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Wireless Data Transmission in Underwater Hydroacoustic Environment Based on MIMO-OFDM System and Application Adaptive Algorithm at the Receiver Side

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Abstract: To increase the transmission speed in wireless data transmission systems, it is necessary to change either the bandwidth or the spectral efficiency, or both simultaneously. Systems based on Multi-Input Multi-Output (MIMO) methods can significantly increase spectral efficiency through parallel transmission using several transmitters and receivers. Such systems are particularly attractive for use in underwater acoustic communications systems, which are normally bandwidth-reduced. MIMO system along with OFDM (Orthogonal Frequency-Division Multiplexing) is a popular technology used in wireless networks to provide a high data transfer rate and resistance to multipath and fading of the channel. The implementation of such a system requires being aware of the channel condition at the receiver, and can be provided by means of using channel parameter estimation schemes. The adaptation task on the receiving side, apart from peak of pattern formation in the direction of the signal expected, also includes the interference-source suppression, that is, the issue of implementing spatial filtering of interference from other directions. However, since the signal and noise direction of arrival are unknown, we get a system with adaptive antenna array (AA). In the proposed research, a phase antenna array was used with controlled weighing.

Keywords: Antenna array (AA), MIMO, OFDM, Multipath, Adaptive algorithm, Hydroacoustic channel.

1 Introduction

The study of the world's ocean for research purposes, the search for minerals on the seabed and the discovery of the oil field have sparked the brisk growth of wireless systems of hydroacoustic communication. The ability of such systems to transmit data in conditions of poor interference situation is one of the main indicators of system performance. This indicators are characterized

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by the probability of an error in the transmitted bitstream information at a given signal-to-noise ratio. The situation is worsened if the channel is an environment in which the signal can reach the receiving antenna through a lots of paths as a result of reflection from the sea surface, the bottom and various underwater objects that can be located at different depths. In this regard, the developers of wireless sonar systems have the task of reducing the probability of incorrect recognition of information in the receiving device. To increase noise immunity, there are various techniques, for example, increasing the signal power, thereby increasing the signal-to-noise ratio, or applying noise-immune encoding of digital information, as well as using adaptive modulation of the signal modulation scheme in the transmitter. However, it is not always possible to achieve the desired results because increasing the signal power can be up to a certain limit, associated with the electrical strength of the nodes or the permissible maximum radiation power causing cavitation. Noiseless coding adds redundancy to the transmitted information stream, which leads to a decrease in the efficiency of using the allocated frequency band. Adaptive modification of the type of signal modulation requires a certain synchronization of the receiver and the transmitter and cannot always be simply realized. In addition, the use of single-frequency modulation schemes reduces the stability of the communication system to signal fading. For a hydroacoustic medium, there is another feature, which consists in a strong increase in the attenuation of hydroacoustic signals with increasing frequency, which does not allow increasing the data rate due to the expansion of the used frequency band. Solve the problem of fading through the use of multi-frequency modulation, which is well proven in fading management/combat. A problem with the extension of the frequency band is possible if we use space-time coding communication systems. In such systems, signal transmission is carried out using several spatial streams that separate the common frequency band. To reduce the influence of multipath propagation, it is possible to apply adaptive algorithms of space-time signal processing that allow spatial filtration under conditions of a complex picture of the propagation of signals in a wireless channel.

The adaptive processing is the processing signals outputted from the array antenna and receiving antenna characteristics allows to generate a desired shape orientation to suppress unnecessary pathways in environmental conditions with many paths. Which path the system chooses depends on the criterion by which the optimal weight vector is selected. For example, in the proposed study, the criterion for maximizing the average power in the receiver is considered. In this case, the adaptive system forms the maximum of the directivity characteristic in the direction of the path with the maximum power and zeros on the remaining paths. As a result, the interference of the signals decreases in the receiver, and the probability of the bit error reduced. It should be noted that such a criterion is applicable in the absence of external interference.

