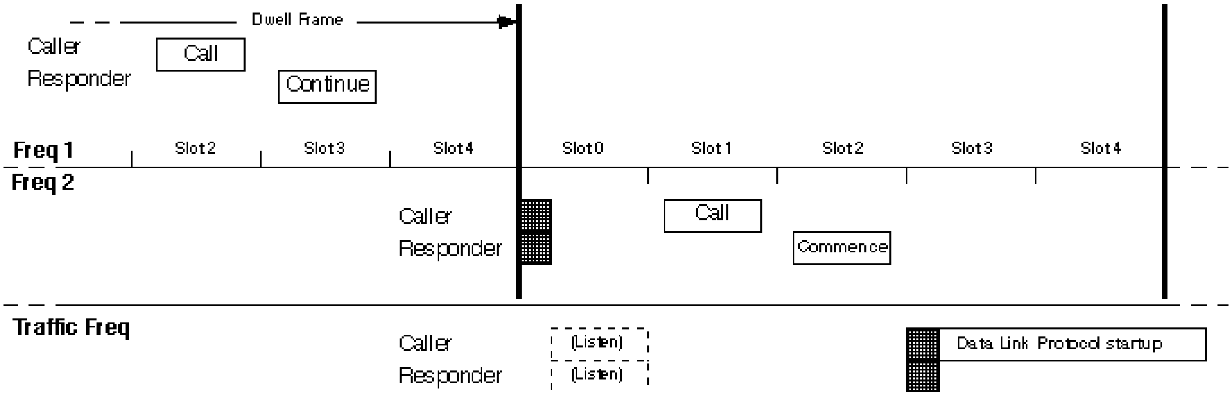

Fig. 2. Example of 3G Link Establishment in Synchronous Mode

If the call doesn't result in a link, the caller will try again during the next dwell on the next calling channel in the responding station's scan list.

E. Third-Generation ARQ Protocol

The 3G ARQ protocol is quite straightforward compared to the 2G ARQ protocols. It simply conveys data over a link, and leaves message-oriented functions to higher layers. At the conclusion of 3G ALE link setup, a caller with data traffic to send initiates a 2-way traffic setup handshake that synchronizes the time bases of the data link terminals, and determines the direction and mode of data transfer. Following this handshake, the link runs in either high-throughput or robust ARQ mode; the former is used for long messages and the latter for short messages or especially challenging channels.

III. SIMULATION APPROACH

This investigation employed a NetSim simulator and two network scenarios described below.

A. NetSim Overview

The NetSim family of simulators [4, 5] implements a discrete-event communications network simulation architecture depicted in Fig. 3. Each of the modules shown functions independently, and implements its respective function at a level of detail appropriate for the investigation.

- Traffic sources generate voice or data messages according to specified inter-arrival time and message size distributions.
- The HF Node Controller (HFNC) at each station implements network-layer protocols and station-wide control.
- ALE controllers implement the ALE protocol and waveform under study. (The waveform is simulated as the probability of correct frame reception *vs*. signal-to-noise ratio.)

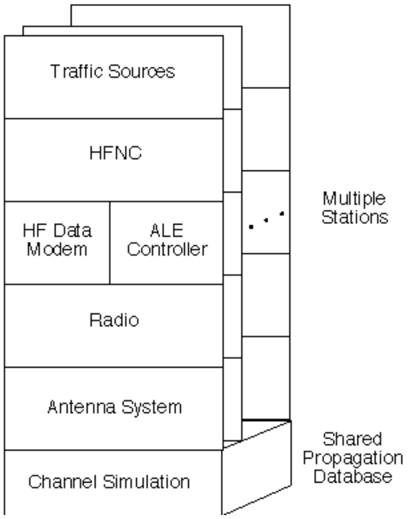

Fig. 3. NetSim Simulator Structure

- Radio and antenna modules determine power and noise levels, intermodulation distortion, gain versus azimuth, etc.

When a radio is tuned to a particular frequency, it receives 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 plus distortion.

The channel model used in most NetSim simulations is the "Walnut Street" model of ionospheric propagation (validated by the Joint Interoperability Test Center), along with a direct wave model for aircraft within line of sight at altitude. Estimates of median SNR and first and ninth deciles of SNR for a link are computed using VOACAP. These are then used to generate representative random processes for path loss on the links of interest, using linear interpolation between hourly predicted values plus lognormal variation about this line for intermediate-term variation plus Rayleigh fading. For comparison with other simulations, however, the Walnut Street model can be replaced with a fixed-SNR model.

B. Air-to-Ground Scenario

The air-to-ground scenario is representative of a large-scale mostly-voice network. A fleet of 115 aircraft fly (during daylight hours, local time) among bases on the East Coast of the US, Europe, and the Central Command theater, as shown in Figure 4. The simulation runs for 24 hours in June with a sunspot number of 100.

