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Performance Evaluation of Underwater Acoustic Communications Utilizing Low Complexity Encoding and Decoding Algorithms

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Abstract— Channel coding is an essential requirement for digital communication systems, particularly for underwater acoustic channels, to perform accurately and reliably in the presence of ambient noise, absorption loss, interference, and much other impairment. Low complexity encoding and decoding algorithms are investigated i.e. order statistic decoding (OSD) of block codes for various modulation schemes and assumptions of underwater acoustic channel such as distance and multipath effects. These simple algorithms improve the bit error rate (BER) significantly unlike uncoded systems or other complex systems utilizing convolutional codes.

Keywords— BER, BPSK, Channel coding, Decoding, Multipath, OSD, QPSK, SNR, Underwater communication.

I. INTRODUCTION

Underwater acoustic communication system has become a hot area for research recently. This attention comes from potential applications of such channel including sharing of navigation information, control of autonomous underwater vehicles (AUV), and undersea command and control. Thus, the environment of this channel imposes many characteristics such as: small number of network nodes, large transmission distance, and frequent packet exchange [1]. The underwater acoustic communication channel is one of the most challenging wireless communication media known to man. There exists no typical acoustic channel or standard channel models till the present day [2]-[4]. The complexity of underwater acoustic channels is initiated by the ocean environment characteristics which include significant delay, double-side-spreading, Doppler-spreads, frequency-selective fading, absorption at high frequencies, ambient noise at low frequencies and limited usable bandwidth [5]. Moreover, horizontal underwater channels are prone to multipath propagation due to refraction, reflection and scattering [2]. New innovations of rapid data rate correspondence for picture and video transmission are additionally attractive to improve the coming era of productive underwater communication scenarios. On the other hand, current acoustic correspondence advancements can just give constrained information rates because of the specific physical components of channels [6]. So, wireless communication still needs significant improvements for underwater channels as have been done in [7]-[9]. All this makes the underwater acoustic signal fluctuate randomly. As such, the selection of modulation and error correction techniques is very challenging.

Channel coding is important to protect the transmitted signal against noise and all other impairments in underwater channels in similar manner as in wireless space channels. It is obvious that digital communication systems of underwater channels need to achieve high reliability in the presence of noise and interference [10]. Forward error correction (FEC) coding is one of the most effective tools to achieve this goal. Also, it should be noticed that because underwater communication commonly used symbol demodulation schemes which do not depend on the noise power, bit error performance without error correction coding will not

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be improved [11]. Thus, FEC is a type of error correction and detection schemes of underwater channels that should be investigated more deeply than in [12], [13]. This is done by considering more scenarios and various assumptions of channels. In this paper, the performance of certain channel coding schemes with effective and simple decoding algorithms is investigated deeply based on wide and various assumptions and parameters of underwater channels. Simple block codes are utilized with effective decoding algorithm such as order statistics decoding (OSD). This decoding algorithm has achieved high reliability with low complexity in space wireless communications over AWGN and fading channels [14], [15].

In this paper, we investigate OSD-based decoding strategies for linear binary block codes. Our aim is to investigate low complexity decoding schemes that provide large or valuable coding gains and, most importantly, are well-suited for implantation in underwater channel environments. The remainder of this paper is organized as follows. The details of the system model of acoustic channels are introduced in Section II. In Section III, simulation results of channel coding performance with different scenarios and parameters for underwater acoustic channel utilizing different modulation schemes are presented and discussed. Conclusions are drawn in Section IV.

II. SYSTEM MODEL

In this model, we consider single input single output system (SISO) as shown in Fig. 1. It consists of information source, encoder, and modulator (BPSK or QPSK) in the transmitter side. The underwater acoustic channel model is utilized as a link between the transmitter and receiver. The receiver side consists of demodulator and OSD decoder. In this system, codewords of a linear binary block code *C* are transmitted over underwater acoustic channels. The code *C*, denoted as (N, K, d_{min}), has dimension *K*, block length *N*, and the minimum Hamming distance between any two codewords d_{min}. Binary codewords $C \in Z_2^N$ where $Z_2 = \{0,1\}$ are generated from a source of information bits $u \in Z_2^K$ using the generator matrix $G \in Z_2^{K \times N}$ [14], i.e., *C* = uG. In the receiver side, OSD decoder is implemented as in [14] and [15] to execute soft decision decoding based on the reliabilities of the received symbols through channel. The OSD decoder chooses the codeword *C* from the coding list with the minimum Euclidian distance to the received sequence after reordering according to reliabilities.

