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IMPROVEMENT OF COMPLEX RESOURCE MANAGEMENT OF SPECIAL-PURPOSE COMMUNICATION SYSTEMS

Mykhailo Koval
Doctor of Military Sciences, Head of University*
Oleg Sova
Corresponding author
Doctor of Technical Sciences, Senior Researcher, Head of Department
Department of Automated Control Systems
Military Institute of Telecommunications and Information Technologies named after Heroes of Kruty
Moskovsky str., 45/1, Kyiv, Ukraine, 01011
E-mail: soy_135@ukr.net
Oleksandr Orlov
Doctor of Sciences in Public Administration, Professor, Head of Department
Department of Digital Technologies and Electronic Government
Educational and Scientific Institute «Institute of Public Administration»
V. N. Karazin Kharkiv National University
Svobody sq., 4, Kharkiv, Ukraine, 61022
Andrii Shyshatskyi
PhD, Senior Researcher, Head of Department
Department of Robotic Systems Research**
Yurii Artabaiev
PhD, Head of Department
Research Department of Combat Crews**
Oleh Shknai
PhD, Leading Researcher
Research Department
Military Unit A1906
Melnikova str., 81, Kyiv, Ukraine, 04050
Andrii Veretnov
PhD, Leading Researcher
Research Department
Central Scientifically-Research Institute of Armaments and Military Equipment of the Armed Forces of Ukraine
Povitroflotskyi ave., 28, Kyiv, Ukraine, 03049
Oleksandr Koshlan
PhD, Head of Department
Scientific Department of General and Resource Planning*
Yevhen Zhyvylo
PhD, Head of Department
Department of Communications and Automated Troop Management Systems*
Iryna Zhyvylo
PhD, Junior Researcher
National Scientific Center «M. D. Strazhesko Institute of Cardiology»
Narodnoho Opolchennia str., 5, Kyiv, Ukraine, 03680
*The National Defence University of Ukraine named after Ivan Cherniakhovskyi
Povitroflotskyi ave., 28, Kyiv, Ukraine, 03049
**Research Center for Trophy and Perspective Weapons and Military Equipment
Degtyarivska str., 13/24, Kyiv, Ukraine, 04119

The object of the research is a special-purpose communication system. The relevance of the research lies in the need for complex management of resources of special-purpose communication systems. The resources of the special-purpose communication system are defined as: spatial, temporal, frequency and hardware resources. Destabilizing factors include: intentional interference; denial-of-service cyber attacks and fire damage to individual elements of the special-purpose communication system. The method of complex management of resources of special-purpose communication systems was improved. The difference between the proposed method and the known ones is that the specified method contains improved procedures:

– determination of the impact of destabilizing factors on the special-purpose communication system;

– description of special-purpose communication systems of various architectures;

– determination of the rational route of information transmission and operation mode of communication devices in the general special-purpose communication system;

– consideration of uncertainty about the state of the special-purpose communication system;

– determination of the number of necessary forces and means of communication, which must be increased for the full functioning of the special communication system. The improved method provides a gain of 20–26 % compared to classical approaches to the management of resources of special-purpose communication systems. The improved method can be used at the control points of the communication system of groups of troops (forces) while planning the organization of communication and at the stage of operational management of the communication system

Keywords: special-purpose communication system, destabilizing factors, communication system resources, communication system topology

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1. Introduction

Currently, a single global information space is being built between elements of various-purpose management systems. The main differences of this architecture are the use of high-level integration systems based on the principles of building the Internet.

For this purpose, a transition is being made from different types of independently functioning subsystems to integrated communication and data transmission systems (IC DTS) providing transmission and «seamless» connection. «Seamlessness» refers to the elimination of manual operations while connecting subscribers and exchanging data between disparate communication systems.

This, in turn, requires the use of multifunctional communication devices, which allow end-to-end management of communication system parameters.

The multifunctionality of communication devices is realized through the use of a wide class of signals, coding methods, measures to increase immunity, information transmission modes, algorithms for choosing a rational topology and information transmission route [1, 2].

The approximate relationship between parameters and control variables by levels of the open systems interconnection model is given in Table 1.

At the same time, upon detailed analysis of the data given in Table 1, it becomes clear that for effective management of special-purpose communication system resources, it is necessary to manage each of them at several levels of the OSI model. This is due to the fact that each of the resources of the special-purpose communication system is located at several levels of the OSI model.

However, there is a contradiction between science and practice:

– in practice – the need for complex management of each of the resources of the special-purpose communication system at each of the levels of the OSI model;

– in science – the limitation of the existing scientific and methodical management of special-purpose communication system resources at each of the levels of the OSI model.

Given the above, an urgent scientific task is to develop a method for the complex management of resources of special-purpose communication systems, which would allow for end-to-end and complex management of resources of a special-purpose communication system at each of the levels of the OSI model.

2. Literature review and problem statement

The work [4] defined the tendency to create unified platforms of hardware devices of radio frequency and digital signal processing for the joint solution of communication and radar tasks. However, the work does not provide specific mechanisms for managing the parameters of GSM communication networks for airspace monitoring and does not take into account the general resources of the specified systems.

The work [5] substantiated ways for increasing the efficiency of the trunking communication systems of Ukraine. However, this type of radio communication is not resistant to the influence of radio electronic suppression devices and also does not take into account the general resources of the systems.

The work [6] developed ways to increase the efficiency of using radio frequency resources in cognitive radio networks. At the same time, the mentioned work does not consider the influence of destabilizing factors on the quality of communication.

