PERFORMANCE ENVELOPE OF BROADBAND HF DATA WAVEFORMS

Eric E. Johnson
Klipsch School of Electrical and Computer Engineering
New Mexico State University

ABSTRACT

Parallel efforts are underway in the frequency management and the radio and waveform design communities to support data communications over HF radio channels wider than conventional 3 kHz allocations. In this paper, we analyze the potential performance of such "wideband" HF data channels as a function of spectrum allocation, coding, channel characteristics, and waveform overhead.

INTRODUCTION

For many years, both voice and data communications in the High-Frequency (HF) radio bands have been restricted to channel bandwidths no wider than 3 kHz (although occasionally a single transmitter was allowed to occupy up to four adjacent 3 kHz channels with independent transmissions on each channel). This permitted efficient sharing of the very limited spectrum available, and was appropriate for the services historically provided over HF channels: voice and low-speed data. However, recent years have seen increasing demand for higher-speed data transmission over HF links, and regulatory agencies are now examining the possibility of allocating single HF channels wider than 3 kHz.

In this paper, we explore the performance gains that might be realized by faster HF modems in a selection of data applications.

Spectrum allocations in the 3 – 30 MHz band

Global management of the radio spectrum resides with the International Telecommunications Union (ITU), an agency of the United Nations. Policies of the ITU are implemented by national administrations such as the Federal Communications Commission (FCC) in the United States. Such agencies attempt to fairly balance the competing needs of all users of the spectrum. Typically, we will find blocks of frequencies reserved for each of the many services (e.g., Fixed, Mobile, Aeronautical, Amateur) and special uses such as Radio Astronomy. Channel widths (in Hertz) vary over the electromagnetic spectrum as well as within each band.

In the 3 to 30 MHz band (the nominal HF band), most channels for two-way communication (i.e., not broadcasting) are allocated only 3 kHz [1], although special uses (especially in the Amateur bands) may be allocated narrower channels. Some military users have historically been allocated two (or even four) adjacent channels for Independent Sideband (ISB) operation. For example, the LINK-11 tactical data link sends the same information in two adjacent channels, achieving some extra robustness to fading when diversity combining at the receiver takes advantage of the imperfect correlation of the two channels.

Characteristics of current HF narrowband modems

In the nominal 3 kHz channel used for single sideband (SSB) 2-way communications in many HF bands, current data modems typically occupy less than the full allocation, due to the characteristics of the filters used to limit adjacent channel interference. For example, the passband provided by current military radios extends from 300 to 3050 Hz. The shaded area in Figure 1 shows the frequency response as a function of offset from the carrier frequency.

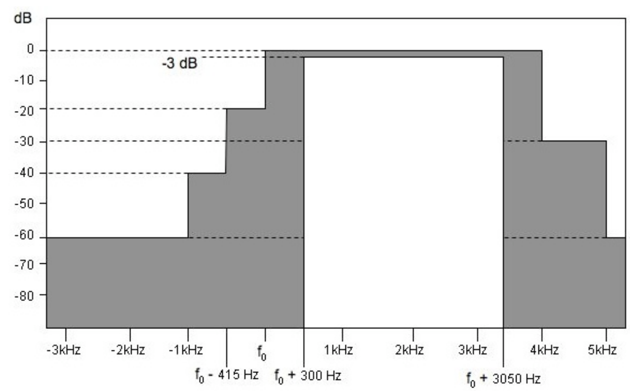

Figure 1: 3 kHz Channel Passband Characteristics

The fading, multipath, and noise characteristics of HF channels require advanced techniques to provide data rates much beyond those used by teleprinters from the early days of HF operation. Modern HF modems tend to use one of two broad approaches to achieve data rates up to 9600 bps in a 3 kHz channel: parallel-tone schemes such as Orthogonal Frequency Division Multiplexing (OFDM) and single-tone waveforms with adaptive equalization.

- The single-tone approach requires somewhat more signal processing than OFDM in a given bandwidth, and that processing differential increases with the occupied bandwidth.
- On the other hand, OFDM waveforms exhibit a higher peak-to-average ratio (PAR), or crest factor, than single-tone waveforms.

