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DEVELOPMENT OF AN ADAPTIVE MULTI-CHANNEL CORRELATION SIDELOBE CANCELLER FOR ACTIVE NOISE INTERFERENCE BASED ON THE GRAM-SCHMIDT ORTHOGONALIZATION PROCEDURE

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The object of the study is the process of adapting a multi-channel correlation sidelobe canceller to work in conditions of radio-electronic countermeasures based on the Gram-Schmidt orthogonalization procedure. The proposed approach allows developing a fast, recursive algorithm for searching for optimal values of weight coefficients. Such an algorithm will ensure fast adaptation of the sidelobe canceller to a complex interference-target situation, which can change rapidly. The obtained result of the coefficient of suppression of active noise interference in a constant value approaches the optimal value determined by the Wiener-Hopf equation, which indicates the effectiveness of the proposed approach.

By using the Gram-Schmidt orthogonalization procedure, it was possible to obtain high stability of the procedures for calculating the optimal values of weight coefficients, in contrast to other considered approaches. The proposed approach can be practically implemented in existing radar systems for suppressing active noise interference.

During the study, it was found that the adaptive multi-channel correlation sidelobe canceller in a steady-state mode works similarly to adaptive phased antenna arrays – it has the same efficiency in spatial signal selection and in compensation of active noise interference.

When suppressing four active noise interference, the suppression coefficient is –23.35 dB. With an increase in the number of interferences at the input of the four-channel sidelobe canceller, the suppression level deteriorates rapidly. With five, six, seven, eight interferences – –22.90 dB, –21.54 dB, –20 dB, –17.02 dB, respectively. Such changes are due to the number of active interferences, which is greater than the number of compensation channels

Keywords: multi-channel sidelobe canceller, sidelobe canceller, decorrelation, compensation channel, Gram-Schmidt procedure, Gram-Schmidt orthogonalization procedure

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1. Introduction

The modern development of electronic countermeasure systems has created a threat of the formation of a complex and dynamic interference-target environment, which jeopardizes the effectiveness of modern radars. In military and civilian applications, radars encounter active noise interference (ANI), created both intentionally and unintentionally (by contamination of the radio frequency space). Electronic countermeasure systems are capable of rapidly changing the types and parameters of active interference. Therefore, modern radars must be able to adapt in real time to changes in the interference-target environment in order to ensure high efficiency of detection, accuracy and tracking of targets. The task of compensating for active interference is performed by an adaptive antenna array or a multi-channel correlation sidelobe canceller (SLC). Due to the high computational resource consumption of antenna array adaptation, an acute issue arises in the development of fast methods for compensating for active interference. Therefore, research aimed at developing new algorithms for rapid adaptation of the sidelobe canceller to the interference-target environment with high dynamics of changes is extremely relevant.

2. Literature review and problem statement

The problem of low speed of the sidelobe canceller interference adaptation algorithm is outlined in [1]. The proposed operation of the correlation SLC based on the stochastic gradient adaptation algorithm. Although the algorithm itself is simple, the main drawback is the strong dependence of the speed on the number, location and intensity of interference sources. The above conditions form the input data on which the initial vector of the sidelobe canceller weight coefficient values depends. In [2], the author investigates their influence on the speed of the SLC adaptation algorithm and shows that there is a best-formed vector of weight coefficient values. But the issue of forming such a vector remains unresolved.

Therefore, in the study [3], another approach to finding optimal values of the SLC tuning coefficients is proposed.

However, the non-recursive algorithm used requires a large amount of input data and complex calculations, which leads to an increase in the adaptation time. An option to overcome these difficulties may be to reduce the order of complexity of the calculation. This approach is used in [4] due to signal segmentation. However, this solution did not affect the reduction of the adaptation time of the sidelobe canceller. The reason for this is the fundamental need to accumulate a large amount of input data. A simplified adaptation algorithm is shown in [5]. The author proposes to introduce signal delay elements into each compensation channel. Indeed, this approach is simpler and does not increase the number of calculations, but the adaptation speed remains low.

The solution may be to improve the sidelobe canceller based on the Opelbaum method [6]. This is done by replacing the procedure for determining the correlation coefficients by the low-pass filter in the inverse correlation loop circuit. To determine the optimal values of the low-pass filter coefficients, the author proposes to use a homogeneous first-order differential equation. However, the disadvantage of this approach is the need to solve a system of differential equations, the number of which is equal to the number of compensation channels. In turn, this approach requires complex calculations. A new approach in [7] may be proposed as an option for solving the problem. The main idea is to subtract the complex corrected signals in the channels from the part of the main channel signal that is divided between the compensation channels. Indeed, this allows solving the differential equations independently. However, as a result of using the average value of the interference to adjust each compensation channel, some of them will be much worse compensated.

