EMBEDDED HF CHANNEL PROBES/SOUNDERS

D. Mark Haines and Bert Weijers

Propagation Branch
Electromagnetic Sciences Division
Rome Air Development Center
Hanscom AFB MA

ABSTRACT

Many HF communication requirements could be satisfied best by systems which are capable of real time propagation monitoring; however, approaches using ancillary ionospheric sounders have resulted in configurations which are too expensive, too bulky and operationally burdensome. Real-time monitoring is especially critical on high latitude channels which suffer unique disruptions due to auroral and polar activity. This paper explores techniques which utilize a host communication's system's RF electronics on a non-interference (i.e. time shared) basis to produce channel measurement data superior to that obtained by conventional pulse or chirp sounders. The techniques all can be implemented using available microprocessor components, which, if already available in the host system, can result in a major increase in capability with no increase in hardware. Results from an experimental system are presented.

INTRODUCTION

The Rome Air Development Center's Ionospheric Propagation Section is currently making measurements at a network of field stations in order to statistically characterize HF channels in the mid-latitude, auroral and polar regions [1]. A great deal of analysis went into the selection of a system and waveform which could provide all the required channel parameter measurements. The major requirements were:

- 1) 20 μ s time resolution of multipath propagation delays
- 2) Doppler spread associated with individual propagation modes (a scattering function [2])
- 3) 2 - 60 MHz frequency range
- 4) high spatial coherence to support high resolution spatial measurements
- 5) rapid channel measurement capability such that successive measurements can track short-term variations in channel response and
- 6) sufficient processing gain to provide high quality measurements with 100-500 watt transmitters.

Our analysis lead us to a popular communication waveform (coherent PSK) which in turn suggests the basic concept of this paper. That is to utilize a communication system to track propagation characteristics, automatically establish links (including relays), and communicate,

all using the same RF hardware. This would eliminate ancillary networking and sounding subsystems. Furthermore we will show that the coherent spread-spectrum channel measurement waveform has some very desirable properties as a communication signal, and especially as a multiple access network coordination channel.

BACKGROUND

This section will present the unique problems associated with the wideband HF channel then develop a non-exhaustive feasibility analysis of candidate waveforms. The preferred waveform will then be compared to conventional sounding techniques to determine its relative merits for the task of channel characterization.

The Problem - The oblique HF channel typically exhibits a discrete, time dispersive impulse response due to multiple simultaneously active propagation paths whose relative propagation delays are typically 0 to 3 ms. These arise mainly due to multiple "reflections" from the same ionospheric layer although mixed modes (eg. involving both E and F layers) are not uncommon. Even more subtle, though, is the nearly continuous (as opposed to discrete) spreading which is typically on the order of 10-100 μ s. There are at least three mechanisms contributing to this continuous dispersion:

1. "Ripples or patches" in the electron density of the ionosphere randomly satisfy the geometry for off-great-circle propagation (i.e. sidescatter) [11]

Fig. 1 Ionogram showing continuous dispersion of up to 1msec

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2. This same non-uniformity of the electron density allows some energy to propagate to a higher altitude before finding a critical density [3] and turning around.

3. Broad bandwidth signals will be returned from a range of altitudes simply because each spectral component has its own virtual height [3].

A mixture of these mechanisms can result in a continuous "smear" in the impulse response as illustrated by Fig. 1 which is an oblique ionogram made between New York and Thule, Greenland.

In order to communicate using a coherent modulation scheme we must detect the phase of each resolvable multipath component, which is statistically independent of the phase of any other component. Fig. 2 is a complex phasor diagram depicting the phase of three multipath components in a received signal. Since the ionospheric channel is a linear system [1] this representation is equally applicable to discretely or continuously dispersed multipath and to many more than three resolvable time delays. At very low signaling rates the vector sum of these phasors is approximated quite well by the vector sum of a sinusoidal reference tone (a pilot tone or carrier is the conventional means of phase locking a coherent receiver). The problem arises when one wishes to resolve these multipath components and coherently process each separately. This is accomplished by modulating the signal at a very fast rate since,

$$1/\text{bandwidth} = \text{time resolution} \quad (\text{Eq. 1})$$

and then demodulating one multipath component at a time by synchronizing the receiver to that component's time delay. However, Eq. 1 shows that