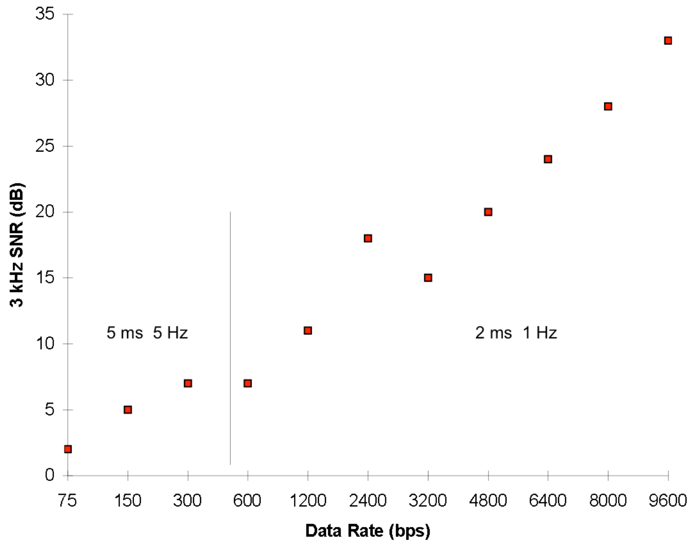

Figure 2: SNR Allowed for 1E-5 BER for 3 kHz Single-Tone Waveforms

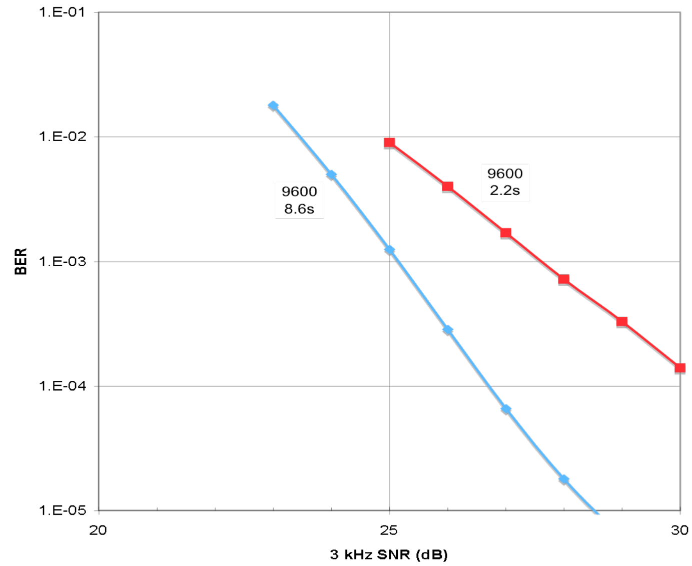

Figure 3: BER Performance of 9600 bps Single-Tone Waveform

We can gauge the state of the art from a recent competition between single-tone and OFDM waveforms to achieve standardization in NATO [2]. In laboratory testing of the competing waveforms, the higher PAR of the OFDM waveform required 1.4 to 1.8 dB more reduction in drive level to avoid clipping in solid state power amplifiers. Even ignoring this drawback, a single-tone waveform achieved higher performance in multipath fading channels, and so was standardized in NATO STANAG 4539 and US MIL-STD-188-110B.

The performance of this standard single-tone HF SSB waveform is summarized in the figures above. Figure 2 shows the SNR at which modems are required to achieve 10^{-5} BER at various data rates, while Figure 3 shows measurements of BER versus SNR for the military 9600 bps waveform (single-tone, 64 QAM) with a long interleaver (8.6 s) and a medium interleaver (2.2 s) in a fading channel (2 ms multipath spread, 1 Hz Doppler spread).

Previous developments in wider-band HF modems

Two systems using more than 3 kHz for data over HF are already fielded today: broadcast channels up to 20 kHz wide (Digital Radio Mondiale [3]), and the “bonding” of multiple 3 kHz channels for a single data circuit.

<u>ISB and general channel bonding (military 2-way)</u>

Where 3 kHz allocations remain the rule, it is possible to achieve data throughputs greater than 9600 bps by using multiple channels in parallel. If the parallel channels are close in carrier frequency (e.g., Independent Sideband – ISB), their propagation characteristics and SNR will be similar, though their fading may be somewhat uncorrelated. In this case, the same modulation can be used on every channel, and spreading channel bits from a single coded bit stream over the channels can achieve some gain from diversity combining. This technology (see Figure 4) is standardized in MIL-STD-188-110B Appendix F.

