Design and System Implications of a Family of Wideband HF Data Waveforms

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ABSTRACT

The current US MIL-STD-188-110B [1] is being revised and will include an appendix defining a family of wideband HF data waveforms supporting bandwidths from 3 kHz to 24 kHz in increments of 3 kHz. This family of waveforms, designed by engineers at Harris Corporation and Rockwell Collins, extends the high performance serial tone modem technology of the current MIL-STD-188-110B standard, which was designed primarily to operate in a 3 kHz sideband, to wider bandwidths and much higher data rates. The waveforms can provide user bit rates up to 120,000 bps, and allow users the option of selecting the bandwidth and modulation to optimize modem performance based on the HF channel characteristics. The NATO Beyond Line-Of-Sight Communications Ad Hoc Working Group (BLOS Comms AHWG) is currently monitoring this development and may include this wider-bandwidth capability in a future NATO STANAG.

This paper begins with a brief discussion of the HF data communications and networking requirements that led to a waveform design effort considering higher bandwidths. This is followed by a detailed discussion of the key design decision and tradeoffs involved in designing a family of waveforms for radio bandwidths of 3 to 24 kHz, where it is necessary to provide reliable communications connectivity under a wide range of expected channel impairments. Next, the paper examines the system implications of these design decisions, considering how this new wideband capability can be best integrated and applied in a tactical military radio usage scenario, the implications of these wideband waveforms for Automated Link Establishment (ALE), and the potential applicability of cognitive radio techniques in areas such as intelligent selection of the communications bandwidth and other waveform parameters. The paper concludes with a discussion of the results of preliminary on-air testing of the new waveforms. Links tested include a relatively short east-west link in western New York State and a long north-south link between New York and Florida.

1.0 INTRODUCTION

The High Frequency (HF) band is used primarily for maritime, military and aeronautical systems and long distance AM broadcasting [2]. Military users are typically allocated channels with bandwidths of 3 kHz and occasionally of 1.24 kHz. Broadcast stations are typically allocated 12 kHz to allow for standard AM broadcasting. Over the last twenty years, several NATO standards [3][4][5][6] and US military standards [1][7] have been developed which provide very reliable communications over 3 kHz HF links. The highest data rate currently available in these standards with Forward Error Correction (FEC) and interleaving is 9600 bits per second (bps).

In recent years, there has been a growing need from the user community for higher data rates and this has led to the revision of MIL-STD-188-110B (110B). The new appendix of the revised standard, MIL-STD-188-

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14. ABSTRACT

The current US MIL-STD-188-110B [1] is being revised and will include an appendix defining a family of wideband HF data waveforms supporting bandwidths from 3 kHz to 24 kHz in increments of 3 kHz. This family of waveforms, designed by engineers at Harris Corporation and Rockwell Collins, extends the high performance serial tone modem technology of the current MIL-STD-188-110B standard, which was designed primarily to operate in a 3 kHz sideband, to wider bandwidths and much higher data rates. The waveforms can provide user bit rates up to 120,000 bps, and allow users the option of selecting the bandwidth and modulation to optimize modem performance based on the HF channel characteristics. The NATO Beyond Line-Of-Sight Communications Ad Hoc Working Group (BLOS Comms AHWG) is currently monitoring this development and may include this wider-bandwidth capability in a future NATO STANAG. This paper begins with a brief discussion of the HF data communications and networking requirements that led to a waveform design effort considering higher bandwidths. This is followed by a detailed discussion of the key design decision and tradeoffs involved in designing a family of waveforms for radio bandwidths of 3 to 24 kHz, where it is necessary to provide reliable communications connectivity under a wide range of expected channel impairments. Next, the paper examines the system implications of these design decisions, considering how this new wideband capability can be best integrated and applied in a tactical military radio usage scenario, the implications of these wideband waveforms for Automated Link Establishment (ALE), and the potential applicability of cognitive radio techniques in areas such as intelligent selection of the communications bandwidth and other waveform parameters. The paper concludes with a discussion of the results of preliminary on-air testing of the new waveforms. Links tested include a relatively short east-west link in western New York State and a long north-south link between New York and Florida.

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110C (110C) [8], defines a new family of wideband waveforms, which extends the high performance serial tone modem technology of the current MIL-STD-188-110B standard to wider bandwidths and much higher data rates. The waveforms, designed by engineers at Harris Corporation and Rockwell Collins, can occupy bandwidths from 3 kHz up to 24 kHz in increments of 3 kHz, providing user bit rates up to 120,000 bps. The various waveform designs included in the family allow users the option of selecting the bandwidth and modulation to optimize modem performance based on the HF channel characteristics. The NATO Beyond Line-Of-Sight Communications Ad Hoc Working Group (BLOS Comms AHWG) is currently monitoring this development and may include this wider-bandwidth capability in a future NATO STANAG.

This paper begins with a brief discussion of the HF data communications and networking requirements that led to a waveform design effort considering higher bandwidths.

This is followed by a detailed discussion of the design criteria and the tradeoffs involved in designing a family of waveforms for radio bandwidths of 3, 6, 9, 12, 15, 18, 21 and 24 kHz, where it is necessary to provide reliable communications connectivity under a wide range of expected channel impairments. The details of waveform format, modulation, forward error correction coding, interleaving, and robust preamble design are all discussed. The achieved Bit Error Rate (BER) and Block Error Rate (BLER) performance of the designed waveforms is investigated via a calibrated HF channel simulation model, to better understand their performance in HF multipath fading environments.

Next, system implications are examined, with an emphasis on how to best integrate and use this new wideband capability in a tactical military radio usage scenario. A discussion of the designed waveform’s parameters and how they may be optimally adjusted to improve throughput based on channel propagation, noise, and interference is provided. Cognitive mechanisms that may be used to monitor channel conditions and to adapt the waveforms’ parameters accordingly are next discussed. The role of Automatic Link Establishment (ALE) is addressed: existing ALE protocols – both 2G and 3G – are examined to determine how they may be enhanced to support the necessary cognitive capabilities required for reliable and efficient wideband HF data communications under real-world channel conditions. This section concludes with an examination of the challenges of providing wideband HF capabilities in a flexible, usable form within the user interfaces of a tactical radio system.

The paper concludes with a discussion of the results of preliminary on-air testing of the new waveforms. Links tested include a relatively short east-west link in western New York state and a long north-south link between New York and Florida.

2.0 WAVEFORM DESIGN OBJECTIVES, DESIGN DECISIONS, AND PERFORMANCE IMPLICATIONS

2.1 Design Objectives

In order to establish the design goals of the new family of wideband waveforms, it is first necessary to understand the physical media in which they will be used (i.e. HF channel characteristics). The HF channel can be represented as a multi-path time-varying environment which produces both time and frequency spreads [9]. For mid-latitude HF circuits, the amount of multi-path (often called delay spread) can range up to 6 ms and the fade rate (often called Doppler spread) can be as high as 5 Hz. However, more typical values are 2 ms and 1 Hz, respectively, which are the basic parameters of the standardized CCIR Poor HF channel [10], or as it is now referred to in the latest ITU Recommendation [11], the Mid-Latitude Disturbed Channel condition.

Besides the physical characteristics of HF, it is also important to understand the needs of the users and their applications. In recent years, HF systems have begun utilizing Automatic Repeat and Request (ARQ) protocols to provide error-free data delivery (i.e. STANAG 5066 [12] and the STANAG 4538 LDL and HDL protocols [13]). Thus, waveforms need to be designed to work well with these newer applications as well as the more traditional ones (such as broadcast and point-to-point message handling systems).

In addition, one of the latest applications of HF has been to network together naval ships in close proximity to each other. This particular application is over surface wave links which present much more benign channel conditions and much higher signal-to-noise ratios (SNRs) than are commonly encountered on HF sky-wave links.

Based on all of the above, the following three sets of designs goals steered the design of the waveforms.

General Design Goals:

1) Bandwidths extending from 3 kHz up to 24 kHz, in increments of 3 kHz
2) As the data rate is decreased, the waveform becomes more robust
3) Variable length preamble (i.e. long for HF sky wave links, short for surface wave links)
4) Performance similar to that of the MIL-STD-188-110B 3 kHz waveforms
5) Broadcast capability without “autobaud” (i.e. receive modem must know all waveform parameters)
6) Tail-biting FEC codes (similar to 110B) to reduce coding overhead
7) “Nice” data rates

HF design goals:

1) Multipath tolerance of at least 6.45 msec
2) Long interleaver setting (approximately 7.68 seconds)
3) Doppler spread tolerance of at least 8.333 Hz (for the lowest data rate waveforms)
4) Robust low rate modulation format similar to that of STANAG 4415 [4]

Surface Wave design goals (i.e. highest data rate waveforms):

1) Multipath tolerance of at least 3.33 msec
2) Ultra Short interleaver setting (approximately 120 msec)
3) End of Transmission (EOT) marker
4) High FEC code rates (i.e. rate 8/9, 9/10) to achieve the highest possible data rates

2.2 Modulation Characteristics

The design of the new wideband HF waveforms is very similar to that of the 110B Appendix C waveforms [1]. A few modifications have been made to allow for greater flexibility. As in 110B, each transmission begins with a block referred to as the “transmit level control” (TLC) block. The TLC length can be tailored to match the radio characteristics. No information is carried by the TLC, and it is intended solely for the purpose of radio TGC (transmit gain control), ALC (automatic level control) and AGC (automatic gain control) settling before the actual preamble is sent/received. Following this, a variable length preamble (110B Appendix C has a fixed length) is transmitted which is used for reliable synchronization and "autobauding" at the start of a transmission. The variable length aspect of the preamble allows a user to select the preamble length based on expected channel conditions. For example, a maritime surface wave application may benefit from a very short preamble while a very challenging multipath fading channel may require a very long preamble. This variable length preamble is then followed by alternating blocks of known and unknown symbols. The known symbols are used to track the time-varying multipath channel and the unknown symbols carry the user data (after encoding and interleaving).

Eight bandwidths are available starting at 3 kHz and extending up to 24 kHz in increments of 3 kHz. Each bandwidth offers up to 13 different data rates. Modulations ranging from 2-ary phase shift keying (2-PSK) up to 256-ary quadrature amplitude modulation (256-QAM) are used. The lowest data rate in each bandwidth (i.e. waveform ID (WID) 0) is based on the very robust STANAG 4415 Walsh modulation format [4]. A brief summary of the data rates (in bits per second) is presented in Table 1. The entries with a "-" are not used. The green colored data rates are those of the surface wave waveforms.

