Staring Link Establishment for High-Frequency Radio

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***Abstract*— Progress in signal processing continues to enable welcome advances in high-frequency (HF) radio performance and efficiency. The latest data waveforms use channels wider than 3 kHz to boost data throughput and robustness. This has driven the need for a more capable Automatic Link Establishment (ALE) system that links faster and adapts the wideband HF (WBHF) waveform to efficiently use available spectrum. In this paper, we investigate the possibility and advantages of using various non-scanning ALE techniques with the new wideband ALE (WALE) to further improve spectrum awareness and linking speed.**

***Index Terms*—High-frequency radio, automatic link establishment**

I. Introduction

Historically, HF radio was a temperamental medium that was limited to low data rates. Modern HF radio employs two technologies that have largely overcome these drawbacks: automatic link establishment and "wideband" waveforms that can carry over 100 kbps of data. These technologies are briefly reviewed in this section to provide background for the rest of the paper. Further details may be found in [1].

A. Automatic Link Establishment

HF radio is renowned for its ability to communicate over the horizon via "skywave" (ionospheric) channels. However, this is not trivial to accomplish. Among other challenges, the necessary refraction of electromagnetic waves by the ionized plasma of the ionosphere is a frequency-selective phenomenon. The range of usable frequencies varies with the time of day and season, space weather conditions, and the geometry of the path connecting the stations. Thus, a key requirement in using HF skywave communications is finding a frequency that will support the desired link.

In the early days of beyond-line-of-sight communications, scientists produced mathematical models of the ionosphere that could be used to guide the frequency-selection process. In recent decades, however, an alternative approach has been found to be simpler and more reliable in choosing a channel for communications: measure current propagation rather than try to predict it, and use a channel that is *known* to work. This latter approach is known as Automatic Link Establishment (ALE) because the process of periodically measuring the usability of available frequencies and selecting a channel based on these measurements is under microprocessor control.

The basics of ALE are as follows:

- A pool of frequencies is assigned for use by a network of stations. The range of frequencies in the pool is selected to cover all expected propagation conditions (day and night, summer and winter, quiet and disturbed ionosphere, etc.).
- Radios that are listening for calls continually scan through this pool of frequencies, pausing when a signal is detected that might be addressed to them.
- When directed to set up a link, an ALE radio consults its database of recent propagation measurements between itself and the desired destination station(s) to find a usable frequency. These measurements may have been collected while traffic was exchanged with other stations or via an explicit overhead process of sending "sounding" transmissions, whose sole purpose is measuring propagation.
- If the calling radio knows the scanning schedule of its desired destination station, it can simply emit its call on the selected frequency at exactly the time that that station will be listening there; such a call can be very short (around one second). However, if stations are scanning asynchronously the call must be of sufficient duration that the desired station(s) will encounter it at some point during the scanning cycle; thus "scanning" calls are typically much longer than synchronous calls.

Two generations of ALE are currently fielded:

- Second-generation (2G) ALE systems usually operate in asynchronous scanning mode, and as a result employ scanning calls that can last 10 seconds or more depending on the number of channels scanned.
- Third-generation (3G) ALE systems normally operate in synchronous mode, with calls of around 1 s *after waiting for the called station to dwell on the desired channel.*

The time to set up a link using ALE includes a short "listen before transmit" interval to ensure that the channel is not occupied, followed by the time for the call and one or two additional short transmissions in a link-setup handshake. Of course, the first attempt may not succeed in setting up a link, so additional calls and handshakes may be required before user communications can begin.

B. Wideband Data

For many years, both voice and data communications in the HF radio bands have mostly been restricted to channel bandwidths no wider than 3 kHz. This provided for efficient sharing of the very limited spectrum available, and was appropriate for the services historically provided over HF channels: voice and low-speed data. Recently, increasing demand for higher-speed data transmission over HF links—along with steady growth in processing resources—have driven the development of waveforms that efficiently use much wider channels (up to 48 kHz).

