Underwater Modem-Based Navigation Aids

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Abstract— **The utility of low power underwater digital acoustic communications (acomms) has a practical commercial history of fewer than 15 years. While earlier techniques provided data rates of perhaps 40 bits per second (bps), current non-coherent methods support data rates of many hundreds of bps, and coherent techniques provide many thousands of bps. Major enhancements in both DSP and memory electronics have had a major impact on communications performance. Equally important, these enhancements have enabled us to use those same electronics to design and field underwater systems that perform multiple functions in addition to communications. Modems of necessity use complex waveform for a variety of purposes, including acquisition, alignment, and modualtion. These waveforms are also appropriately useful in providing undersea navigation aids for autonomous platforms. The modem-supported platforms then are able to perform autonomous tasks with remote modem-equipped sensors and distributed networks. An important example is an undersea glider acting as a data truck to extract both raw and pre-processed data from deep ocean sensor systems. Examples of modem-supported sensors are described.**

I. INTRODUCTION

The utility of low power underwater digital acoustic communications (acomms) has a practical commercial history of fewer than 15 years. Among the first tentative ventures into building commercial modems was Datasonics' (a Massachusetts company) collaboration with the Woods Hole oceanographic Institution (WHOI) to produce a simple frequency shift keyed (FSK) modem [1]. This modem was able to transmit/receive at approximately 40 bits per second (bps), and that only when the channel conditions were highly favorable.

Subsequent funding from the Space and Naval Warfare Systems Command (SPAWAR), Office of Naval Research (ONR), other Navy laboratories, and commercial activities brought considerable advancement to what was to become a long line of modems. In the interim, Datasonics was purchased by Benthos, and now Benthos has been purchased by Teledyne. Modem capabilities have grown from a few tens of bps with marginal reliability to today's wide range of modulation schemes suitable for many environmental and operational conditions. At the same time, the size and power consumption of the modem has declined dramatically. The current generation electronic components, known as the Telesonar modem, is described in a later section.

The original purpose of the Telesonar modem was to be the platform for the development of undersea networking via the US Navy's Seaweb program [2]. This was the focus of the first funded efforts from SPAWAR, and this continues to be a major focus today. At the same time, ONR and other Navy laboratories have supported programs directed at the development of modem-based navigation aids, autonomous offboard sensors, and portable modem-based tracking ranges.

This paper is the second of two prepared for this conference. The first, "Underwater Acoustic Communications: Practice, Modeling, and Commentary" provides a discussion of the impediments to acomms plus some description of the Telesonar modem. This paper begins with the methods used in the modem for communications, but concentrates on examples of the uses to which a robust and flexible modem can be put – in addition to simply conveying information.

II. COMMUNICATIONS METHODS

We first describe the modulation techniques used in the Telesonar modem. Three quite distinct modulations schemes each support different applications and provide different capabilities. All such schemes provide a transition to placing energy into the channel from a common path of data preparation. That path includes forward errorcorrection coding (ECC) and symbol interleaving. The modulations all support standard base-2 Galois field arithmetic, with alphabet sizes of M = {2,4,8, etc.} [1]. We provide a brief overview of each modulation scheme in the following sections.

A. Frequency Hopping

Frequency Hopping (FH) involves the placement of short continuous wave (CW) tonals at specific locations in frequency as time passes. Generally, we consider the placement of only one tone at one time, although this is not a fundamental requirement. Each tone conveys approximately ½ bit of information, with M = 2. Tones are orthogonally-spaced in frequency, and the scheme provides for approximately 80 bps of (true) data rate. Our scheme uses a pseudo-random frequency placement for the tones, and we employ a number of similar tonals as a precursor for signal acquisition and alignment.

There are three primary advantages to this form of waveform: the scheme is very tolerant of exceedingly long multipath; it is very good for low Signal-to-Noise Ratio (SNR) applications; and it can be made tolerant of the simultaneous presence of similar waveforms from multiple sources. That is, this can be considered a Code Division Multiple Access (CDMA) technique. There are also three drawbacks: the scheme is only tolerant of range rate (relative velocity) consistent with the inverse of the tonal duration; the range resolution is approximately limited by the tonal duration; and the data rate is quite low (80 bps in our case). Figure 1 shows a simple example in the time-frequency plane where M = 2 (binary).