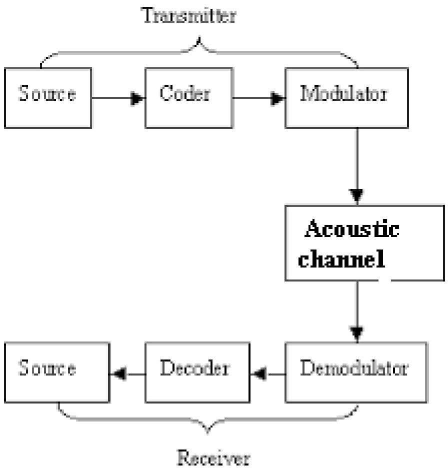

Fig. 1. System model for SISO

III. CHANNEL MODEL

In this work, using of the underwater acoustic channel is considered. The model of this channel is shown in Fig. 2. In this case, the signal is transmitted in a direct path between TX and RX. The signal also propagates via reflections from the surface and bottom, resulting in a multipath effect with much larger time dispersion then that of wireless propagation in air.

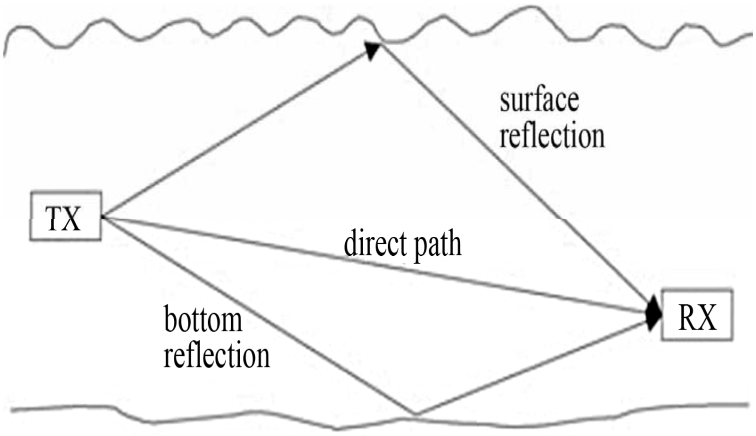

Fig. 2. The scenario of shallow water multipath propagation [4]

The codeword C generated by encoder is interleaved and mapped to binary phase shift keying (BPSK) sequences $x \in \{+1,-1\}$ before transmission, i.e. $x_{i=} (-1)^{Ci}$, where x_i denotes the ith component of vector x, and $i = 1,2,\cdots,N$. For QPSK modulator, the output of modulator is a complex baseband In-phase (**I**) and Quadrature (**Q**) symbol sequence. The codewords are interleaved and mapped to QPSK transmitted symbol sequence $x_k = x_{IK} + jx_{QK}$, where $x_{IK}, x_{QK} \in \{\mp1,\mp3\}$ and each modulation symbol are obtained from codeword $C_{ik}, i = 1,2$. In this model, coherent detection is assumed; and the channel phases are known in the receiver side.

A. Path Loss and Absorption Coefficient

The received signal at destination is written as:

$$\mathrm{R_i = H(l,f)_i x_i + N(f)_i} \tag{1}$$

Where $H(l,f)_i$ is the overall transfer function of the underwater acoustic communication channel which is described in [16], [17]:

$$H(l,f) = \sum_{p=0}^{P-1} \frac{\Gamma_p}{\sqrt{A(l_p,f)}} e^{-j2\pi f \tau_p} \tag{2}$$

Where $A(l,f)$ is the acoustic path loss which can be represented as:

$$A(l,f) = A_0 l^k \alpha(f)^l \tag{3}$$

The Path loss of an underwater acoustic communication channel depends on the transmission distance and signal frequency.
A_0 is a unit-normalizing constant; k is the spreading factor; and $\alpha(f)$ is the absorption coefficient. The absorption coefficient can be expressed using Thorp's empirical formula [16], [17]:

$$\alpha(\mathrm{f}) = 0.11\frac{\mathrm{f}^2}{1+\mathrm{f}^2} + 44\frac{\mathrm{f}^2}{4100+\mathrm{f}^2} + 2.75 \times 10^{-4}\mathrm{f}^2 + 0.003 \tag{4}$$

where f is given in kHz; and the absorption coefficient is given in dB/Km. τ_p models stand for additional losses incurred on the p^{th} path (e.g. cumulative reflection loss) where $\tau_p = \frac{l_p}{c}$ is the path delay; and c is the nominal speed of the sound underwater (1500m/s). The propagation paths are considered by l_p where $p = 0, \cdots, p-1$.

