Chirp-Based LPD/LPI Underwater Acoustic Communications with Code-Time-Frequency Multidimensional Spreading

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ABSTRACT

Most underwater acoustic communication systems incorporate well-recognized, easily detectable narrowband signals modulated over low-frequency carriers at high transmission powers, which ultimately limits LPD/LPI performance of the communication scheme. While there have been promising works concentrating on LPD/LPI performance, they are for the most part based on direct-sequence spread spectrum (DSSS) techniques, which have been shown to be blindly detectable in previous work at relatively low SINR values. As a result, there is likely significant room to improve the LPD/LPI performance of underwater acoustic communication schemes. To this end, in this paper, we propose the preliminary design of a novel communication scheme based on transmitting chirp signals that are further spread over a multidimensional domain spanning code, time, and frequency. We evaluated the performance of the proposed scheme both with simulation and experimental studies.

Keywords

Low Probability of Detection, Low Probability of Interception, Robust

1. INTRODUCTION

As of today, mainstream approaches designed to achieve efficient underwater communications at the physical (PHY) layer of the communication protocol stack have mostly been focused on designing spectrally efficient yet robust modulation schemes and receivers to operate on the limited bandwidth available in the underwater acoustic channel [1, 2]. Yet, existing technology in this domain is for the most part based on transmitting well-recognized, easily detectable narrowband signals modulated over low-frequency carriers at high transmission powers, which ultimately limits the stealthiness of the communication scheme with LPD/LPI (Low Probability of Detection/Low Probability of Interception) performance. A limited number of works have focused specifically on stealthy communication techniques. This body of work largely follows the successful and well-understood approach of adopting direct-sequence spread spectrum (DSSS) techniques with either coherent or non-coherent modulations [3–5]. The main motive behind this approach is to take advantage of the processing gain that comes from spread-spectrum encoding, which enables to carry out communications at relatively low signal levels and achieve high LPD/LPI performance. [6,7] focus on the same goal with an alternative approach that exploits frequency diversity instead of coding to achieve processing gain. While these works achieved promising results, there is clearly significant room to improve the LPD/LPI performance of the underwater communication schemes.

To address this need, in this paper, we propose a novel acoustic transmission scheme for stealthy underwater communications based on transmitting chirp signals that are further spread over a multidimensional domain spanning code, time, and frequency. The proposed scheme uses chirp-based acoustic pulses with ultrasonic spectral content following an frequency- and time-hopping pattern together with a superimposed spreading code. Therefore, it enables higher LPD/LPI performance compared to schemes that consider only a single dimension, i.e., code or frequency and provides a hopping-coding pattern that is not easily recognizable or detectable. Moreover, chirp signals are ubiquitous in the underwater environment (e.g., dolphin clicks [8, 9]); therefore, it is not easy for an adversary to detect the transmissions and associate them with a communication system.

We conducted a performance evaluation study for the proposed transmission scheme on a multi-scale simulator that evaluates underwater chirp-based communications at two different levels, i.e., (i) at the wave level by modeling acoustic propagation in selected reference scenarios, (ii) at the bit level by simulating in detail the proposed chirp-based transmission schemes. In addition, we performed an experiment evaluation of the proposed scheme by implementing the proposed scheme on our custom software-defined acoustic platform [10–12] and conducted field experiments in a

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harbor in Los Angeles, CA.

The remainder of this article is organized as follows. We first describe the proposed LPD/LPI transmission scheme in Section 2. Then, in Section 3 we provide both simulation and experimental performance evaluation Finally, we draw conclusions in Section 4.

2. CHIRP-BASED LPD/LPI SCHEME

Based on the considerations and needs, we design and propose a novel, robust LPD/LPI transmission scheme that uses chirp-based acoustic pulses with ultrasonic spectral content following a frequency- and time-hopping pattern together with a superimposed spreading code. The scheme is designed to enable higher LPD/LPI performance compared to state-of-the-art schemes that consider only a single dimension (i.e., code, time, or frequency) and provides a hopping-coding pattern that (i) is not easily recognizable or detectable by an adversary; (ii) can be robustly detected in adverse channels by a friendly receiver that is aware of the frequency-time hopping pattern, as well as of the spreading code used.

