Design of a New Stress Wave Communication Method for Underwater Communication

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***Abstract*—Underwater communication is crucial for subsea engineering. Currently, although a variety of available technologies are available for underwater communication, almost all of them are highly dependent on the conditions of the subsea environment. Hence, underwater communication is still a challenging issue. This paper develops a new stress wave communication method that can be implemented along steel pipes for underwater data transmission. In this work, we analyze stress wave propagation along pipelines, and the corresponding channel response shows the features of dispersion and frequency selectivity. Thus, a suitable carrier frequency is then selected and binary shift keying (BPSK) is applied to encode information into the carrier stress wave. The proposed single-input-single-output (SISO) communication system was implemented on a steel pipe and experiments were conducted both when in air and seawater. Results demonstrate the validity and stability of the proposed method. The communication data rate of the method can reach 1000 bps with a low bit error rate (BER). The proposed method shows great promise for enabling underwater communication with lower loss and longer range than conventional underwater communication methods.**

***Index Terms*—Stress Wave Communication (SWC); Underwater Communication; Binary Phase Shift Keying Modulation (BPSK); Piezoelectric Transducers; Single Input-Single Output (SISO); Bit Error Rate (BER).**

I. INTRODUCTION

A. Background and Motivation

UNDERWATER communication plays a critical role in many subsea engineering applications and researches, such as offshore exploration, oceanographic data acquisition, pollution monitoring, climate monitoring, among others[1]. Currently, there are four major communication methods for underwater communication, including Radio Frequency (RF) communication, Free-space Optical (FSO) communication, Magnetic Induction (MI) communication and Acoustic Wave (AW) communication[1]. RF communications utilize electromagnetic waves as the carrier wave, and transmit data within the 3kHz to 300GHz bandwidth. In contrast to that EM waves possess the capability of penetrating through most objects and traveling long distances when in air, they are susceptible to electromagnetic interferences and rapidly attenuate in aquatic environments due to the high electrical conductivity and permittivity of water. Particularly, seawater will cause EM waves to attenuate exponentially with respect to increasing frequencies[2, 3]. Around twenty years ago, the extremely low frequency (ELF) communications system set up by the U. S. Navy, allowing the ELF waves to penetrate seawater at depths of less than 300 meters for data transmission with the submarines, was considered as the only successfully deployed underwater radio frequency technology[4].

FSO utilizes optical carrier waves to deliver packaged data in free space. FSO can reach up to 40 Gbps [5]. However, in marine environments, FSO communication is vulnerable to absorption, scattering and dispersion, and communication distance is highly dependent on the state (e.g. turbidity) of the subsea environment [6]. So far, in most proposed underwater optical communications, the scale of communication distance ranges from meters to tens of meters [7-9]. MI is an emerging communication method for underwater or underground wireless communications relying on time variant magnetic fields for data transmission. The propagation speed and data rate of MI can reach high values and can compensate for the presence of propagation delay. MI communication is much less susceptible to underwater environment than other technologies. However, recent mathematical modeling [10-12] of MI underwater communication in complex environments indicated the transmission range is still limited within 10 to 100 meters. AW is the most popular underwater communication technique based on acoustic waves transmission through both stationary and mobile nodes. In recent years, tremendous progress has been made on modulation schemes of underwater AWC [13-16]. Acoustic waves have demonstrated a longer traveling distance than both EM waves and FSO. However, the main disadvantages of AW underwater communications include multipath propagation, limited bandwidth, and low speed [17] due to time-varying and complex underwater environment. Recently, efforts have been made to mitigate multipath effect of underwater AW multiple-input-multiple-output (MIMO) communications [18-20].

Stress wave communication (SWC) method and variations of the method have recently been proposed [21-23], and compared to the existing underwater communication methods, stress wave communications can reach a longer range with a relatively fast transmission speed. Stress wave communications are mainly focused on two aspects: 1) through-metal-wall data transmission and 2) logging while drilling (LWD). The most common through-metal-wall data transmission system comprises of one external transducer and one internal transducer coupled together through the conducting medium[24,25]. Regarding stress wave communication in LWD, recent researches suggest that the estimated maximum achievable transmission speed reached 22 kbps using adaptive OFDM along the drilling string[26,27]. Recent implementation of stress wave communication on pipeline structures have opened the door for potential application in subsea communications. Jin et al. developed a time reversal based pulse position modulation (TR-PPM) stress wave communication method along a metal pipe[28-30]. Huang et al. applied an Electro Magnetic Acoustic Transducer (EMAT) and a piezoceramic sensor to develop a stress wave communication channel through a metal pipe and accomplished data transmission based on Amplitude Shift Keying (ASK) modulation[31]. Joseph et al. demonstrated stress wave communication across one water-filled pipe in the urban water distribution systems (WDSs) using amplitude modulation (AM) and achieved a data rate up to 100 bps[32].

Stress wave (SW) propagation along a pipeline structure is not heavily affected by the surrounding underwater environment. Moreover, SW travels at a relatively fast speed along metal medium with low cost. Thus, it is a potentially reliable method to be utilized for underwater communication, especially long-distance communication. However, until now, there is only few reported works related to underwater stress wave communication. In 2015, Chakraborty et al. developed a chirp -on-off keying (Chirp-OOK) based stress wave communication method to help with frequency selectivity of the channel along a 4.8-meter pipe and stated the achievement of underwater data transmission with a data rate of 100 bps[33]. Therefore, it is promising to explore methods of achieving underwater stress wave communications, which can be implemented on commonly found underwater pipelines in subsea oil and gas industry.

B. Research Problem and Contributions of this Study

A new stress wave communication method is proposed in this paper to address the reported drawbacks and unsolved essential issue in the existing communication methods for long distance underwater communication. The contributions of the new method are summarized in the following three aspects:

1) To characterize the channel features, we analyzed the stress wave propagation in multiple metal pipeline structures.

2) To identify a fitting carrier wave frequency located within the pass-band and select an appropriate data modulation scheme, we utilized the least square (LS) estimation method to determine the channel response of the metal pipe. According to the analysis results, BPSK is the best candidate for the data modulation scheme due to its simplicity, low BER and high performance.

3) To achieve the underwater communication, we implemented a single input-single output (SISO) communication system successfully. The experimental result shows that the communication data rate of our method can reach 1000 bps, and it has the low BER.

To the best knowledge of the authors, this paper is the first reported instance of stress wave communication method with BPSK modulation along the pipeline structure for the underwater communication. To demonstrate the feasibility and stability of the proposed stress wave communication method, an underwater communication experiment was implemented. The experimental results demonstrated the effectiveness of this new stress wave communication method for the underwater long distance communication.

