

EXTENSION OF DIGITAL MODULAR RADIO TO HF DOMAIN

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ABSTRACT

General Dynamics C4 Systems extends the Digital Modular Radio (DMR) system to the High Frequency (HF) domain. Base-band serial and parallel tone modem functionality is integrated with embedded, AIM-based KY-99A, KWR-46, and KG-84C cryptographic algorithms plus single-sideband (SSB) radio frequency (RF) modulation to provide four channels of HF plain text (PT) and cipher text (CT) communication. An Automatic Link Establishment (ALE) controller is added, to provide call management and link quality monitoring capabilities for both HF line-of-sight (LOS) and sky wave channels, in the first software defined radio (SDR) system funded by the United States Navy.

1. INTRODUCTION

The DMR (Digital Modular Radio) is a software defined radio (SDR) system, certified by the National Security Agency (NSA) and evaluated by the Joint Interoperability Test Command (JITC) that is currently being deployed by the United States Navy on a variety of platforms including ships, submarines, and land based sites such as the Pentagon – see Figure 1. DMR is a multi-channel, multi-processing radio covering 2 MHz to 2 GHz and providing four independent RF to base-band communication circuits, each capable of running a software defined waveform. (A ‘waveform’ consists of programmable software and firmware processing elements providing base-band and RF modulation and demodulation, forward error correcting (FEC), interleaving, encryption/decryption algorithms, and protocol control layers necessary for communication).

DMR replaces a diverse set of legacy equipment, including transceivers, cryptographic devices and VOCODERS, by providing the same communication services in a compact, integrated form. DMR can simultaneously operate with the same or multiple waveforms on its four independent channels.

**DMR
(4 channels)**

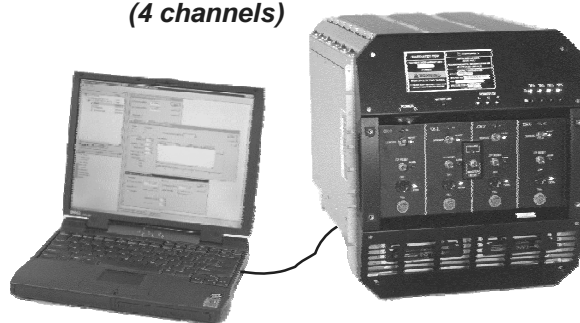


Figure 1 DMR Radio and HMI Workstation

Each channel has independent signal processing, RF hardware and encryption engine capability, and is set-up and controlled by the channel’s processor. DMR has integrated audio/ VOCODER elements and digital I/O port control. DMR is designed for full-duplex operation, but can operate half-duplex or simplex as required. Each channel can operate in a frequency scan mode or, in pairs of channels, as a regenerative repeater.

DMR can receive new waveforms deployed to the field without hardware modification. Table 1 summarizes the UHF and VHF waveforms currently implemented on the DMR.

Table 1 Legacy Waveforms Currently Supported by DMR

| Waveform | Modes | Internal Crypto |
|-------------|-------------------------|-----------------|
| SATCOM | 181, 182, 183 | KYV5 |
| SINCGARS | ICOM, SIP/ESIP | KYV5 |
| HaveQuick | I, II | KY-57/58 |
| UHF Link 11 | --- | --- |
| UHF Link 4a | --- | --- |
| FM | Voice, Data | KY-57/58 |
| AM | Civil, Military | KY-57/58 |
| ATC | 25kHz, 8.33kHz Channels | --- |
| VHF/UHF LOS | --- | --- |

Table 2 Legacy Waveforms being Developed for DMR

| Waveform | Modes | Internal Crypto |
|----------|---|-----------------------|
| HF | Serial tone, Parallel tone, Teletype, ALE, Voice, CW, Link 11 | KYV-5, KWR-46, KG-84C |

This paper discusses the elements of DMR that support its claim as a SDR and the high frequency (HF) waveforms, shown in Table 2, recently added to the DMR's repertoire.

2. DMR AS SOFTWARE DEFINED RADIO

The DMR architecture provides a hardware and software platform on which different waveform applications operate. This relationship is similar to that of a personal computer and the applications it runs. The DMR platform provides the necessary hardware resources to host the signal, cryptographic and audio processing, along with the base-band and RF I/O necessary for any DMR waveform. It also provides services that allow operator intervention, such as instantiating or activating a waveform, configuring waveform parameters, and tearing down waveforms. Each task occurs independently for each channel or waveform application, much the same as applications are opened and closed on a personal computer.