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20th century HF data modems support up to 9600 bps in a 3 kHz skywave channel. Wideband HF (WBHF) modems (standardized in MIL-STD-188-110C Appendix D) offer up to 120 kbps when channels of up to 24 kHz are available. The highest-speed waveforms (e.g., 96 kbps and 120 kbps in 24 kHz channels) are specified only for operation in surface-wave channels, but these waveforms often work over skywave channels when fading and multipath conditions are not too severe. 48 kHz waveforms have been proposed but not yet standardized, and offer twice the data rate of the 24 kHz waveforms.

II. WIDEBAND ALE

In the initial applications of WBHF, the link was either set up manually, or 2G or 3G ALE was used to select the channel and set up the link. The bandwidth and data rate were then set using some other mechanism.

These early demonstrations proved the feasibility and usefulness of WBHF, but to gain the full benefits of the higher-speed data capabilities we need to address two issues:

- Users with wideband allocations are generally not promised that entire wideband channels will be free of interference. When narrowband interference occurs within a channel, a WBHF user has two choices: fill the entire channel with a sufficiently robust waveform to work through the interference, or adjust the waveform to use only the interference-free portion of the channel. The latter approach will generally provide more satisfactory results, but requires detailed spectrum sensing and coordination with the other station(s).
- The speed of WBHF enhances the data carrying capabilities HF in two interesting dimensions: long-running, high-bandwidth applications such as real-time video over HF become feasible, and messaging applications can become much more interactive. In the latter case, however, the time to set up a link can dominate the time to send a packet, so we will need a faster ALE to keep up.

To illustrate the latter point, consider a large 2G ALE network with a scan list of 18 channels. Simulations show such a network will have an average link establishment time of around 25 s. The time to set up a link using 2G ALE, and then transfer a 50 kB file using WBHF is shown in Fig. 1, for channel bandwidths ranging from 3 to 24 kHz.

Clearly, the benefits of using WBHF are not fully realized in situations like this, when the time to set up the link can exceed the time to transfer the file once the link is established.

A. WALE Description

A new wideband ALE (WALE) protocol is now under development that addresses both of these goals:

- Automatic detection of spectrum occupancy informs selection of the channel bandwidth to use on a link [2].
- Link setup is faster than 2G or 3G ALE in both synchronous and asynchronous modes.

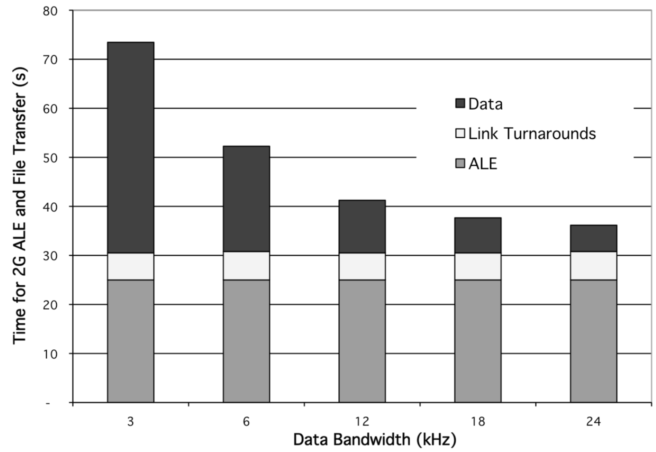

Fig. 1: Time to Send 50 kB using 2G ALE and WBHF in a large network

The 4G ALE system, also known as Wideband ALE or WALE, will use waveforms derived from the WBHF waveforms for its transmissions [3], and draws ideas from both second- and third-generation ALE for its protocols. WALE link setup involves the exchange of 80-bit words *on a 3 kHz channel* in either a 2-way or a 3-way handshake. At the end of this handshake, the linked stations immediately commence either voice communications or a WBHF data exchange. Both synchronous and asynchronous scanning are supported.

The scanning call in 4G ALE departs from the approach used in both 2G and 3G ALE, in which the address of the called station is repeated throughout the scanning call. In 4G, the repeated transmission is an unaddressed, known bit pattern so *all* scanning receivers will be captured and held until the address is sent in the Call PDU that terminates the calling transmission. This was deemed acceptable due to the very short scanning call used in asynchronous 4G ALE.