All this gives grounds to argue that it is advisable to conduct research to solve the problem of increasing the adaptation speed of sidelobe cancellers by developing new, fast, recursive algorithms for searching for optimal values of weight coefficients.

3. The aim and objectives of the study

The aim of the study is the rapid adaptation of a multichannel active interference sidelobe canceller by developing a method for determining optimal weight coefficients based on the Gram-Schmidt orthogonalization procedure. The obtained method will provide tuning of the sidelobe canceller in real time using recurrent algorithms that require minimal computational costs.

To achieve the aim, the following objectives are expected to be performed:

– to formulate a criterion for the optimality of calculating the values of weight coefficients based on the results of studying the operation of the mathematical model of the sidelobe canceller in the adaptation process;

– to determine approaches to applying the Gram-Schmidt procedure to solve the problem of optimal determination of the sidelobe canceller coefficients;

– to simulate the operation of a 4-channel sidelobe canceller in a complex interference-target environment.

4. Materials and methods

The object of the study is the process of adapting the sidelobe canceller in electronic warfare conditions.

A comparative analysis of existing approaches to SLC adaptation in terms of computational complexity and computing power was conducted.

The method of decomposition of the structural diagram of the sidelobe canceller [8], shown in Fig. 1, was applied.

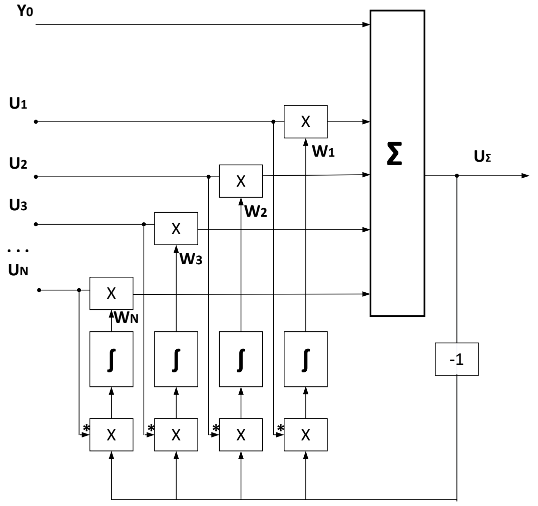


Fig. 1. Structural diagram of an adaptive multi-channel correlation sidelobe canceller [8]

Based on the analysis of the structure, it is hypothesized that to solve the problem of fast adaptation of the sidelobe canceller, signal processing and determination of the weight coefficients of the compensation channels must be carried out in an N-dimensional linear space.

The assumption is made that the dimension of the space N is equal to the number of compensation channels plus one (the main channel of the sidelobe canceller).

To construct a linear N-dimensional space, instead of using orthogonal trigonometric functions or orthogonal polynomials, a simplification is made that the basis of the space is built on the basis of the vectors of the received signals in the compensation channels and the signal at the output of the sidelobe canceller. The orthogonality of the basis vectors is ensured by the Gram-Schmidt procedure, for the implementation of which the recurrent least squares method is used.

The study of the effectiveness of the proposed approach was carried out on the basis of digital modeling of the SLC operation, according to the model of a complex interference-target situation in the environment of special software MATLAB Online (USA).

5. Results of the study of the adaptation of the sidelobe canceller to a complex interference-target situation

5. 1. The criterion for the optimality of calculating the values of weight coefficients based on the mathematical model of the sidelobe canceller in the adaptation process

According to the results of the structural analysis of the scheme presented in Fig. 1, and the modeling of the SLC operation, it was determined that the antennas of the compensation channels can be individual elements of the phased array (PA) or special (additional) antennas that are fixed on the corresponding sides of the antenna array. Thus, when building the SLC, there is no need to interfere with the design of the PA or other radar antenna system.

The number of compensation channels N is determined by the number of ANI sources [9], which are likely to affect the operation of the radar. The signal at the SLC output [7, 1]:

$$U_\Sigma(t)=Y_0(t)+U_K^T(t)\cdot W(t), \qquad (1)$$

where $Y_0(t)$ – the main channel for receiving a signal from the radar antenna; $U_K(t)=\{U_1(t),U_2(t),U_3(t),\ldots,U_N(t)\}^T$ – the vector of signals received in N-channels of interference compensation; $W(t)=\{W_1(t),W_2(t),W_3(t),\ldots,W_N(t)\}^T$ – the vector of weighting coefficients in N-channels of interference compensation.