Table 1: Modulation, Bandwidth and Data Rate.

WID	3 kHz	6 kHz	9 kHz	12 kHz	15 kHz	18 kHz	21 kHz	24 kHz
0 - Walsh	75	150	225	300	375	450	525	600
1 – 2-PSK	150	300	600	600	600	1200	600	1200
2 - 2-PSK	300	600	1200	1200	1200	2400	1200	2400
3 - 2-PSK	600	1200	2400	2400	2400	4800	2400	4800
4 – 2-PSK	1200	2400	-	4800	4800	-	4800	9600
5 – 2-PSK	1600	3200	4800	6400	8000	9600	9600	12800
6 - 4-PSK	3200	6400	9600	12800	16000	19200	19200	25600
7 - 8-PSK	4800	9600	14400	19200	24000	28800	28800	38400
8 - 16-QAM	6400	12800	19200	25600	32000	38400	38400	51200
9 - 32-QAM	8000	16000	24000	32000	40000	48000	48000	64000
10 - 64-QAM	9600	19200	28800	38400	48000	57600	57600	76800
11 - 64-QAM	12000	24000	36000	48000	57600	72000	76800	96000
12 - 256-QAM	16000	32000	45000	64000	76800	90000	115200	120000

2.3 Interleaving Options

Four interleaver sizes are available for all the waveforms in Table 1. The smallest interleaver size spans approximately 120 milliseconds and each larger interleaver is four times the length of the preceding interleaver. Table 2 summarizes the four interleaver options.

Table 2: Interleaver Options.

Interleaver	length, secs
UltraShort (US)	~ 0.12
Short (S)	~ 0.48
Medium (M)	~ 1.92
Long (L)	~ 7.68

The block interleaver consists of a single dimension array starting at index 0 up to index N-1 (where N is the interleaver size in bits). Bit n is loaded into the interleaver by using the following equation

$$\text{Load Location} = (n * \text{Interleaver\_Increment\_Value}) \text{ Modulo } (N) \qquad (1)$$

The "Interleaver_Increment_Value" in equation (1) is selected such that bit soft decisions at the input to the FEC decoder are fairly balanced (i.e. adjacent bits after deinterleaving are not the same bit location in M-PSK or M-QAM constellations). An additional constraint on the "Interleaver_Increment_Value" is that adjacent bits after deinterleaving must be separated by several alternating blocks of known/unknown frames over the air. The larger the interleaver size, the larger this separation can be made. This constraint helps improve performance on slow fading channels.

2.4 Coding Options

Iterative codes were not considered for the new wideband HF waveforms due to the requirement that the standard be free of any 'Intellectual Property' (i.e., turbo codes are patented technology). Thus, the coding choice for the new wideband waveforms was to use the standard rate 1/2 constraint length 7 convolutional code that has been used for over two decades in 110A. In addition, repetition coding and puncturing was used to create a wide range of coding options which help the waveforms to achieve all of the 'nice' data rates shown in Table 1.

Recall from section 2.1 that very high code rates (i.e. 8/9, 9/10) will be used to attain the highest data rates for surface wave links. Very high puncturing of convolutional codes can result in very weak codes. Thus, an optional constraint length 9 code was added since it will be a much stronger code when highly punctured. So a user now has the option of selecting a k=7 or a k=9 code. A k=9 constraint length code is 4 times the computational complexity of the k=7 code, so care must be taken when selecting this option. A battery powered tactical radio may wish to conserve power by selecting the k=7 code while a strategic platform may benefit from the added performance of the k=9 code with only a small effect on its power budget.

Table 3 provides the code rates that will be used for each modulation and bandwidth. Table 4 provides the puncturing and repetition patterns. Note that the puncturing patterns can be also found in [14]. The entries with a "-" are once again not used.

Table 3: Modulation, Bandwidth and Code Rate.

WID	3 kHz	6 kHz	9 kHz	12 kHz	15 kHz	18 kHz	21 kHz	24 kHz
0 - Walsh	1/2	1/2	1/2	1/2	1/2	1/2	1/2	1/2
1 - 2-PSK	1/8	1/8	1/8	1/8	1/12	1/8	1/16	1/8
2 - 2-PSK	1/4	1/4	1/4	1/4	1/6	1/4	1/8	1/4
3 - 2-PSK	1/3	1/3	1/2	1/3	1/3	1/2	1/4	1/3
4 - 2-PSK	2/3	2/3	-	2/3	2/3	-	1/2	2/3
5 - 2-PSK	3/4	3/4	3/4	3/4	3/4	3/4	2/3	3/4
6 - 4-PSK	3/4	3/4	3/4	3/4	3/4	3/4	2/3	3/4
7 - 8-PSK	3/4	3/4	3/4	3/4	3/4	3/4	2/3	3/4
8 - 16-QAM	3/4	3/4	3/4	3/4	3/4	3/4	2/3	3/4
9 - 32-QAM	3/4	3/4	3/4	3/4	3/4	3/4	2/3	3/4
10 - 64-QAM	3/4	3/4	3/4	3/4	3/4	3/4	2/3	3/4
11 - 64-QAM	8/9	8/9	8/9	8/9	8/9	8/9	4/5	8/9
12 - 256-QAM	8/9	8/9	5/6	8/9	8/9	5/6	9/10	5/6

Table 4: Puncture and Repetition Patterns.

Code Rate	K=7 Puncture Pattern	K=9 Puncture Pattern	Number of Repeats
9 / 10	111101110 100010001	111000101 100111010	n/a
8 / 9	11110100 10001011	11100000 10011111	n/a
5 / 6	11010 10101	10110 11001	n/a
4 / 5	1111 1000	1101 1010	n/a
3 / 4	110 101	111 100	n/a
2 / 3	11 10	11 10	n/a
1 / 2	n/a	n/a	n/a
1 / 3	n/a	n/a	2/3 Repeated 2x
1 / 4	n/a	n/a	1/2 repeated 2x
1 / 6	n/a	n/a	1/2 repeated 3x
1 / 8	n/a	n/a	1/2 repeated 4x
1 / 12	n/a	n/a	1/2 repeated 6x
1 / 16	n/a	n/a	1/2 repeated 8x

2.5 Performance Under Simulated Channel Conditions

The new family of wideband waveforms presents quite a challenge for performance testing since there are almost 832 possible test choices. For this paper, only waveform IDs 5 through 10 using the Long interleaver setting will be evaluated for bandwidths of 3, 6, 12, and 24 kHz. Packet error rate (PER) for a 1000 bit packet will be the measure of performance.

2.5.1 Additive White Gaussian Noise (AWGN) Channel

Figure 1 shows the performance of the 12 kHz waveforms on the AWGN channel [15]. Note that the performance of the 12 kHz waveforms with the k=7 code is very similar to the performance of the 110B Appendix C waveforms, if the SNR value used is in their respective bandwidth (i.e. SNR in 3 kHz bandwidth for 110B and in 12 kHz for Figure 1). In fact, all 4 bandwidths were tested and performance was within 0.5 dB when the same WID is compared. Also, the k=9 code provided up to 1 dB additional gain in performance. Note that although the absolute SNR is not provided, it should be very close to already published data [1][6].

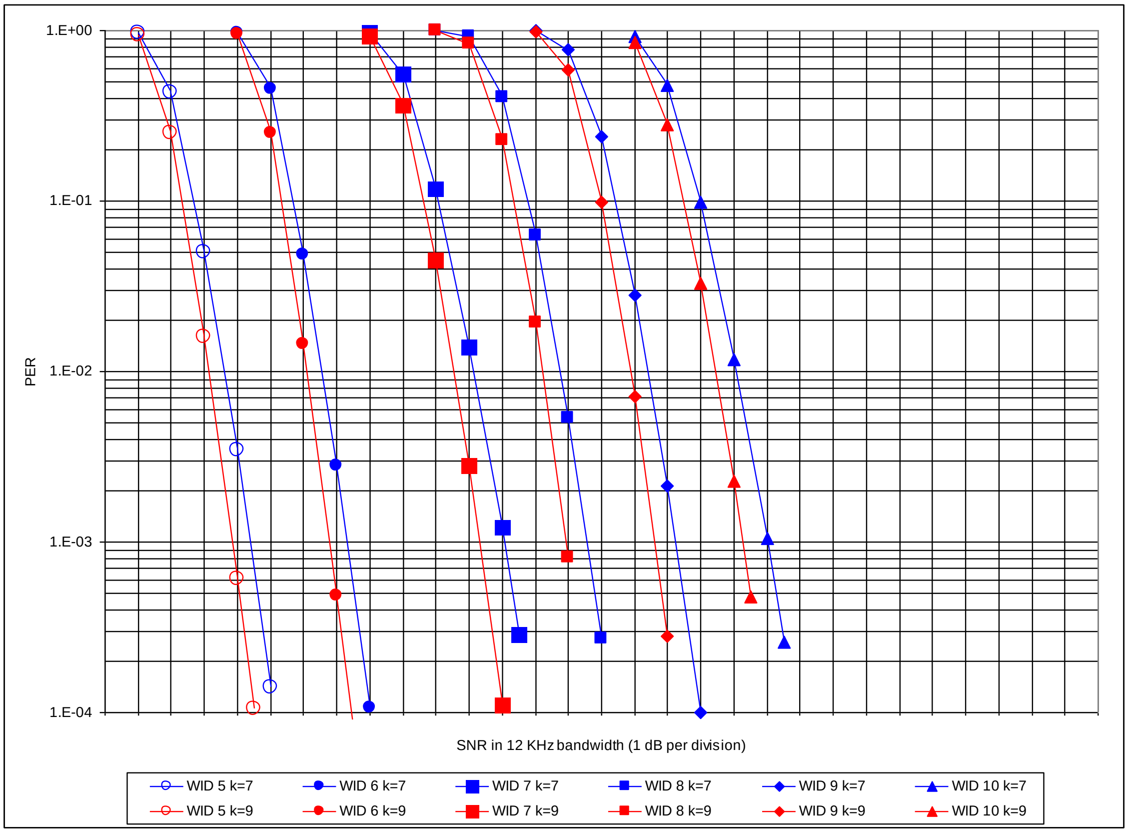


Figure 1: AWGN Performance for 12 kHz Waveforms (k=7 and k=9).