The rest of this paper is organized as follows. In Section II, the design process of the new stress wave communication method is presented. Section III presents the experiment and result discussion to illustrate the effectiveness and applicability of the proposed communication method. The concluding remarks and future works are summarized in Section IV.

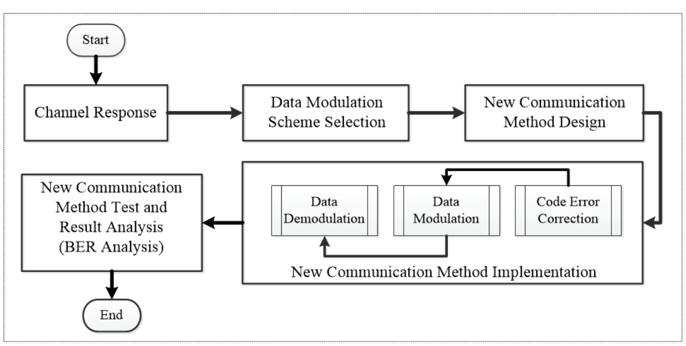

Fig. 1: Flow chart to explain the proposed method.

II. A New Stress Wave Communication Method with BPSK Modulation

The goal of this paper is to address unsolved essential issues for the underwater communication discussed in Section I. To develop the stress wave communication method, we begin from the fundamental analysis of the research problem. Through the development of the theory behind the mathematical model, the key components of the communication method can be determined; from there, the new communication method can be fleshed out in full detail.

A. Principle Statement

The detailed development of the proposed stress wave communication method is shown in Fig. 1. The development procedure can be summarized in three steps: 1) carrier wave frequency selection, 2) selection of data modulation scheme, and 3) BPSK based communication method setup . The detailed description of each step is presented as follows.

Firstly, stress wave propagation in metal pipeline structures is analyzed. Meanwhile, the channel response is evaluated for the design of the data modulation scheme.

TABLE I: Velocities of stress wave in different metal materials

Wave Mode	Steel	Copper	Iron	Aluminium
Longitudinal, C_L	5000 (m/s)	3650 (m/s)	3900 (m/s)	5000 (m/s)
Transversal, C_T	3200 (m/s)	2250 (m/s)	2450 (m/s)	3050 (m/s)

Secondly, according to the results of response analysis, the binary phase shift keying (BPSK) scheme has been selected for the data modulation in favor of its low bit error rate (BER) and simplicity among the different phase shift keying (PSK) schemes. Thus, BPSK can be easily integrated into the proposed communication method.

Finally, based on the BPSK modulation scheme, a new stress wave communication method has been designed and tested.

B. Theoretical Background for Proposed Method

According to the working process of the proposed method as shown in Fig. 1, the corresponding theoretical background mathematical models are presented as follows.

1) Evaluation of Stress Wave Propagation in Pipeline Structures: Stress wave propagation in pipelines can be categorized into three types of modes, namely the longitudinal mode (L), Transversal mode (T) (or shear wave) and flexural mode (F) (a type of surface wave) [34-36]. Among them, longitudinal mode and Transversal mode are symmetric, while flexural mode is anti-symmetric. In Table I, the velocities of stress wave in multiple metal materials are listed [37]. To select a suitable carrier wave channel, a mathematical model is needed [38]. As shown in Fig.2, a pipeline structure with cylindrical coordinate system, (r, θ, z), we assume Φ is a scalar function and A is a vector function, then any displacement field, u, can be expressed in the following manner

$$u = \bigtriangledown_{\Phi} + \bigtriangledown \times A. \tag{1}$$

For time-harmonic waves propagating in the axial (the z-axis) direction of the cylindrical wave guide, the displacement potentials can be obtained by the following equations.

$$\varphi = \phi(r) cos(m\theta + \theta_0) exp[i(k_z z - wt)], \tag{2}$$

$$\psi_r = \psi_r(r) sin(m\theta + \theta_0) exp[i(k_z z - wt)], \tag{3}$$

$$\psi_\theta = \psi_\theta(r) cos(m\theta + \theta_0) exp[i(k_z z - wt)], \tag{4}$$

$$\psi_z = \psi_z(r) sin(m\theta + \theta_0) exp[i(k_z z - wt)]. \tag{5}$$

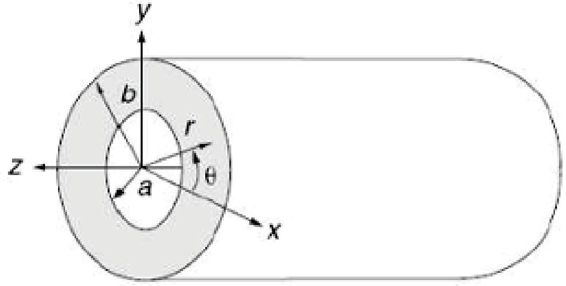

Fig. 2: A cylindrical waveguide with the cylindrical coordinate system.

where θ_0 is an arbitrary constant. As the functions should be periodic in the circumferential direction for stress wave propagating in the axial direction, $m = 0$ or $m \in \mathbb{Z}$.

The general solution to the waves propagating in the axial direction of this hollow cylinder is given by Eq.(2), Eq.(3), Eq.(4), and Eq.(5). The Bessel functions of second kind should be retained in this case, because the presence of both incoming (toward the center) and outgoing (away from the center) stress waves is necessary to satisfy the traction-free boundary conditions on both the inner and outer surfaces. For Torsion motion, $T(m, r)$, u_θ should be the only nonzero displacement component. Furthermore, it is independent of θ. These conditions are met by setting $A_n = B_n = m = 0$, $n \in \{1, 2\}$, and $\theta_0 = \frac{\pi}{2}$ in the integral solution. As Longitudinal, $L(m, r)$, stress waves refer to the axially symmetrical motion in the cylinder. The presence of displacement components characterize the longitudinal stress wave in the radial and axial directions, and none in the θ-direction. Vanishing of the determinant can yield the corresponding dispersion equations.

2) Channel Response: Channel response is important in communication for scheme design and data recovery. In our research, least square (LS) estimation method [39] is utilized. LS estimation uses the input and measured output data to build a model. The model coefficients are obtained by minimizing the errors between the measured output and predicted output.

Given the value of x, the best prediction of y (mean square error) is the mean $f(x)$ of y given y. thus,

$$y = f(x) + noise.$$

Here, the function $f(x)$ is called a regression function. It is to be estimated from sampling n covariables and their responses $(x_1, y_1), \cdots, (x_n, y_n)$.

