THIRD-GENERATION TECHNOLOGIES FOR HF RADIO NETWORKING

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ABSTRACT

Second-generation HF automation (e.g., MIL-STD-188-141A) provided a sufficiently robust, reliable, and interoperable link establishment technology to produce 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, 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 techniques that reduce overhead traffic so that the limited HF spectrum could support larger networks and more data traffic.

This paper describes a "third generation" of HF radio automation technology that provides significant advances in modem technology, link establishment, network management, and data throughput. One goal of the third-generation technology development effort for MIL-STD-188-141B was to efficiently support bursty data traffic in peer-to-peer networks with hundreds of stations. The constraints that this imposes on linking, message delivery, and routing table maintenance improve the performance of star-topology and smaller peer-to-peer networks as well.

INTRODUCTION

This paper presents an overview of an integrated suite of advanced technologies that collectively provide an HF radio subnetwork. The major components are as follows:

- automatic link establishment (ALE)
- data link protocol (DLP)
- automatic link maintenance (ALM)

Several additional components or features are being standardized in MIL-STD-188-141B or MIL-STD-187-721D, including linking protection, time-of-day synchronization, ECCM operation, routing and related functions, and so on, but these are not addressed here. At this writing, the standards had not been finalized, so the technology described here may differ from the final standards.

This suite of HF automation technologies builds upon the "second generation" technologies in MIL-STD-188-141A and FED-STD-1052, and are backward compatible with the second generation. However, the new system represents a significant improvement in technology and performance and is consequently termed "third generation." Some of the key improvements are listed below:

- Faster link establishment
- Linking at lower SNR (estimated 8-10 dB improvement in AWGN and fading channels)
- Improved channel efficiency: handles more stations and heavier traffic
- ALE and DLP use same family of waveforms
- Higher DLP throughput for short and long messages
- Better support for Internet protocols and applications

This new generation of open standards is the result of ideas and comments from a broad base of government, industry, and academic research and development.

SYSTEM ARCHITECTURE

Second-generation HF automation provided a sufficiently robust, reliable, and interoperable ALE technology to produce 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, 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 techniques that reduce overhead traffic so that the limited HF spectrum could support larger networks and more data traffic.

One goal of the third-generation technology development effort was to efficiently support bursty data traffic in peer-to-peer networks with hundreds of stations. The resulting constraints on linking, message delivery, and routing table maintenance improve performance in star-topology and smaller peer-to-peer network as well.

The third-generation design 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.) Likewise, when equipment permits half- or full-duplex operation (distinct transmit and receive frequencies), third-generation ALE and ALM can find and use good channels in each direction independently. Single-channel operation is the default, however, because it uses channels more efficiently.

AUTOMATIC LINK ESTABLISHMENT

Third-generation ALE (3G-ALE) is designed to quickly and efficiently establish one-to-one and one-to-many (both broadcast and multicast) links. 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.

Scanning

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*.

Calling Channel Management

Assignment of channels to 3G-ALE scan lists may be static, or it may be managed dynamically via the network management protocol (HNMP or SNMP). This provides a direct means for propagation prediction programs or external sounders to optimize scan lists "on the fly."

Channels will usually be assigned to scanning sequence in non-monotonic frequency order. By alternating among frequency bands in adjacent dwells (to the extent feasible for the receiving equipment) we usually increase the probability of linking success in the next dwell when the frequency just tried did not propagate.

Addressing

One of the functions of the subnetwork layer is translation of upper-layer addresses (e.g., IP addresses) into whatever peculiar addressing scheme the local subnet uses. The addresses used in 3G-ALE PDUs are 11-bit binary numbers. In a network operating in synchronous mode, these addresses are partitioned into a 5-bit dwell group number and a 6-bit member number within that dwell group. Up to 32 dwell groups of up to 60 members each are supported (1920 stations per net). Four additional addresses in each group (member numbers 1111xx) are reserved for temporary use by stations calling into the network.

When it is desired to be able to reach all network members with a single call, and traffic on the network is expected to be light, up to 60 network member stations may be assigned to the same dwell group. However, this arrangement does not take full advantage of the 3G calling channel congestion avoidance techniques. To support heavier call volume than the single-group scheme will support, the network members should be distributed into multiple dwell groups. This results in spreading simultaneous calls more evenly over the available frequencies.

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 Figure 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 synchronization uncertainty of ±50 ms, plus transmitter attack and AGC settling time.