DMR is controlled remotely over an Ethernet connection using SNMP (Simple Network Management Protocol). A single human-machine interface (HMI) can control multiple DMR channels and units. The distributed software architecture is object oriented and based on the common object resource broker architecture (CORBA) standard. The software is based on an open architecture, developed in modular form to facilitate easy updates and replacements. Software controls all functionality of the DMR and is loaded using the HMI. The HMI is the primary interface for setting up, loading, and reconfiguring the DMR and controls built-in test, which provides extensive hardware and software test and diagnostic capabilities.

The software platform, including common infrastructure and control software enables such capabilities as instantiating and tearing down a radio channel, conveying alarms and warnings to the operator and enabling general wave-form operation. The security software enables the Type 1 security capabilities, to include encryption/-decryption, key management and enforcing the radio's security boundaries. The RF software provides control for the internal and external RF components, while the inter-networking software enables routing data both internally and externally to various devices or networks.

DMR radio functionality is 100% software defined. Waveform functionality is achieved by instantiating the software waveform elements onto the software platform or infrastructure. A DMR waveform typically executes on several processors and field programmable gate arrays (FP-

GAs) allocated for a particular channel. The waveform software is organized as a collection of communicating CORBA objects in a fashion similar to the structure of the Software Communications Architecture (SCA). The code for these objects and FPGA images resides on an integrated solid-state disk drive and is loaded by the DMR platform software as needed when a waveform is launched.

3. RF FRONT END

The RF hardware is a predominant driver of the cost, size, power, and performance of a radio. For an SDR like DMR, this is particularly challenging because of the stringent requirements from the various tactical radios. The dominant RF requirements in a military environment are the strong-signal handling capability while simultaneously providing a high quality output with high sensitivity. The resulting preselector, IF and channel filters, optimized for high dynamic range, coupled with high performance amplifiers and mixers, provide a radio capable of operating in a difficult cosite environment such as shipboard.

In DMR the RF design is a heterodyne transmitter and a direct conversion (zero-IF) receiver. The zero-IF receiver has low inherent spurious products over a wide tuning range, simplifying the overall RF complexity and size. The normal limitations of this type receiver, such as dc offsets and gain/phase imbalances, required both good analog matching as well as digital correction processing. General Dynamics C4 Systems has developed a high performance, wide-tuning receiver that meets the demands of the tactical military environment.

4. OVERVIEW OF THE DMR HF WAVEFORM

The HF waveform was a late addition for DMR. It consists of the three major subsystems as shown in Figure 2. The *HF Radio* subsystem performs the core SSB AM modulation of a 3 kHz base-band audio signal. The *User Waveform* subsystem performs a variety of transformations on the base-band signal, including vocoding, COMSEC and data modulation. The *ALE Controller* subsystem provides second-generation Automatic Link Establishment (ALE) services for the User Waveform. The User Waveform and ALE Controller subsystems share the traffic path through the HF Radio. Control functions within these subsystems arbitrate the use of this path.

The HF Radio is half-duplex and provides either independent sidebands (ISB) or single-sideband (upper or lower), either with or without carrier. The User Waveform subsystem can be configured to support either voice or data traffic in a variety of ways summarized in Table 3. The entire HF waveform can be operated in one of four modes as summarized in Table 4.