Fig. 2 Phasor representation of three multipath components

a zero bandwidth reference tone cannot be resolved in time, therefore its phase would be a vector sum of all multipath components and would have no relation to the phase of any single component which precludes detection of the correct polarity during PSK demodulation. This makes synchronous demodulation impossible which means that two orthogonal phase references (quadrature demodu-

lation) must be provided and all subsequent signal processing must be performed on complex (I and Q) signals. Therefore, the measured phase of each delay component is relative to the arbitrary phase of the receiver's local oscillator (the I axis in Fig. 2) which is no longer phase locked to the transmitter, therefore highly stable and accurate frequency standards and synthesizers are required at both ends.

CANDIDATE WAVEFORMS

We determined early on that in order to enable detection of signals received with negative signal-to-noise ratios (S/N) and to provide Doppler measurements, coherent (and therefore two channel complex) signal processing would be necessary. As an example the system of Fig. 3 produces a binary phase shift keyed (BPSK) waveform modulated by $p(t)$, a maximal length sequence code [7] which has optimal auto-correlation properties.

Fig. 3. Spread Spectrum Waveform

Ideally,

$$\int_0^T p(t)p(t-\Delta)dt = \overline{p(t)p(t-\Delta)} = \begin{cases} 0 & \text{for } \Delta \neq 0 \\ 1 & \text{for } \Delta = 0 \end{cases}$$

but for the maximal length code,

$$\int_0^T p(t)p(t-\Delta)dt = \begin{cases} -1/N & \text{for } \Delta \neq 0 \\ -1 & \text{for } \Delta = 0 \end{cases} \quad (2)$$

where N = number of bits (chips) in the code. Therefore for a 1023 length code the peak to sidelobe ratio of this autocorrelation function is over 60 dB. The received signal is a composite of delayed (delayed by d_i , the group path delay associated with each multipath propagation mode) replicas of the transmitted signal which can be resolved by adjusting the code delay (Δ) in Fig. 4a to be synchronous with one delayed replica at a time, resulting in a complex impulse response of the channel as a function of time delay (Δ). The "-" denotes a complex (I and Q) value.

The RADC Channel Probe employs the technique of Fig. 4b implemented digitally by sampling a single I and a Q baseband record and computing all lag values of a complex cross-correlation with the known code. This resolves all multipath components using the same sampled data record which eliminates the possibility that the channel transfer function has changed between steps of the

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delay parameter (Δ).

$$A_0 = \sum_i a_i f_c(t-d_i) p(t-d_i)$$

$$\tilde{A}_1 = \sum_i \tilde{a}_i p(t-d_i)$$

$$\tilde{A}_2 = \sum_i \tilde{a}_i p(t-d_i) p(t-\Delta)$$

$$\tilde{A}_2 = \begin{cases} \tilde{a}_i \text{ for } \Delta = d_i \pm nT \\ -\tilde{a}_i/N \text{ for } \Delta \neq d_i \pm nT \end{cases}$$

Fig. 4a Synchronous

$$B_0 = \sum_i a_i f_c(t-d_i) p(t-d_i)$$

$$\tilde{B}_1 = \sum_i \tilde{a}_i p(t-d_i)$$

$$\tilde{B}_2 = \int_0^T \sum_i \tilde{a}_i p(u-d_i) p(u-t) du$$

$$\tilde{B}_2 = \begin{cases} \tilde{a}_i \text{ for } t = d_i \pm nT \\ -\tilde{a}_i/N \text{ for } t \neq d_i \pm nT \end{cases}$$

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Fig. 4b Matched filter

Another technique for the detection of the BPSK waveform is to process a modulated IF signal rather than the baseband signal. By replacing $f_c(t)$ in Fig. 4b with $f_{LO}(t)$ and replacing $p(-t)$ with $p(-t)\cos(\omega_{IF}t)$ Fig. 4b would accurately represent this technique.

Fig. 5a. Complex baseband detection of coded BPSK

Fig. 5b. IF detection of coded BPSK.