The work [7] proposed a dynamic channel selection algorithm based on the fuzzy inference system (FIS), which is able to select the most available channel with the desired bandwidth, the minimum required signal-to-noise ratio, and the probability of error detection. The shortcoming of the proposed algorithm is that it does not take into account the influence of destabilizing factors and system resources.

The work [8] developed a radio resource access controller based on a sliding window. At the same time, the specified controller does not allow taking into account destabilizing factors present in radio communication channels, such as intentional interference and fading.

The work [9] proposed a method for monitoring the radio frequency spectrum and network architecture, for regulating the spectrum distribution and managing the use of the radio frequency spectrum. At the same time, the proposed approach does not allow taking measures aimed at improving their immunity and does not take into account possible changes in the network architecture.

Table 1

Approximate relationship between parameters and control variables by levels of the OSI model (The Open Systems Interconnection model)

OSI level	Management objects	Key optimization parameters	Control influence of the node
Physical	Radio channel within radio communication with neighboring nodes	Bandwidth, channel transmission time, battery power consumption, transmission power, antenna pattern, etc.	Transmission power (direction), type of modulation, type of correction code, parameters, etc.
Channel	Radio channels within radio communication with neighboring nodes	Bandwidth and transmission time in the channel, battery power consumption, amount of service information, etc.	Channel-level exchange algorithms: deterministic, random, hybrid; package and receipt sizes
Network	One or more transmission routes	Amount of service information, route parameters (time of construction and existence, quantity, throughput, delivery time, battery power consumption, etc.)	Network-level exchange algorithms: table, probe, hybrid, wave asymmetric, hierarchical, etc. Topology management algorithms
Transport	Information direction of communication	Bandwidth, time and variation of its transmission in the direction	Queue management algorithms. Overload window size, timeout time, etc.
Practical	Node, neighbor nodes, network zone, entire network	Bandwidth, transmission time and time variation, battery power consumption, transmission security	Application-level information exchange algorithms (protocols), coordination and intellectualization by OSI levels

The work [10] proposed an algorithm for controlling the parameters of cognitive radio networks, namely optimal power, optimal speed and optimal amount of information. This control is based on a genetic algorithm. At the same time, the proposed algorithm takes into account only mutual interference caused by the mutual influence of users on each other, without the peculiarities of constructing radio communication systems.

The work [11] proposed a method for determining the location of radio communication devices depending on the efficiency of radio electronic suppression. The proposed method makes it possible to increase the efficiency of radio communication, however, the increase in radio communication efficiency is limited only to determining the optimal location of radio communication facilities. Also, this work does not take into account other resources of communication systems besides spatial.

The work [12] proposed to use clustering algorithms to manage the radio resources of radio communication devices. The proposed algorithm is based on the distribution of radio frequencies between clusters. At the same time, this approach does not allow for adaptation to the influence of intentional interference and implementation of other immunity improvement mechanisms. This leads to incomplete utilization of communication system resources.

The work [13] proposed to use artificial intelligence in the tasks of increasing the efficiency of cognitive radio networks. At the same time, this research is intended only for general training (adaptation) of cognitive radio networks without specifying the factors affecting its effectiveness.

The work [14] proposed adaptive algorithms for adjusting the threshold values of parameters of radio communication systems. This research allows you to distinguish a useful signal against the background of noise, adapt to the signal environment. At the same time, the study does not allow complex management of the parameters of special-purpose radio communication systems.

Given the fact that to manage the resources of special-purpose communication systems, it is necessary to process input data of different measurement units and origin, it is proposed to conduct an analysis of algorithms for processing different types of data.

The work [15] developed a generalized metric in the problem of analyzing multidimensional data with different characteristics. The essence of the proposed metric is that it allows building clustering, classification and association algorithms based on it using classical processing methods. However, this metric does not allow efficient functioning in conditions of insufficient computing resources.

The work [16] considered the problem of processing information from various technical monitoring devices. As a possible solution to the problem, it is proposed to apply a generalized information processing method based on the method of clustering territorially combined monitoring information sources and use a frame model of the knowledge base for the identification of monitoring objects. The clustering method is based on the Lance-Williams hierarchical agglomerative procedure using Ward's metric. The frame model of the knowledge base is built using object-oriented modeling tools. The disadvantage of the proposed generalized method is that it does not take into account the relative importance of the events that occur and the inability to work in conditions of insufficient computing resources. Also, the shortcomings of the mentioned method include the impossibility to redistribute computing resources between elements to increase the efficiency of information processing.

According to the analysis of the works [2, 4–17], the following can be stated:

– they do not allow end-to-end management of the resources of special-purpose communication systems, but only carry out separate management influences at a separate level of the open systems interconnection model for a single resource;

– the approaches proposed in the listed works were aimed at finding partial solutions to communication planning problems in the operations of groups of troops (forces);

– they do not take into account the impact of management decisions of a separate resource on another resource of the special-purpose communication system.

3. The aim and objectives of the study

The aim of the study is to improve the method of complex management of resources of special-purpose communication systems, which would make it possible:

– to take into account the influence of destabilizing factors on the functioning of the special-purpose communication system;

– to manage the system resources at the levels of the open network interconnection model;

– to forecast the state of the special-purpose communication system;

– to take into account the influence of management decisions of a separate resource on another resource of the special-purpose communication system;

– to determine the necessary communication hardware that must be involved to ensure the communication of groups of troops (forces) in operations.

To achieve the aim, the following objectives were set:

– to formalize the tasks of resource management of special-purpose communication systems for maximum throughput;

– to develop an algorithm for complex management of resources of special-purpose communication systems;

– to evaluate the effectiveness of the improved method of complex management of resources of special-purpose communication systems.