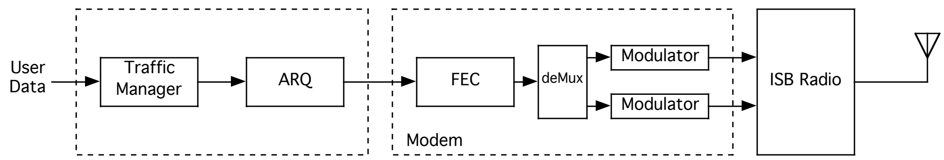

Figure 4: ISB Modem Operation

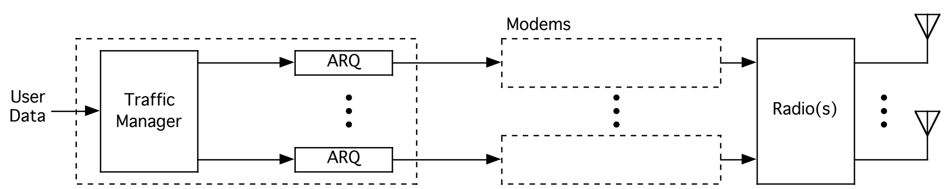

Figure 5: Non-Adjacent Channel Operation

Operation in multiple channels whose characteristics differ too greatly to support the same modulation may be accommodated by running separate error- and flow-control processes in each channel (Figure 5).

DRM (commercial broadcast)

A new global standard technology for digital broadcasting in the MF and HF bands is known as Digital Radio Mondiale (DRM) [3]. Using a scalable OFDM technology, DRM is able to operate in channels ranging from 4.5 to 20 kHz. In its most lightly coded version, a DRM signal in a 20 kHz channel can carry up to 72 kbps.

NEW HF WIDEBAND TECHNOLOGY

The desire for increased data rates over HF channels has prompted loosely coordinated thrusts in parallel in the regulatory and design communities that may soon lead to the use of channels up to 24 kHz wide for 2-way data communications.

Question before the ITU

In most of the services (e.g., fixed, land mobile, aeronautical mobile) there is no bandwidth restriction for HF systems in the Radio Regulations. The traditional 3 kHz allocations are a legacy left over from the radio telephony era [4]. However, the topic of wider allocations in the (channelized) Maritime Mobile bands is an Agenda Item (1.9) for the 2011 World Radiocommunication Conference. This discussion provides an opportunity to present the capabilities of wider-bandwidth HF modems that could then be used to encourage national administrations to allocate suitable HF channel widths for high-speed data in the other services.

Wideband radio specs

The US military standard for HF radio equipment, MIL-STD-188-141, is currently in revision. The new edition, MIL-STD-188-141C, is likely to include specifications for HF radio passbands of (nominally) 6, 12, and 24 kHz. A proposed passband mask is shown in Figure 6. Here f_0 is the suppressed carrier frequency in an SSB system, and B is the bandwidth.

Wideband waveform possibilities

Both single- and parallel-tone waveforms are candidates for carrying data through the new, wider HF channels. In this section, we estimate and analyze the characteristics of hypothetical waveforms for a 12-kHz channel.

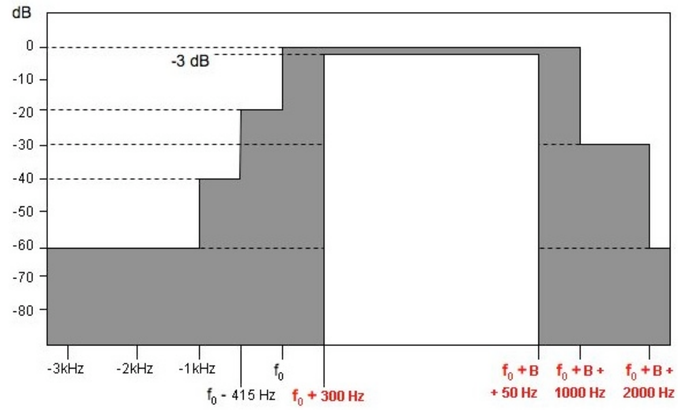

Figure 6: Proposed Wider-Bandwidth Radio Passband

Single-tone

Equipment in the field today is capable of bonding up to four 3 kHz channels (4-ISB) to form a single data channel [5]. Using a variation on the MIL-STD-188-110B QAM waveform family, 64 kbps can be achieved in a 4-ISB surface-wave channel, using 256 QAM modulation on four individual subcarriers. (The actual passband contains four 2750 Hz channels for a total of 11 kHz.)