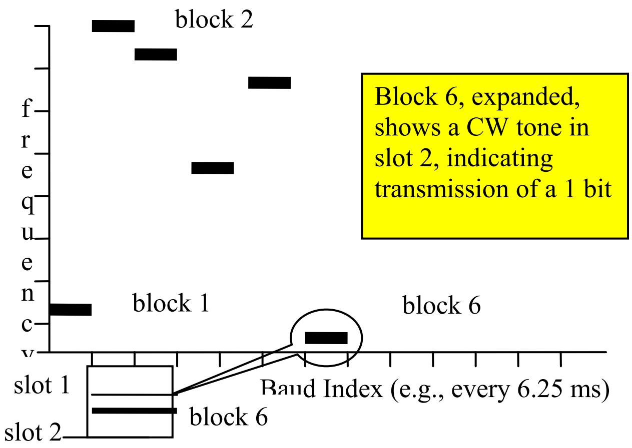

Fig. 1. Example of Frequency-Hopped Binary FSK.

B. *Multi-Channel M-ary FSK*

The term multi-channel M-ary FSK is not properly descriptive, but it has become the standard term used to describe the principal modulation method used in the Telesonar modem. In this scheme we simultaneously transmit 32 tones spanning a 5120-Hz bandwidth. Two of the outer tones are used for Doppler tracking, while the remainder carry information. Each information tone may be placed in any of four adjacent frequency slots, which together form a block (there are thus 30 blocks). The selection of the slot is decided by the M=4 alphabet. At a data rate of 2400 bps, we transmit raw data without recourse to ECC or any other form of 'protection." At 1200 bps, we add ECC. For more reduced rates, we add various forms of redundancy and/or temporal separation of the tones. Available data rates range from 140 bps to 2400 bps. Figure 2 provides an example of this method.

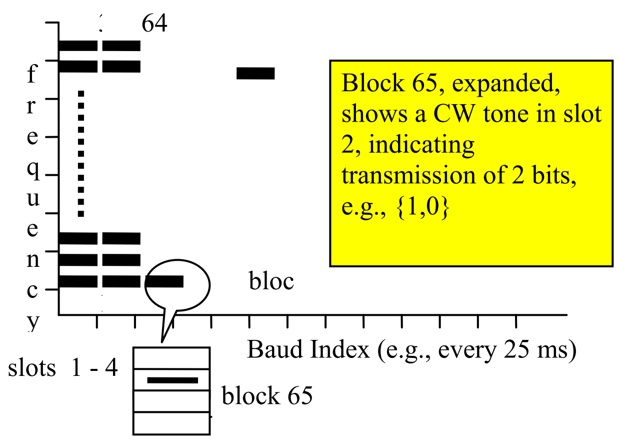

Fig 2. Example M=4 MFSK scheme transmitting 2 symbols with each tone.

Unlike the FH method, for this scheme we use several precursor waveforms for acquisition and alignment. In particular, this includes a patented method which permits these small, battery-powered devices to communicate with high-speed platforms [3]. However, this method is ill-suited for multi-access applications.

C. *M-ary PSK*

This scheme supports communications at data rates from 2560 bps to approximately 15 kbps, although the latter is suitable only for ideal channels. Here we encode symbols via the use of extremely short tonals, all at the same frequency, with the phase of each tonal conveying the desired information. The success of this technique depends on the robustness of the Decision Feedback Equalizer (DFE) which resides at the receiver and which attempts to invert the propagation channel, as defined by its impulse response. In essence, the inversion process attempts to coherently combine all multipath into a single equivalent path. The performance of the DFE in turn is dependent on the statistical stationarity of the channel and the capability of the processor to handle the requisite number of feedforward and feedback equalizer taps (within the time defined by the tonal duration). The current implementation of the equalizer in the Telesonar modem handles approximately 2-3 ms of multipath, and thus is best suited for vertical channels.