4. Materials and methods

The object of the study is a special-purpose communication system. The hypothesis of the study consists in the complex management of the resources of the special-communication system at the levels of the OSI model, and if it is impossible to perform the tasks related to the organization of communication, to increase the reserve of forces and communication means to the required level.

Performance evaluation and modeling of the improved method of complex management of resources of special-purpose communication systems proposed in the study was carried out in MathCad 14 software (USA).

In the course of the study, the general provisions of artificial intelligence theory were used to solve the problem of analyzing and forecasting the state of the special-purpose communication system. Conceptual provisions of system dynamics were used for describing dynamic changes in the state of the special-purpose communication system. The simulation was carried out using MathCad 2014 software (USA) and an AMD Ryzen 5000 series PC (USA).

5. Results of the study on complex resource management of special-purpose communication systems

5. 1. Formalization of the problem of resource management of special-purpose communication systems for maximum bandwidth

It is proposed to carry out end-to-end management of the resources of special-purpose communication systems with relative observance of the hierarchy at each level of the open systems interconnection basic reference model.

The resources of the special-purpose communication system were defined as management of:

– a spatial resource;

– a time resource;

– a frequency resource;

– a reserve of technical communication means.

Destabilizing factors include:

– intentional interference;

– denial-of-service cyber attacks;

– fire damage to elements of the special-purpose communication system.

The special-purpose communication system was presented from the standpoint of graph theory in the form of a tree. At the same time, the root of the tree was matched with the control subsystem of the second level (I_2, U_2) and the vertices of this tree, which are located at a distance of one edge from the root – Q the control subsystem of the first level (I_{11},U_{11}),..., (I_{1q},U_{1q}),...,(I_{1Q},U_{1Q}). Each subsystem includes a control (identification) unit I and a management unit U. Let us consider Q zero-level subsystems, which are two edges away from the root of the tree. These subsystems represent interacting processes of exchange of operational and service information flows in the management system P_1, ..., P_q, ..., P_Q [4–6].

For the q-th control subsystem of the first level (I_{1q},U_{1q}) $q=\overline{1,Q}$, we introduce the following notations:

– $X_{1q}(k)$ is the set of vectors, the state of the q-th controlled subnet, where $x_{1q}(k)=\{x_{1q}^{a}(k)\}$, $a=\overline{1,a_{1q}}$ with the dimension $a_{1q}\times 1$;

– $\tilde{X}_{1q}(k)$ is the set of evaluation vectors $\tilde{x}_{1q}(k)=\{\tilde{x}_{1q}^{a}(k)\}$, $a=\overline{1,a_{1q}}$, with the dimension $a_{1q}\times 1$;

– $U_{1q}(k)$ is the set of control vectors of the q-th controlled subnet $u_{1q}(k)=\{u_{1q}^{b}(k)\}$, $b=\overline{1,b_{1q}}$, with the dimension $b_{1q}\times 1$;

– $Y_{1q}(k)$ is the set of vectors of local variables that are issued to the upper-level control subsystem $y_{1q}(k)=\{y_{1q}^{d}(k)\}$, $d=\overline{1,d_{1q}}$, with the dimension $d_{1q}\times 1$;

– $Z_{1q}(k)$ is the set of vectors of local output variables $z_{1q}(k)=\{z_{1q}^{d}(k)\}$, $d=\overline{1,d_{1q}}$, with the dimension $d_{1q}\times 1$.

For the second-level management subsystem, respectively:

– $\tilde{X}_2(k)$ is the set of vectors of generalized estimates $\tilde{x}_2(k)=\{\tilde{x}_2^{l}(k)\}$, $l=\overline{1,l_r}$, with the dimension $l_r\times 1=\left(\sum_{q=1}^{Q}a_{1q}\right)\times 1$;

– $Y_{2q}(k)$ is the set of vectors that are issued to the lower-level control subsystem $y_{2q}(k)=\{y_{2q}^{d}(k)\}$, $d=\overline{1,d_{2q}}$, with the dimension $d_{1q}\times 1$;

– $Z_{2q}(k)$ is the set of vectors coordinating the output variables issued to lower-level control subsystems $z_{2q}(k)=\{z_{2q}^{d}(k)\}$, $d=\overline{1,d_{2q}}$, with the dimension $d_{2q}\times 1$.

As a result, for the q-th subsystem of zero level P_q, $q=\overline{1,Q}$, we have:

– $c_{qp}(k)$ – the set of connection vectors $c_{qp}(k)=\{c_{qp}^{mn}(k)\}$, $m=\overline{1,m_q}$, $n=\overline{1,n_q}$, between the p-th and q-th subsystems (p, $q=\overline{1,Q}$, $p\neq q$);

– $\pi_q(k)$ – the set of vectors of external influences $\Pi_q(k)=\{\pi_q^{l}(k)\}$, $l=\overline{1,l_q}$, with the dimension $l_q\times 1$.

The set of state vectors of a special-purpose communication system $X(k)=\bigcup_{q=1}^{Q}X_{1q}(k)$ may include vectors of any state variables affecting the quality of the special-purpose communication system and the efficiency of its operation. The main ones include:

– the vector of information load parameters of a special-purpose communication system (characterizes the number of information messages that must be transmitted per unit of time at a given bandwidth):

$$\Lambda(k)=\left\|\Lambda_1(k),\ ...,\ \Lambda_q(k),\ ...,\ \Lambda_Q(k)\right\|^{T}; \quad (1)$$