Two interoperable modes are available: Fast WALE links quickly on voice-quality channels, while the more robust Deep WALE should be capable of setting up links in the most challenging situations, including channels with more noise than signal. Unlike 3G ALE, the choice between Fast or Deep WALE can be made on a call-by-call basis because receivers listen for both types of calls.

In the current waveform design, the duration of the Fast WALE PDU (including the overhead for transmit level control and a synchronization preamble) is 360 ms, while the Deep WALE PDU takes 1.32 s.

B. WALE Simulation

An initial investigation of the linking speed possible with the new 4G ALE system used measurements of early prototypes of the waveforms in a modified NetSim [4] simulation of air-to-ground voice calling in a global network of interconnected high-power HF stations.

Each aircraft makes about one call per hour, with each call lasting about 5 minutes. The quality-of-service metric chosen for this study reflects a user's perception of network performance: the delay from when the user requests a link until he can begin using the link. In the case of HF ALE systems, this will include the time for the system to select a channel and destination station, listen on that channel to avoid interfering with active traffic, and perform the ALE handshake. If the handshake fails, the clock keeps running while the system makes further attempts to establish a link with some ground station in the network. Thus, although most linking attempts succeed on the first attempt, some may drag on for several minutes.

The linking times achieved by the three generations of ALE technology in this air-to-ground scenario [4] are shown in cumulative form in Fig. 2: the fraction of all calls completed within the latency shown on the horizontal axis.

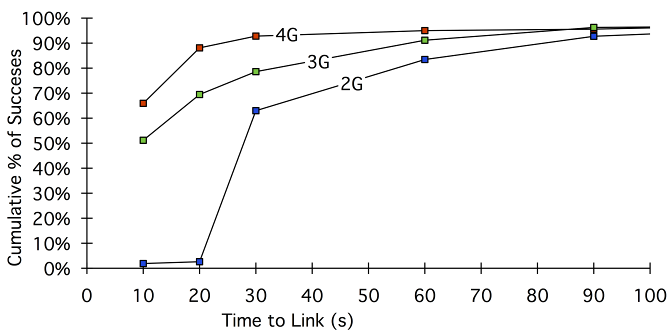

Fig. 2: Cumulative Probability of Linking Success in AMC 100 Scenario

The median linking latencies (i.e., half of all calls succeeded within the indicated time) for the three generations are listed below in Table I, along with the minimum time to set up a link asynchronously:

TABLE I
ALE Linking Times in AMC 100 Scenario

ALE Technology	Scanning	Median Linking Time	Min Async Linking Time
2G (18 ch)	Async	25 s	23 s
3G (5+13 ch)	Sync	10 s	–
4G (18 ch)	Async	6 s	5.5 s

For the asynchronous 2G and 4G systems, the average linking time is dominated by the scanning call time, which is determined by the scanning dwell time and scan set size chosen for a network. For this simulation, a 4G scanning dwell time of 215 ms was used, a figure suggested by some initial waveform simulations. In a smaller network, 4G ALE could be substantially faster than these results. For example, a network with a scan set of 10 channels and 100 ms dwells might link in less than 4 s (including LBT), rather than the 6 s in Table I.

III. Staring ALE

The vagaries of ionospheric propagation require an HF radio network to be able to use any of a wide range of frequencies for communications. To date, automated HF networks have employed scanning to listen for calls on that range of frequencies. However, scanning introduces delays in link establishment in a number of ways:

- In asynchronous networks, a calling transmission must be long enough to capture scanning receiver(s).
- In synchronous networks, the call can be short, but it cannot be sent until the desired receiver is listening on the selected channel.
- In either case, a listen-before-transmit interval is required before placing the call because the calling station is usually not aware of current channel occupancy.