A hypothetical single-tone waveform that fills a solid 12 kHz channel might use the same 256 QAM constellation on a single 6400 Hz subcarrier, modulated at 9600 symbols per second, with rate 7/8 coding, to achieve 64 kbps. Lower data rates would use more robust channel coding and less-dense constellations.

OFDM

A 12-kHz DRM-style waveform with light coding might achieve a data rate of 43.2 kbps (scaled from the 72 kbps waveform in a 20-kHz channel).

Computational Complexity

As noted above, the computational load of a Decision Feedback Equalizer (DFE) for the single-tone waveforms scales poorly with increasing channel bandwidth, compared to the FFT used with OFDM waveforms. Using analytical results from Thales France [6] and Rockwell-Collins Canada [7], the MIPS requirements for waveform processing as a function of channel bandwidth, assuming a DFE for 5 ms time spread, might be:

Table 1: Waveform Processing Requirements (MIPS)

Channel Bandwidth	3 kHz	4.5 kHz	9 kHz	12 kHz	20 kHz
Single tone	20	45	180	320	889
OFDM	14	28	50	69	110

From these estimates we see that the somewhat higher potential performance of the single-tone 12 kHz waveform comes with a substantially higher computational cost than an OFDM waveform, although this level of performance is still within reach of current signal processing hardware.

APPLICATIONS

This section discusses a few example applications in which the higher data rate of the wider-bandwidth waveforms could offer a qualitative improvement in mission performance. These applications help us to explore the concerns and design tradeoffs for the wideband waveforms, so additional waveform details emerge here.

Large files to fast movers

To illustrate the tradeoffs of using wideband HF (WBHF) waveforms with an ARQ protocol, consider an application in which "fast movers" are only within range of a transmitter for a few minutes. In this case, the hard limit on link lifetime determines the maximum file size that can be sent. Higher data rates will allow for larger files (e.g., images versus text) to be successfully handed off as a fast mover flies through the contact region.

In this application, we need to consider not only the raw speed of the data modem, but also overhead including link setup, link turnaround times, and the speed and robustness of ARQ acknowledgments.

- Initial contact for link setup should use a "calling channel," distinct from the traffic channels. Research has shown that overall network efficiency is best when calling channel occupancy is low (availability is high), while traffic channel occupancy is high [8]. It makes little sense to dedicate a wideband channel to be lightly used, so we assume that contact will be made, and the link set up, using a narrowband (3 kHz) channel for second- or third-generation automatic link establishment. Link setup typically requires on the order of ten seconds.
- After link setup is complete, the participating stations commence data transfer on a wideband channel. The ground station will send a burst of data and then wait for an acknowledgement from the fast mover. The interval between data bursts contains the time to send the ACK plus two link turnaround times. Current modem and COMSEC technology requires about 2 seconds per link turnaround [9].
- With these relatively slow link turnarounds, it makes little sense to return the ARQ acknowledgments using a high-speed waveform. In general, ACKs need to be sent using a more robust waveform than data, since a lost ACK requires retransmission of an entire burst of data packets. We could either use a separate narrowband channel for ACKs (perhaps running full duplex?), or include a very robust, low-speed waveform for sending short bursts in a wideband channel. This could use long symbol sequences for each bit, as is done in the 75 bps narrowband waveform in MIL-STD-188-110B or STANAG 4415.

A common concern in ARQ applications is the optimum interleaver size to use in the modem. BER performance in a fading channel can be improved by an order of magnitude by using a very long interleaver, but the interleaver length establishes the time quantum for data transfers. Thus there is a tension between interactivity and throughput, resulting in a wide range of interleaver sizes.