2.5.2 Mid-Latitude Disturbed Channel (MLDC)

Figure 2 shows the performance of the 12 kHz waveforms on the MLDC [11]. Similar to 2.5.1, the performance of the 12 kHz waveforms with k=7 was very similar to the performance of the 110B Appendix C waveforms for the CCIR Poor channel [1][6]. For the 4 bandwidths tested, performance was within 1 dB when same WID is compared. Similar to the AWGN channel, the k=9 code provided up to 1 dB additional gain in performance. For reference purposes, Figures 1 and 2 have the same starting and ending SNR value.

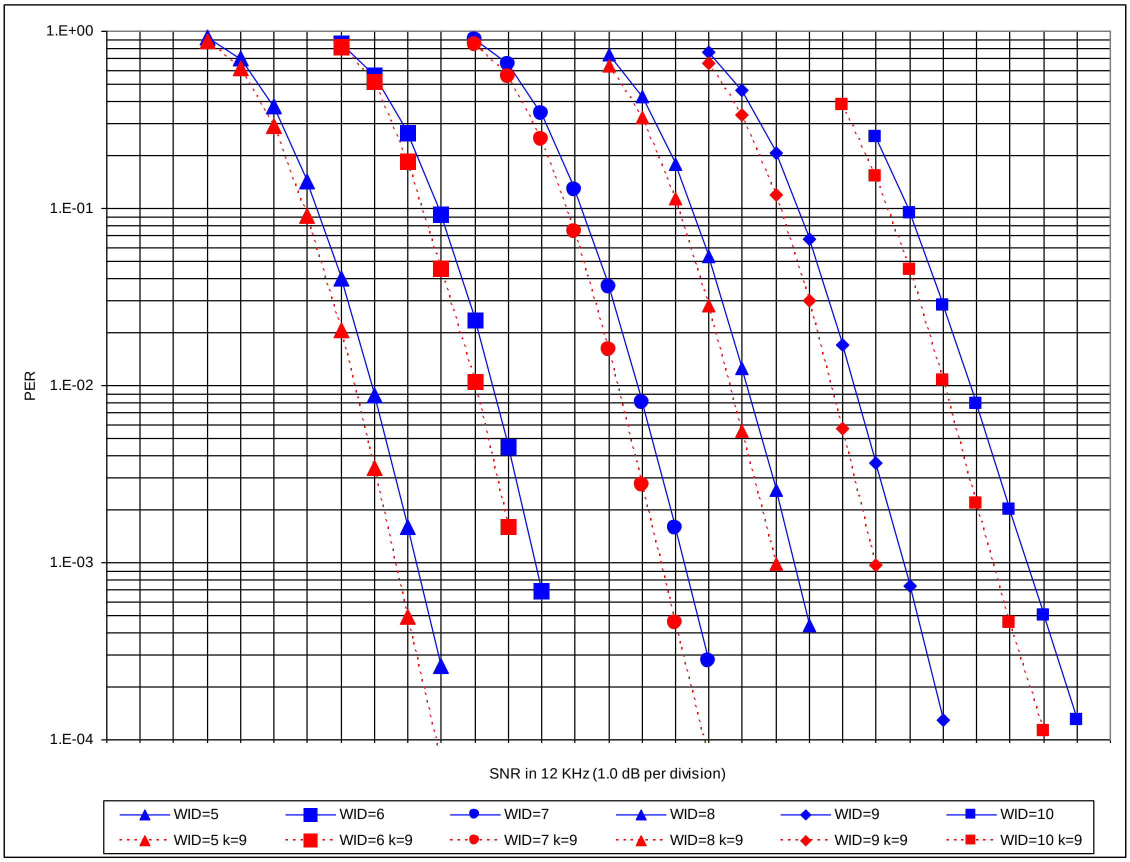


Figure 2: Mid-Latitude Disturbed Channel for 12 kHz Waveforms (k=7 and k=9).

2.5.3 Decoder-Aided Equalization and Decoding (DAED)

Decoder-aided equalization and decoding (DAED) has been shown to produce some significant performance gains on HF multipath fading channels [16]. Figure 3 provides the performance of the 12 kHz waveform for WID 10 on the Mid-Latitude Disturbed Channel for the standard demodulation and after one iteration of the DAED. Applying DAED to the k=7 code provided almost 2.5 dB improvement in performance while the k=9 code had less than 2 dB of improvement (for a PER of 10-3). The same experiment was performed on WID 8 and the gain of DAED after one iteration was roughly 1.5 dB for both the k=7 and k=9 codes. For WID 6, about 1 dB of improvement was measured for both constraint length codes after one iteration.

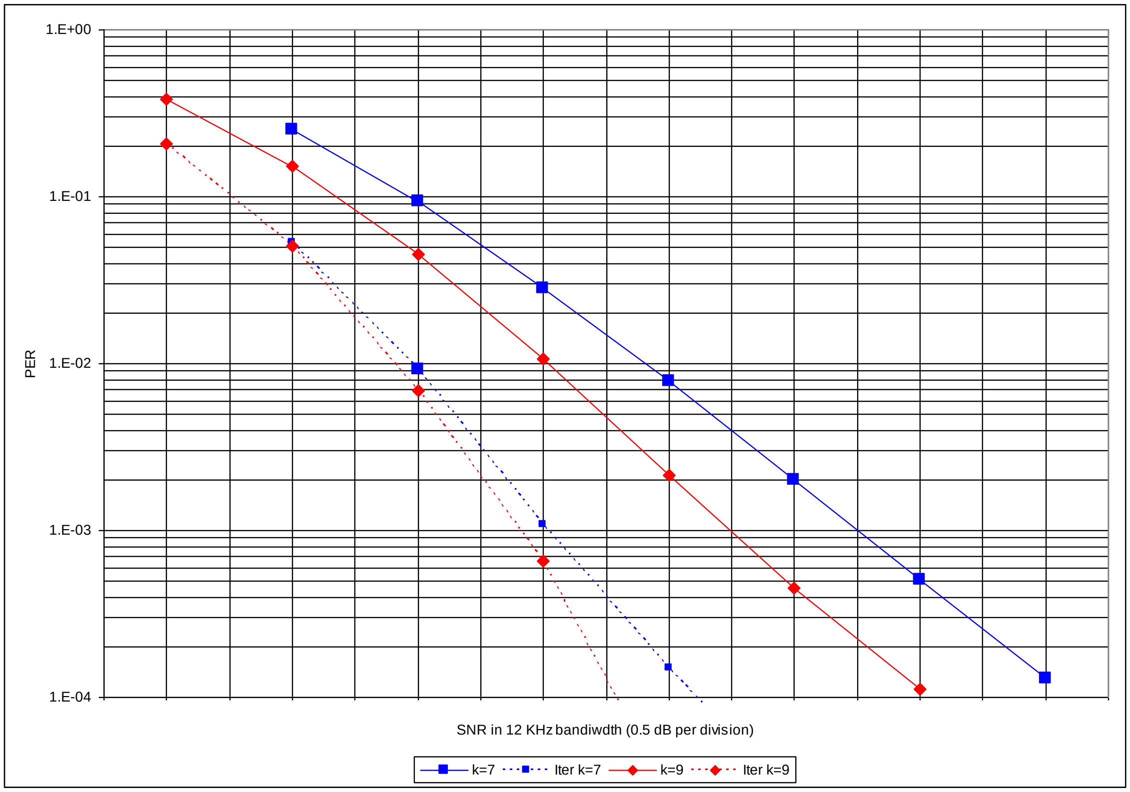


Figure 3: DAED Performance for Mid-Latitude Disturbed Channel (WID=10, k=7 and k=9).

Figure 4 provides the performance on a channel with two equal power paths where the first path is not fading and the second path has a 2 Hz fade rate. This channel will be given the name “Rician” channel [6]. As can be seen, over 3 dB improvement in performance is gained after one iteration of the DAED for the k=7 code and a little over 2 dB for the k=9 code. For WID 8, the gain for both codes was about 1.7 dB. For WID 6, the gain of both codes was roughly 1 dB.

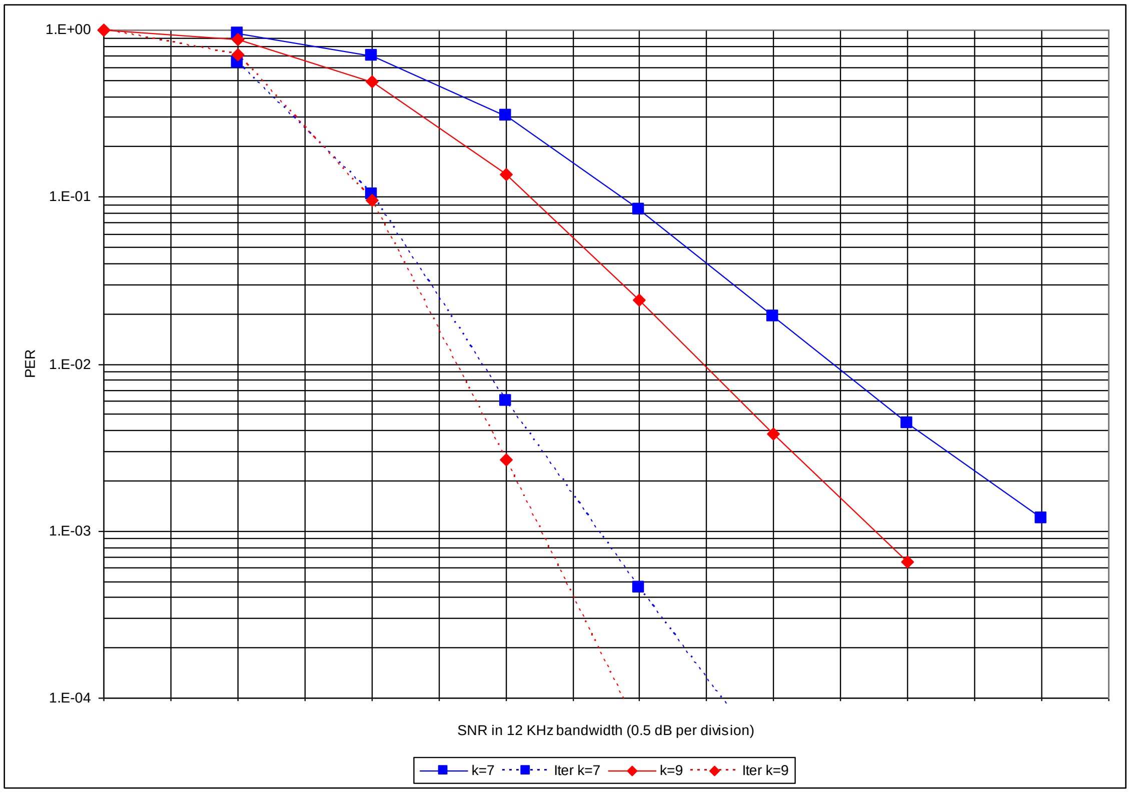


Figure 4: DAED Performance for Rician Channel (WID=10, k=7 and k=9).