During the SLC operation, the values of the weighting coefficients W are calculated based on the correlation of the new values of the signals at the SLC output and the compensation channels. As can be seen from Fig. 1, integrators are used in each feedback loop of the SLC. Then, the change in the values of the weighting coefficients W can be described by a first-order differential equation [9]:

$$T\frac{dW}{dt}+W(0)=-\int_0^T U_k^*(t)\cdot U_\Sigma(t)\,\mathrm{d}t, \qquad (2)$$

where T – the SLC adaptation time; $W(0)$ – the vector of the initial values of the weighting coefficients in each compensation channel; * – the complex conjugation operation.

The mathematical model of the SLC showed that the effectiveness of radar protection against ANI depends on the calculated weighting coefficients W in the compensation channels. The main goals of the SLC adaptation are to determine the optimal values of the weight coefficients, at which the greatest suppression of the ANI will be ensured. Upon completion of the adaptation time T, the constant value of the weight coefficient vector W_{st} will be determined by the formula:

$$W_{st}=-\langle U_k^*,U_\Sigma\rangle, \qquad (3)$$

where $\langle U_k^*,U_\Sigma\rangle=\int_0^T U_k^*(t)U_\Sigma(t)\,\mathrm{d}t$ – the scalar product of the vectors U_k^*,U_Σ [10].

The content of equation (3) shows that after the adaptation is completed, the vectors U_k^*,U_Σ will be orthogonal. There is no correlation between the signal at the SLC output and the compensation channels, the signals are decorrelated. As a result, the ANI signals at the SLC output are compensated.

Thus, the criterion for optimal adaptation of the SLC is formulated – the level of orthogonality of the vector of interference signals in the compensation channels and the signal vector at the SLC output:

$$\langle U_k^*,U_\Sigma\rangle=0. \qquad (4)$$

Unlike the gradient and quasi-Newton methods [1] of optimal search for sidelobe canceller coefficients, the application of criterion (4) allowed solving the optimal adaptation problem without using systems of partial differential equations. The solution of the optimal problem within the framework of the matrix algebra apparatus based on simpler and faster procedures and algorithms is proposed.

5. 2. Determination of approaches to the application of the Gram-Schmidt procedure to solve the problem of optimal determination of the sidelobe canceller coefficients

To determine the analytical expression for calculating the vector of weight coefficients of the compensation channels of the SLC, the scalar product (3) and criterion (4) are considered, then:

$$\begin{aligned}
&-W_{st}=\langle U_k^*,U_\Sigma\rangle,\\
&\langle U_k^*,U_\Sigma\rangle=0,\\
&U_k^*\left(Y_0+U_K^TW_{opt}\right)=U_k^*Y_0+U_k^*U_K^TW_{opt}=0,\\
&U_K^*U_K^TW_{opt}=-U_K^*Y_0,\ W_{opt}=-\frac{R_{YK}}{R_{KK}},\\
&-W_{st}=W_{opt}=-\frac{R_{YK}}{R_{KK}},\\
&W_{st}=R_{KK}^{-1}R_{YK},
\end{aligned} \qquad (5)$$

where $R_{KK}=\overline{U_K^*U_K^T}$ – the correlation matrix of signals in the active interference compensation channels; $R_{YK}=\overline{U_K^*Y_0}$ – the correlation vector of signals in the main channel and active interference compensation channels.

Expression (5) is the well-known Wiener-Hopf equation for determining the optimal weight coefficients of adaptive PA [8, 11]. It is concluded that the adaptive multi-channel correlation sidelobe canceller of the ANI, after the completion of adaptation and determination of the optimal weight coefficients of the compensation channels, works similarly to adaptive PAs.

Such an SLC, when compensating for the ANI, has the same efficiency as the adaptive PA in spatial signal selection [8].

To assess the SLC efficiency, depending on the level of achieved signal decorrelation (4), the previous structural scheme of the SLC was modified and it is possible to obtain a new scheme, presented in Fig. 2.

Compared to the diagram in Fig. 1, the common coefficient "–1", of the feedback loop, is transferred to each compensation channel. The ANI signals in the main channel and compensation channels are the same:

$$Y_0(t)=U_1(t)+U_2(t)+U_3(t)+\ldots+U_N(t). \qquad (6)$$

Expression (6) is formulated in vector form:

$$\begin{aligned}
&Y_0(t)=U_1(t)\cdot 1+U_2(t)\cdot 1+U_3(t)\cdot 1+\ldots+U_N(t)\cdot 1,\\
&Y_0=U_K^TI,
\end{aligned} \qquad (7)$$

where $I=\{1,\ldots,N\}^T$ – the vector with N unit elements.