2 The Proposed Method

2.1 Mathematical model

The hydro-acoustic channel is a complex environment that changed from time to time. The main features of the propagation medium include the growth of attenuation with increasing frequency of transmitted signals, various reflections, reverberations and a low speed of propagation of signals, which leads to interference and distortions of the transmitted signal in the receiving antenna. To combat signal fading, the present work uses a multifrequency modulation of signals with orthogonal frequency multiplexing of channels – OFDM. Features of OFDM technology is that the signal is divided into several slowly varying subcarriers, which are more resistant to signal fading. In addition, for OFDM modulation, the loss of part of the signal spectrum does not lead to a complete loss of transmitted information, which is an advantage for transmitting some types of data, for example video recordings from cameras located on board a submarine. A detailed look at the selected type of modulation, its features and methods of forming OFDM symbols can be found in [1 – 3].

Due to limitations on the operating frequency band and the frequency of the carrier oscillation, the problem arises of applying new approaches to the transmission of sonar signals. Such approaches include methods based on spatial coding, which are already actively used in radio communication [4]. For hydroacoustics, this direction of research also causes interest, which is considered in the research [5 – 6]. Methods of spatial signal processing allow to increase the transmission rate due to the use of a lots of transmitting and receiving antennas. In this case, each transmitting antenna radiates its own signal in the overall frequency range of the communication system. Fig. 1 shows the structure of a MIMO-based communication system.

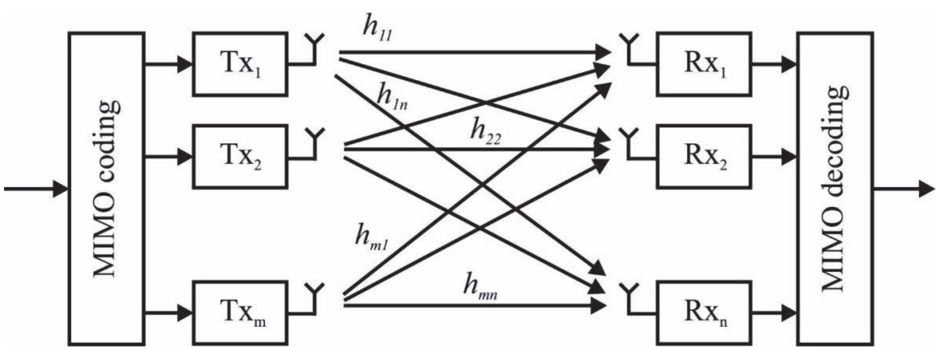

Fig. 1 – *The transmission of information flow scheme for MIMO-systems.*

This figure also indicates the transmission factors between each pair of transmit and receive antennas. Generally, these coefficients are complex and describe the impulse response of the wireless sonoacoustic communication channel. The case will be considered when the number of transmitting and receiving antennas is the same, but the situation is possible, the number of transmitting antennas may be greater than the receiving antennas or vice versa. The situation with an unequal number of MIMO antennas at the receiver complicates the algorithms for demodulating spatial signals.

The signal propagation environment is described by a matrix of channel parameters that are the transmission coefficients between all pairs of receive and transmit antennas

$$\boldsymbol{H}(t,\tau)=\begin{bmatrix} h_{11}(t,\tau) & h_{12}(t,\tau) & h_{13}(t,\tau) & \ldots & h_{1N_t}(t,\tau) \\ h_{21}(t,\tau) & h_{22}(t,\tau) & h_{21}(t,\tau) & \ldots & h_{2N_t}(t,\tau) \\ h_{31}(t,\tau) & h_{32}(t,\tau) & h_{33}(t,\tau) & \ldots & h_{3N_t}(t,\tau) \\ . & . & . & \ldots & . \\ h_{N_r1}(t,\tau) & h_{N_r2}(t,\tau) & h_{N_r3}(t,\tau) & \ldots & h_{N_rN_t}(t,\tau) \end{bmatrix}.$$