Supposing that a radio platform only had enough computational horsepower to demodulate the waveforms with DAED using a k=7 code or no DAED but with a k=9 code, it is clear from Figures 3 and 4 that DAED would be the better choice. In fact, for all multipath fading channels simulated to date, DAED with k=7 code provides better performance than no DAED with k=9 code.

2.5.4 Spatial Diversity

A very powerful technique that can significantly improve performance on multipath fading channels is spatial diversity. Three important assumptions are typically made when simulating spatial diversity: independent fading observed for each diversity path, independent noise for each diversity path and same channel conditions for each diversity path (i.e. same SNR, fading conditions).

Figure 5 shows the performance of applying 2nd order spatial diversity to WID 10, long interleaver for 3, 6, 12, and 24 kHz bandwidths on a Mid-Latitude Disturbed channel. The solid lines are the performance with no diversity and the dotted lines are the performance with diversity. The x-axis is labelled “SNR in WBW” which means SNR in the waveform bandwidth. As can be seen, the benefits of spatial diversity are quite significant as over 6 dB improvement in performance is observed for all the bandwidths. This figure also confirms that the SNR performance for the same WID for different bandwidths will be close to the same, as long as the SNR is in the waveform’s respective bandwidth. Additional interleaver sizes were tested and even larger diversity gains were measured for the shorter interleavers.

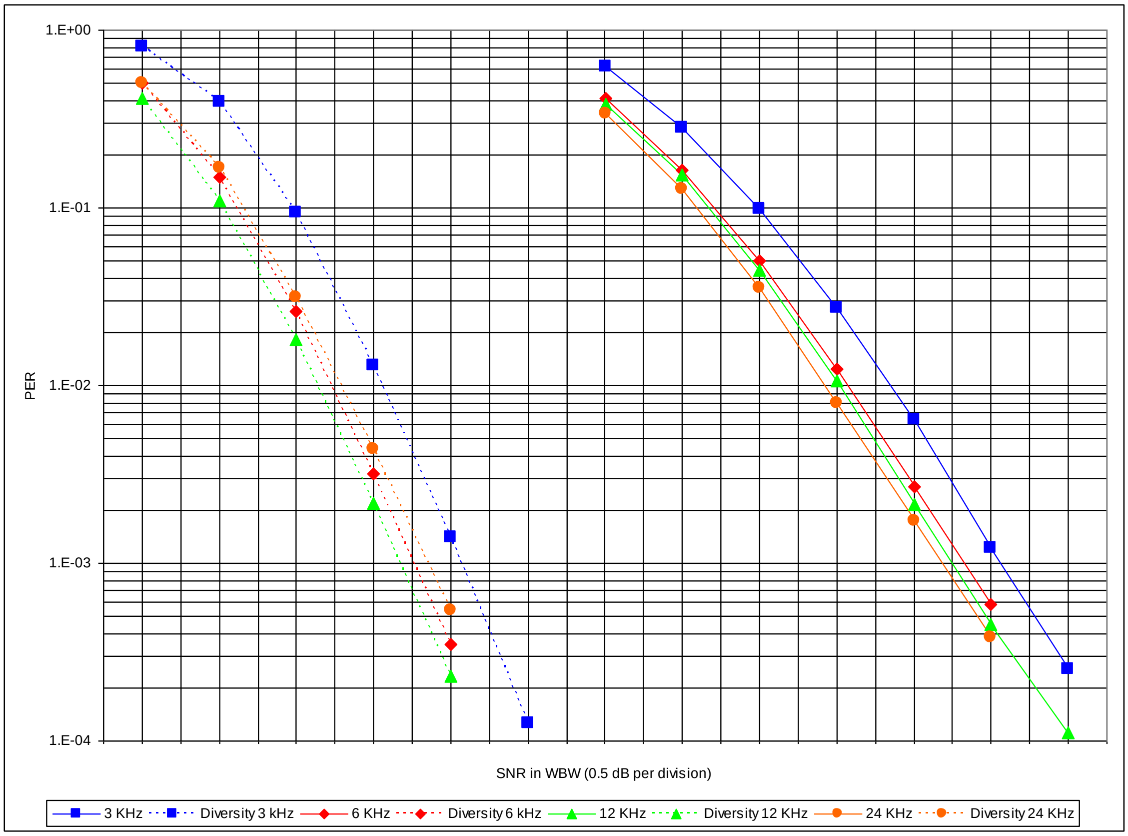


Figure 5: Spatial Diversity Results of WID 10 L for 3, 6, 12, and 24 kHz.

The main drawback of spatial diversity is that a second antenna and radio (at receive site) are required, in addition to a modem capable of combining the two receive paths. Furthermore, in order to obtain these large diversity gains, the three assumptions mentioned at the start of section must be true and only on-air testing can verify how valid these assumptions really are. Note that the spacing between the two receive antennas will be a key factor in meeting the previously mentioned assumptions.

3.0 COGNITIVE WIDEBAND ALE CONCEPTS

The design of the wideband HF waveform family gives rise to some significant challenges in their use. The possibilities to select from a variety of bandwidths, modulation formats, code rates, interleaver depths, and even code constraint lengths makes the application of some form of intelligence necessary in order to achieve the best possible communications performance (and quality of service) under variable HF channel conditions. The advent of *cognitive radio* has given rise to new concepts and techniques applicable to these challenges [20]; this section of the paper explores the applicability of these techniques to Automatic Link Establishment and waveform parameter selection in systems employing the new wideband HF waveforms.

3.1 Waveform Parameter Adaptation

One key requisite for effective use of the wideband HF waveforms will be selection of the waveform parameters offering the best possible quality of service under the prevailing channel conditions. Since HF channel conditions vary over time, often unpredicatably, it is necessary that this selection be done *adaptively*, based on the best available estimates of channel conditions and an understanding of how these channel conditions affect the usability and performance of the various waveforms in the family. This section considers the impact of channel conditions on waveform performance, and how a system can select waveform parameters so as to adaptively optimize performance.

3.1.1 HF Channel Characteristics

The sky-wave HF channel is time and frequency dispersive, in addition to containing noise from natural and man-made sources. Channel behaviour varies over time, making repeatable performance measurements difficult or impossible to obtain. For this reason, the Watterson Model [17] of HF sky-wave channel behaviour has been developed and used in characterizing HF system performance for some years [11]. This model consists of a complex tap delay line with variable complex signal gains that have Rayleigh distributed amplitudes and are low pass filtered to a Gaussian spectrum. The fundamental parameters of the HF channel that dominate waveform performance are the Multi-path Spread (MS), Doppler Spread (DS) and Signal to Noise Ratio (SNR). The channel model represents these as elements of a channel profile consisting of the relative signal gains and delays of each multi-path component; the Doppler spread or fading bandwidth of each path component; and the overall average signal to noise ratio. The tap delay line of the Watterson model is the mechanism that implements and defines the multi-path power profile and the amount of Doppler spread occurring on each path. Calibrated Gaussian noise is added to the output of this tap delay line to establish a desired SNR. Finally, a number of interferers may be implemented and added to the signal. The Watterson model was originally developed and validated for channels of approximately 10 kHz bandwidth or less. The validity of this model at 24 kHz still needs to be evaluated.

3.1.2 Waveform Parameters and their Impact on Performance

The proposed suite of wideband HF modem waveforms described in section 2 of this paper have been designed to provide excellent performance over HF sky-wave channels as well as unprecedented very high data rate capabilities over benign surface-wave links. The waveforms have been designed to increase in robustness, relative to SNR, multi-path spread and Doppler spread as the waveform selection is lowered from ID 12 to 0. Table 5 identifies the waveform parameters that are user selectable and the impact of their selection on modem performance.

Table 5: User Selectable Wideband HF Waveform Parameters.

Waveform Parameter	Comment
Preamble Duration	The low bit rate modulated preamble has a variable length (1-18 frames) as well as a variable number of repetitions as supported by an embedded count. As the duration of the preamble is increased, its robustness to SNR, MS and DS increases.
Waveform ID	The lowest complexity modulation used, Walsh Orthogonal modulation, is extremely robust to SNR, MS, and DS. As the modulation varies along the continuum from PSK-QPSK-8PSK-16QAM-32QAM-64QAM-256QAM, the robustness of the waveform to SNR, MS and DS diminishes.
Convolutional Code Constraint Length	The proposed standard provides the option of a k=7 convolutional code or a more robust k=9 convolutional code, with the idea that systems will choose one constraint length or the other depending on radio platform computational capacities. The k=9 code provides somewhat better error correction performance at the price of significantly higher computational complexity. Irrespective of which constraint length is selected, code rates as low as 1/16 and as high as 9/10 can be used, as determined by the combination of bandwidth and waveform ID. In general, the lower the code rate, the more robust the waveform performance will be relative to SNR, MS and DS.
Interleaver Depth	The interleaver is used to spread contiguous bursts of errors that occur on the channel over a larger period of time. The FEC of MIL-STD-188-110C performs better in correcting uniformly-distributed (non-bursty) errors; interleaving serves to make the error distribution more nearly uniform over time. As the duration of the interleaver in seconds is increased, longer fade durations can be accommodated at the cost of increased latency of the data transfer.