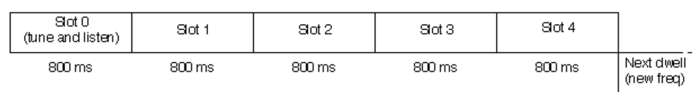

Figure 1: Synchronous Dwell Structure

Synchronous Calling Overview

The 3G-ALE synchronous calling protocol seeks to find suitable channel(s) for traffic and transition to them as quickly as possible. This minimizes occupancy of the calling channels, which is important in any CSMA system. 3G-ALE calls indicate the type of traffic to be carried (in general terms); the first traffic channel(s) that will support this grade of service will be used. The system normally does not spend time seeking the *best* traffic channel (although such operation is possible).

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 then listen on the calling channel for other calls during the slots that precede its call. If it detects a handshake, it will defer its call. If no handshake is detected that will extend into its chosen slot, the calling station will send a Call PDU (described later) in its slot and listen for a response in the next slot.

When a station receives a Call PDU addressed to it, it will respond in the next slot with a Handshake PDU. The Handshake PDU may designate a good traffic channel for transmissions to that responding station. If it does, both stations will tune to that traffic channel and commence the traffic protocol described in the call.

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. The calling station will again select a slot and start the handshake in this new dwell by sending a Call PDU. If the calling station does not succeed in establishing a link after calling on all calling channels, it will normally abort the linking attempt to avoid further channel occupancy.

Listen-before-transmit. Every calling station that will send a PDU during a dwell listens on its intended calling channel during the slots that precede its transmission (except Slot 1). If it detects a handshake, it will defer its call until an available slot or until the next dwell. Thus, early slots in a dwell may preempt later slots.

Prioritized Slot Selection. The probability of selecting a slot 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 and late slots for low priorities would exhibit inordinate congestion in crisis and/or routine times. Any number of priority levels can be accommodated in this way.

Note that a handshake that starts in Slot 4 will extend into Slot 0 of the following dwell, but will not overlap any of the calling slots in that dwell.

Third-Generation ALE PDUs

The contents of the various PDUs used by 3G-ALE are shown in Figure 2. The PDUs used in one-to-one calling are the Call and Handshake PDUs mentioned above. These two key PDUs are discussed below. The more specialized PDUs are discussed later, in conjunction with their respective protocols.

Call PDU. The Call PDU needs to convey sufficient information so that the called station will know whether it wants to respond, and what to look for in its traffic channel database. The Call PDU therefore reports

- the calling station identification
- what resources will be needed if the call is accepted
- what traffic channel quality is required.

The Call Types in the Call PDU are listed below:

Call Type	Description
Packet Data	Traffic will use the 3G ARQ protocol. Negative SNR OK.
HF Modem Circuit	Traffic will use an HF data modem (e.g., for 2G-ARQ or digital voice). Need positive SNR.
Voice Circuit	Orderwire voice traffic. Need SNR ≥ 10-15 dB.
High-Quality Circuit	Traffic (voice or wireline modem) needs higher SNR than orderwire.
Unicast	One-to-one call, caller will designate the traffic channel.
Multicast	One-to-many call, caller will designate the traffic channel.
Link Release	Caller announces release of called station(s) and the traffic channel.

The full called station address is not needed in the Call PDU, because the called station group number is implicit in the choice of the channel that carries the call.

Handshake PDU. The Handshake PDU is used by both calling and responding stations. It is sent only after a Call PDU has established the identities of both stations in one-to-one link establishment, as well as the key characteristics of the traffic that will use the link.

- The Link ID field contains a hash of the calling and called addresses for use in collision resolution.
- Commands include Continue Handshake ("I don't have a good traffic channel yet"), Abort Handshake, and Commence Traffic.
- The argument field carries either a channel number for traffic or a reason for not linking.