The evaluation of the matrix is performed based on the transmission of a training sequence of signals, the structure of which is known in advance at the receiver. In the case of using OFDM signals, pilot signals are used to estimate channel characteristics. For the MIMO-OFDM system, algorithms for estimating the channel matrix from the pilot signals can be found in [7-9]. To simulate a wireless hydroacoustic communication system, you must have a mathematical model of the transmission propagation. In the case of radio communications, there are different standards that describe the channel characteristics in free space, but for hydroacoustics there is no such standard, since the description of the medium depends strongly on the time of year and the water area of interest. Therefore, we use the mathematical model of the channel and the assumptions adopted in [10 – 12]. Parameters of the simulation will be similar, presented in [13]. The feature of the presented model is that it is suitable for wireless communication systems based on antenna arrays, which can be used to develop adaptive algorithms. Adaptive antenna arrays are used in communication systems, where it is necessary to form the directivity characteristic of the required shape for spatial filtering of signals [14 – 15]. The article deals with the case when it is necessary to form the directivity characteristic in the direction of the source of the useful signal and zero to the sources of interference, and the direction to this or that is not known a priori. Such an adaptive processing system is obtained from an ordinary phase antenna array by using weight processing.

2.2 The proposed method

To reduce the influence of multi-path signal components, an adaptive processing algorithm is proposed in the work that performs spatial filtering of signals by adaptively changing the form of the receiving antenna's directivity characteristic. Adaptation is performed by weight processing of space-time signals from the outputs of antenna array elements. The resulting formed equivalent directional characteristic whose form is determined by the selected algorithm forming weight coefficients. In the present paper, the criterion of maximizing the signal / (interference + noise ratio) is used. The process of calculating the weight vector is based on the calculation of eigenvalues and eigenvectors of the spatial correlation matrix [14 – 15].