Suppose $f(x)$ is known up to a finite number $p \leq n$ of parameters $\beta = (\beta_1, \cdots, \beta_p)'$, that is, $f(x) = f_\beta(x)$. We estimate β by the value $\widehat{\beta}$ that gives the best fit to the data. The least squares estimator, which is denoted by $\widehat{\beta}$, is that value of b that minimizes

$$\sum_{i=1}^{n} (y_i - f_b(x_i))^2, \tag{6}$$

over all possible b.

Then, the linear regression method is used to optimize the least squares estimator. We consider $f_\beta(x)$ is a linear function of β, then

$$f_\beta(x) = x_1\beta_1 + \cdots + x_p\beta_p, \tag{7}$$

where $(x_1, \cdots, x_p)$ stand for the observed variables used in $f_\beta(x)$.

To write down the least squares estimator for the linear regression model, it is convenient to use matrix notation. Let

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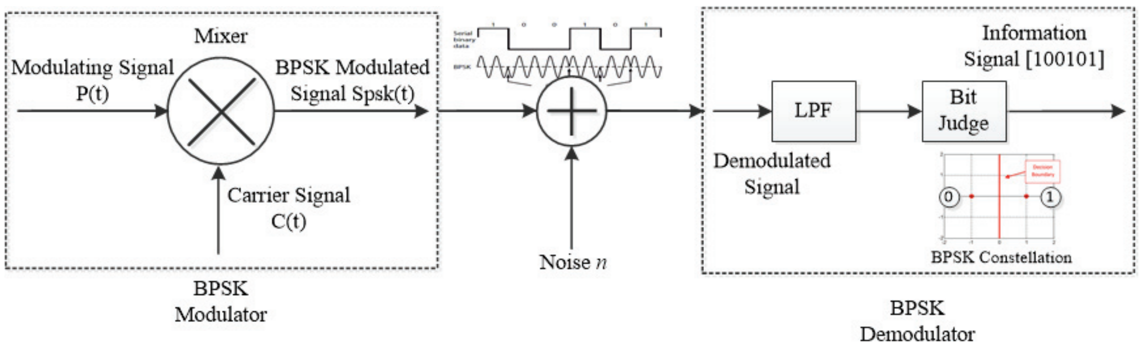

Fig. 3: Basic rule of BPSK.

$y = (y_1, \cdots, y_n)^{'}$, and X be the $n \times p$ data matrix of the n observations on the p variables

$$X = \begin{bmatrix} x_{1,1} & \cdots & x_{1,p} \\ \vdots & \cdots & \vdots \\ x_{n,1} & \cdots & x_{n,p} \end{bmatrix} = (X_1, \cdots, X_p),$$

where X_j is the column vector containing the n observations on variable j, $j \in \{1, \cdots, n\}$. Denote the squared length of an n-dimensional vector V by $\|V\|^2 = V^{'}V = \sum_{i=1}^{n} v_i^2$. To construct confidence intervals for the components of $\widehat{\beta}$, or linear combinations of these components, one needs an estimator of the covariance matrix of $\widehat{\beta}$. The covariance matrix of estimator $\widehat{\beta}$ is

$$(X^{'}X)^{-1}\sigma^2,$$

where σ^2 is the variance of the noise. Finally, a confidence interval for β_j is obtained by taking the least squares estimator $\widehat{\beta_j} \pm$ a margin as follows

$$\widehat{\beta_j} \pm c\sqrt{var(\widehat{\beta_j})},$$

where c depends on the chosen confidence level.

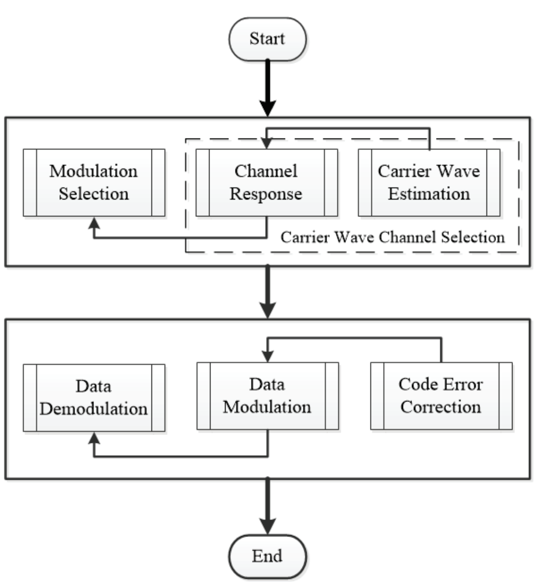

Fig. 4: New Communication Method Development Process.

3) BPSK Modulation and Demodulation: Generally, the phase-coherent modulation and demodulation procedure of BPSK can be depicted as Fig.3 [40]. The mathematical model of BPSK is presented as follows.

Assume the transmitting information can be modeled as an N-bit binary sequence $a_i \in \{0, 1\}$, and $i \in \{1, 2, , N\}$. Then, the modulating signal $P(t)$ is deduced by converting the binary sequence to a non-return-to-zero signal,

$$P(t) = \sum_{i=1}^{N} (2a_i - 1) \cdot rect\left(\frac{t - \frac{2i-1}{2} \cdot T_b}{T_b}\right). \quad (8)$$

where T_b represents the bit duration

Let $C(t)$ denote the carrier wave with the following properties,

$$C(t) = A_c cos(2\pi \cdot f_c t). \quad (9)$$

where f_c is the carrier's frequency.

The BPSK modulated wave $S_{psk}(t)$ can be obtained by

$$\begin{aligned} S_{pak}(t) &= P(t) \cdot C(t) \\ &= \sum_{i=1}^{N} (2a_i - 1) \cdot rect\left(\frac{t - \frac{2i-1}{2} \cdot T_b}{T_b}\right) \\ &\cdot A_c cos(2\pi \cdot f_c t). \end{aligned} \quad (10)$$