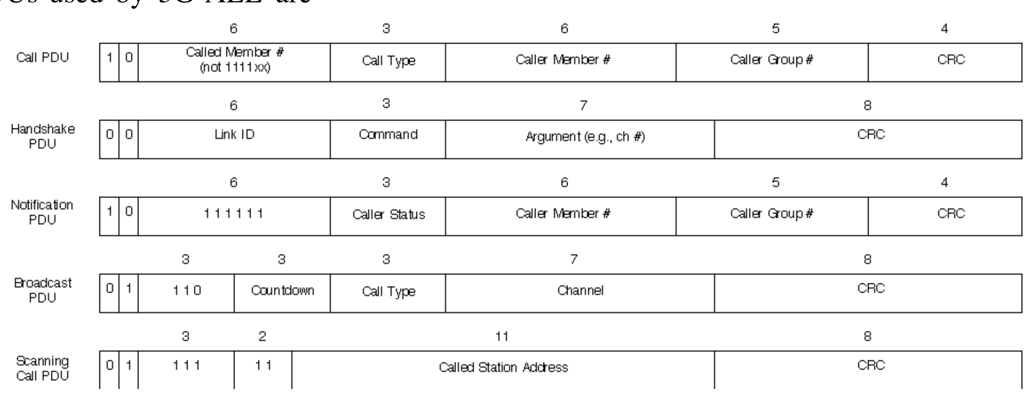

Figure 2: 3G-ALE Protocol Data Units

One-to-One Link Establishment

The one-to-one linking protocol identifies a frequency or pair of frequencies for traffic use relatively quickly (within a few seconds), and minimizes channel occupancy during this link establishment process. The synchronous mode ALE protocol is illustrated in Figure 3.

A station will normally commence the link establishment protocol immediately upon receiving a request to establish a link with another station, although it may defer the start of calling until the called station will be listening on a channel believed to be propagating. The latter option serves to reduce channel occupancy, and does not preclude calling on the bypassed channels later if the link cannot be established on the favored channel.

Scanning Phase. Stations idle in the Scanning Phase, in which at least one receiver per station synchronously scans its assigned channels, listening for calls. When a station needs to establish a link with another station, it enters the Probing Phase and sends Call PDUs on the frequencies monitored by the called station until a link for traffic has been established or the attempt is aborted.

Probing Phase. Only the station that initiates link establishment enters the Probing phase, and it does so when it is ready to begin sending Call PDUs. Upon entry to the Probing phase, the caller calculates the frequency being monitored by the station to be called and, if necessary, tunes to that frequency. During each frame, it selects a slot for sending its Call PDU as described above, sends the PDU, and listens for a response (a Handshake PDU).

On receipt of a Continue Handshake command, the calling station will make no further transmissions during the current dwell frame, although it will combine the received quality of the Handshake PDU with the traffic channel occupancy measured earlier to decide whether that traffic channel is usable. During the next dwell frame, the calling station will again listen to a traffic channel in the vicinity of the new calling channel during Slot 0, and send a Call PDU in a slot chosen in accordance with the procedure described earlier. Receipt of an Abort command will terminate the linking attempt and return the calling station to the Scanning Phase.

Receipt of a Commence Traffic command prompts the calling station to enter the Traffic Phase.

Responding Phase. When a station that is listening for calls receives a Call PDU addressed to it, it briefly enters the Responding Phase. In response to an error-free one-to-one Call PDU addressed to it, an available station returns a Handshake PDU in the next slot:

- An Abort Handshake command is returned when the responding station is not willing to accept the call.
- A Continue Handshake command is returned if it is willing to accept the call, but has not yet found a suitable traffic channel.
- A Commence Traffic command, designating a traffic channel, is returned when a suitable traffic channel is known.

A called station does not remain in the Responding Phase after sending its response: it either returns to the Scanning Phase (Abort or Continue Handshake), or proceeds to the Traffic Phase (Commence Traffic).

Traffic Phase. When the called station enters the Traffic Phase, it sets a timeout that will cause a return to the Scanning Phase if the calling station does not quickly initiate a traffic protocol. A longer timeout is used when voice traffic was announced in the call than when packet traffic or a modem circuit was indicated.

When the caller receives a Handshake PDU containing a Commence Traffic command from the called station, it also enters the Traffic Phase. Normally, it will immediately commence traffic setup for an ARQ protocol or alert the operator to commence voice traffic. However, if the traffic channel is either occupied or noisy at the calling station, it may seek an alternate channel for sending and/or receiving traffic using the ALM protocol.

At the end of the Traffic Phase, the called station simply returns to the Scanning Phase. The calling station, however, may be programmed to return to the calling channel that carried the successful handshake, wait for the called dwell group to scan to that channel, and send a Link Release call that informs the group that the called station and the traffic channel are again available.

