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CHAPTER 5

INTELLECTUAL METHODS FOR EVALUATING THE STATE OF UAV CHANNELS

ABSTRACT

In this section of the research, intellectual methods for assessing the state of unmanned aerial vehicle (UAV) channels are proposed. During the study, the authors:

1. Developed an intellectual method for assessing the state of UAV channels based on the application of fuzzy set theory and artificial neural networks, which, while being sufficiently simple, allows for obtaining highly accurate solutions. The distinctive features of the proposed method include:

- simultaneous assessment of the UAV channel state based on multiple evaluation indicators (impulse response, frequency response, and bit error rate);
- real-time continuous assessment of several channel state characteristics;
- continuous assessment of multiple channel state characteristics in both the downlink and uplink channels;
- obtaining channel state assessments for each indicator on separate layers of the neural network through the construction of membership functions;
- following the assessment of individual channel characteristics by separate neural network layers, a generalized channel state assessment is formed at their output.

2. Proposed a methodology for identifying the state of UAV control and data transmission channels.

The novelty of the proposed methodology lies in:

- considering a corrective coefficient during calculations to account for the degree of uncertainty regarding the state of UAV channels;
- adding a corrective coefficient to address data noise resulting from distortions in information about UAV channel states;
- reducing computational costs when assessing the state of UAV channels;
- enabling calculations with input data of various natures and units of measurement.

KEYWORDS

Artificial intelligence, heterogeneous data processing, control and data transmission channels, reliability, efficiency.

5.1 DEVELOPMENT OF A METHOD FOR INTELLECTUAL ASSESSMENT OF UNMANNED AERIAL VEHICLE CHANNEL STATES

A generalized (comprehensive) assessment refers to obtaining an evaluation of the state of each UAV channel by a separate layer of the neural network based on frequency response, impulse response, and bit error rate [1–21]. After the layers of the neural network perform their evaluations, a generalized channel state assessment is formed at its output [22–30]. This generalized assessment enables the determination of mechanisms for adjusting UAV channel characteristics in terms of power level, frequency range, and conducting a quantitative evaluation of interference impact using the bit error rate [31–41].

Fig. 5.1 illustrates the principle of using an artificial neural network for assessing UAV channel state parameters.

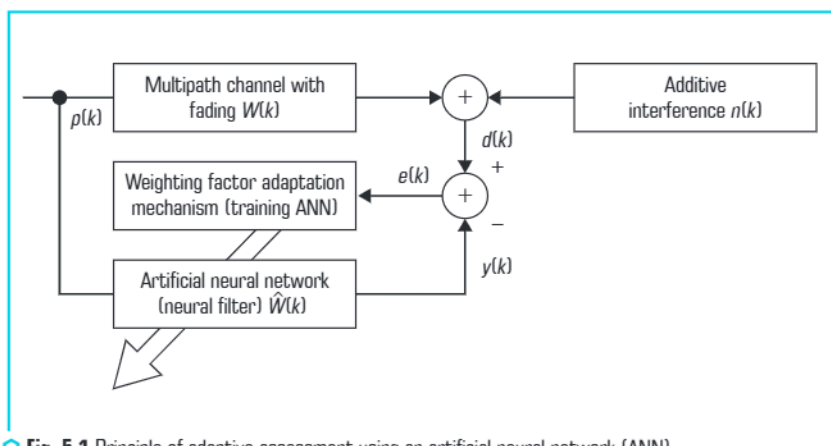


Fig. 5.1 Principle of adaptive assessment using an artificial neural network (ANN)

The method for intellectual assessment of UAV channel states, the implementation algorithm of which is shown in **Fig. 5.2**, consists of the following stages.

1. Input of initial data.

The parameters of the transmitting device and the communication channel are entered $\Psi = \{\psi_i\}$, $i = \overline{1, m}$, where $\psi_1 \dots \psi_m$ – the signal ensemble positionality M , and the maximum power of the useful signal are specified $P_{c, \max}$; threshold values for the signal-to-noise ratio (SNR) are specified Q_{thr}^2 , the information transmission rate is specified v_i , parameters of the error-correcting code are specified (code rate R ; the number of errors the code can correct s).

Constraints: modulation type – quadrature amplitude modulation (QAM), phase modulation (PM); signal ensemble dimensionality: $4 \leq M \leq 256$; type of error-correcting code – convolutional codes with a rate $R = 0.5$ – 0.9 .

2. Assessment of the UAV channel state.

Let's explain the procedure for assessing the channel state. The channel state assessment procedure involves obtaining a comprehensive evaluation of the UAV channel state. This procedure includes the parallel calculation of the channel's impulse response x_1 , the frequency response of the channel state x_2 and the bit error rate x_3 .

Thus, obtaining a comprehensive evaluation of the UAV channel state can be represented [1–9] as follows:

$$y = f(x_1, x_2, \dots, x_n).$$

Artificial neural networks (ANNs), which are adaptive systems simulating the functionality of the nervous system of living organisms, are widely used for adaptive signal processing, modeling, analysis, and evaluation of the performance of UAV channels.

Adaptive filters using ANNs are capable of functioning effectively under conditions of a priori uncertainty about the properties of the external environment [10]. In the proposed method, each layer of the neural network evaluates an individual characteristic of the UAV channel state. Subsequently, the output of the neural network forms a generalized assessment of the UAV channel state.

3. Evaluation of the frequency response of the UAV channel.

Let the signal received at the analyzed frequency be represented as $A_s(t)$ and the additive concentrated interference $B_n(t)$ is a narrowband, quasi-stationary normal random process with a symmetric spectrum. Under these assumptions, these processes can be represented through their quadrature components [11]:

$$A_s(t) = Y_s(t)\cos\omega_s t + Y_n(t)\sin\omega_s t, \quad (5.1)$$

and

$$B_n(t) = X_s(t)\cos\omega_n t + X_n(t)\sin\omega_n t, \quad (5.2)$$

where $Y_s(t)$, $X_s(t)$ – in-phase; $Y_n(t)$, $X_n(t)$ – components represent the signal and interference, respectively; ω_s and ω_n – denote the mean frequencies of the signal and interference spectra. Going forward, it is possible to assume that $\omega_s \approx \omega_n = \omega_0$, with ω_0 precisely determined.

In the case of Rayleigh fading, which is most typical for channels with multipath propagation of radio waves, the quadrature components of the signal $Y_s(t)$, $Y_n(t)$ and the interference $X_s(t)$, $X_n(t)$ are pairwise independent normal Markov random processes with zero mean and variances $\sigma_{Y_s}^2 = \sigma_{Y_n}^2 = \sigma_s^2$, $\sigma_{X_s}^2 = \sigma_{X_n}^2 = \sigma_n^2$ [42–55].

The correlation functions of the quadrature components in this case can be expressed as:

$$R_{Y_s}(\tau) = R_{Y_n}(\tau) = R_{Y_{qw}}(\tau) = \sigma_s^2 e^{-\alpha_s \tau}, \quad (5.3)$$

and

$$R_{X_s}(\tau) = R_{X_n}(\tau) = R_{X_{qw}}(\tau) = \sigma_n^2 e^{-\alpha_n \tau}, \quad (5.4)$$

where $\alpha_s = \frac{1}{\tau_s}$, $\alpha_n = \frac{1}{\tau_n}$ – the parameters of the correlation functions characterize the rates of change of the signal and interference in the quadrature channels of reception, respectively.

To obtain smoothed estimates of the signal and interference voltages over the evaluation interval ($\hat{y}(t) = 20 \lg \hat{A}_s(t)$ and $\hat{x}(t) = 20 \lg \hat{B}_n(t)$), the dependencies can be utilized through the corresponding estimates of the quadrature components smoothed over the same time interval:

$$\hat{y}(t) = 20 \lg \sqrt{\hat{Y}_s^2(t) + \hat{Y}_n^2(t)}, \quad (5.5)$$

$$\hat{x}(t) = 20 \lg \sqrt{\hat{X}_s^2(t) + \hat{X}_n^2(t)}. \quad (5.6)$$

The estimate of the ratio of smoothed signal and interference voltages (levels) is determined by the following expression:

$$s(t) = y(t) - x(t). \quad (5.7)$$

The model that defines the variation of the smoothed components of the signal $\tilde{Y}_{qw}(t)$ and interference $\tilde{X}_{qw}(t)$ in each quadrature measurement channel in discrete time is described in a two-dimensional state space by the vector difference stochastic equation of the form:

$$\tilde{\mathbf{X}}(k+1) = \Phi(k+1)\tilde{\mathbf{X}}(k) + \Gamma(k+1)\tilde{\mathbf{U}}(k), \quad (5.8)$$

where $\tilde{\mathbf{X}}(k+1) = \left\| \tilde{Y}_{qw}(k+1), \tilde{X}_{qw}(k+1) \right\|^T$ – the state vector of the signal and intentional interference components:

$$\Phi(k+1) = \text{diag} \left\| e^{-\alpha_y \Delta t}, e^{-\alpha_x \Delta t} \right\|;$$

$$\Gamma(k+1) = \text{diag} \left\| \sqrt{\frac{2}{\alpha_y}} (1 - e^{-\alpha_y \Delta t}); (1 - e^{-\alpha_x \Delta t}) \right\|;$$

where $\tilde{\mathbf{u}}(k) = \|\tilde{U}_1(k), \tilde{U}_2(k)\|^T$ – the vector of white Gaussian noise with zero mean and a covariance matrix:

$$Q(k) = \text{diag} \left\| \frac{\alpha_y \sigma_y^2 (1 + e^{-\alpha_y \Delta t})}{2(1 - e^{-\alpha_y \Delta t})}; \frac{\alpha_x \sigma_x^2 (1 + e^{-\alpha_x \Delta t})}{2(1 - e^{-\alpha_x \Delta t})} \right\|,$$

where σ_y^2 and σ_x^2 – variances; α_y and α_x – the parameters of the correlation functions of the smoothed quadrature components of the signal and interference, respectively.

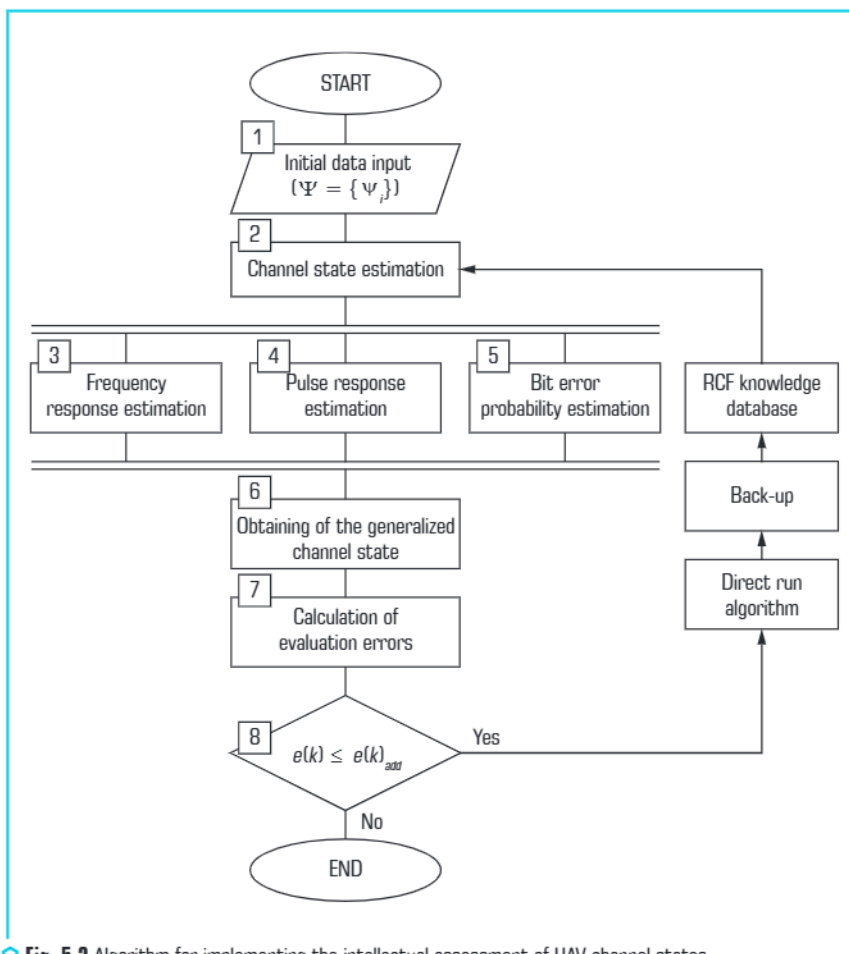


Fig. 5.2 Algorithm for implementing the intellectual assessment of UAV channel states