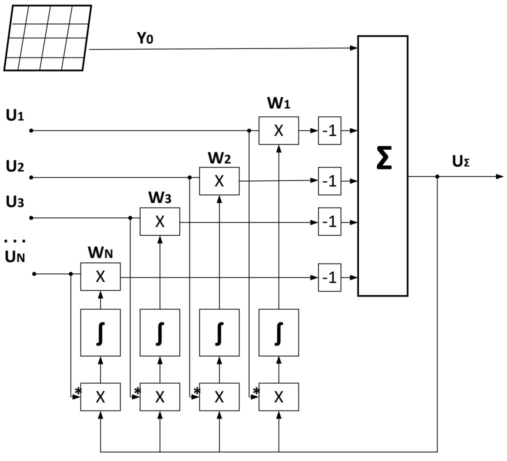


Fig. 2. Modified structural diagram of adaptive multi-channel correlation sidelobe canceller

Substituting (6) into (1) and obtaining the signal at the SLC output:

$$\begin{aligned}&U_\Sigma(t)=\left(U_1(t)+U_2(t)+U_3(t)+\ldots+U_N(t)\right)-\\&-U_1(t)\cdot W_1(t)-U_2(t)\cdot W_2(t)-\\&-U_3(t)\cdot W_3(t)-\ldots-U_N(t)\cdot W_N(t)\Rightarrow\\&\Rightarrow U_\Sigma(t)=U_1(t)\cdot\left(1-W_1(t)\right)+U_2(t)\cdot\left(1-W_2(t)\right)+\\&+U_3(t)\cdot\left(1-W_3(t)\right)+\ldots+U_N(t)\cdot\left(1-W_N(t)\right).\end{aligned}\tag{8}$$

According to formula (3), the value of the weighting coefficients in the steady state approaches the value of the correlation coefficient between the interference signal at the SLC output and the signal in the compensation channel, then the parameter d_i – the decorrelation index of the two corresponding signals:

$$d_i=1-W_i(t),\tag{9}$$

and the vector of decorrelation indices:

$$D=\left\{d_1,d_2,d_3,\ldots,d_N\right\}.\tag{10}$$

Taking into account expressions (9) and (10), equation (8) is obtained in vector form:

$$U_\Sigma=U_K^TD.\tag{11}$$

The total suppression coefficient of active interference signals in the SLC:

$$K=10\cdot\log\frac{P_{in}}{P_{out}},\tag{12}$$

where P_{in} – the total power of active interference signals in the main channel; P_{out} – the total power of active interference signals at the SLC output.

Then, from expression (7), the input power will be equal to:

$$\begin{aligned}&P_{in}=Y_0^2=\left(U_K^TI\right)^2=U_K^TI\cdot U_KI^T=\\&=U_K^TU_K\cdot I^TI=U_K^2,\end{aligned}\tag{13}$$

and the output power of the sidelobe canceller is determined from expression (11):

$$\begin{aligned}&P_{out}=U_\Sigma^2=(U_K^TD)^2=U_K^TDU_KD^T=\\&=U_K^TU_KDD^T=U_K^2D^2.\end{aligned}\tag{14}$$

Substituting (13) and (14) into expression (12), let's obtain:

$$K=10\cdot\log\frac{U_K^2}{U_K^2D^2}=10\cdot\log\frac{1}{D^2}.\tag{15}$$

Analysis of equation (15) shows that the value of the active interference suppression coefficient is determined by the level of decorrelation of the ANI signals at the SLC output and the signals in the compensation channels, and by fulfilling the criterion presented in expression (4).

The task of SLC adaptation is to determine the optimal values of the weighting coefficients W_i for each compensation channel. The main indicator of the adaptation process is the speed of the W_i determination algorithms. Several common approaches to solving the problem are known [1]:

– correlation sidelobe cancellers of interference based on stochastic gradient adaptation algorithms;

– quasi-Newton adaptation algorithms based on maximum likelihood estimates of correlation matrices of Gaussian interference;

– quasi-Newton adaptation algorithms based on regularized varieties of maximum likelihood estimates of correlation matrices;

– adaptive multi-stage lattice filters based on factorized representations of matrices, inverse correlation matrices of Gaussian noise, or their approximations.