As described in the part of stress wave propagation, the propagation characteristics of stress wave along a pipe are determined by wave equations as well as boundary conditions, which is particularly complicated. Nevertheless, we can model the channel of point-to-point SWC on a pipe as a multipath channel, in which its impulse response can be represented by,

$$h(t) = \sum_{l=0}^{L-1} \alpha_l g_l(t - \tau_l), \quad (11)$$

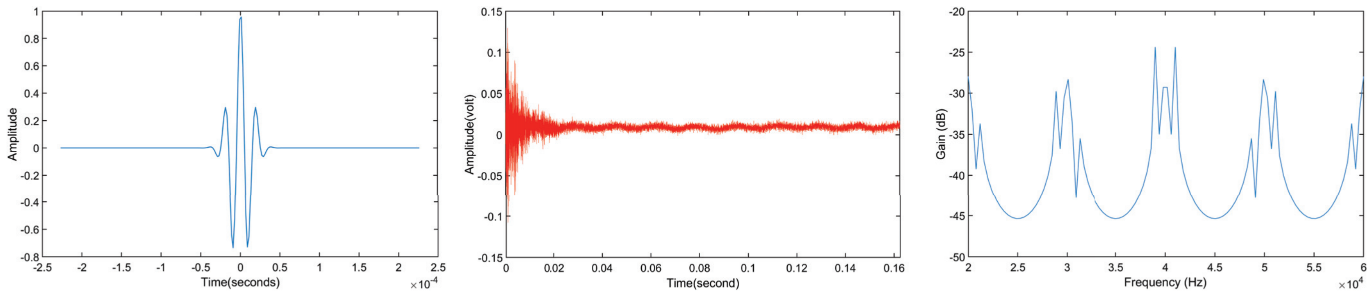

Fig. 5: (a).Gaussian-modulated sinusoidal pulse; (b). Response waveform at the sensor; (c).Frequency response of the channel

where L is the number of existing propagation paths along the pipe between the transducer and sensor. α_l represents the gain coefficient of the $l-th$ path and τ_l is the corresponding delay. Here, we consider the function g_l as the comprehensive propagation effect of the $l-th$ path under multiple modes. Therefore, the received signal can be written as

$$R(t) = S_{pak}(t) \cdot h(t) + p(n). \tag{12}$$

Here, $p(n)$ represents the noise generated along with the procedure of data transmission. Normally, the noise follows the Gaussian probability distribution as follows.

$$p(n) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{\frac{-(n-\mu)^2}{2\sigma^2}}. \tag{13}$$

where $\mu = 0$ and $\sigma^2 = \frac{N_0}{2}$. Hence, the bit error probability or rate (BER) with BPSK is derived as follows

$$P_b = \frac{1}{2} erfc(\sqrt{\frac{S_{pak}(t)}{N_0}}). \tag{14}$$

4) Hamming Code Error Correction: The most common types of error-correcting codes used in random access memory (RAM) are based on the codes devised by R. W. Hamming [41]. In the Hamming code, k parity bits are added to an n-bit data word, forming a new word of $n+k$ bits. The bit positions are numbered in sequence from 1 to $n+k$. Those positions numbered with powers of two are reserved for the parity bits. The remaining bits are the data bits. The Hamming code can be used for data words of any length. In general, for k check bits and n data bits, the total number of bits, $n+k$, that can be in a coded word is at most $2_k - 1$. In other words, the relationship $n+k \leq 2_k - 1$ must hold. This relationship gives $n \leq 2_k - 1 - k$ as the number of bits for the data word. When the word, which length is n, is read from memory, the check bits and also the parity bit P are evaluated over the entire n bits. If $P = 0$, the parity is correct (even parity). However, if $P = 1$, the parity over the n bits is incorrect (odd parity). However, it is not guaranteed to detect all such errors.

C. A New Communication Method Design and Implementation

According to the new stress wave communication method development process as shown in Fig. 4, the entire process is divided three steps: 1) carrier wave channel selection, 2) data modulation selection, 3) BPSK based communication method implementation. The entire implementation process follows the corresponding theoretical background mathematical models in Section II. The detailed process are presented as follows.

1) Carrier Wave Channel Selection: A piezoceramic actuator stack preloaded between two masses serves to generate the stress wave, which acts as the carrier wave for the proposed communication method. The prestressing offered by the masses helps to direct the majority of the stress wave energy into the pipe wall. A piezoceramic plate, which serves as the sensor, is located in 2.3 meters away from the transducer. Of note is that stress waves can interfere constructively at certain frequencies but destructively at other frequencies. Thus, a suitable channel can be identified according based on the amount of interference. Meanwhile, from Table I, it is clear that stress waves traveling with different modes can reach the longest distance in the steel pipeline structure.

With the LS estimation, a Gaussian-modulated sinusoidal pulse (shown in Fig. 5 (a)) is utilized to identify single-input-single-output (SISO) channels from the transducer to the sensor. After pulse propagates through the pipeline, the received waveform displays significant dispersion as shown in Fig. 5 (b). According to the results of the LS estimation, we estimate the frequency range of SISO channel from $20,000Hz$ to $60,000Hz$. As shown in Fig. 5 (c), the frequency response indicates the proper bandwidth for the communication through the channel. Since the $40,000Hz$ stress wave is in the pass-band of the channel, and is the center frequency which can be generated by the transducer, it is selected as the carrier wave for our proposed communication method.

2) Data Modulation Selection: For wireless communication, there are three major classes of digital modulation techniques, which include Amplitude-shift keying (ASK), Frequency-shift keying (FSK) and Phase-shift keying (PSK). Among these three techniques, PSK is the most powerful and efficient modulation technique. Moreover, while operating within the same bandwidth of ASK, PSK is less susceptible to errors while achieving a higher data rate of transmission than ASK and FSK [42] . BPSK, which is a form of PSK,

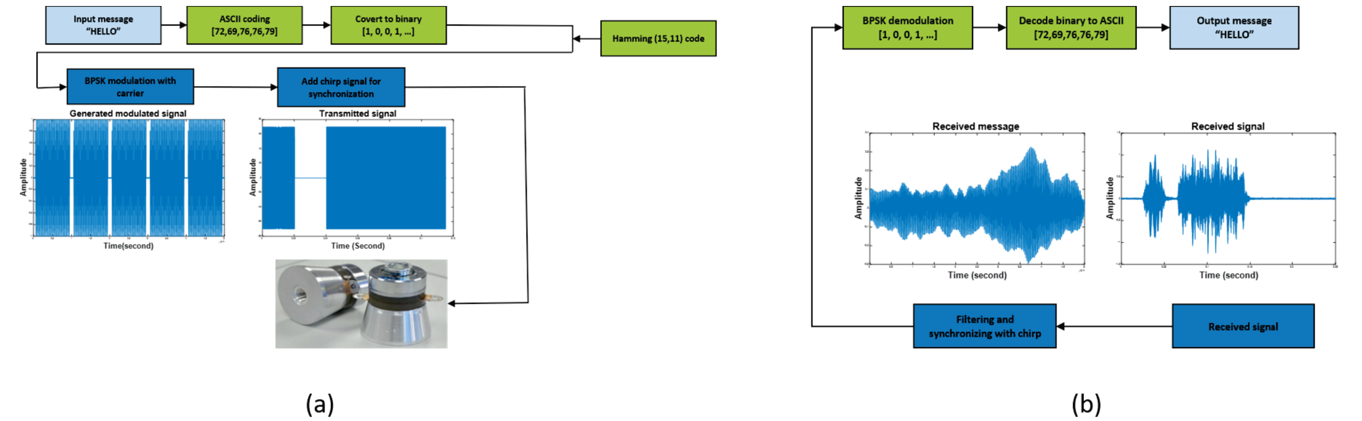

Fig. 6: Communication process using the new stress wave communication method. (a) Data Modulation, (b) Data DeModulation

uses two phases separated by $180°$ and so can also be termed 2-PSK. From Table II, BPSK has the lowest BER in PSK and also the highest performance [43, 44].