– the vector of delays in the transmission of information messages of a special-purpose communication system (characterized by a deterioration of the bandwidth of special-purpose communication systems):

$$H(k)=\left\|H_1(k),\ ...,\ H_q(k),\ ...,\ H_Q(k)\right\|^{T}; \quad (2)$$

– the vector of parameters of the radio-electronic environment of the military radio communication subsystem of the special-purpose communication system (the number of operating frequencies suppressed by radio-electronic warfare means that do not meet the bandwidth requirements):

$$\aleph(k)=\left\|\aleph_1(k),\ ...,\ \aleph_q(k),\ ...,\ \aleph_Q(k)\right\|^{T}; \quad (3)$$

– the vector of frequency resources of the radio communication subsystem of the special-purpose communication system (total number of working frequencies):

$$\Im(k)=\left\|\Im_1(k),\ ...,\ \Im_q(k),\ ...,\ \Im_Q(k)\right\|^{T}; \quad (4)$$

– the vector of hardware resources of the special-purpose communication system (total number of network devices in the special-purpose communication system):

$$\Upsilon(k)=\left\|\upsilon_1(k),\ ...,\ \upsilon_q(k),\ ...,\ \upsilon_Q(k)\right\|^{T}. \quad (5)$$

Input data for modeling the state of a special-purpose communication system used for calculations:

1. Calculations are based on the special communications system of an operational group of troops (forces) consisting of:

– 50 W radio communication equipment – 120 units;

– 5 W radio communication equipment – 500 units;

– 1 W radio relay communication devices – 100 units;

– 3 W satellite communication devices – 100 units;

– tropospheric communication devices – 40 units;

– level 3 network devices – 400 units.

5. 2. Development of an algorithm for complex resource management of special-purpose communication systems

The improved method of complex management of resources of special-purpose communication systems consists of the following sequence of actions (Fig. 1):

1. Input of initial data. Initial data on the state of the special-purpose communication system, the type of operation of the group of troops (forces) and the task of organizing communications in the group of troops (forces) are entered.

2. Entering information about the degree of a priori uncertainty about the state of the communication system. At this stage, the degree of uncertainty of the data on the state of the special-purpose communication system is determined

based on the works of the authors [17–23]. Possible degrees of the uncertainty of information about the state of the special-purpose communication system: full awareness, partial uncertainty, complete uncertainty [24–29].

3. Determination of control influences on the special-purpose communication system. At this stage, based on the description of the state of the special-purpose communication system, the control influences on the physical, channel and network levels of the special-purpose communication system are determined. The basis of the specified procedure of the improved method is the method developed by the authors in the previous studies [2, 3, 17, 18].

4. Forecasting the state of the special-purpose communication system. At this stage, the state of the special-purpose communication system with the determined composition of forces and means of communication is forecasted. Forecasting the state of the special-purpose communication system at this stage is carried out using the approaches developed in previous studies [2, 3, 17, 18].

5. Determination of the necessary forces and means of communication for expanding the special communication system.

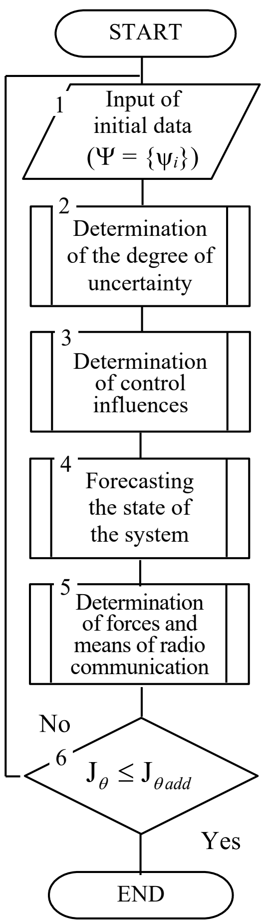

Fig. 1. Algorithm for the implementation of the improved method of complex management of resources of special-purpose communication systems

The decision to build up forces and means of communication of a group of troops (forces) is made after it is impossible to solve the tasks of organizing communication in the existing organizational and staff structure after step 4.

Let us consider in more detail the specified procedure for determining the necessary forces and means of communication in a special-purpose communication system. The task of synthesizing information technology for managing the processes of coordinated functioning and complex resource management of special-purpose systems can be formulated as the «task of finding optimal control influences». The specified tasks transfer the special-purpose communication system under consideration from the specified to the required structural state, which characterizes both the current state of the objects included in the given type of structure, and the state of relations between them.

Thus, the value of the state of the existing and «new» communication system of a group of troops (forces) $CTC < U^t, S_\delta^{*tf} >$ is required, at which [3, 7, 9, 18]:

$$J_\theta\left(X_\chi^t, \Gamma_\chi^t, \mathrm{Z}_\chi^t, F_{<\chi,\chi'}^t, \prod_{(\delta,\tilde{\delta})}^t, t \in (t_0, t_f]\right) \to \underset{<U^t, S_\delta^{*tf}>\in\Delta g}{extr},$$

$$\Delta_g\left\{< U^t, S_\delta^{tf} > \middle| R_\beta\left(X_\chi^t, \Gamma_\chi^t, \mathrm{Z}_\chi^t, F_{<\chi,\chi'}^t, \prod_{(\delta,\tilde{\delta})}^t]\right) \le \tilde{R}_g\right\}, \qquad (6)$$

$$U^t = \prod_{<\delta_1,\delta_2>}^{t_1} \circ \prod_{<\delta_2,\delta_3>}^{t_2} \prod_{<\delta,\delta>}^{t_f}; \beta \in \mathbf{B},$$

