Performance Evaluation of Underwater Acoustic Communication using Trigonometric Chirp Modulation

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***Abstract*—In this paper, we propose an underwater acoustic communication based on trigonometric chirp modulated waveforms. We show that a usual system with linear chirp modulation requires wide bandwidth. Therefore, a Doppler resilient and robust underwater digital communication system based on a non-linear frequency modulation as trigonometric chirp technique has been presented.**
To evaluate the performance of trigonometric chirp modulation technique over AWGN channel, Rayleigh fading and Rician channels with and without Doppler effect, we have conducted some simulations. It is demonstrated that the performance of proposed method, even in lower spreading factors gives better performance than an LFM chirp modulated system in terms of bit error rate.

***Keywords*—Underwater Acoustic Communication, Linear frequency Modulation (LFM), Trigonometric Chirp, Doppler Shift, Rayleigh Fading, Rician Fading.**

I. Introduction

Over past decades, many underwater wireless communication technologies have been proposed and applied as ocean exploration, oceanography data collection, control over autonomous underwater vehicles, undersea navigation and etc.

When studying problems of sending data from transmitter to receiver, the distortion induced by the channel lead us to analyze for then being able to choose a right signal waveform. A reliable underwater acoustic communication is challenging because of some channel characteristics such as; small bandwidth, high power attenuation, fast time variation of the channel response, fading along of multipath propagation and Doppler effect due to relative speed between the receiver and the transmitter.

Actually in UWA communication, due to the low velocity of acoustic waves (roughly 1500 m/s) Doppler shift is larger than terrestrial radio frequency communication. But this is not the only impact of Doppler in acoustic waves. Unlike the case of radio transmission which Doppler shift is usually modeled as a frequency offset, the effect of Doppler shift on the symbol duration cannot be neglected. Significant Doppler shift results loss of information and frame desynchronization, as well. In addition to relative speed between the source and the receiver, different sampling frequencies also yield to signal compression-expansion. This means that for example, if our DAC is not accurate, we have to consider this problem in the system.

Recently, there have been considerable attempts to design robust receivers which prosperously equalize the channel and also increase transmission rate.

Chirp spread spectrum (CSS) techniques use chirp signals for data transmission. Chirp is a sinusoidal signal whose frequency decreases or increases over a specified time duration. Chirps as another spread spectrum signals are commonly used in radar applications and many years later in sonar due to its good temporal resolution of auto correlation function and also, considerable processing gain obtained from correlation measurement in the receiver [1]–[9]. In march 2007, IEEE introduced CSS physical layer in its new standard as 802.15.4 a, allowing CSS to be used in various application such as industrial control, sensor networking, real time location systems and medical devices [10].
Some characteristics of chirp modulations make it robust to multipath with low Doppler sensitivity. We know that linear frequency modulation (LFM) is the simplest chirp waveform. It has some advantages in comparison to non-linear chirps such as easy generation by different technologies, mostly simple to process by a matched filter or similar techniques. Accordingly, more applications for the CSS system based on linear chirps have been developed than that for non-linear types. But the main drawback is obtaining orthogonality between two LFM signals. A large time-bandwidth product, known as spreading factor, is needed. Either considerable symbol duration or wide bandwidth causes large spreading factor. The time-bandwidth product of a linear CSS should be more than 70 to achieve relatively acceptable orthogonality between its symbols for binary signaling. As we know, significant bit rate is more preferable [11]. Thus, by necessity a classical LFM signal will occupy undesirable large bandwidth especially at high speed data rate. So it is important to choose a pair of chirp signals

which will be sufficiently orthogonal in small spreading factors to sending information. Nevertheless, non-linear chirps have not attained high prevalent like linear type, so far. Probably it is because of limited availability of non-linear-FM generation and processing devices, more complexity of system, derivation of performance evaluation can be troublous, as well. By accepting these issues, desired performance can be achieved with considerable reduction in bandwidth. Better performances due to some intrinsic properties of non-linear chirps were motivation of our research.

In this paper, we use trigonometric chirp signals to modulate binary data. To obtain a better performance, it is preferable to consider two orthogonal chirp signals. At the receiver, we consider a matched filter to correlate the received signal with a known signal. We illustrate that a trigonometric chirp modulated system has better performance over AWGN and different fading channels in contrast with a system based on LFM chirp.

