A NEW MFSK ACOUSTIC MODEM
FOR OPERATION IN ADVERSE UNDERWATER CHANNELS

Kenneth F. Scussel
Datasonics, Inc.
P.O. Box 8
Cataumet, MA 02534
kscussel@datasonics.com

Joseph A. Rice
Naval Command, Control and Ocean Surveillance Center
RDT&E Division (NRaD)
Acoustics Branch, Code D881
San Diego, CA 92152
rice@nosc.mil

Steve Merriam
Delphi Communication Systems
Burlington, MA 01803
smerriam@delcomsys.com

ABSTRACT

With U.S. Navy SBIR funding, Datasonics has teamed with Delphi Communication Systems and Naval Command, Control & Ocean Surveillance Center, RDT&E Division (NRaD) to develop a new acoustic telemetry and ranging (telesonar) modem. Periodic transmission of digital message packets satisfies most telesonar applications, including data reporting from oceanographic sensors, controlling autonomous devices, monitoring offshore-oil equipment, and communicating with undersea vehicles. These applications are well served by robust, low-data-rate, noncoherent, Multiple Frequency Shift Keying (MFSK) signaling offering greater affordability, networkability, and energy conservation than coherent modems. Well designed MFSK signaling furthermore provides superior reliability in noisy, doubly spread, forward-scattered, horizontal channels such as those found in littoral ocean environments. This paper describes the design of the new telesonar type-A MFSK acoustic modem providing communication rates of 100 to 2400 bit/s. Improved performance in adverse transmission channels is obtained from increased signaling diversity and stronger coding techniques based on symbol sets derived from Hadamard matrices. The new product also preserves the 1-of-4 MFSK modulation mode used in the Datasonics ATM-850 modem. The parallel goal of reduced cost is achieved by the new modem electronics design and packaging.

非相干通信的优点

提出新的MFSK-modem

什么是1of4MFSK?

I. INTRODUCTION

Low-data-rate underwater acoustic telemetry has been used for more than 25 years. Initially, FSK and pulsed modulation techniques provided a basic command and control capability for acoustic releases, offshore oil industry equipment, and other specialized devices.

In 1988 Datasonics and Woods Hole Oceanographic Institution (WHOI) developed a DSP-based acoustic modem capable of low-error-rate digital data transmission at rates up to 1200 bit/s in multipath transmission channels. The resulting product is the Datasonics ATM-850 modem, on the market now for over five years. It uses multiple-frequency-shift-keying (MFSK) modulation with 8 tones transmitted simultaneously on a double-sideband carrier. The ATM-850 consists of signal-processing electronics, power amplifier and transmit/receive hydrophone. It is available in a full-ocean-depth pressure housing or a shipboard deckbox.

The ATM-850 is the present state-of-the-art, commercial-off-the-shelf (COTS) product with more than 75 systems delivered worldwide. Applications include offshore oil operations, AUV control, remote recovery of data from deep-sea instrumented moorings, and a variety of commercial and military instrumentation links. This broad customer base has led to incorporation of user-friendly interfacing and operation.

Building on this successful technology,

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Datasonics, Delphi Communications Systems, and Naval Command, Control & Ocean Surveillance Center, RDT&E Division (NRaD) have collaborated to develop a new acoustic modem with improved performance and reduced cost using recent advances in signal-processing hardware and software.

Datasonics is a leading supplier of underwater acoustic modems and sonar equipment. Delphi was founded by Dr. John G. Proakis of Northeastern University who has been instrumental in developing new acoustic communication technology through a collaboration with WHOI. The new MFSK modem work is funded through a Navy SBIR contract technically managed by NRaD on behalf of the SPAWAR Naval Systems Command. This SBIR contract is a component of the larger NRaD science & technology effort advancing telesonar technology for distributed surveillance networks and remote-control applications.

II. TELESONAR TYPE-A MODEM

The new acoustic modem, refered to as the "type-A telesonar modem," extends the Datasonics ATM-850 modem capability by incorporating several new and innovative features. The type-A telesonar modem is expected to serve several new applications involving distributed undersea surveillance networks and remote control of undersea devices.