The classic alternative to a scanning receiver is a "staring" receiver [5], which continuously monitors the entire range of desired frequencies. Compared to a scanning receiver, a staring receiver requires substantially greater processing capability to be able to listen for calls on all of the assigned channels in parallel, but staring achieves commensurate benefits:

- When receivers are always listening on all channels, there is no need for a long scanning call. Therefore, calling transmissions can be very short.
- Calls can be sent immediately without waiting until the called station is dwelling on the selected channel.
- No listen-before-transmit (LBT) time is required to check for channel occupancy, because the receiver at the calling station will already be aware of what is happening on every channel. Furthermore, because the monitoring is continuous, channel occupancy will be more accurately known than is possible using only a brief LBT sample that can miss voice or interactive data transmissions.

Such benefits have led to recent investigations of a variety of parallel receiving schemes for use in HF link setup, including both single-receiver and multiple-receiver architectures.

A. *Full-band Receiver*

A straightforward approach to building a staring receiver for HF radio is simply to digitize the entire HF spectrum from 2 through 30 MHz. As noted in [6], however, this will require extremely high dynamic range and resolution to detect faint incoming calls in the presence of strong signals elsewhere in the HF band (e.g., from shortwave broadcasters).

The Finnish company Kyynel is reportedly applying cognitive radio techniques with a single-receiver staring ALE design in their Cognitive Networked HF system [7].

Unlike other approaches, using a full-band receiver supports use of any temporarily unused spectrum (white space) rather than just the pool of assigned frequencies.

B. *Multiple Receivers*

Another approach to supporting the staring ALE idea is to use multiple narrowband receivers to monitor only the assigned frequencies and thereby avoid high-power interferers.

Research in Sweden [8] follows this approach, using multiple narrowband Tayloe detectors [9] to process incoming signals. Candidate calls are fed to an ALE demodulator and protocol engine for processing.

When the number of assigned channels (C) is greater than the number of receivers available (N), the system must scan, but calls can still be immediate if the caller knows the scanning schedule and selects one of the N current channels for a link. For small N, this approach might be feasible in a compact form factor for manpack or mobile applications.

At the large base stations commonly used to support regional and global HF networks, a complete set (N = C) of receivers, demodulators, and protocol engines may already be available. In such stations today, the receivers are typically all scanning (when not linked). Station software designates one scanning receiver to respond to calls, while the others silently accumulate sounding data for use in case they are designated to originate a call. Switching such stations to (narrowband) staring ALE operation might require only a software change.

C. Staring Wideband ALE

Switching from scanning, narrowband ALE (2G or 3G) to staring, wideband ALE would require an upgrade to both radio and control software. A software-defined radio for staring wideband operation must be able to process the WALE and WBHF waveforms as well as to continually monitor and characterize the occupancy of one or more wideband channels. As noted above, use of multiple fixed-frequency receivers to implement staring WALE will require control software to coordinate frequency selection and call processing.

IV. Implementing Staring WALE

In this section we investigate some of the design decisions that might arise in implementing staring WALE. A large network that includes a mix of base stations and mobile users provides a useful subject for this thought experiment. The goal of implementing staring WALE in such a network would be to improve the speed and efficiency of wideband data applications on both fixed-to-mobile and mobile-to-fixed links.

A. Architecture

The network architecture described here is just one concept for building a large staring WALE network. Others are certainly possible.

In such a network, the base stations are typically interconnected among themselves, and also connect to data and voice networks. A mobile user that can link with any base station then has access to all of the connected resources.

Each base station in this staring WALE network would be equipped with a wideband transmitter and receiver for each assigned channel (N = C). The base station radios would not scan. Each of them would feed link quality measurements and channel occupancy information to a local connection management server. Because each radio maintains constant awareness of the occupancy of its assigned channel, LBT would not be needed before calls.

For this exercise, let’s assume that mobile radios are constrained to have fewer parallel receivers than the number of channels assigned to the network (N < C). Rather than require the mobile radios to scan, we instead assign to each mobile station a subset of N channels that can be used for calling that station. Each mobile radio stares at its assigned “stare set.” The stare sets need not be the same for all mobile stations.