The remainder of this paper is organized as follows. In section II, the orthogonality of LFM and trigonometric chirp as a type of non-linear frequency modulation have been investigated. In section III, performances over additive white gaussian noise (AWGN) and two fundamental fading channels for underwater acoustic systems as Rayleigh and Rician have been evaluated. In section IV, a real analytical measurement is given which predicts our simulated results. Finally, section V concludes this paper.

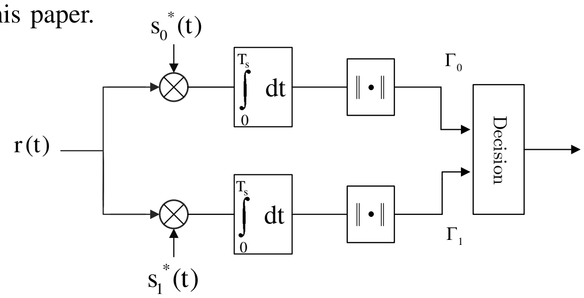


Fig. 1: Block Diagram of Optimum Non-Coherent Detector.

II. SYSTEM MODEL

In this section, signal waveforms have been expressed mathematically. The orthogonality and Doppler effect on the signals will be discussed, too.

A. LFM

As we know, the chirp signals can be classified into two types; "linear chirp", in which the instantaneous frequency decreases or increases with time in a linear form and "non-linear chirp", in which the instantaneous frequency is a non linear function of time. LFM probably is the most popular frequency modulation due to its low complexity. It is widely used before in radar and sonar applications. Here, it is applied to perform an underwater digital communication. Linear Up and Down chirp can be expressed as

$$\begin{cases} Down: & s_0(t) = \cos\left[2\pi(f_c t - \frac{B}{2T_s}t^2)\right] \quad 0 \le t \le T_s \\ Up: & s_1(t) = \cos\left[2\pi(f_c t + \frac{B}{2T_s}t^2)\right] \quad 0 \le t \le T_s \end{cases} \tag{1}$$

f_c is the carrier frequency. Both signals have a common bandwidth B, and T_s is the chirp duration in second. We will send s_0 as a bit 0 and s_1 as a bit 1. At the receiver as shown on Fig.1, where an AWGN channel considered with $n \sim N(0, \frac{N_0}{2})$, two decision variables are produced:

$$\Gamma_i = \|\langle r, s_i \rangle\|, \qquad i = 0, 1 \tag{2}$$

Where $\|\langle *, * \rangle\|$ is the absolute value of the inner product between observation r and transmitted signal s_i. So, we can consider the hypothesis test as follows

$$\begin{cases} H_0: & r = s_0 + n \\ H_1: & r = s_1 + n \end{cases} \tag{3}$$

According to the non-coherent maximum a posteriori (MAP) detector, the decision rule will be

$$\|\langle r, s_0 \rangle\| - \|\langle r, s_1 \rangle\| \gtrless_{H_1}^{H_0} \quad 0 \tag{4}$$

Choosing H_1 when H_0 occurs and also vice versa, means an error happens. By totally analyzing expression (4), we know that inner product of LFM signals is not equal to zero and performance degradation can be occurred due to this non orthogonality. So, we look for orthogonal signals [11].

Subsequently, the orthogonality between symbols can be considered through evaluation of cross correlation coefficient. Let E_b be the bit energy and defined as

$$E_b = \int_0^{T_s} s_i^2(t)dt, \qquad i = 0, 1 \tag{5}$$

To evaluate the performance of chirp signaling techniques, the cross correlation coefficient is one of the important factors. If we define ρ as the cross correlation coefficient between down-chirp and up-chirp signals, we have:

$$\rho = \frac{1}{E_b}\int_0^{T_s} s_0(t)s_1(t)dt \tag{6}$$

By considering the signals in base band, ρ will be

$$\rho = \frac{2}{T_s}\int_0^{\frac{T_s}{2}} (e^{\mp j\pi\frac{B}{2T}t^2})^* e^{\pm j\pi\frac{B}{2T}t^2} dt \tag{7}$$

Using some straightforward manipulations, it can simplified as

$$|\rho| = \frac{1}{\sqrt{BT_s}}\sqrt{(\int_0^{\sqrt{BT_s}} \sin\frac{\pi x^2}{2}dx)^2 + (\int_0^{\sqrt{BT_s}} \cos\frac{\pi x^2}{2}dx)^2} \tag{8}$$

The above equation is composed of two famous integration as Fresnel integrals. From (8), we can see ρ depends on spreading factor *BT*. As shown in Fig.2, the cross correlation coefficient decreases rapidly from 0 to 20 *(secHz)*. For $\rho \le 0.1$, we should choose *BT* more than 70 *(secHz)*. This is why LFM system requires a wide bandwidth for high data rate communication.

