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MATHEMATICAL MODEL OF THE FUNCTIONING OF AN AUTOMATED MILITARY RADIO COMMUNICATION SYSTEM IN THE PROCESS OF ITS PROTECTION AGAINST RADIO RECONNAISSANCE BY RADIO EXCHANGE BY RATIONAL ROUTES

The article presents the general provisions and essence of the approach to building a mathematical model of the functioning of an automated military radio communication system in the process of its protection against radio reconnaissance by radio exchange along rational routes. The main components of the mathematical model of the functioning of an automated military radio communication system in the process of its protection against radio reconnaissance by radio exchange along rational routes with low intelligence availability are considered. The general structure of a mathematical model of the functioning of an automated military radio communication system in the process of its protection against radio reconnaissance by radio exchange along rational routes is proposed. It is shown that in the basic modeling unit of the subprocess of determining the rational routes of radio exchange among the set of possible ones, an optimization problem is solved. The result of solving this optimization problem is presented in tabular form for convenience. The analytical expressions for the third-rank tensor of the intelligence accessibility of individual branches of the radio communication system structure are obtained.

Keywords: *model, mathematical modeling, automated systems, military radio communication, signal, information exchange, radio reconnaissance, intelligence availability, training material and technical base, training of troops, training base, training complex, artificial intelligence, functioning algorithms.*

Statement of the problem. Repulsing the large-scale armed aggression of the russian federation against Ukraine is accompanied by the acquisition of new capabilities, both modern (and promising) means of radio communication and means of radio intelligence, which leads to significant changes in the functioning of military radio communication systems during their protection against radio intelligence. An integral part of this issue is the construction of mathematical models of the functioning of military radio communication systems in the process of their protection against radio reconnaissance.

The existing methodology for constructing mathematical models of the functioning of military radio communication systems in the process of their protection against radio reconnaissance to some extent does not meet the needs that are necessary for research on the functioning of modern and advanced automated military radio communication systems in the process of their protection against modern and advanced radio reconnaissance means. And, first of all, due to the lack of mathematical models that would correspond to promising options for the functioning of an automated military radio communication system in the process of its protection against radio reconnaissance.

Analysis of the latest research and publications. A number of publications by Ukrainian and foreign scientists are devoted to the research area considered in the article [1–10]. In these publications, mathematical models of the functioning of military radio communication means and systems in the process of their protection against radio reconnaissance are developed, taking into account more than two dozen different indicators of their radio masking level. The proposed mathematical models are mainly probabilistic in nature, so verification of their adequacy requires a large amount of statistical material, which is not always possible. In addition, the application of these models is complicated by the fact that new generation radio reconnaissance systems are able to detect military radio communications almost instantly with a probability close to one, provided they are intelligence-available.

Existing models are built on the basis of the capabilities of radio communications and radio reconnaissance assets of the old fleet and are based mainly on the use of such energy characteristics as signal-to-noise ratio, neglecting the decision-making process regarding the presence of useful signals at the receiver outputs of both enemy radio reconnaissance assets and their own system.

Therefore, these studies practically do not take into account the capabilities of modern and future means of radio communication, means of radio intelligence and the specifics of the decision-making process regarding the availability of useful signals at the outputs of their receivers.

The purpose of the article is to develop an approach to constructing a mathematical model of the functioning of the automated system of military radio communication in the process of its protection from radio intelligence by radio communication along rational routes.

Summary of the main material. According to the general provisions of the theoretical foundations of the methodology of mathematical modeling of the functioning of the automated system of military radio communication in the process of its protection from radio intelligence, the mathematical model of the functioning of the automated system of military radio communication in the process of its protection from radio intelligence by radio communication along rational routes with low intelligence availability has four basic blocks: a unit for obtaining and analyzing information about the current state of radio communications, enemy radio reconnaissance systems, physical and geographical conditions in the operational area as a medium for the propagation of electromagnetic waves; block for modeling the subprocess of formation of possible radio communication routes; module of modeling the subprocess of assessment of the current values of the coefficient of reconnaissance accessibility of possible radio communication routes, taking into account different modes of operation of radio communication facilities in their individual sections; block of modeling the subprocess of determining rational radio communication routes among the set of possible ones.

