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A Modem Design for Underwater Acoustic Networking in the High North

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***Abstract*—We design a software modem for long range underwater acoustic communications in ice-covered oceans. The modem is equipped with three coded modulation schemes achieving 1.8, 21.4 and 96.2 bps, respectively. In addition, we design a new large-scale underwater channel simulator and test the modem performance in the underwater environment of Baffin Bay. Our analysis shows that ranges of more than 200 km can be achieved during summer months provided that the link exploits the ducted sound propagation. During winter months, however, this performance may not be always possible and multiple hops will be needed to cover the same range. The results presented in this work are the basis for the study of adaptive routing solutions for data delivery in multi-hop networks [1].**

I. INTRODUCTION

Ad-hoc Underwater Acoustic Networks (UANs) consisting of mobile and static nodes will play a pivotal role in future surveillance operations in polar regions. Yet, network design is challenged by the harsh polar environment, which renders network deployment tedious and costly. Consequently, a sparse network topology must cover distances of hundreds of kilometers. Acoustic signals can travel long distances under ice, however, these signals suffer distortions due to repeated ice scattering. Moreover, the relative low speed of sound (1500 m/s) results in extreme channel latency limiting the command and control of Autonomous Underwater Vehicles (AUVs). These facts necessitate a dedicated design of communication signals, networking protocols as well as a careful consideration of hardware solutions.

Unfortunately, the current studies addressing communications in polar regions are scarce. The most representative work is perhaps by Freitag et al [2]. The authors reported rates of 5-10 bps over ranges of 70-90 km based on the WHOI MicroModem. The signals used either 700 Hz or 900 Hz carrier frequency with maximal bandwidth of 96 Hz. It is worthy to note that the transmitter/receiver was placed within the observed sound channel of the waveguide, which was at a depth of about 100 m. In [3], it is reported a data rate of 1-bit/s over ranges of about 400 km with phase modulated signals. In [4], the researchers transmitted navigation signals to an AUV operating close to the ice canopy, however, ranges up to only 2 km were accomplished. The reason for this short range communications was the complex double duct propagation under the ice.

In this short paper, we design a modem that uses three physical layer (PHY) schemes tailored to polar channels. The first scheme is based on Frequency Hopping-Binary Frequency-Shift Keying (FH-BFSK) modulation. The second is a combination of Binary Phase-Shift Keying (BPSK) and Orthogonal Frequency-Division Multiplexing (OFDM) (termed as BPSK-OFDM hereafter). The third combines Trellis Coded Modulation (TCM) with OFDM (termed as TCM-OFDM hereafter). Furthermore, we design a new large-scale simulator that builds upon the Arctic BELLTEX ray tracer [5] and includes multipath fading statistics, platform mobility and impulsive ambient noise. To showcase the modem's performance, it is tested in the Baffin Bay environment, where a network of 21 mobile/static nodes covering an area of 100x240 km^2 is considered. The proposed PHY schemes are compared in terms of range vs. Packet Error Rate (PER). Furthermore, our results are fed into the network simulator of [1] to develop adaptive routing solutions.

II. CHOICE OF FREQUENCY BAND

Selecting the appropriate bandwidth and carrier frequency for our signals is not straightforward as there is a trade-off between the propagation physics and hardware products. The physics of sound absorption in the ocean indicate that frequencies less than 1000 Hz must be selected for ranges close to 100 km [6]. For frequencies less than 250 Hz the transducers available in the market are either few meters long or weigh hundreds of kilos. Consequently, such transducers may not be suitable for AUV operations. A transducer that achieves a practical balance between operational bandwidth and physical size is the HMS-AT650 [7]. That transducer offers a bandwidth of 400 Hz at a center frequency of 650 Hz and requires 42 Watts acoustic power (60% efficiency) to yield a source level of 185 dB re 1μPa @ 1 m. Hence, in the remainder of this work, our signal design is based on the HMS-AT650 hardware.