B. Noise Model

The noise in underwater acoustic channels is presented as N_i in (1). There are several types of noise in the underwater environment and so-called ambient noise; the acoustic channel noise can be classified into four types with corresponding equations given below [16]:

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

$$10\log N_s(f) = 40 + 20(s - 0.5) + 26\log(f) - 60\log(f + 0.03) \tag{6}$$

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

$$10\log N_{th}(f) = 20\log(f) - 15 \tag{8}$$

Where s is the shipping activity factor ranged between 0 and 1; w is the wind speed m/s; N_t denotes for turbulence noise; N_S is the shipping noise; N_w is the noise caused by wind and rain; and N_{th} is the thermal noise. The total ambient noise in underwater channels is now given by:

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

For all above empirical equations, the power spectral density (psd) of all components is considered in dB re μ Pa per Hz as a function of frequency in kHz.

C. Signal to Noise Ratio

The signal to noise ratio (SNR) in (10) is a function of frequency and transmission distance. The transmitted power P is fixed at $2x10^6$ dB re μ Pa; and Δf is the receiver noise bandwidth (a narrow band around the frequency f) [18]:

$$SNR(l, f) = \frac{P / A(l, f)}{N(f)\Delta f} \tag{10}$$

IV. SIMULATION RESULTS AND ANALYSIS

We carry out soft-decision decoding of some BCH codes and utilize low complexity decoding algorithms such as OSD for different scenarios of underwater acoustic channels. Fig. 3 to Fig. 9 compare the BER performances using computer simulations. The BER of the (128, 64 and 22) BCH code, convolutional code and uncoded system over direct link underwater acoustic channels is shown in Fig. 3. We observe that BCH code with OSD (1) has better performance than convolutional code for BER larger than 10^{-3} and OSD (1) outperforms uncoded systems by at most 2.5dB for the BERs smaller than 10^{-3}. Also, we can notice that OSD (1) decoding of BCH (128, 64 and 22) can achieve approximately the same BER as convolutional code at large SNR with reduction in performance less than 1dB. A slightly smaller coding gain (less than 1dB) of the convolutional code in comparison to OSD (1) of BCH at larger values of the SNR is well-compensated for by the significant reduction in complexity of the decoding for OSD. Furthermore, BCH with OSD (1) can trade-off the BER and complexity of the uncoded system and convolutional code, especially at small BERs.

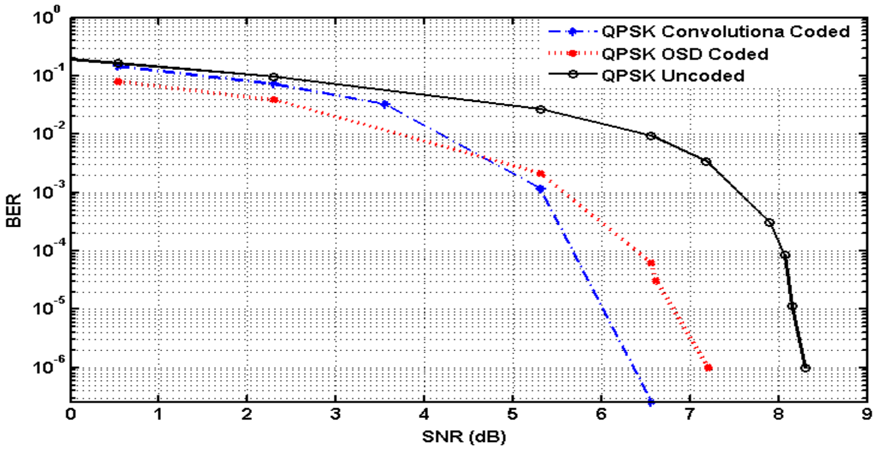

Fig. 3. Comparison between convolutional code ½ rate $(133,171)_8$ and OSD (1) for fixed distance at 3km using QPSK