ARQ operation over HF skywave channels benefits from being able to change data rates (and perhaps interleaver length) on the fly. For this reason, the synchronization preambles in existing narrowband waveforms (MIL-STD-188-110 and STANAG 4539) include an embedded code that informs the receiver what data rate and interleaver setting are used in the data to follow. We anticipate that such information will be incorporated in the WBHF waveforms as well.

Surveillance video

An interesting one-way application for WBHF is the delivery of surveillance video streams over HF skywave channels. In such continuous streaming applications, sync on data could be valuable.

Video applications will require data rates at the upper end of the range for WBHF (≥38 kbps) to carry even limited-quality imagery (e.g., 15 frames per second at a resolution of 160 x 120). Operation in the fading and multipath distortion that is typical of long-haul skywave paths may not be possible for a lightly coded waveform (such as the 64 kbps single-tone waveform using rate 7/8 coding mentioned above).

<u>Long-haul: UAV</u>

Currently, most UAV video is sent via satellite or line-of-sight radio channels. WBHF offers the intriguing possibility of beyond line-of-sight communications to *and from* a UAV via HF radio. Of course, powering an HF transmitter and mounting an HF antenna on a UAV pose challenges.

<u>NVIS: ground forces</u>

A somewhat less challenging opportunity for delivering video over WBHF arises with ground forces in mountainous or dense urban terrain, where near-vertical incidence skywave (NVIS) is used to overcome the lack of line-of-sight between a video source and its users.

Common operating picture (surface wave)

For our third example application, consider the one-to-many communication involved in maintaining a common operating picture (COP) among vessels in a naval battle group. Propagation is via the (relatively benign) surface wave channel, but nodes in this HF LAN must share the channel. Often, a token passing channel access protocol is used. Except during link turnarounds while the token is passed, the channel is in use continually, so we can expect to deliver data very efficiently using the WBHF waveforms.

EVALUATION

For an initial evaluation of the WBHF concept, the following hypothetical wider-bandwidth waveforms are applied to the applications defined above, and their performance is estimated using analysis and simulation.

Data Rate	FEC Code Rate	Estimated SNR for 10^{-5} BER	
		8.4 s intlv	2.1 s intlv
64,000	7/8	38	–
48,000	3/4	31	35
38,400	3/4	27	31
19,200	3/4	16	20
1,200	1/4	5	9

- The synchronization preamble contains one or more segments lasting 0.21 s, and can occur in the middle of a transmission to announce a data rate change.
- Interleaver depth can be 8.4 s, 2.1 s, or 0.42 s.
- Link turnaround times are assumed to take 1 s (half in the modem, half in COMSEC).

Results: File transfer

In our first scenario, a unit on the ground needs to send a file to an aircraft moving rapidly through the theater. A link is established as soon as the aircraft comes within extended line of sight. At this extreme range, the path loss may be as much as 100 dB greater than when the aircraft passes near the ground transmitter, so the data rate must adapt to the varying SNR during the link. The STANAG 5066 ARQ protocol that is used to send the file includes automatic data rate adjustments with no over-the-air overhead.

To gauge the potential advantage of using the wideband waveform, we compare the amount of data that can be sent during the transit of the "fast mover" using a fixed RF power output (10 to 1000 W) with either 3 or 12 kHz waveforms. Note that a fixed power output will produce a higher SNR in a narrowband system.

Two scenarios are evaluated here. First, a hasty setup with the sending antenna only 10 feet off the ground, and the fast mover flying at 600 kt at 5,000 feet above ground level (AGL). In this low and fast scenario, the narrowband transmitter is able to link with the aircraft at distances ranging from 30 to 50 miles, while the wideband system links at 10 to 30 miles, depending on the transmitter power. Despite the shorter range and the reduced SNR of the wideband system, its higher peak throughput is sufficient to provide almost three times as much data to the aircraft as it flies through the theater.

