Performance of Coherent Modulation Scheme Used in Acoustic Underwater Communication System

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Abstract

The development of an acoustic underwater communication system for shallow waters is still a big scientific and construction challenge. Currently, non-coherent modulations in combination with strong channel coding are used to achieve reliable communication with low rate in such a channel. To obtain transmission with a higher transmission rate, it is required to use coherent modulation. This paper presents the assumptions of such a transmission system and the results of data transmission carried out by this system in the channel with the Rician fading, which reflects the short range shallow water channel. A digital version of the carrier phase modulation known as Phase-Shift Keying was selected for simulation.

Keywords: underwater acoustic communications, shallow underwater channel, coherent modulation

1. Introduction

The task of the underwater acoustic communication system is error-free data transfer of large amounts of data. In the shallow waters channel there are unfriendly conditions for its implementation. The obtained transmission rates are usually low, and the variability of propagation conditions in the channel contributes to transmission errors. In such a channel, the multipath propagation has an influence on transmitted signal due to its reflections from the boundary surfaces of the channel and objects present in the water. On the receiving side, the signal from a direct path and the paths obtained during reflections is received. The transmitted signal suffers the refraction, which is caused by a significant changes of sound velocity as a function of depth. Multipath propagation and refraction produce time dispersion in the transmitted signal. The movement of the communication system's transmitter and receiver causes the Doppler effect, resulting in the time-domain scaling of an original broadband communication signal. This phenomenon also has a significant impact on the communication system's performance. The development of an acoustic underwater communication system for shallow waters is still a big scientific and construction challenge.

In order to implement reliable acoustic underwater communication systems, incoherent modulations are usually used in combination with strong channel coding. They enable data transmission at a rate of hundreds of bits per second [1-3]. Obtaining higher transmission rates for this modulation method is possible as a result of a significant widening of the system operating band, which is obtained by using multiple hydroacoustic transducers or antennas [4]. Avoiding these inconvenient hardware system complications requires the use of coherent modulation. This is a significant complication of the receiver requiring considerable computing power to implement the channel's equalizer algorithm [5-7]. However, with the computing power offered by modern signal processors, this does not constitute any significant limitation in the implementation of the system.

This article presents the performance of an underwater communication system using BPSK coherent modulation, in a configuration with one transmit and one receiving antenna (SISO). For the development of the communication system concept, simulation tests were carried out in channels with Rician fading, which reflect the short range shallow water channels.

2. Underwater communication system

The considered acoustic underwater communication system assumes the use of carrier phase modulation. This modulation changes the phase of the carrier wave signal at a fixed frequency in accordance with a predetermined scheme assigned to the given order. The digital variant of this modulation is called Phase-Shift Keying (PSK) [5]. The phase value from the range $< 0, 2\pi)$ is used to transmit data and carrier phases of transmitted signals are:

$$\theta_m = \tfrac{2\pi m}{M}, \;\; m = 0, 1, \dots, M-1. \tag{1}$$

For binary phase modulation BPSK (M = 2) there are two carrier phases $\theta_0 = 0$ and $\theta_1 = \pi$. In turn, for QPSK (M = 4) there are four carrier phases $\theta_0 = 0$, $\theta_1 = \pi/4$, $\theta_2 = \pi/2$ and $\theta_2 = 3\pi/4$. Symbol k is the number of bits per transmitted symbol where $M = 2^k$. The transmitted signal waveforms in the symbol interval $< 0, T >$ can be expressed as:

$$s_m(t) = \sqrt{\frac{2E_s}{T}} \cos\left(2\pi f_c t + \frac{2\pi m}{M}\right), \;\; m = 0,1, \dots, M-1, \tag{2}$$

where E_s is the energy transmitted per symbol. A digital phase-modulated signals are represented geometrically as two-dimensional vectors:

$$\boldsymbol{s}_m = \left(\sqrt{E_s} \cos\left(\frac{2\pi m}{M}\right) \quad \sqrt{E_s} \sin\left(\frac{2\pi m}{M}\right)\right). \tag{3}$$

Space constellation diagrams for M = 2 (BPSK) and M = 4 (QPSK) are presented in Figure 1.