The basic unit for obtaining and analyzing information on the current state of radio communications, the enemy's radio intelligence system, physical and geographical conditions in the operational area, as a medium for the propagation of electromagnetic waves, will be considered as a block of initial data for further modeling. Such initial data, in addition to the initial data considered in a similar block of the mathematical model of the functioning of the automated system of military radio communication in the process of its protection from radio reconnaissance by the rational purpose of modulation types to its means, should include:

$\boldsymbol{Gr} = (\mathrm{M}, \boldsymbol{G})$ – graph of the structure of the military radio communication system, where $\mathbf{M}$ is the set of vertices (means of radio communication), $\mathbf{G} = (G_1, G_2, \dots, G_g)$ – a set of branches (direct communication lines between radio communication facilities);

λ_{sp} – a specified level of radio intensity;

τ_{sp} – a specified level of time delay in the delivery of information packages;

σ_{sp} – a specified level of variance of the time delay in the delivery of information packets;

p_{sp} – a given level of probability of timely delivery of information packages;

λ_{sp}^{los} – a specified level of intensity of loss of information packets;

ml – information directions in the military radio communication system ($\forall\, m \in [1, M]$, $\forall\, l \in [1, M]$, $\forall\, m \neq l$);

k_{ml} – partial information flows of each information direction ($k \in [1, K]$);

$m_{G_1} l_{G_1}$, $m_{G_2} l_{G_2}$, … , – $m_{G_g} l_{G_g}$ means of radio communication, between which there are direct communication lines (generalized system of military radio communication);

$\varphi_{G_1}, \varphi_{G_2}, \dots, \varphi_{G_g}$ – capacity of the branches of the structure of the military radio communication system;

$j^{(G_1)}, j^{(G_2)}, \dots, j^{(G_g)}$ – rational assignment of modulation types to the branches of the radio communication system structure;

$\boldsymbol{\Lambda}_{(k_{ml})G}$ – 2-tensor of radio communication intensity in one information direction (in general form);

$\boldsymbol{T}_{(k_{ml})G}$ – 2-tensor of time delays in the delivery of information packets for one information direction (in general);

$\boldsymbol{P}_{(k_{ml})G}$ – 2-tensor of probabilities of timely delivery of information packets for one information direction (in general form);

$\boldsymbol{\Sigma}_{(k_{ml})G}$ – 2-tensor of variances of time delays in the delivery of information packets for one information direction (in general form);

$\boldsymbol{RD}_{(ml)G}(\boldsymbol{\Lambda})$ – 2-tensor of intelligence accessibility of individual branches of the radio communication system depending on the intensity of information exchange (in general);

$\boldsymbol{RD}_{(ml)G}(\boldsymbol{T})$ – 2-tensor of intelligence accessibility of individual branches of the radio communication system depending on the time delays of information exchange (in general);

$\boldsymbol{RD}_{(ml)G}(\boldsymbol{\Sigma})$ – 2-tensor of intelligence accessibility of individual branches of the radio communication system depending on the variances of time delays of information exchange (in general);

$\boldsymbol{RD}_{(ml)G}\ (\boldsymbol{P})$ – 2-tensor of intelligence accessibility of individual branches of the radio communication system depending on the probabilities of timely information exchange (in general).

The basic block of modeling the subprocess of formation of possible routes of information exchange is based on the procedure of decomposition of a graph $\boldsymbol{Gr} = (\boldsymbol{M}, \boldsymbol{G})$ into a set of its simple chains $\boldsymbol{\Xi} = \xi_1\xi_2\ldots\xi_\vartheta$ for each information direction *ml*, known in discrete mathematics.

The basic block of modeling the subprocess of estimating the current values of the coefficient of intelligence accessibility of possible radio communication routes, taking into account different modes of operation of radio communication facilities in their individual sections, is based on analytical ratios for the coefficient of intelligence availability of military radio communication facilities in different modes of operation, analytical dependence for the intelligence availability coefficient of a separate branch of the structure of the radio communication system and tensors $\boldsymbol{A}_{\Xi G}$ conversion of basis $\mathbf{G}$ to basis $\boldsymbol{\Xi}$. This base unit can be represented by Figure 1.

In the block of formation of generalized tensors of the second rank (2-tensors) of radio communication quality indicators, generalization to all information directions $K_{ml}G_g$ of dimensional 2-tensors of radio communication quality indicators for one information direction is carried out. This procedure is carried out in order to ensure that all possible features of the quality of radio communication on the scale of the entire military radio communication system are taken into account during its protection from enemy radio reconnaissance and their generalization. Obtaining generalized 2-tensors of indicators of the quality of radio communication at the scale of the radio communication system will allow a correct approach to solving the problem of determining rational routes of radio communication in the system on the basis of finding a compromise between the quality of radio communication and requirements for intelligence accessibility as separate means of military radio communication, radio communication routes and the radio communication system as a whole. It is also a convenient tool for assessing the current state of the capabilities of the military radio communication system to ensure high-quality information exchange in the command and control system of troops (forces).