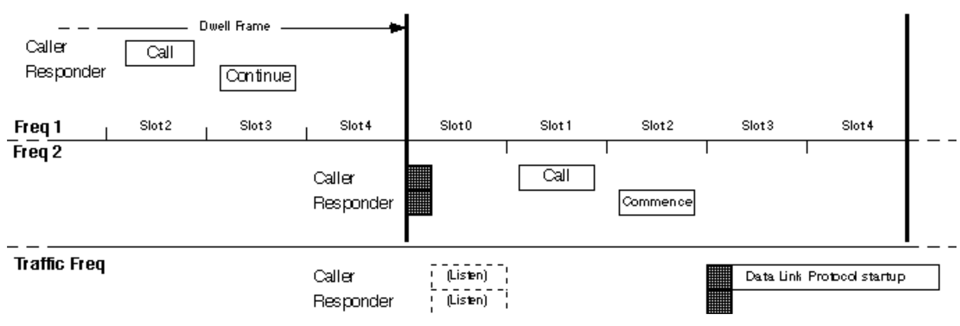

Figure 3: Example of 3G Link Establishment in Synchronous Mode

Unicast Calling. In some situations it is desirable for the calling station to designate the traffic channel for a point-to-point link. The Unicast call type is used in these cases, and indicates that the called station should not respond, but instead listen for a Handshake PDU from the calling station in the slot that follows the Call PDU. Both stations then proceed to the Traffic Phase on the designated channel.

One-to-Many Calling

One-to-many calling includes both broadcast and multicast protocols.

Multicast Calls. A multicast call employs a separate 6-bit multicast address space. 3G-ALE controllers are programmed to recognize multicast addresses to which they subscribe. The multicast protocol is similar to the unicast protocol: the caller sends a Call/Commence Traffic PDU sequence that directs the called stations to a traffic channel where they are to set a timeout and listen for the type of traffic associated with that multicast address.

Broadcast PDU and Protocol. The Broadcast PDU simply directs every station that receives it to a particular traffic channel. A station may announce a broadcast to multiple dwell groups by repeating the Broadcast PDU on multiple channels during one or more dwells. The PDU contains a dwell countdown that indicates when a broadcast will begin.

Notifications

The Notification PDU carries the address of the sending station. The 3-bit Station Status field carries the current sending station status (e.g., Nominal, Going silent, etc).

Stations that are commencing radio silence (or EMCON), or that are voluntarily departing from the network, may notify other stations of this status change to reduce the effects of upper-layer routing protocols having to discover this change in status.

Notification PDUs are sent in randomly selected slots using the same probability distributions as broadcasts.

Sounding

Sounding will normally be unnecessary in 3G-ALE systems. With synchronous scanning, knowledge of propagating channels will have only slight effect on linking latency unless non-propagating channels are removed from the scan list.

In asynchronous 3G-ALE networks, however, sounding may be desired if propagation data is unobtainable by other means. In this case, periodic transmissions of a repeated Notification PDU indicating Nominal station status will serve the purpose.

Asynchronous Operation

The Scanning Call PDU is sent repeatedly to capture scanning receivers when a network is operating in asynchronous mode. The remainder of the asynchronous-mode handshake is similar to synchronous mode.

WAVEFORMS

Both linking and data transfer PDUs are conveyed over the channel by a family of PSK waveforms that are derived from the highly-successful MIL-STD-188-110A serial-tone modem. The new waveforms are optimized for bursts rather than long transmissions, which gives the system improved agility (see MIL-STD-188-141B.)

THIRD-GENERATION DATA LINK PROTOCOL

The 3G ARQ protocol is much more streamlined (and nimble) than the FED-STD-1052 ARQ protocol. It simply conveys data over a link, and leaves message-oriented functions to higher layers.

The caller initiates a 2-way handshake on a channel (after 3G ALE) 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-rate or robust mode; the former is used for long messages and the latter for short messages or especially challenging channels.

The high-rate mode is a selective-repeat protocol. Series of fixed-size frames are sent at 4800 bps, after which a robust burst from the responder acknowledges frames received error-free. Retransmissions of NAKed frames carry FEC bits instead of data bits, with code-combining used at the receiver to attempt to reconstruct frames received with errors. The code rate ranges from 1 to 1/4 on a frame-by-frame basis.

The robust mode uses very robust waveforms and a stop-and-wait protocol. It cycles the channel more quickly than the high-rate mode, which makes it better suited for quickly transferring small messages over marginal channels. This mode should be especially effective in supporting transport-layer ARQ frames such as TCP acknowledgements. When the TCP maximum transmission unit (MTU) is small, this mode will also be an efficient means for reliably carrying user data over challenging links.

For long messages in a CCIR Poor channel, an implementation of the high-rate mode maintains a 7-8 dB advantage over 1052 ARQ at a given throughput, and achieves roughly 50-100% better throughput at a given SNR. The robust mode achieves a 10 dB improvement over 1052 ARQ for short messages in low-SNR CCIR Poor channels.

CONCLUSION

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. It includes an integrated subnetwork layer, ALE, ALM, and ARQ protocols, and a family of robust PSK modem waveforms. Simulations and prototype measurements indicate that the new generation of technology will support order-of-magnitude improvements in network size and traffic throughput, while reaching perhaps 10 dB deeper into the noise to provide connectivity in challenging environments.