Consequently, BPSK is an appropriate modulation scheme with the selected carrier frequency $(40,000HZ$ stress wave) for digital transmission in the proposed communication method. In addition, Hamming code error correction is applied in the information coding to minimize inter-symbol interference.

3) BPSK based communication method implementation: The presented communication method uses BPSK for data modulation and demodulation. In the communication process, stress waves may distort while propagating along a pipeline. Thus, the space between each symbol should be considered to reduce the phase distortion caused by superposition. Hence, initially, the hamming code error correction method is used to pre-process the input data. Then, BPSK is utilized to modulate the error-corrected data.

Propagation delay and the wave dispersion can induce an unrecognizable starting point of the carrier wave (stress wave) and thereby introduce ambiguity into the demodulation process. To address this issue, the auto-correlation function is utilized to determine the time lag of the received signal [45]. In our proposed method, a chirp signal has been added to the modulated carrier waveform as a prefix of the data-pack. Given the chirp signal, $s(t)$, the auto-correlation, $R_{ss}(\tau)$, can be obtained by

$$R_{ss}(\tau) = \int_{-\infty}^{\infty} s(t+\tau)\overline{s(t)}d_{\tau} = \int_{-\infty}^{\infty} s(t)\overline{s(t+\tau)}d_{\tau}$$

where τ is the time lag and $\overline{s(t)}$ is the complex conjugate of $s(t)$.

Through optimization of the above auto-correlation function, we can obtain one peak point, which is the exact starting point. Finally, the received carrier waves can be demodulated with BPSK demodulation, and the BER can be estimated as well. Fig. 6 illustrates the whole communication process using our proposed method.

TABLE II: Comparison of Modulation Techniques

Modulation Technique	BER(dB)	Modulation Technique	BER(dB)
BPSK	10.6	8-PSK	18.5
D-BPSK	12.6	ASK	20
QPSK	13.6	16-QAM	20.5
4-QAM	13.6	16-PSK	24.3
OOK	14.5	32-QAM	24.4
8-QAM	17.6	FSK	26

III. Experiments and Result Analyses

To verify the performance of the new stress wave communication method, an underwater communication experiment has been setup. The detailed experimental verification process is as follows.

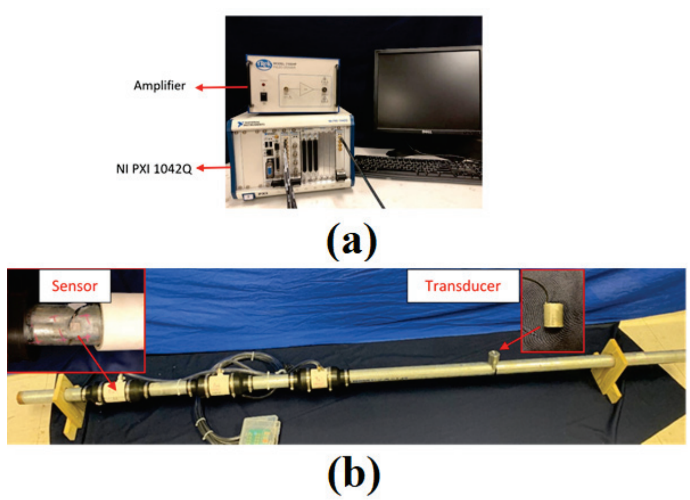

Fig. 7: The underwater communication experiment setup.

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A. Experiment Setup

An underwater communication experiment is conducted on a galvanized steel pipe with dimensions of $53.8 \times 50.8 \times 3048$ mm ($OD \times ID \times L$). A piezoelectric transducer and a piezoelectric sensor, both waterproofed, are coupled with the pipe and served as the communication transmitter and receiver, respectively. Fig.7 (a) shows the pipe and the installed piezoelectric elements.

As shown in Fig.7 (b), in the data processing of the underwater communication experiment, a combined data acquisition and digital-to-analog (for wave generation) system (National Instrument $PXI-1042Q$) run with NI LabVIEW served as the data transceiver. To ensure that the received discrete digital signal can be completely recovered, the sampling frequency is initialized to be 10 times of the carrier wave frequency. The signal processing is accomplished with Matlab.

B. Experiment Implementation

The pipe is tested in three different positions: 1) in air; 2) at the same level with the water surface (partially submerged); 3) totally immersed into seawater. Fig. 8 shows the underwater communication experiment in the field test.

The text string 'HELLO' is used to test the communication method. The string is first transferred to the $(15, 11)$ Hamming error-correcting code to filter errors. During this process, every 11-bit stream is expanded to a 15-bit stream. The non-return-to-zero signal represents the text 'HELLO' with the bit rate of 1000 bps. Fig. 9 shows the transmitting signal.

C. Experimental Results and Discussion

As shown in Fig.10, based on the comparison between transmitting signal (last 2 bits) and received signal for each case, the received signals suffer from higher attenuation when the pipe is in seawater. The received signal amplitude at position 2 is approximately one third of the amplitude at position 1. The amplitude from position 2 to position 3 does not experience apparent change. All the received signals can be successfully interpreted despite the dispersion and distortion in the received signal. Theoretically, stress wave can travel a long distance with less loss [46, 47], which makes it potential to realize long-distance underwater communication. Due to waveform elongation, there are no gaps in the period between every two bits. Hence, with error correction coding and simplified BPSK modulation scheme, the received signal can be successfully demodulated to the original information 'HELLO'.

As shown in Fig.12, Monte Carlo simulations are conducted to estimate the BER according to the values of SNR for each case. In the Fig 12, the in-air experimental results bear the greatest BER while underwater experimental results have lower BER, although the received amplitude in air is much higher than that of the underwater experiment. As shown in Fig. 11, The constellation scatter plot of each case indicates that the performance of underwater tests is better because the scatter points are more concentrated. The exact reason for the improved performance needs to be further explored with theoretical and numerical investigation. The results presented in the experiments have given rise to a speculation that some propagation modes of the stress waves may be dampened by seawater, as positions 2 and 3 suggest a higher damping ratio compared with air.