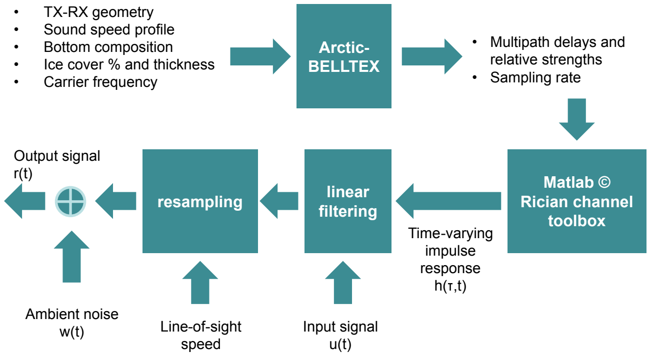

Fig. 1. Building blocks of channel simulator.

III. Channel simulator

The block diagram of the simulator is seen in Figure 1. The Arctic-BELLTEX ray tracer is used to provide the number of eigenrays for each transmitter-receiver pair. This ray tracer builds upon BELLHOP [8] where the surface ice draft is generated via Goff's stochastic model [9]. Arctic-BELLTEX takes as inputs: the signal carrier frequency, the transmitter/receiver depth, sound speed vs. depth, ice draft parameters and bathymetry vs. range. The resulting output is all eigenrays that connect the transmitter-receiver pair. In addition, each eigenray n is associated with a travel delay τ_n and a power gain $\bar{a}_n$.

To account for any time-varying propagation effects, we model the strength of each eigenray as a Gaussian random process $a_n(t)$ with flat power spectral density and average power $\bar{a}_n$. Hence, the baseband channel impulse response $h(\tau, t)$ (with respect to the carrier frequency 650 Hz) can be expressed as

$$h(\tau, t) = \sum_{n=1}^{N} a_n(t)\delta(\tau - \tau_n), \tag{1}$$

where N is the number of physical paths that connect the transmitter with the receiver and $\delta(\tau)$ is the Dirac function. If $u(t)$ denotes the transmitted signal, then the (noiseless) channel output, $y(t)$, is written in terms of a time-varying convolution sum as follows:

$$y(t) = \int_{-\infty}^{+\infty} h(\tau, t)u(t-\tau)d\tau = \sum_{n=1}^{N} a_n(t)u(t - \tau_n). \tag{2}$$

Platform mobility is simulated by changing the sampling rate of $y(t)$ to $y(t(1+\Delta))$. If the mobile (*e.g.,* AUV) moves towards/away the receiver at speed v then, the received signal is expected to be time compressed/dilated by a factor of $\Delta = v/c$, where c denotes the nominal sound speed (1500 m/s). In case of signal compression, we have $\Delta > 0$ while for signal dilation $\Delta < 0$. Finally, an impulsive noise signal is added to the channel output to simulate a specific Signal-to-Noise Ratio (SNR).

We now briefly cite particular environmental data of Baffin Bay.

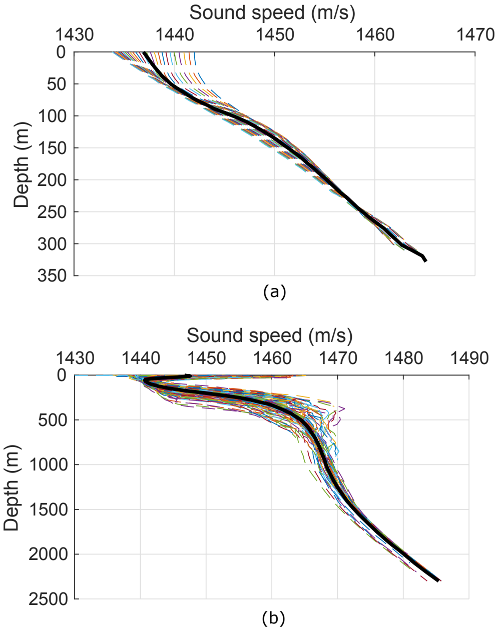

Fig. 2. Measured sound speed profiles from years 1977-2016: (a) October to April; (b) May to September. In both plots, the thick black lines indicate the average sound speed profiles.

1) Sound speed profile: The National Oceanic and Atmospheric Administration (NOAA) database [10] is used to acquire sound speed data in Baffin Bay. Figure 2(a) and Figures 2(b) show, respectively, the measured sound speed profiles for different months over the period 1977-2016. We note that during winter months (October to April) sound is refracted upwards and hence suffering significant scattering losses due to repeated bounces off the ice surface. On the other hand, during summer months (May to September), we observe a sound channel whose depth is close to 60 m. Any sound ray trapped within this sound channel may travel long distances since there is no interaction with the ocean boundaries.

