Performance Analysis of Underwater Acoustic Communication System

Karan Kumar Singh and P.R Sahu
Department of Electronics and communication Engineering
IIT Bhubaneswar
Email: 21ec01029@iitbbs.ac.in and prs@iitbbs.ac.in

***Abstract*—Underwater sensor nodes are vital for a variety of applications, including oceanographic data collection, pollution monitoring, offshore exploration, disaster prevention, assisted navigation, and tactical surveillance. They are integral to unmanned or autonomous underwater vehicles (UUVs, AUVs) equipped with sensors, which facilitate the exploration of underwater resources. Underwater acoustic networking serves as the foundational technology for these applications, enabling collaborative monitoring tasks across diverse environments. In the realm of non-linear acoustics, the parametric effect presents numerous acoustic applications currently utilized in different sectors. In underwater acoustics, these technologies significantly benefit environmental monitoring and security by facilitating controlled and efficient information transmission. A critical consideration in these technologies is the selection of the most suitable modulation technique to meet communication requirements and less error. Amplitude sine sweep modulation, examining their non-linear propagation characteristics. where non-linear demodulation plays a crucial role in determining the Bit Error Rate (BER) relative to Signal-to-Noise Ratio (SNR).**

This letter investigates the bit error rate for AM sine sweep modulation with attenuated signals and noise signals for a suitable matched filter. Furthermore, the paper addresses the main challenges in developing efficient matched filters and dealing with channel time variability.

- **Keyword** : Underwater acoustic network,parametric effect,non-linear acoustics.

I. Introduction

Underwater sensor networks enable applications such as oceanographic data collection, pollution monitoring, offshore exploration, disaster prevention, assisted navigation, and tactical surveillance. These networks involve unmanned or autonomous underwater vehicles (UUVs, AUVs) equipped with sensors, which require underwater communication for coordination and data relay to onshore stations. Wireless underwater acoustic networking is the key technology, with UnderWater Acoustic Sensor Networks (UW-ASNs) consisting of sensors and vehicles that self-organize to adapt to ocean environments. [1]

Applications include:

- **Ocean sampling**: Networks of sensors and AUVs can perform adaptive sampling of the 3D coastal ocean environment. [2]
- **Environmental monitoring**: UW-ASNs can monitor pollution, ocean currents, weather, climate change, marine ecosystems, and track marine life.
- **Undersea explorations**: These networks can detect oilfields, lay undersea cables, and explore minerals. [3]
- **Disaster prevention**: Sensors can provide tsunami warnings and study submarine earthquakes. [4]
- **Assisted navigation**: Sensors identify seabed hazards, locate rocks, and perform bathymetry profiling.
- **Tactical surveillance**: AUVs and sensors monitor areas for reconnaissance and intrusion detection. [5]
- **Mine reconnaissance**: AUVs with sensors detect mine-like objects and perform environmental assessments.

Traditional underwater monitoring involves deploying sensors that record data to be recovered later, [6] which has limitations such as lack of real-time monitoring, no system reconfiguration, no failure detection, and limited storage capacity. Real-time monitoring via underwater networks with wireless acoustic links is necessary.

When an acoustic signal interacts in a non-linear medium, secondary frequencies are formed through the addition and subtraction of the original frequencies. This parametric effect, first studied by Westervelt, [7] occurs when a wave with a carrier frequency is modulated by a low frequency, resulting in new frequencies related to the modulating frequency. This effect increases directivity and allows low frequencies to propagate over greater distances but has poor conversion efficiency. Theoretical studies by Moffett and Mello [8], [9]aid in designing primary transient signals to generate parametric signals with specific characteristics. The pressure distribution of the secondary beam is proportional to the second derivative of the primary beam's [10] envelope squared, with parameters including the vibrating surface area, modulation envelope, distance, time, medium non-linearity, density, speed of sound, and absorption coefficient.

$$p_{\text{param}} = \left(1 + \frac{B}{2A}\right) \frac{p^2 S}{16\pi \rho c^4 a \chi} \frac{\delta^2}{\delta t^2} \left[E\left(t - \frac{x_0}{c}\right)\right]^2 \sim \frac{\delta^2}{\delta t^2} E^2$$

Challenges in underwater acoustic networks include limited bandwidth [11], impaired channels, high propagation delays, high error rates, power limitations, and sensor failures. Research is needed to develop efficient communication protocols

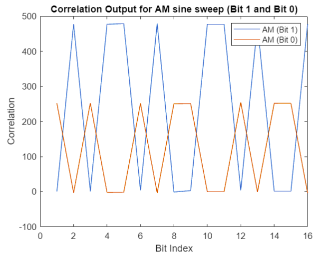

Fig. 1. correlation output of AM modulation

to address these challenges and enhance underwater monitoring and exploration.

