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Adaptive Algorithm for Wireless Data Transmission (Including Images) Based on SISO System and OFDM Technique

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Abstract: The efficiency of wireless systems to transmit information in a complex interference situation is one of the main indicators of the effectiveness of the system, which can be characterized by the probability of an error in the transmitted message. This characteristic depends on the interference situation of the communication channel and the nature of the signals propagation in the medium. If the medium has a multi-path character, the signal interferes with the receiving antenna, causing signal fading. So the developer of wireless communication devices is faced with the task of increasing the noise immunity of the system. It can be increased in various ways, for example, by using adaptive processing algorithms for spatio-temporal signals. In this paper we solve the problem of improving noise immunity in wireless communication systems by applying an algorithm of adaptive spatial-temporal signal processing in the receiver based on an adaptive antenna array, which allows spatial filtering under conditions of a complex pattern of signal propagation in a channel with reflections. Calculation of weights for the adaptation algorithm in the article is based on the theory of eigenvalues and vectors of the spatial correlation matrix.

Keywords: Antenna array (AA), SISO, Multipath, Adaptive algorithm, Coding, OFDM.

1 Introduction

At present, the development of wireless technology has affected all areas of human activity. The devices for wireless data transmission can be found everywhere: broadcasting, television, various information exchange devices. The quality of the transmitted information depends on the level of the received signal on the noise background, if the distance between the transmitter and the receiver increases, the signal-to-noise ratio decreases, resulting in the probability of erroneous reception of information. If the channel is multi-path and the signal comes to the receiving point after multiple reflections (for example, different buildings), so the situation of signal fading in the receiver is possible. Fading can be effectively controlled by multifrequency modulation

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types that allow dividing a common frequency band into many slowly changing signals that are less prone to fading. An example of this kind of modulation is OFDM (Orthogonal Frequency–Division Multiplexing) [1 – 4, 9 – 12]. One of this technology features is the effective use of allocated frequencies due to the orthogonal allocation of subcarriers. A plurality of parallel data streams are generated using subcarriers in the total frequency band which are modulated independently, and then transmitted in a single OFDM-symbol. This approach converts the frequency-selective channel into parallel flat sub channels. Since the distance between sub-carriers is minimal, then the demodulation capabilities need to keep orthogonality.

Data transmission over a communication channel with a low probability of bit error is possible up to a certain bit rate with a given signal-to-noise ratio. Therefore, in addition to the adaptive algorithm, in order to increase the noise immunity of the wireless system, let's consider the use of channel coding schemes. Such coding is a series of transformations of the original bit sequence, as a result of which the transmission of information flow becomes more resistant to the deterioration of the quality of the transmitted information caused by noise, interference and signal fading. Channel coding allows reaching a compromise between bandwidth and the probability of bit error.

The situation can be improved by using of adaptive algorithms for spatio-temporal signal processing [5 – 8]. Adaptive antenna arrays are used in the communication systems where it is necessary to form the directivity characteristic of the required shape for spatial filtering of signals. In the article we consider the case when it is necessary to form the directivity characteristic of the receiving antenna in the direction of the source of the desired signal and zero at the sources of interference, and the direction to one or another is unknown a priori. Spatial filtering allows eliminating the influence of multipath components of the channel on the transmitted information quality by reducing the probability of errors that occurs due to the influence of fading.

Optimum weight vector depends on the optimality criterion (a maximum signal-to interference plus noise ratio criterion, average power optimality criteria minimum at the antenna output and the minimum mean square error). In practice, the task of adaptation is the search for optimal weights that correspond to the extremes of the objective functions of the adaptive antenna array. The effectiveness of spatial filtering is influenced by how accurately the weight vector estimate is obtained during the adaptation process.

The adaptation criterion introduced in the article allows to select the arrival path with the maximum power and to suppress others. This reduces the interference signals in the receive antenna and improves the noise immunity of the system.