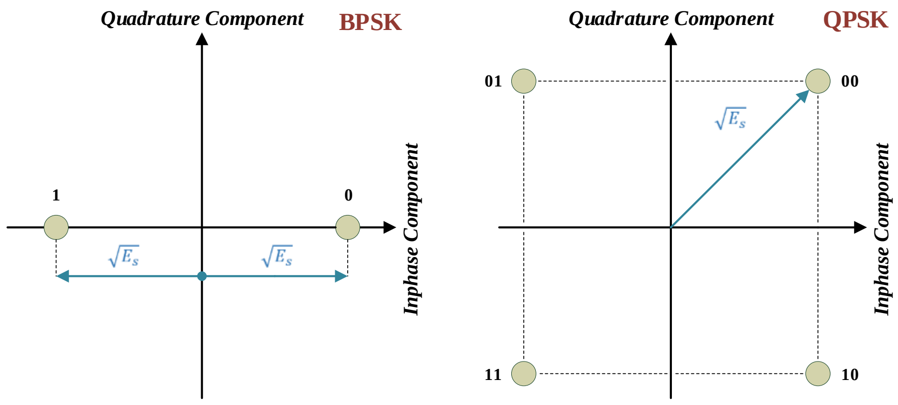

Figure 1. Space constellation diagrams for BPSK and QPSK

Figure 2 shows the determined error bit rate (BER) for the case of transmission data through channels with Additive White Gaussian Noise (AWGN) for BPSK and QPSK modulation. The BER is simulated in function of E_b/N_0, which is the ratio of the symbol energy to noise spectral density in dB.

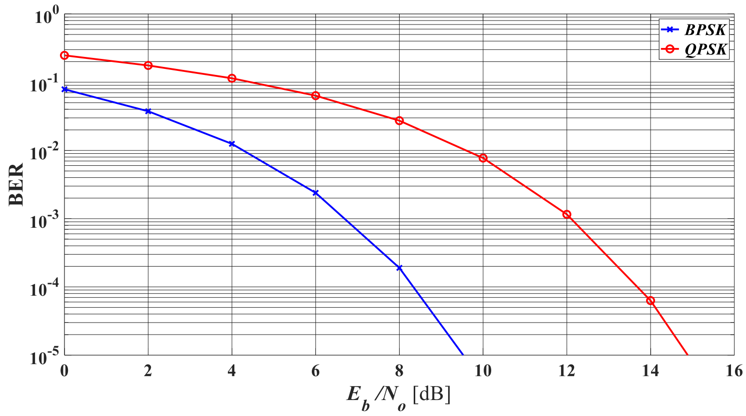

Figure 2. Bit error rate of BPSK and QPSK modulation in AWGN channel

To achieve BER = 10^{-3}, BPSK modulation required $E_b/N_0 \approx 7$ dB and QPSK modulation $E_b/N_0 \approx 12$ dB. For BPSK modulation, BER takes lower values than for QPSK modulation and higher order modulation. The obtained simulation results encourage the use of BPSK modulated signals in further studies.

Figure 3 shows the space constellation diagram for a series of 1000 symbols received, which were subjected to BPSK modulation and were transmitted in the AWGN channel with $E_b/N_0 = 5$ dB.

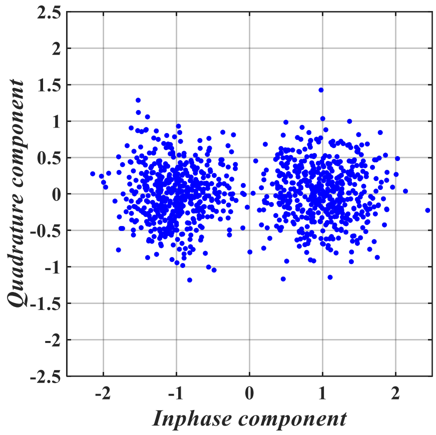

Figure 3. Space constellation diagram for BPSK modulation used in AWGN channel (E_b/N_0 = 5 dB)