Basics. The proposed scheme is designed based on the principle of transmitting a chirp signal with a frequency- and time-hopping pattern following pseudo-random sequences, and with a superimposed spreading code. Chirp-based transmission, frequency- and time-hopping patterns, and spread-spectrum encoding enables a communication scheme with high LPI/LPD performance, receiver performance that is robust and resilient against severe channel effects (i.e., multipath, scattering, and Doppler), and hardly identifiable characteristics that are not easily associated with a specific system employing them.

Why Chirp Transmissions? Chirp modulation or linear frequency modulation (LFM) was first used in [13]. Since then, chirp signals have been used as a communication technology that can enable low data rate, robust, low-power (LPD/LPI) wireless communications on simple-design, low-cost transceivers in different applications including indoor wireless communications [14], multiuser applications [15,16], and WLAN [17] and WPAN [18] applications. Chirp signals also have been proposed in the UWA communications literature as highly reliable but low data rate alternatives [10,19,20].

The characteristics of chirp transmissions appear to ideally address the requirements of an LPI/LPD scheme. First, their *high processing gain (time-bandwidth product) and resilience against severe channel effects, i.e., multipath, scattering, Doppler effect,* enables high LPD/LPI performance since robust reception performance under low signal-to-noise (SNR) conditions reduces the need for high transmission power [21]. Second, the *wideband nature* of chirp signals results in high LPD/LPI performance since the low power spectral density reduces the probability of detection and intercepts. Third, chirp signals are *ubiquitous in the underwater environment* (e.g., dolphin clicks [8,9]). Therefore, they cannot be easily associated with a specific communication system. Finally, chirps can be easily generated with mostly digital processing, and data rate can be flexibly traded for power spectral density and range.

Basic Signaling. Consider a combined frequency- and time- hopping strategy, as in Fig. 1, which defines a frequency spectrum B_t divided in N_f sub-bands of bandwidth B_s and a slotted time divided in chips of duration T_c, with

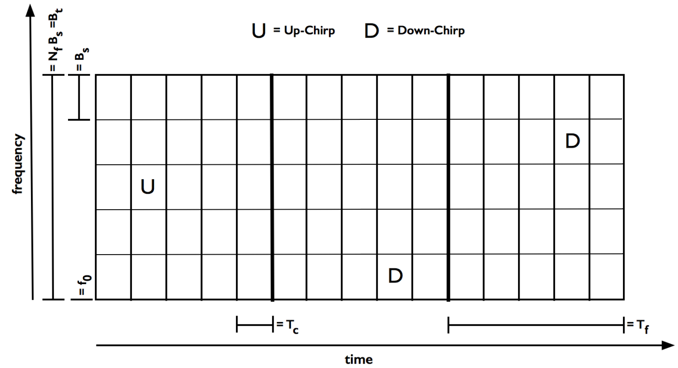

Figure 1: Example of an ongoing transmission using frequency-hopping frame length, time-hopping frame length, and spreading code length equal to 5, 5, 3, respectively. Frequency-hopping sequence $FH = \{2, 0, 3\}$, time-hopping sequence $TH = \{1, 3, 3\}$, and spreading code sequence $SC = \{1, -1, -1\}$. Sending information bit 1.

chips organized in frames of duration $T_f = N_h \cdot T_c$ where N_h is the number of chips per frame.

The system transmits one chirp signal in one chip per frame on one sub-band, and determines in which chip and sub-band to transmit based on a *time hopping sequence* (THS) and a *frequency hopping sequence* (FHS), respectively. Both time and frequency hopping sequences are based on pseudo-random sequences generated by seeding random number generators. Moreover, we introduce a channel coding scheme to improve the receiver performance against channel non-idealities. Various channel coding solutions have been presented in [22–25] with different performance levels and computational complexity. In the proposed scheme, we represent each information bit with *pseudo-orthogonal spreading codes* because of (i) limited computational complexity and (ii) inherent resilience to multipath [26–28].

A chirp signal is characterized by a time-varying instantaneous frequency, which changes in time from an initial value f_0 to a final value f_1. In the time domain, the signal can be expressed as

$$c(t) = \begin{cases} A\cos(2\pi f_0 t + \pi\mu t^2) & 0 \leq t \leq T, \\ 0 & \text{otherwise,} \end{cases} \tag{1}$$

where A is the amplitude of the chirp, f_0 is the initial chirp frequency, $\mu = \frac{f_1 - f_0}{T}$ is the chirp frequency-variation rate, while T represents the chirp period. We refer to a chirp with parameter $\mu > 0$ as an up-chirp; otherwise, we call it a down-chirp. Up and down chirp signals are almost orthogonal to each other. The total bandwidth of the chirp signal can be obtained as $B = f_1 - f_0$.