The signal and interference in each quadrature measurement channel are observed in an additive mixture with measurement noise:

$$\tilde{Z}_{qw}(k+1) = \mathbf{A}(k+1)\tilde{\mathbf{X}}(k+1) + \tilde{N}_{qw}(k+1), \quad (5.9)$$

where $\mathbf{A}(k+1) = \|\mathbf{1}, \mathbf{1}\|$, and $\tilde{N}_{qw}(k+1)$ – a Gaussian white sequence with zero mean and a covariance function:

$$R_n(k, l) = \sigma_n^2 \delta_{k,l}.$$

The solution to the optimal filtering problem for the state and observation model described by equations (5.8) and (5.9) leads to the following recursive computational algorithm [12]:

$$\begin{aligned} \tilde{\mathbf{X}}(k+1) = & \left\| e^{-\alpha_y \Delta t} \hat{Y}_{qw}(k), e^{-\alpha_x \Delta t} \hat{X}_{qw}(k) \right\|^T + \mathbf{K}(k+1) \times \\ & \times \left\{ \tilde{Z}_{qw}(k+1) - \left[e^{-\alpha_y \Delta t} \hat{Y}_{qw}(k) + e^{-\alpha_x \Delta t} \hat{X}_{qw}(k) \right] \right\}. \end{aligned} \quad (5.10)$$

In expression (5.10), the matrix weighting coefficient is determined as:

$$\mathbf{K}(k+1) = \left\| \frac{\rho_{11}(\Delta t) + \rho_{12}(\Delta t)}{\rho_{11}(\Delta t) + 2\rho_{12}(\Delta t) + \rho_{22}(\Delta t) + \sigma_n^2}, \frac{\rho_{22}(\Delta t) + \rho_{12}(\Delta t)}{\rho_{11}(\Delta t) + 2\rho_{12}(\Delta t) + \rho_{22}(\Delta t) + \sigma_n^2} \right\|, \quad (5.11)$$

where

$$\begin{aligned} \rho_{11}(\Delta t) &= P_{11}(k) e^{-2\alpha_y \Delta t} + \sigma_y^2 (1 - e^{-2\alpha_y \Delta t}), \\ \rho_{12}(\Delta t) &= P_{12}(k) e^{-(\alpha_y + \alpha_x) \Delta t}, \\ \rho_{22}(\Delta t) &= P_{22}(k) e^{-2\alpha_x \Delta t} + \sigma_x^2 (1 - e^{-2\alpha_x \Delta t}). \end{aligned} \quad (5.12)$$

In expressions (5.12) $P_{11}(k)$, $P_{22}(k)$, $P_{12}(k) = P_{21}(k)$ – elements of the mean-square error matrix of the estimation after k k -measurement steps.

The computational algorithm described by (5.10)–(5.12) can be utilized for analyzing the quality of UAV channels using specific test signals.

When monitoring the quality of UAV channels directly during the information transmission process, uncertainty arises regarding the presence or absence of signals in the reception channels.

One of the most constructive approaches to addressing this issue is the synthesis of computational control algorithms based on the combined application of signal detection procedures and parameter estimation for both the signals and concentrated interference.

Let the binary signals $A_s^{(l)}(t)$ ($l = 1, 2$) have identical energy and, like the additive interference $B_n(t)$ be narrowband, quasi-stationary Markov random processes with symmetric spectra. Frequency-modulated signals $A_s^{(l)}(t)$ ($l = 1, 2$) can be represented through their quadrature components:

$$A_s^{(l)}(t) = Y_s(t) \cos \omega_0 t + Y_n(t) \sin \omega_0 t. \quad (5.13)$$

Without loss of generality, let's consider the case of symmetric interference of concentrated noise on the signals:

$$B_n(t) = X_n(t) \cos \omega_0 t + X_n(t) \sin \omega_0 t. \quad (5.14)$$

For Rician and Rayleigh radio communication channels, the dynamics of the quadrature components of the signal and interference at discrete time moments t_k ($k = 0, 1, 2, \dots$) can, by analogy with expression (5.8), be represented by systems of stochastic vector difference equations:

$$\bar{\mathbf{X}}_{s(n)}(k+1) = \Phi(k+1) \bar{\mathbf{X}}_{s(n)}(k) + \Gamma(k+1) \bar{\mathbf{U}}(k), \quad (5.15)$$

where

$$\bar{\mathbf{X}}_s(k+1) = \left\| \bar{Y}_s(k+1), \bar{X}_s(k+1) \right\|^T;$$

$$\bar{\mathbf{X}}_n(k+1) = \left\| \bar{Y}_n(k+1), \bar{X}_n(k+1) \right\|^T;$$

$$\bar{\mathbf{U}}(k) = \left\| \bar{U}_1(k), \bar{U}_2(k) \right\|^T.$$

The matrices $\Phi(k+1)$, $\Gamma(k+1)$ and $Q(k)$ however, instead of the parameters α_y , α_x and σ_y^2 , σ_x^2 are used, respectively α_{s^*} , α_n and $\sigma_{s^*}^2$, σ_n^2 .

It should be noted that the time discretization interval:

$$\Delta t = t_{k+1} - t_k \quad (k = 0, 1, 2, \dots),$$

is chosen under the condition $\Delta t \ll \min(\tau_s, \tau_n)$. According to statistical data, the values of the correlation intervals for the amplitudes of fading signals (interference) in UAV channels range from tenths of a second to several seconds [56–64].

The scalar observation equations for signals and interference in the presence of noise can be written as follows:

$$\begin{aligned} \bar{z}(k+1) = & \chi \left[\mathbf{A}\bar{\mathbf{N}}_s(k+1)\cos\omega_{01}k\Delta t + \mathbf{A}\bar{\mathbf{N}}_s(k+1)\sin\omega_{01}k\Delta t \right] + \\ & + (1-\chi) \left[\mathbf{A}\bar{\mathbf{N}}_s(k+1)\cos\omega_{02}k\Delta t + \mathbf{A}\bar{\mathbf{N}}_s(k+1)\sin\omega_{02}k\Delta t \right] + \bar{N}(k+1), \end{aligned} \quad (5.16)$$

where $\mathbf{A} = \begin{bmatrix} 1 & 1 \end{bmatrix}$; χ – a random variable such that:

$$\chi = \begin{cases} 1 & \text{with probability } P; \\ 0 & \text{with probability } Q = 1 - P, \end{cases}$$

where P, Q – the a priori probabilities of signal transmission $U_s^{(1)}(t)$ (in particular, $P = Q = 0.5$); $\bar{N}(k+1)$ – normal white noise with zero mean and a covariance function $R_n(k, l) = \sigma_n^2 \delta_{k,l}$.

The optimal decision rule, according to the ideal observer criterion for a priori equally probable transmitted signals, at time $T_a = n\Delta t$ is defined by the inequality:

$$\Lambda[\bar{z}(n)] > 0, \quad (5.17)$$

where the logarithm of the likelihood ratio is expressed in sequential form as:

$$\Lambda[\bar{z}(k+1)] = \ln \left\{ \frac{w[\bar{z}(k+1)/\chi=1]}{w[\bar{z}(k+1)/\chi=0]} \right\} = \Lambda[\bar{z}(k)] + \ln \left\{ \frac{w[\bar{z}(k+1)/\bar{z}(k), \chi=1]}{w[\bar{z}(k+1)/\bar{z}(k), \chi=0]} \right\}, \quad (5.18)$$

where $\Lambda[\bar{z}(0)] = 0$.

The posterior probability densities $w[\bar{z}(k+1)/\bar{z}(k), \chi]$ in expression (5.18) are Gaussian and, in this case, take the form:

$$\begin{aligned} w[\bar{z}(k+1)/\bar{z}(k), \chi] = & \left\{ 2\pi \det[\mathbf{A}\mathbf{P}(k+1/k)\mathbf{A}^T + \sigma_n^2] \right\}^{-1/2} \times \\ & \times \exp \left\{ - \frac{\left\{ \bar{z}(k+1) - \mathbf{A}\Phi(k+1) [\widehat{\mathbf{X}}_s(k)\cos\omega_{01}k\Delta t + \widehat{\mathbf{X}}_s(k)\sin\omega_{01}k\Delta t] \right\}^2}{2\pi[\mathbf{A}\mathbf{P}(k+1/k)\mathbf{A}^T + \sigma_n^2]} \right\}, \end{aligned} \quad (5.19)$$

where $\bar{\mathbf{X}}_s(k) = \|\widehat{\mathbf{Y}}_s(k), \widehat{\mathbf{Y}}_s(k)\|^T$; $\bar{\mathbf{X}}_n(k) = \|\widehat{\mathbf{Y}}_n(k), \mathbf{X}_n(k)\|^T$ – the vectors of estimates of the quadrature components of the signal and concentrated interference, calculated similarly to the algorithm in (5.15); $\mathbf{P}(k+1/k)$ – the transition matrix of estimation errors.

Based on expressions (5.17)–(5.19), let's arrive at the following recursive computational algorithm for joint detection and estimation:

$$\begin{aligned}
 & \sum_{k=0}^{n-1} \left\{ \bar{z}(k+1) - \mathbf{A}\Phi(k+1) [\hat{\mathbf{X}}_s(k) \cos \omega_{01} k \Delta t + \hat{\mathbf{X}}_n(k) \sin \omega_{01} k \Delta t] \right\}^2 > \\
 & > \sum_{k=0}^{n-1} \left\{ \bar{z}(k+1) - \mathbf{A}\Phi(k+1) [\hat{\mathbf{X}}_s(k) \cos \omega_{02} k \Delta t + \hat{\mathbf{X}}_n(k) \sin \omega_{02} k \Delta t] \right\}^2 <
 \end{aligned} \quad (5.20)$$

Under conditions of interference structurally similar to the signal, it is necessary to perform separate real-time estimation of the amplitudes of the signal and interference without prior decisions on the reception of informational symbols. For this, information about the time autocorrelation functions of the modulated signal and interference at the output of UAV channels is required.

Such an estimation establishes the degree of influence of the manipulation speed ratio of the signal and interference, as well as the rate of change in the characteristics of the propagation environment, on the radio channel quality. This enables recommendations to be made for selecting optimal operating frequencies for UAV channels, considering the correlation properties of the channels, signals, and interference.

4. Evaluation of the impulse response of UAV channels.

The estimation of impulse responses at the k -th step for UAV channels will be represented by the weight coefficient matrix of the Focused Neural Network Filter (FNNF) in the form:

$$H_{MMO}(k) = \begin{bmatrix} W_i^{11}(k) & W_i^{12}(k) & \dots & W_i^{1N}(k) \\ W_i^{21}(k) & W_i^{22}(k) & \dots & W_i^{2N}(k) \\ \dots & \dots & \dots & \dots \\ W_i^{N1}(k) & W_i^{N2}(k) & \dots & W_i^{NN}(k) \end{bmatrix}, \quad (5.21)$$

where $W_i^{MN} = [w_0^{MN}, w_1^{MN}, \dots, w_{L-1}^{MN}]^T$ – the column vector represents the samples of the impulse response in the direction from the M_i -th transmitter to the N_i -th receiver of the UAV.

5. Evaluation of the bit error rate (BER) for UAV channels.

The measurement results for the bit error rate of a specific signal type are obtained according to the mathematical relationships derived in [65–71].

6. Obtaining a generalized assessment of the UAV channel state.

During the channel state evaluations (**Steps 3–5**), it becomes necessary to form a generalized assessment of the UAV channel state.

The primary tool of fuzzy logic, which allows transforming expert knowledge in the form of "IF-THEN" rules into mathematical models, is the membership function [72–80].

For this task, the membership function characterizes the degree of confidence of an expert that a certain value belongs to a fuzzy concept (term). Methods of fuzzy logical inference enable linking the membership functions of indicators and the signal-interference environment in the presence of a channel model expressed through "IF-THEN" rules.

$$a_i^p = \int_{\underline{x}_i}^{\bar{x}_i} \mu^{a_i^p}(x_i) / x_i, \quad (5.22)$$

$$d_j = \int_{\underline{d}}^{\bar{d}} \mu^{d_j}(d) / d. \quad (5.23)$$

Thus, the result of the UAV channel state assessment can be represented as [80–86]:

$$y = f(x_1, x_2, \dots, x_n), \quad (5.24)$$

where x_1, x_2, \dots, x_n – the set of input parameter values of the UAV channel state, and y is the result of the UAV channel state assessment.