3.1.3 Waveform Characterization

One of the goals of an effective cognitive wideband ALE system would be to select values for the waveform parameters described above, adaptively, based on the observed or inferred characteristics of the available channels. One input needed for this selection process is a full characterization of the performance of each of the possible combinations of transmission format and bandwidth, specifying the level of performance each format and bandwidth is predicted to achieve under the current estimated channel conditions. An adaptive waveform selection algorithm would use this characterization to select the format and bandwidth providing the best trade-off of quality of service (data rate, bit or frame error rate, latency, overall reliability) vs. resource (channel) utilization.

As was mentioned above, the three primary characteristics of an HF link responsible for determining waveform performance are the multi-path profile, the fading characteristics of each path, and the overall SNR. The ITU-R F.1487 [11] recommends one method of characterizing waveform performance.

Figure 6 displays an HF modem performance surface which was obtained by measurement. The measurement assumes a two path Watterson channel model, varies the amount of delay between the paths MP and the Doppler Spread DS, and measures the SNR required to achieve a specified bit Error Rate (BER) or Packet Error Rate. Ideally it would be preferable to collect these data for all combinations of the 13 transmission formats (Waveform IDs), eight possible bandwidths, four possible interleaver lengths, and the two possible constraint lengths: 832 combinations in all.

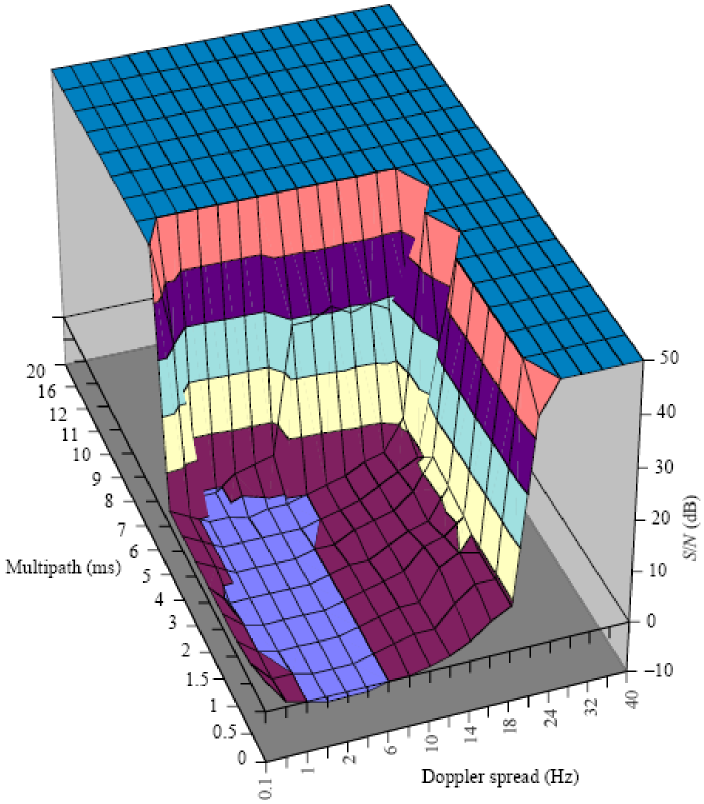


Figure 6: Example Performance Surface for a 300 bps 8-PSK Serial Tone Modem [4].

The time required to obtain the full suite of performance measurements for every one of these combinations may appear prohibitive. In reality, SNR variation across the bandwidths should be less than a dB or so and therefore it may be possible to test at a single bandwidth, perhaps 12 kHz, and extrapolate. Additionally, it may be possible to assume a fixed gain of one dB for the difference between constraint lengths, further reducing the size of the waveform characterization database and the time required to populate it.

3.1.4 Waveform Optimization

Waveform optimization for HF radio systems has always been a multidimensional problem. The variation of propagation, dependent on time of day, month and year, interference, and system components such as antenna systems and transmit power all impact the ability to communicate at a given time over a given HF link.

Today's adaptive HF radio systems successfully address most of these issues through the use of propagation prediction, Automatic Link Establishment, and data link protocols. The definition of a multi bandwidth HF data modem standard adds another dimension to the solution of how to best utilize HF frequency resources. The added dimensionality of bandwidth provides several different methods of optimizing the HF link.

In an HF radio system with fixed average and peak transmit power there is an immediate 3dB penalty each time the bandwidth is doubled. This arises because the transmit power has stayed the same but the increased bandwidth presents double the noise power resulting in an SNR in the new bandwidth that has decreased by 3 dB. Optimization of wideband HF data modem parameters involve balancing this 3 dB penalty associated with doubling the bandwidth of the waveform with gains achieved by selecting different modulation schemes which may in fact require less SNR and provide acceptable throughput.

A first method of optimization can be achieved by increasing the waveform bandwidth. If this is done and the modulation and coding scheme is kept constant, the data modem will be able to convey user data at higher rates providing the user with increased throughput and shorter transmission times. These higher data rates come at the cost of a higher required SNR or transmit power. On HF data links that have some amount of SNR headroom this method provides a mechanism to increase throughput.

A second method of optimization, given a requirement of a fixed data rate, is to examine the waveform options at all available bandwidths and utilize the option which provides the required throughput at the minimum cost of received SNR or transmit power. In this case the transmit power may be decreased to conserve battery power or alternatively a more robust data transfer will be achieved.

Both of these optimization approaches can be best illustrated by examining the following tables. Table 6 highlights the user bit rates available at bandwidths of 3, 6, 12, and 24 kHz.

Table 6: User Bit Rates 3, 6, 12, 24 kHz.

WID	3 kHz	6 kHz	12 kHz	24 kHz
1 – 2-PSK	150	300	600	1200
2 - 2-PSK	300	600	1200	2400
3 - 2-PSK	600	1200	2400	4800
4 – 2-PSK	1200	2400	4800	9600
5 – 2-PSK	1600	3200	6400	12800
6 - 4-PSK	3200	6400	12800	25600
7 - 8-PSK	4800	9600	19200	38400
8 - 16-QAM	6400	12800	25600	51200
9 - 32-QAM	8000	16000	32000	64000
10 - 64-QAM	9600	19200	38400	76800

Table 7 highlights the required Signal to Noise Density Ratio (SNDR) in order to achieve a bit error rate of 10^{-4} for each waveform in an ITU-R mid-latitude disturbed channel [11]. In general the expectation is that the required SNR would be the same for each bandwidth within each column assuming that the SNR was specified in the signal bandwidth. In actuality the SNR values are fairly close with minor variation introduced by different FEC code rates and waveform mini-probe overhead. The data however is presented in terms of SNDR where the required SNDR would be expected to increase by 3dB with each doubling of bandwidth. The values in Table 7 are relative to the SNDR required by WID 1 in 3 kHz so that performance can easily be compared between waveform options at different bandwidths.

Table 7: Relative SNDR for 10^{-4} BER.

WID	3 kHz	6 kHz	12 kHz	24 kHz
1 – 2-PSK	0	3	6	9
2 - 2-PSK	2.5	4.8	7.5	10.5
3 - 2-PSK	5.2	8	10.5	13.5
4 – 2-PSK	8.2	10.2	13.2	16.2
5 – 2-PSK	12	14.5	17.5	20.5
6 - 4-PSK	16	18	21	24
7 - 8-PSK	20	22	25.2	28.2
8 - 16-QAM	23.2	25.2	28.5	31.5
9 - 32-QAM	26.5	28.5	31.5	34.5
10 - 64-QAM	30	32	35	38

An example of the first optimization can be seen by examining Tables 6 and 7. If the data modem were performing well at 9600 bps in 3 kHz bandwidth, the bandwidth could be increased from 3 kHz to 24 kHz and an on-air bit rate of 38400 bps could be achieved. If the relative SNDR were 38 dB, an on-air bit rate of 76800 bps could be achieved. In this example it is achievable because of excess SNDR. If this was not the case the higher bit rate would be achievable by increasing the transmit power by the required amount. An example of the second optimization can also be seen by examining Tables 6 and 7. If the data modem is performing marginally at 9600 bps in 3 kHz bandwidth with a relative SNDR of just under the required 30 dB, we have several options for improved performance at 9600 bps. By adjusting the bandwidth to 6 kHz we can achieve 9600 bps by utilizing WID 7, which would only require a SNDR of 22 dB, providing an 8 dB advantage. The bandwidth could also be adjusted to 24 kHz, where the SNDR required would only be 16.2 dB, giving us an advantage of 13.8 dB. This 13.8 dB advantage could be used to decrease the transmit power while maintaining better data performance.

In summary, two different methods for optimizing HF data link performance are now available due to the multi-bandwidth data modem that has been presented. First, in the case of excess SNDR, the bandwidth can be increased to provide a higher user data throughput with correspondingly shorter on-air transmission times. Second, in the case of a fixed throughput requirement, the bandwidth can be increased in order to gain additional signal transmit power reserve. This reserve can be reduced through lower transmit power and corresponding longer battery life, utilized to increase the robustness of the data transfer, or a combination of both.

3.2 The Role of a Cognitive Wideband ALE System

3.2.1 Background

Furman and Koski [18] provide an overview of ALE and discuss areas for consideration in the fielding of a next generation ALE system. All ALE systems must perform four basic tasks: frequency management, channel selection, link establishment, and link maintenance. Frequency management includes establishing the number of stations to be deployed, their call signs or addresses, and the assignment of frequencies to channels and channels to channel groups. Inherent in this planning is the topology of the deployed network, defining which stations can communicate with which. This planning is generally supported by a separate computer system running a software application such as the Harris RF-6550H™ Radio Programming Application. Once an ALE system is deployed and a link setup is requested, the next common step is channel selection. In this step, the calling station attempts to select a channel likely to be optimal or at least suitable for communications with the destination station. Most ALE implementations keep some form of internal scoring of observed channel quality for each channel/destination pair for use in channel selection. (Many also provide a way to call on a specified channel, independent of any score or quality metric.) Once a channel has been selected, the link establishment process can begin with a linking attempt on the selected channel; however, linking attempts on other channels may also be necessary if the selected channel is found not to be suitable due to path degradation or channel occupancy not reflected in its channel score. Once a link has been established and is being used for communications, link maintenance techniques can be employed to re-assess the quality of the link and, if the quality of the current channel has degraded relative to that of other channels, drop the current link and re-link on a higher-quality channel. Wideband channel allocations have an impact on each of these functions.