The train of chirps may be modulated based on binary orthogonal keying (BOK) by leveraging the quasi-orthogonality of up and down-chirps by encoding a '1' information symbol with an up-chirp and a '-1' information symbol with a down-chirp. The signal $s(t, i)$ generated by the system to convey the i^{th} symbol can be expressed based on (1) as

$$\hat{t} = (t - c_i T_c - iT_f), \tag{2}$$

$$s(t,i) = \begin{cases} \cos(2\pi f_{k_i}\hat{t} + (1-d_i)\pi B_s\hat{t} + d_i\pi\mu\hat{t}^2) & 0 \le \hat{t} \le T_c, \\ 0 & \text{otherwise}, \end{cases} \quad (3)$$

where $\mu = \frac{B_s}{T_c}$, $\{c_i\}$ is the time hopping sequence, with $0 \le c_i \le N_h - 1$, $\{k_i\}$ is the frequency hopping sequence, with $0 \le k_i \le N_f - 1$, $\{d_i\}$ is the information-bearing sequence, $d_i \in \{-1, 1\}$, and the amplitude of the the chirp is assumed to be '1' without loss of generality. The resulting data rate, in chirps per second, is expressed as:

$$R(N_h) = \frac{1}{T_f} = \frac{1}{N_h T_c}. \quad (4)$$

By regulating the FH frame length N_f and TH frame length N_h, i.e., the average inter-chirp time, a user can adapt its transmission rate, processing gain, and as a consequence modify the average radiated power and therefore the communication range of the system.

At the receiver, frame synchronization and "time hopping" synchronization must be performed to properly decode the received signal. Frame synchronization consists of finding the correct time alignment between the transmitter frame and the receiver frame. This is achieved through an energy-collection approach. During the frame synchronization, the transmitter sends an a-priori-known sequence, i.e., a preamble. Specifically, we use a doppler-sensitive sequence, i.e., m-sequence, to leverage Doppler scale estimation as well. After correlating the received signal and the preambles pre-scaled by different Doppler scaling factors, the receiver identifies both the starting point of the frame as the time instant and the estimated Doppler scale based on the largest correlation peak. The next step consists of finding the frequency- and time-hopping sequences to hop chip-by-chip and correlate the received chirps. This is achieved by seeding the random generator with the same seed used by the transmitter, and therefore generating the same pseudo-random frequency and time-hopping sequences.

Once both synchronization processes have been accomplished, the receiver decodes the received signal by "listening" in the time chips of interest and correlating the received chirp according to the modulation scheme in use.

Coding and Modulation. A channel code can reduce the effect of channel non-idealities and accordingly increase the receiver performance. Various channel coding solutions have been proposed [22–25] with different performance levels and computational complexity. We rely on *pseudo-orthogonal spreading codes* because of their limited computational complexity and inherent resilience to multipath. Each symbol (i.e., bit) is spread by multiplying it by a binary code before transmission. At the receiver side, with prior knowledge of the code used at the transmitter, the signal can be de-spread, and the original information recovered.

We adopt a modulation scheme that we refer to as BOK-spreading. In BOK-spreading, the information bit is spread using BOK-modulated chips, consequently the pseudo-orthogonal spreading code can be defined as a pseudorandom code of N_s chips with $a_j \in \{-, 1\}$. With frequency- and time-hopping, (2) and (3) can be rewritten as

$$\hat{t} = (t - c_j T_c - jT_f), \quad (5)$$

$$s(t,i) = \sum_{j=0}^{N_s-1} \cos(2\pi f_{k_j}\hat{t} + (1-(a_j d_i))\pi B_s\hat{t} + (a_j d_i)\pi\mu\hat{t}^2), \quad 0 \le \hat{t} \le T_c, \quad (6)$$

where chip information is carried in the quasi-orthogonality up- and down-chirps.