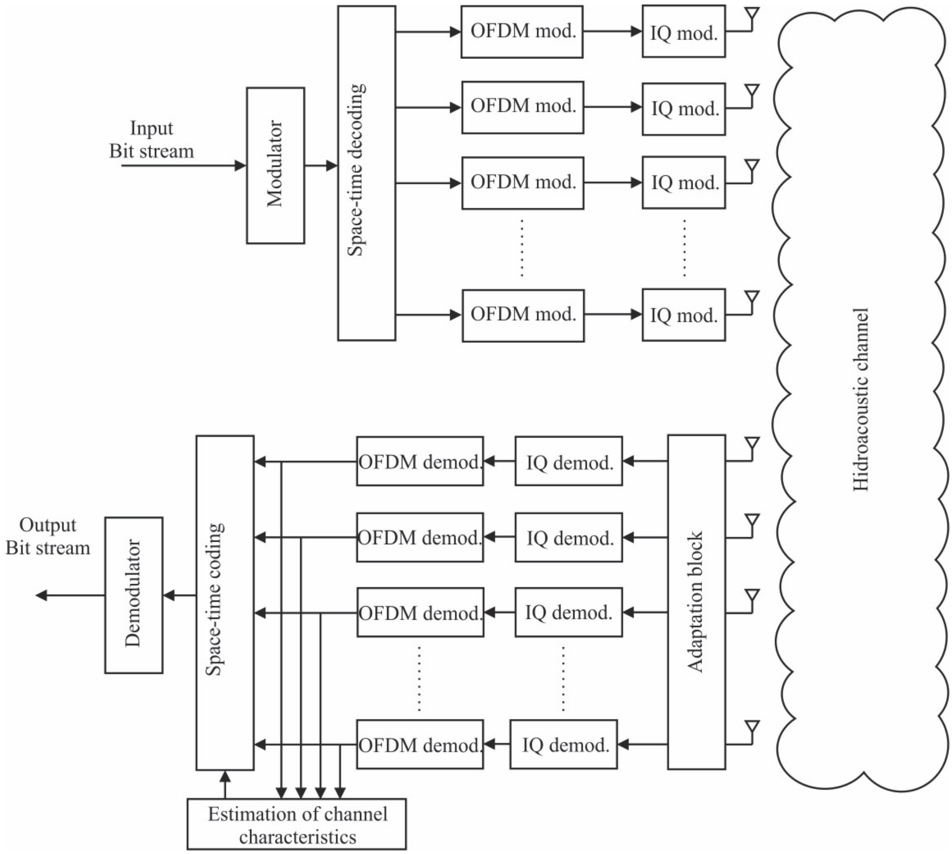

Fig. 2 – *Generalized block diagram of MIMO-OFDM system.*

The eigenvalues of the correlation matrices represent the physical meaning of the power signal paths which come into an aperture of the antenna array at different angles. As a result, if you select the maximum value of the eigenvalue, it will correspond to the path that has the maximum power, and the corresponding eigenvector corresponding to this number is a weight vector to form the maximum of the directivity characteristic in this direction and zeros in the directions of other sources. As a result, the selected adaptation criterion allows one to select only an optimum signal source and to suppress other, allowing the likelihood of bit errors in the received message.

For modeling purposes, a structural diagram of the hydroacoustic communication system was developed (Fig. 2), the input data of which is a bitstream, which can be voice information, image, video signal or control commands. The input bit stream is fed to a modulator where the signal is modulated by one of the digital modes of modulation, and then spatial coding is performed. The resulting independent streams are fed to the OFDM modulator at the output, which has a complex envelope of the signal, the spectrum of which is transferred to the carrier wave using a quadrature modulator. The received signal is radiated into a hydroacoustic medium and enters the receiving antenna, where after the adaptive processing unit, the OFDM signal spectrum is transferred to the intermediate frequency with its demodulation in the OFDM demodulator. Further, decoding of the space-time signal is performed with demodulation of the information from the subcarriers, resulting in the output of the transmitted bit stream.

3 Experimental Results

In the present study to evaluate the effectiveness of the developed adaptive algorithm was carried out computer modeling of hydroacoustic communication system. It included the following experiments:

1. The analysis of bit error probability versus signal / noise ratio;
2. The analysis of the dependence of bandwidth at different signal / noise ratio;
3. The image transfer efficiency was calculated by using the communication channel adaptation algorithms.

The probability of a bit error is determined by the formula [18],

$$BER = \frac{N_{err}}{N_{total}}, \tag{1}$$

where in N_{err} – number of incorrectly received bits; N_{total} – total number of transmitted bits.

The channel capacity can be calculated using the formula [17]

$$C = \max(\log_2[\det(\boldsymbol{I}_{NRx} + \frac{\rho}{N_{TX}}\boldsymbol{HH}^H)])\,[\text{bit / s / Hz}], \tag{2}$$

where ρ is the signal-to-noise ratio (SNR); ***H*** is the spatial matrix of channel characteristics.

Let us consider how the probability of a bit error for a sonar system based on MIMO-OFDM changes with a change in the signal-to-noise ratio. The parameters of the OFDM signal depend on delays in the propagation medium and have a value of the order of 50 ms, with the chosen parameters of the hydroacoustic medium simulation presented in [17].The delay time required to determine the guard interval length OFDM-signal which is used to reduce intersymbol interference at the receiver, and according to [3] must be greater than the maximum delay of signal propagation. The signal bandwidth is chosen to be 20 kHz, which is divided into K=4096 subcarriers. The duration of the resulting OFDM symbol can be determined by the formula

$$T = \frac{K}{B} = \frac{4096}{20000} = 204.8\,[\text{ms}]\,. \tag{3}$$

The selection of the number of subcarriers below 4096 is not effective, since the duration of the guard interval remains unchanged throughout the entire transmission time of the message, and hence the efficiency in the transmission of information will decrease. The number of independent spatial streams is assumed to be equal to two, as a result, a MIMO system of 2×2 is obtained. The transmission requires using a rarefied antenna array (5λ order or more) to reduce the spatial correlation, which leads to errors in the decoding of the signal at the receiver [20]. The receiving antenna array is divided into blocks that perform the formation of an adaptive directivity characteristic. To ensure high spatial correlation, a dense antenna array with a distance between elements of the order of 2λ is used for reception. In the general case, each receive antenna (unit) generates its independent directional characteristic. The channel model takes into account the presence of a direct path, which will have the least propagation delay and attenuation. As a result, the adaptive algorithm described above will form the maximum of the directivity characteristic in the direction of this path. The obtained effect can be visually seen by constructing the antenna pattern of the antenna after the weight processing in the adaptive processor, Fig.3, where two independent directivity diagrams of the antenna blocks are constructed after adaptation. The same figure shows the true direction to the straight path, and the maximum is directed, as expected, in this direction and zeros in the direction of the other sources. As a result, we get a sort of spatial filter that allows us to isolate the signal from the source of interest and to suppress the rest.