Fig. 5a shows a complex impulse response obtained from baseband processing while Fig. 5b shows the matched filter output resulting from the

IF detection technique. Both plots result from a channel simulation computer program and include two multipath components plus -6dB additive noise.

ALTERNATE WAVEFORMS

MSK- MSK's unique properties result from making a frequency shift precisely at the time the sinusoidal waveform $s(t)$ reaches its maximum or minimum value. This results in a narrower spectrum and lower sidelobes than the PSK counterpart [2]. The MSK mark symbol $\text{mrk}(t)$ contains one half cycle more sinusoid than the space symbol, $\text{spc}(t)$, therefore by definition they are orthogonal,

$$\int_0^T \text{mrk}(t) \text{spc}(t) dt = \int_0^T \cos[n\pi t/T] \cos[(n+1)\pi t/T] dt = 0 \quad (3)$$

where T is the duration of one symbol. Because the two symbols are orthogonal they can represent the "0" and "1" bits of the spreading code and

Fig. 6 IF Detection of MSK waveform

still retain its optimal auto-correlation function. The MSK matched filter output of a received multipath signal (computer simulation) is shown in Fig. 6 where $n = 3$.

DPSK - To clarify the following discussion, I will assume binary DPSK. By comparing the phase of the received signal to that received one bit frame ago (bit frame = $1/\text{bit rate}$) a DPSK system determines whether the phase is the same or has been inverted. Therefore, the first bit in any transmission is meaningless, but each subsequent bit has its predecessor as a differentially coherent phase reference [4]. At very low bit rates this works quite well since as portrayed in Fig. 2, the phases of the multipath components form a coherent vector sum which allows each bit to be characterized by a single phase. However, when the bit rate exceeds the channel's coherence bandwidth, the multipath components never "agree on" the phase and rather than a vector sum of multipath phasors in the RF, IF and baseband we have a linear sum of independently modulated components in the RF and IF and a sum of $2N$ products in the baseband where N is the number of incoherent (i.e. resolvable) multipath components. For instance suppose a received signal contains two components

$$r(t) = a_1 \exp[j\phi_1(t)] + a_2 \exp[j\phi_2(t)] \quad (4)$$

where $\phi(t)$ is the differentially phase encoded binary information signal (bit stream). The multiplier block in the detection circuitry (see Fig. 8.8-1 in [4]) creates a baseband,

$$b(t) = a_1^2 \exp[j2\phi_1(t)] + a_2^2 \exp[j2\phi_2(t)]$$

(the differentially coherent terms)

$$+ 2a_1a_2 \exp[j\phi_1(t) + j\phi_2(t)] \quad (5)$$

(the incoherent terms)

These incoherent terms are a meaningless self generated noise which obscures the measurement of the channel's impulse response as seen in Fig. 7, a simulation of a maximal length coded DPSK channel with three discrete multipath components, corresponding to the three largest correlation peaks in Fig. 7.

Fig. 7 Baseband detected DPSK coded waveform

CODED BPSK AS A SOUNDER/CHANNEL PROBE.

Pulse and linear FM (chirp) waveforms are the most popular conventional HF channel measurement tools. This section will compare these to the RADC Channel Probe waveform to assess the relative merits of this "communication signal" for use as a sounder. The standard for comparison will be a 0.1% duty cycle pulse sounder with 10 μ s time resolution. Peak output power is 10 KWatts (ie. average power = 10 Watts)

As shown in Fig. 8 a chirpsounder provides a 1:1 peak/average power ratio and using a 100KHz/sec sweep rate can attain 10 μ sec time delay resolution by analyzing the received signal to a 1 Hz frequency resolution. Therefore, using a 500 watt transmitter, the chirpsounder provides a S/N for any given time delay component which is equivalent to a 50 MWatt peak power pulse sounder. Fig. 1 was made by a chirpsounder.

To make the BPSK probe into a sounder we simply step the carrier frequency in a precisely timed sequence under automatic control. The coded BPSK waveform requires a 100kbps chip rate to achieve the 10 μ s resolution and when filtered in a 200 KHz IF bandwidth provides a 1:.93 peak - average power ratio. Using a 1023 length code (which provides 10.23 ms of unambiguous delay resolution) and a 500 watt transmitter the resulting S/N for any given time delay is equivalent to that of a 500 KWatt peak power pulse sounder. With less than a 10 Hz channel or system induced Doppler spread, four repetitions of this code can be coherently averaged, gaining 6 dB in S/N (2 MWatt pulse sounder). If this averaging has resulted in a positive S/N, then up to 40 sec more of incoherent averaging is also feasible.