The telesonar type-A modem is designed to meet the requirements of two distinct user communities. For Navy use in littoral waters it is important that the underwater communications have a low-probability- of-detection (LPD) and low-probability-of-intercept (LPI). In most Navy applications where this noncoherent modem will be used, a data rate of 100 bit/s will suffice. Commercial users, on the other hand, often have applications requiring higher data rates not requiring LPD/LPI operation. To serve both user communities, the modem is equipped with the capability for two independent types of modulation. The first is the Hadamard code, which can be used in applications where LPD/LPI is required and in commercial applications where reliable low data rates are required. The other is the standard 1-of-4 MFSK code for commercial users where higher data rates are required.

In both cases, the modem uses a maximum 5120-Hz bandwidth, with the standard system operating in the 8-13 kHz frequency band. A uniform 40-Hz spacing yields 128 tones, 120 for data transmission and 8 for signal tracking. The operating band may be readily shifted over a range between 1 and 32.5 kHz for future implementations. At frequencies below the standard 8-13 kHz band, the useful bandwidth of most COTS transducers will be less than 5 kHz. Therefore, the data rate capability will decrease at those operating frequencies. A comparison of parameters and specifications for the two modulation schemes is shown in Table 1.

MODEM PARAMETER	*HADAMARD MODULATION*	*1-of-4 MFSK MODULATION*
Operating Frequency Range (Excluding Transducer)	1 to 35 kHz	1 to 35 kHz
Data Rate (selectable) Maximum Minimum	 1200 bits/s 100 bits/s	 2400 bits/s 300 bits/s
Processing Features: 1/2 rate convolutional coding 1/3 rate convolutional coding repetition 12.5 ms Multipath guard period 25 ms Multipath guard period	 Yes Yes Yes Yes Yes	 Yes Yes Yes Yes Yes
Bandwidth (maximum)	5120 Hz	5120 Hz
Number of Frequencies (tones) Available	128	128
Frequency Separation	40 Hz	40 Hz
Data Encoding at maximum data rate	5 bits mapped in 20 tones (20, 5) 60 data tones transmitted 30 bits/frame period	2 bits mapped in 4 tones 30 tones transmitted 60 bits/frame period
Data Frame period	25 msec	25 msec
Symbol Timing and Doppler Correction	2-4 bin tone Groups	2-4 bin tone Groups
Wake-up Coding	2 tone, 13 chip Barker code	2 tone, 13 chip Barker code
Acquisition Coding	BPSK or PN sequence	BPSK or PN sequence
Acoustic Source Level per Tone:	+190 dB ref 1 μpa	+190 dB ref 1 μpa
Acoustic Source Level Across Band:	+172 dB ref 1 μpa	+175 dB ref 1 μpa

Table 1. A comparison of modulation modes

III. MODULATION

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The underwater acoustic communication channel exhibits time dispersion on the order of tens of milliseconds because of multipath. This causes data symbols transmitted in adjacent time intervals to overlap at the receiver resulting in Inter-Symbol Interference (ISI). Additionally, multiple occurrences of the same symbol at the receiver with different delays causes frequency-dependent fading due to destructive interference. Both effects increase the Bit Error Rate (BER) in the communication link. Thus, modulation schemes for underwater communications must combat multipath effects for optimum performance.

MFSK modulation has been proven by the Datasonics ATM-850 series product to be a robust scheme for underwater data transmission. This product uses 1-of-4 MFSK where one tone in a group of four represents a specific 2-bit sequence. Several tones from independent groups of four tones are transmitted simultaneously to communicate up to 16 bits per 12.8-ms symbol frame. Detection at the receiver is performed using the FFT by measuring the signal power in adjacent bins to determine the active tone from each group of four spectral bins. The ATM-850 provides frequency diversity to combat fading using double sideband modulation.