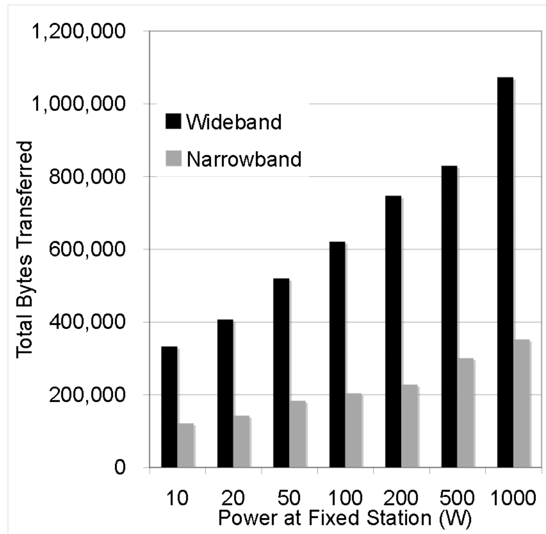

Figure 7: File Transfer in Low and Fast Scenario

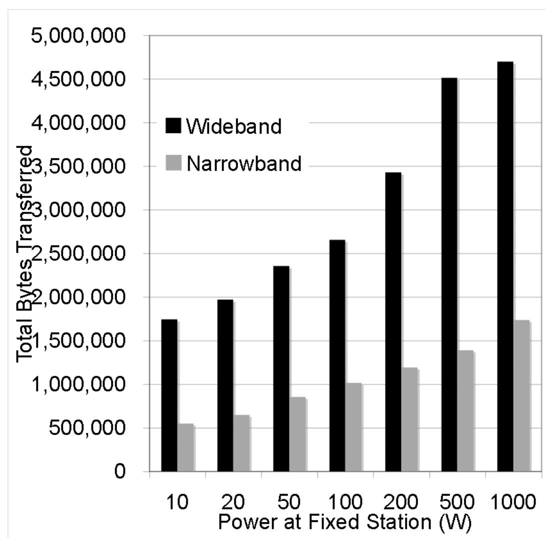

Figure 8: File transfer to Higher-Altitude Aircraft

The second example, a more deliberate setup, has the sending antenna 30 feet above the ground, and the aircraft flying at 500 kt at 30,000 feet AGL. In this case, the range of the narrowband system reaches out to 50 to 250 miles, while the wideband range also improves to 40 to 100 miles.

In Figure 8, we see a sharp jump in data successfully sent by the wideband system for 500-1000W power level. This is due to its ability to start sending relatively high-speed data at a range of 100 miles. Again, the wideband system achieves a roughly threefold improvement at each power level.

Results: Surveillance

For our video surveillance application, we consider two scenarios: a UAV sending video via a long skywave link, and a ground-based observation post sending video via near-vertical-incidence skywave (NVIS) to observers in the next valley. In both cases, we attempt to carry H.264 compressed video streams (15 frames per second at a resolution of 160 x 120), using WBHF waveforms robust enough for skywave channels (38.4 or 48 kbps).

The H.264 compression application is assumed to "slice" the video stream to match the packet size used by the MAC layer (e.g., 300 bytes) to limit corruption of the video due to packet losses. If we allow a 1% packet loss rate, we can tolerate a bit error rate of 3E-6. This will require about 33 dB SNR in 12 kHz for the 38.4 kbps waveform, and about 36 dB for the 48 kbps waveform.

UAV Scenario

For a tactical UAV such as the Aerostar, up to 500W may be available to the payload, while a Predator can supply 1.8 kW. Unless the receiving site is carefully chosen for very low noise, it will be difficult to achieve the needed SNR from an Aerostar, due to transmit power limitations. However, when a 1 kW transmitter can be used skywave paths may provide satisfactory video over WBHF channels during most of the day.

Figure 9 is a VOACAP prediction for SNR density on a 1515 km path in Central Asia in October during high solar activity, with a log-periodic antenna at the receiver and 1 kW into a 0 dBi antenna on the UAV. It appears that 38 kbps is supported except during the pre-dawn hours, and that 48 kbps (for somewhat better video) is available during the morning and evening.

NVIS Scenario

In the NVIS scenario from a ground observation post one valley away from the users, we find similarly promising performance. Figure 10 shows the VOACAP prediction for a 68 km NVIS link in October with low solar activity, using a 200W transmitter and yagi antennas at both ends. Just as in the UAV case, the 38 kbps waveform is supported during most of the day, with 48 kbps in the morning and evening.

This pattern is typical of results seen over a range of months, sunspot numbers, and path lengths in both scenarios: limited video is usually available via WBHF.