3. Simulations - transmission in channel with fading

As a result of multipath propagation phenomenon the hydroacoustic signal sent by the transmitter reaches the receiver in the form of its many components shifted relative to each other in time.This causes intersymbol interference (ISI) and fading of the received signal. Such an acoustic underwater channel can be presented as a linear filter whose low-pass impulse response $h(\tau,t)$ is the sum of the impulse responses corresponding to all n propagation paths, where each of these paths is described by the corresponding amplitude $a_n(t)$, phase $\varphi_n(t)$ and delay τ_n(t). Delay τ applies only to paths obtained during reflections and the value of these paths depends on their geometry. The number $N(t)$ is the maximum number of propagation paths during transmission, depending on t. It is assumed that the individual components of the incoming signal are mutually uncorrelated.

It is assumed that the transmitted signal $s(t)$ has a form:

$$s(t) = Re[s_{LP}(t)\; e^{j2\pi f_c t}], \tag{4}$$

where $s_{LP}(t)$ is the low-pass complex envelope signal $s(t)$ and f_c is the nominal carrier frequency. Omitting the presence of noise, the received signal can be represented as:

$$x(t) = \sum_{n=1}^{N(t)} a_n\,(t) s[t - \tau_n(t)]. \tag{5}$$

By substituting equation (4) for equation (5) the expression (6) is obtained:

$$x(t) = Re\left[\sum_{n=1}^{N(t)} a_n\,(t) e^{-j2\pi f_c \tau_n(t)} s_{LP}\big(t - \tau_n(t)\big)\right] e^{j2\pi f_c t} \tag{6}$$

and the equivalent low-pass reception signal has the form:

$$x_{LP}(t) = \sum_{n=1}^{N(t)} a_n\,(t) e^{-j2\pi f_c \tau_n(t)} s_{LP}\big(t - \tau_n(t)\big). \tag{7}$$

The complex low-pass impulse channel impulse response of a multipath underwater channel can be presented in the form (8) [4]:

$$h(\tau, t) = \sum_{n=1}^{N(t)} a_n\,(t) e^{-j\varphi_n(t)} \delta\big(\tau - \tau_n(t)\big), \tag{8}$$

where $\varphi_n(t)=2\pi\, f_c\, \tau_n(t)$. The above form of low-pass complex impulse response $h(\tau,t)$ relates to a non-stationary underwater channel, in which the received signal parameters (amplitude, phase and delay) are functions of time t.

However, for the shallow water environment there is a lack of distinguished, even generalized, classes of acoustic underwater channels. This fact results mainly from a large variety of existing channels, where almost every water reservoir is additionally characterized by strong changes in channel parameters over time.

Modeling using a deterministic underwater channel model a limited degree of suitability in practical solutions due to the absence of expected universality. It is usually used to analyze channels with known parameters such as, for example, a measuring pool. Therefore, a stochastic model of the underwater channel is commonly used to carry out research of data transmission in underwater channel with fading. Although this model does not take into account all factors influencing the properties of the communication channel, it largely describes the statistical conditions of the considered environment and has a large practical aspect. In order to model the communication channel, it is considered as a stochastic process for which the impulse response values of the channel are random variables with given probability distributions [5].

In this article, the considered configuration of the communication channel assumes the occurrence of a direct propagation path (LOS - *line-of-sight*). Therefore, the Rician channel model has been used, which is used when both, the direct and the reflected signals are received. The dominant direct component is usually associated with the direct propagation path with the highest power. The channel model with Rician fading is suitable for the simulation of a small range transmission channel [5].