The ranges of the input parameters $x_i \in [\underline{x}_i, \bar{x}_i]$, $i = \overline{1, n}$ and the output value $y \in [\underline{y}, \bar{y}]$ or the UAV channel state evaluation is assumed to be known. Here $x_i(\underline{x}_i, \bar{x}_i)$ – denotes the lower (upper) limits of the input parameters, and $x_i, i = \overline{1, n}$, $y(\underline{y}, \bar{y})$ – represents the lower (upper) limits of the identification result.

Let $X^* = \langle x_1^*, x_2^*, \dots, x_n^* \rangle$ – be the vector of fixed values of the input parameters of the UAV channel state, where $x_i^* \in [\underline{x}_i, \bar{x}_i]$, $i = \overline{1, n}$. The decision-making task is to determine the result x^* of the UAV channel state assessment based on the information about the input parameter vector $y^* \in Y$. A necessary condition for the formal solution of this task is the existence of the dependence (5.24). To establish this dependence, the signal-interference environment and the output decision on the generalized channel state assessment must be represented as linguistic variables defined on universal sets [9, 10, 12, 14–18]:

$$X_i = \left[\underline{x}_i, \bar{x}_i \right], \quad (5.25)$$

$$Y = \left[\underline{y}, \bar{y} \right]. \quad (5.26)$$

To evaluate such linguistic variables, it is proposed to use qualitative terms that constitute a term set [9, 10, 12, 14–18]:

$A_i = \{a_i^1, a_i^2, \dots, a_i^{g_i}\}$ – linguistic term of the variable x_i , $i = \overline{1, n}$, $D = \{d_1, d_2, \dots, d_m\}$ – linguistic term of the variable y , where a_i^p – p -th linguistic term of the variable x_i , $p = \overline{1, g_i}$, $i = \overline{1, n}$; d_j – j -th linguistic term of the variable y ; m – the number of different decisions. The cardinalities of the term sets A_i , $i = \overline{1, n}$ can vary, i.e. $(g_1 \neq g_2 \neq \dots \neq g_n)$. The names of terms $a_i^1, a_i^2, \dots, a_i^{g_i}$ may differ for different linguistic variables x_i , $i = \overline{1, n}$.

The linguistic terms $a_i^p \in A_i$ and $a_i^p \in A_i$ i $d_j \in D$, $p = \overline{1, k_i}$, $i = \overline{1, n}$, $j = \overline{1, m}$ must be considered as fuzzy sets defined on the universal sets X_i, Y (5.25), (5.26).

The fuzzy sets a_i^p and d_j are determined by the relationships [9, 10, 12, 14–18]:

$$a_i^p = \int_{x_i}^{\bar{x}_i} \mu^{a_i^p}(x_i) / x_i, \quad (5.27)$$

$$d_j = \int_d^{\bar{d}} \mu^{d_j}(d) / d, \quad (5.28)$$

where $\mu^{a_i^p}(x_i)$ – the membership function of the variable $x_i \in [x, \bar{x}]$, $i = \overline{1, n}$ to the term $a_i^p \in A_i$, $p = \overline{1, k_i}$; μ^{d_j} – and the membership function of the variable $y \in [y, \bar{y}]$ to the term-decision $d_j \in D$, $j = \overline{1, m}$. In relationships (5.27) and (5.28), the integral symbols indicate the aggregation of pairs $\mu(u) / u$.

Let N – the amount of expert survey data linking the input indicators and the output assessment of the UAV channel state is distributed as follows:

$$N = g_1 + g_2 + \dots + g_m,$$

where g_j – the number of expert data points corresponding to an output decision is $d_j \in D$, $j = \overline{1, m}$, m – the number of output decisions is $g_1 \neq g_2 \neq \dots \neq g_m$.

The number of selected expert data points is less than the total possible combinations of changes in the input indicators of the UAV channel state.

After numbering, the known expert data about the channel state can be presented in the form of a knowledge matrix [9, 10, 12, 14–18] (Table 5.1).

The knowledge matrix is formed according to the following rules:

– the dimension of such a matrix is $(n+1) \times N$, where $(n+1)$ – the number of rows, $N = g_1 + g_2 + \dots + g_m$ – the number of columns;

– the first n columns correspond to the input indicators of the UAV channel state x_i , $i = \overline{1, n}$ and $(n+1)$ -th column corresponds to the values d_j the output decision y , $j = \overline{1, m}$;

– each row of the matrix represents a specific combination of values of the input indicators of the UAV channel state, assigned by an expert to one of the possible channel state values d_j the first g_j rows correspond to the value d_1 , while the last g_m rows correspond to the value d_m ;

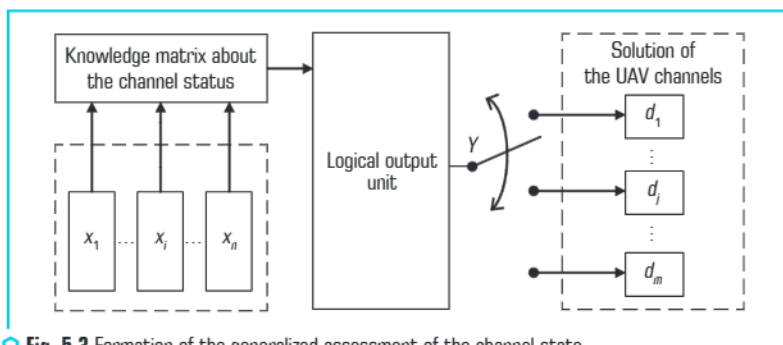
– the element a_i^{jp} , located at the intersection of the i -th column and jp -th row, corresponds to the linguistic assessment of the indicator x_i in the row of the fuzzy knowledge base with the number jp , the linguistic assessment a_i^{jp} is selected from the term – set of the corresponding indicator x_i i.e. ($a_i^{jp} \in A_i, i = \overline{1, n}, j = \overline{1, m}, p = \overline{1, j}$).

Thus, expression (5.24), which establishes the relationship between the input indicators x_i and the output assessment y , is formalized into a system of logical statements (5.30), based on the fuzzy knowledge base represented by the knowledge matrix (Table 5.1).

Graphically, the process of generalized assessment of the UAV channel can be depicted as shown in Fig. 5.3.

● **Table 5.1** Fuzzy knowledge matrix of UAV channels

The number of the input combination of values	Input variables UAV channels				Output variables
	x_1	x_2	x_i	x_n	Y
11	a_1^{11}	a_2^{11}	... a_i^{11} ...	a_n^{11}	d_1
12	a_1^{12}	a_2^{12}	... a_i^{12} ...	a_n^{12}	
...	
$1g_1$	$a_1^{1g_1}$	$a_2^{1g_1}$... $a_i^{1g_1}$...	$a_n^{1g_1}$	d_i
$j1$	a_1^{j1}	a_2^{j1}	... a_i^{j1} ...	a_n^{j1}	
$j2$	a_1^{j2}	a_2^{j2}	... a_i^{j2} ...	a_n^{j2}	
...	
$1g_j$	$a_1^{1g_j}$	$a_2^{1g_j}$... $a_i^{1g_j}$...	$a_n^{1g_j}$	
...
$m1$	a_1^{m1}	a_2^{m1}	... a_i^{m1} ...	a_n^{m1}	d_m
$m2$	a_1^{m2}	a_2^{m2}	... a_i^{m2} ...	a_n^{m2}	
...	
mg_m	$a_1^{mg_m}$	$a_2^{mg_m}$... $a_i^{mg_m}$...	$a_n^{mg_m}$	



○ **Fig. 5.3** Formation of the generalized assessment of the channel state

From the analysis of the UAV channel functioning under various signal conditions, let's determine the directions for assessing the quality of the UAV channel.

These include the similarity of indicators characterizing the quality of the UAV channel and changes during the communication session until the decision on the channel quality is made.

The formation of the generalized assessment of the UAV channel state can be written as an equation:

$$D(k) = f \left[\begin{matrix} Y_1(k-1), \dots, Y_n(k-1), \\ Z_1(k-1), \dots, Z_n(k-1) \end{matrix} \right],$$

where $Y_1(k-1)$ – a vector characterizing the first indicator of the UAV channel quality assessment at $k-1$ the assessment step; $Y_n(k-1)$ – a vector characterizing the n -th indicator of the UAV channel quality assessment at $k-1$ the modeling step; $Z_1(k-1), \dots, Z_n(k-1)$ – vectors characterizing the generalized assessment of the channel for each of the quality evaluation indicators.

In turn, the vector of communication channel quality assessment is determined by the following indicators:

$$Y_1, \dots, Y_n, Z_1, \dots, Z_n = \{k_{11}(x), \dots, k_n(x)\}.$$

The possible states of the signal environment in the channel are defined by the set $d \in \{d_1, d_2, d_3\}$, where d_1 – the channel meets the standard (corresponds to maximum frequency efficiency); d_2 – individual quality indicators of the channel exceed the standard and require adjustment; d_3 – the channel is unsuitable for operation. The task of evaluation is to match each combination of signal environment indicators to one of the decisions d_i , $i = \overline{1,3}$. The indicator $g_{11}, \dots, g_{21}, \dots, g_{141}, \dots, g_{145}$ will be considered as linguistic variables [12].

The formation of the generalized assessment of communication channel quality can be represented as a multi-level hierarchical tree of logical inference corresponding to the following states:

$$d = f_d(Z_1 \dots Z_n), \quad (5.29)$$

$$Z = f_z(Y_1 \dots Y_n), \quad (5.30)$$

$$Y_n = f_{y_n}(g_{n1}(x), g_{n2}(x), g_{n3}(x), g_{n4}(x), g_{n5}(x)). \quad (5.31)$$

For indicators with a quantitative representation, the range of variation is divided into four quanta. This enables the transformation of the continuous universal $U = [\underline{u}, \bar{u}]$ into a discrete five-element set [12]:

$$U = \{u_1, u_2, \dots, u_5\},$$

where

$$u_1 = \underline{u}, u_2 = \underline{u} + \Delta_1, u_3 = \underline{u} + \Delta_2, u_4 = \underline{u} + \Delta_3, u_5 = \underline{u} + \Delta_4,$$

where $\Delta_1 + \Delta_2 + \Delta_3 + \Delta_4 = \bar{u} - \underline{u}$, $\bar{u}(\underline{u})$ – the lower and upper bounds of the indicator's range of variation, respectively. Then, all pairwise comparison matrices will have a dimension of 5×5 . The choice of four quanta is determined by the ability to approximate nonlinear curves using five points [12].

To evaluate the values of linguistic variables $g_{11}, \dots, g_{21}, \dots, g_{141}, \dots, g_{145}$ let's use a qualitative term scale. For evaluating linguistic variables D, Z_n, Y_n it is possible to use the following term sets: $D, Z_1, \dots, Z_n, Y_1, \dots, Y_n = \{\text{channel parameters meet the standard, some channel parameters exceed the standard and require adjustment, channel is unsuitable for operation}\}$.

Each of the introduced terms represents a fuzzy set, defined by the corresponding membership function. In general, the input variables x_1, x_2, \dots, x_n can be specified by a number, a linguistic term, or based on the thermometer principle [12].

The evaluation of the UAV channel is performed using fuzzy logical equations [12], which constitute a knowledge matrix and a system of logical statements. These equations allow the computation of membership function values for different assessment results with fixed input indicator values. The decision with the highest membership function value is proposed as the result of the evaluation process [12].

The linguistic assessments α_j^{ip} of the variables x_1, x_2, \dots, x_n which are part of the logical statements regarding the decisions d_j , $j = \overline{1, m}$ (5.27), (5.28), are considered as fuzzy sets defined on universal sets:

$$X_i = \left[\underline{x}_i, \bar{x}_i \right], \quad i = \overline{1, n}.$$

Let $\mu^{ip}(x_i)$ – be the membership function of the indicator $x_i \in \left[\underline{x}_i, \bar{x}_i \right]$ to the fuzzy term $i = \overline{1, n}$, $j = \overline{1, m}$, $p = \overline{1, l}$; $\mu^{dj}(x_1, x_2, \dots, x_n)$ – be the membership function of the input variable vector $X = (x_1, x_2, \dots, x_n)$ to the output assessment $y = d_j$, $j = \overline{1, m}$. The relationship between these functions is determined by the fuzzy knowledge base and can be represented as the following logical equations:

$$\begin{aligned} \mu^{dj}(x_1, x_2, \dots, x_n) &= \mu^{d1^1}(x_1) \wedge \mu^{d2^1}(x_2) \wedge \dots \wedge \mu^{d1^l} \vee \\ &\vee \mu^{d1^2}(x_1) \wedge \mu^{d2^2}(x_2) \wedge \dots \wedge \mu^{d1^p}(x_n) \dots \\ &\dots \mu^{d1^j}(x_1) \wedge \mu^{d2^j}(x_2) \wedge \dots \wedge \mu^{d1^j}(x_n), \quad j = \overline{1, m}. \end{aligned} \quad (5.32)$$

These equations are derived from the fuzzy knowledge base by substituting variables (linguistic terms) with membership functions and replacing the operations AND and OR with the operations \wedge and \vee .

