Adaptive interference compensation method

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Abstract. The article is devoted to the consideration of the method of adaptive compensation of interference to information transmission systems using space-time coding technology. When such systems use two or more antennas for transmitting information and the same number of antennas for receiving, it becomes possible to compensate for interference signals. The investigated compensation method is based on the introduction of adaptive filters into each of the input channels of the information transmission system. Adaptive filters are tuned to the process of the mixture of the useful signal and interference so that after the processing the sum of the interference components at the output of the compensator is minimized, and the useful signal does not deteriorate on average. The expressions that determine the algorithm of the adaptive noise compensator are given. The compensator for interference signals coming from a powerful airfield radar was built for the ground radio relay communication system with double antenna spacing. It has been shown experimentally that the compensator suppresses radio impulse interference from 30 to 40 decibels in different frequency channels of the microwave link.

1. Introduction
In connection with the rapid development of info telecommunications, information transmission systems increasingly have to work under the influence of external interference. One of the most effective methods of dealing with interference is their compensation in the information transmission channel [1]. Compensation of interference signals until the 70s of the last century was rarely used. With the development of centimeter and millimeter wavelengths, methods of space-time coding (MIMO) of signals, in which the transmission and reception of data are carried out by systems of several antennas, began to develop successfully. Reception of several copies of a useful signal, distorted to varying degrees by fading and interference, became the basis for the further development of the theory of adaptive filtering and its special case - interference compensation methods [2].

The essence of compensation methods when using MIMO is determined by the sequential execution of the following operations:

- The formation in some way of a compensation reception channel containing interfering interference signals correlated with interference in the main reception channel.
- Adaptive adjustment of the compensation signal parameters in order to increase the compensation efficiency.
- Alignment of the signals of the compensation and main channels according to the time, amplitude and phase parameters of interference signals.
• Subtraction of the compensation signal from the signal of the main receiving channel.

The purpose of this article is to develop a method for adaptive noise compensation and its analysis.

2. Analysis of interference compensation methods

Compensation methods can be with constant tuning and adaptive, in which the dynamic characteristics of the system change very difficult. The ability to deal with interfering signals in cases where notch and linear filtering methods fail, as well as the versatility of methods for compensating for interfering signals, have ensured their widespread use in telecommunication practice [3]. The great possibilities of compensation methods are also associated with their ability to deal with interfering signals under conditions of a priori uncertainty of the interference environment, when the system has a minimum of information about interfering signals [4].

The simplest method of forming a compensation channel suggests using an additional receiver, which receives mainly an interference signal. This way of organizing a compensation channel is quite effective and has been studied in detail in relation to radar problems [5]. The method is effective when the directions of possible arrival of interference signals and their properties are a priori known, for example, in medical diagnostics. Another way of creating compensation channel signals involves using the main channel signals for these purposes [6]. The device is shown in figure 1 a) and contains an adaptive noise filter (ANF), inverter and adder. The method is effective if it is possible, using the a priori known differences in useful and interfering signals, by means of special processing to get rid of the useful signal components using the ANF in the auxiliary channel, assuming all the remaining components to be interfering [7]. This method illustrated in detail by the adaptive transient noise compensator of multichannel communication equipment, considered in [1], and the compensator of spurious emissions of radio transmitting devices, described in [2]. Convenient for implementation methods of interference compensation when the system operates with a set of MIMO signals [8]. In this case, adaptive filters (AF) introduced into each of the input channels, operating in such a way that after processing in them the sum of interference components at the output of the compensator minimized, and the useful signal does not deteriorate on average. The structure of this method shown in figure 1 b).

3. Adaptive filtering algorithms

Adaptive filters are the main link of interfering signal compensators and designed either to form an estimate of the interference signal, or to process input influences in such a way as to minimize interfering signals at the output of the adaptive interference compensator (AIC). In this case, the optimality criteria that determine the preference of a certain method or compensation algorithm are not unambiguous and depend largely on the systems used and the telecommunication section where the method is applied. For example, in radio communications, hardware developers most often use the criteria of a minimum mean square error (RMS) and a maximum signal-to-interference ratio $S / (N+I)$ or a minimum probability of a bit error rate (BER) [9].

Adaptive filtering refers to non-linear filtering, since the parameters of the input channels of the compensators are subject to random fluctuations in time, which requires continuous AF adjustment. For compensators that have a separate channel for receiving interfering signals, an analysis was carried out in [10], which determined the basic rule of such compensators - to minimize the average signal power.
at the output of the circuit. Let us take into account, in the development of work [10], the components of additive thermal noise. At the output of the circuit, we have a signal:

\[ Z = S + (Y - \hat{Y}) + (n_1 - n_2), \]

where: \( S \), \( Y \) - useful and interfering signals at the system input, respectively; \( \hat{Y} \) - an estimate of the interfering signal \( Y \) coming from the AF included in the compensation channel of the system; \( n_1 \) is the additive noise of the main receiving channel; \( n_2 \) is the additive noise of the compensation channel that has passed AF.