The telesonar type-A modem described here improves BER performance under multipath conditions using more robust techniques to combat fading and ISI. Additionally, Navy requirements for LPD/LPI are met using spread spectrum-like techniques whereby more bandwidth is used to transmit data at a lower rate. The new modem employs both 1-of-4 MFSK and Hadamard MFSK as selectable modulation coding schemes. 1-of-4 MFSK permits the maximum data rate of 2400 bit/s while Hadamard MFSK permits up to 1200 bit/s. A new symbol frame time of 25 ms has been implemented, allowing a tone spacing of 40 Hz. This provides added frequency diversity by using more tones in the same bandwidth. Figure 1 is the spectrum of a 2400-bit/s 1-of-4 MFSK signal with thirty 2-bit tone sequence being transmitted.

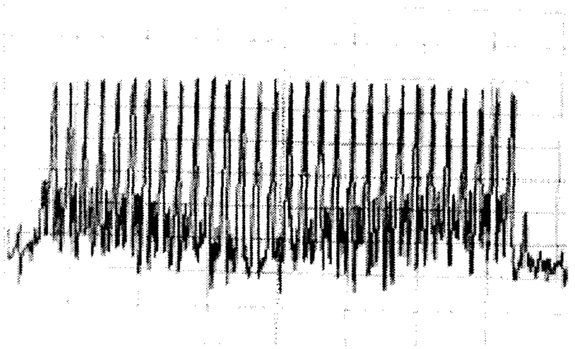

Figure 1. Spectrum of 2400 bit/s 1-of-4 MFSK

The new 1-of-4 MFSK is similar to the previous ATM-850 product, however there are now 128 frequency bins allowing a maximum of 60 bits to be transmitted in a 25-ms symbol frame. In addition, flexibility is provided in software to increase frequency diversity by mapping a given set of two data bits to one or more groups of four tones. In the most redundant case, two bits could be mapped to all 30 groups of four tones, providing significant anti-fading/anti-noise capability at the expense of a low 80-bit/s throughput.

A more efficient approach to combat fading is provided by Hadamard MFSK. This mode relies on the use of codewords derived from the family of (20,5) Hadamard codes. These 20-bit codewords each have 10 ones and 10 zeros. 32 different codewords are used where each is mapped to a unique pattern of 5 input bits. Every sixth tone of the 120 total tones is mapped to a bit of a codeword. Ones in each codeword indicate active tones and zeros indicate inactive tones. Up to 6 codewords or 30 bits can be encoded simultaneously in the available 120 tones. By choosing every sixth tone, each codeword is spread over 4800 Hz of bandwidth. The coding gain provided by the Hadamard codes allows one or two tones to fade without significant impact on the received BER. As in the 1-of-4 MFSK case, the same set of 5 bits can be encoded in 2, 3, or 6 codewords to further increase frequency diversity at the expense of data rate. LPD/LPI applications with low data rate requirements are likely to use multiple Hadamard codewords to send the same 5 bits so that sufficient energy per bit is obtained while minimizing the levels of the discrete tones. Hadamard codes increase the effective receiver SNR by providing additional coding gain. Hence Hadamard codes are a more efficient use of the available spectrum than arbitrary mapping of bits to more and more 1-of-4 MFSK tone groups. Figure 2 shows the improvement in modem BER performance using Hadamard (20,5) MFSK relative to 1-of-4 MFSK with diversity 2 (D2). The simulated results were obtained using the Rayleigh channel model representing more pessimistic propagation conditions than would typically be encountered. In the simulation, the Hadamard scheme uses 20 tones (10 active) to send 5 bits, while the 1-of-4 MFSK D2 scheme uses 8 tones (2 active) to send 2 bits. Both methods have a bandwidth expansion factor of 4, i.e., both require 4 tones of bandwidth for each bit sent. Clearly the Hadamard scheme provides a significant decrease in BER for increasing levels of SNR per bit. At low SNR per bit the curves cross which might prompt one to select 1-of-4 MFSK for

LPD/LPI applications. However, note that the Hadamard scheme uses 2 active tones per bit while the 1-of-4 scheme uses 1 active tone per bit. Thus a modem using the Hadamard (20,5) MFSK scheme can transmit tones 3dB lower than a comparable 1-of-4 MFSK D2 scheme.