Let us consider how the signal constellation of the received signal changes in this case (Fig. 4).

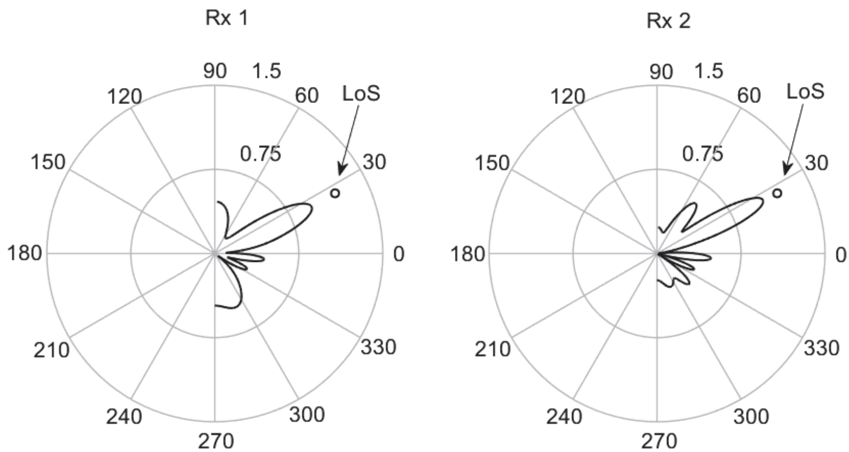

Fig. 3 – *Adapted directivity pattern in a receiver for a signal / noise ratio of* 7 dB.

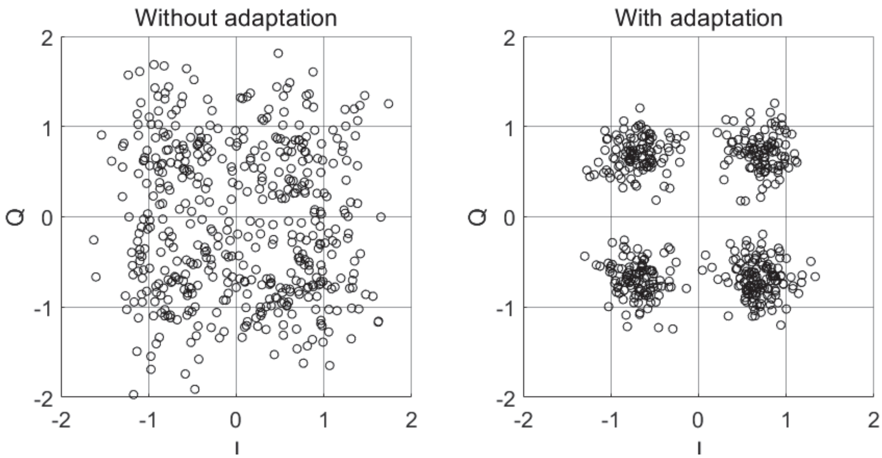

Fig. 4 – *Signal constellation after demodulation in the receiver with SNR of* 5 dB.

The analysis of the result obtained in Fig. 4 shows that the range of signal values in the constellation is significantly reduced in the receiver with adaptive processing, which reduces the probability of an error in receiving information. A decrease in the probability of error in relation to the signal-to-noise ratio is shown in Fig. 6.

As can be seen from the figure, the adaptive algorithm allows achieving a significant error reduction, and already at 20 dB the probability is reduced by 25 times compared to the system where a similar receiver is used, without spatial filtering though. In addition, adaptive processing has a positive effect on the bandwidth of the channel. This influence is reflected in Fig. 6.