- The aircraft take off at intervals throughout the day.
- Each aircraft places (on average) one 5-minute voice call per hour while en route. (Intervals and durations are exponentially distributed.) Ground stations are selected adaptively.
- Each aircraft carries a single ALE radio with a 400W PA.
- Each of 14 ground stations spread around the globe has two identical 3G-ALE-equipped radios, each with a 4 kW PA.
- All antennas are omnidirectional.
- Eighteen channels are available. Various combinations of calling and traffic channels have been simulated.
- Ground stations sound on each calling channel every 45 minutes. Aircraft do not sound.

The need for aircraft to adaptively select ground stations is perhaps the most interesting aspect of this scenario, and was the cause for sounding by the ground stations.

C. Mesh Network Scenario

Data message performance was evaluated using two mesh networks (i.e., networks in which any station may call any other station). The smaller network comprised ten stations (one ALE radio each), each of which called the other nine in

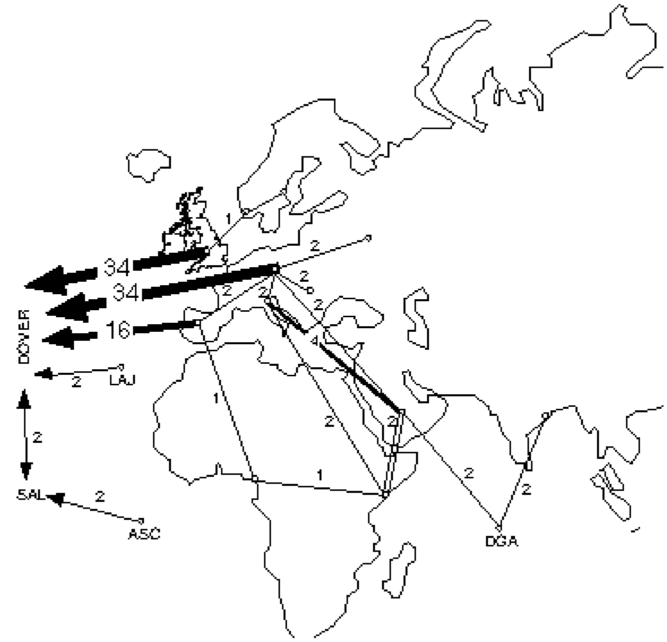

Fig. 4. Air-to-ground scenario

roughly equal proportions. A larger network consisting of 100 stations (again, one ALE radio each) had more structured message flows, with each station exchanging traffic with its four nearest neighbors in a toroid topology. Message rates were varied to offer 100 through 1000 (or 2500) messages per hour (total) to the network. Message interarrival times were exponentially distributed. Message lengths were fixed at 5, 10, 15, and 30 seconds. To permit comparison with other studies, a fixed-SNR channel model was used; all links had path losses to produce 11 dB SNR when no interference was present. Eighteen channels were allocated (9 calling, 9 traffic). Sounding was not needed, and was not used.

IV. RESULTS

The following metrics were selected for our two scenarios:

- For the air-to-ground scenario, link establishment latency.
- For the mesh scenario, network message throughput.

A. Linking Latency in Air-to-Ground Scenario

Fig. 5 depicts the fraction of all calls completed within 10, 20, 30, 60, and 90 s by 2G and 3G ALE networks under identical loading. The 3G network used 18 frequencies, with 5 allocated for calling channels and the other 13 used for traffic; this was the optimum mix for this scenario. The 2G network used the same frequencies, shared between ALE and traffic.

The 2G ALE network has a minimum linking time of just over 18 s, so it is not surprising that it completed no links in less than 10 s. The 3G ALE network, with a dwell of 4 s, completed roughly 50% of its links in less than 10 s, and in general was significantly faster than 2G ALE in establishing links. This was due to both the faster 3G ALE call and the robust waveform which permitted the 3G system to make contact on poor calling channels but then redirect traffic to a better (voice quality) channel.

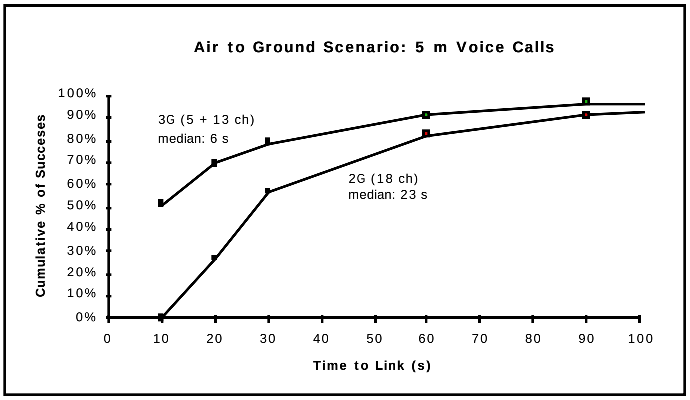

Fig. 5. Linking latency in air-to-ground scenario: 2G and 3G ALE

Channel utilization on the calling channels ranged from 1% (sounding only) to a peak of 4%. Such low utilization of these CSMA/CA channels allowed most calling stations to place a call in every dwell until a link was established. Utilization of the traffic channels during the busy hours averaged 28% to 49%, with some hourly channel utilizations of 83%. The decoupling of traffic and calling channels effectively reduced the “back pressure” this exerted on the linking process. It would be interesting to develop and evaluate a mechanism for decoupled calling and traffic channels in 2G networks.