System performance of BCH (32, 16 and 8) with OSD (2) over 3km and 5km distances which uses QPSK is depicted in Fig. 4 and Fig. 5 with various multipaths. The figures indicate that considering direct path only outperforms the cases of three and six paths. For example, at BER of 10^{-4}, the required SNR for direct path is around 7dB, whereas in case of three multipaths, the SNR is almost three times that required for single path. And for six paths, the SNR needs to be doubled compared with three paths.

For 10km transmission distance, even though the single path is still showing superior performance, the three and six path curves become closer as shown in Fig. 6; the deviation of three path curve from three paths is around 2dB at BER of 10^{-4}. Moreover, the distance effect becomes more obvious than it is in the multipaths.

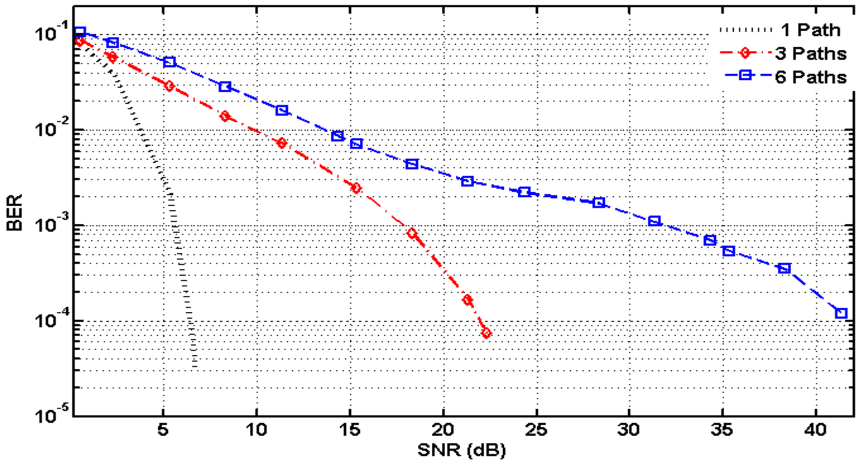

Fig. 4. Multipath effect for fixed distance at 3km using QPSK with BCH (32, 16 and 8) and OSD (2)

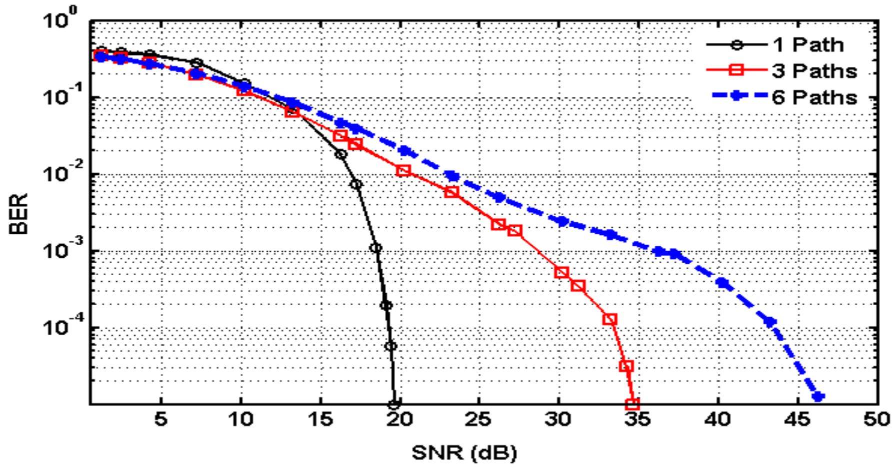

Fig. 5. Multipath effects for fixed distance at 5km using QPSK with BCH (32, 16 and 8) and OSD (2)