2 The Proposed Method

A communication system with one transmit and one receiving antenna is considered, such systems are called SISO (Single Input Single Output) and in combination with OFDM technology to combat signal fading in a multipath channel [9 – 14]. To provide high data transfer speed in such systems without bandwidth expansion it is possible due to application of multi-position types of digital manipulation of carrier wave, for example 16-QAM, 32-QAM, etc. However, this approach leads to a decrease in noise immunity and at the same signal-to-noise ratio the quality of the provided services in the field of wireless data transmission worsen. Thus, in order to maintain the quality of the services provided at a high level, it is necessary to solve the problem of reducing the probability of a bit error. The first thing that can be done is to apply noise-immune encoding, which allows to correct errors in transmitted information packets, one such approach will reduce the effective bit rate, but will allow to achieve an acceptable error probability against a background of some increase in speed. The second approach is to develop algorithms for spatial signal processing, which allows you to filter sources (paths) over space (angular coordinates). Such processing is possible due to the formation of the receiving antenna characteristic, which can be adapted to the changing conditions of signal propagation.

The proposed method of adaptation consists in the weight processing of signals from the outputs of antenna array elements of the receiving antenna and allows forming the antenna directivity characteristic, the character that will depend on the chosen adaptation criterion. The criterion chosen in the work is based on the maximization of the signal/(interference + noise) ratio, in which the adaptive processor will form the maximum of the directivity characteristic in the direction to the path with the maximum power and zeros to the remaining paths.

Considered method is based on a correlation approach [15, 16]. At first it is necessary to calculate the spatial correlation matrix for adaptation task:

$$\boldsymbol{R}_{xx}(i,j) = E\left\{\boldsymbol{X}(i)\cdot\boldsymbol{X}^{H}(j)\right\} = \frac{1}{L}\sum_{i=0}^{L-1}\boldsymbol{X}(i)\cdot\boldsymbol{X}^{H}(j)\,. \tag{1}$$

The matrix in expression (1) can be represented as a spectral decomposition into eigenvalues and eigenvectors

$$\boldsymbol{R}_{xx} = \boldsymbol{V}\boldsymbol{\Lambda}\boldsymbol{V}^{H}\,,$$

where $\boldsymbol{V}$ is the unitary matrix of eigenvectors; $\boldsymbol{\Lambda}$ is the diagonal matrix of the eigenvalues λ_n:

$$\boldsymbol{V} = \begin{bmatrix} \boldsymbol{V}_1 & \boldsymbol{V}_2 & \ldots & \boldsymbol{V}_n \end{bmatrix},\ \boldsymbol{\Lambda} = \begin{bmatrix} \lambda_1 & 0 & 0 & 0 \\ 0 & \lambda_2 & 0 & 0 \\ 0 & 0 & \ddots & 0 \\ 0 & 0 & 0 & \lambda_n \end{bmatrix}.$$