In case of Doppler effect, since the source and the receiver move with relative speed ν, the signal waveform suffers a

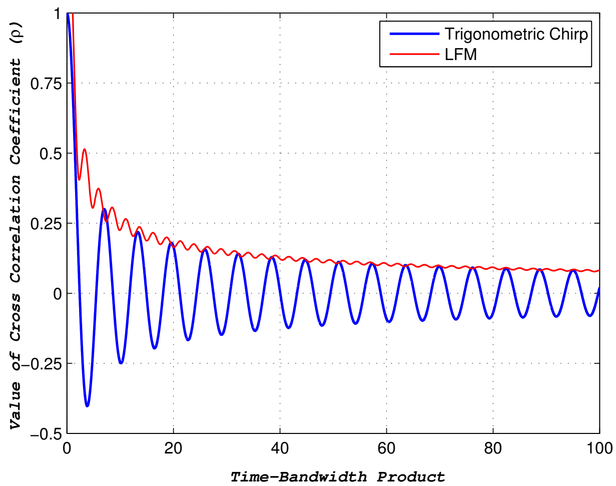


Fig. 2: Correlation Coefficient for LFM and Trigonometric Chirp.

compression-expansion. This phenomena can be modeled as

$$s_d(t) = s_i\left(t(1-\frac{\nu}{c})\right) \qquad i = 0,1 \tag{9}$$

Where c is the velocity of acoustic waves in water environment, s_i is transmitted signal, s_d is transmitted signal which is impressed only by Doppler effect. Also, we know that Doppler frequency shift is $\Delta f_d = \frac{\nu}{c} f_c$.

B. Trigonometric Chirp

Generally, a pair of chirps can be written as following

$$\begin{aligned} f_0(t) &= \cos\left[2\pi(f_c t - B\theta(t))\right] \qquad 0 \le t \le T_s \\ f_1(t) &= \cos\left[2\pi(f_c t + B\theta(t))\right] \qquad 0 \le t \le T_s \end{aligned} \tag{10}$$

The instantaneous frequency of a chirp as "chirp rate μ" which is defined by $\mu(t) = \frac{d\theta(t)}{dt}$, denotes the type of chirp signal. Now, it is necessary to express that the trigonometric chirp signal has different types based on its frequency spectrums. Here, we use full period trigonometric chirps whose frequency spectrum is a full period cosine or sine curve, just because of better performance in comparison to other types. Then, full period trigonometric chirp can be presented as

$$\begin{aligned} s_0(t) &= \cos\left[2\pi\left(f_c t - \frac{BT_s}{4\pi} sin(2\pi\frac{t}{T_s})\right)\right] \qquad 0 \le t \le T_s \\ s_1(t) &= \cos\left[2\pi\left(f_c t + \frac{BT_s}{4\pi} sin(2\pi\frac{t}{T_s})\right)\right] \qquad 0 \le t \le T_s \end{aligned} \tag{11}$$

The cross correlation between two full period trigonometric chirps can be evaluated numerically [12]. The result is shown in Fig.2. Under the same condition of time-bandwidth, the system based on the full period trigonometric chirp requires much narrow bandwidth in comparison with an LFM chirp modulated system for a predefined data rate.

III. Simulation Results

Although trigonometric chirp signals have better orthogonality in comparison to LFM, but the performance of trigonometric chirps in underwater environment have to be investigated over different channels. we will not go into detail of theoretical *BER*. Here, for showing that the non-coherent detector of trigonometric chirp systems have better performance, it is adequate to illustrate the experimental results and also, the quiet performances have been carried out by simulation for LFM and trigonometric chirp signal comparatively.