For SLC adaptation, it is proposed to apply the Gram-Schmidt orthogonalization procedure [12], which will ensure compliance with the optimization criterion (4).

The set of vectors of discrete K – signal samples at the SLC input will have the following form:

– $Y_0=\{y(1), y(2), y(3),..., y(K)\}$ – the vector of discrete signal samples in the main SLC channel;

– $U_1=\{u_1(1), u_1(2), u_1(3),..., u_1(K)\}$ – the vector of discrete signal samples in the 1st SLC compensation channel;

– $U_2=\{u_2(1), u_2(2), u_2(3),..., u_2(K)\}$ – the vector of discrete signal samples in the 2nd SLC compensation channel;

– $U_N=\{u_N(1), u_N(2), u_N(3),..., u_N(K)\}$ – the vector of discrete signal samples in the N-th SLC compensation channel.

Using the Gram-Schmidt orthogonalization procedure, let's construct a set of orthogonal vectors:

$$Y_{0\perp},U_{1\perp},U_{2\perp},\ldots,U_{N\perp},\tag{16}$$

where ⊥ – the sign of the vector orthogonalization with respect to other vectors.

At the SLC output, a vector is obtained in which the ANI signals will be suppressed by a certain value according to formula (15).

In contrast to the SLC structure specified in [8], it is proposed to apply a new structure of the sidelobe canceller, Fig. 3 [12]. Such a structure will provide recursive parallel-serial decorrelation of ANI signals in accordance with the orthogonalization condition (4), and will have high stability of the calculation procedures.

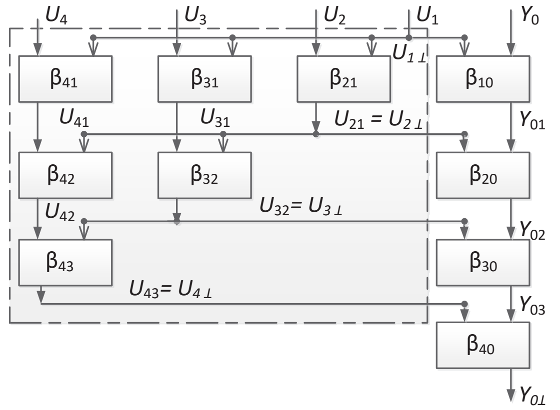


Fig. 3. Structural diagram of an adaptive 4-channel correlation sidelobe canceller based on the Gram-Schmidt procedure

The SLC scheme (Fig. 3) is built from unified β blocks with two inputs [12], in which the decorrelation procedure of two input signals takes place. The determination of the weighting coefficients $\beta_{i,l}$ is carried out on the basis of the recurrent least squares method (LSM) and does not require rotation of high-order correlation matrices (CM) [13].

5. 3. Modeling the operation of a four-channel sidelobe canceller in a complex interference-target environment