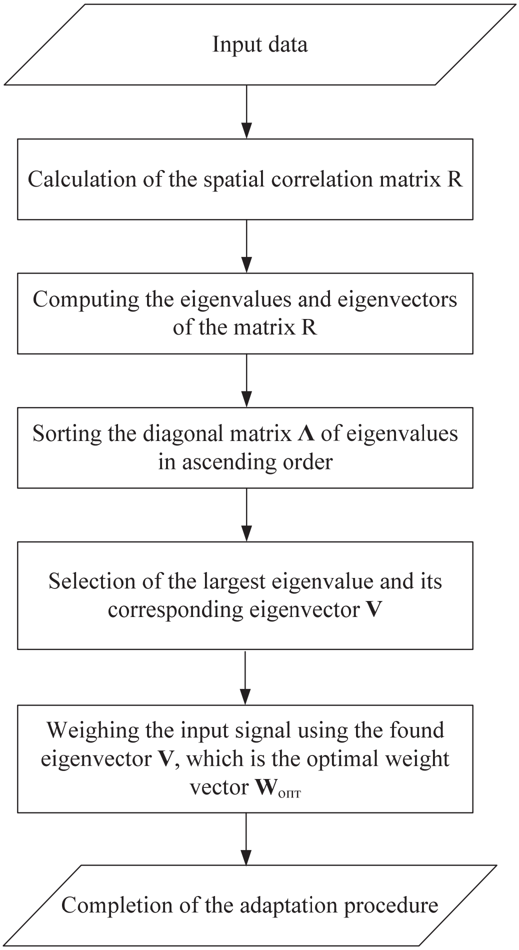


Fig. 1 – The *algorithm of the adaptive processor.*

The eigenvalues of the correlation matrix are the powers of the sources, and in the case under consideration, the paths along which the signal comes. This implies the condition that the number of sources (paths) should not be greater than the number of eigenvalues of the spatial correlation matrix, whose eigenvectors are weighting factors for processing the signal from the output of the elements of the antenna array. From the theory of adaptive antenna arrays [7] it is known that if you choose the maximum eigenvalue, then this number will correspond to the path through which the signal with maximum power comes, and to form a maximum in the direction of this source, you must use the eigenvector corresponding to the selected maximum eigenvalue. Fig. 1 shows the algorithm of the adaptive processor in the receiving antenna unit.

In the adaptive processor there is an inaccuracy in the formation of the directivity characteristic, which is related to the fact that it is impossible to obtain the true value of the correlation matrix due to the limited averaging time. Another feature of the presented adaptive algorithm is the need to provide a high spatial correlation for this, it is necessary that the distance between the elements of the receiving antenna array is as small as possible.

3 Experimental Results

Consider the results of modeling, which are the probabilistic characteristics of a bit error with and without channel coding, the type of the directivity characteristic, and the results of image transmission over the communication channel. As already mentioned above, the principle of adaptation is that the path of the signal with the maximum power is selected according to the chosen criterion. If the communication channel has a direct path, then it will have the maximum power, since it has the shortest delay time, and therefore is the shortest path and is not distorted by various reflections. As a result, it is expected that, with the adaptation, the maximum directivity characteristic will be directed precisely to this path. Let us check the proposed theory, taking as a basis the channel and parameters, as in [15].

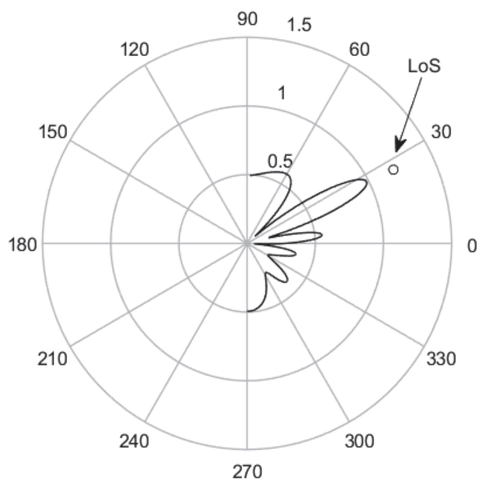


Fig. 2 – *Adapted directional pattern after weight processing with SNR of 5 dB.*

Let's construct an antenna pattern after weight processing for a signal-to-noise ratio of 5 dB, while using the simulation results, we also note the true angle of the arrival of the direct path in this diagram (Fig. 2).

The results obtained in Fig. 2 the results show that the adaptive algorithm correctly calculated the weight vector and allocated a line of sight path, and in the direction of the remaining paths sent a minimum or zero directional characteristics. It is suppose that the weighting operation should positively affect the demodulation of the signal in the receiver. To check this assumption it is possible, having considered a signal constellation of signals of subcarriers OFDM-symbol in Fig. 3 (for a signal to noise ratio of 5 dB).