D. *Signal acquisition and alignment*

Acomms typically operates on the assumption that the arrival time of the signal is a completely unpredictable event. Therefore, it is necessary to incorporate a mechanism that can detect the arrival. It is also necessary to ascertain the precise start of the modulated message and to estimate the influences of channel spreading and platform range rate. It may also be desirable to estimate the spreading characteristics of the channel, as well as the SNR for the received signal. In the Telesonar modem these are done nearly simultaneously.

With any wireless communications system provisions must be made to accommodate rapid relative velocity among users of the system. This is especially true of underwater communications, which have limited bandwidth and otherwise difficult channels. All communications signals contain components used for acquisition and alignment, where, in the broadest sense, alignment pertains to both the temporal and spectral identification of the modulated portion of the larger signal. A typical signal component is a linear period modulated (LFM) waveform. This is processed with a "matched filter" using as a filter an exact replica of the transmitted LFM. The peak of the filtered output indicates the arrival time of the signal. When relative velocity (i.e., range rate) occurs, the waveform is distorted by temporal compression or dilation, which has the affect of also compressing/dilating the spectral content of the waveform. In this case the basic filter is no longer a good "match" for the received signal. The distortion causes a decrease in the peak filtered response, as well as loss of precision in estimation of temporal alignment. Furthermore, nothing is revealed about the spectral distortion of the signal. The desire here is to substitute an acquisition/synchronization subsystem which can provide acquisition of a packet and provide satisfactory alignment with the modulated message over a wide span of range rates. At the same time the acquisition must provide initial estimation of the range rate so the remainder of the signal can be corrected to enable the demodulation to proceed as if there were no motion present.

The classic method for solving this problem is to form a multi-hypothesis, maximum likelihood estimator, wherein a "bank" of filters are formed, each reflecting a different hypothesis of range rate. The number of filters used must account for the degree of spectral distortion imposed by the motion. Typically, a new filter must be used when the adjacent filter peak is reduced by 50%. The system then observes all of the filtered outputs and chooses that one with the largest peak. This "best" choice of filter then determines the range rate, which observation can be used to correct the remainder of the signal for the imposed spectral distortion.

The approach just described is considered optimal under typical conditions of an additive white Gaussian noise channel. However, the computational burden is very high, and, as in our case, may be prohibitive for a small, battery-powered digital signal processor (DSP). We have developed an alternative acquisition signal, which is robust in the presence of range rate, and which is composed of a primary and secondary pair of waveforms, to identify the range rate. The combination of the two is used for purposes of both temporal and spectral alignment. (see reference [3])

E. Channel impulse response estimation

The output of the broadband matched filter may be interpreted as a band-limited estimate of the channel impulse response (IR). For example, Figure 3 shows six plots, each of which shows the output of a matched filter applied to a series of closely-spaced received broadband signals. The upper left-hand and lower right-hand plots show reference signals obtained from a distance of 1 meter. The others show signals received from a source positioned approximately 100 m distant, in approximately 30 meters of water. These plots show both SNR (discussed below) and estimates of the channel impulse response. We estimate the duration of the IR by first estimating the start of the IR (it may not be at the strongest peak), then computing the point at which, for example, 95% of the energy is observed to represent the duration. With a drifting surface ship supporting the receiving hydrophone, it is apparent that the IR changes dramatically, but our algorithm does a credible job of correctly estimating the duration.

F. SNR estimation

One may estimate the output *SNRo* for a matched filter <u>squared</u> output *Z* from

$$SNRo = ((Pz - Mz)/\sigma z),$$

where *Pz* is the peak signal plus noise output, *Mz* is the mean of the noise (only), and σz is the standard deviation of the noise (only) output. The input *SNRi* may then be estimated via the

simple relationship

$$\mathrm{SNRo} = \mathrm{SNRi}*(\mathrm{TWs})$$

where *T* is the duration of the signal (chirp) and *Ws* is the bandwidth spanned by the signal. This estimate is valid for additive Gaussian white noise in the absence of multipath, but it is a reasonably good indicator of "true" SNR under many real-world conditions.