where J_θ is the cost, time, resource indicators characterizing the efficiency of the special communication system; $\theta \in \Theta$ is the set of indicator numbers; χ is the set of indices corresponding to the structures of the special-purpose communication system; $T \in (t_0, t_f]$ is the time interval for which the special communication system functions and the communication organization process is implemented; $X_\chi^t = \{X_{\chi l}^t, l \in L_\chi\}$ is the set of elements included in the structure of the dynamic alternative system graph (DASG) G_χ^t (a set of DASG vertices), by which the controlled structural dynamics of the special-purpose communication system at time t is specified; $G_\chi^t = \{\chi_{<\chi l,l'>}^t, l, l' \in L_\chi\}$ is the set of DASG arcs of type G_χ^t, reflecting the relationships between its elements at time t; $\mathrm{Z}_\chi^t = \{z_{<\chi l,l'>}^t, l, l' \in L_\chi\}$ is the set of parameter values, quantifying the relationship of the corresponding DASG elements; $F_{<\chi,\chi'>}^t$ is the description of the influence of different structures of the special-purpose communication system on each other at time t; $\prod_{<\tilde{\delta},\tilde{\tilde{\delta}}>}^t$ is the composition of the structural state of the special-purpose communication system with numbers $\tilde{\delta}, \tilde{\tilde{\delta}}$ at time t; Δ_g is the set of dynamic alternatives (a set of structures and parameters of the special-purpose communication system, «new» and existing special-purpose communication systems and a set of programs for their operation); U^t is the control influences that allow synthesizing the structures of special-purpose communication systems that are being built up and implemented; $\tilde{R}_g$ is the given values; «o» is the composite mapping operation; **B** is the set of numbers of space-time, technical and technological restrictions that determine the processes of implementation of programs for building up and functioning of a special-purpose communication system [2].

At the build-up stage, first of all, the operating parameters of the elements and subsystems of the special-purpose communication system are changed.

The study proposes to consider a special-purpose communication system as a complex dynamic object consisting of a set of structures. Communication between them occurs through the transmission of information about the status of operations, the intensity of data transmission and processing flows, as well as information about the state of various resources, services and basic services.

This approach allows us to present the stage of parallel operation and expansion of the special-purpose communication system as a process of updating (improving the characteristics) of information services supporting the special-purpose communication system. We present the process of software management of the expansion of the special-purpose communication system:

$$\frac{dx_n^{(s,l)}}{dt}=\sum_{r=1}^{p_s}u_{n\,r}^{(s,l)}(t); \quad (7)$$

$$\frac{dx_n^{(s,l)}}{dt}=\sum_{n=1}^{m_j}w_{n\,r}^{(s,l)}(t); \quad (8)$$

$$\frac{dx_{rS_l}^{(s,l)}}{dt}=\omega_{rS_l}^{(s,l)}(t). \quad (9)$$

Restrictions on management actions:

$$0\le u_{n\,r}^{(s,l)}(t)\le\left[e_{n\,r}^{(s,l)}\left(1-\gamma_r^{(m,\delta)}(t)\right)+\bar{e}_{n\,r}^{(j)}\gamma_r^{(m,\delta)}(t)\right]w_{n\,r}^{(s,l)}; \quad (10)$$

$$\sum_{l=1}^{k_v}\sum_{n=1}^{m_j}V_n^{(s,l)}w_{n\,r}^{(s,l)}(t)\le\left[V_r^{(j)}\left(1-\gamma_r^{(m,\delta)}(t)\right)+\bar{V}_r^{(j)}\gamma_r^{(m,\delta)}(t)\right]; \quad (11)$$

$$\sum_{l=1}^{k_v}\sum_{n=1}^{m_j}u_n^{(s,l)}(t)\le\left[P_r^{(j)}\left(1-\gamma_r^{(m,\delta)}(t)\right)+\bar{P}_r^{(j)}\gamma_r^{(m,\delta)}(t)\right]; \quad (12)$$

$$\sum_{r=1}^{p_s}w_{n\,r}^{(s,l)}(t)\begin{bmatrix}\sum_{\pi\in G_c}\left(\alpha_\pi^{(s,l)}-x_\pi^{(s,l)}\right)+\\+\sum_{k\in G_c}\left(\alpha_k^{(m,r)}-x_k^{(m,r)}\right)\end{bmatrix}=0,\forall l; \quad (13)$$

$$\sum_{r=1}^{p_s}w_{n\,r}^{(s,l)}(t)\le\varepsilon_n,\forall n;\sum_{n=1}^{m_j}w_{n\,r}^{(s,l)}(t)\le\theta_r,\forall r; \quad (14)$$

$$\omega_{rS_l}^{(s,l)}\left(a_{S_l}^{(s,l)}-x_{S_l}^{(s,l)}\right)=0; \quad (15)$$

$$w_{nr}^{(s,l)}\in\left\{0,u_{vln}^{(b,j)}\right\};\gamma_r^{(m,\delta)}(t),\omega_{rS_l}^{(s,l)}\in\{0,1\}. \quad (16)$$

Boundary conditions:

$$\text{for } t=t_0: x_n^{(s,b)}(t_0)=x_r^{(s,l)}(t_0)=x_{rS_l}^{(s,l)}(t_0)=0;$$

$$\text{for } t=t_f: x_n^{(s,l)}(t_f)=$$
$$=a_n^{(s,l)};x_r^{(s,l)}(t_f),x_{rS_l}^{(s,l)}(t_f)=x_{rS_l}^{(s,l)}(t_0)\in\mathbf{R}^1. \quad (17)$$

Quality indicators of software management of the expansion of the special-purpose communication system:

$$J_4=\sum_{n=1}^{m_j}\sum_{r=1}^{p_s}\int_{t_0}^{t_f}\delta_{nr}^{(s,l)}(\tau)\cdot w_{nr}^{(s,l)}(\tau)\mathrm{d}\tau; \quad (18)$$

$$J_5=\sum_{l=1}^{k_v}\sum_{r=1}^{p_s}\sum_{r=1}^{m_j}\int_{t_0}^{t_f}c_{nr}^{(s,l)}(\tau)w_{nr}^{(s,l)}(\tau)\mathrm{d}\tau; \quad (19)$$

$$J_6=\frac{1}{2}\sum_{l=1}^{k_v}\sum_{n=1}^{m_j}\left(\alpha_n^{(s,l)}-x_n^{(s,l)}(t_f)\right)^2. \quad (20)$$

In relations (8)–(20), the following notations are adopted:

– $x_r^{(s,l)}$ is the variable that characterizes the state of execution of the operation of providing the necessary information services for performing communication tasks $A_v^{(b,j)}$.