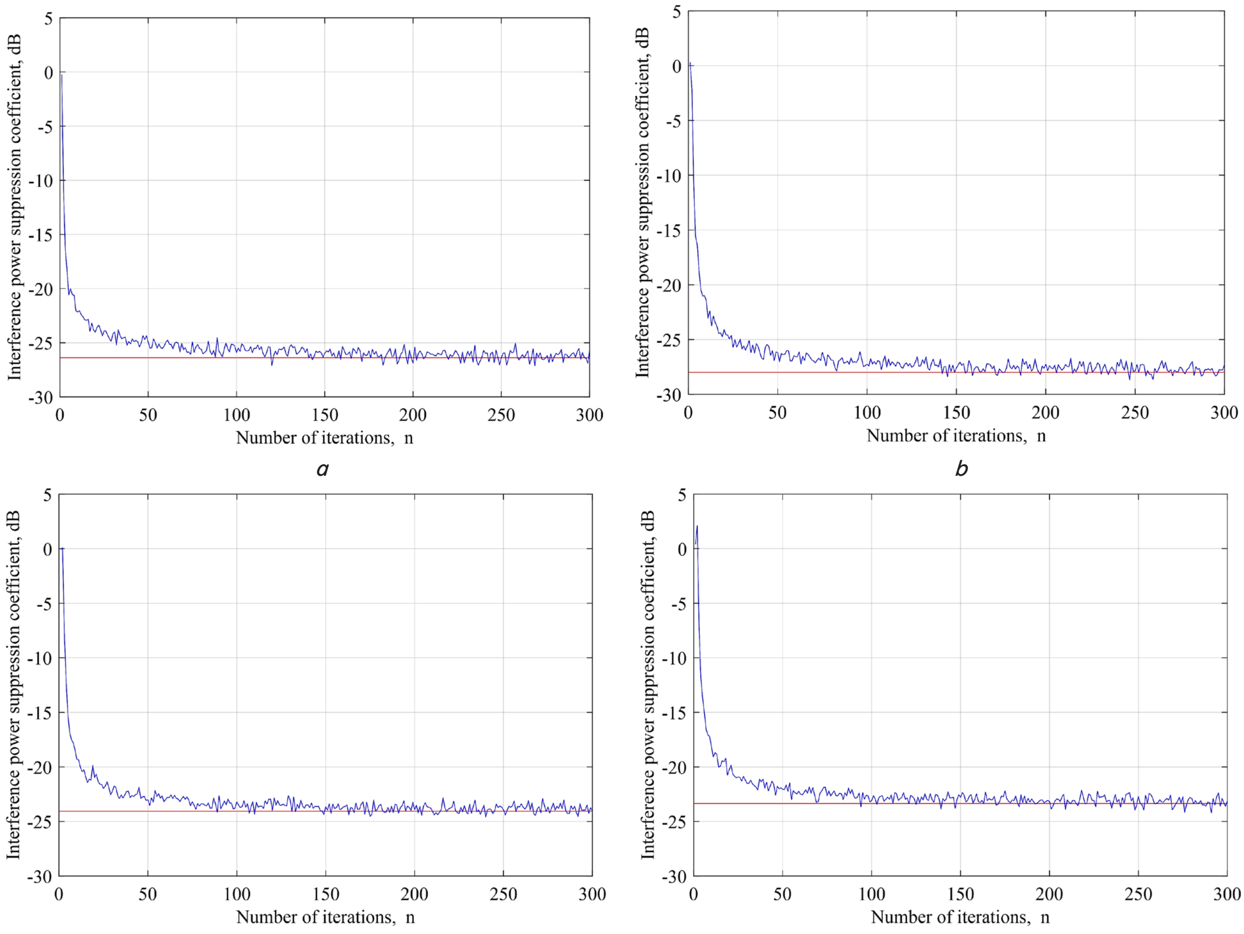
The operation of a 4-channel SLC was simulated in two stages. The simulation results will be compared with the optimal values of ANI suppression, which is determined by the Winner-Hopf equation (5).

A model of an interference-target environment in which the ANI radiation powers will be the same, and the bearings to the interference sources have different values, has been formed. The value of the active noise interference power was chosen to be 25 W, with a normal (Gaussian) distribution law of the random variable.

The first stage of modeling was carried out in accordance with the parameters given in Table 1. Fig. 4 presents the results of the sidelobe canceller operation, where the red line indicates the optimal value of the ANI suppression coefficient according to the Wiener-Hopf equation, and the blue line indicates the achieved value of the suppression coefficient. The parameter for assessing the SLC effectiveness, during the modeling, was the interference suppression coefficient.

The value of the ANI total suppression coefficient in the 4-channel SLC is given in Table 1.

Analysis of the simulation results at the first stage showed that the SLC adaptation to the interference-target situation occurs in real time. The constant value of the suppression coefficient approaches the optimal values determined by the Wiener-Hopf equation (5) in less than a hundred iterations. This, in turn, shows the SLC efficiency and the speed of adaptation based on the proposed method.



a *b* *c* *d*

Fig. 4. Results of operation simulation of a 4-channel correlation sidelobe canceller: *a* — one source of interference; *b* — two sources of interference; *c* — three sources of interference; *d* — four sources of interference

Table 1

Parameters of the SLC model at the first stage

Number of ANI sources	Bearing to ANI source, degree	Suppression coefficient, dB
1	–7	–26.38
2	–7, 8	–27.98
3	–7, 8, 15	–24.06
4	–13 , –7, 8, 15	–23.35