In Fig. 1, we show an example of a combined frequency- and time hopping and BOK-spreading strategy. Since the spreading operation associates N_s chips to one information bit, the information rate will now be $R(N_h, N_s) = \frac{1}{N_s T_f} = \frac{1}{N_s N_h T_c}$, while the energy per bit is increased by a factor N_s. Note that there is a tradeoff between robustness to noise and multipath (which increases with longer spreading codes), and energy consumption and information rate.

In BOK-spreading, the receiver can use the spreading code employed at the transmitter to obtain the correlator template. As a result, it is important to observe that *unlike BPSK-modulated chirp signals that need a coherent receiver with accurate channel knowledge for decoding, a simple non-coherent energy detector receiver is sufficient.* The latter requires frame synchronization only, and its implementation complexity is significantly lower.

Signal-to-Noise Ratio. Before processing, the Signal-to-noise ratio (SNR) at the receiver can be expressed as

$$\text{SNR}_{\text{int}} = \frac{P\ g}{\eta}, \quad (7)$$

where P is the average power per chirp signal emitted by the transmitter, g is the path gain between the transmitter and the receiver, and η is the noise energy.

Chirp signals offer a processing gain proportional to the time-bandwidth product (TB), which enables higher signal-to-noise ratio (SNR) at the receiver after processing. Unlike narrowband pulses, T and B of chirps signals can be increased independently to reach higher processing gain, and accordingly higher receiver SNR. The processing gain can be expressed as [21]

$$PG = \frac{TB}{0.886}. \quad (8)$$

In addition to the processing gain, the receiver has SNR gain that is introduced by the spreading code. As a result, we can express the SNR for chirp transmission at the receiver after processing, similar to impulsive transmissions [22, 29], as

$$\text{SNR}_{\text{rec}}(\mathbf{N_f}, \mathbf{N_h}, \mathbf{N_s}) = (\frac{T_c B_s N_s N_h N_f}{0.886})SNR_{int}. \quad (9)$$

Since we are only considering a single user scenario, interference can be neglected. From (9), it can be observed that increasing (or decreasing) the spreading code N_s, leads to an increase (decrease) in the receiver SNR.

3. PERFORMANCE EVALUATION

We evaluate the proposed transmission scheme both with simulation studies by using a multi-scale simulator that evaluates underwater chirp-based communications at two different levels, i.e., (i) at the wave level by modeling acoustic propagation in selected reference scenarios, (ii) at the

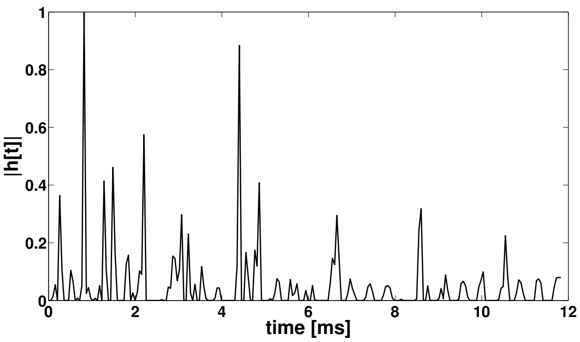

Figure 2: Transfer function of the channel.

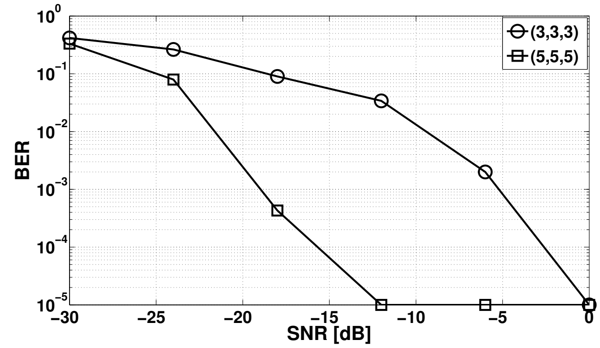

Figure 3: BER versus SNR for different sets of frequency-hopping frame length, time-hopping frame length, and spreading code length (N_f, N_h, N_s) (simulation results).