2) Sea ice cover: We use satellite images from the European Space Agency (ESA) [11] to acquire approximate values for the surface ice coverage and ice thickness, two necessary parameters used by Arctic-BELLTEX. For summer months, the surface ice cover and ice-thickness is about 30 % and 0.8 m respectively. For winter months, the ice cover and thickness is about 70 % and 1.5 m, respectively. As an example, Figures 3(a) and (b) show two ice drafts that Arctic-BELLTEX generates based on the above parameters. Note that when the ice draft is less than 1 cm (practically no ice), Arctic-BELLTEX uses the reflection coefficient of the air-sea interface.

3) Bathymetry and seabed types: The gridded bathymetric data from the General Bathymetric Chart of the Oceans (GEBCO) [12] has provided the required bathymetry. Note that Baffin Bay's maximum depth is about 2250 m. The National Geophysical Data Centre's Deck41 data-base [13] has provided the bottom sediment database. We have found that the seabed of Baffin Bay includes mainly a mixture of

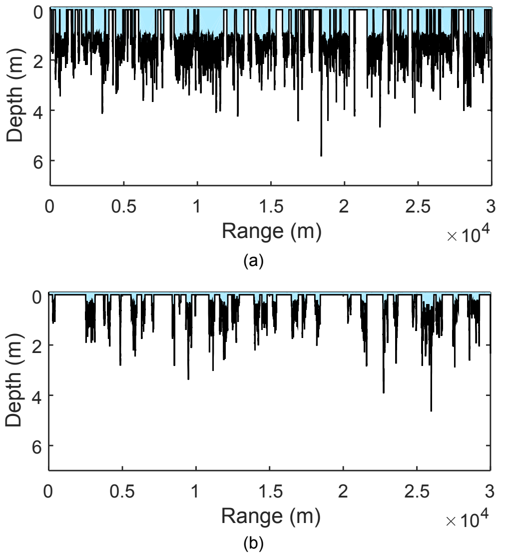

Fig. 3. Ice drafts in blue and black color: (a) 70 % cover and 1.5 m thickness; (b) 30 % cover and 0.8 m thickness.

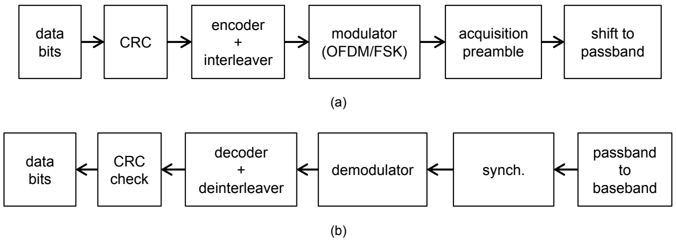

Fig. 4. General transceiver block diagram: (a) transmitter; (b) receiver.

silt, clay and sand.

4) Ambient noise: Ambient ocean noise is largely dictated by ice-related phenomena [14]. These phenomena are spatially and time varying, where the ratio of open water versus ice coverage and wind speeds determine the ambient noise levels. Although the dominant power of ambient noise in the Arctic lies within the 2-200 Hz band [15], the impulsive nature of icequakes can affect higher frequencies. Unfortunately, we could not find any ice-related noise Power Spectral Densities (PSDs) for Baffin Bay in the open literature. In this work, ambient noise is assumed to follow the Symmetric alpha-Stable distribution (SαS) [16]. This distribution has been used to model diverse phenomena such as random fluctuations of gravitational fields, economic indexes, and radar clutter [17].