Additional advantages for the coded CW waveform are that phase information is so easily extracted making coherent processing on an array of receivers, or correction of Doppler or frequency standard offsets possible. The hardware is also much simpler than the conventional systems.

TRANSMITTING DATA

As a communication signal the BPSK waveform must be altered in some way to convey information. Since the received signal is coherently detected, any version of M-ary PSK can be employed; however, this brings us back to the previous problem of detecting an absolute phase polarity (eg. mark or space) in the received multipath wideband signal. We have seen that a pilot tone or DPSK scheme is undesirable, but a modification to the differential coherence technique has many advantages. We call it differential phase code shift keying (DPCSK). By selecting the phase of each code repetition (holding it constant throughout the code duration, T) based on message bits we can change phase to represent a "1" or maintain the same phase as the previous code symbol to represent a "0". For binary DPCSK this is accomplished by simply inverting the spreading code, which causes a sudden π radian phase shift in each of the resolved multipath components of the received complex impulse response.

To expand our modulation scheme to support M-ary symbols the spreading code itself will have to be selectable which requires the receiver to matched filter all possible codes. For instance, if a 4 code set is available and each DPCSK code repetition could have 2 phases we now have an 8 element symbol set and can send three bits simultaneously. If 4 more maximally orthogonal codes (eg. Gold or Kasami codes [6],[8],[9]) are selected a second message or multiplexed bits of a single message can be transmitted simultaneously on quadrature carriers at the same carrier frequency. This results in a four phase signal which is actually a vector sum of two binary codes. The receiver can detect the two codes simultaneously with minimal cross-talk because the correlation peaks will occur in two different matched filters. Now we have two sub-channels each with an 8-ary symbol set, thus 6 bits can be transmitted simultaneously. At 50 symbols/sec this results in 300 baud throughput.

During the development of the Channel Probe system we discovered that the ideal correlation properties of the maximal length code can easily be destroyed by the HF channel. As shown in [7] the matched filter must contain a previous or succeeding repetition of the code along with the repetition which results in the primary correlation peak, otherwise you are detecting the aperiodic maximal length code which [7] shows to have an undesirable autocorrelation function. On a dispersive channel these aperiodic code properties will arise unless all multipath components are present in the signal from the beginning to the end of each sampled data record. This means that when stepping frequency in a sounder mode or when changing codes or phases in a message

Fig. 8 Pulse, chirp and coded sounder comparison

mode, a guard time must be inserted to ensure that all received multipaths are excited by signals of the same phase and frequency before the receiver begins sampling. For instance at 10 kbps using a 127 length code (12.7 ms code duration) the last 73 bits (7.3 ms) of the code should be sent first followed immediately by the full 127 bits. With as much as 7.3 msec of multipath spread the receiver could still sample the same waveform on each multipath.

Fig. 9 8 sec sequence of channel impulse response magnitude, 4.7MHz 7/10/85 Ava, NY to Boston MA

Our Channel Probe employs an Intel 8088 based Zenith microcomputer with a GPIB (IEEE-488) interface. This system requires 85 ms to perform a full complex cross-correlation of the 127 length code (10 kbps) and 6 seconds to process a 1023 length code (100 kbps). Samples of successive impulse response measurements are shown in Figs 9 and 10. Fig. 9 shows the magnitude of 32 impulse responses (100 μ sec resolution) over an 8 sec. period (note the local lightening strike interference) while Fig. 10 shows the Doppler induced polarity inversion of the I channel correlation of a 100 KHz (20 μ sec resolution) probe signal. The processing algorithm also locates

the correlation peak, stores its magnitude and computes the average value of all correlation lags. This provides an immediate assessment of S/N and timing synchronization which together indicate whether a valid signal is being received. DPCSK data can then be detected simply by analyzing the differential polarity of the correlation peak (or peaks) from one message symbol to the next.