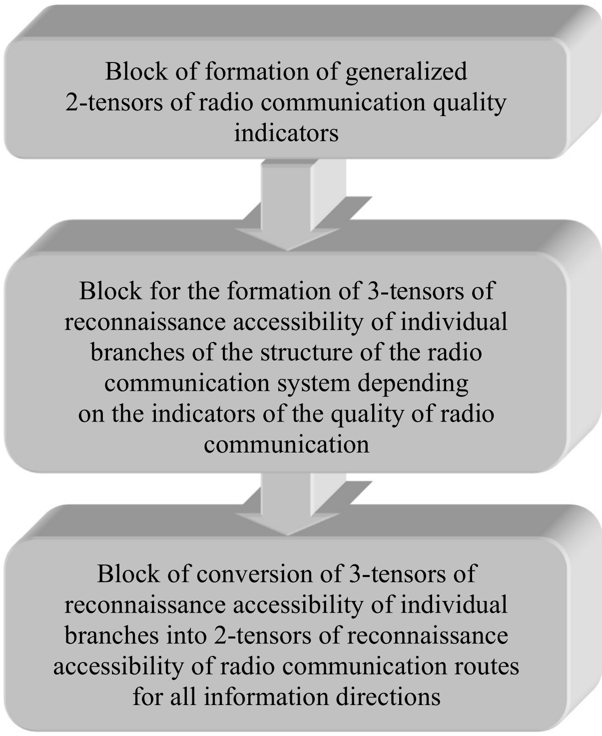

Figure 1 – Structure of the basic unit for modeling the subprocess of estimating the current values of the coefficient of reconnaissance availability of possible radio communication routes

In the block of formation of tensors of the third rank (3-tensors) of reconnaissance accessibility of individual branches of the structure of the radio communication system, depending on the indicators of the quality of radio communication, the generalization of 2-tensors of intelligence accessibility to all modes of operation of radio communication facilities is carried out.

Taking into account all modes of operation of radio communication facilities, the 2-tensor of reconnaissance accessibility $\boldsymbol{RD}_{(ml)G}(\boldsymbol{\Lambda})$ will take the form $7G_g\,g\sum_{m,l}K_{ml}$ of a dimensional 3-tensor of intelligence accessibility of individual branches of the structure of the radio communication system $\boldsymbol{RD}_{(ml)Gj}(\boldsymbol{\Lambda})$ (Figure 2).

Taking into account all modes of operation of radio communication facilities, the 2-tensor of intelligence accessibility $\boldsymbol{RD}_{(ml)G}(\boldsymbol{T})$ is transformed into $7G_g\,g\sum_{m,l}K_{ml}$ a dimensional 3-tensor of intelligence accessibility of individual branches of the network $\boldsymbol{RD}_{(ml)Gj}(\boldsymbol{T})$ (Figure 3).