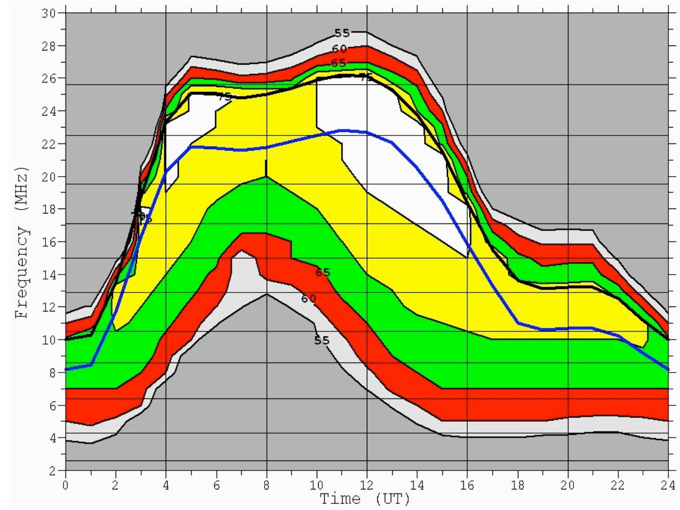

Figure 9: SNR on 1515 km Path, October, SSN 130

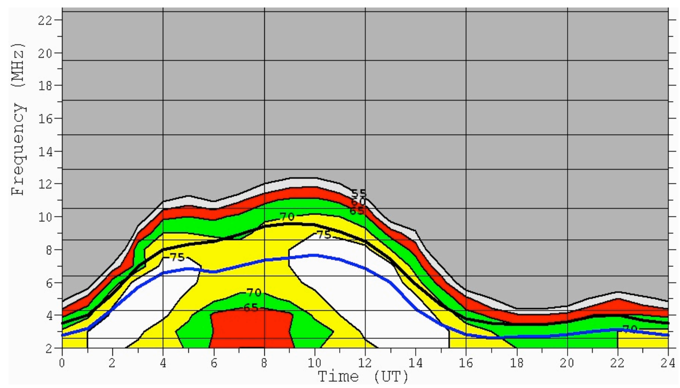

Figure 10: SNR on NVIS Path, October, SSN 10

Results: COP

In this surface-wave naval scenario, a group of six ships shares a wideband channel using token passing.

- All of the ships are able to broadcast reports to the other battle group members as the token circulates. Upon receiving the token, each ship is permitted to transmit for up to 11 s before passing the token. Each token tenure will normally consist of a 2.1 s interleaver at 1200 bps to send ACKs and the token, optionally preceded by 8.4 s of data sent at 64 kbps.
- One ship (node A) receives a COP downlink via SATCOM and pushes a filtered subset to the rest of the battle group via the WBHF LAN. This node sends a data packet each time it receives the token.

Two cases are considered:

- Node A receives one token tenure per token rotation (the "token passing" case)
- Node A receives half of the token tenures, alternating with the other ships ("polling" case)

Total LAN throughput is plotted below for these two cases versus the fraction of time that the non-SATCOM nodes send a data packet. For comparison, the throughput using 2-ISB operation at 19,200 bps is also shown.

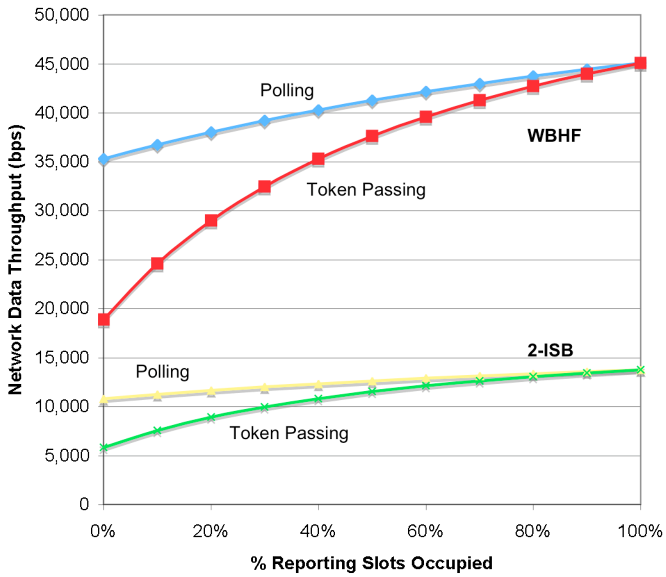

Figure 11: Data Throughput in COP Application

Throughput reaches just over 45 kbps in both cases using WBHF, a 3-fold improvement over 2-ISB with only twice the spectrum; more power is required to achieve the necessary SNR, but this is less problematic on large vessels than on small UAVs. When the "picket" stations have little data to send, the polling case achieves higher throughput, as expected, but the polling procedure results in uniformly longer intervals between opportunities for the picket stations to report, as seen in Figure 12.