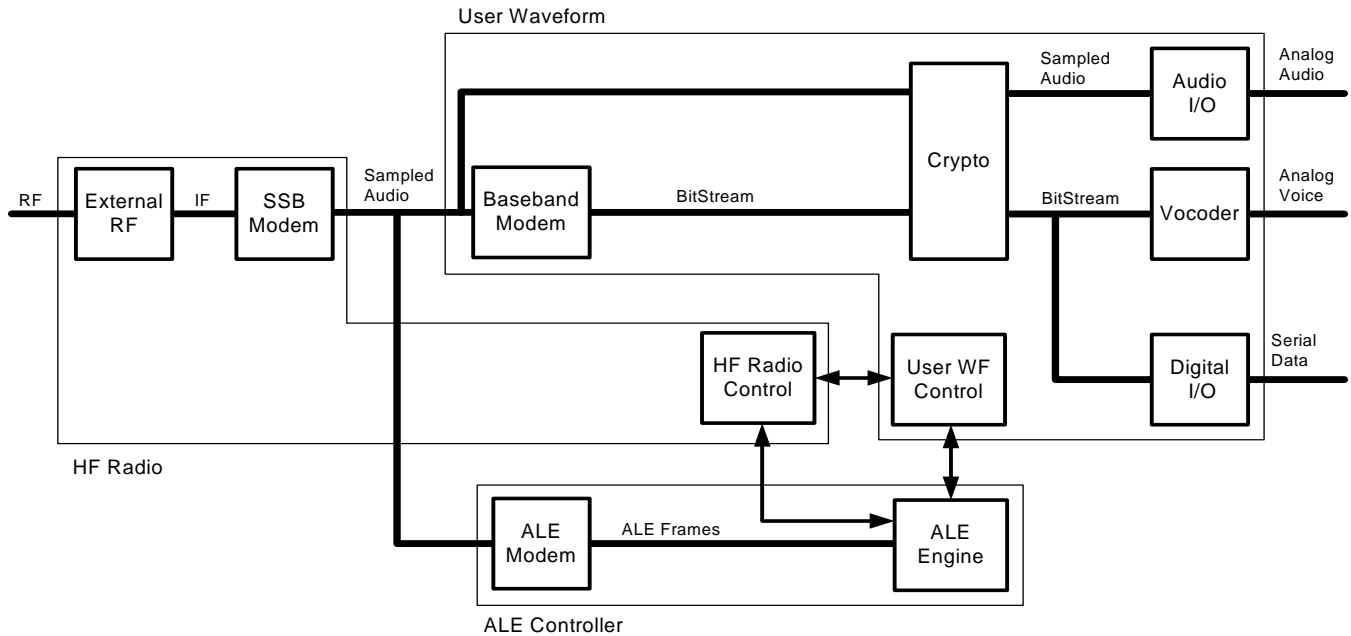


Figure 2 DMR HF Functional Architecture

Table 3 User Waveform Configurations

| Configuration | Base-band Modem | Internal Crypto | User I/O |
|-----------------|-----------------|-----------------|---|
| Voice | --- | --- | Analog Voice |
| CW | Single Tone | --- | Analog Audio |
| Teletype | Binary FSK | --- | Digital Data |
| External KY-99A | --- | --- | Digital Data, Digital Voice (LPC-10e) |
| External KG-84C | Serial Tone | --- | Digital Data |
| External KWR-46 | Serial Tone | --- | Digital Data |
| Internal KY-99A | Parallel Tone | KY-99A | Digital Data or Digital Voice (MELP, LPC-10e) |
| Internal KG-84C | Serial Tone | KG-84C | Digital Data |
| Internal KWR-46 | Serial Tone | KG-84C | Digital Data |
| Link-11 | --- | --- | Analog Voice |

Although the Voice and Link-11 configurations appear identical, they actually employ different audio ports since the latency bounds for Link-11 require a shorter traffic path.

Table 4 DMR HF Major Operating Modes

| Operating Mode | Description |
|--------------------|--|
| Repeating | The HF Radio subsystems in each of two separate channel HF waveforms are coupled via base-band audio to provide the functions of a repeater. |
| Frequency Scanning | The HF Waveform scans through a sequence of frequencies, pausing whenever significant energy is sensed. |
| Manual Control | The ALE Controller is halted. Configuration of the HF Radio is entirely under the control of the operator. |
| ALE Control | The ALE Controller configures the HF Radio in accordance with link establishment procedures and the content of its database. |

5. SSB MODEM

The single-sideband (SSB) modem employs a Weaver algorithm to generate and recover the desired sidebands for transmission or reception and to generate or suppress the HF carrier. All processing is accomplished digitally using base-band mixing, filtering, and constructive or destructive combining of the in-phase and quadrature signals.