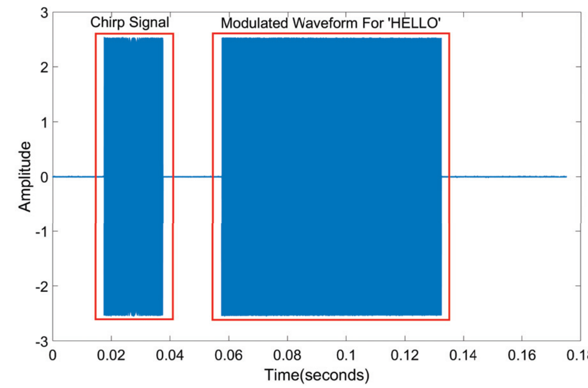

Fig. 9: the transmitting signal.

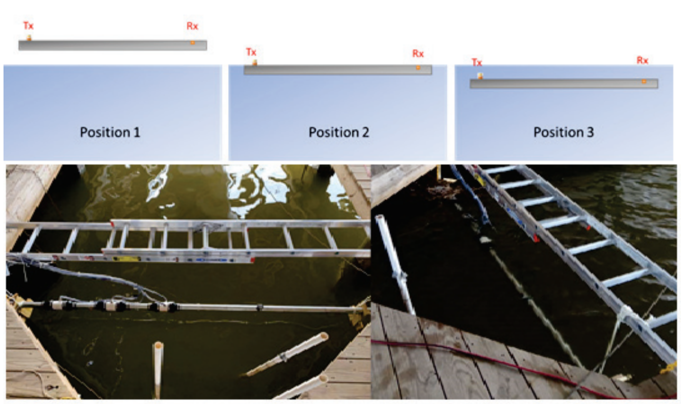

Fig. 8: The underwater communication experiment implementation.

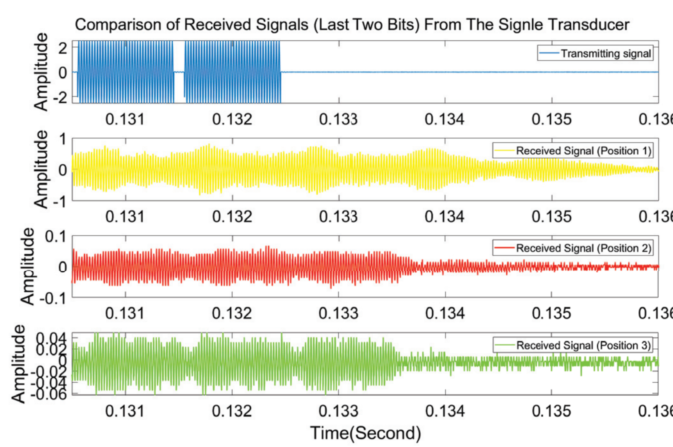

Fig. 10: Result comparison in the different position .

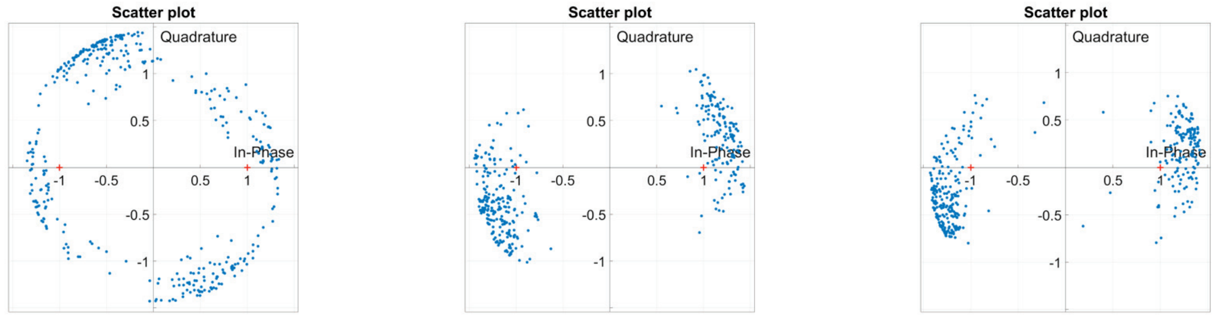

Fig. 11: Constellation diagrams. (Left) position 1; (middle) position 2; (right) position 3.

IV. Conclusion and Future Work

In this paper, we successfully developed a new stress wave communication method with Binary Phase Shift Keying (BPSK) modulation along a galvanized steel pipeline for underwater communication. LS estimation is utilized to analyze the channel response and the suitable carrier frequency is set to be 40,000 Hz. In order to achieve good communication performance under the situation of severe stress wave dispersion, BPSK scheme is utilized to modulate data. Meanwhile, the Hamming Code Error Correction method is used to minimize the inter-symbol interference, and an autocorrelation function is utilized to determine the time lag of the received signal as well. Underwater communication experiments were conducted and the results demonstrated the effectiveness and feasibility of the proposed method. The communication data rate of the proposed method can reach 1000 bps with a low BER when the pipe is totally immersed into seawater. Through the experimental results, our proposed method shows great promise for the long-distance underwater communication.

The proposed stress wave communication method for underwater long-distance communication has limitations and there exists much room for improvement in transmission data rate and BER performance. More specifically, our future work will involve SWC as detailed below:

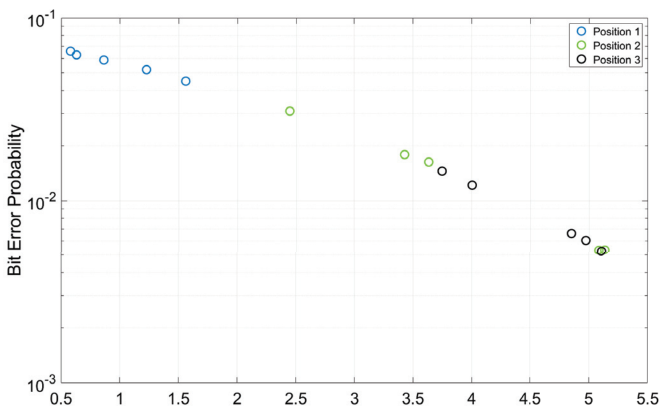

Fig. 12: BER comparison in different positions.