The superscript «*s*» means that the corresponding variable is a part of the software control model of the expansion of the special-purpose communication system.

The superscript «*l*» means the service information operation of the special-purpose communication system, which «consumes» the information service;

– $u_{nr}^{(s,l)}(t)$ is the intensity of support of the service operation (internal service) $F_{<n,r>}^{(s,l)}$ by the resource of the special-purpose communication system $B_r^{(s,l)}$;

– $x_r^{(s,l)}$ is the variable, the current value of which is numerically equal to the total duration of engagement of special-purpose communication system resources $B_r^{(s,l)}$;

– $w_{nr}^{(s,l)}(t)$ is the duration of using the special-purpose communication system resource $B_r^{(s,l)}$ to support the information service (internal services) $D_{<l,n>}^{(s,b)}$ $w_{nr}^{(s,l)}(t)=1$ if the special-purpose communication system resource is allocated and functioning;

– $x_{rS_l}^{(s,l)}$ numerically determines the time interval from the end of maintenance of the internal service $F_{<n,r>}^{(s,l)}$ by the special-purpose communication system $B_r^{(s,l)}$ to the given final time;

– $\omega_{rSl}^{(s,l)}(t)$ is the auxiliary control action. It takes the value «1» if the special-purpose communication system has completed the maintenance of the internal service $F_{<n,r>}^{(s,l)}$;

– $V_n^{(s,l)}$ is the amount of memory required to store output and intermediate data allocated for the internal maintenance operation;

– $e_r^{(j)},V_r^{(j)},P_r^{(j)}$ are the set values (constants) characterizing the maximum intensity of implementation of internal services on the resource of the special-purpose communication system $B_r^{(s,l)}$ (before building up);

– $\gamma_r^{(m,\delta)}(t)$ is the auxiliary control action taking the value «1» at time *t*, if a transition is made from existing ($e_r^{(j)},V_r^{(j)},P_r^{(j)}$) to new $\bar{e}_r^{(j)},\bar{V}_r^{(j)},\bar{P}_r^{(j)}$ parameters of information resources B_j in the subsystem of the special-purpose communication system;

– $a_n^{(s,l)}$ is the volume of internal service operations to support a given external service;

– $\delta_{nr}^{(s,l)}(t)$ is the function that allows you to assess the overall quality of providing internal services $F_{<n,r>}^{(s,l)}$ of the special-purpose communication system at the stage of joint functioning and expansion;

– $c_{nr}^{(s,l)}(t)$ is the cost function of time describing indirect, i.e. operational costs (administration, technical support, etc.) associated with the operation and expansion of a specific information service.

5. 3. Evaluation of the efficiency of the improved method of complex management of resources of special-purpose communication systems

Research on the efficiency of the proposed improved method of complex resource management of special-purpose communication systems was conducted.

According to the initial data given in section 5.1, an assessment of the management efficiency of spatial, temporal and frequency resources of the special-purpose communication system was carried out (Fig. 2). We specify the modeling conditions for this case:

– frequency-hopping spread spectrum (FHSS) radio communication devices: frequency range – 30–512 MHz; transmitter power – 10 W; emission bandwidth – 12.5 kHz, receiver sensitivity – 120 dB; the number of radio communication devices in the network – 5; the number of frequency channels for reconfiguration – 10,000; the number of reconfigurations – from 333.5 to 1,000 jumps/sec;

– radio electronic suppression (RES) complexes – 2; frequency range – 30–2000 MHz; transmitter power – 2,000 W;

maximum frequency band that can be suppressed simultaneously – 80 MHz, type of interference – frequency-shift barrage noise jamming, as one of the most common and the effect of which is well known; the strategy of the RES complex – dynamic.

4 LimeSDR (USA) programmable transceivers with GNU Radio (Germany) software were connected to the PC and a RIGOL DG5252 (Germany) noise generator that simulated the operation of the RES complex.

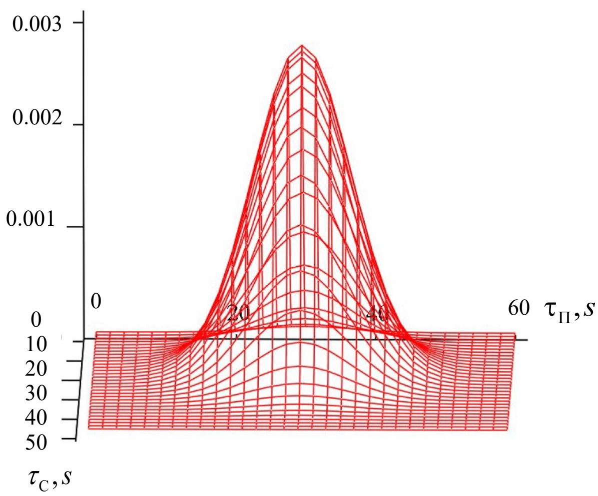

Fig. 2. Dependencies of the message duration on the response time of the RES complex

Analysis of the obtained dependencies (Fig. 2) shows that the value $f(\tilde{\tau}_C, \tilde{\tau}_\Pi)$ is less than the threshold value. Therefore, in this case, the decision is made mainly on the basis of the analysis of changes in the duration of the message, which was affected by interference $(\tilde{\tau}_C)$ and the pause after it $(\tilde{\tau}_\Pi)$.