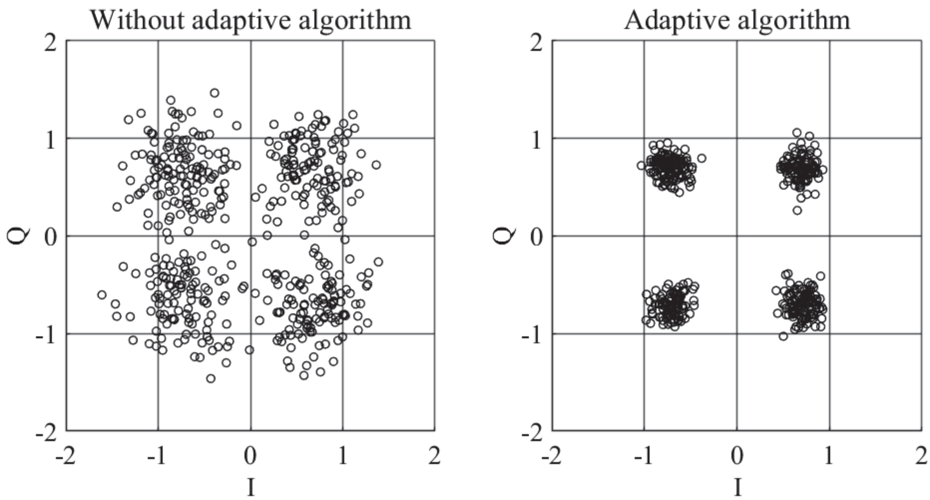


Fig. 3 – *Signal constellation after demodulation in the receiver at 5dB SNR.*

From Fig. 3 that for the receiver with adaptive processing (on the right) the scatter of the value of the signal constellation is insignificant relative to the true value of the vector, and, consequently, the error probability tends to zero. If we look at the constellation of the receiver without adaptation (on the left), we can see that the values of the received vector may mistakenly take adjacent values, which will probably lead to an increase in the bit error and improper demodulation of the received information.

In order to numerically evaluate the efficiency of the developed algorithm, we construct the probability of a bit error for the receiver with and without adaptation (Fig. 4).

From the results obtained, it can be concluded that adaptation can significantly reduce the probability of error and thereby improve the noise immunity of the communication system.

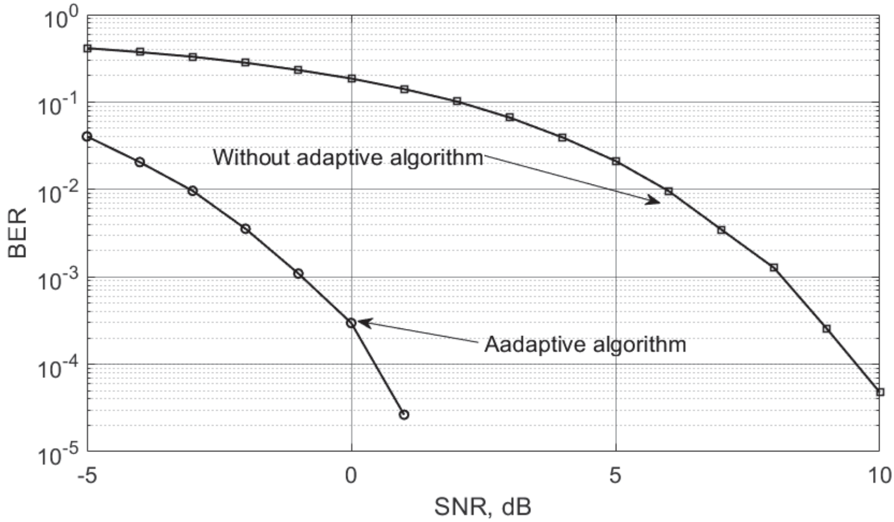


Fig. 4 – *The probability of a bit error for the adaptive algorithm.*

A situation is also possible where the error probability obtained with the help of adaptation for a given interference situation is insufficient, as, for example, in control systems for unmanned vehicles. In this case, channel coding algorithms should be used. Let us first consider as a coding algorithm a simple linear method for encoding Hamming [17 – 19]. And we will construct the dependence of the probability of bit error for a communication system using encoding for a receiver with adaptive processing and without it (Fig. 5).