Stare sets should be assigned using the following principles:

- Provide high probability of propagation on at least one <base station, stare set frequency> pair throughout the mission duration and area.
- Reduce congestion by minimizing stare set overlap among potentially contending mobile stations.
- Provide shared frequencies among stations that require direct mobile-to-mobile communications.

B. Sounding

Sounding would be useful for routing as well as for channel selection in this network. The base stations would sound on all of the assigned frequencies, while the mobile stations would sound only on their stare set frequencies. As a result, the base stations would not need to be programmed with the stare sets of the various mobiles: a base station would only call a mobile on frequencies on which the mobile has recently sounded.

When a station receives a sounding transmission it stores the following:

- The station that sent the sound. The receiving station now knows that the sending station is reachable.
- The channel that carried the sound, and the quality of that channel (e.g., SNR).

Mobile stations use their local databases of <station, channel, quality> tuples for both routing (selecting a base station) and channel selection when they need to establish a link.

Base stations likewise maintain databases of <station, channel, quality> tuples for use in channel selection, but also share with a central server the list of mobile stations that they can reach (for global routing). For example, a data message from an external SIPRNET user, addressed to a particular aircraft, would be routed to the base station(s) with the best recent connectivity to that aircraft.

A sounding transmission in a staring WALE network will consist of a single WALE PDU. Either Fast or Robust coding could be used, resulting in either 360 ms or 1.32 s per sounding transmission. The contents of the WALE Sound PDU are not yet specified, but it may be possible to include not only the identification of the sounding station but also a bit vector of local interference levels it senses in the sub-channels of the wideband channel carrying the sound.

C. Calling

Channel selection offers a wide scope for optimization in a staring WALE network. The inputs to a channel selection algorithm include the type and volume of traffic to be carried on the new link, recent propagation measurements (and interference levels) from soundings by the desired destination station, and local channel occupancy measurements.

WALE calls occupy only 3 kHz of a wideband channel. The default placement of a call is the 3 kHz channel just above the center of the channel, so this is where the narrowband WALE demodulator will normally be listening. However, if staring receivers are able to simultaneously demodulate all of the sub-channels of a wideband channel, the caller could select a different sub-channel when needed to avoid interference.

D. Performance Estimate

The time required to set up a link using staring WALE can be much shorter even than for scanning WALE. Because we eliminate the listen-before-transmit time and the scanning call time, a staring WALE handshake could be completed in about a second:

- The Call PDU in Fast WALE lasts 360 ms.
- Propagation delay plus processing time at the called station may require 100 – 200 ms.
- The Confirm PDU also lasts 360 ms on the air.
- Return propagation and caller processing times add another 100 – 200 ms.

Thus we get a rough estimate for a 2-way link setup of 920 – 1120 ms. A 3-way handshake would require about half a second more.

Revisiting Fig. 1, the time to send a 50 kB file in a large 2G ALE network, we can now estimate the time required to send that same file in a staring WALE network. The results are shown in Fig. 3. Clearly, the use of staring WALE removes link setup as a significant component of file transfer overhead.

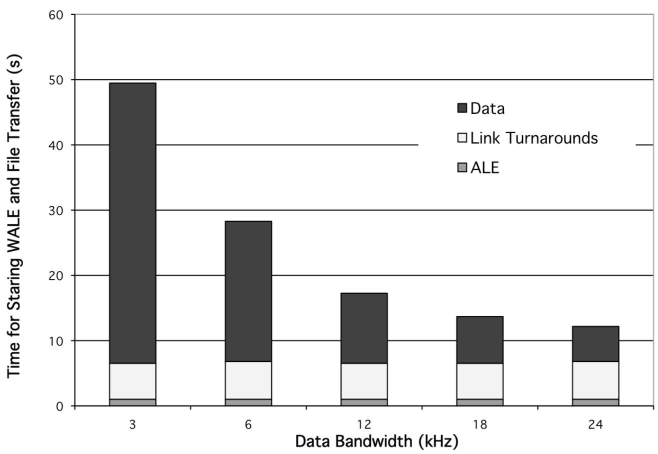

Fig. 3: Time to Send 50 kB using Staring WALE and WBHF

V. Simulation Results

Staring WALE offers the promise of not only faster linking, but also more efficient use of the HF spectrum, due to the elimination of scanning calls and scanning sounds. In this section, we evaluate the impact of staring WALE on both linking time and channel use in the classic Air-to-Ground simulation scenario [4].