3.2.1.1 Frequency Management

Bandwidth is now an additional parameter that must be factored into the frequency management process. In the general case, the use of wider-bandwidth channels makes it possible to field a network of HF stations whose frequency allocation contains channels of different bandwidths. The bandwidth of each channel needs to be considered when assigning channel resources to networks and links. For example, it may make more sense to assign wideband channels to the most heavily loaded links, such as backbone or upper-echelon links in a hierarchical network. Alternatively, it may be desirable to use a wideband channel for links requiring more robust data transfer at a required bit rate. In these cases, use of a wider-bandwidth channel allows the modulation complexity to be decreased for a given data rate, giving an overall SNR advantage to the wider-bandwidth solution and thereby providing more robust data delivery. The bandwidth modulation and bit rate tradeoffs of wideband HF systems are discussed more thoroughly in Furman, Nieto [19].

A further level of complexity arises when the potential scarcity of frequency resources is considered. It may be necessary to carefully analyze whether the assignment of a wider bandwidth to a particular link is desirable when the communications capacity of the entire network is considered, or whether it may be preferable to divide the wider bandwidth into narrower (e.g., 3 kHz) channels in order to increase channel availability.

3.2.1.2 Channel Selection

Bandwidth must now also be factored into channel selection. It may be desirable to select a wider-bandwidth channel for a link, but the channel must be propagating and also relatively free from friendly or hostile interference. If interference is present on some significant portion of the band, it may still be desirable to link on the channel, but in such a way as to use the interference-free portion of the channel for subsequent communications. In this approach, the channel selection process must, in addition to recommending a bit rate and modulation, also recommend the bandwidth and an offset from carrier frequency to fully define the channel to be used.

The fundamental task of channel selection is to select a propagating channel that provides some specified level or quality of service. A secondary task of channel selection might be to provide a recommendation as to what waveform (modulation type, code rate, etc.) can be supported on the selected channel. Usually, both of these tasks are accomplished by transmitting some sort of probe or link quality assessment waveform that supports the measurement of received signal characteristics such as SNR, multi-path and Doppler spread, and interference profile. These measurements may be made in real time, based on averaged observations and processing of signals received over some time interval, or a combination of both.

3.2.1.3 Link Establishment

The link establishment handshake may be similar to that employed by either 2G or 3G ALE systems, but now must also convey the recommended bandwidth and offset of the selected best channel. A good question is: in a wideband HF system, which bandwidth should be used for the link establishment signalling?

3.2.1.4 Link Maintenance

Link maintenance involves the selection of new channel parameters, possibly some or all of frequency, waveform modulation, and bandwidth. This may be initiated from either side of the link as conditions degrade, or may be automatically scheduled to occur after a specified time period of channel use.

3.2.2 Cognitive ALE

Koski and Furman [20] have previously addressed the application of cognitive radio concepts to HF communications functions including ALE. In one viewpoint, HF ALE has always been a cognitive radio function in that, by its nature, it is dealing with a highly variable propagation and interference environment and must learn which frequencies are propagating, share this information among nodes, and establish communication with other radio systems. However, there is some controversy over whether this suffices to make ALE a cognitive capability or a merely adaptive capability.

The SDR Forum is currently working on definitions of what constitutes a cognitive radio. Their current definition is: “An approach to wireless engineering wherein the radio, radio network, or wireless system is endowed with the capacities to: (1) acquire, classify, and organize information (aware), (2) retain information (aware), (3) apply logic and analysis to information (reason), and (4) make and implement choices (agency) about operational aspects of the radio, network, or wireless system in a manner consistent with a purposeful goal (intelligent)”[21]. By these criteria, ALE appears to be a bona fide cognitive capability. However, this paper will follow [20] in not attempting to defend a position on this question.

Currently deployed ALE systems must: (1) probe and measure channel characteristics, classifying channels as propagating, interfered, usable or unusable, (2) store channel quality information for each combination of channel and destination radio system, (3) decide which channels provide the most effective use of the available frequency resources, and (4) relay this information and co-ordinate the formation of useful links. A wideband HF ALE system must perform all of these functions with the additional dimensions of allocated bandwidth, usable bandwidth, and usable bandwidth offset.

3.3 Wideband ALE Approaches

3.3.1 Requirements

Summarizing Section 3.2, the requirements of a cognitive wideband ALE system are:

- Handle a set of HF channels that may be of different bandwidths, from 3 to 24 kHz referenced from a sideband carrier
- Determine which of these HF channels is propagating and the available bandwidth of each channel. Note the available bandwidth may be less than the allocated bandwidth due to propagation and interference.

- Establish the desired link and prepare for data transfer.
- Provide a link maintenance function to update and reorganize the HF link as needed.

3.3.2 Suggested Approaches

3.3.2.1 Frequency Management

Maslin [22] defines frequency management as the process of selecting the best frequency according to the prevailing conditions. Successful frequency management depends upon the ability to predict, measure and react to a range of parameters that characterize both the propagation path and noise. Frequency management systems are primarily responsible for the pre deployment planning of an HF radio system or network. In order to fully optimize wideband HF channels the following concepts should be considered:

- Channels should be managed with attributes of bandwidth and capacity
- Links should be managed with a capacity attribute that could be used to assign wider bandwidth channels where they can be best utilized
- Additionally, links requiring robust delivery of data under predicted difficult channel conditions may choose wider bandwidth channels to achieve a specified delivery rate utilizing a lower order / more robust modulation scheme.

3.3.2.2 Channel Selection

Different ALE systems employ different methods of gathering measurements in order to perform channel selection. Most systems include some form of propagation prediction (usually as part of the frequency assignment phase), passive reception of link establishment signalling, and some form of channel probing and scoring, generically referred to as Link Quality Analysis (LQA).

Several different approaches could be considered for channel selection probe signalling. The selection of a single approach is complicated by the desire to be able to select a portion of an allocated wideband channel for use based on noise or interference.

Approach 1: Probe bandwidth matched to allocated channel. In this approach, the probe waveform is matched in bandwidth to the allocated bandwidth of each channel. This provides a mechanism of detecting propagation and estimating the channel characteristics of SNR, multi-path and Doppler spread, and interference level. This approach is not recommended because of its inability to easily partition and then select the largest contiguous subset of usable bandwidth from the channel under evaluation.

Approach 2: 3 kHz segmented probe. In this approach the probe waveform is implemented in 3 kHz segments of the allocated channel. In a serial approach the waveform is transmitted sequentially on each 3 kHz segment of the allocated bandwidth in each channel. This method measures the channel characteristics of each 3 kHz segment and then uses that information to select the best channel as well as the best contiguous subset of usable bandwidth on that channel. The major disadvantage of this approach is the time required to probe each 3 kHz segment sequentially. An alternative to this approach is to utilize a transmit waveform containing 3 kHz waveform segments transmitted simultaneously, one for each 3 kHz portion of the band, and processed individually at the receiver. This approach will limit the time required to probe the bandwidth but will suffer from a peak power limitation requiring the average transmitted power to be reduced by a factor greater than simple bandwidth expansion. These approaches are not recommended.

Approach 3: 3 kHz centred probe with LBT capability. This approach assumes that under sky-wave propagation conditions, the channel characteristics will be similar enough across the entire specified channel bandwidth so that a single 3 kHz probe waveform in the centre of the bandwidth can be used to measure the channel propagation characteristics. The notable exception to this will be during propagation transitions when the measured channel straddles the propagation boundary. This centred waveform approach is coupled with a suite of Listen Before Transmit techniques that passively monitor the entire allocated channel during scanning or dwelling periods and estimate an interference profile. This approach can be further enhanced by not limiting the probe to the centre of the allocated bandwidth, but instead moving the probe alignment with each successive probe transmission so as to better sample the allocated bandwidth. This approach is recommended as a suitable approach for incorporating wideband ALE capabilities into an existing ALE standard.

3.3.2.3 Link Establishment

As was mentioned in section 3.2, the link establishment process must convey the selected channel, the selected bandwidth, and the offset of the selected bandwidth relative to the center of the allocated channel. The called station does not know the selected bandwidth and offset and therefore a common bandwidth and offset should be used in link establishment signalling. Additionally, since robust delivery of this relatively small amount of data is desired, it is recommended that link establishment signalling be performed in the nominal 3 kHz bandwidth of each assigned channel, either centred or shifted based on TOD to allow passive receiver systems to sample more of the allocated bandwidth. A similar approach can be used for the link maintenance signalling.

3.3.3 Integration with Existing ALE Systems

There are several advantages to basing the design of a wideband ALE system on an existing 3 kHz bandwidth system. This provides a ready framework, lower development cost and easy backward compatibility with existing 3 kHz systems. A common approach for both 2G and 3G based systems would be to open up the receive bandwidth to the maximum of 24 kHz while maintaining the standard 3 kHz ALE signal detection and simultaneously processing the maximum bandwidth with various Listen Before Transmit (LBT) and interference detection techniques.

3.3.3.1 A Second Generation ALE Based Approach

US MIL-STD-188-141B defines the second-generation or 2G ALE system. A 2G ALE system is fundamentally an asynchronous system in which each station, while not actively participating in communication, is scanning through a set of frequencies or channels at a rate of 2, 5 or 10 channels per second. The standard allows for each station to have multiple call signs or addresses and to simultaneously scan multiple channel groups (sets of channels) associated with the station’s potentially multiple call signs or “self addresses”. A scanning station scans through the concatenated list of all channels associated with its multiple self addresses. A 2G connection or link setup process consists of a three-way handshake executed on a single channel. The channel is selected by the originating station which transmits the call. This call is of sufficient duration to guarantee that the called station’s scanning receiver can detect the call, stop scanning, and dwell continuously on the channel on which it was received. The called station replies with a response to signify that it correctly received and can accept the call addressed to it. The calling station completes the handshake by transmitting an acknowledge signal.

In a simple implementation, the signal detection would still be performed by processing the assigned 3 kHz sub-section, but the entire observed bandwidth could simultaneously be processed with various (LBT) techniques to determine the levels, types, and spacing of any significant interferers.

MIL-STD-188-141B provides an already defined mechanism, the CMD ("command") word, for conveying additional data during the linking process [23]. Specific CMD words are defined in the standard to convey various kinds of information such as LQA scores. A new CMD word could be defined to convey the required information for linking on wideband channels. For instance, the first character 'L' could be used to signify linking information and could include two 3-bit fields signifying the bandwidth to be used and the offset from carrier.