The system (5.32) can be written compactly as:

$$\mu^{dj}(x_i) = \bigvee_{p=1}^l \left[\bigwedge_{i=1}^n \mu^{dip}(x_i) \right], \quad j = \overline{1, m}. \quad (5.33)$$

Fuzzy logical equations are an analog of the fuzzy logical inference procedure introduced by Zadeh [9, 10, 12, 14–18], which is performed using the operations of "fuzzy (min-max) composition", where the operations AND and OR correspond to the min and max operations, respectively. From (5.33), obtain:

$$\mu^{d_i}(x_i) = \max_{\rho = \overline{1}, l_i} \left\{ \min_{j = \overline{1}, n} [\mu^{\rho j}(x_i)] \right\}. \quad (5.34)$$

From expression (5.34), it is evident that calculating the membership function requires only the membership functions of the variables to the fuzzy terms. Let's consider the procedure for calculating the membership function used in this method.

When selecting indirect methods for constructing the membership function, which transform expert information into a form convenient for use in UAV channel assessment, it is necessary to consider the computational complexity of implementation. For instance, constructing a membership function based on the pairwise comparison method requires forming a pairwise comparison matrix and solving the characteristic equations of this matrix to determine its eigenvector. However, this method has high computational complexity. Considering the possibility of calculating the membership function using ranking assessments, which are relatively easy to obtain through expert surveys, let's use the pairwise comparison method to calculate the membership function.

The algorithm for calculating the membership function of the UAV channel state includes the following Steps:

1. Select the quality indicator of the UAV channel to be assessed x_j , $j = \overline{1}, m$.
2. Set of fuzzy terms is specified $\{u_1, u_2, \dots, u_j\}$, which are used for evaluating x .
3. For each term u_i , $i = \overline{1}, l$ a pairwise comparison matrix is formed:

$$T = \begin{pmatrix} 1 & \frac{r_2}{r_1} & \frac{r_3}{r_1} & \dots & \frac{r_n}{r_1} \\ \frac{r_1}{r_2} & 1 & \frac{r_3}{r_2} & \dots & \frac{r_n}{r_2} \\ \dots & \dots & \dots & \dots & \dots \\ \frac{r_1}{r_n} & \frac{r_2}{r_n} & \frac{r_3}{r_n} & \dots & 1 \end{pmatrix}, \quad (5.35)$$

where $r_s(u_i)$ – the rank of element $u_i \in U$, which characterizes the significance of this element when forming the properties described by the corresponding fuzzy term \tilde{S} .

The matrix (5.35) has the following properties:

- the elements of the main diagonal are equal to 1 ($t_{ii} = 1, i = \overline{1}, n$);
- relative to the main diagonal, the elements are related by the expression $t_{ij} = 1 / t_{ji}$;
- the condition of transitivity holds: $t_{ig}t_{gj} = t_{ij}$, since $\frac{r_i}{r_g} \frac{r_g}{r_j} = \frac{r_i}{r_j}$.

Thanks to these properties, the elements of other rows in the matrix T can easily be found from the known elements of one row. If the elements t_{gj} , $g, j = \overline{1}, n$ are known, any element t_{ij} can be found as:

$$t_{ij} = t_{gj} / t_{gi}, \quad i, j, g = \overline{1}, n.$$

Since matrix (5.35) can be interpreted as a pairwise comparison matrix of ranks, a twelve-point Saaty scale [18] can be used for expert evaluation of the elements of this matrix.

For the case:

$$t_{\bar{q}} = r_i / r_j = \begin{cases} 1 - \text{no advantage of } r_i \text{ over } r_j; \\ 3 - \text{small advantage of } r_i \text{ over } r_j; \\ 5 - \text{larger advantage of } r_i \text{ over } r_j; \\ 7 - \text{substantial advantage of } r_i \text{ over } r_j; \\ 9 - \text{clear cut advantage of } r_i \text{ over } r_j; \\ 11 - \text{absolute advantage of } r_i \text{ over } r_j; \\ 2, 4, 6, 8, 10 - \text{interim comparison evaluation.} \end{cases}$$

4. Membership functions are determined as follows:

1) based on absolute rank assessments r_i , $i = \overline{1, n}$, which can be defined using a nine-point scale (1 – lowest rank, 9 – highest rank);

2) based on relative rank assessments $r_i / r_j = t_{\bar{q}}$, $i, j = \overline{1, n}$, which are determined by the pairwise comparison matrix (5.35), the membership function is calculated for each term.

The normalization of the obtained membership functions is performed by dividing by the highest membership degrees.

These relationships enable the calculation of the membership function using rank assessments, which are relatively easy to obtain when using neuro-fuzzy networks.

Using the knowledge matrix, the expert information about the UAV channel state can be represented as a system of fuzzy logical statements (5.35), which link the values of the input indicators x_i with one of the possible decisions d_j , $j = \overline{1, m}$:

$$\begin{aligned} & IF (x_1 = \alpha_1^{11}) AND (x_2 = \alpha_2^{11}) AND \dots AND (x_n = \alpha_n^{11}) OR (x_1 = \alpha_1^{12}) \\ & (x_2 = \alpha_2^{12}) AND \dots AND (x_n = \alpha_n^{12}) OR \dots OR (x_1 = \alpha_1^{1h}) AND (x_2 = \alpha_2^{1h}) \\ & AND \dots AND (x_n = \alpha_n^{1h}), THEN y = d_m, \end{aligned} \quad (5.36)$$

where d_j ($j = \overline{1, m}$) – the linguistic assessment of the output variable y , which is defined from the term set D ; a_j^p – the linguistic assessment of the input indicator x_i in the p -th row j -th disjunction, chosen from the term set A_i ($i = \overline{1, n}, j = \overline{1, m}, p = \overline{1, k_j}$); g_j – the number of rules that define the output variable's value $y = d_j$.

Let's call the system (5.36) a fuzzy knowledge base, which is used to form a set of assessments for each of the indicators of the channel state evaluation [18, 19].

The fuzzy logical relations (5.36), along with the membership function of the fuzzy terms, allow the evaluation of the UAV channel state through the following algorithm:

1. The values of the quality indicators of the UAV channel are fixed according to the predefined criteria $X^* = (x_1^*, x_2^*, \dots, x_r^*)$.
2. Using the membership function calculation algorithm, the membership function $\mu^i(x_i^*)$ is determined for the fixed values of the indicators x_i^* , $i = \overline{1, m}$.
3. Using the logical equations (5.36), let's calculate the membership function $\mu^{d_i}(x_1^*, x_2^*, \dots, x_m^*)$ for the state vector $X^* = (x_1^*, x_2^*, \dots, x_r^*)$ for all states d_1, d_2, \dots, d_n . In this case, the logical operations AND (\wedge) and OR (\vee) over the membership functions are replaced with the operations min and max [9, 10, 12, 14–18].
4. The decision d_j^* is determined for which:

$$d_j = \operatorname{argmax}_{j = \overline{1, m}} (\mu d_j(x_i)).$$

The data in the matrices form a fuzzy knowledge base for assessing the quality of the UAV channel [17].

Using the tables and the AND and OR operations, a system of logical equations is written, linking the membership functions of the quality assessment decisions for the UAV channel with the membership functions of destabilizing factors. Thus, knowing the values of the membership functions for fuzzy terms, the quality of the UAV channel can be evaluated by solving the logical equations described above. The result of applying the proposed hierarchical system of fuzzy logical equations is the degree of membership of the UAV channel's state.

The output result of the evaluation and the quality indicators of the UAV channel are presented as linguistic variables, which are evaluated using the provided methods.

7. Calculation of the estimation error and training of the artificial neural network (ANN).

The principle of intellectual parameter estimation for the UAV channel using an ANN is shown in **Fig. 5.2**. It involves inputting a known training (learning) discrete sequence $p(k)$, into the ANN, which is processed in the neural network filter (ANN). As a result, the output signal $y(k)$ is obtained. This output signal is compared with the signal (sample) $d(k)$, received on the UAV channel's receiving side. The difference between them forms the error signal $e(k)$ (filter mismatch).

To correct the estimated values of the weight vector coefficients – the taps of the delay line, it is possible to use the following recursion:

$$\widehat{W}(k+1) = \widehat{W}(k) - \mu \nabla J(\widehat{W}(k)) = \widehat{W}(k) + 2\mu P^T(k)e(k), \quad (5.37)$$

where μ – the learning rate parameter of the neural network filter (NNF),

$$\begin{aligned} \nabla J(\widehat{W}(k)) &= \frac{\partial e(k)}{\partial \widehat{w}(k)} = \frac{\partial e(k)}{\partial d(k)} \frac{\partial d(k)}{\partial \widehat{w}(k)} = -2P^T(k)d(k) + 2P^T(k)y(k) = \\ &= -2P^T(k)(d(k) - y(k)) = -2P^T(k)e(k). \end{aligned} \quad (5.38)$$

In the theory of artificial neural networks (ANNs), there are various methods for selecting the value of the learning rate parameter μ , with its value either remaining constant during the learning process or being adjusted adaptively. Fixing the value of the learning rate is considered the simplest form of determination, but it has many drawbacks and is now relatively rarely used. However, this method remains the most effective during the training of the neural network filter (NNF). The constant value of the learning rate parameter is set within the range ($0 < \mu < 1$).

The task of the adaptive neural network filter is to minimize the error signal $e(k)$. To achieve this, an adaptation mechanism (tuning) of the weight coefficients of the neural network filter is used based on the analyzed error signal $e(k)$.

The adaptation (tuning) procedure involves searching for unknown parameters that ensure the adequacy of the neural network. The back-propagation method [9, 17] was used for training the neural network. Each iteration of the training procedure consists of two stages – the forward and backward passes.

The first stage of the training procedure (forward pass algorithm) follows the sequence of Steps:

1. Calculate the total weighted input signal $\rho_j(k)$ of each neuron of the current layer:

$$\rho_j(k) = \sum_{i=1}^{N_{i-1}} v_i w_{ij}. \quad (5.39)$$

2. Calculate the output signal $y_j(k)$ of each neuron of the current layer:

$$y_j(k) = \frac{1}{1 + e^{-k\rho_j(k)}}. \quad (5.40)$$

3. If the current layer is not the output layer, move to the next layer and repeat the procedure from **Step 1**.

4. Calculate the error $e(k)$ of the neural network:

$$e(k) = \frac{1}{2} \sum_{j=1}^{N_K} (y_j(k) - \bar{d}_j(k))^2, \quad (5.41)$$

where $\bar{d}_j(k)$ – the reference output value of the j -th neuron of the output layer, where N_K – the number of neurons in the output layer.

The second stage of the training procedure (backward pass algorithm) follows the sequence of Steps:

1. Determine the rate of change of the error with respect to the output signal for each neuron in the output layer (EA):

$$EA_j^K = \frac{\partial e(k)}{\partial y_j(k)} = (\bar{d}_j(k) - y_j(k)). \quad (5.42)$$

2. Determine the rate of change of the error with respect to the total input signal of each neuron in the current layer (EI):

$$EI_j^i = \frac{\partial e(k)}{\partial p_j(k)} = EA_j^i y_j(k) (1 - y_j(k)). \quad (5.43)$$

3. Determine the rate of change of the error with respect to the weight on the input connection of each neuron in the current layer (EW):

$$EW_{ij}^i = EI_j^i y_i(k). \quad (5.44)$$

4. Determine the rate of change of the error with respect to the activity of the neuron in the previous layer (EA):

$$EA_i^{i-1} = \frac{\partial e(k)}{\partial y_i(k)} = \sum_{j=1}^{N_i} EI_j^i w_{ij}^i, \quad (5.45)$$

where w_{ij}^i – the weight of the connection between the j -th neuron in the output layer and the i -th neuron in the input layer.