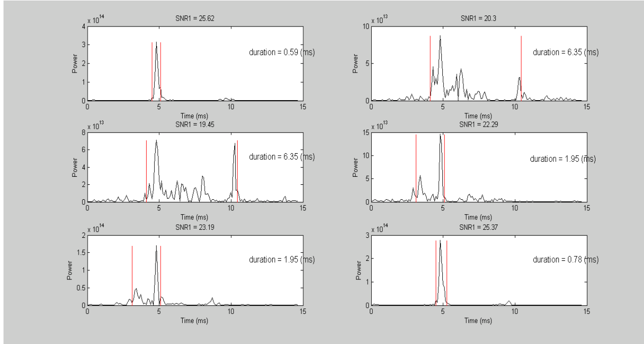

Fig. 3. Estmates of the channel impulse response based upon a band-limited matched filter applied to a chirp signal.

III. -BASED NAVIGATION AIDS

We discuss two very different forms of modem-based navigation aid. The first is a very small, USBL-like device, and the second is an underwater equivalent to GPS.

A. The DAT

The Directional Acoustic Transponder (DAT) is an extension to the Teledyne Benthos Telesonar modem which automatically estimates the azimuthal and vertical arrival angles of a message sent by a remote modem. The system is a "modified" ultra-short baseline (USBL), which, unlike most competitive systems, uses a broadband component of a typical modem message to form estimates of arrival angle(s). While conventional USBL devices employ tonal signals, the appropriate processing of wide band signals provides far better combined range and arrival angle estimation, especially at low SNR. The device offers a clear 360 degree field of view in azimuth, and an approximate vertical coverage spanning 140 degrees (from vertical). At modest SNRs our azimuthal and vertical bearing accuracies are approximately ± 2 degree.

Range between two modems is obtained via 2-way messaging. 2-way accuracy is approximately 0.5 meters at all ranges, neglecting propagation effects (e.g., refraction). If a remote modem queries a DAT with a range command, the DAT responds with a message containing the received angles. The requesting modem estimates range based on the turn-around time. The DAT may also return its own geo-location, which then is sufficient information for the remote modem to estimate its own position.

We can place the DAT on a moving platform as we have integrated an extremely small, low power 3-D rotational motion detection package, with compass.

We emphasize that the DAT is an adjunct to a standard 4th generation Telesonar modem. As such, a user has full access to our entire suite of underwater communications capabilities. The DAT in no way compromises any communications function – it simply estimates the angles of arrival for every Telesonar message addressed to it, and passes the information on to its host. If the modem/DAT receives a range request from a remote modem, it automatically responds with the estimated angles.

Figure 4 shows, in the lower picture, one type of PCB board layout including the required attached multi-channel signal conditioning board. (Both the standard modem (upper right) and the smaller Compact Modem (left) are also shown). The multi-channel board may be physically separated and connected via ribbon cable, as shown, or it may be stacked. A combined hydrophone/transducer stack is shown in Figure 6, along with the required electronics. The modem board set alone is approximately 135x76x72 (mm). When fully awake (receive mode), the combined unit consumes approximately 0.6 W.

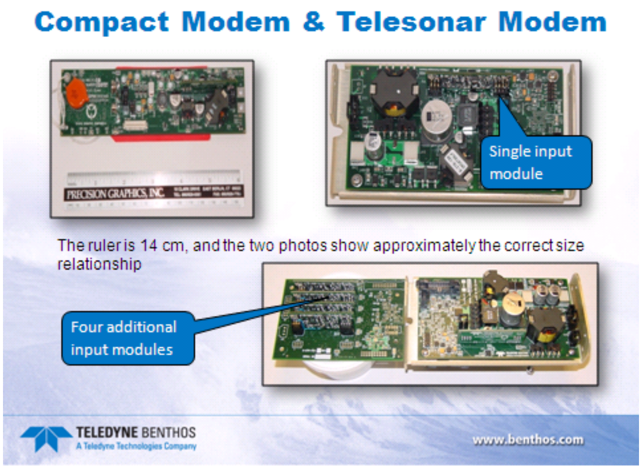

Fig. 4. Photographs of various DAT and other modem components

The DAT requires a hydrophone assembly separate from the modem transducer, although the two may be "potted" together as a vertical stack, as shown in Figure 5. The two may also be physically separated, generally a more suitable configuration for a UUV (unmanned underwater vehicle).