6. PARALLEL TONE MODEM

The Parallel Tone Modem, PTM, was implemented per the ANDVT spec (MIL-C-28883A) and the KY-99A spec (ON406620). This modem supports data modes with rates of 300, 600 1200, 2400 bps and a digital voice mode at a rate of 2400 bps. The data modes use 16 simultaneous tones, each tone employing differential QPSK modulation. The voice mode is more spectrally efficient using 39 tones, each QPSK differentially encoded. The PTM utilizes the KYV-5 algorithm for its internal encryption/decryption.

The PTM synchronizes both time and frequency during the preamble reception. An accurate time/frequency synchronization and follow-on tracking loops are critical for inter-symbol interference (ISI) free performance. For the differential phase system, the previous frame is used as a reference phase for the current frame for both generation and resolution of each tone's phase rotation. An initial fixed phase frame is used as a reference frame for the first frame of data.

Since time diversity improves the performance of coded communications systems in fading, or impulsive-noise channels, the PTM utilizes a block interleaver that feeds Golay code words into rows. Once the interleaver block is fully loaded, data is read out column by column. Space diversity or data repeating can also mitigate the effects of fading, and is used on the 300 and 600 bps modes. The fact that space diversity can mitigate the effects of a fading channel is ideal for the digital voice mode, where the delay of an interleaver cannot be tolerated, and space diversity can be utilized. One significant advantage of the parallel-tone format is the ease with which space diversity reception is implemented.

7. SERIAL TONE MODEM

The Serial Tone Modem (STM) provides half-duplex operation using either upper or lower single-sideband modulation, with or without carrier suppression. The STM can be configured to support encrypted - either internal or external - or unencrypted traffic in several ways as summarized in Table 5 [1, 2, 3, 4].

The STM provides all the processing, forward error correction and interleaving necessary to meet the required military standards. Additionally, the STM operates in multipath environments as defined by MIL-STD-110A, and consequently includes channel estimation and equalization [10, 11]. In addition to the 110A modes, the STM is capable of operating in various STANAG modes in the presence of multipath interference, which requires special acquisition and tracking operation to meet this challenging performance requirement.

Table 5 Serial Tone Modem Waveform Configurations

| Waveform Mode | Inter-leaver Length | I/O Rates | Internal/External Crypto |
|------------------|-----------------------|--|--|
| MIL-STD-188-110A | Long Short None | 75, 150, 300, 600, 1200, 2400, 4800 | Internal KG-84C External KG-84C Internal KWR-46 External KWR-46 |
| STANAG 4285 | Long Short None | 75, 150, 300, 600, 1200, 2400, 3600 | Internal KG-84C External KG-84C Internal KWR-46 External KWR-46 |
| STANAG 4529 | Long Short None | 75, 150, 300, 600, 1200 | Internal KG-84C External KG-84C Internal KWR-46 External KWR-46 |

8 AUDIO PROCESSING

Audio processing in the DMR HF waveforms has been designed to support all modes of operation, from pulse code modulation (PCM) for plain text voice, to LPC-10e and MELP vocoding [15] for cipher text applications. By using common rate conversion and band pass filtering a seamless transition from one mode of operation to another can be achieved without waveform tear down and re-instantiation.

9. AUTOMATIC LINK ESTABLISHMENT

The ALE Controller implements Second Generation Automatic Link Establishment (2G ALE) in accordance with MIL-STD-188-141 [14]. The ALE Controller and the User Waveform share the use of the HF Radio subsystem. The ALE Controller functions much as a telephone operator, selecting and setting up the best communications link and then giving it to the User Waveform for further use. When the link is no longer needed, the ALE Controller is used to tear the previous link down.

An ALE *link* is nothing more than an agreement between several ALE capable radios (*stations*) to use compatible configurations of their HF transceivers. Each such configuration is known as a *channel*. A link is rather like a conference call; once established, stations can continue to join or leave the link, by negotiating with one of the already linked stations. Each station keeps track of the other stations with which it has negotiated the use of the link's channel. So long as this set of "linked stations" is non-empty, the station considers itself to be "linked."

These negotiations employ *handshakes*; well defined exchanges of short control messages (*frames*) between

several stations. The ALE standard defines several kinds of handshakes. Some are between just two stations, others are between one station and a known set of stations, and still others are simply broadcasts. Since each handshake requires the exchange of ALE frames on the link's channel, there may be a mixture of ALE traffic and User traffic on the channel of an established link [8, 5, 6].

