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Further Evidence for Using Polar Codes for Low Overhead Error Correction Encoding in Underwater Acoustics

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14. ABSTRACT

Polar coding is a linear block coding method notable for its channel capacity-achieving performance with low-complexity encoding and decoding algorithms. This memorandum will provide additional evidence in support of the previously published Formal Report entitled, "Using Polar Codes for Low Overhead Error Correction Encoding in Underwater Acoustics." It will present new support for the application of polar codes to frequency shift keying (FSK) modulation. Polar codes are ideal within a presumed channel description, here an additive white Gaussian noise (AWGN) was assumed. Compared with traditional rate-1/2 convolutional error correction encoding, polar was shown to have lower probability of bit error and had less overhead – another critical concern for very short transmission frames.

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EXECUTIVE SUMMARY

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FURTHER EVIDENCE FOR USING POLAR CODES FOR LOW OVERHEAD ERROR CORRECTION ENCODING IN UNDERWATER ACOUSTICS

1. INTRODUCTION

Underwater acoustic communications present unique challenges compared to its terrestrial radio frequency counterparts. An acoustic channel often suffers from noise, multipath, reverberation, attenuation, fading, as well as spatial and temporal variability. In order to mitigate the bit errors caused by these effects, strong channel coding is often utilized. Due to limited bandwidth, acoustic communications often can only support low data rates, especially at long ranges. This, combined with the short coherence time of underwater acoustic channels, leads to the need for short transmission packets. Fortunately, practical underwater systems like instruments, gliders, and unmanned underwater vehicles mostly need short command and control or sensing messages in order to stay connected with each other. Therefore, effective encoding with low overhead is essential.

This paper will instead consider the usage of polar codes for short frame underwater communications. A new at-sea experiment that further demonstrates the effectiveness of polar codes for underwater acoustic communications was performed and encoded FSK transmissions were made. The new location contains significantly more reverberation. Comparisons against convolutional encoding will show that it is an improved technique to reduce error.

2. METHOD

2.1 Polar Codes

The details of the application of Polar codes to acoustic communications were first described here [1]. This paper will provide additional evidence of its superior performance with lower overhead. Polar is a type of block code that involves two key operations: channel combining and channel splitting. Quickly summarized, this method converts the block and the distortion of the channel, into a polarized bit streams that are characterized as being a good or bad representation of the ideal channel. It has been shown theoretically that as the size of the block increases the number of good representations approaches Shannon capacity. However, polar codes are quite effective even when the size of the block is small. Despite its exceptional performance, the algorithm complexity is far less than comparable hybrid codes, especially at the receiver [2].

2.2 Noncoherent Binary Frequency Shift Keying

Frequency shift keying (FSK) modulates the frequency of the carrier signal so as, to carry information. For digital baseband signals, it represents data through discrete variations in the frequency of a carrier signal. In binary FSK, the instantaneous frequency (or tone) of a constant-amplitude carrier signal is shifted between two values by the baseband digital message. FSK is not particularly susceptible to additive white Gaussian noise (AWGN), because noise affects the carrier's amplitude and not its frequency. Noncoherent FSK demodulation is less bandwidth efficient than coherent FSK, but requires, at most, only an additional

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1 dB more received signal power than that for coherent FSK for the same probability of bit error. In practical terms, the noncoherent receive system is easier to build since it doesn't require a reference signal with the additional benefit of being Doppler tolerant.