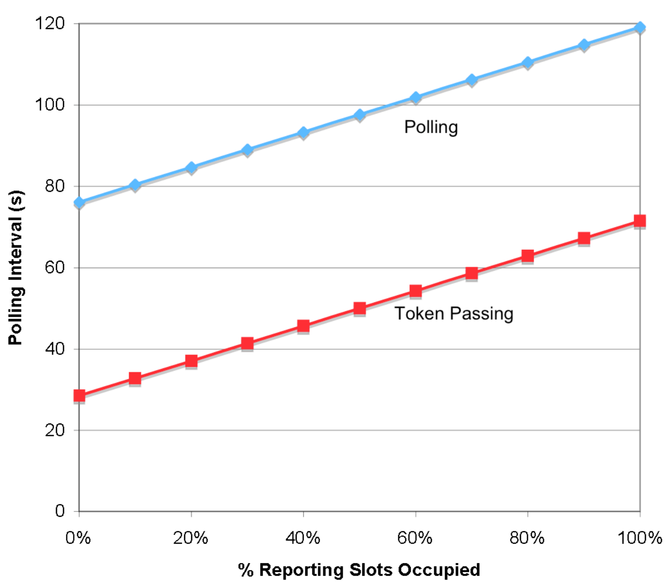

Figure 12: Polling Interval in COP Application

CONCLUSIONS AND FUTURE WORK

A convergence of efforts in spectrum management and radio and modem engineering may soon yield wider channels for use in passing data via HF radio. In this paper, we have outlined the promise and the challenges in achieving a significant leap in data throughput in a number of HF applications. For example:

- In real-time file transfer applications, WBHF permits sending much larger files (perhaps images versus just text) or heavier COP traffic.
- It may be possible to send low-rate video over WBHF (e.g., from UAVs beyond line of sight).

Of course, the use of aggressive waveforms requires high SNR to realize these high throughputs, and the availability of high transmitter power may be an issue in some applications. However, it also becomes possible to achieve current high data rates (9.6–19.2 kbps) with reduced constellation density (and lower SNR) when operating over wider channels so power-limited applications will also benefit from wider channel allocations.

Development and testing of WBHF waveforms is now underway with a goal of standardization in 2010.

ACKNOWLEDGEMENTS

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REFERENCES

1. NTIA, *Manual of Regulations and Procedures for Federal Radio Frequency Management, January 2008 Edition*, section 5.3.1, footnote 1: "In other than exceptional cases the practice is to authorize 3 kHz as the necessary bandwidth for normal voice intelligibility."
2. "Results of the Evaluation of High Speed Waveform Modems for STANAG 4539," DERA Portsdown West, UK, April 2000.
3. ETSI Standard 201 980 V2.1.1, "Digital Radio Mondiale (DRM)," System Specification, 2006.
4. N Serinken, private communication, March 2009.
5. R Blocksome, "The MDM-Q9604 HF Modem," HFIA 2005, http://www.hfindustry.com/Feb05/Feb2005_Presentations/Rod%20MDM-Q9604.ppt, San Diego, February 2005.
6. D Mérel and J-P Gayrard, "Very High Data Rate HF Modem Survey," presentation to NATO SC/6 AHWG/1 (Beyond-Line-of-Sight Communications), June 2004.
7. M Jorgenson, private communication, July 2009.
8. E Johnson, "Simulation Results for Third Generation HF Automatic Link Establishment," *Proceedings of MILCOM '99*, IEEE, 1999.
9. E Johnson, M Balakrishnan, and Z Tang, "Impact of Turnaround Time on Wireless MAC Protocols," *Proceedings of MILCOM 2003*, IEEE, 2003.