In the simulations, we have considered the underwater communication system impaired by additive white Gaussian noise, Doppler effect and multipath fading. Some fading environments such as Rayleigh and Rician, that represent most practical aspects of underwater acoustic channels are considered.

A. AWGN Channel

The performance as *BER* vs. E_b/N_0 in noisy channel for the linear and full period trigonometric chirp with different bandwidth is shown in Fig.3

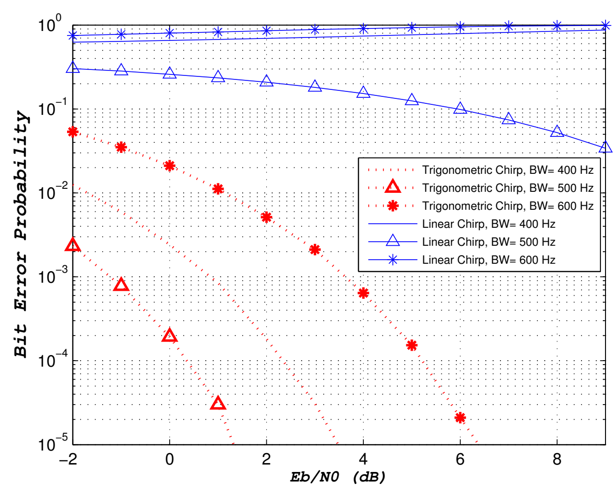


Fig. 3: Linear and Trigonometric chirp BER over AWGN Channel, T = 20 ms.

We observe lower *BER* for trigonometric chirp than LFM with different bandwidth. Also, as shown in Fig.3, we should pay attention that increasing bandwidth does not mean better performance, necessarily. In the following Fig.4, the simulated results of the detector over a noisy channel with and doppler effect is shown. As we know, Doppler shift is impacted by several parameters such as carrier frequency f_c, sound velocity in water c and relative speed between the source and the receiver ν.
In the simulations, a carrier frequency of $f_c = 8$ *kHz* and different relative speeds were used.

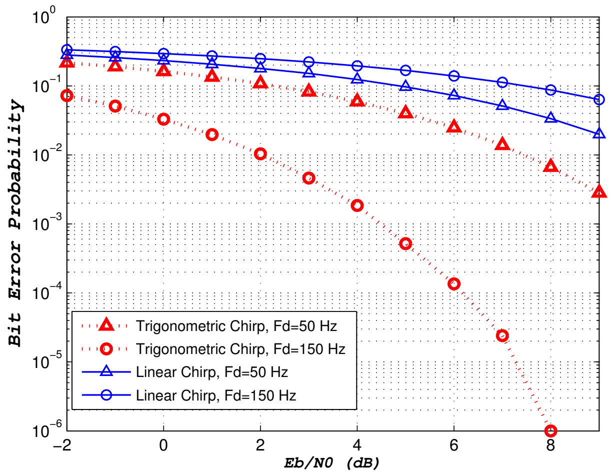


Fig. 4: Linear and Trigonometric chirp Bit Error Rate over Noisy and Doppler Channel, BT = 4 and $f_c = 8kHz$.

Also, Fig.5 shows that how the performances of both linear and trigonometric chirp are affected by different Doppler shifts in a fixed *SNR* and *BT*. We can see that the full period trigonometric chirp in low Doppler frequencies has better performance due to its mathematical nature.

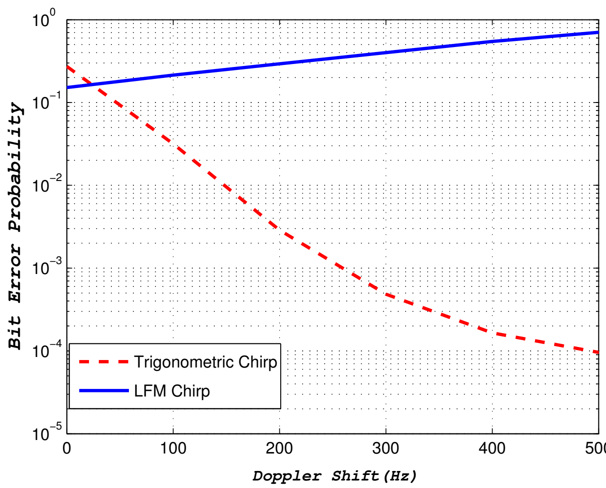


Fig. 5: Linear and Trigonometric chirp Bit Error Rate vs. Doppler Shift, BT = 4, SNR = 2 dB and $f_c = 8kHz$.