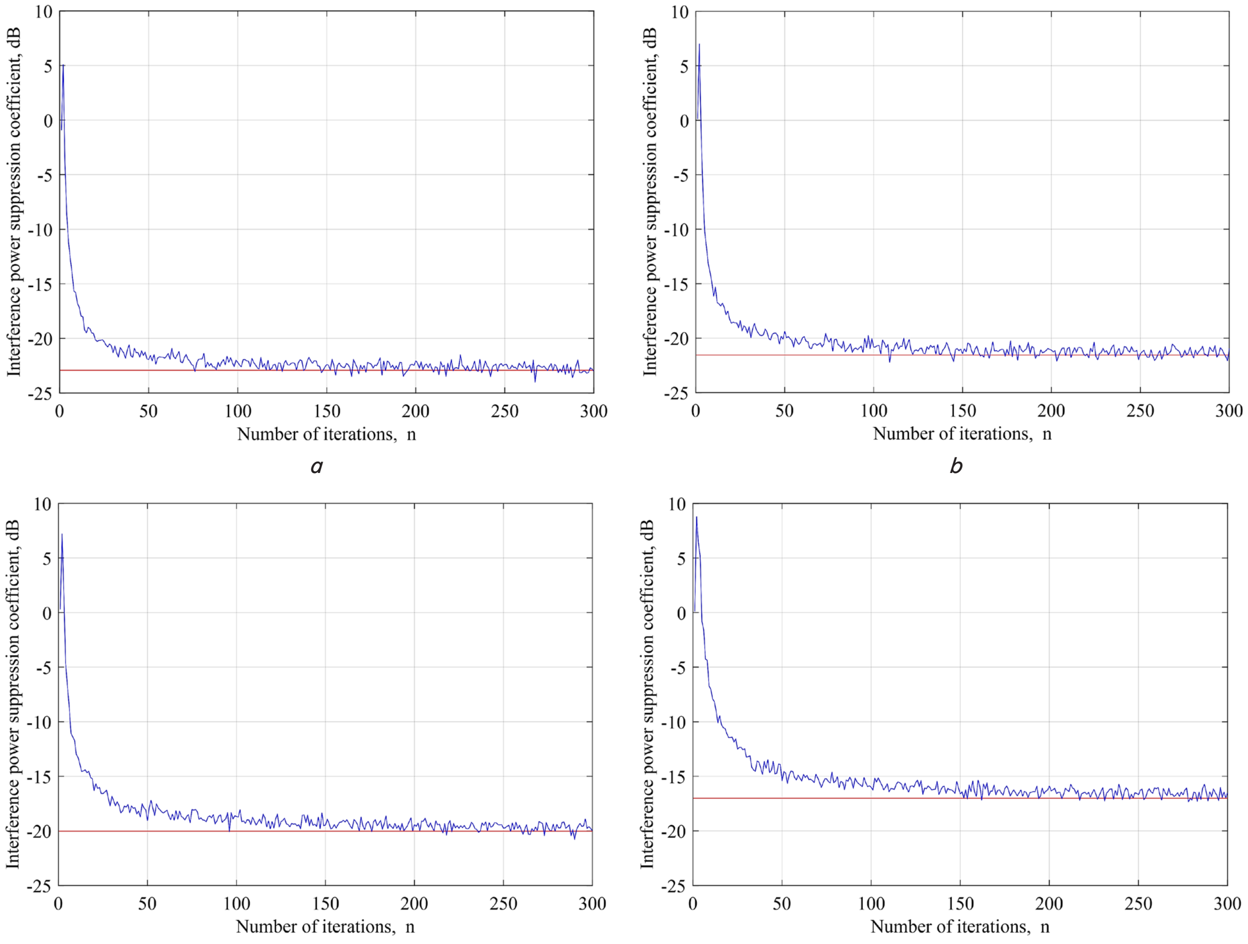
When the number of interferences increases to four, the suppression coefficient deteriorates by 3.03 dB. The optimal condition for the ratio of the SLC efficiency and the cost of computing resources is the correspondence of the number of ANI sources to the number of compensation channels. Under this condition, the ANI suppression coefficient is –23.35 dB.

The second stage of simulation was carried out for a more complex interference-target situation, in accordance with the parameters given in Table 2. The result of the sidelobe canceller operation is presented in Fig. 5, where the red line indicates the optimal value of the ANI suppression coefficient according to the Wiener-Hopf equation, and the blue line indicates the achieved value of the suppression coefficient.

The value of the ANI total suppression coefficient in the 4-channel SLC is given in Table 2.

After 150–200 iterations, the value of the suppression coefficient approaches the optimal values. The number of required adaptation iterations is twice as large. This change is due to the larger number of sources of active-noise interference, in which the optimal condition for the ratio of the SLC efficiency and the cost of computing resources is not met. With an increase in the number of interferences, the value of the ANI total suppression coefficient rapidly decreases, Table 2.