B. Message Throughput in Mesh Network Scenario

Fig. 6 plots message throughput achieved as a function of message load offered in a 10-station mesh network. Note that the throughput achieved is monotone non-decreasing as the offered message rate is increased, as expected in a CSMA/CA network. Previous work [6] showed that 2G ALE networks without listen-before-transmit (LBT) exhibited catastrophic breakdown in throughput under high loads, and that 10-station

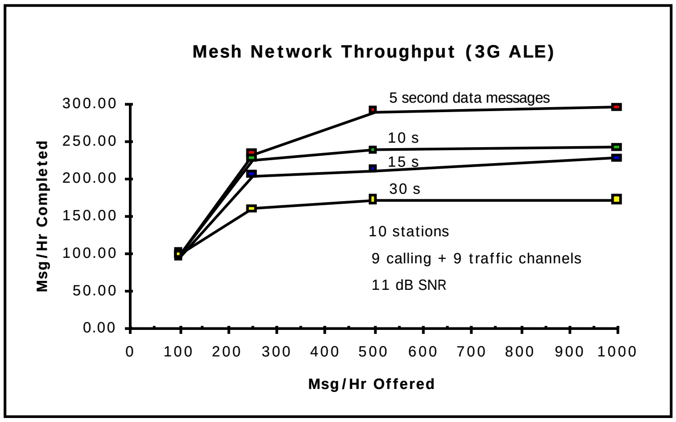

Fig. 6. 3G mesh network throughput for 10 stations

2G ALE networks with LBT saturated at about 15 messages per hour for 5 s messages [2]. The current results suggest that the 3G approach will yield more than an order of magnitude improvement in data message throughput for comparable small (e.g., 10-station) networks.

Fig. 7 illustrates the scalability of 3G technology to a larger data network (100 stations). It is clear that the 100-station mesh network has not saturated at an offered load 10 times greater than the saturation throughput of the 10-station network. However, it does not achieve 10 times the throughput of the smaller network, possibly because the number of channels was held fixed.

Analysis of the simulation results yields the following observations:

- It appears that the single ALE radio at each station is the bottleneck in the 10-station network. At an offered load of 250 messages per hour (25 messages per hour per station), 7 of the 10 stations were linked more than 85% of the time, and none was linked less than 60% of the time.
- Station utilization in the 100-station network ranged from 1% to 14% at an offered load of 250 messages per hour (2.5 messages per hour per station), and was somewhat lower at 25 messages per hour per station than the corresponding figures for the 10-station network.
- Channel utilization did not reach saturation in the 100-station network at an offered load of 2500 messages per hour. Calling channel utilization ranged from 24% to 27%, while traffic channel utilization ranged from 31% to 74%.

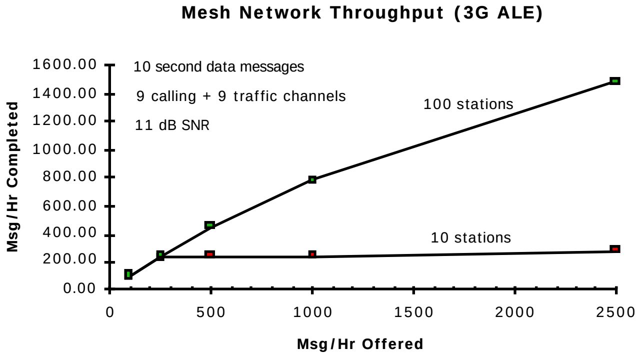

Fig. 7. 3G mesh network throughput for 10 and 100 stations

V. CONCLUSION

The third generation of HF automation technology was designed to achieve order-of-magnitude improvements in network size, message throughput, and SNR requirements, as compared with current second-generation technology. The simulation results presented here suggest that third-generation technology is approaching or has met each of these goals.

Ongoing simulation studies include the effects of varying the dwell and slot timing to accommodate NATO HF House requirements, an evaluation of approaches for channel assignments, and optimization of slot selection probabilities.

The scenarios used here did not require simulation of the ARQ protocol, but integration of the 3G ARQ protocol is a key topic for future work.

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