5. Update the connections between neurons using the gradient rule:

$$w_{ij}^i[k+1] = w_{ij}^i[k] + \gamma EW_{ij}^i, \quad (5.46)$$

where γ – the learning rate (iteration step); k – the iteration step number.

Transition to the next layer.

If the specified layer is not the input layer, repeat all procedures starting from **Step 2**.

The training continues until an acceptable error is achieved.

As the activation function in the neural network filter (NNF), a linear function is chosen. This allows, analogously to digital filters, to compute the NNF output in response to the input signal $p(k)$ and its previous values $p(k), \dots, p(k-L-1)$ using the following formula:

$$y(k) = \sum_{l=0}^{L-1} p(k-l) \hat{w}_l(k) = P^T(k) \hat{W}(k), \quad (5.47)$$

where $\hat{W}(k) = [\hat{w}_0(k), \hat{w}_1(k), \dots, \hat{w}_{L-1}(k)]^T$ – the column vector of weight coefficient estimates for the generalized characteristic of the radio channel at the k -step; $P(k) = [p(k), p(k-1), \dots, p(k-L-1)]^T$ – the column vector of the contents of the delay line of the NNF at the k -step; L – represents the memory of the UAV channel and the number of taps in the delay line at the input of the NNF.

The process of obtaining the values of the UAV channel state assessment is directly related to the training of the neural network filter (NNF).

The training (learning) sequence vector $P(k)$, corresponding to the set of realizations of the random scalar $d(k)$ together form the training dataset for the neural network filter (NNF):

$$T = \{P(k), d(k)\}_{k=1}^{\Theta}, \quad (5.49)$$

where Θ – the length of the training sequence is denoted.

The estimation error of the received signal $d(k)$ is given by:

$$e(k) = d(k) - y(k) = d(k) - P^T(k) \widehat{W}(k). \quad (5.50)$$

Using the learning criterion based on minimizing the mean square error, let's take the cost function for the evaluation as:

$$J(\widehat{W}(k)) = E_T \{e^2(k)\}_{k=1}^{\Theta}, \quad (5.51)$$

where E_T – the averaging operator over the entire training dataset T .

To obtain the optimal estimates of the weight coefficients for the neural network filter (NNF), it is possible to use the well-known gradient descent method. For this, it is necessary to compute the instantaneous gradient of the estimation error [9, 19].

An example of obtaining the generalized assessment of the UAV channel state is presented. **Table 5.2** provides the definition of the membership function for the fuzzy terms based on the given indicators, while **Table 5.3** shows an example of forming the generalized (comprehensive) assessment of the UAV channel state.

● **Table 5.2** Definition of membership functions for fuzzy terms based on given indicators of UAV channel state evaluation

Values of indicators for UAV channel state evaluation	Universal set	Evaluation terms	Membership function
Impulse response	1–10	Channel in normal condition	0.91–1
		Out of range	0.4–0.9
		Channel unfit for use	< 0.3
Frequency response	1–10	Channel in normal condition	0.91–1
		Out of range	0.4–0.9
		Channel unfit for use	< 0.3
Bit error rate	1–10	Channel in normal condition	0.91–1
		Out of range	0.4–0.9
		Channel unfit for use	< 0.3

● **Table 5.3** Example of forming the generalized (comprehensive) assessment of the UAV channel state

Values of indicators for channel state evaluation	Calculated membership functions	Decision on the channel state
Impulse response	0.080474451	The channel is unfit for operation. There are numerous interferences across the entire bandwidth of the channel. The bit error rate is low and does not allow the channel to be used for transmitting any type of information
Frequency response	0.080474451	
Bit error rate (BER)	0.050553799	

Four types of signals were used in the modeling: phase modulation (FM-4 and FM-8), quadrature amplitude modulation (QAM-16), and signal-code constructions (SCC) with 8 states and 64 points in the constellation.

In the modeling of the method, it is assumed that the method is convergent when, after 15 iterations of the generalized Viterbi algorithm, the error $\epsilon(k)$. The error remained below -36 dB after 15 iterations of the generalized Viterbi algorithm [14].

It is possible to conduct a comparative evaluation of the proposed method in comparison with existing ones. The following input data were used in the modeling: MIMO 8×8 configuration, modulation type – phase modulation, signal ensemble dimensionality $M = 256$; and error-correcting code type – convolutional codes with a rate $R = 0.9$.

The comparison was made using the Zero Forcing (ZF) method, the algorithm optimized according to the Minimum Mean Square Error (MMSE) criterion, and the Maximum Likelihood (ML) method.

The comparative analysis of the proposed method with known methods shows that the proposed method allows for an average 30% increase in the speed of channel state estimation in MIMO systems, thus improving the interference immunity of UAV channels.

Fig. 5.4 shows the focused neural network filter built based on a linear adaptive summator, with its operating procedure for evaluating the state indicators of UAV channels. **Fig. 5.5** shows one of the design implementations of the focused neural network filter for UAV channels.

The method proposed in the work is advisable to use when developing software for modules (blocks) that evaluate prospective radio communication systems, based on the open architecture interfaces of version SCA 2.2.

5.2 DEVELOPMENT OF THE METHODOLOGY FOR IDENTIFYING THE STATE OF CONTROL AND DATA TRANSMISSION CHANNELS OF UNMANNED AERIAL VEHICLES (UAVS)

Let the output of the UAV channels be represented by measurements that form a sample of volume s , and $\{y_i, t_i\}, i = \overline{1, s}$, where $y_i \in R$ – the measurements of the UAV channels' output at a given moment in time $t_i \in [0, +\infty)$, $u = u(t)$ – the known data controls the input of the UAV channels.

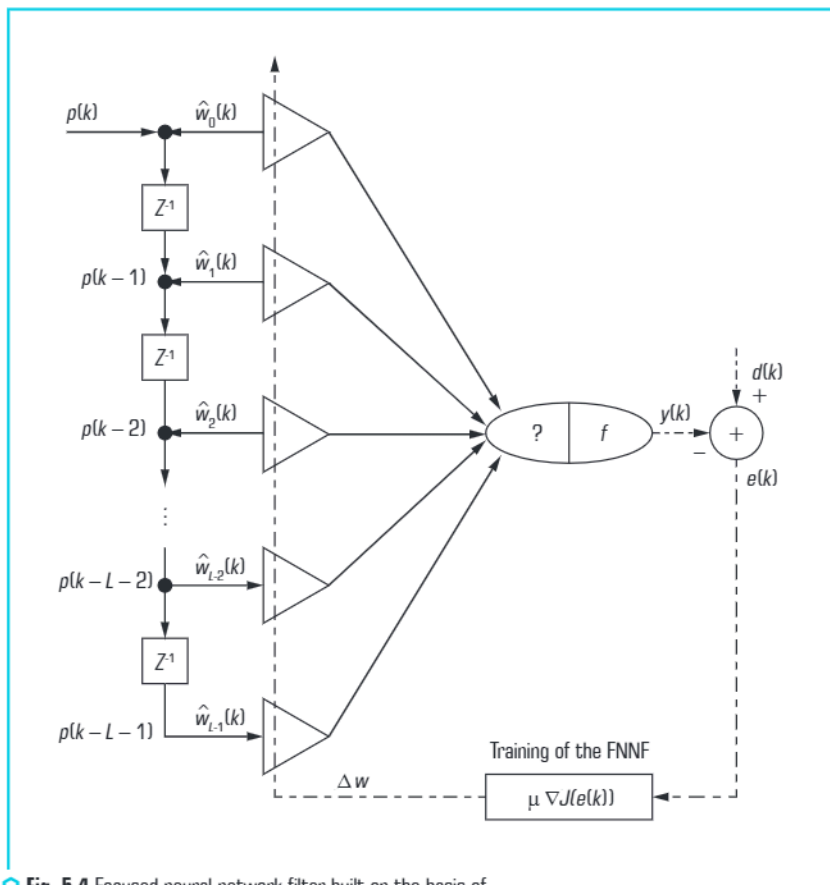


Fig. 5.4 Focused neural network filter built on the basis of a linear adaptive summator

It is also known that the system is linear and is described by a linear differential equation of the form, and the initial condition of the equation is known:

$$a_k \cdot x^{(k)} + a_{k-1} \cdot x^{(k-1)} + \dots + a_0 \cdot x = b \cdot u(t), \quad (5.52)$$

$$x(0) = x_0.$$

It is necessary to determine the system parameters and the order n of the differential equation from the sample data, which let's consider as bounded, i.e., $n-1 \leq M$, $M \in N$. It is assumed that an additively distributed symmetric noise $\xi : M(\xi) = 0$, $D(\xi) < \infty$, and $y_i = x(t_i) + \xi_i$.

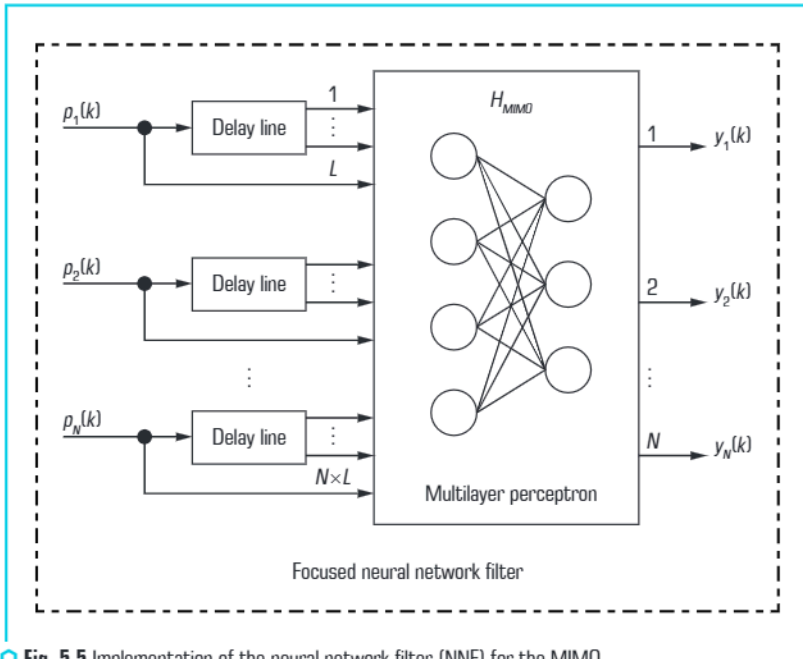


Fig. 5.5 Implementation of the neural network filter (NNF) for the MIMO transmission scheme

Thus, when the order of the system is unknown, we are solving the structural-parametric identification problem. The task will be partially parameterized since the maximum derivative degree that enters the equation is determined in advance, limiting the dimensionality of the search space. This formulation was first discussed in [20] and further developed in [21].

It is possible to assume that for a system of any order, its coefficient at the highest degree equals 1, as follows:

$$x^{(k)} + \frac{a_{k-1}}{a_k} \cdot x^{(k-1)} + \dots + \frac{a_0}{a_k} \cdot x = \frac{b}{a_k} \cdot u(t), \quad (5.53)$$

or

$$x^{(k)} + \tilde{a}_k \cdot x^{(k-1)} + \dots + \tilde{a}_1 \cdot x = \tilde{b} \cdot u(t). \quad (5.54)$$

Then, the solution to the identification problem will be sought as a differential equation of order $m \leq M$, $M \in N$, such that the solution to the Cauchy problem with given initial conditions:

$$\begin{aligned} x^{(k)} + \hat{a}_k \cdot x^{(k-1)} + \dots + \hat{a}_1 \cdot x &= \hat{b} \cdot u(t), \\ \hat{x}(0) &= x_0, \end{aligned} \quad (5.55)$$

with parameters $\hat{a} = (0 \dots 0 \quad \hat{a}_m \dots \hat{a}_1 \quad \hat{a}_0)^T \in R^n$, i.e., $n = M + 1$, which deliver the extremum of the chosen function.

$$\begin{aligned} I_1(a) &= \sum_{i=1}^N \left| y_i - \hat{x}(t_i) \right| \Big|_{\hat{a}=a} \rightarrow \min_{a \in R^n}, \\ I_2(a) &= \max_i \left| y_i - \hat{x}(t_i) \right| \Big|_{\hat{a}=a} \rightarrow \min_{a \in R^n}. \end{aligned} \quad (5.56)$$

To estimate the process model in the form of (5.53) as a solution to one of the extremum search problems: (5.54) or (5.55), it is necessary to have information about the initial position of the system so that the Cauchy problem can be solved.