Firstly, the feasibility of our proposed SWC using BPSK has been demonstrated in an SISO system. In order to improve communication speed and make better use of available bandwidth, Orthogonal Frequency Division Multiplexing (OFDM) is considered as a reliable approach to be utilized in a multi-input-multi-output (MIMO) communication system. MIMO-OFDM combines MIMO technology and OFDM for the purpose of achieving high data rate over multiple antennas. OFDM encodes data on multiple closely spaced subcarrier frequencies, and on each subcarrier, data is modulated with conventional modulation schemes (including PSK modulation schemes) at a relatively low data rate [48]. Orthogonality between each subcarrier ensures that data can be transmitted in parallel over one channel. Therefore, compared to the proposed method which utilizes a single carrier frequency to encode data, MIMO-OFDM has potential to enhance system capacity in SWC along pipelines over different sensor nodes. Nevertheless, as presented in Fig. 5, the frequency response of the channel shows narrow passbands, which makes it more difficult to assign multiple subcarriers and guard intervals over current channel to achieve successful MIMO-OFDM compared to BPSK. Future work will focus more on exploring feasible approaches to implement high-data-rate MIMO-OFDM into stress wave communications through pipelines.

Secondly, the proposed SWC method is experimentally verified on a 3-meter long straight steel pipe. In the future work, SW communication should be tested on longer and more complex pipelines and structures to verify the feasibility of networking SWC.

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Conflict of Interests

Potential Conflict of Interests: Dr. Gangbing Song holds financial interest in AEM which is a startup company in structural health monitoring.

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REFERENCES

[1] N. Saeed, A. Celik, T. Y. Al-Naffouri, and M. S. Alouini, 2018 ”Underwater optical wireless communications, networking, and localization: A survey,” *arXiv preprint arXiv:1803.02442*.

[2] A. Palmeiro, M. Martin, I. Crowther and M. Rhodes, 2011 ”Underwater radio frequency communications,” *in OCEANS, 2011 IEEE-Spain*, pp. 1-8: IEEE.

[3] E. Jimenez, G. Quintana, P. Mena, P. Dorta, I. Perez-Alvarez, S. Zazo, M. Perez and E. Quevedo, 2016, August. ”Investigation on radio wave propagation in shallow seawater: Simulations and measurements.” *In 2016 IEEE Third Underwater Communications and Networking Conference (UComms)* (pp. 1-5). IEEE..

[4] C. Lake, 2001 ”Extremely low frequency transmitter site clam lake, Wisconsin,”.

[5] W. S. Tsai et al., 2016 ”A 50-m/40 Gb/s 680-nm VCSEL-based FSO communication,” *IEEE Photonics Journal*, vol. 8, no. 2, pp. 1-8.

[6] D. Anguita, D. Brizzolara, G. Parodi, and Q. Hu, 2011 ”Optical wireless underwater communication for AUV: Preliminary simulation and experimental results,” *in OCEANS, 2011 IEEE-Spain,* pp. 1-5: IEEE.

[7] H. Kaushal, G. Kaddoum, 2016 ”Underwater optical wireless communication,” *IEEE access*, vol. 4, pp. 1518-1547.

[8] M. Z. Chowdhury, M. T. Hossan, A. Islam, Y. M. Jang, 2018 ”A comparative survey of optical wireless technologies: Architectures and applications,” *IEEE Access*, vol. 6, pp. 9819-9840.

[9] J. Li, F. Wang, M. Zhao, F. Jiang, N. Chi, 2019 ”Large-coverage underwater visible light communication system based on blue LED employing equal gain combining with integrated PIN array reception,” *Applied optics*, vol. 58, no. 2, pp. 383-388.

[10] H. Guo, Z. Sun, P. Wang, 2017 ”Multiple frequency band channel modeling and analysis for magnetic induction communication in practical underwater environments,” *IEEE Transactions on Vehicular Technology*, vol. 66, no. 8, pp. 6619-6632.

[11] B. Gulbahar, O. B. Akan, 2012 ”A communication theoretical modeling and analysis of underwater magneto-inductive wireless channels,” *IEEE Transactions on Wireless Communications*, vol. 11, no. 9, pp. 3326-3334.

[12] M. C. Domingo, 2012 ”Magnetic induction for underwater wireless communication networks,” *IEEE Transactions on Antennas and Propagation*, vol. 60, no. 6, pp. 2929-2939.

[13] P. Sahu and M. Singh, 2009.”Multichannel direct sequence spectrum signaling using code phase shift keying,” *Computers and Electrical Engineering*, vol. 35, no. 1, pp. 218-226.

[14] L. Wan et al., 2013 ”Field tests of adaptive modulation and coding for underwater acoustic OFDM,” *in Proceedings of the Eighth ACM International Conference on Underwater Networks and Systems*, p. 35: ACM.

[15] A. Song, M. Badiey, A. E. Newhall, J. F. Lynch, H. A. DeFerrari, B. G. Katsnelson, 2010 ”Passive time reversal acoustic communications through shallow-water internal waves,” *IEEE Journal of Oceanic Engineering*, vol. 35, no. 4, pp. 756-765.

[16] A. Radosevic, R. Ahmed, T. M. Duman, J. G. Proakis, M. Stojanovic, 2014 ”Adaptive OFDM modulation for underwater acoustic communications: Design considerations and experimental results,” *IEEE Journal of Oceanic Engineering*, vol. 39, no. 2, pp. 357-370.

[17] J. Saini, B. K. Dixit, 2016 ”Prospects and Challenges of Underwater Acoustic Sensor Networking: A review,” *Indian Journal of Science and Technology*, vol. 9, no. 36, 2016.

[18] S. Kalita, R. Kaushik, M. Jajoo, P. Sahu, 2016 ”Performance Enhancement of a Multichannel Uncoordinated Code Hopping DSSS Signaling Scheme Using Multipath Fading Compensator,” *Journal of Circuits, Systems and Computers*, vol. 25, no. 11, p. 1650145.

[19] S. Kalita, P. Sahu, 2015 ”An anti-jamming underwater communication transceiver model using uncoordinated direct sequence spread spectrum technique,” *in 2015 2nd International Conference on Electronics and Communication Systems (ICECS)*, pp. 972-976: IEEE.

[20] S. Roy, T. M. Duman, V. K. McDonald, 2009 ”Error rate improvement in underwater MIMO communications using sparse partial response equalization,” *IEEE Journal of Oceanic Engineering*, vol. 34, no. 2, pp. 181-201.

[21] S. Siu, Q. Ji, W. Wu, G. Song, and Z. Ding, 2014, ”Stress wave communication in concrete: I. Characterization of a smart aggregate based concrete channel,” *Smart Materials and Structures*, vol. 23, no. 12, p. 125030.