The ALE Controller is assigned a small set of channels. When unlinked, the Controller scans these channels. When it recognizes a frame addressed to itself, it performs the handshake indicated by the frame. (A linked Controller also engages in handshakes, but only on the link's channel.) When an unlinked Controller is requested to link, it repeatedly tries the specified handshake on each of the channels that it has in common with the targeted station(s), starting with the channel that (in its estimation) would be the best for communication and working its way down towards the worst channel. This approach tends to shorten the average time to establish a link and gives preference to channels that will disrupt user traffic the least [9].

To rank the channels, the ALE Controller maintains a Link Quality Matrix. The identifier of a channel and a remote ALE station addresses each matrix cell. The cell contains *link quality metrics* (estimates of BER and SINAD) observed when communicating with that station on that channel. Since the quality of HF channels fluctuates, the controller gives less credence to older metrics when ranking channels. The data in this matrix is retained persistently.

The ALE Controller obtains estimates of the link quality metrics by observing ALE traffic. Channel quality is not always symmetrical between the two stations. The ALE Controller obtains a remote station's observations about a channel, by requesting them during a handshake. To keep a reasonably current picture of the channel quality, the ALE Controller takes every opportunity to collect these metrics.

The ALE Controller occasionally sounds, emitting an ALE frame that simply conveys its address. Sounding gives other stations an opportunity to observe link quality. Sounds are initiated both manually and automatically (when the ALE Controller has not transmitted any frames for a prescribed interval).

The ALE Controller implements the protocol stack summarized in Table 6. The rightmost column indicates which functional block in Figure 2 implements that portion of the stack.

The Application layer performs the procedures for handshaking, channel scanning, and sounding by exchanging packets with remote stations.

Table 6 DMR ALE Protocol Stack

| Protocol Layer | Functions | DMR Element |
|----------------|---|-------------|
| Application | Handshakes Channel Scanning Sounding | ALE Engine |
| Transport | Channel Configuration Traffic Path Arbitration Frame Formatting | |
| Link | Golay Coding Interleaving Redundancy | ALE Modem |
| Physical | Baseband Modulation | |

The Transport layer sends and receives packets. It acquires and configures the HF Radio to transmit or receive according to the current channel settings. It verifies that the channel is clear before initiating a handshake. It encodes outbound packets as frames, sequences of 24-bit ALE words. It reconstructs inbound packets from inbound stream of words, and updates the Link Quality Matrix.

The Link layer performs forward error correction services. Each word in an outbound frame is Golay encoded, interleaved and triplicated to create a channel word [7]. The inbound path performs majority voting, deinterleaving and Golay decoding.

The Physical layer implements ALE Waveform itself: continuous phase FSK employing eight orthogonal tones, with a symbol rate of 125 baud/sec. This layer also provides notifications of channel activity, both ALE and otherwise, to the Transport layer.

SUMMARY

The military requires reliable information to be readily available in multiple locations to effectively operate in critical tactical situations. The collective information needed - both digital and voice - provides a staggering amount of data to monitor, communicate and manage in a very dynamic environment. To succeed, this information must be presented to the battlefield decision-makers in an efficient, organized manner so informed, real-time decisions can be made that affect the performance and security of a brigade, a division, or the whole military.

Software-defined radios, as well as other cutting edge sensors, networking and new communication equipment are helping to meet these needs. DMR is a substantial force multiplier for the military, making possible communications across many different types of platforms and military services, enabling them to operate in a joint manner and enabling critical, real-time information to reach decision makers who can better commit resources to meet our nation's needs.

DMR also facilitates interoperability between the U.S. Military, Civil Agencies and NATO Forces for voice and

data communications. DMR supports flexible infrastructures providing universal connectivity with legacy radio performance and providing connectivity to wire-line systems with an open architecture, published application programming interfaces (API), and adherence to international standards for application development and portability of software [17].

DMR is the first full 2 MHz to 2 GHz, multi-channel, multi-processing Software Defined Radio (SDR) system to integrate RF transceivers, Modems, Cryptographic Algorithms, Audio and VOCODER processing, and I/O Protocol to support a variety of Communication Waveforms spanning the UHF, VHF, and HF frequency domains. The DMR HF radio is the only commercially available SDR with embedded communications security that will be certified for transmission of U.S. classified information in the HF range.

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