In general, the vector of the initial position of the system, if it is not known initially, can be numerically estimated, which, of course, is not always possible and depends on the properties of the sample. Another option for determining the initial position of the system is to include the vector in the optimization task. Typically, for many tasks, the observation process starts from a steady state, so all coordinates of the initial position for UAV channels are set to 0, except for the output position of the UAV channels.

It is possible to assume that it is necessary to build a mathematical model of the dynamic process, which it is possible to represent in matrix form:

$$\dot{\tilde{x}}' = \hat{A} \cdot \tilde{x}(t) + \hat{B} \cdot u(t), x(0) = x_0, \quad (5.57)$$

where $\hat{A} = (\hat{a}_{ij})_{i=1, j=1}^{n,n}$ – the matrix of the system of linear differential equations is represented as:

$\hat{B} = (\hat{b}_{ij})_{i=1, j=1}^{n,m}$ – the matrix of the right-hand sides, control coefficients; $\tilde{x}(t) \in R^n$ – state model

of the UAV channels; $u(t) \in R^m$ – control actions, represented as a vector function.

Given that several different outputs of the UAV channels are observed, which may differ in the amplitude of the response, it is necessary to normalize each individual criterion. To do this, it is possible to define the diameter of the measurement set for each observed output by including the initial position of the output in this set. Then, the criterion takes the following form:

$$I(a) = \sum_{i=1}^{N_0} \frac{\sum_{j=1}^{s_j} \left| y_i^j - \hat{x}^j(t_i^j) \right|}{\sup(|a-b| : a, b \in Y^i \cup X_0^i)} \Big|_{\hat{a}=a} \rightarrow \min_{A, B} \quad (5.58)$$

where N_0 – the number of UAV channel outputs; $s_j, j = \overline{1, N_0}$ – the sample size for each UAV channel output; $y_j^i, i = \overline{1, \overline{s_j}}, j = \overline{1, N_0}$ – the measurements of the outputs forming the samples; $t_j^i, i = \overline{1, \overline{s_j}}, j = \overline{1, N_0}$ – the measurement times for each j -th output; $\sup(|a - b| : a, b \in Y^i \cup X_0^i)$ – the diameter of the measurement set for each output; $\hat{z}^j(t) | \hat{A} = A, \hat{B} = B$ – j -th output of the model with matrices A, B .

Criterion (5.58) is analogous to the criterion for a system with one input and one output, as in (5.56). Thus, the task of identifying the UAV channels has been reduced to searching for the extremum in the space of vectors with real coordinates. At the same time, the peculiarities of representing the structure of UAV channels lead to complex behavior of the objective function near certain points of the space, where the first coordinates of the vector approach 0.

The methodology for identifying the state of the control and data transmission channels of UAVs consists of the following interconnected procedures:

1. *Input of initial data about the state of the UAV channels.*
2. *Initialization of the initial model based on expressions (5.52)–(5.58).*
3. *Input of correction coefficients for noise and prior uncertainty about the state of the UAV channels using the expressions [22].*

Given the lack of prior information about the coefficients and the order of the differential equation, using binary representation of the optimization variables becomes difficult and inefficient in terms of finding a solution.

According to the accepted transition from the vector, i.e., the individual, to the differential equation, the vector, given the specifics of the chosen representation of the solution, contains information about the order, structure, and coefficients of the differential equation, which must be taken into account for improving the algorithm's performance.

4. *Determination of the order of the differential equation.*

Let \hat{a} – be the vector containing the solution to the problem, then $j_{\text{order}} \in N, j_{\text{order}} \leq M, j_{\text{order}} : \hat{a}_{j_{\text{order}}} \neq 0, \hat{a}_i = 0, i)_{j_{\text{order}}}$. If $\hat{a}_M \neq 0 \rightarrow j_{\text{order}} = M$. Then the order of the equation will be determined by the index j_{order} . Considering the proposed approach to determining the order of the differential equation, it is important that the algorithm for solving the problem has the ability to maintain certain coordinates equal to 0.

5. *Rounding of vector coordinates.*

One of the special modifications of the algorithm was the introduction of the rounding operation for vector coordinates:

$$op_j^i = \text{round}(op_j^i), j = \overline{1, n}, i = \overline{1, N}, \quad (5.59)$$

where $\text{round}(\cdot) : R \rightarrow Z$ – a function that rounds a number to its nearest integer. This operator, which influences the objective parameters of the algorithm, solves the task of converting the vector coordinates into integers. Since, for representing the system's structure, it is important that in some cases a certain number of solution coordinates consecutively approach zero, and the stochastic

search algorithm disturbs variables due to the nature of the mutation operation, an operator is needed that would maintain the found order. The rounding operator is applied immediately after the mutation operator, and after rounding, a local improvement of the obtained population occurs.

6. Mutation of individuals in the population.

To enhance the effectiveness of the solution search regarding the state of a heterogeneous dynamic object, the mutation operator was modified in such a way that the mutation probability for

each pair of objectives – strategic parameters is $\rho_m = \frac{1}{q}$. Thus, random disturbances do not lead

to a significant spread of individuals in the next population around a certain found solution, which is not eliminated during the subsequent local improvement of the alternative after rounding.

7. Generation of the initial population.

Since random selection of coefficients for the initial population will not lead to the appearance of diverse solutions that correspond to equations of different orders, considering such a representation of solutions, the population will be generated as follows:

1. For each individual, with probability $\frac{1}{M}$ the order of the differential equation is selected.
2. For the chosen order i_{order} each non-zero coordinate is solved uniformly over the interval $[-5, 5]$.
3. All strategic parameters of the individual are randomly selected uniformly over the interval $[0, 1]$.

The proposed scheme was selected as the best through the trial-and-error process of different initial solution generation variants.

It is necessary to account for some specifics of the local improvement of alternatives using the proposed random coordinate descent algorithm. The rounding operator (5.59) applied to each coordinate results in the loss of solution accuracy due to the truncation of the mantissa. To compensate for the loss of precision and improve the overall efficiency of the algorithm, it is necessary for the coordinate descent to take such a number of steps that, with the chosen step length, the rounded coefficient could be refined in such a way that the value returned would precede the integer.

End.

To evaluate the effectiveness of the proposed methodology, 100 systems were randomly generated: 10 systems for each order of the differential equation, from the first to the tenth. The parameters of each system were randomly selected as follows: $\bar{a}_k^i \sim U(-5,5)$, $\bar{b}_k \sim U(-5,5)$, $i = \bar{1}, \bar{10}$, $k = \bar{1}, \bar{i}$. The operating time of the system was chosen to be 5.

The control function for all analyzed tasks was chosen to be a unit function, i.e., $u(t) = 1$. The sampled data are selected from the numerical solution of the differential equation. $\{x_i, t_i\}$, $i = \bar{1}, \bar{T} / \bar{h}_{\text{ode}}$ – the numerical solution of the system. Then, for the given sample size $s \ll T / h_{\text{ode}}$, $s = 100$ select s different points are randomly selected from the numerical solution of the differential equation.

To evaluate the effectiveness of the optimization algorithm's parameters, the identification of UAV channels without disturbances in the measurement channels was considered, so that this factor

would not introduce additional complexity into the task and the obtained solutions could be assessed. For this reason, the sample size was chosen to be sufficiently large to assess its representativeness, i.e., to ensure that the sampled data encompassed all the features of the transient process.

For each individual system, 20 runs of the algorithm were performed with specific settings. All initial conditions for these tasks were set to zero. The population size was chosen to be 50, and the number of populations was set to 50. The parameters of the local descent were $N_1 = 50$, $N_2 = 50$, and $N_3 = 1$ if $h_1 = 0.05$.

The study of the effectiveness of the proposed methodology showed that the average fitness increases as the order of the real object approaches the established parameter-limit of the maximum model order. This suggests that the algorithms should work in such a way as to retain the ability to reduce the system order while maintaining the equality of the first coordinates at 0. Therefore, modifying the mutation or introducing the rounding operator leads to significant improvement. It is also important to note that the increase in fitness is related to the fact that, over the observation period, a higher-order system behaves in such a way that it is easier to build its model than, under similar conditions, a lower-order model.

The transient processes of different systems may coincide over a certain interval, so only increasing the observation interval for the system output and increasing the frequency of measurements can improve the efficiency of finding a solution. On the other hand, this may be due to the presence of a large number of local optima and a strong attraction zone.

CONCLUSIONS

1. A method for the intellectual evaluation of the state of UAV channels is proposed, based on the use of fuzzy sets and artificial neural networks.

Despite its simplicity, the method allows obtaining quite accurate solutions. Key features of the proposed method include:

- state of the UAV channels is evaluated in parallel across several indicators of their state (impulse response, frequency response, and bit error probability);
- evaluation of several channel state characteristics of UAVs is continuously performed in real-time;
- evaluation of several characteristics of the UAV channel's state is continuously carried out in both the downlink and uplink channels;
- the state of the UAV channel is evaluated for each indicator on a separate layer of the neural network using the construction of the membership function;
- after evaluating each channel characteristic on a separate neural network layer, a generalized assessment of the channel's state is formed at the output.

The evaluation obtained using the proposed intellectual evaluation method matches the results obtained using the optimal algorithm based on the minimum mean square error criterion. Additionally, these results are computed 30 % faster, which reduces the adaptation time of the radio

communication device. A key factor determining the effectiveness of the proposed comprehensive method is the degree of training of the neural network to the signal environment.

2. To reduce the neural network training time and increase the efficiency of the proposed method, it is advisable to preload the knowledge bases of the signal environment. This will minimize the network training time and simplify the adaptation process of the radio communication device by an average of 15 %.

3. The proposed method for the intellectual evaluation of the UAV channel's state can be implemented in programmable architecture-based communication devices. To achieve this, it is necessary to adapt the signal processor through additional software for the specific transceiver device. This software should be developed on the SCA 2.2 platform.

4. The study presents the development of a methodology for identifying the state of UAV control and data transmission channels.

The novelty of the proposed methodology lies in:

- accounting for the corrective coefficient based on the degree of uncertainty regarding the state of UAV channels in the calculations;
- adding a corrective coefficient for the noise in the data resulting from the distortion of information about the UAV channel's state;
- reducing computational costs when evaluating the state of UAV channels;
- ability to perform calculations with input data that differ in nature and units of measurement.

This methodology is recommended for implementation in specialized software used for analyzing the state of complex technical systems and making management decisions.

REFERENCES

1. Dudnyk, V., Sinenko, Y., Matsyk, M., Demchenko, Y., Zhyvotovskiy, R., Repilo, I. et al. (2020). Development of a method for training artificial neural networks for intelligent decision support systems. *Eastern-European Journal of Enterprise Technologies*, 3 (2 (105)), 37–47. <https://doi.org/10.15587/1729-4061.2020.203301>
2. Sova, O., Shyshatskyi, A., Salnikova, O., Zhuk, O., Trotsko, O., Hrokholskyi, Y. (2021). Development of a method for assessment and forecasting of the radio electronic environment. *EUREKA: Physics and Engineering*, 4, 30–40. <https://doi.org/10.21303/2461-4262.2021.001940>
3. Pievtsov, H., Turinskyi, O., Zhyvotovskiy, R., Sova, O., Zvieriev, O., Lanetskii, B., Shyshatskyi, A. (2020). Development of an advanced method of finding solutions for neuro-fuzzy expert systems of analysis of the radioelectronic situation. *EUREKA: Physics and Engineering*, 4, 78–89. <https://doi.org/10.21303/2461-4262.2020.001353>
4. Zuiiev, P., Zhyvotovskiy, R., Zvieriev, O., Hatsenko, S., Kuprii, V., Nakonechnyi, O. et al. (2020). Development of complex methodology of processing heterogeneous data in intelligent deci-