Assuming that the envelope of the impulse response $R = |h(\tau,t)|$ has a real component R_r and imaginary component R_i, which are independent random variables with Gaussian distributions $N(\mu_r,\sigma^2)$ and $N(\mu_i,\sigma^2)$ with respective mean values μ_r and μ_i, and variance σ^2, where $R = \sqrt{R_r^2 + R_i^2}$, the envelope of the received signal has the Rice distribution with the probability density function described as (9):

$$p_{Rice}(r) = \frac{r}{\sigma^2} e^{\frac{-(r^2+s^2)}{2\sigma^2}} I_0\left(\frac{rs}{\sigma^2}\right) \quad \text{for} \quad r \geq 0, \tag{9}$$

hence, the amplitude of the direct path signal has the form (10):

$$s = \sqrt{\mu_r^2 + \mu_i^2}\,. \tag{10}$$

I_0 is the modified Bessel function of the first kind and zero order. An important parameter of the Rician model is K factor, which determines the ratio of the direct path component (dominant component) to the power in the all the other components. It can be expressed as (11):

$$K = \frac{s^2}{2\sigma^2}\,. \tag{11}$$

The phase $\varphi_n(t)$ of received signal is uniformly distributed in the interval $[0, 2\pi]$.

In order to estimate the performance of BPSK modulation, the first simulation tests were carried out in *a channel with flat fading* (non-selective channel), for which the influence of multipath effect is neglected. In these tests, BER was determined depending on the value of Rice K factor. In flat fading channel, all frequency components of transmitted signal are subject to the same attenuation and phase shift. For slow fading case, the attenuation and phase can be considered as a constant during at least one symbol interval. The received signal reaches the receiver through single fading path and this signal can be expressed as (12):

$$x(t) = a_n(t)e^{-j\varphi_n(t)}s_{LP}(t) + n(t), \tag{12}$$

where $n(t)$ is the random variable of white Gaussian process. The obtained tests results for different Rice K factor values are presented in Figure 4. With the increase of the K value, smaller BER values are obtained for specific E_b/N_0 values. To obtain BER=10^{-3}, $E_b/N_o \approx 12.5$ dB (K = 3 dB), $E_b/N_o \approx 9.5$ dB (K = 6dB) and $E_b/N_o \approx 7$ dB (K = 9 dB), is required.

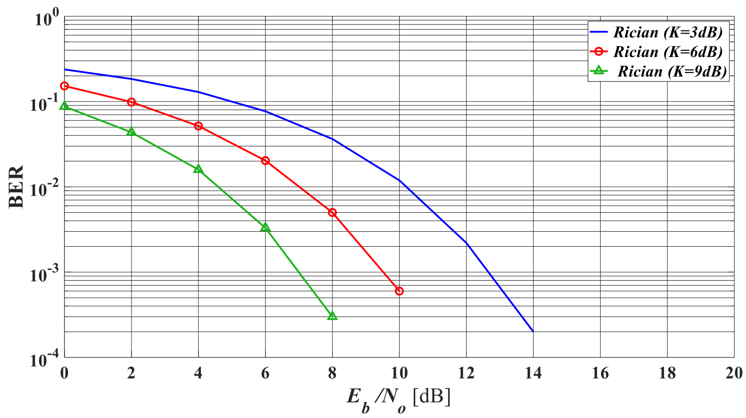

Figure 4. Bit error rate of BPSK modulation in Rician channel with flat fading

The second tested channel is a channel with *frequency-selective fading*, characteristic of the influence of multipath effects [8]. In frequency-selective fading case, the received signal consists of multiple copies of transmitted signal, attenuated and delayed in time. The path parameters for a specific transmitter-receiver configuration have been pre-determined, i.e. delays of multipath components and their average path gain, where average path gain is normalized to 0 dB. The parameters are supposed to reflect the transmission between the transmitter and the receiver, which are 300 m away, in a 20 m deep water reservoir, with the same transmitter and receiver depth of 10 m.

Simulation tests included the execution of numerous simulations, and in the article are present results for two sets of parameters. Figure 5 presents the determined *BER* values for different Rice *K* values and the following path parameters: delay τ_1 = 4.75 ms and average path gain g_1 = -3 dB. To get BER = 10^{-3}, $E_b/N_o \approx 17$ dB (for K = 3 dB), $E_b/N_o \approx 10$ dB (K = 6 dB) and $E_b/N_o \approx 6$ dB (K = 9 dB), is required.