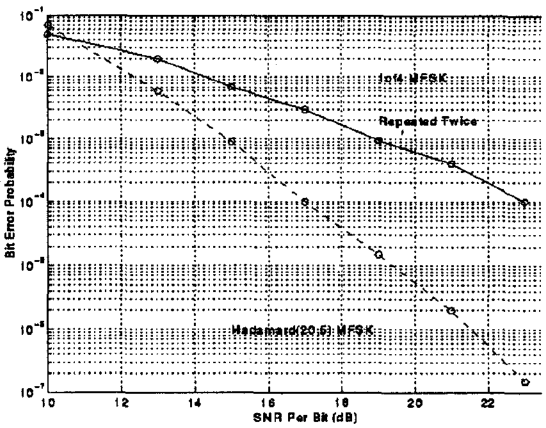

Figure 2. BER performance of Hadamard (20,5) MFSK and 1-of-4 MFSK with diversity 2 (D2)

ISI is reduced only by providing a mechanism to avoid symbol overlap due to multipath delay. The new modem design implements this feature by prepending a portion of a given data symbol to its beginning at the transmitter. The length of the prepended signal (multipath guard period) is selectable and is optimally set to the length of time significant multipath persists in the communication channel. Clearly this reduces the data transmission rate; however, the receiver will be able to track symbol periods within which there is no ISI. Since the transmitter and receiver are FFT-based, the signal phase for a given transmitted tone is guaranteed to be continuous across the boundary between the symbol and the prepended portion even if the prepended portion is longer than the symbol itself. This implies that the symbol period of acoustic signal processed at the receiver will be free of discontinuities from adjacent symbols or from own-symbol multipath interference. Therefore the common effect known as DFT "leakage" will be avoided in the receiver FFT result and the level of self-noise or interference is greatly reduced.

Another new feature added to the MFSK modem is the ability to translate the 5-kHz band anywhere within the 1-35 kHz spectrum. This allows the modem to be tailored to different applications with diverse interference characteristics and ranges. This is accomplished in software using a quadrature mixer that converts between passband and baseband and interpolation (decimation) stages in the transmitter (receiver.)* A time- and frequency-scaling feature has also been added so that applications below 10 kHz with limited transducer bandwidth can use ½, ¼, or 1/8 of the 5120 Hz band while increasing the symbol period of 25ms by 2, 4, or 8.

* Frequency utilization from 160Hz to 70 kHz is available with hardware filter modifications.

IV. TRANSMITTER SIGNAL PROCESSING

The transmitter signal processing is shown in Figure 3. Information bits from the user are optionally encoded using rate ½ or 1/3 convolutional codes for error correction. The output of the data encoder is mapped to frequency tones using the 1-of-4 or Hadamard mapping. Tones for symbol tracking are also added. The phase of the frequency domain signal is randomized to avoid large peak-to-average power ratio signals at the output. The spectrum is inverse FFT'd to obtain a time-domain baseband signal sampled at 10,240 Hz. The baseband signal is then interpolated to 153,600 Hz and quadrature mixed to a passband carrier prior to digital-to-analog conversion.

V. RECEIVER SIGNAL PROCESSING

The receiver signal processing is shown in Figure 4. Acoustic data sampled at 153,600 Hz are obtained from the A/D converter and resampled at a slightly different sample rate depending on the Doppler shift present in the communication channel. Automatic Gain Control detects the signal level and adjusts it as necessary via external hardware. A quadrature mixer converts the signal to complex baseband. The baseband signal is decimated at a 10,240 Hz sample rate. Early-Late gate processing is performed on the tracking tones to determine symbol timing. Adjustments are made for timing errors and to eliminate the prepended signal sent for the Multipath guard period if enabled. A complex 256-point FFT converts the signal to the frequency domain where Hadamard or 1-of-4 decoding is performed in conjunction with noncoherent combining. Finally, a hard-decision Viterbi decoder interprets the convolutionally encoded data. The final information data are sent to the user.