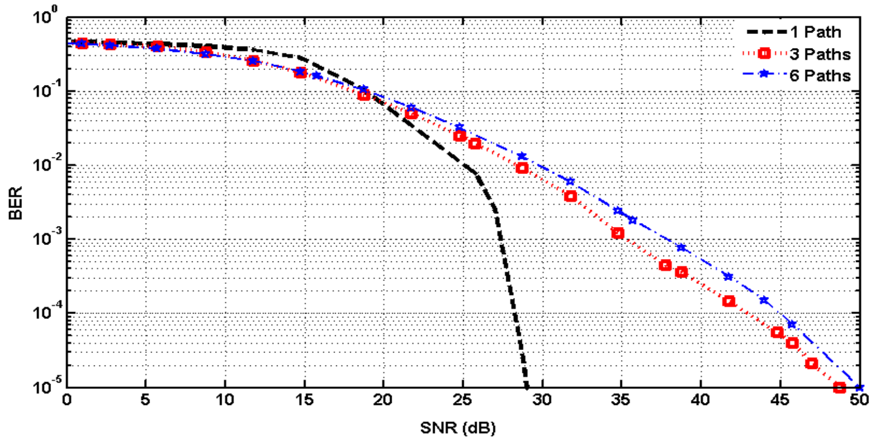

Fig. 6. Multipath effect for fixed distance of 10km using QPSK with BCH (32, 16, 8) and OSD (2)

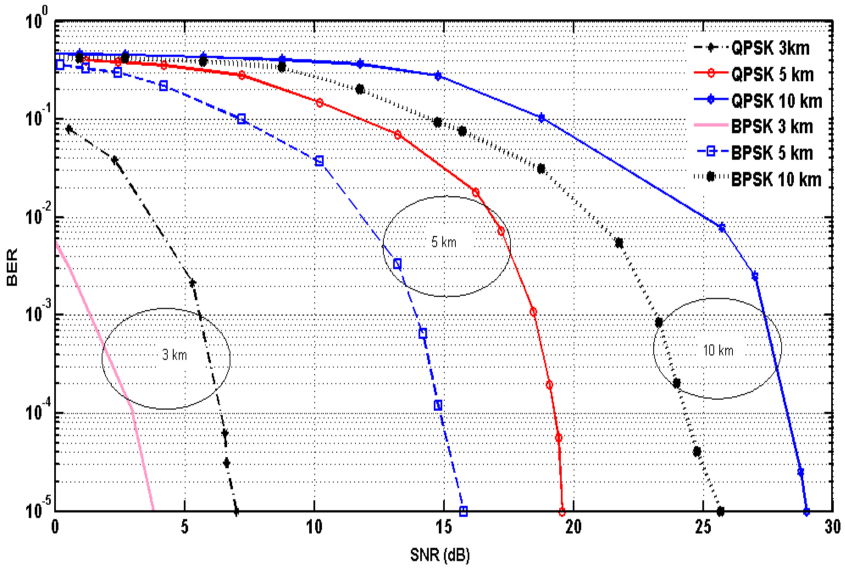

Fig.7. Performance of QPSK and BPSK with various distances and direct path only with BCH (32, 16 and 8) and OSD (2)

The performance of both BPSK and QPSK transmission over underwater acoustic channel is presented in Fig. 7 which considers one path and various transmission distances. BPSK is clearly better than QPSK. However, QPSK gives better bandwidth efficiency with some penalty of SNR of around 4dB compared with BPSK. Increasing the transmission distance deteriorates system performance in both cases of BPSK and QPSK.