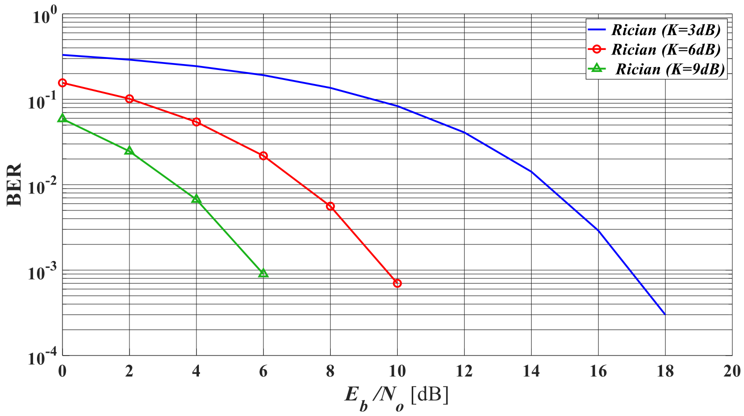

Figure 5. Bit error rate of BPSK modulation in Rician channel with frequency-selective fading (*direct path + one delayed path*)

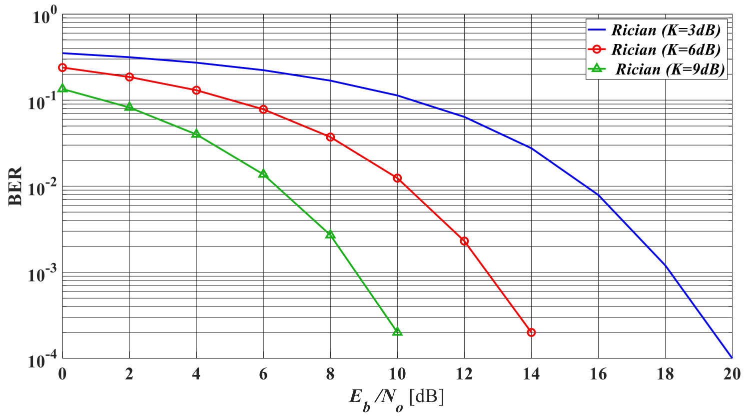

Figure 6. Bit error rate of BPSK modulation in Rician channel with frequency-selective fading (*direct path + two delayed paths*)

Figure 6 contains the determined BER values for different K values and the following parameters: (first path) delay τ_1 = 4.75 ms and average path gain g_1 = -3 dB, (second path) delay τ_2 = 7.45 ms and average path gain g_2 = -4.6 dB. It follows that to ensure the transmission with the value of BER = 10^{-3}, $E_b/N_o \approx$ 18 dB (for K = 3 dB), $E_b/N_o \approx$ 12.5 dB (K = 6 dB) and $E_b/N_o \approx$ 8.5 dB (K = 9 dB), is required.

4. Conclusions

Simulation tests of the acoustic underwater data transmission system using coherent modulation have been carried out. This modulation allows to achieve high transmission rates in comparison with non-coherent modulations. Obtaining a reliable transmission with BER = 10^{-3} for the AWGN channel requires $E_b/N_o \approx$ 7 dB, while for the channel with flat fading $E_b/N_o \approx$ 12.5 (for K = 3dB) is required. In turn, for two tested channels with frequency-selective fading of specified parameters to obtain the same BER can be achieved using $E_b/N_o \approx$ 17 (for K = 3 dB) and $E_b/N_o \approx$ 18 (for K = 3 dB). For the channels with fading, when the increase of Rice K factor, a reduction in the required E_b/N_o is observed.

However, these are still significant values of E_b/N_o, when the efficient communication system is considered. The conducted tests, in particular those concerning the channel with frequency-selective fading with assumed simple channel parameters, showed the necessity of applying countermeasures to transmitted of signal fading, eg channel coding and channel correction techniques.

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