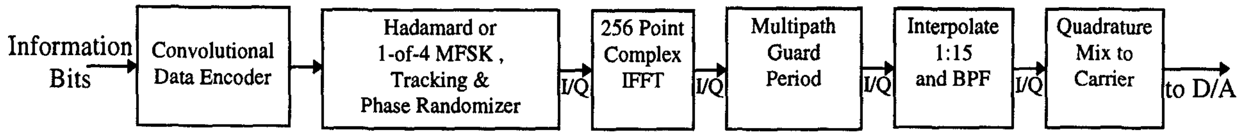

Figure 3. Transmitter signal encoding

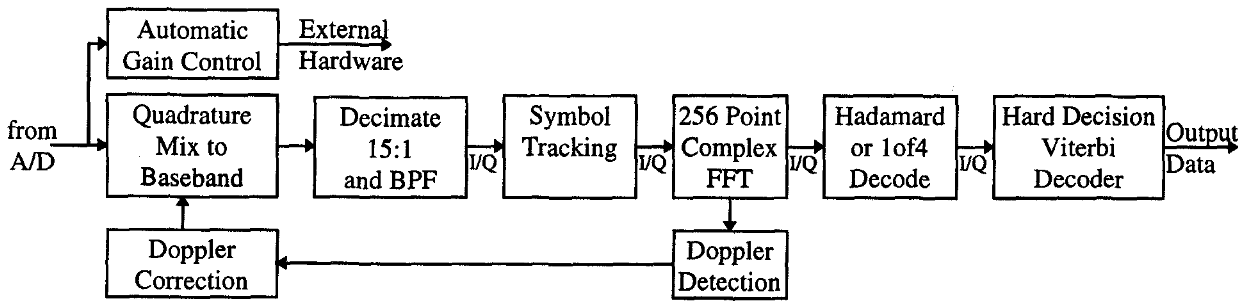

Figure 4. Receiver signal processing

VI. HARDWARE IMPLEMENTATION

The goal of the hardware implementation has been to reduce cost and improve performance relative to the ATM-850 hardware. This is accomplished by using a lower cost DSP, performing additional functions at the DSP, and reducing the complexity of the analog circuitry. The ATM-850 used a 32-bit floating-point DSP, whereas this new design makes use of a 16-bit fixed-point DSP. This DSP provides the required processing power with less energy and memory demand. The ATM-850 uses an undersampling A/D converter requiring an expensive 5 pole anti-aliasing filter. The new design uses oversampling to reduce anti-aliasing filter cost and increase the dynamic range of received signals. A benefit of this implementation is that it minimizes the hardware changes required to switch between carrier frequencies. Another cost reduction is having the AGC controlled by the software. The software AGC furthermore provides easy measurement of in-band ambient noise compared to a hardware AGC circuit.

Figure 5 is a block diagram of the overall modem. The DSP can be run by either a slow clock or a fast clock. In the slow clock mode, all functions are shut down except a low-power receiver. In this mode the DSP is capable of processing coded wakeup signals. This allows the modem to operate in a standby mode with a current drain of less than 4 milliwatts. Upon receiving a valid wakeup, the DSP powers up the receiver and switches to the fast clock, allowing incoming data signals to be processed. Transmit waveforms go out through D/A converter, power amplifier, T/R network, and to the transducer. Transmit signal level is adjustable, allowing power control to deliver sufficient but not excessive SNR at the receiver. Power control provides transmission security, power conservation and improved multiple-access networking.

The serial interface allows control of the modem by a host PC or other processor through a standard RS-232 or RS-422 interface. RS-232 allows connection to most PCs and instruments at rates up to 9600 baud. RS-422 allows the modem electronics to be placed closer to the transducer, allowing the host PC or instrument to be several kilometers from the electronics. This provides an alternative to noisy, lossy analog connections to the transducer via long cables.

A datalogging capability using 900 Kbytes of nonvolatile memory is available for buffering and storage of incoming data. In many applications it is desirable to store data for some time period before acoustic transmission.