The following Figure 6 shows measured performance of the DAT when used in a reference mode. Here, the DAT was positioned on the floor of Cape Cod Bay in approximately 20 meters of water, and a small boat with an over-the-side modem was allowed to drift from three selected locations. The results are presented in color, with the colored line indicating the boat track from a particular location, and the clusters of the same color indicating the estimated location of the DAT. We see that the clusters are reasonably tight, as anticipated. The general positions of the clusters are somewhat separated due to multipath conditions

In general, 2-way communications between a sensor and an attached modem is via a serial link – RS 232/485. We do not support USB. The modem has two modes: "command" and "on-line." In the command mode, the modem itself is being addressed (e.g., for range commands, or battery voltage status). In the on-line mode, anything that is sent over the serial port is transmitted exactly as received (e.g., NMEA strings). We do not in any way compress, parse, or use the information within the transmitting or receiving modems. We do add our own error correction coding (ECC) and CRC error checking. The link between the DAT and the modem is proprietary and should not concern a user.

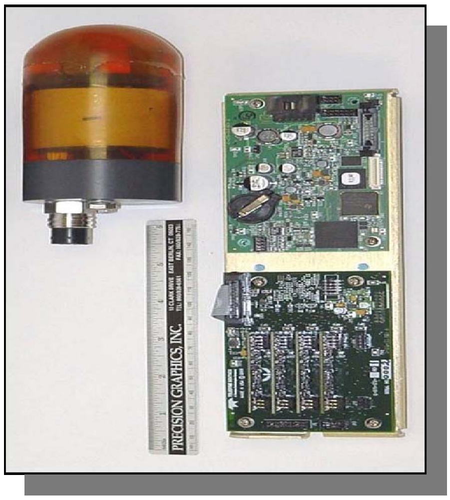

Fig 5. All modem components, including wet-end.

The DAT has many applications, some of which are indicated in Figure 7. We describe the glider-based data truck in more detail in the next section.

B. An At-Sea Data Truck

Marine is an organization within the Teledyne Corporation which combines capabilities of a large number of ocean product companies. Two of those companies, Teledyne Webb Research and Teledyne Benthos have recently been combined into one company. Pertinent to this discussion, Teledyne Webb provides the Slocum Glider, a UUV employed world wide in oceanographic research, while Teledyne Benthos provides acomms modems to an even wider community. The combined company has now integrated the two products, providing the user with the same level of command and control of the glider as now exists via Iridium or other RF-based modems. In addition, the modem on the glider provides several new advantages, as indicated in Figure 8:

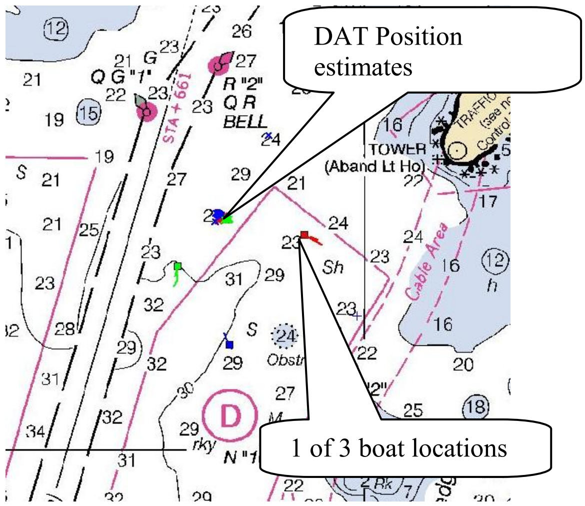

Fig. 6. A DAT experimentation showing positioning accuracy obtained from 3 remote modems.