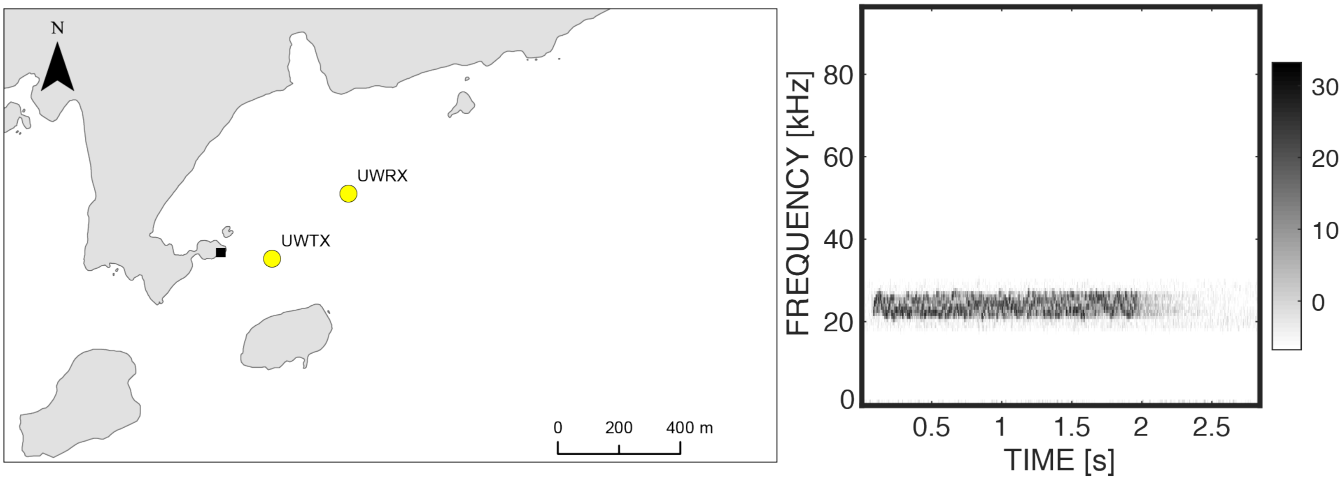

Fig. 1 —The experiment site was in the in the Stockholm Archipelago. The spectrogram on the right shows a measured frequency hopping incoherent FSK transmission made at a short range.

3. EXPERIMENT

The Undersea Surveillance and Communication Project Agreement (USC PA): Sea Trial 3 (ST3) experimental area is shown in Fig. 1. Complete experimental details of ST3 can be found in [3], while the purpose [4] and summary [5] are also available. Other communication sequences transmitted during ST3 can be found here [6]. The area of interest for the acoustic communications portion of the ST3 was located in depths between 30 to 40 m. The bottom consisted of mud over a hard scarp. Underwater communication measurements were made with a stationary transmitter (UWTX) and receiver (UWRX). The water column was almost completely mixed with a sound speed of 1448 m/s. Reverberation was severe and had a duration of approximately 3 seconds.

Transmissions were made November 6th, 2019 from an ITC1001 transducer located 12 m above the bottom. The receive array was located 0.3265 km away and consisted of 8 hydrophones distributed from the bottom to 25 m sampled at 192 kS/s. Communication waveforms were sent with a center frequency of 24,000 Hz, a bandwidth of 5,120 Hz, and a symbol duration of 6.25 ms. The unencoded data rate was 160 bps. A preamble of 30 symbols was used for synchronization. A measured, bandpass filtered waveform is shown to the right in Fig. 1. This high SNR reception is the same waveform that will be used for the calculations depicted later in Fig. 2.

The raw data consisted of 120 bits with an 8-bit cyclic redundancy check. Besides polar, the best nonsystematic rate-1/2 convolutional code with maximal minimum free distance (constraint length 9, g(0) = 561, and g(1) = 753) also was used to encode the data. The encoded data was of length 256 bits and 272 bits in length for polar and convolutional, respectively. After interleaving, the data was modulated as a frequency hopping FSK transmission. The available bandwidth was divided into 17 hops to mitigate frequency-selective fading. Combining interleaving with the decoding reduces the effects of burst errors. The signal durations were 1.79 s and 1.89 s for polar and convolutional, respectively.

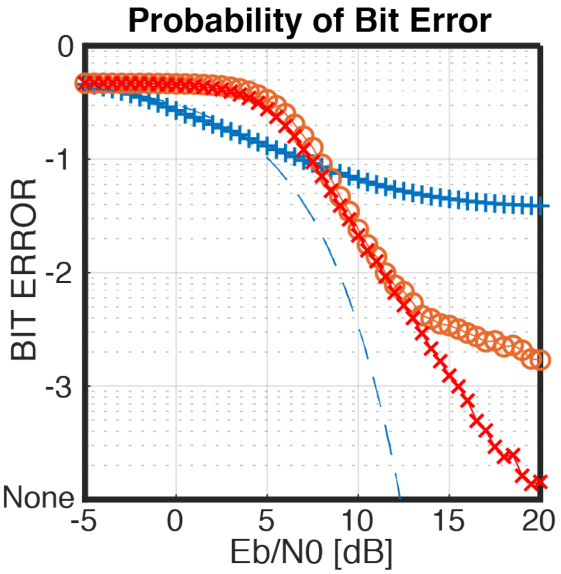

Fig. 2—Probability of bit error (BE) vs. Energy/Noise density per bit. The dashed line is the theoretical noncoherent binary frequency shift keying performance in the presence of additive white Gaussian noise. The *y*-axis terminates at 10^{-4} BE and thus includes perfect transmissions. The measured performance (“+”) was based on measured at-sea signals. The convolutional (“O”) and polar (“X”) results are after error correction encoding. In the field, polar outperformed convolutional encoding with less overhead.