3.3.3.2 A Third Generation ALE Based Approach

A Third Generation ALE system is fundamentally a synchronous system. All stations in a 3G net scan through a set of frequency channels in a lock-step fashion. While scanning, a 3G receiver will dwell on each frequency for 1.35 seconds (in STANAG 4538 FLSU)[13]. 3G ALE employs a two-way call/response handshake. The on-air signalling of this handshake is based on a family of robust high performance burst serial tone waveforms and is covered in detail in the standard. The third "confirm" step of the 2G ALE handshake is eliminated in 3G ALE since it is unnecessary if linking is successful; if the calling station fails to receive the response, it transmits a very robust TERM transmission to cause the called station to resume scanning.

In a simple implementation, the signal detection would still be performed by processing the assigned 3kHz sub-section but the entire observed bandwidth could be processed with various (LBT) techniques to determine the levels, types and spacing of any significant interferers. The TrafficType field of the FLSU link set-up PDUs presently contains a sufficient number of unused field-values to permit a subset of them to be used to specify a suitable bandwidth for WBHF transmission.

4.0 ON-AIR PERFORMANCE TESTING

4.1 Summary

This section presents the goals of preliminary on-air tests of the wideband HF data modem, describes the tests performed, and summarizes and discusses their results.

4.2 Performance Testing

4.2.1 Overview

Harris has implemented the wideband HF data modem standard as it exists in draft form as of early 2010. As this is a preliminary implementation, there are some deviations from the standard. For instance, only the bandwidths of 3, 6, 12 and 24 kHz have been implemented. Additionally, the Harris implementation uses an earlier design of the waveform preamble that provides equivalent performance and functionality to that which is described in the standard. The Harris implementation has been developed on prototype hardware in a 20 Watt tactical radio package.

Initial on-air testing of the wideband HF data modem was conducted in May and June of 2010 on an NVIS link of approximately 167 km from Rochester, NY, USA to Stockbridge (Munnsville), NY, USA. This is predominantly an east-west path.

4.2.2 On-Air Test Goals

There were several goals to this preliminary on-air test of the new MIL-STD-188-110C Wideband HF Data Modem. The main goal was to place a prototype wideband tactical HF man-pack on the air and verify operation before beginning a campaign of on-air testing.

- Deploy prototype wideband tactical military HF equipment
- Test over a challenging NVIS link
- Determine which bandwidths and corresponding bit rates could be supported over a tactical NVIS link. Examine the on-air performance relationships between different waveform options at different bandwidths
- Preliminary evaluation of STANAG 4538 – 3 kHz 3G ALE as a linking mechanism for wider bandwidth channels.

4.2.3 Test Setup

Table 8 provides a list of equipment utilized at the Rochester NY base station and at a remote facility in Stockbridge NY.

Table 8: Equipment Utilized for On-Air Test.

Rochester, New York	Stockbridge, New York
Harris RF-5800H man-pack radio system	Harris RF-5800H man-pack radio system
Harris RF-5834 400 Watt power amplifier	Harris RF-5833 150 Watt power amplifier Harris RF-382 coupler Harris RF-5245 pre / post selector
Harris prototype wideband HF man-pack radio	Harris prototype wideband HF man-pack radio
Broadband terminated folded dipole antenna	Harris RF-1912 antenna

The RF-5800H systems were used to perform 3G ALE LQA exchanges in order to select the best frequency. All 3G ALE signalling is limited to the 3 kHz currently defined in STANAG 4538. Once the RF-5800H systems were linked on the best frequency the prototype wideband HF radios were enabled. In Rochester the prototype radio was used as an exciter to drive the 400Watt power amplifier where an average transmitter power of approximately 170 Watts was achieved. In Stockbridge the prototype wideband radio was connected to the receive antenna. At this point Bit Error Rate (BER), 1000 bit Packet Error Rate (PER), as well as channel characteristics could be measured.

Tactical Military HF radio equipment was used specifically in order to see if wideband HF would be suitable for links where the equipment would have size, weight and power constraints and relatively modest transmit power.

4.2.4 Propagation Prediction

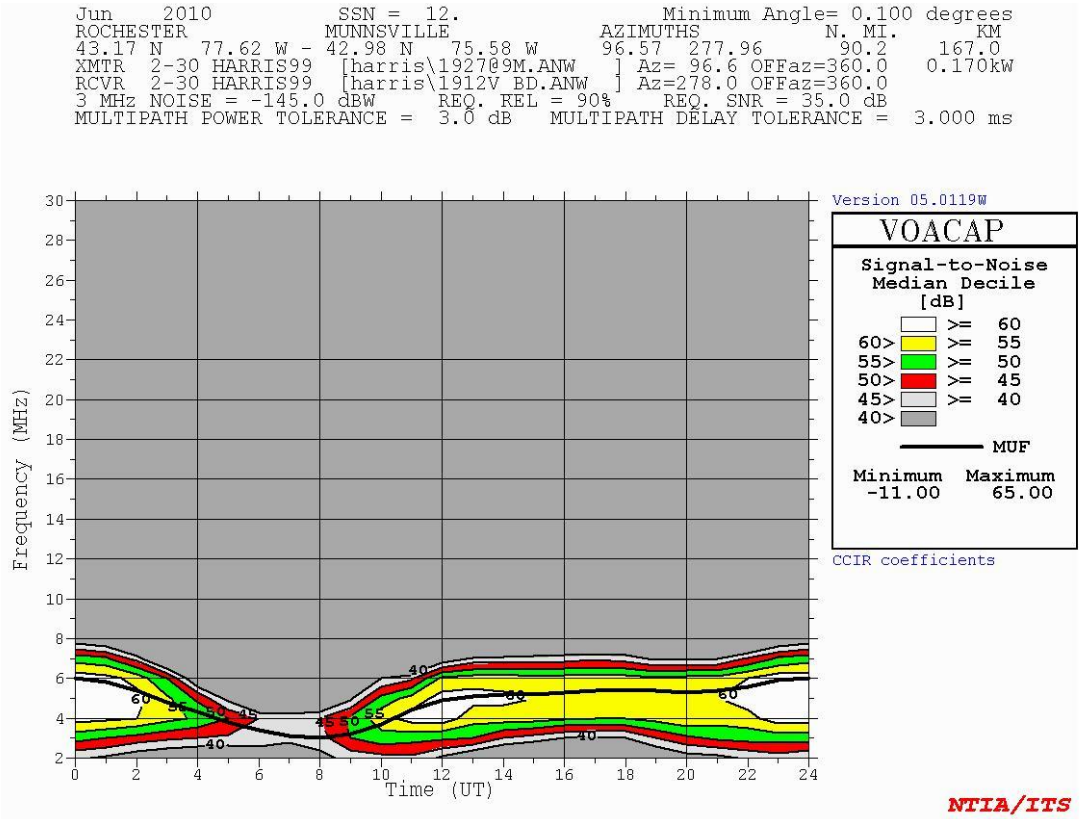
VOACAP [24] was used to predict the propagation between Rochester New York and Stockbridge New York. This is a 167 km east – west link that supports Near Vertical Incidence Sky-wave (NVIS) propagation. Figure 1 displays the VOACAP output for Signal to Noise Ratio in 1 Hz bandwidth. This prediction utilizes models of the antennas deployed, the average transmit power of 170 Watts and the predicted Smoothed Sun Spot (SSN) number of 12 for June of 2010. VOACAP predicts that during the daylight hours a relatively narrow frequency band of 4 to 6 MHz is propagating giving 3 kHz median SNR values of 20 to 25dB.

Harris obtained a Special Temporary Authorization (STA) from the FCC for several 24 kHz channels to test and evaluate the new wideband HF data modem standard. Approximately ten channels in the above frequency range were available for use.

4.2.5 Observations and Test Results

4.2.5.1 General Observations

Testing was performed during the daylight hours of approximately 10:00 to 15:00 hrs. local time consistent with the VOACAP prediction. A secondary receiver, connected to a second RF-1912 antenna, was used to monitor a 3 kHz segment of each transmission from Rochester. The propagating frequency band, determined via 3G ALE LQA, was in very close agreement with the VOACAP prediction between 4 and 6 MHz. All selected channels had significant single path fading, with an occasional low power secondary path at a delay of approximately 0.5 ms which could be discerned by the modem channel estimate. Received SNR variation in excess of 20 dB over a time period of several minutes was observed.



```
Jun    2010          SSN =  12.                Minimum Angle= 0.100 degrees
ROCHESTER           MUNNSVILLE            AZIMUTHS          N. MI.      KM
43.17 N   77.62 W - 42.98 N   75.58 W     96.57  277.96       90.2    167.0
XMTR  2-30 HARRIS99  [harris\1927@9M.ANW   ] Az= 96.6 OFFaz=360.0   0.170kW
RCVR  2-30 HARRIS99  [harris\1912V BD.ANW  ] Az=278.0 OFFaz=360.0
3 MHz NOISE = -145.0 dBW     REQ. REL = 90%     REQ. SNR = 35.0 dB
MULTIPATH POWER TOLERANCE =  3.0 dB   MULTIPATH DELAY TOLERANCE =  3.000 ms
```

Figure 7: VOACAP Prediction.

4.2.5.2 Test Results

Each test segment would normally begin with a 3G ALE LQA being originated from Rochester. This allowed the radios to evaluate the link and rank each possible test frequency. The frequencies used were manually selected based on the LQA measurements. Once linked on a selected frequency the prototype wideband HF radios were used.

Table 9 summarizes the test segments executed on June 9, 2010. Each table entry identifies the bandwidth, modulation, bit rate, duration of the test, measured Bit Error Rate, measured packet Error Rate, the number of bytes transferred error free and the longest error free duration. Data was transferred error free in bandwidths of 3, 12, and 24 kHz.

Table 9: Test Segment Summary.