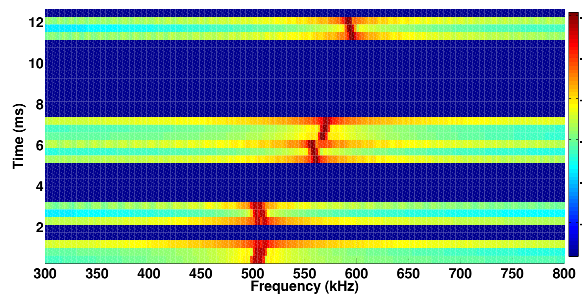

Figure 4: Spectrogram of an actual transmissions of $d_i = 1$ using frequency-hopping sequence $FH = \{11, 13, 18\}$ with $N_f = 30$, time hopping sequence $TH = \{2, 0, 2\}$ with $N_h = 3$, and BOK spreading codes $SC = \{-1, 1, -1\}$ with $N_s = 3$.

bit level by simulating in detail the proposed chirp-based transmission schemes and with experimental studies by implementing the proposed scheme on our custom software-defined acoustic platform [10–12] and conducting field experiments in the waters of an harbor in Los Angeles, CA.

3.1 Simulation Results

We conducted a set of simulation studies to evaluate the performance of the propose scheme. For this purpose, we defined chirp signals that with duration of $T_c = 1$ ms and bandwidth $B_s = 5$ kHz, where the smallest frequency component f_0 is selected as 100 kHz. In our simulations, we adopted the channel transfer function (illustrated in Fig. 2) that we had acquired in previous lake experiments [10]. As it can be observed, the channel shows severe multipath, which allows us to evaluate the proposed scheme under the most challenging conditions.

We evaluated the bit-error-rate (BER) performance of the proposed scheme for varying SNR values. Figure 6 presents BER versus SNR values for different sets of frequency-hopping frame length, time-hopping frame length, and spreading code length (N_f, N_h, N_s), specifically (3, 3, 3) and (5, 5, 5). As expected, we observe that the BER is a decreasing function of the SNR and that by using larger frequency and time -hopping frame and spreading code lengths the BER is further reduced. Moreover, most importantly, we also observe that, even at very small SNR values, the proposed scheme can still offer robust BER performance. This means that even if we use very small transmission power to significantly improve the LPD/LPI performance, we can still obtain a robust communication link.

3.2 Experimental Results

In this section, we present two different set of experiments to showcase the performance of the proposed scheme. The first set of experiments are from a water tank while the second set of experiments are conducted at sea.

3.2.1 Tank Tests

We conducted experiments in a water test tank of dimensions $2.5\,\text{m} \times 2\,\text{m} \times 1\,\text{m}$. We deployed two custom software-defined acoustic platforms [10–12] as it is illustrated in Fig. 5. In this set of experiments, our objective was to (i) showcase the performance of code, frequency, and time hopping; (ii) study tradeoffs between data rate and robustness. To that end, we selected 100 kHz as the smallest frequency component and used chirp signals that with duration of $T_c = 1$ ms and bandwidth $B_s = 5$ kHz.

First, we evaluated the BER performance for varying SNR values for the same set of frequency-hopping frame length, time-hopping frame length, and spreading code length that we have used in the simulation results and compared them with Binary Chirp Spread-Spectrum (B-CSS) communication scheme. As it can be observed from Fig. 6, the proposed hopping scheme outperforms the B-CSS in terms of BER performance. Moreover, similar to the simulation results, we observed that using larger frequency- and time-hopping frame and spreading code lengths improves the BER performance, while degrades the data rate performance. Specifically, while B-CSS can support a data rate of 910 bit/s, hopping scheme with the set (3,3,3) and (5,5,5) can support data rates of 110 bit/s and 40 bit/s, respectively.

Second, we evaluated the BER performance for a fixed set of hopping scheme (3,3,3) for different durations of chirp signals. We used chirp signals that with duration of $T_c = 1$ ms, $T_c = 1$ ms, and $T_c = 0.5$ ms, which supports data rates of 55 bit/s, 110 bit/s, and 220 bit/s, respectively. In Fig. 7, we observed that chirp signals with longer durations offer better BER performance at the expense of lower data rates. As a result, we can tradeoff BER performance for data rate based on the applicational requirements.