4. RESULTS

Figure 2 depicts the probability of bit error (BE) vs. Energy/Noise density per bit (E_B/N_0). The dashed line is the theoretical noncoherent binary frequency shift keying performance in the presence of AWGN. The (“+”) line depicts unencoded BE. This was estimated by taking a measured at-sea reception of relatively high SNR, and then adding AWGN of various strength to form a large ensemble from which to estimate average BE. It is apparent that at higher E_B/N_0 the at-sea data diverges from theoretical expectations. This is because the assumption that only AWGN is present is invalid. In fact, multipath, fading, Doppler, reverberation, and spatially colored noise are present. Simply increasing the source level does not yield significantly improved results. The convolutional (“O”) and polar (“X”) results shown in Fig. 2 are the BE after error correction encoding. In the field, polar outperformed convolutional encoding with less overhead. While both encoding techniques were designed for AWGN channels, the polar method appears more robust to AWGN and is, instead, primarily impacted by other sources of error.

Though not a conventional metric, rather than averaging to get the probability of bit error, it is possible to use the mean of the ensemble to estimate the point at which error-correction encoding is more beneficial than detrimental, on average. That E_B/N_0 threshold was 7.58 dB for polar encoding vs. 8.14 dB for convolutional encoding.

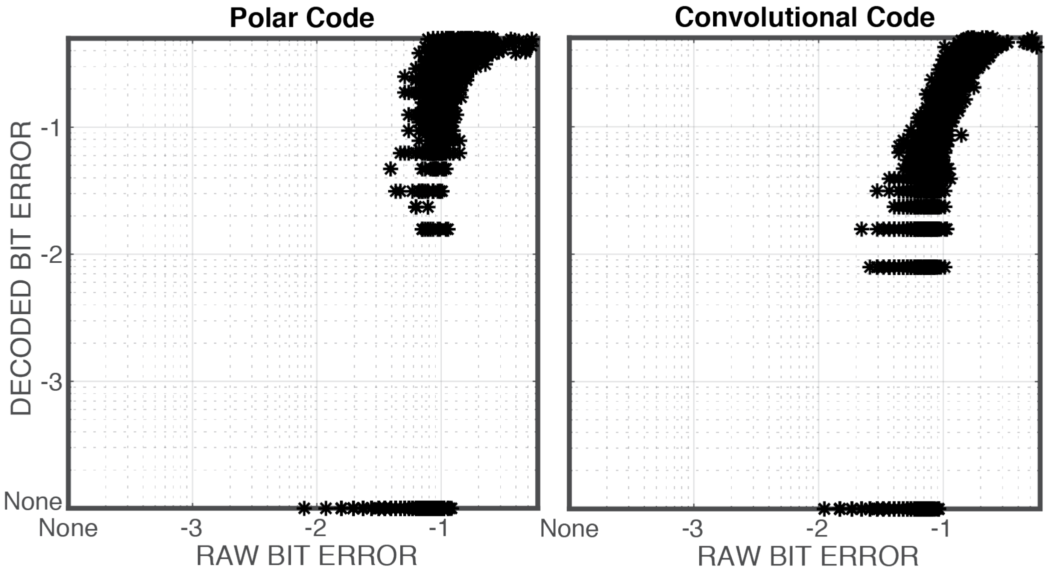

Fig. 3—Probability of the raw bit error versus the probability of decoded bit error for polar (left) and convolutional (right) encoding. The *y*-axis terminates at 10^{-4} BE and thus includes perfect transmissions. Of the 1000's of transmissions, Polar coding was twice as likely to produce 0 error and only needed an input of about 1/10 errors to consistently produce perfect decoding.

During the communication portion of ST3, over 3000 FSK transmissions were received. Instead of just comparing output BE vs versus input signal to noise ratios, it is also useful to analyze output BE for a given input BE. The probability of decoded BE for polar (left) and convolutional (right) encoding is shown in Fig. 3 for given raw probability of BE. Polar encoding was 2.03 times as likely to produce 0 BE as was convolutional encoding. Polar only needed an input BE of about 1/10 to consistently produce errorless decoding.

5. SUMMARY

Rate-1/2 polar and convolutional error correction encoding were compared and polar was shown to have lower probability of bit error. These methods were demonstrated on measured at-sea acoustic transmissions via noncoherent frequency shift keying demodulation. In addition to having a higher coding gain, it also had less overhead – another critical concern for very short transmission frames. Both of the encoding methods utilized were both designed within the presumption of an additive white Gaussian noise channel. While both still performed favorably in the presence of multipath, Doppler, and reverberation, the polar coding gain was more impacted.

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