B. Rayleigh and Rician Fading Channels

In this section, the performance of a CSS system using linear and trigonometric chirp signals over two fundamental channels i.e. Rayleigh fading channel with Doppler shift and Rician fading channel, will be illustrated in Fig.6 and Fig.7.

In Rician fading channel with a basic point of view, we can consider the K factor as

$$K = \frac{Power \quad of \quad LOS \quad path}{Power \quad of \quad Non \quad LOS \quad paths} \tag{12}$$

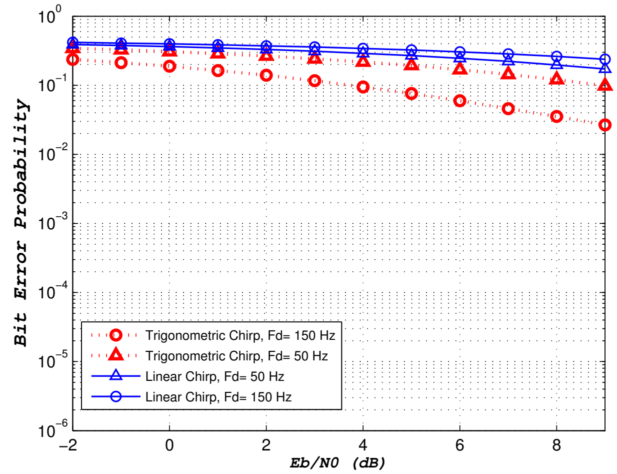


Fig. 6: Linear and Trigonometric chirp Bit Error Rate over Rayleigh fading Channel, BT = 4 and $f_c = 8kHz$.

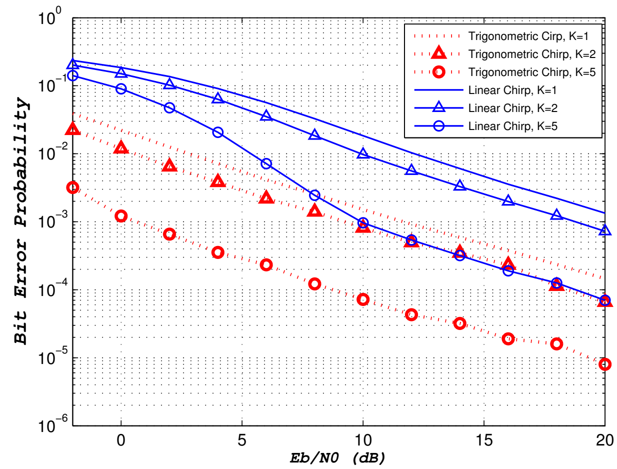


Fig. 7: Linear and Trigonometric chirp Bit Error Rate over Rician Channel, BT = 4.

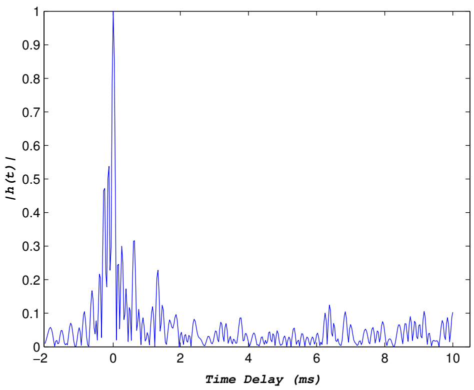
As shown in Fig. 6 and Fig. 7, the full period trigonometric chirp modulated system has better performance in comparison with the system based on an LFM chirp modulated over fading channels.