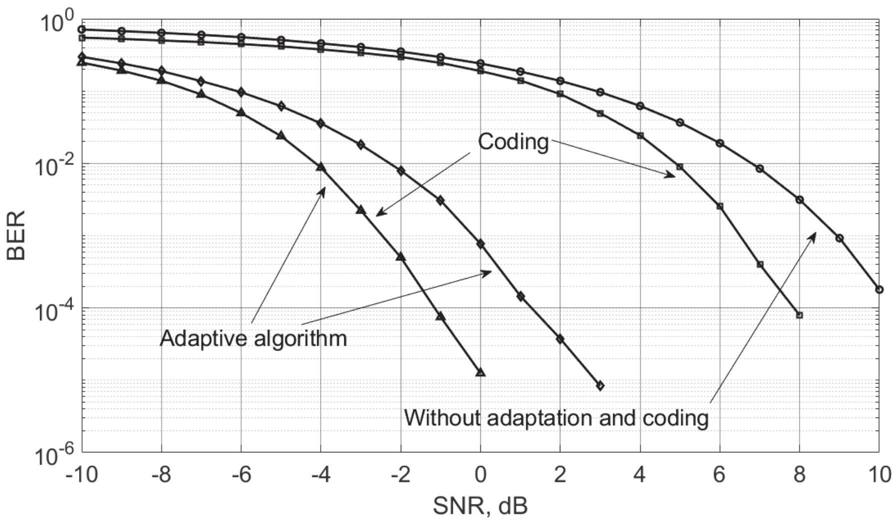


Fig. 5 – *The probability of a bit error for the SISO-OFDM system with various combinations of adaptation algorithms and the Hamming code.*

It shows the probability of a bit error for a receiver with and without adaptive processing, combined with the use of channel coding. The encoding conditions are as follows: the original message is divided into blocks of 15 bits, of which 11 are information bits, hence, the effective transmission rate will decrease like

$$R_c = \frac{k}{n} = \frac{15}{11} = 1.36 .$$

As can be seen from the Fig. 5 that it is possible to achieve a noise immunity of the communication system by 2–3 dB due to a decrease in the transmission rate of useful information. As is well known, Hamming codes are not a powerful coding tool, so consider another type of channel coding – Reed-Solomon codes [20]. For a clear comparison with the results obtained for Hamming coding, the redundancy is set to the same. Let us consider how this will change the error probability shown in Fig. 6.

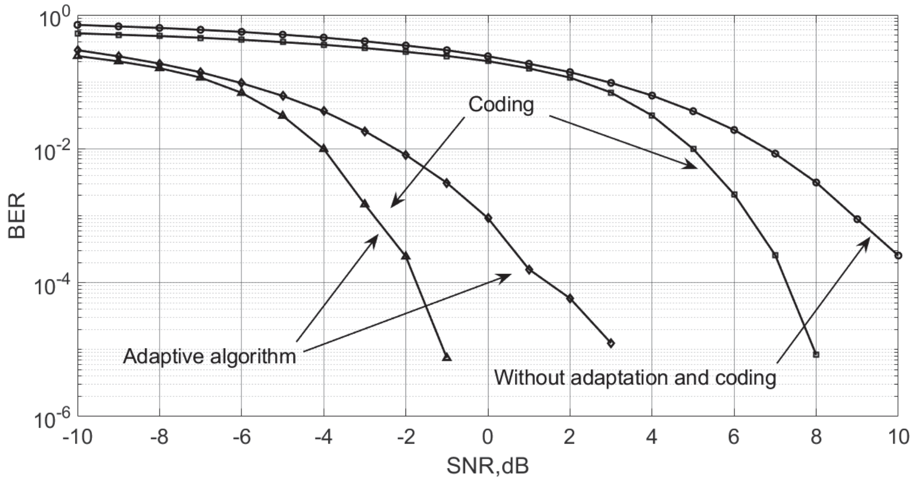
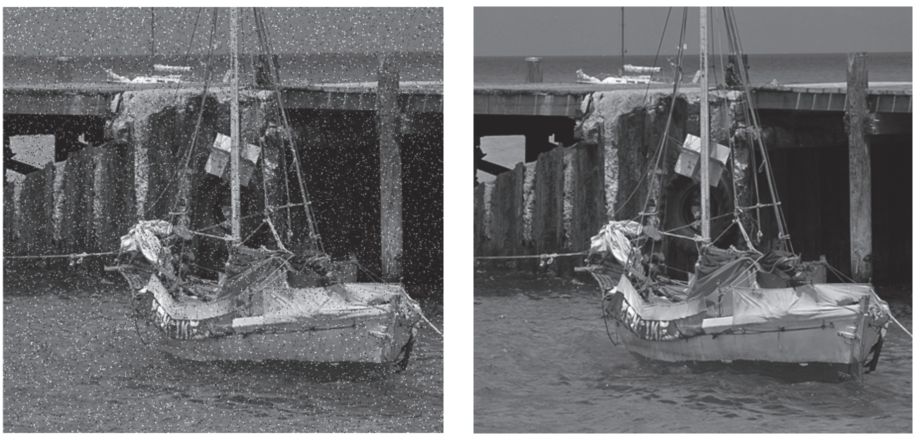