[22] S. Siu, J. Qing, K. Wang, G. Song, and Z. Ding, 2014, ”Stress wave communication in concrete: II. Evaluation of low voltage concrete stress wave communications utilizing spectrally efficient modulation schemes with PZT transducers,” *Smart Materials and Structures*, vol. 23, no. 12, p. 125031.

[23] Q. Ji, M. Ho, R. Zheng, Z. Ding, and G. Song , 2015 ”An exploratory study of stress wave communication in concrete structures,” *Smart Structures and Systems*, vol. 15, no. 1, pp. 135-150.

[24] D. J. Connor, G. F. Cummings, and M. J. Star, 1997 ”Acoustic transformer with non-piezoelectric core,” *ed: Google Patents*.

[25] R. P. Welle, 1999 ”Ultrasonic data communication system,” *ed: Google Patents*.

[26] C. Rein, 2003 ”Remote energy supply process and system for an electronic information carrier,” *ed: Google Patents*.

[27] K. Manolakis, U. Krger, K. Krger, M. Gutierrez-Estevez, S. Mikulla, and V. Jungnickel, 2011”Borehole communication with acoustic ofdm,” *in Int. OFDM-Workshop (InOWo11)*.

[28] M.A. Gutierrez-Estevez, U. Krger, K.A. Krueger,K. Manolakis, V. Jungnickel, K. Jaksch, K. Krueger, S. Mikulla, R. Giese, M. Sohmer, and M. Reich, 2013, April. ”Acoustic broadband communications over deep drill strings using adaptive OFDM.” *In 2013 IEEE Wireless Communications and Networking Conference (WCNC)* (pp. 4089-4094). IEEE.

[29] Y. Jin, D. Zhao, and Y. Ying, 2012 ”Time reversal data communication on pipes using guided elastic wavespart I: basic principles Proc,” *SPIE Health Monitoring of Structural and Biological Systems*, vol. 7984, pp. 1-12.

[30] Y. Jin, Y. Ying, and D. Zhao, 2013 ”Data communications using guided elastic waves by time reversal pulse position modulation: Experimental study,” *Sensors*, vol. 13, no. 7, pp. 8352-8376.

[31] X. Huang, J. Saniie, S. Bakhtiari, and A. Heifetz, , 2018, ”Applying EMAT for ultrasonic communication through steel plates and pipes,” *in 2018 IEEE International Conference on Electro/Information Technology (EIT)*, pp. 0379-0383: IEEE.

[32] K. M. Joseph, T. Watteyne, and B. Kerkez, 2018 ”Awa: Using water distribution systems to transmit data,” *Transactions on Emerging Telecommunications Technologies*, vol. 29, no. 1, p. e3219.

[33] S. Chakraborty, G. J. Saulnier, K. W. Wilt, E. Curt, H. A. Scarton, and R. B. Litman, , 2015 ”Low-power, low-rate ultrasonic communications system transmitting axially along a cylindrical pipe using transverse waves,” IEEE transactions on ultrasonics, ferroelectrics, and frequency control, vol. 62, no. 10, pp. 1788-1796.

[34] D. C. Gazis, 1959 ”Threedimensional investigation of the propagation of waves in hollow circular cylinders. I. Analytical foundation,” *The journal of the Acoustical Society of America*, vol. 31, no. 5, pp. 568-573.

[35] F. Seco and A. R. Jimnez, 2012 ”Modelling the generation and propagation of ultrasonic signals in cylindrical waveguides,” *in Ultrasonic waves: InTech*.

[36] W. H. Tranter, T. S. Rappaport, K. L. Kosbar, and K. S. Shanmugan, 2004 ”Principles of communication systems simulation with wireless applications.” *Prentice Hall New Jersey*.

[37] Z. Nazarchuk, V. Skalskyi, and O. Serhiyenko, 2017. ”Propagation of elastic waves in solids.” *In Acoustic Emission*(pp. 29-73). Springer, Cham.

[38] D.N. Alleyne, M.J.S. Lowe, and P. Cawley, 1998. ”The reflection of guided waves from circumferential notches in pipes”. *Journal of Applied mechanics*, 65(3), pp.635-641.

[39] H.W. Sorenson, 1970. ”Least-squares estimation: from Gauss to Kalman.” *IEEE spectrum*, 7(7), pp.63-68.

[40] P. Chevalier and F. Pipon, 2006. ”New insights into optimal widely linear array receivers for the demodulation of BPSK, MSK, and GMSK signals corrupted by noncircular interferences-application to SAIC.” *IEEE Transactions on Signal Processing*, 54(3), pp.870-883.

[41] A.R. Calderbank and P.W. Shor, 1996. ”Good quantum error-correcting codes exist.” *Physical Review A*, 54(2), p.1098

[42] J.M. Tjensvold, 2007, September. ”Comparison of the IEEE 802.11, 802.15. 1, 802.15. 4 and 802.15. 6 wireless standards.” In *IEEE: September* (Vol. 18).

[43] D.R. Pauluzzi and N.C. Beaulieu, 2000. ”A comparison of SNR estimation techniques for the AWGN channel.” *IEEE Transactions on communications*, 48(10), pp.1681-1691.

[44] J. Tewari, and H.M. Singh, 2016. ”Performance Comparison of Digital Modulation Techniques used in Wireless Communication System.” *International Journal of Innovative Research in Computer and Communication Engineering*, 4(7).

[45] T. Misaridis, and J.A. Jensen, 2005. ”Use of modulated excitation signals in medical ultrasound. Part III: High frame rate imaging.” *IEEE transactions on ultrasonics, ferroelectrics, and frequency control*, 52(2), pp.208-219.

[46] D. S. Drumheller, 1993 ”Attenuation of sound waves in drill strings,” *The Journal of the Acoustical Society of America*, vol. 94, no. 4, pp. 2387-2396.

[47] D. S. Drumheller, S. D. Knudsen, 1995 ”The propagation of sound waves in drill strings,” *The Journal of the Acoustical Society of America*, vol. 97, no. 4, pp. 2116-2125.

[48] G. L. Stuber, J. R. Barry, S. W. Mclaughlin, Y. Li, M. A. Ingram, and T. G. Pratt, 2004 ”Broadband MIMO-OFDM wireless communications,” *Proceedings of the IEEE*, vol. 92, no. 2, pp. 271-294.

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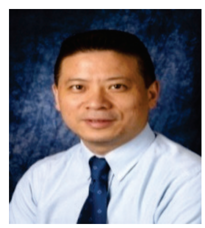

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