To demonstrate the learning efficiency of an evolving artificial neural network, forecasting of the time security of a special-purpose communication system was carried out. To conduct the experiment, a training sample containing data on the state of the special-purpose communication system was used. 5,000 observations from this sample were used for the experiments. The training sample contained 3,000 observations, the test sample had 2000 observations.

The square root of the root mean square error was used as a criterion for forecasting quality.

Multilayer perceptron (MLP), radial basis neural network (RBNN) and evolving artificial neural network were used to compare the forecasting quality.

The forecasting results for different systems are presented in Table 2.

Table 2

Forecasting results for different systems

System name	Number of configurable parameters	RMSE (training)	RMSE (test)	Time, s
Multilayer perceptron	51	0.1058	0.1407	0.1081
Radial-basis neural network	21	0.1066	0.2155	0.1081
Evolving cascade system with neo-fuzzy nodes	20	0.0784	0.1081	0.1081

The indicated results can be seen from the results in the last lines of Table 1, as the difference of the Xie-Beni index.

From Fig. 3, it can be concluded that the RES device affected approximately 10 % of the hopset with narrowband interference, which can be effectively corrected with correction codes.

Fig. 4 shows the simulation of the operation of the RCD and RES means under the influence of frequency-shift noise interference.

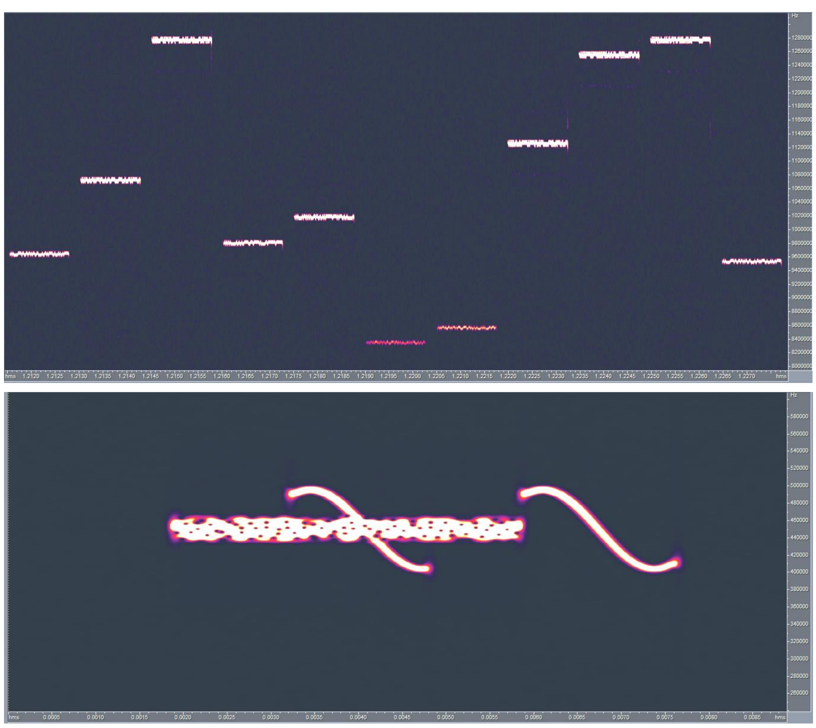

Fig. 3. Operation of 4 transceivers according to the specified method and the RIGOL DG5252 noise generator