II. AM MODULATION WITH PARAMETRIC SINE SWEEPS

[12]This technique involves varying the amplitude of a carrier signal according to the modulating signal (the information signal).

In digital case:

- An ascending sweep for bit 1.
- A descending sweep for bit 0.

A. Mathematical Representation

$$p_H(t) = \sin\left(2\pi\left[\frac{f_H - f'_H}{T}t + f_H t\right]\right) \tag{1}$$

- f_H: Initial frequency of the sweep.
- f'_H: Final frequency of the sweep.
- T: Total duration of the sine sweep.

B. Frequency Sweep

- Ascending Sweep for Bit 1: The frequency increases from f_H to f'_H over time (T).
- Descending Sweep for Bit 0: The frequency decreases from f'_H to f_H over time (T).

III. CHALLENGES IN UNDERWATER COMMUNICATION

Communicating through underwater channels presents unique challenges due to the properties of water and how it affects signal transmission :

A. Signal Attenuation

Water absorbs and scatters signals, especially at higher frequencies.It has express by Ainslie & Macc0lm Equation [13].

a) Ainslie & McColm Equation: The Ainslie & McColm equation proposed in 1998 is based upon the Fisher & Simmons model. However, it proposes some extra relaxation frequencies and simplifications to derive the following equation, hence increasing the applicability and probability of getting more accurate results:

$$\alpha = 0.106\frac{f_1 f^2}{f_1^2 + f^2}e^{\left(\frac{pH-8}{0.56}\right)} + 0.52\left[1 + \frac{T}{43}\left(\frac{S}{35}\right)\frac{f_2 f^2}{f_2^2 + f^2}e^{-\frac{D}{6}} + 4.9\times 10^{-4} f^2 e^{\frac{T}{27}}\right] \tag{2}$$

Here, f is frequency in kHz,
T is temperature in degrees Celsius,
D is depth in meters,
S is salinity in parts per thousand,
and f_1 and f_2 are frequencies caused by boric acid and magnesium sulphate in kHz.

$$f_1 = 0.78e^{\frac{T}{26}}\sqrt{\frac{S}{35}} \tag{3}$$

$$f_2 = 42e^{\frac{T}{17}} \tag{4}$$

This McColm model also takes into account the effects of the pH of sea water. The equations for f_1 and f_2 are also simplified and represented in kHz.

B. Limited Bandwidth

Underwater communication typically relies on acoustic waves, which have a much lower bandwidth compared to radio waves used in air, limiting data transfer rates.

C. Noise

Natural (e.g., marine life, waves) and man-made (e.g., ship engines, sonar) noises [14] can interfere with communication signals.

a) Turbulence Noise: Turbulence noise is caused by disturbances or irregularities in the flow of water around an obstruction Turbulence noise is denoted by $N_t(f)$ in dB re micro Pa per Hz by:

$$10\log N_t(f) = 17 - 30\log f \tag{5}$$

b) Shipping Noise: Shipping noise is the noise produced by ship traffic. It depends on the number of ships and their proximity to the area of interest. It is denoted as $N_s(f)$ in dB re micro Pa per Hz (with s as the shipping factor which lies between 0 and 1 for low and high activities respectively).

$$10\log N_s(f) = 40 + 20(s - 0.5) + 26\log f \tag{6}$$

c) Wave Noise: Wave noise is caused due to the movement of waves in the sea or ocean. It is denoted as $N_w(f)$ in dB re micro Pa per Hz (with w as the wind speed in m/s).

$$10\log N_w(f) = 50 + 7.5\sqrt{w} + 20\log(f) - 40\log(f + 0.4) \tag{7}$$

d) Thermal Noise: Thermal noise is denoted as $N_a(f)$ in dB re micro Pa per Hz, which can be taken as additive white Gaussian noise.

$$10\log N_a(f) = -15 + 20\log f \tag{8}$$

e) Total Noise: The overall noise power spectral density for a given frequency f can be computed by adding all types of noise as [15]:

$$N(f) = N_t(f) + N_s(f) + N_w(f) + N_a(f) \tag{9}$$

IV. Bit Error Rate

It is defined as the ratio of the number of bits received in error to the total number of bits sent during a specified time interval.