In the classic version of this scenario, we have 14 high-power base stations distributed globally, each with up to 10 scanning, split-site radio systems. A fleet of 113 aircraft fly typical air transport missions, mostly trans-Atlantic but also within Europe, Africa, and Asia. All base and mobile stations share an ALE scan set of 18 channels.

To evaluate staring link establishment, we modify this scenario as follows:

- The ALE frequency pool is reduced to 10 channels, and all base stations have 10 staring radios, one per channel.
- Each aircraft gets a radio that stares at 4 channels, and can process ALE signals on all four simultaneously, but can only make and sustain a single link at a time.

The 10-channel frequency pool was selected from the 18-channel scan set by noting the most-used frequencies in the scanning simulations, followed by adjustments to retain global coverage. Likewise, the stare set for each aircraft was selected based on previous simulation results, with a goal of minimizing interference among aircraft in the same theater.

We compare the simulation results for staring WALE to results for scanning WALE *using the same frequency pool*. In Fig. 4, we see that staring WALE indeed links noticeably faster than scanning WALE. Since we're setting up narrowband links for voice traffic, a 2-way handshake is sufficient, and provides even faster linking when the first call succeeds.

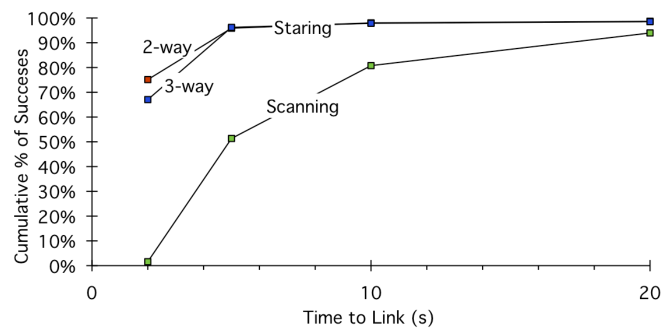

Fig. 4: Cumulative WALE Linking Success: Modified AMC 100 Scenario

The median linking latencies for these three cases are listed below in Table II:

TABLE II
WALE Linking Times in Modified AMC 100 Scenario

ALE Technology	Scanning	Minimum Linking Time	Median Linking Time
Scanning WALE (3-way)	Async	4.1 s	5.3 s
Staring WALE (3-way)	—	1.6 s	1.6 s
Staring WALE (2-way)	—	1.2 s	1.2 s

The median linking time for the scanning case (5.3 s) is a bit shorter than the 6 s from Table I because we are scanning only 10 channels here (versus 18). The faster linking for both staring WALE cases is due to the elimination of the LBT delay before placing a call as well as the scanning call.

Note that the median linking time for each staring system is identical to its minimum, but the scanning system takes more than a second longer than the minimum, on average. This is due to channel congestion: the calling radio often finds that its first few choices of calling channel are busy, and spends 600 ms per channel listening, while searching for a clear channel.

This is indirect evidence that the staring technology reduces channel congestion. However, the simulator also produces direct evidence in the form of hourly statistics of channel use. These are plotted in "heat map" form in Fig. 5. The color thresholds in Fig. 5 are as follows:

	Blue	less than 10% utilization
	Yellow	10% to 40%
	Red	more than 40%

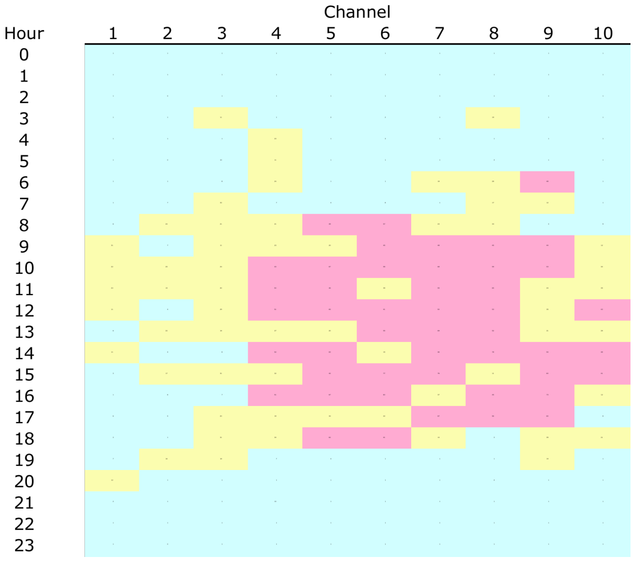

Fig. 5a: Channel Utilization for Scanning WALE (3-way Handshake)

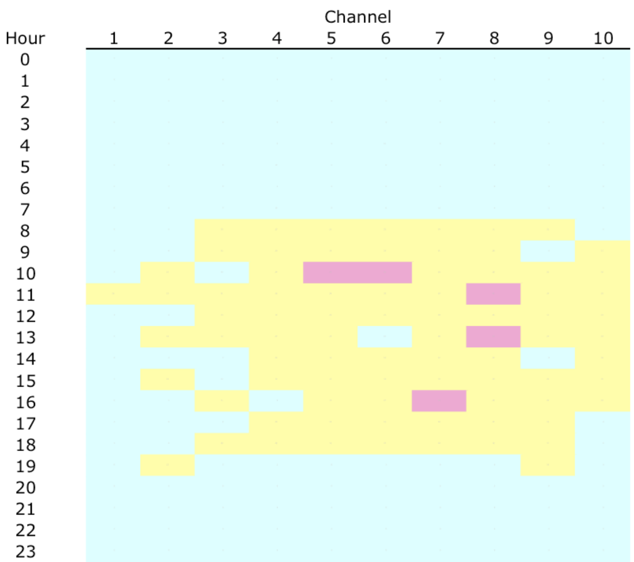

Fig. 5b: Channel Utilization for Staring WALE (3-way Handshake)

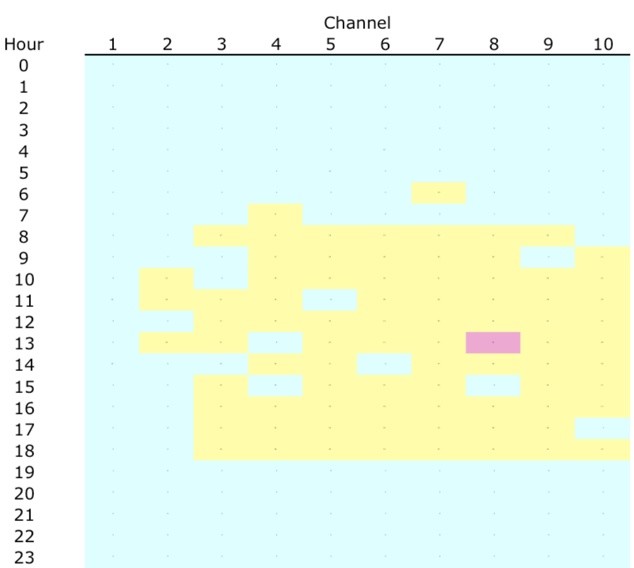

Fig. 5c: Channel Utilization for Staring WALE (2-way Handshake)

It is clear from Fig. 5 that eliminating the extended calls and sounds used in a sounding system results in reduced channel utilization. It is possible that restricting each aircraft to use only a subset of the channels also reduces congestion.

VI. Conclusions

A new wideband ALE technology is now under development for HF radio networks that promises increased linking speed as well as automated management of the new wideband HF data waveforms specified in MIL-STD-188-110C. In this paper, we have discussed both wideband ALE and the notion of eliminating scanning through the use of staring receivers. The combination of staring WALE and WBHF waveforms offers the potential of greatly improving the performance of HF radio data networks in both military and civilian applications.

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