Fig. 10 4 sec sequence of channel impulse response real component only, 6.9MHz, 7/12/85, Ava to Boston

SUMMARY

The following list of capabilities summarizes the coded DPCSK waveform. After receiving only one code repetition (20msec) a matched filter detection algorithm can:

- 1) provide bit synchronization
- 2) measure the signal's phase
- 3) determine received S/N
- 4) measure the channel impulse response
- 5) provide angle of arrival if a multiple receiver array is used.
- 6) confirm signal presence by verifying coincidence of correlation peaks in the two subchannels

Furthermore the waveform provides the basis for transmitting data, for monitoring propagation over any range of frequencies (sounding), for correcting frequency offsets, for resolving conflicting transmissions in multiple access channels, for initializing an adaptive channel equalizer, for automatic acquisition of channels, for monitoring connectivity of a network, for adjusting transmitter output power (to reduce interference and increase covertness), for location of transmitters, for synchronization to network master time standards and any number of additional special purpose applications. We feel that over an HF channel the power, flexibility and accuracy of such a waveform is superior to any other for the dual role of channel probing/sounding, and data transmission.

SECTION 2 - NETWORK IMPLEMENTATION

OVERVIEW

The purpose of this section is to illustrate a

networking scheme which uses the special features of the DPCSK spread spectrum waveform described in the previous section. This network makes use of some large fixed ground stations which provide powerful antenna arrays as well as high power transmitters to get through during difficult propagation conditions. These stations can also serve as gateways to other communications media. However care was taken to preserve a fully distributed architecture which maintains gracefully degrading capabilities as any or all of the high power stations go off-line. This network is for illustrative purposes only and is not an operational capability under development nor does it pretend to be optimized in any way.

The network can consist of geographically widely separated stations consisting of smaller "user terminals" and larger more capable "backbone stations". The user terminals will normally contact other user terminals directly but when direct contact cannot be made for any reason, links can be established through any one of the backbone stations. The following are the major features of this network:

- 1) Network frequencies are split into two categories, channel acquisition frequencies and communication frequencies. Assignment of particular frequencies to these categories will be rotated periodically as often as desired. The channel acquisition frequencies will only be used to track propagation conditions and to establish links between stations in the network. The communications frequencies will be used for actual message transfer.

- 2) All frequencies will be categorized into sub-bands logarithmically spaced throughout the HF band. One acquisition frequency will be assigned per sub-band and all other available frequencies in that sub-band then become communication frequencies. It is thereafter assumed that propagation on the acquisition frequency is representative of propagation on all frequencies in that sub-band. This assumption is most valid if the acquisition frequency is the highest frequency in its sub-band, therefore the selection of acquisition frequencies also defines upper and lower sub-band limits.

- 3) Backbone stations make dedicated sounder transmissions on channel acquisition frequencies each 15 minutes which consist of 250kHz steps from 2 - 50MHz at 20 steps per second for a total of 9.6 seconds per sounder sweep. They are also the primary relay points when direct channels cannot be established. Backbone stations are the principle source of network timing and due to the properties of the DPCSK waveform master network timing can be derived from any one of the backbone station's transmissions.

- 4) All terminals constantly monitor all acquisition channel traffic, keeping a record (a connectivity map) of terminals received, frequency received, and signal-to-noise ratios (S/N). During idle acquisition blocks (a term explained later) each terminal scans the communication frequencies gathering statistics on locally received noise and interference to support selection of future operating frequencies.

- 5) Each network terminal is a potential store

and forward relay point but will be requested to perform as such only as a last resort.

- 6) Each network terminal is identified and accessed by a unique terminal address. It is also assigned a group address and a broadcast address such that several terminals may receive the same message simultaneously.

- 7) The network will have multiple channel acquisition protocols for link establishment. These levels are acquisition of a user-to-user channel, acquisition of a user-to-backbone channel (including possible relay), acquisition of a single relay store and forward channel, acquisition of a specific group or all network terminals, and network connectivity sounding.

CHANNEL ACQUISITION PROTOCOL

- 1) Channel Acquisition Timing- We considered both persistent and non-persistent carrier sensing multiple access protocols (CSMA) and selected a modified p-persistent scheme [8].