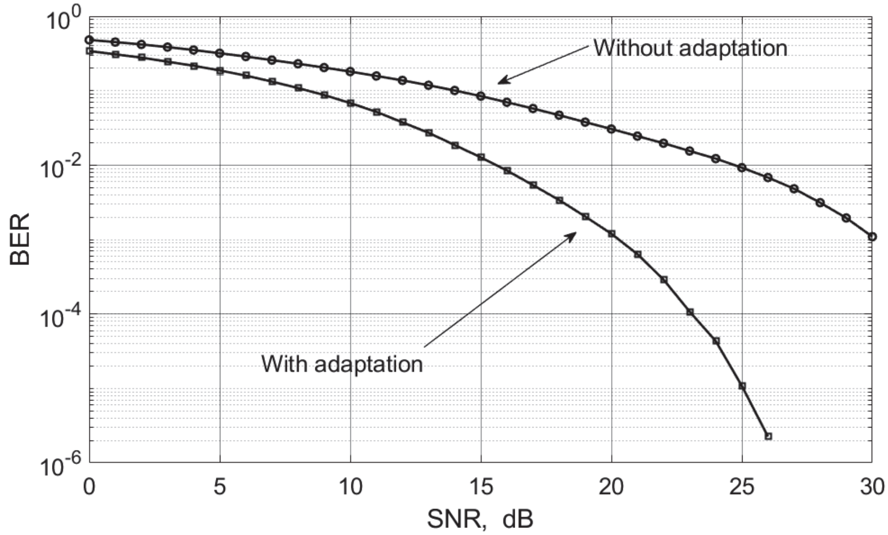

Fig. 5 – *The probability of bit error for a communication system using adaptive processing and without.*

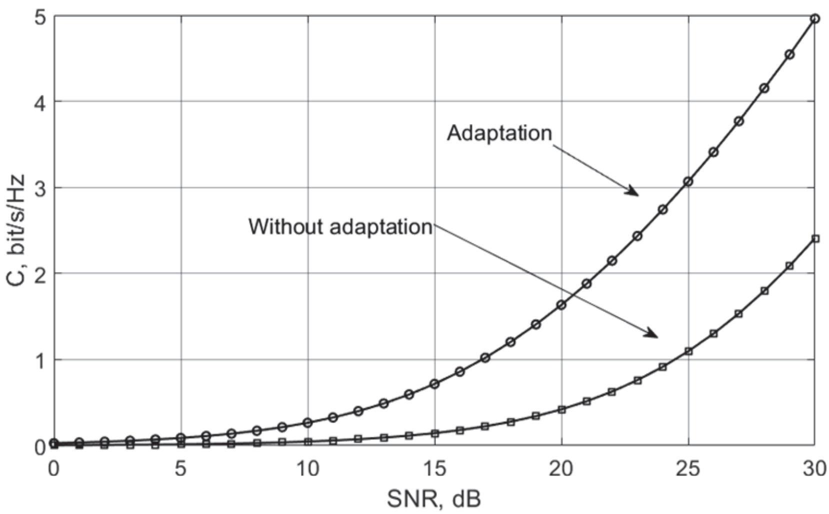

Fig. 6 – *Dependence of bandwidth using adaptive processing and without it.*

For a clearer result a computer experiment of image transfer was conducted (Fig. 7) along the hydroacoustic communication channel. The original image is a bit stream of information which is modulated, encoded and converted into multiple parallel streams, and then transmitted through a propagation medium. Similarly to the previous experiment, we consider the result of the image reconstruction at the receiver using the adaptation algorithm and without (Figs. 8 and 9) for a given signal / noise ratio of 10 dB.

Fig. 7 – *Original image.*

Fig. 9 and Fig. 10 allow a visual assessment of the influence on the channel noise immunity the use of spatial filtering. For a quantitative estimate of the transmitted information it is necessary to use one of the existing metrics of image quality evaluation given in [21]. In this work, we used the metric of the mean square error (MSE), which is described by the following formula

$$MSE = \frac{1}{MN}\sum_{j=1}^{M}\sum_{k=1}^{N}(x_{j,k} - x'_{j,k})^2 , \qquad (4)$$

where M and N are the image size; x is the original image; x' is the received image.