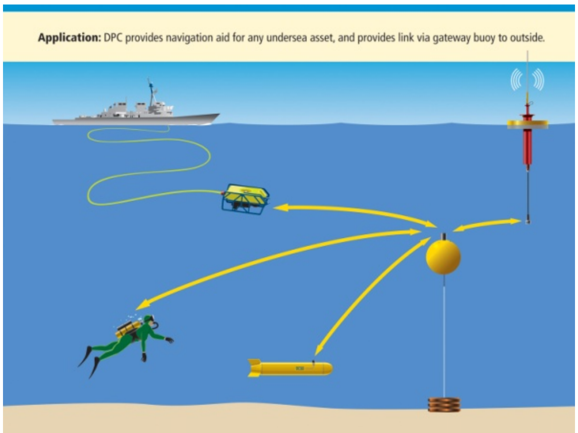

Fig. 7. Multiple DAT applications as a navigation aid for divers, UUVs, and ROVs.

The inherent ranging function of the modem enables the glider to approach a remote modem/sensor simply by maneuvering to decrease range. If the remote device includes a DAT, the glider is provided with precise range, bearing, and depth to support maneuvering.

The host computer aboard the glider can use its own acomms modem to initiate a data transfer from the bottom device. The glider can then receive instructions, for example from the same bottom device, instructing it where to go next (if within a network), or it can go to the surface, achieve an RF link, and transfer the data to a remote station.

The sea floor node can be any sensor system of the user's choice. Teledyne Benthos has developed a modem-based product incorporating the SD-card data recorder (see our other paper) which integrates with sensors such as an acoustic doppler current profiler (ADCP) to provide access to individual, time-stamped files. These can now be uploaded autonomously to our data truck, or via another surface-positioned modem (e.g., a deckbox) aboard a vessel.

IV. Conclusions

Underwater acoustic communications is a maturing technology even though a considerable amount of research is still underway at academic and commercial institutions around the world. In developing and fielding acomms systems, developers and users should understand the actual performance needed for particular tasks. While it is intellectually satisfying to discovert advanced methods for achieving high data rate acomms, it is often the case that quite low data rates, achieved though very robust techniques, is the more important consideration.

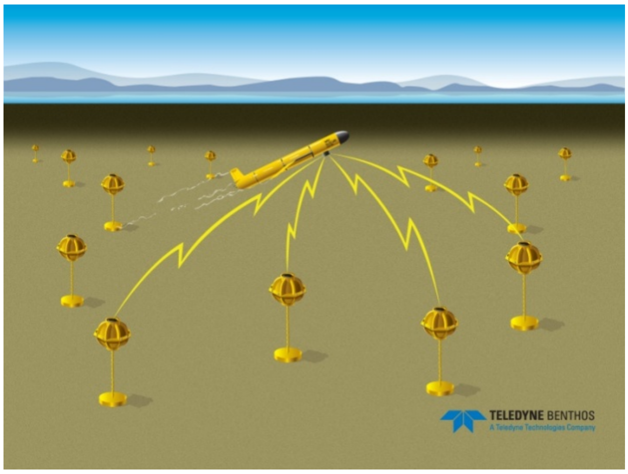

Fig. 8. The Glider/Modem Data Truck Concept

The integration or incorporation of acomms (and the computer infrastructure required for its success) with underwater sensing and navigation capabilities offers a new and rewarding avenue of research and development. For example, a typical USBL navigation sytem is highly subject to false alarms, but when coupled with robust acomms, the false alarm rate immediately approaches zero. However, this integration must be power-efficient. A major consideration of most underwater systems is conservation of energy resources. To that end it is important to utilize every means possible to reduce consumption: fixed-point DSPs, sleep modes, and efficient programming being among the most important.

Aclnowledgements

This document has been cleared for public release by the DoD's Office of Security Review, Case 10-S-2211.

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