- sion support systems. *Eastern-European Journal of Enterprise Technologies*, 4 (9 (106)), 14–23. <https://doi.org/10.15587/1729-4061.2020.208554>
5. Kuchuk, N., Mohammed, A. S., Shyshatskyi, A., Nalapko, O. (2019). The Method of Improving the Efficiency of Routes Selection in Networks of Connection with the Possibility of Self-Organization. *International Journal of Advanced Trends in Computer Science and Engineering*, 8 (1.2), 1–6.
 6. Shyshatskyi, A., Zvieriev, O., Salnikova, O., Demchenko, Ye., Trotsko, O., Neroznak, Ye. (2020). Complex Methods of Processing Different Data in Intellectual Systems for Decision Support System. *International Journal of Advanced Trends in Computer Science and Engineering*, 9 (4), 5583–5590. <https://doi.org/10.30534/ijatcse/2020/206942020>
 7. Pozna, C., Precup, R.-E., Horvath, E., Petriu, E. M. (2022). Hybrid Particle Filter–Particle Swarm Optimization Algorithm and Application to Fuzzy Controlled Servo Systems. *IEEE Transactions on Fuzzy Systems*, 30 (10), 4286–4297. <https://doi.org/10.1109/tfuzz.2022.3146986>
 8. Yang, X.-S., Deb, S. (2013). Cuckoo search: recent advances and applications. *Neural Computing and Applications*, 24 (1), 169–174. <https://doi.org/10.1007/s00521-013-1367-1>
 9. Mirjalili, S. (2015). The Ant Lion Optimizer. *Advances in Engineering Software*, 83, 80–98. <https://doi.org/10.1016/j.advengsoft.2015.01.010>
 10. Yu, J. J. Q., Li, V. O. K. (2015). A social spider algorithm for global optimization. *Applied Soft Computing*, 30, 614–627. <https://doi.org/10.1016/j.asoc.2015.02.014>
 11. Mirjalili, S., Mirjalili, S. M., Lewis, A. (2014). Grey Wolf Optimizer. *Advances in Engineering Software*, 69, 46–61. <https://doi.org/10.1016/j.advengsoft.2013.12.007>
 12. Koval, V., Nechyporuk, O., Shyshatskyi, A., Nalapko, O., Shknaï, O., Zhyvylo, Y. et al. (2023). Improvement of the optimization method based on the cat pack algorithm. *Eastern-European Journal of Enterprise Technologies*, 1 (9 (121)), 41–48. <https://doi.org/10.15587/1729-4061.2023.273786>
 13. Gupta, E., Saxena, A. (2015). Robust generation control strategy based on Grey Wolf Optimizer. *Journal of Electrical Systems*, 11, 174–188.
 14. Chaman-Motlagh, A. (2015). Superdefect Photonic Crystal Filter Optimization Using Grey Wolf Optimizer. *IEEE Photonics Technology Letters*, 27 (22), 2355–2358. <https://doi.org/10.1109/lpt.2015.2464332>
 15. Nuaekaew, K., Artrit, P., Pholdee, N., Bureerat, S. (2017). Optimal reactive power dispatch problem using a two-archive multi-objective grey wolf optimizer. *Expert Systems with Applications*, 87, 79–89. <https://doi.org/10.1016/j.eswa.2017.06.009>
 16. Koval, M., Sova, O., Orlov, O., Shyshatskyi, A., Artabaiev, Y., Shknaï, O. et al. (2022). Improvement of complex resource management of special-purpose communication systems. *Eastern-European Journal of Enterprise Technologies*, 5 (9 (119)), 34–44. <https://doi.org/10.15587/1729-4061.2022.266009>

17. Ali, M., El-Hameed, M. A., Farahat, M. A. (2017). Effective parameters' identification for polymer electrolyte membrane fuel cell models using grey wolf optimizer. *Renewable Energy*, 111, 455–462. <https://doi.org/10.1016/j.renene.2017.04.036>
18. Zhang, S., Zhou, Y. (2017). Template matching using grey wolf optimizer with lateral inhibition. *Optik*, 130, 1229–1243. <https://doi.org/10.1016/j.ijleo.2016.11.173>
19. Khouni, S. E., Menacer, T. (2023). Nizar optimization algorithm: a novel metaheuristic algorithm for global optimization and engineering applications. *The Journal of Supercomputing*, 80 (3), 3229–3281. <https://doi.org/10.1007/s11227-023-05579-4>
20. Saremi, S., Mirjalili, S., Lewis, A. (2017). Grasshopper Optimisation Algorithm: Theory and application. *Advances in Engineering Software*, 105, 30–47. <https://doi.org/10.1016/j.advengsoft.2017.01.004>
21. Braik, M. S. (2021). Chameleon Swarm Algorithm: A bio-inspired optimizer for solving engineering design problems. *Expert Systems with Applications*, 174, 114685. <https://doi.org/10.1016/j.eswa.2021.114685>
22. Thamer, K. A., Sova, O., Shaposhnikova, O., Yashchenok, V., Stanovska, I., Shostak, S. et al. (2024). Development of a solution search method using a combined bio-inspired algorithm. *Eastern-European Journal of Enterprise Technologies*, 1 (4 (127)), 6–13. <https://doi.org/10.15587/1729-4061.2024.298205>
23. Yapici, H., Cetinkaya, N. (2019). A new meta-heuristic optimizer: Pathfinder algorithm. *Applied Soft Computing*, 78, 545–568. <https://doi.org/10.1016/j.asoc.2019.03.012>
24. Duan, H., Qiao, P. (2014). Pigeon-inspired optimization: a new swarm intelligence optimizer for air robot path planning. *International Journal of Intelligent Computing and Cybernetics*, 7 (1), 24–37. <https://doi.org/10.1108/ijicc-02-2014-0005>
25. Shyshatskyi, A., Romanov, O., Shknaï, O., Babenko, V., Koshlan, O., Pluhina, T. et al. (2023). Development of a solution search method using the improved emperor penguin algorithm. *Eastern-European Journal of Enterprise Technologies*, 6 (4 (126)), 6–13. <https://doi.org/10.15587/1729-4061.2023.291008>
26. Yang, X.-S. (2012). Flower Pollination Algorithm for Global Optimization. *Unconventional Computation and Natural Computation*, 240–249. https://doi.org/10.1007/978-3-642-32894-7_27
27. Gomes, G. F., da Cunha, S. S., Ancelotti, A. C. (2018). A sunflower optimization (SFO) algorithm applied to damage identification on laminated composite plates. *Engineering with Computers*, 35 (2), 619–626. <https://doi.org/10.1007/s00366-018-0620-8>
28. Mehrabian, A. R., Lucas, C. (2006). A novel numerical optimization algorithm inspired from weed colonization. *Ecological Informatics*, 1 (4), 355–366. <https://doi.org/10.1016/j.ecoinf.2006.07.003>
29. Qi, X., Zhu, Y., Chen, H., Zhang, D., Niu, B. (2013). An Idea Based on Plant Root Growth for Numerical Optimization. *Intelligent Computing Theories and Technology*. Berlin: Heidelberg, 571–578. https://doi.org/10.1007/978-3-642-39482-9_66

30. Bezuhlyi, V., Oliynyk, V., Romanenko, I., Zhuk, O., Kuzavkov, V., Borysov, O. et al. (2021). Development of object state estimation method in intelligent decision support systems. *Eastern-European Journal of Enterprise Technologies*, 5 (3 (113)), 54–64. <https://doi.org/10.15587/1729-4061.2021.239854>
31. Mahdi, G. A., Shyshatskyi, A., Prokopenko, Y., Ivakhnenko, T., Kupriyenko, D., Golian, V. et al. (2021). Development of estimation and forecasting method in intelligent decision support systems. *Eastern-European Journal of Enterprise Technologies*, 3 (9 (111)), 51–62. <https://doi.org/10.15587/1729-4061.2021.232718>
32. Sova, O., Radzivilov, H., Shyshatskyi, A., Shevchenko, D., Molodetskyi, B., Stryhun, V. et al. (2022). Development of the method of increasing the efficiency of information transfer in the special purpose networks. *Eastern-European Journal of Enterprise Technologies*, 3 (4 (117)), 6–14. <https://doi.org/10.15587/1729-4061.2022.259727>
33. Zhang, H., Zhu, Y., Chen, H. (2013). Root growth model: a novel approach to numerical function optimization and simulation of plant root system. *Soft Computing*, 18 (3), 521–537. <https://doi.org/10.1007/s00500-013-1073-z>
34. Labbi, Y., Attous, D. B., Gabbar, H. A., Mahdad, B., Zidan, A. (2016). A new rooted tree optimization algorithm for economic dispatch with valve-point effect. *International Journal of Electrical Power & Energy Systems*, 79, 298–311. <https://doi.org/10.1016/j.ijepes.2016.01.028>
35. Murase, H. (2000). Finite element inverse analysis using a photosynthetic algorithm. *Computers and Electronics in Agriculture*, 29 (1-2), 115–123. [https://doi.org/10.1016/s0168-1699\(00\)00139-3](https://doi.org/10.1016/s0168-1699(00)00139-3)
36. Zhao, S., Zhang, T., Ma, S., Chen, M. (2022). Dandelion Optimizer: A nature-inspired meta-heuristic algorithm for engineering applications. *Engineering Applications of Artificial Intelligence*, 114, 105075. <https://doi.org/10.1016/j.engappai.2022.105075>
37. Paliwal, N., Srivastava, L., Pandit, M. (2020). Application of grey wolf optimization algorithm for load frequency control in multi-source single area power system. *Evolutionary Intelligence*, 15 (1), 563–584. <https://doi.org/10.1007/s12065-020-00530-5>
38. Dorigo, M., Blum, C. (2005). Ant colony optimization theory: A survey. *Theoretical Computer Science*, 344 (2-3), 243–278. <https://doi.org/10.1016/j.tcs.2005.05.020>
39. Poli, R., Kennedy, J., Blackwell, T. (2007). Particle swarm optimization. *Swarm Intelligence*, 1 (1), 33–57. <https://doi.org/10.1007/s11721-007-0002-0>
40. Bansal, J. C., Sharma, H., Jadon, S. S., Clerc, M. (2014). Spider Monkey Optimization algorithm for numerical optimization. *Memetic Computing*, 6 (1), 31–47. <https://doi.org/10.1007/s12293-013-0128-0>
41. Yeromina, N., Kurban, V., Mykus, S., Peredrii, O., Voloshchenko, O., Kosenko, V. et al. (2021). The Creation of the Database for Mobile Robots Navigation under the Conditions of Flexible Change of Flight Assignment. *International Journal of Emerging Technology and Advanced Engineering*, 11 (5), 37–44. https://doi.org/10.46338/ijetae0521_05

42. Maccarone, A. D., Brzorad, J. N., Stone, H. M. (2008). Characteristics And Energetics of Great Egret and Snowy Egret Foraging Flights. *Waterbird*, 31 (4), 541–549. <https://doi.org/10.1675/1524-4695-31.4.541>
43. Ramaji, I. J., Memari, A. M. (2018). Interpretation of structural analytical models from the coordination view in building information models. *Automation in Construction*, 90, 117–133. <https://doi.org/10.1016/j.autcon.2018.02.025>
44. Pérez-González, C. J., Colebrook, M., Roda-García, J. L., Rosa-Remedios, C. B. (2019). Developing a data analytics platform to support decision making in emergency and security management. *Expert Systems with Applications*, 120, 167–184. <https://doi.org/10.1016/j.eswa.2018.11.023>
45. Chen, H. (2018). Evaluation of Personalized Service Level for Library Information Management Based on Fuzzy Analytic Hierarchy Process. *Procedia Computer Science*, 131, 952–958. <https://doi.org/10.1016/j.procs.2018.04.233>
46. Chan, H. K., Sun, X., Chung, S.-H. (2019). When should fuzzy analytic hierarchy process be used instead of analytic hierarchy process? *Decision Support Systems*, 125, 113114. <https://doi.org/10.1016/j.dss.2019.113114>
47. Osman, A. M. S. (2019). A novel big data analytics framework for smart cities. *Future Generation Computer Systems*, 91, 620–633. <https://doi.org/10.1016/j.future.2018.06.046>
48. Nechyporuk, O., Sova, O., Shyshatskyi, A., Kravchenko, S., Nalapko, O., Shknai, O. et al. (2023). Development of a method of complex analysis and multidimensional forecasting of the state of intelligence objects. *Eastern-European Journal of Enterprise Technologies*, 2 (4 (122)), 31–41. <https://doi.org/10.15587/1729-4061.2023.276168>
49. Merrikh-Bayat, F. (2015). The runner-root algorithm: A metaheuristic for solving unimodal and multimodal optimization problems inspired by runners and roots of plants in nature. *Applied Soft Computing*, 33, 292–303. <https://doi.org/10.1016/j.asoc.2015.04.048>
50. Poliarush, O., Krepych, S., Spivak, I. (2023). Hybrid approach for data filtering and machine learning inside content management system. *Advanced Information Systems*, 7 (4), 70–74. <https://doi.org/10.20998/2522-9052.2023.4.09>
51. Balochian, S., Balochian, H. (2019). Social mimic optimization algorithm and engineering applications. *Expert Systems with Applications*, 134, 178–191. <https://doi.org/10.1016/j.eswa.2019.05.035>
52. Lenord Melvix, J. S. M. (2014). Greedy Politics Optimization: Metaheuristic inspired by political strategies adopted during state assembly elections. 2014 IEEE International Advance Computing Conference (IACC), 1157–1162. <https://doi.org/10.1109/iadcc.2014.6779490>
53. Moosavian, N., Roodsari, B. K. (2014). Soccer League Competition Algorithm, a New Method for Solving Systems of Nonlinear Equations. *International Journal of Intelligence Science*, 4 (1), 7–16. <https://doi.org/10.4236/ijis.2014.41002>
54. Hayyolalam, V., Pourhaji Kazem, A. A. (2020). Black Widow Optimization Algorithm: A novel meta-heuristic approach for solving engineering optimization problems. *Engineer-*