To exclude dimension mean square error we normalize the result obtained by the (4), the average brightness value of the original image, which is calculated as follows:

$$S^2 = \frac{1}{MN}\sum_{j=1}^{M}\sum_{k=1}^{N}(x_{j,k})^2 . \qquad (5)$$

Based on these formulas we can construct a graph of the normalized mean square error values as a function of signal / noise ratio (Fig. 10). In this case, the image transfer speed is doubled compared to a conventional communication system.

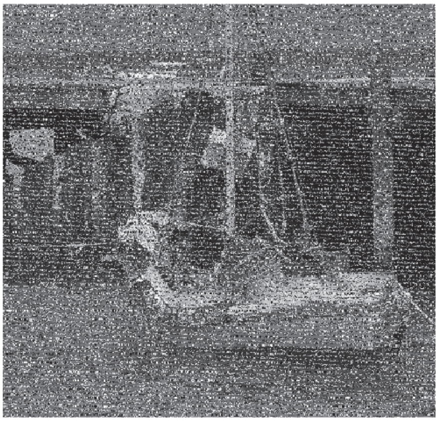

Fig. 8 – *Image transmission over the communication channel with the MIMO-OFDM* 2×2 *system without adaptation.*

Fig. 9 – *Image transmission over the communication channel with the MIMO-OFDM* 2×2 *system without adaptation.*

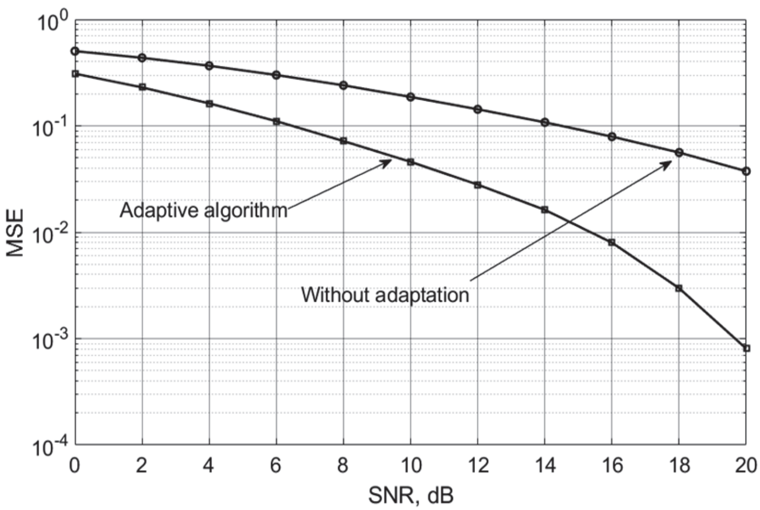

Fig. 10 – *Dependence of the normalized mean-square error of the image on the signal-to-noise ratio.*

6 Conclusion

In the proposed paper, simulation was conducted of a wireless data transmission antenna arrays for underwater hydroacoustic channel. The adaptive algorithm has been proposed for processing spatio-temporal signals based on the formation of an equivalent directional characteristics of the receiver antenna array in the signal arrival highest power direction in one of channel propagation paths. Modeling of the transmission of the image over the wireless hydroacoustic channel was made, resulting in a visual representation of the effect of the adaptation algorithm on the transmitted information. The results obtained also include: a quantitative estimate of the quality of transmitted information, the dependence of the standardized mean square error on the signal-to-noise ratio, the dependence of the channel capacity with and without adaptive processing, the probability of a bit error depending on the signal-to-noise ratio. The computer experiment showed that the adaptive algorithm allows achieving a significant error reduction and already at 20 dB its probability is reduced by 25 times compared to a similar receiver without spatial filtering and the data transmission speed is increased.

7 Acknowledgement

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