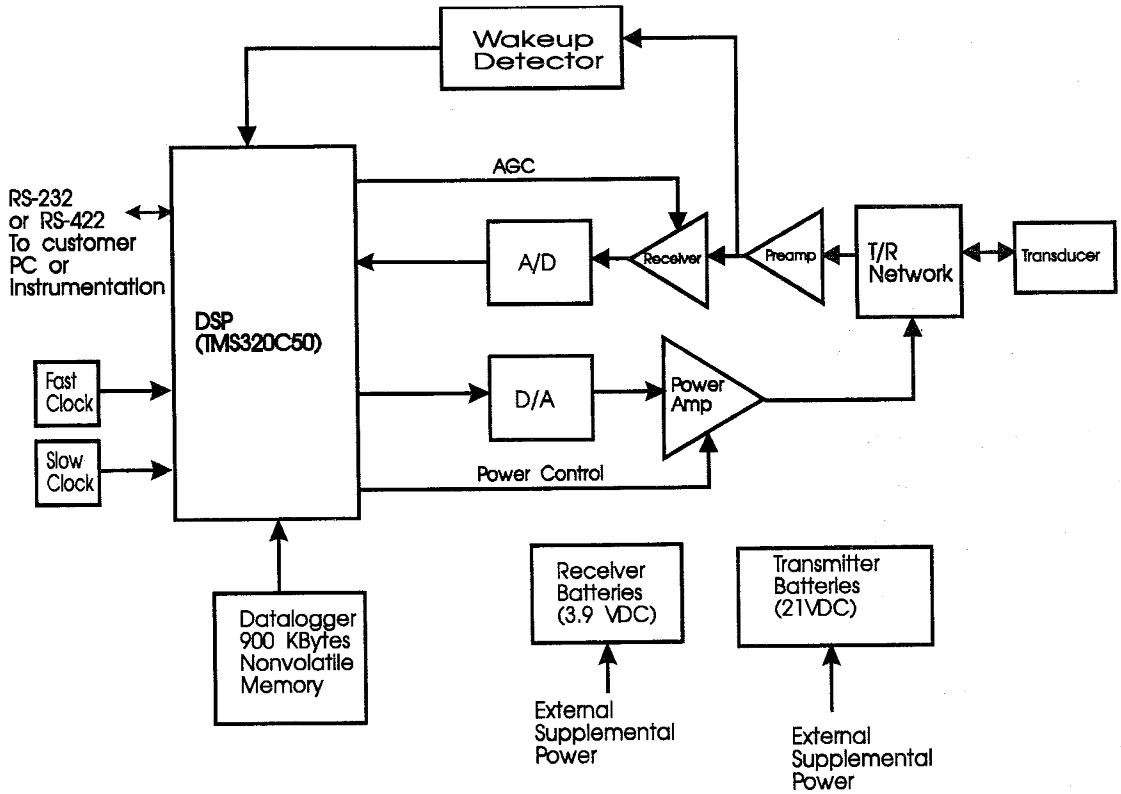

Figure 5. Modem block diagram

All modem electronics are placed onto two PC boards. One PC board contains transmitter, preamp, and TR network, while the other PC board has the DSP and associated electronics. These two PC boards are mounted in a 3½-inch diameter pressure housing. The PC board with DSP is shown in Figure 6. The transmitter PC board and a receiver battery, are installed on the back side of the mounting frame shown in Figure 6. The 3½-inch diameter pressure housing has a connector for the serial interface and for input of receive and transmit power. A longer case includes both transmit and receive batteries with a connector for input of external battery source. The electronics can also be installed in a shipboard deckbox. Figure 7 shows a photo of the AC powered shipboard deckbox and transducer.