IV. MODEM DESIGN

The general block diagram of the modem is depicted in Figure 4. Two different packets are generated to serve our communications purposes. The *header* packet contains 7 bytes of information plus 1 byte of Cyclic Redundancy Check (CRC) and is meant to convey short control messages such as node health status or packet reception acknowledgments. The *cargo* packet contains 30 bytes of information plus 2 bytes of CRC and is meant to convey payload data. We use three PHY schemes to transmit the packets:

- The FH-BFSK signal uses a rate-1/2, constraint length-9 convolutional code to encode the packets. The interleaving process permutes the channel symbols in each packet by a fixed spreading value. The chip duration is 250 ms and the waveform occupies 352 Hz of bandwidth. The resulting *goodput* (defined as the number of information bits delivered at the receiver per unit time, excluding any overhead) is 1.8 bps. The demodulator is based on energy detection and the decoder is based on the Viterbi algorithm with hard decision metrics.
- The BPSK-OFDM signal uses a rate-1/2, constraint length-7 convolutional code. The coded bit sequence is mapped into BPSK channel symbols and then is randomly interleaved. The resulting sequence is further coded by applying Direct Sequence Spread-Spectrum (DSSS) modulation with a Kasami sequence of length three.
- The TCM-OFDM signal uses the same convolutional code as BPSK-OFDM. The coded bit sequence is mapped into 4-PSK channel symbols and then is randomly interleaved.

Both BPSK-OFDM and TCM-OFDM use 256 carriers spanning 400 Hz of bandwidth and a cyclic prefix length of 150 ms. The issue of high Peak-to-Average Power Ratio (PAPR) is addressed by reserving a small number of sub-carriers to reduce the large peaks of the OFDM signals [18]. Accounting for the overall overhead (PAPR symbols, pilot symbols for channel estimation, and cyclic prefix), the resulting goodput for BPSK-OFDM and TCM-OFDM is 21.4 and 96.2 bps, respectively. Their decoder is based on the Viterbi algorithm with soft decision metrics

The acquisition portion of each waveform is 16 tones transmitted in FH-BFSK fashion. The receiver front-end uses a bank of 16 narrowband filters, one matched to the frequency/duration of each tone. The acquisition threshold (PER$<$0.5) in SαS noise for FH-BFSK, BPSK-OFDM and TCM-OFDM is close to 0 dB, 9 dB, and 12 dB, respectively. We have noticed that noise impulsiveness introduces a penalty of about 7-15 dB with respect to Gaussian noise. Figures 5 (a)-(c) show the three passband signals generated by our modem. The sampling rate is 2048 Hz.

V. SIMULATION RESULTS

The considered Baffin Bay network is depicted in Figure 6(a). The network consists of 21 nodes and so the number of different link combinations is 21·20/2=210. The distance between nodes 1→2, 8→9, and 15→16 is 40 km. The ocean depth in that area ranges from about 200 m to 2000 m. The following assumptions are in order:

- The transmitter source level is 185 dB re 1μPa @ 1 m and placed at 60 m of depth.
- The receiver is equipped with a vertical line array of 96 elements with $\lambda/2$ spacing, λ being the wavelength at 650 Hz. The topmost hydrophone is placed at 30 m

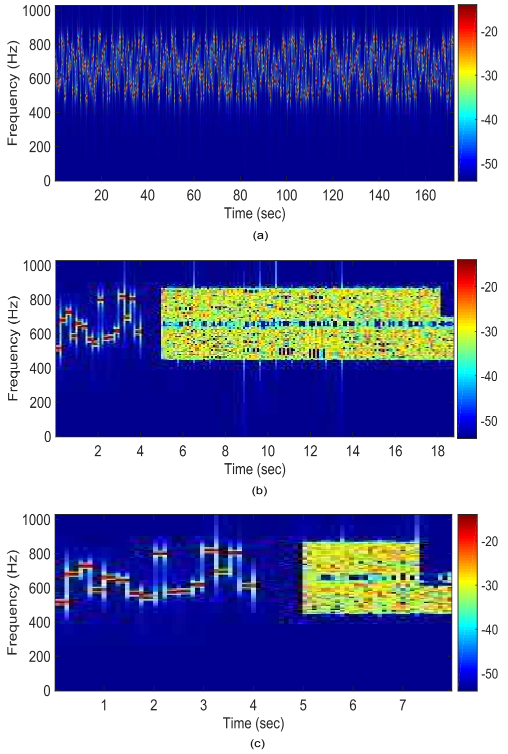

Fig. 5. Spectrograms of the transmitted signals: (a) FH-BFSK (b) BPSK-OFDM; (c) TCM-OFDM. The power intensity is in dB scale. At the beginning of each signal, there is a 4-s FH-BFSK acquisition preamble. For BPSK-OFDM and TCM-OFDM, there is an 1 s silent period between the preamble and the information-bearing signal.

depth. Only the hydrophone with the maximal SNR is used (single-input single-output channel).