IV. Experimental Results

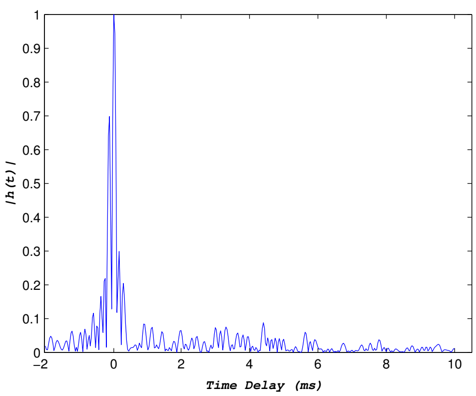
The set of our underwater experiments were conducted in a water tank with $3m \times 1m \times 0.6m$ dimensions in the Sonar laboratory at Shiraz University, using one *SX147* spherical transducer and one *B&K* hydrophone type *8105*. Different time duration T = 10 and 20 *msec* were used for transmission. We sent about 3500 bits of information with spreading factor BT = 4, sampling frequency f_s = 32 *kHz* and carrier frequency f_c = 8 *kHz* for linear and trigonometric chirp signals. Each frame contained 100 bits/frame, a 10 *msec* LFM signal as probe signal for synchronization at the beginning of frame and a 50 *msec* silence as Guard before the data and one another Guard after that were structured as the data packet.

TABLE I: Real UWA trials for LFM and Trigonometric when BT = 4

LFM		**Trigonometric**	
T (ms)	*BER*	*T (ms)*	*BER*
10	0.0063	**10**	0
20	0.0055	**20**	0



(a) $|h(t)|$, BT = 4 and T = 20 ms



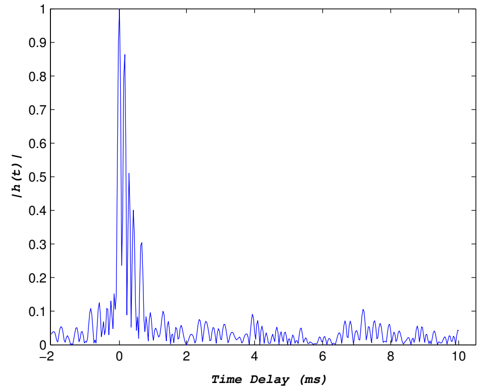
(b) $|h(t)|$, BT = 4 and T = 10 ms

Fig. 8: Channel Impulse Response of Water Tank

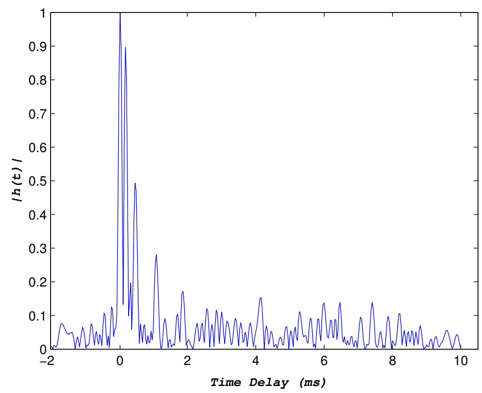
We can observe that even at a low spreading factor, when *SNR* is sufficient (for first trial is between 18 - 23 *dB* and on the average 20.88 *dB*) trigonometric chirp signal has approximately ideal performance. Also, when a relative speed about 2 m/s is conducted to the system, the Doppler shift is $\Delta f_d = \frac{\nu}{c} f_c \cong 10.67$ *Hz* and *SNR* is between 6 - 19 *dB* and on the average 11.92 *dB*, the results is as follows

TABLE II: Real UWA trials for LFM and Trigonometric when BT = 4, $f_c = 8kHz$ and $\nu = 2m/s$

LFM		**Trigonometric**	
T (ms)	*BER*	*T (ms)*	*BER*
10	0.2772	**10**	0.147
20	0.1941	**20**	0.0813



(a) $|h(t)|$, BT = 4 and T = 20 ms



(b) $|h(t)|$, BT = 4 and T = 10 ms

Fig. 9: Channel Impulse Response of Water Tank in presence of Doppler effect

V. CONCLUSION

In this paper, by using simulations, theoretical analysis and real experiments, it has been illustrated that excluding the Doppler effect, the performance of the CSS system based on trigonometric chirp outperforms that of Linear chirp based system in AWGN and other fading channels, especially when the spreading factor is small enough. Generally, *BER* of CSS systems using both LFM and trigonometric chirp increases when Doppler shift increases as well. But, for the trigonometric chirp it decreases in some practical lower Doppler frequencies and it is one of important results of this signaling. So, it is concluded that under limited bandwidth condition, the full period trigonometric chirps can be replaced to the linear chirps for better system performance.

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