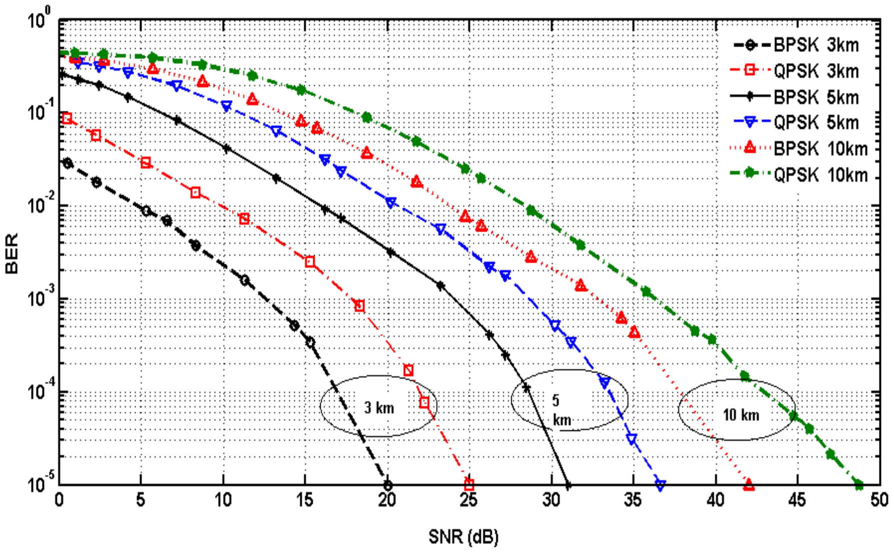

Fig. 8. Performance of QPSK and BPSK with various distances and three multipaths with BCH (32, 16 and 8) and OSD (2)

Furthermore, three multipath channel scenarios are modeled as shown in Fig. 8. The same analogy is found in comparing with Fig. 7 except that the curves are getting much closer due to multipath effects.

Fig. 9 shows the results of six multipaths with various transmission distances. It can be noted that the curve of QPSK at 3km intersects with the curve of BPSK at 5km at SNR around 25dB. Another intersection can be seen at 30dB SNR, where the BPSK at 10km intersects with the curve 5km QPSK. Moreover, the multipath has a severe effect which produces more noticeable as the curves fluctuate.

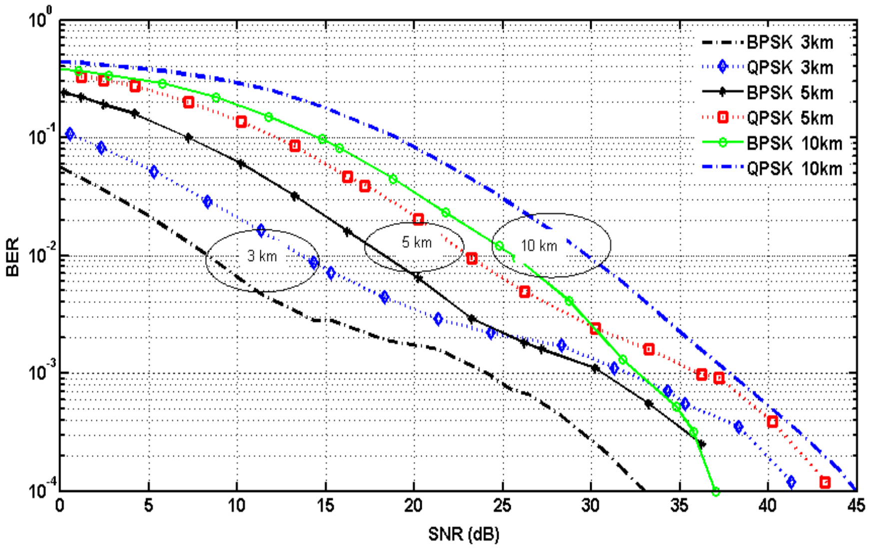

Fig. 9. Performance of QPSK and BPSK with various distances and six multipaths with BCH (32, 16 and 8) and OSD (2)

V. CONCLUSION

Low-complexity soft-decision decoding techniques OSD for linear binary block codes of small to medium block length were investigated for different modulation schemes such as BPSK and QPSK. Different assumptions and parameters of acoustic underwater channel such as various distances and multipath between transmitter and receiver were received. In this manner, the contribution of simple codes to simple decoding algorithms can improve the transmission robustness and protect the transmitted data from errors. A coded system with BCH for direct path of BPSK achieved almost the same performance of convolutional code with very low complex system of OSD decoder. Moreover, such a simple BCH coded system improves the BER performance significantly compared to uncoded systems. Furthermore, the direct path outperforms the cases of three and six paths for both types of the examined modulation schemes BPSK and QPSK. For a lager transmission distance i.e. 10km, even though the single path is still showing superior performance, the three and six paths curves become closer. Moreover, the distance effect contributes more significantly to performance degradation than the multipath effect for both BPSK and QPSK. By comparing different types of modulation of such simple coded systems over under acoustic channel, results show that for direct link the BER performance of BPSK is clearly better than QPSK. However, QPSK gives better bandwidth efficiency with some penalty of SNR than with BPSK. Future work would investigate higher bandwidth-efficient modulation schemes such as quadrature phase shift keying.

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