A. Mathematical Representation

$$\text{BER} = \frac{N_b}{N_t}$$

B. Derivation of Bit error rate for AM sine sweep modulation

Let for '0' bit

$$S_1(t) = \sin\left(2\pi\left(\frac{f_1 - f_2}{T}\right)t + 2\pi f_2 t\right)$$

Let for '1' bit

$$S_2(t) = \sin\left(2\pi\left(\frac{f_2 - f_1}{T}\right)t + 2\pi f_1 t\right)$$

where $f_2 > f_1$ Now, taking two basis functions

$$\phi_1(t) = \frac{S_1(t)}{\sqrt{E_1}}$$

$$\phi_2(t) = \frac{S_2(t)}{\sqrt{E_2}}$$

we can write the modulated signal in the term of basis function:

$$S_1(t) = S_{11}(t)\cdot\phi_1(t) + S_{12}(t)\cdot\phi_2(t)$$

$$S_2(t) = S_{21}(t)\cdot\phi_1(t) + S_{22}(t)\cdot\phi_2(t)$$

After passing through channel signal become

$$r(t) = \left(S_1(t)10^{-\alpha D/20}\right) + n(t)$$

$$r(t) = \left(S_2(t)10^{-\alpha D/20}\right) + n(t)$$

where $n(t) = N\left(0, \frac{N_0}{2}\right)$

On the receiver side, let's assume $S_1(t)$ was transmitted

$$y(t) = \int_0^T r(t)\phi(t)\,dt$$

$$y_1(t) = \int_0^T \left(S_{11}(t)\cdot\phi_1(t) + S_{12}(t)\cdot\phi_2(t)\right)10^{-\alpha D/20}\phi_1(t)\,dt + \int_0^T n(t)\phi_1(t)\,dt$$

So,

$$y_1(t) = kS_{11} + n_{11}$$

where $k = 10^{-\alpha D/20}$. Similarly,

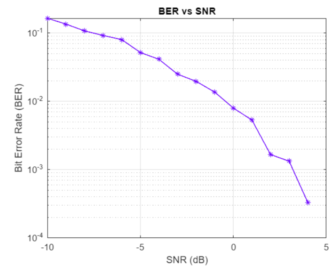

Fig. 2. Ber plot for AM sine sweep modulation

$$y_2(t) = kS_{12} + n_{12}$$

Now

$$y|_{s1}(t) = (y_1; y_2)$$

and $S_{12} = 0$, then

$$y|_{s1}(t) = \left(k\sqrt{E_b} + n_{11}(t); n_{12}\right)$$

The mean of $y_1(t)$ is

$$\mu[y_1] = k\sqrt{E_b}$$

The variance of $y_1(t)$ is

$$\text{var}[y_1] = \frac{N_0}{2}$$

Similarly, for $y_2(t)$, the mean is 0 and the variance is $\frac{N_0}{2}$. And the mean and variance of $y(t)$:

$$\text{mean} = -k\sqrt{E_b}$$

$$\text{variance} = \frac{N_0}{2} + \frac{N_0}{2} = N_0$$

$$f_y(y|s_1) = \frac{1}{\sqrt{2\pi N_0}}\exp\left(-\frac{(y + k\sqrt{E_b})^2}{2N_0}\right)$$

Probability of error when S_1 was transmitted [16, pp. 381]

$$P_e = \int_{k\sqrt{\frac{E_b}{N_0}}}^{\infty} \frac{1}{\sqrt{2\pi}}\exp\left(-\frac{(z)^2}{2}\right)dz$$

$$P_e = Q\left(k\sqrt{\frac{E_b}{N_0}}\right)$$

Signal power on the receiver side is $k^2\cdot E_b$
Noise power = N_0
Therefore,

$$BER = Q\left(\sqrt{\text{SNR}}\right)$$

BER is a critical parameter for determining the quality and reliability of a communication link. A lower BER indicates a higher quality of service. Engineers use BER to design and optimize communication systems, choosing appropriate error correction techniques and signal processing methods to minimize errors. Continuous monitoring of BER helps in maintaining and troubleshooting communication systems, ensuring that they operate within acceptable error rates. and To create an efficient matched filter for underwater communication, focus on adaptive filtering, diversity techniques, robust error correction, Doppler compensation, and energy-efficient design to maintain performance and reliability.

V. Conclusion

Underwater sensor networks are crucial for a variety of applications, including oceanographic data collection, pollution monitoring, and tactical surveillance. The effectiveness of underwater communication is significantly challenged by the unique properties of the underwater environment, such as signal attenuation, limited bandwidth, and noise interference from natural and man-made sources.

This paper investigates the bit error rate (BER) for amplitude modulation (AM) sine sweep modulation under different conditions, including attenuated and noisy signals. The results demonstrate that the AM sine sweep modulation technique is the best, as it allows both bits to be distinguished accurately, as shown in Figure 1. This finding underscores the importance of developing efficient matched filters that can adapt to channel time variability and improve communication reliability.

Techniques such as adaptive filtering, diversity methods, robust error correction, Doppler compensation, and energy-efficient design are critical for maintaining the performance and reliability of underwater communication systems. Overall, the study emphasizes the need for continued research and development in underwater acoustic networking to enhance monitoring and exploration capabilities, ensuring robust and efficient data transmission in underwater environments.

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