In such an interference-target situation, the SLC will not provide a sufficient level of suppression, so the radar will not be able to work effectively.



a

b

c

d

Fig. 5. Results of operation simulation of a 4-channel correlation sidelobe canceller: *a* – five sources of interference; *b* – six sources of interference; *c* – seven sources of interference; *d* – eight sources of interference

Table 2

Parameters of the SLC model at the second stage

Number of ANI sources	Bearing to ANI source, degree	Suppression coefficient, dB
5	–13, –7, 8, 15, 20	–22.90
6	–17, –13, –7, 8, 15, 20	–21.54
7	–17, –13, –7, 8, 15, 20, 27	–20.00
8	–33, –17, –13, –7, 8, 15, 20, 27	–17.02

6. Discussion of the results of the development of a method for determining optimal weighting coefficients for sidelobe canceller adaptation

In the process of analyzing the mathematical model of the correlation sidelobe canceller, it was revealed that it is possible to apply the criterion for determining optimal weighting coefficients in the form of orthogonalization of the interference signal vectors at the SLC output and compensation channels (4). The use of such a criterion allowed to form a new approach, in which, unlike the classical analysis of the correlation coefficients of interference signals, the optimization problem is solved on the basis of the decorrelation indices of the corresponding signals.

When formulating analytical expressions for calculating the optimal coefficients, it was shown that the obtained formulas are similar to the Wiener-Hopf equation (5). This equation is obtained on the basis of the criterion of the minimum square of the error and is used for the adaptation of phased array antennas. Thus, the proposed adaptation approach according to criterion (4) shows that the SLC after the adaptation process has the same efficiency and works similarly to adaptive PAs, in spatial signal processing and suppression of ANI signals.

Unlike the SLC classical structural scheme (Fig. 1), a modification of the scheme is proposed, where the general coefficient "–1" is transferred to each channel (Fig. 2). This allowed to build a matrix model of the SLC operation, which confirmed the dependence of the active interference suppression coefficient on the decorrelation indices (15).

A feature of the proposed approach to adaptation, in contrast to studies [1, 2] in which gradient algorithms are used, is the rejection of algorithms for searching for optimal values of weight coefficients for individual SLC channels. This approach required the construction of a new sidelobe canceller structure (Fig. 3). Unlike the known schemes [3], the feature of the proposed one is the absence of the concept of "compensation channel weight coefficient" as such. In the process of recursive adaptation, partial weight coefficients are calculated in unified blocks β for the entire SLC scheme. The use of the Gram-Schmidt procedure allows to immediately achieve orthogonality of signal vectors, i.e., to compensate for interference at the SLC output. This feature allowed to provide an order of magnitude faster SLC adaptation (Fig. 4) to the interference-target situation compared to the results presented in [1].

When analyzing the SLC effectiveness in different conditions, a number of limitations were identified. First, for effective operation, the interference signal should not correlate with the radar signal. Second, effective suppression of active interference occurs when the number of compensation channels is greater than or equal to the number of AS sources.

The disadvantage of the developed structure is a longer adaptation time of the sidelobe canceller when interacting with a single interference source, compared to the result given in [1]. In the future, this drawback can be eliminated by using digital devices designed for parallel data processing.

The development of this research will be the organization of spatio-temporal signal processing for joint compensation of active and passive interference based on the same optimization criterion (4) and the application of the Gram-Schmidt orthogonalization procedure.

7. Conclusions

1. In contrast to known approaches based on determining the correlation index between signals in the SLC channels, an adaptation approach based on signal decorrelation is proposed. An optimality criterion for solving the SLC adaptation problem is formed – the level of orthogonality of the interference signal vectors in the compensation channels and the signal vector at its output. This allowed developing a simple and fast algorithm for searching for optimal coefficient values.

2. It is shown that the active interference suppression coefficient is inversely proportional to the level of decorrelation of the ANI signals at the SLC output and input. In the sidelobe canceller based on Gram-Schmidt orthogonalization, in contrast to known schemes in which weighting coefficients are calculated for each compensation channel, partial adaptation weighting coefficients are calculated as a whole. An increase in the SLC adaptation speed is ensured by organizing parallel-sequential calculation of partial weighting coefficients. Under the conditions of two ANI sources, the adaptation speed of the developed SLC is 6.5 times higher compared to the presented results [1] under similar conditions.

3. The optimal condition for the ratio of SLC efficiency and computational resource costs is the correspondence of the number of ANI sources to the number of compensation channels. Under this condition, the ANI suppression coefficient is – 23.35 dB. With an increase in the number of interferences, the value of the total ANI suppression coefficient rapidly decreases to the level of –17.02 dB with eight ANI sources.

Conflict of interest

The authors declare that they have no conflict of interest regarding this study, including financial, personal, authorship or other nature, which could affect the study and its results presented in this article.

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Data availability

The manuscript has no related data.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the presented work.

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