The signal power at the output of the system is defined as:

\[
E[Z^2] = E[S^2] + E[(Y - \hat{Y})^2] + E[(n_1 - n_2)^2] + 2E[S(Y - \hat{Y})] + 2E[(n_1 - n_2)] + 2E[S(Y + n_2)(n_1 - n_2)].
\]

If the filter is set to minimize \( E[Z^2] \), then this does not happen at the expense of reducing the useful signal \( S \), since only the channel containing interfering signals \( Y + n_2 \) is subject to control. Since the useful signal, interference and additive noise are not mutually correlated, the power characteristics from their products are equal to zero and only the signal power \( E[Z^2] \), interference \( E[(Y - \hat{Y})^2] \) and additive noise \( E[(n_1 - n_2)^2] \) remain at the ACP output. ANF tuning will mean minimizing to \( E[Z^2] \)

\[
\min E[Z^2] = E[S^2] + \min E[(Y - \hat{Y})^2] + \min E[(n_1 - n_2)^2].
\]

Since there is no signal \( S \) at the output of the circuit, adaptation to the minimum output power leads to the fact that in this case \( Z \) is the best, in the sense of the minimum standard deviation, estimate of \( S \) and will be the best estimate of \( Y \). AIC of single-channel compensators functioning in accordance with the diagram shown in figure 1 a) have a feature that they are formed as close as possible to the interfering signal \( Y \) its estimate \( \hat{Y} \), while, based on the a priori known differences in the useful and interfering signals, they filter out the useful signal \( S \), sending only the estimate \( \hat{Y} \) to the adder.

In works [3, 4, 6] examples of the implementation of such AIC are given and the quality of their work is determined. The studies are based on Wiener's filtering theory and as a result, it was concluded that the AIC, functioning as a balanced bridge completely eliminates the interference \( Y \) at the AIC output, but the additive thermal noises that are not correlated with the useful and interference signals remain uncompensated and tend to increase. Despite the increase in thermal noise \( n_0 \) at the output of single-channel AICs, their noise immunity is much higher than conventional demodulators, which determined their widespread use in the practice of radar, radio communication, in the suppression of in-band spurious emissions in transmitting devices, in hydro acoustics [10].

![Figure 2. Scheme of the adaptive transverse filter.](image-url)
Interference compensators having the structure shown in figure 1 b) are often reduced to adaptive transverse filters (ATF), which perform time and amplitude-phase adjustment of the interference components in various diversity channels in order to minimize their power after summation. An example of such an AF structure is shown in figure 2.

Each transverse filter contains a multi-tap delay line, the signals from the taps of which are multiplied by the complex weighting coefficients \( W_{ni} \) and summed. In this case, the choice of the algorithm for calculating the optimal weight vector \( W_{opt} \) determines both the adaptation time and the complexity of the compensator and the cost of resources for its creation and operation. Let’s find a way to determine the weight vector \( W \). Let in the \( i \)-th branch of the diversity of the compensator shown in figure 2 we have a signal of the form:

\[
Z_i(t) = \mu_i S_0(t) + \sum_{k=1}^{m} \eta_{ik} Y_k(t) + n_i(t),
\]

where: \( S_0(t) \) - normalized useful signal containing information about the message; \( Y_k(t) \) - normalized interference signal of the \( k \)-th interference source \( (1 \leq k \leq m) \); \( n_i(t) \) - is the additive thermal noise of the \( i \)-th branch of diversity; \( \mu_i, \eta_{ik} \) - the coefficients characterizing the transmission of the useful signal and the \( k \)-th interference signal in the \( i \)-th branch of diversity; \( n \) is the number of branches of exploding; \( m \) is the number of independent sources of interference signals.

Let’s move on to the matrix notation, where: \( Z, \mu, n \) - vector columns, size \( n \times 1 \); \( Y \) - vector column, size \( m \times 1 \); \( \eta \) - \( n \times m \) matrix with elements \( \eta_{ni} \). Compensation of interference signals is carried out by combining the input signals \( Z_i(t) \) with some weighting coefficients \( W_i \), which determine the column vector, size \( n \times 1 \):

\[
Z = \mu S_0 + \eta Y + n; \quad Z = \begin{bmatrix} Z_1 \\ Z_2 \\ \vdots \\ Z_n \end{bmatrix}; \quad \mu = \begin{bmatrix} \mu_1 \\ \mu_2 \\ \vdots \\ \mu_n \end{bmatrix}; \quad n = \begin{bmatrix} n_1 \\ n_2 \\ \vdots \\ n_n \end{bmatrix}; \quad Y = \begin{bmatrix} Y_1 \\ Y_2 \\ \vdots \\ Y_m \end{bmatrix}; \quad W = \begin{bmatrix} W_1 \\ W_2 \\ \vdots \\ W_n \end{bmatrix}. \tag{1}
\]

At the ANC output, the \( S / (N+I) \) ratio is determined by the ratio of the signal power to the noise power and, if we neglect the additive noise due to the smallness, then in matrix form we get:

\[
\rho = \frac{W^* \mu^T W}{W^* \eta^T W} = \frac{W^* A W}{W^* B W}, \tag{2}
\]

where: \( *; + \) - signs of complex and hermitian conjugations; \( t \) - transposition sign; \( A = \mu^* \mu^T \) - correlation matrix of useful signals; \( B = \eta^* \eta^T \) - correlation matrix of interference signals.