We have chosen to time multiplex ten acquisition frequencies. All network terminals will tune to frequency 1 at the beginning of each 5 sec period (an acquisition cycle) and step to the next acquisition frequency each 500msec (an acquisition block). See Figure 11 for a graphical representation of this sequence. At the beginning of any 500 msec block any terminal desiring to establish a link applies its assigned persistence parameter, p , to select a random time delay (to stagger initial transmissions) and transmits a pseudo-randomly selected DPCSK symbol using the 300 baud mode of Section 1. For the remainder of the 100 msec period, the terminal listens to see if there will be a potential conflict during that acquisition block. If no other terminals are requesting the acquisition frequency the originating terminal transmits its acquisition message, a 13 symbol DPCSK signal of 260 msec duration. However, if a conflict does arise then each originating terminal again applies its p -parameter, and determines whether or not to send its acquisition message (p -persistence). This allows a distinct possibility that multiple acquisition messages will be transmitted simultaneously. However, this situation is handled very nicely by the DPCSK waveform in that the multiple transmissions come through the matched filter in the same manner as multipath components. At 10kbps the correlation peaks of the multiple transmissions will not overlap in a given receiver unless the radial distances to the transmitters are within 18 miles of each other. With sophisticated processing algorithms (eg. only available at the backbone stations) several messages could be decoded simultaneously even with a 20-30dB difference in signal level. With a simple algorithm however, only the strongest signal would be selected for decoding.

If the originating terminal does not receive acknowledgement, it again applies its persistence parameter, p , and determines how many acquisition cycles to wait before attempting acquisition again on the same frequency. After a second failure, it would contact the most recently received backbone station on its best acquisition frequency such that special treatment may be applied to get the message through.

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Fig. 11 - Channel acquisition timing diagram

2) Acquisition of User-to-User links - The originating terminal will search its record of intercepted acquisition channel transmissions to determine which acquisition frequency would provide the best S/N to the desired destination. Lacking a record of a useful frequency the terminal will predict a propagating frequency using a propagation model which has been corrected on the basis of the real-time soundings received from the backbone stations. The originating terminal encodes the destination address, a currently clear communication frequency, local noise level on that frequency, and its originating address which is then transmitted via DPCSK. When the destination terminal recognizes its address it responds with its address, a currently clear communication frequency (at its end), its local noise on that frequency and the originator's address. Next the originator sends his message on the suggested frequency at a controlled transmitter power level.

3) Acquisition of User-to-Backbone links - The acquisition of a relay channel uses a similar format with the originating terminal sending the backbone station's address, a clear communication frequency, local noise level, and the originator's address. The relay request and the identity of the final destination will be handled at the beginning of the message transfer. Note that after receiving a single DPCSK symbol on its receiver array the backbone station has located the transmission and can now steer a high gain beam on him for the duration of the link. After receiving the message, the backbone station will attempt everything at its disposal to complete the connection to the destination, and will respond immediately to the originating terminal directing it to hold for an end-to-end channel or to sign off.

4) Relays through another user terminal - If a terminal cannot establish a direct link or raise a backbone station he may attempt to find a single relay link through another user terminal. The link acquisition begins by using a broadcast or group call address modified by one bit to indicate a relay request. The remainder of the acquisition message contains the originator's address, followed by the identity of the desired final destination. Having previously divided S/N quality into four categories, only those terminals with the highest S/N channel to the destination will respond thus limiting a possible deluge of responses. The time

resolution capability of the DPCSK waveform again comes into play to resolve and decode only the strongest response. If no response occurs the originating terminal attempts the link again up to four times with the response criterion dropping one S/N category each time. After choosing a relaying point the originating terminal automatically establishes a routine link with the relaying terminal and transmits the message. After receiving the message the relaying terminal establishes a routine link with the final destination and forwards the message without ever decoding it.

5) Acquisition of Group or Broadcast Links - When a group or broadcast message is received the terminal does not acknowledge immediately but tunes to the specified communication frequency to receive the message. Acknowledgement would be handled on communication frequencies and is not a part of the network protocol.

6) Summary - Many details of this network architecture are not fully specified above, but enough information concerning the waveform has been given that the interested reader could evaluate this network architecture for a specific application.

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