	BW (kHz)	MOD	BPS	DUR.(s)	BER	PER	#Error Free Bytes	Longest EF Run(s)
1	24	2PSK	12800	257	1.6e-2	5.72e-2	387500	102
2	24	64QAM	76800	104	8.86e-2	5.67e-1	432125	10.2
3	3	64QAM	9600	184	0	0	221000	184
4	6	64QAM	19200	251	2.52e-4	1.41e-2	594750	154
5	12	8PSK	19200	251	0	0	603250	251
6	24	8PSK	38400	288	2.88e-2	5.8e-2	1300000	112
7	24	4PSK	25600	298	4.86E-6	7.87e-4	951875	286
8	12	16QAM	25600	290	0	0	927250	290
9	12	64QAM	38400	290	1.14e-4	9.26e-3	1378125	86.4
10	24	8PSK	38400	267	0	0	1282125	267
11	24	8PSK	38400	165	0	0	792500	165
12	24	16QAM	51200	4510	7.86e-3	5.31e-2	27332750	337
13	24	64QAM	76800	370	2.44e-2	1.39e-1	2039125	81.6
14	24	8PSK	38400	583	1.79e-6	1.79e-4	2799375	224
15	24	16QAM	51200	634	3.36e-5	2.22e-3	4050500	255
16	24	64QAM	76800	645	2.09e-2	1.63e-1	5176750	30.6
17	24	32QAM	64000	634	4.22e-4	2.55e-2	4944875	91.8
18	24	64QAM	76800	379	5.88e-2	4.49e-1	2372000	20.4
19	12	64QAM	38400	299	9.7e-3	1.39e-1	1237125	67.2
20	24	8PSK	38400	359	8.36e-3	1.05e-1	1541125	81.6
21	24	8PSK	38400	2770	5.86e-3	4.15e-2	12726625	663

Some of the optimizations and tradeoffs discussed in section 3 were noted. For example, tests 2, 3 and 4 highlight that decreasing the bandwidth for a common modulation improves the robustness of the data delivery at the cost of a lower user bit rate. Tests 4, 5 and 9, 10 illustrate how the bandwidth can be increased and the modulation complexity decreased, maintaining the same user bit rate, but improving the robustness of the data transfer.

During the course of the test day two longer duration tests were executed. Test 12 utilized the 24 kHz bandwidth 16 QAM waveform defined by the standard to achieve 51200 bps. Figure 8 displays the SNR measured by the Wideband HF data modem over the course of the test along with the error profile highlighting when modem errors were made relative to SNR variations. This test resulted in significant error free periods of 337 seconds, followed by another error free segment of 296 seconds. During this test 27 Mbytes was transferred error free, based on the number of error free packets.

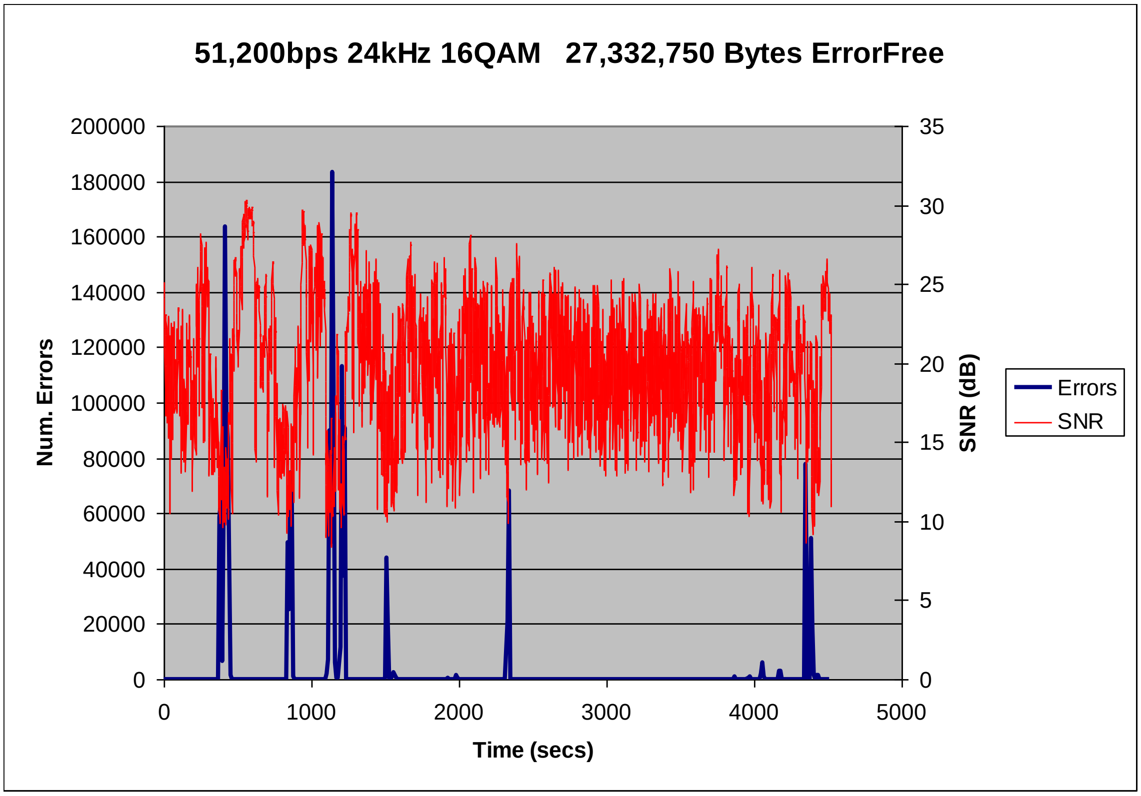


Figure 8: Received SNR versus Bit Error Events.

Figure 9 displays the SNR and error profile results for the second long duration test. This test utilized the 24 kHz 8PSK waveform defined by the standard to achieve 38400 bps. This test had two significant error free periods of 663 seconds followed by 632 seconds. During this test 12 Mbytes was transferred error free, based on the number of error free packets.

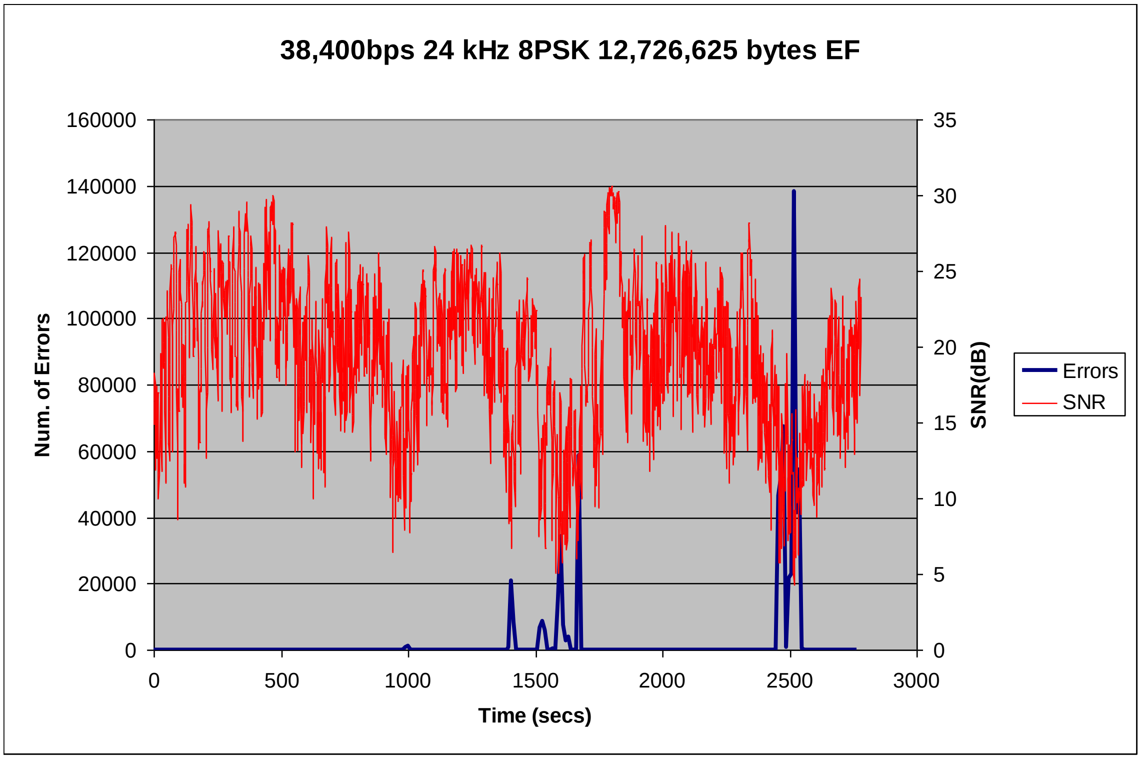


Figure 9: Received SNR versus Bit Error Events.

4.2.6 Performance Discussion

During the on-air test, documented in this paper, Harris has demonstrated a prototype wideband HF tactical man-pack radio and achieved viable operation over a tactical NVIS HF link. During this test the optimizations and tradeoffs that can be made between bandwidth and modulation schemes were explored, illustrating the possible advantages of a multi-bandwidth HF system.

Significantly Harris was able to use STANAG 4538 3G ALE as a means of frequency assessment and selection for a wideband HF data system. STANAG 4538 operates in a 3 kHz bandwidth but was able to locate propagating frequencies for use by the wideband system. There may be some limitations to this approach but it demonstrates that a wideband ALE system may be easily built through simple modifications of the existing ALE standards.

In the course of this testing, the HF Data modem was operated at bandwidths of 3, 6, 12 and 24 kHz and over 87 Mbytes of data were transferred error free as determined by the packet error rate.

5.0 CONCLUSIONS AND FUTURE WORK

In this paper, we have presented the rationale for a new family of wideband HF waveforms, the design considerations that motivated their design, an overview of the design itself, and some examples of measured performance under simulated channel conditions. We have considered the impact of this new waveform family on other elements of an HF communications system, including waveform parameter adaptation and

ALE, observing that cognitive radio concepts and techniques may be applicable in these areas. Finally, we described a series of on-air tests performed by Harris that demonstrate the performance achievable with the waveforms in a low-power radio system. The results show that these waveforms have great promise in ground tactical as well as shipboard applications, yielding usable data rates far above what has been achievable in a 3 kHz bandwidth.

Future work by Harris will include finalizing the modem implementation to match the final US MIL-STD-188-110C and additional on-air testing of this NVIS link as well as longer skywave links (Rochester to Melbourne Florida). Concurrently, Harris will continue to participate in development and review of the new MIL-STD-188-110C standard. Finally, Harris will be addressing the integration of ALE functionality into a wideband HF radio system.

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