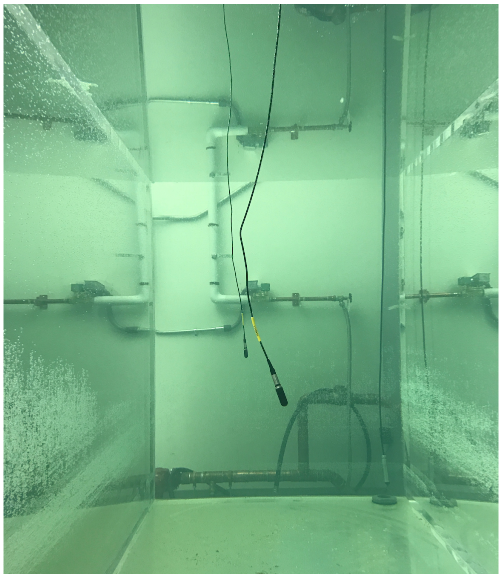

Figure 5: Deployment in the water test tank.

3.2.2 Sea Tests

We also conducted experiments in the Fish Harbor in Los Angeles, California. We deployed two custom software-defined acoustic platforms [10–12] approximately 10 m apart from each other at a depth of 4 m, with approximate total depth of 6.5 m. We used Teledyne RESON TC4038 transducers to operate over the frequency range of 500 to 800 kHz. Similar to our simulation studies, we used chirp signals with duration of $T_c = 1$ ms and bandwidth $B_s = 5$ kHz. We defined a packet length of 3, where each group of 3 frames is preceded by a preamble and each frame is spread with hopping and spreading set of (30, 3, 3). The selected set of hopping scheme offers a data rate of 110 bit/s.

Figure 4 shows the spectrogram of an actual LPI/LPD waveform output. The waveform is preceded by a preamble structured as two simultaneous up-chirps in the first two lowest frequency bins at the first time-hopping slot and two simultaneous down-chirps in the first two lowest frequency bins at the last time-hopping slot. The first part of the preamble is used specifically for packet detection, while the second part is used solely for frame synchronization. Moreover, the combination of these two parts are exploited for Doppler scale estimation. In the experiments, we had successfully transmitted over 100000 bits without having any errors with an average SNR of 19 dB.

4. CONCLUSIONS

We proposed a novel communication scheme enabling high LPD/LPI performance based on transmitting chirp signals that are further spread over a multidimensional domain spanning code, time, and frequency. First, we demonstrated the performance of the proposed scheme with simulation results, which showed that we can have a robust communication link even at very low SNR values. Moreover, we demonstrated the feasibility of the proposed scheme in a real underwater environment by implementing and experimenting with custom software-defined acoustic platforms. As future work, we are planning to fully explore the data-rate/robustness trade-

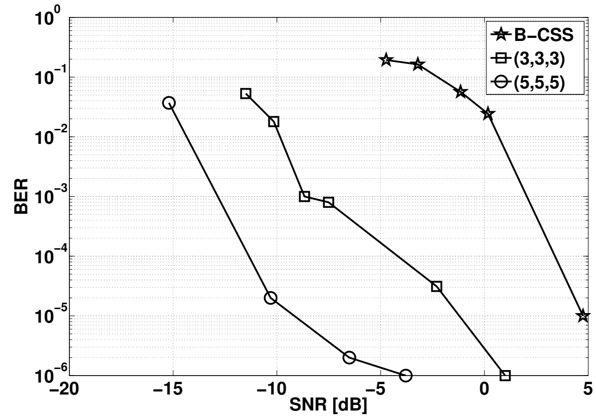

Figure 6: BER versus SNR for different sets of frequency-hopping frame length, time-hopping frame length, and spreading code length (N_f, N_h, N_s) (tank tests).

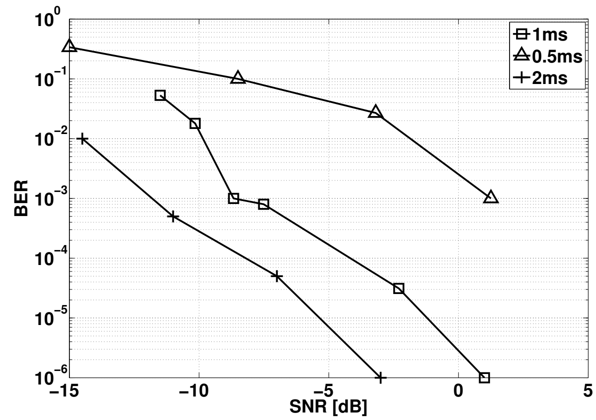

Figure 7: BER versus SNR for different durations of chirp signals (tank tests).

off, evaluate the performance of the system in the presence of narrowband jamming, and and implement a multiple access scheme and a medium access control protocol on top of the proposed scheme.

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