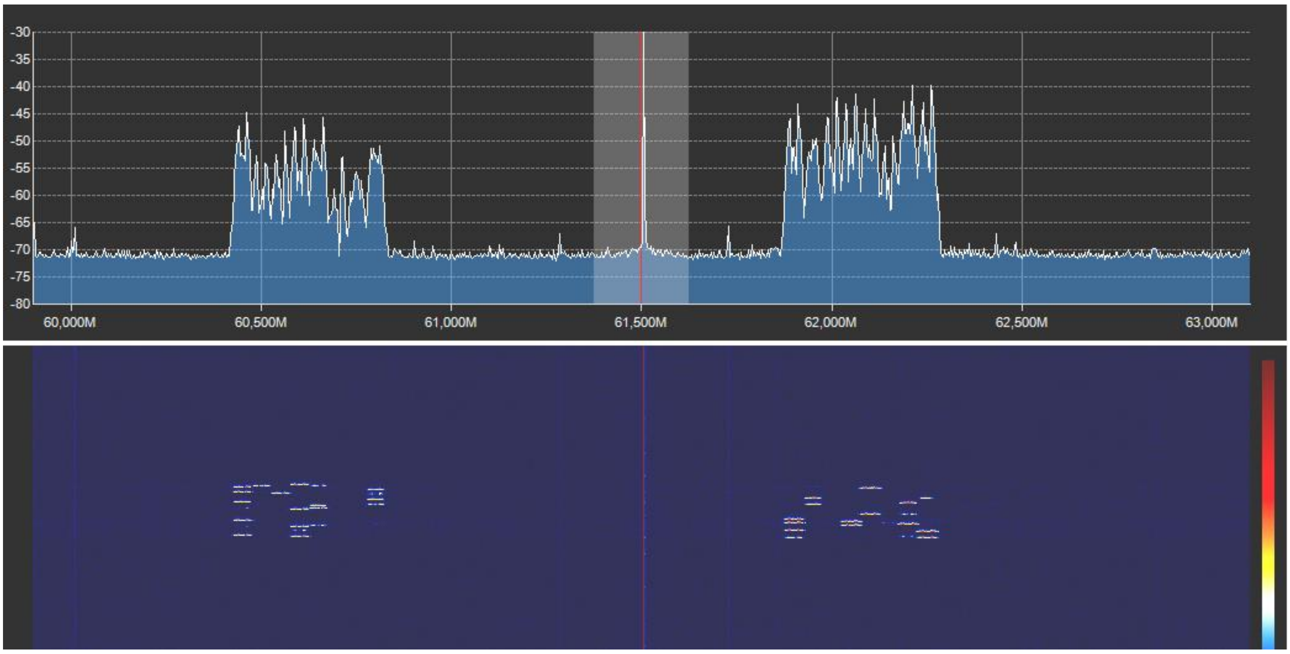

Fig. 4. Simulation of the operation of the RCD and RES means under the effects of frequency-shift noise interference

Table 3

Results of the simulation of the expansion of the special-purpose communication system

Output data	Option I	Option II	Option III
The number of resources that need to be built up in the system	40	50	70
The planned number of system resources to be built up	10	30	65
Time period during heuristic build-up	22	33	44
Time period for build-up using the proposed approach	20	28	41
The value of the resulting quality indicator for heuristic plans	1,117	901	408
The value of the resulting quality indicator for optimal plans	**1,384**	**1,113**	**484**

The results of the simulation show that the efficiency of the special-communication system has increased by 20–26 % under the influence of destabilizing factors.

6. Discussion of the results of developing a method of complex management of resources of special-purpose communication systems

As part of the research, an improved method of complex resource management of special-purpose communication systems is proposed. The operation of the proposed method was simulated in the MathCad 14 software environment.

The main advantages of the proposed method are:

– the use of a complex channel state assessment indicator that takes into account most of the known assessment parameters;

– unambiguity of the obtained assessment of the state of the special-purpose communication system;

– wide scope of use (communication and radar systems);

– simplicity of mathematical calculations;

– increased efficiency of channel state assessment due to the use of artificial intelligence theory;

– ability to synthesize the optimal structure of the communication system.

The disadvantages of the proposed method include:

– loss of informativeness in the channel state assessment due to a comprehensive assessment;

– lower accuracy of assessment by a single parameter of channel state assessment;

– lower accuracy of assessment at the initial stage, associated with the lack of neural network training and the lack of a signal environment base;

– the method is not advisable to use in communication systems if it is necessary to obtain an accurate assessment of the channel state by a separate indicator.

The method will make it possible:

– to identify destabilizing influences on the state of the communication system;

– to assess the state of the channel;

– to ensure effective use of resources of special-purpose networks;

– to increase the speed of assessment of communication channels;

– to reduce the use of computing resources of soft-architecture communication tools;

– to develop immunity-improving measures.

Constraints (11)–(13) determine the possibilities of information processing on the resource $B_r^{(s,l)}$ before and after the corresponding stage of building up the special-purpose communication system.

Constraints (14) determine the technology of information service implementation. The operation included in the service provision process (internal service) cannot be provided until the expansion of the special-purpose communication system involved in this process is completed.

Constraints (15) specify the possibility of simultaneous use of several resources of the special-purpose communication system to ensure the functioning of the internal service and the use of resources of the special-purpose communication system to perform several tasks in parallel. ε and θ are known numbers.

Constraint (16) is an auxiliary one, which is introduced to fix the time when the resources of the special-purpose communication system providing internal service operations expire.

Constraint (17) defines the interval of possible values that the corresponding control influences can take, and forms a connection with the model of communication tasks.

Expressions (18) and (19) define restrictions on the values of the variables at given time points $t=t_0$ and $t=t_f$.

The indicator of type (20) evaluates the quality of planning the processes of operation and expansion of the special-purpose communication system at the level of services.

The indicator of type (21) was introduced to evaluate the total operating costs associated with the processes of building up the special-purpose communication system only at the level of information services.

The indicator (22) was introduced to maximize the number of operations performed only at the level of operation of the special-purpose communication system.

The developed and improved method provides a gain of 20–26 % compared to classical management approaches.

The proposed improved method can be used at the control points of the communication system of troops (forces) groups while planning the organization of communication and at the stage of operational management of the communication system.

This study is a development of research carried out by the authors aimed at developing methodological principles of operational management of radio resources of radio communication systems.

7. Conclusions

1. We formalized the task of resource management of special-purpose communication systems for maximum bandwidth. The specified formalized description allows describing the processes that occur during the operation of the special-purpose communication system and determining measures aimed at increasing the efficiency of the special-purpose communication system.

2. An improved method of complex resource management of special-purpose communication systems was developed. The method allows you to determine the impact of destabilizing factors on a special-purpose communication system and describe a special communication system of different architectures. Also, the method allows determining the rational routes of information transmission and the operation mode of communication devices. Another element of novelty of the proposed method is that it takes into account the degree of uncertainty about the state of the special-purpose communication system. The next element of the novelty of the proposed method is the forecasting of the state of the special-purpose communication system based on fuzzy temporal models and determination of the number of necessary forces and means of communication that must be increased for the full functioning of the special communication system.

3. The positive effect of the implementation of the developed improved method is provided by the following interrelated factors: joint use of the analysis and forecasting procedures; determination of the necessary number of forces and means of communication, which must be included in the special-purpose communication system.

The proposed improved method can be used at the control points of the communication system of troops (forces) groups while planning the organization of communication and at the stage of operational management of the communication system.

The specified method allows increasing the efficiency of the special communication system under the influence of destabilizing factors by 20–26 %, which is confirmed by the simulation results.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

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