Fig. 6 – *Probability of a bit error for the SISO-OFDM system with various combinations of adaptation algorithms and the Reed-Solomon code.*

It can be seen from the Fig. 6 that with equal redundancy, Reed-Solomon codes are more efficient than Hamming codes, since they increase the noise immunity of the system by 3–4 dB. The results obtained for the bit error probability in Fig. 4, demonstrate that even with a signal-to-noise ratio of 0 dB, there are significant differences. This can be seen clearly if you send some useful information through the communication channel and compare it with the original, for example, an image. The original image is shown in Fig. 7.

In Fig. 8 shows the result of image transmission over a communication channel for a receiver with and without an adaptive algorithm for a given signal-to-noise ratio of 3 dB. The number of elements of the antenna array for adaptation is eight.

Fig. 7 – Original image.



(a) (b)

Fig. 8 – *a) Image transmission in the SISO-OFDM system without adaptation; b) Image transmission in the SISO-OFDM system with adaptation.*

The Fig. 8 clearly shows that the image quality for the receiver to adaptation significantly higher than without adaptation. Quantitatively, the dependence of the quality of the transmitted message on the signal-to-noise ratio can be estimated if one of the metrics presented in [21] is used. In this research was used the RMS error metric

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

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

We normalize (1) to the value of the average brightness of the original image

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

Fig. 9 depicts the dependence of the normalized mean square error of the transmitted image on the signal-to-noise ratio equal to 3 dB.

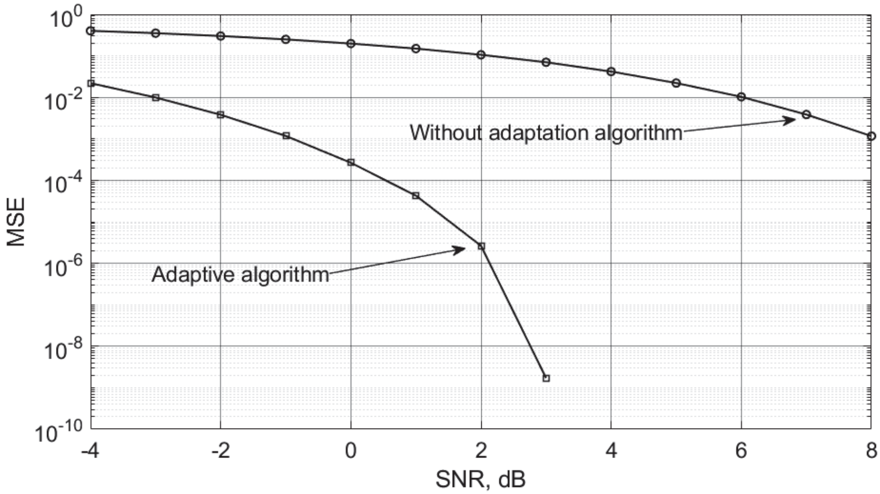


Fig. 9 – *Dependence of the normalized mean square error of the received image on the signal-to-noise ratio in the SISO receiver.*

4 Conclusion

The article study the developed adaptive algorithm for wireless data transmission in the SISO system, which makes it possible to reduce the probability of a bit error by more than two orders of value for a signal-to-noise ratio of 0 dB in a multi-path channel. The result of image transmission over the communication channel for a receiver with and without an adaptive algorithm for a given signal-to-noise ratio showed that the image quality for a receiver with adaptation is much higher than without adaptation. It is noted that with equal redundancy, Reed-Solomon codes are more effective than Hamming codes and allow increasing the noise immunity of the system by 3–4 dB.

Applying an adaptation, it is possible to correctly calculate the weight vector and to isolate the direct path, and in the direction of the remaining paths to obtain a minimum or zero directional characteristics. Also, the adaptation operation positively affects the demodulation of the signal at the receiver.

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