The choice of the algorithm for calculating the optimal weight vector \( W \) is of decisive importance in the implementation of the automatic transmission, since it is this algorithm that determines the complexity, adaptation time, the level of suppression of interference signals, the cost and all other characteristics of the automatic transmission. In [11], it is shown that the optimal in the sense of the minimum RMS, processing of mixtures of interference and useful signals will be in the case of calculating the weight coefficients by the Wiener-Hopf formula:
\[ W = B^{-1} \mu^* \]  

(3)

where \( B^{-1} \) is the inverse correlation matrix of interference; \( \mu^* \) - a column vector characterizing the amplitude-phase distribution of the signal over the input receiving channels.

In practice, the inverse correlation matrix of the signal-noise mixture is measured and then calculated:

\[ R^{-1} = (A + B)^{-1} \]  

(4)

To determine the inverse correlation matrix of interference \( (B^{-1}) \), it is necessary to exclude the influence of the useful signal when calculating the matrix \( R^{-1} \).

Methods for calculating the inverse matrix and methods for eliminating the influence of the useful signal are quite diverse. We only note that the direct calculation of the size \( n \times n \) (where \( n \) is the number of diversity channels) is a rather laborious task, which sharply becomes more complicated with increasing \( n \), since it is required to measure the correlation function with each change in the input voltages. The gradient method is often used, according to which the vector \( W \) must change in the direction of estimating the gradient of the mean square of the error by the recursive expression

\[ W(j+1) = W(j) + \alpha \Delta(j) \]

where \( \Delta(j) \) is the gradient vector of the mean square of the error after the \( j \)-th iteration; \( \alpha \) - coefficient characterizing the adjustment step and affecting the speed and stability of the automatic transmission. Optimality of calculating the weight coefficients with the gradient method is achieved when:

\[ \Delta(j) = 0 \quad \text{and} \quad W(j + 1) = W(j) \]

Substituting into expression (2) the values of the optimal weight coefficients (3), formed in accordance with the criterion of the minimum standard deviation, we obtain the maximum value of the ratio of the signal power and interference for the AIC, shown in figure 2

\[ \frac{P_s}{P_n} = \frac{W^* A W W^* A (B^{-1} \mu^*) A \mu B A}{W^* B W (B^{-1} \mu^*) B \mu B A} = \frac{\mu^T B^{-1} A}{\mu^T B^{-1}} = \mu^T B^{-1} \mu^* \]

(5)

It is of interest to analyze the possibility of complete suppression of interference signals in the described structure. Optimization of the form of weighting coefficients \( W \) leads to the generalized eigenvalue problem:

\[ BW_i = \lambda_i AW_i \]  

(6)

where \( \lambda_i \), \( W_i \) is the \( i \)-th eigenvalue and the \( i \)-th eigenvector corresponding to \( \lambda_i \).

The best compensation of interference signals is achieved when choosing the values of the coefficients \( w_i \), according to expressions (3) and (6). If the correlation matrix of interference is degenerate, then the minimum eigenvalue is equal to zero \( (\lambda_{\min} = 0) \) and full compensation of interference signals is possible [12]. This case corresponds to a situation where the number of diversity channels of the system is greater than the number of independent sources of interfering signals, that is, \( n > m \).

4. Conclusion

The efficiency of using the short-term signal diversity reception system is reduced by the number of independent interference signals to the system and the effective diversity ratio after suppression of
interference signals $N = n - m$, and for $n < m$, complete suppression of interference signals is impossible and requires additional channels for receiving interference signals. Often, interfering signals that have passed the channel with multiple reflections come to the inputs of information transmission systems. In this case, in order to increase the correlation of the interference components of one source of interference at different inputs of the system, the AF of the compensator shown in figure 2 degenerates into adaptive transverse filters and, in addition to the amplitude-phase, time-dependent self-tuning becomes necessary. ATF is used to adjust the correlation coefficients of interference signals in different diversity channels to a value equal to one. In this case, the optimal weight coefficients in various ATF taps are also determined by expression (3), but the inverse correlation matrix of interference signals $R^{-1}$ is constructed taking into account the fact that interfering signals from different inputs of the system that have passed through a channel with multiple reflections differ in shape.

An example of the implementation of the ideas of adaptive compensation of interference in radio communication can serve as work [12], in which to protect tropospheric communication systems from radio impulse interference, an algorithm is used to minimize the power of interfering signals that have passed the radio channel without multiple reflections. The difference between the compensator and the circuit shown in figure 2 consists in the use of a radio-pulse interference detector and a switch, which automatically connect the compensator for the duration of the interference signal and exclude it from the system during the pause between interference pulses. The compensator operates at the intermediate frequency of the system and has been studied for systems with frequency modulated and noise-like signals with a frequency band of useful signals up to 10 MHz. Suppression of interference pulses from 30 to 40 dB was obtained, depending on the value of the $S/(N+I)$ ratio at the inputs of a communication system with a double spatial separation at various durations and repetition rates and filling frequencies of interference radio pulses.

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