- ing Applications of Artificial Intelligence, 87, 103249. <https://doi.org/10.1016/j.engappai.2019.103249>
55. Abualigah, L., Younsri, D., Abd Elaziz, M., Ewees, A. A., Al-qaness, M. A. A., Gandomi, A. H. (2021). Aquila Optimizer: A novel meta-heuristic optimization algorithm. *Computers & Industrial Engineering*, 157, 107250. <https://doi.org/10.1016/j.cie.2021.107250>
 56. Hodlevskiy, M., Burlakov, G. (2023). Information technology of quality improvement planning of process subsets of the spice model. *Advanced Information Systems*, 7 (4), 52–59. <https://doi.org/10.20998/2522-9052.2023.4.06>
 57. Askari, G., Younas, I., Saeed, M. (2020). Political Optimizer: A novel socio-inspired meta-heuristic for global optimization. *Knowledge-Based Systems*, 195, 105709. <https://doi.org/10.1016/j.knosys.2020.105709>
 58. Mohamed, A. W., Hadi, A. A., Mohamed, A. K. (2019). Gaining-sharing knowledge based algorithm for solving optimization problems: a novel nature-inspired algorithm. *International Journal of Machine Learning and Cybernetics*, 11 (7), 1501–1529. <https://doi.org/10.1007/s13042-019-01053-x>
 59. Gödri, I., Kardos, C., Pfeiffer, A., Váncza, J. (2019). Data analytics-based decision support workflow for high-mix low-volume production systems. *CIRP Annals*, 68 (1), 471–474. <https://doi.org/10.1016/j.cirp.2019.04.001>
 60. Harding, J. L. (2013). Data quality in the integration and analysis of data from multiple sources: some research challenges. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, XL-2/W1, 59–63. <https://doi.org/10.5194/isprsarchives-xl-2-w1-59-2013>
 61. Orouskhani, M., Orouskhani, Y., Mansouri, M., Teshnehlab, M. (2013). A Novel Cat Swarm Optimization Algorithm for Unconstrained Optimization Problems. *International Journal of Information Technology and Computer Science*, 5 (11), 32–41. <https://doi.org/10.5815/ijitcs.2013.11.04>
 62. Karaboga, D., Basturk, B. (2007). A powerful and efficient algorithm for numerical function optimization: artificial bee colony (ABC) algorithm. *Journal of Global Optimization*, 39 (3), 459–471. <https://doi.org/10.1007/s10898-007-9149-x>
 63. Fister, I., Fister, I., Yang, X.-S., Brest, J. (2013). A comprehensive review of firefly algorithms. *Swarm and Evolutionary Computation*, 13, 34–46. <https://doi.org/10.1016/j.swevo.2013.06.001>
 64. Sova, O., Radzivilov, H., Shyshatskyi, A., Shvets, P., Tkachenko, V., Nevhad, S. et al. (2022). Development of a method to improve the reliability of assessing the condition of the monitoring object in special-purpose information systems. *Eastern-European Journal of Enterprise Technologies*, 2 (3 (116)), 6–14. <https://doi.org/10.15587/1729-4061.2022.254122>
 65. Khudov, H., Khizhnyak, I., Glukhov, S., Shamrai, N., Pavlii, V. (2024). The method for objects detection on satellite imagery based on the firefly algorithm. *Advanced Information Systems*, 8 (1), 5–11. <https://doi.org/10.20998/2522-9052.2024.1.01>

66. Owaid, S. R., Zhuravskiy, Y., Lytvynenko, O., Veretnov, A., Sokolovskiy, D., Plekhova, G. et al. (2024). Development of a method of increasing the efficiency of decision-making in organizational and technical systems. *Eastern-European Journal of Enterprise Technologies*, 1 (4 (127)), 14–22. <https://doi.org/10.15587/1729-4061.2024.298568>
67. Tyurin, V., Bieliakov, R., Odarushchenko, E., Yashchenok, V., Shaposhnikova, O., Lyashenko, A. et al. (2023). Development of a solution search method using an improved locust swarm algorithm. *Eastern-European Journal of Enterprise Technologies*, 5 (4 (125)), 25–33. <https://doi.org/10.15587/1729-4061.2023.287316>
68. Yakymiak, S., Vdovytskyi, Y., Artabaiev, Y., Degtyareva, L., Vakulenko, Y., Nevhad, S. et al. (2023). Development of the solution search method using the population algorithm of global search optimization. *Eastern-European Journal of Enterprise Technologies*, 3 (4 (123)), 39–46. <https://doi.org/10.15587/1729-4061.2023.281007>
69. Mohammed, B. A., Zhuk, O., Vozniak, R., Borysov, I., Petrozhalko, V., Davydov, I. et al. (2023). Improvement of the solution search method based on the cuckoo algorithm. *Eastern-European Journal of Enterprise Technologies*, 2 (4(122)), 23–30. <https://doi.org/10.15587/1729-4061.2023.277608>
70. Raskin, L., Sukhomlyn, L., Sokolov, D., Vlasenko, V. (2023). Multi-criteria evaluation of the multifactor stochastic systems effectiveness. *Advanced Information Systems*, 7 (2), 63–67. <https://doi.org/10.20998/2522-9052.2023.2.09>
71. Arora, S., Singh, S. (2018). Butterfly optimization algorithm: a novel approach for global optimization. *Soft Computing*, 23 (3), 715–734. <https://doi.org/10.1007/s00500-018-3102-4>
72. Mamoori, G. A., Sova, O., Zhuk, O., Repilo, I., Melnyk, B., Sus, S. et al. (2023). The development of solution search method using improved jumping frog algorithm. *Eastern-European Journal of Enterprise Technologies*, 4 (3 (124)), 45–53. <https://doi.org/10.15587/1729-4061.2023.285292>
73. Alieinykov, I., Thamer, K. A., Zhuravskiy, Y., Sova, O., Smirnova, N., Zhyvotovskiy, R. et al. (2019). Development of a method of fuzzy evaluation of information and analytical support of strategic management. *Eastern-European Journal of Enterprise Technologies*, 6 (2 (102)), 16–27. <https://doi.org/10.15587/1729-4061.2019.184394>
74. Shyshatskyi, A. V., Zhuk, O. V., Neronov, S. M., Protas, N. M., Kashkevych, S. O. (2024). Sukupnist metodyk pidvyshchennia operatyvnosti pryiniattia rishen z vykorystanniam metaevrystychnykh alhorytmiv. *Modern Aspects of Science. Scientific Perspectives*, 529–557. Available at: <http://perspectives.pp.ua/public/site/mono/mono-40.pdf>
75. Shyshatskyi, A. V., Matsyi, O. B., Yashchenok, V. Zh., Trotsko, O. O., Kashkevych, S. O. (2024). Sukupnist metodyk pidvyshchennia operatyvnosti pryiniattia rishen z vykorystanniam kombinovanykh metaevrystychnykh alhorytmiv. *Modern Aspects of Science. Scientific Perspectives*, 558–594. Available at: <http://perspectives.pp.ua/public/site/mono/mono-40.pdf>
76. Kashkevich, S., Dmytriieva, O., Trotsko, O., Shknai, O., Shyshatskyi, A. (2023). Mathematical model of information conflict of information networks. *ScienceRise*, 1, 3–13. <https://doi.org/10.21303/2313-8416.2024.003395>

77. Kashkevych, S. O., Dmytriieva, O. I., Yefymenko, O. V., Pliekhova, H. A., Shyshatskyi, A. V. (2024). Metody otsinky stanu skladnykh dynamichnykh ob'ektiv vykorystanniam bioinspirovanykh alhorytmiv. *Modern Aspects of Science. Scientific Perspectives*, 138–177. Available at: <http://perspectives.pp.ua/public/site/mono/mono-40.pdf>
78. Kashkevych, S. O., Dmytriieva, O. I., Trotsko, O. O., Shknaï, O. V., Shyshatskyi, A. V. (2024). Metod samoorhanizatsii informatsiinykh merezh v umovakh destabilizuiuchykh vplyviv. The development of technical, agricultural and applied sciences as the main factor in improving life. Boston: Primedia eLaunch, 192–218. <https://doi.org/10.46299/ISG.2024.MONO.TECH.2.7.2>
79. Shyshatskyi, A., Dmytriieva, O., Lytvynenko, O., Borysov, I., Vakulenko, Y., Mukashev, T. et al. (2024). Development of a method for assessing the state of dynamic objects using a combined swarm algorithm. *Eastern-European Journal of Enterprise Technologies*, 3 (4(129)), 44–54. <https://doi.org/10.15587/1729-4061.2024.304131>
80. Kashkevich, S., Litvinenko, O., Shyshatskyi, A., Salnyk, S., Velychko, V. (2024). The method of self-organization of information networks in the conditions of the complex influence of destabilizing factors. *Advanced Information Systems*, 8 (3), 59–71. <https://doi.org/10.20998/2522-9052.2024.3.07>
81. Kashkevych, S. O., Dmytriieva, O. I., Plekhova, H. A., Protas, N. M., Neronov, S. M., Shyshatskyi, A. V. (2024). Naukovo-metodychnyi pidkhid z pidvyshchennia operatyvnosti obrobky riznotyprnykh danykh z vykorystanniam metaevrystychnykh alhorytmiv. *Modern Aspects of Science. Scientific Perspectives*, 510–543. Available at: <http://perspectives.pp.ua/public/site/mono/mono-40.pdf>
82. Litvinenko, O., Kashkevich, S., Dmytriieva, O., Neronov, S., Plekhova, G.; Shyshatskyi, A. (Ed.) (2024). The method of self-organization of information networks in the conditions of destabilizing influences. *Information and control systems: modelling and optimizations*. Kharkiv: TECHNOLOGY CENTER PC, 3–34. <https://doi.org/10.15587/978-617-8360-04-7.ch1>
83. Kashkevich, S., Dmytriieva, O., Neronov, S., Plekhova, G., Zhyvylo, Y.; Shyshatskyi, A. (Ed.) (2024). The development of management methods based on bio-inspired algorithms. *Information and control systems: modelling and optimizations*. Kharkiv: TECHNOLOGY CENTER PC, 35–69. <https://doi.org/10.15587/978-617-8360-04-7.ch2>
84. Kashkevich, S., Plekhova, G., Kuchuk, N., Kuvshynov, O., Veretnov, A., Yefymenko, O.; Shyshatskyi, A. (Ed.) (2024). The development of methods for evaluating the state of complex technical systems using artificial intelligence theory. *Information and control systems: modelling and optimizations*. Kharkiv: TECHNOLOGY CENTER PC, 70–101. <https://doi.org/10.15587/978-617-8360-04-7.ch3>
85. Kashkevich, S., Plekhova, G., Yefymenko, O., Kuchuk, H., Davydov, V., Beketov, Y.; Shyshatskyi, A. (Ed.) (2024). The development of methods of learning artificial neural networks of intelligent decision-making support systems. *Information and control systems: modelling and optimizations*. Kharkiv: TECHNOLOGY CENTER PC, 102–137. <https://doi.org/10.15587/978-617-8360-04-7.ch4>

86. Kashkevich, S., Dmytriiev, I., Shevchenko, I., Lytvynenko, O., Shabanova-Kushnarenko, L., Apenko, N; Shyshatskyi, A. (Ed.) (2024). Scientific-method apparatus for improving the efficiency of information processing using artificial intelligence. Information and control systems: modelling and optimizations. Kharkiv: TECHNOLOGY CENTER PC, 138–167. <https://doi.org/10.15587/978-617-8360-04-7.ch5>