- Each link may have zero or 3 knots of speed. In case of mobility, the vertical line array is replaced by a moving platform (AUV), positioned at the maximal SNR depth. The motion effect on the received signal is simulated via changing its sampling rate.
- Each link assumes either summer or winter conditions. The average sound speed profiles of Figure 2(a) and (b) are used.
- Mutlipath time-variability is judiciously chosen to 1.5 s and is decoupled from any platform mobility. Our choice is based on the fact that sea surface motion effects are seriously diminished due to the ice canopy formation.
- The channel delay spread is upper-limited by 150 ms (due to computing limitations).

Figures 6(b) and (c) illustrate, respectively, the average range as a function of the maximal allowed PER for winter and summer conditions. The average range is computed over all links that meet the PER constraint. The environmental impact on modem performance is clear since all PHY schemes perform better in the summer than in the winter. That is because during winter the sound speed profile data infer no ducting and hence our signals suffer extra losses from repeated ice scattering. For instance, the average range increase (from winter to summer) of FH-BFSK, BPSK-OFDM and TCM-OFDM is about 33 km, 15 km and 8 km, respectively, when the maximal allowed PER is 0.6. For the same PER threshold, our summer results show that the maximum achievable range (the plot is omitted for brevity) of FH-BFSK, BPSK-OFDM and TCM-OFDM is about 282 km, 243 km, and 200 km, respectively. On the other hand, during winter, the maximum achievable range of FH-BFSK, BPSK-OFDM and TCM-OFDM is about 151 km, 143 km, and 80 km, respectively.

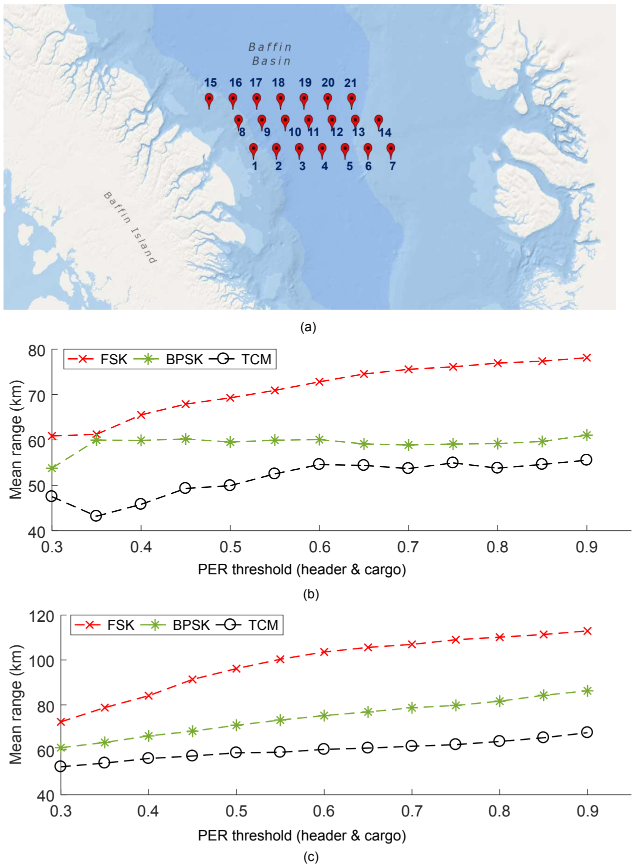

Fig. 6. (a) Baffin Bay multi-hop network topology covering an area of 100x240 km^2. (b) Average range vs. PER threshold for winter. (c) Average range vs. PER threshold for summer.

VI. CONCLUSIONS

Lacking available modem technology to address the need of long range communications in polar regions, we have designed a software modem with bandwidth 400 Hz centered at 650 Hz. The modem has been equipped with FSK and OFDM schemes to better understand the trade-off between PER and range. In addition, we have designed a large-scale underwater acoustic simulator that builds upon the Arctic-BELLTEX [5] and has tested modem performance in the Baffin Bay environment. Our results have shown that the modem could achieve more than 200 km of range during summer months provided that the link could exploit the ducted sound propagation. However, during winter, this requirement may not be always possible and 2-3 hops will be needed to communicate over 200 km.

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