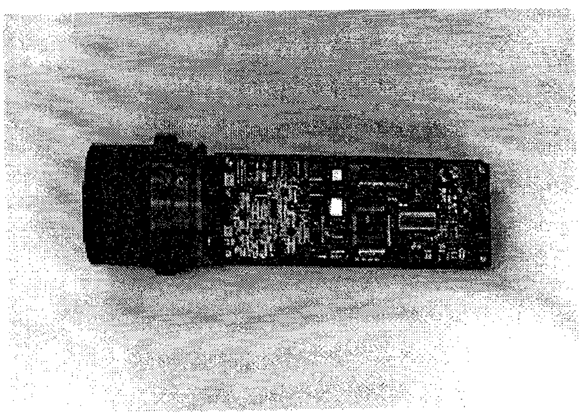

Figure 6. Acoustic modem electronics

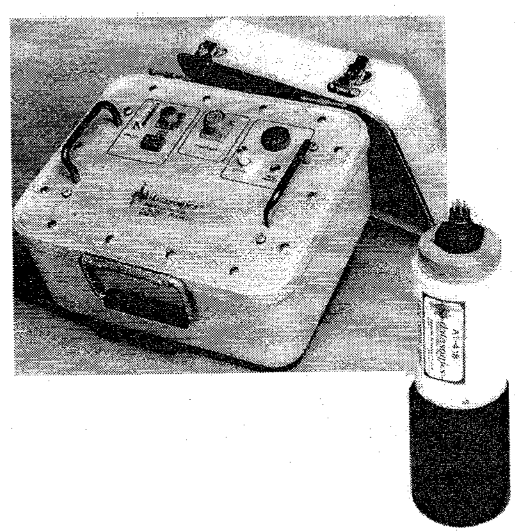

Figure 7. Shipboard deckbox and transducer

OPERATING BAND (kHz)	*DESCRIPTION*	*APPLICATION*
3-7	low-frequency, omnidirectional	long range, high power
8-15	omnidirectional beampattern	AUVs, general purpose
8-15	vertical line array, annular broadside beam	horizontal channels, undersea networks
15-20	vertical line array, annular broadside beam	horizontal channels, undersea networks
15-20	vertical beampattern, -3dB beamwidth 60°	vertical channels, transmitter pointing / receiver steering
25-30	high-frequency, omnidirectional	short range, low power

Table 2. Standard transceive transducers

VII. OPERATING SOFTWARE

The operating software defines the protocol for communicating between two modems and between host and modem. The operating software supports multiple modems, however future work is planned to optimize the operating software for networked applications. The modem-to-modem protocol packetizes the message data. Each packet includes a header at the beginning and a checksum at the end. The header includes the address of the intended receiver, the address of the transmitter, and information which allows the receiver to properly decode the packet. This is an improvement over present ATM-850 protocol which requires that the modems be properly configured prior to deployment. With this protocol the modem initiating the communication initializes the characteristics of the acoustic link.

The modem-to-host interface protocol is based on the Hayes modem AT command set and is used for operator control of all modem functions. Modes of operation include:

A. Command mode: For sending host-to-modem commands. The command mode uses AT commands for switching selecting operating mode, changing parameters in either the local modem or acoustically in the remote modem, running diagnostics, and adjusting transmit power level.

B. On-Line mode: For host-to-host modem communication. The on-line mode allows data to be exchanged between modems in a half-duplex communications link.

C. Low-power mode: In this mode all functions are shut down except a low-power receiver. Either an acoustic wake-up signal or serial data from the host will bring the modem out of low-power mode.

D. Data-logger mode: In this mode incoming data are stored for later transmission. Up to 900 Kbytes can be stored in nonvolatile memory.

E. Transponder mode: Used for modem-to-modem ranging.

VIII. TRANSDUCER CHARACTERISTICS

The acoustic modem is adjustable in operating frequency over a range from 1 kHz to 35 kHz, using a maximum bandwidth of 5 kHz. Several transducers are available, with omnidirectional and directional beam patterns, the choice depending on the requirements of a particular application. Table 2 shows a selection of the available transducers. Any of the transducers described can easily be interfaced to the standard acoustic modem package.

IX. PERFORMANCE RESULTS

Sea testing is expected to begin in July 1997. Results will be presented at the Oceans Conference in Halifax.

X. ACKNOWLEDGMENTS

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