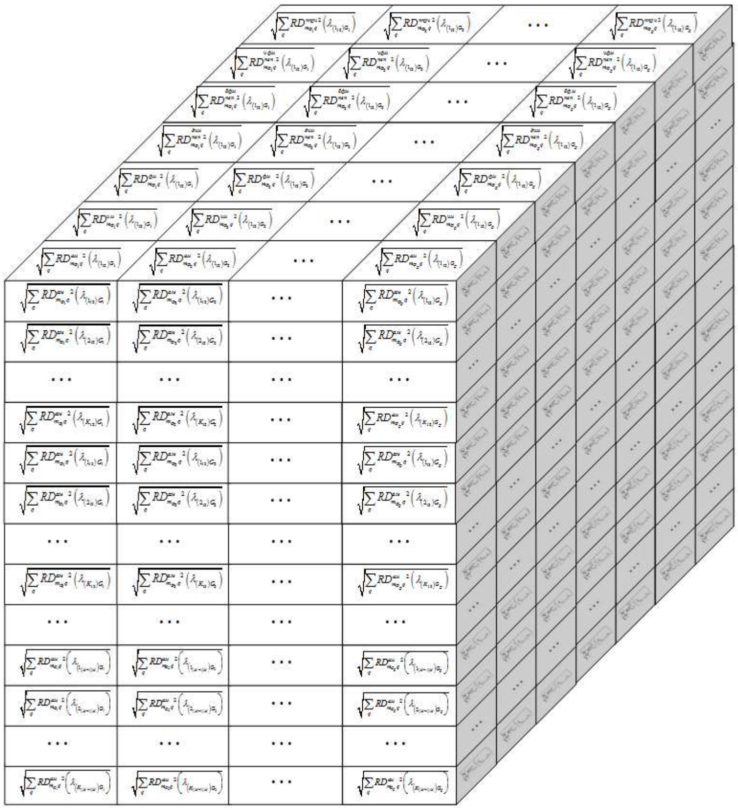

Figure 2 – 3-tensor of intelligence accessibility of individual branches of the network $\boldsymbol{RD}_{(ml)Gj}(\boldsymbol{\Lambda})$

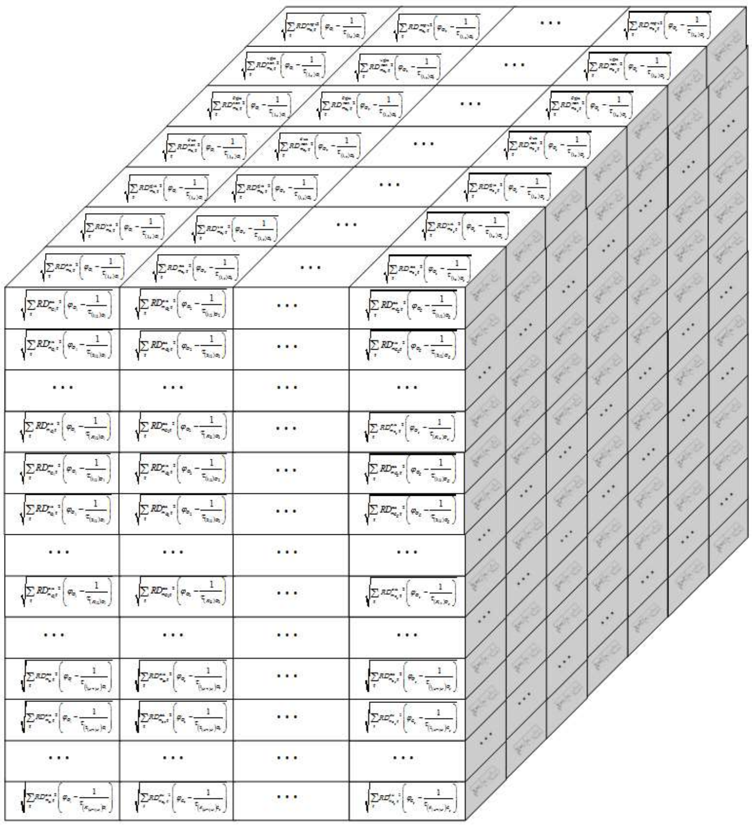

Figure 3 – 3-tensor of intelligence accessibility of individual branches of the network $\boldsymbol{RD}_{(ml)Gj}(\boldsymbol{T})$

Taking into account all modes of operation of radio communication facilities, the 2-tensor of reconnaissance accessibility $\boldsymbol{RD}_{(ml)G}(\boldsymbol{\Sigma})$ will take the form $7G_g g\sum_{m,l} K_{ml}$ of a dimensional 3-tensor of reconnaissance accessibility of individual branches of the network $\boldsymbol{RD}_{(ml)Gj}(\boldsymbol{\Sigma})$ (Figure 4).

The 2-tensor of intelligence accessibility, $\boldsymbol{RD}_{(ml)G}(\boldsymbol{P})$ taking into account all modes of operation of radio communication facilities, is transformed into $7G_g g\sum_{m,l} K_{ml}$ a dimensional 3-tensor of intelligence accessibility of individual branches of the network $\boldsymbol{RD}_{(ml)Gj}(\boldsymbol{P})$ (Figure 5).

The block of conversion of 3-tensors of reconnaissance accessibility of individual branches into 2-tensors of reconnaissance accessibility of radio communication routes for all information directions is based on the use $\boldsymbol{A}_{\boldsymbol{\Xi G}}$ of a tensor as a tensor for converting a basis $\mathbf{G}$ into a Ξ basis.

Then, in general, we can write:

$$\boldsymbol{RD}_{(ml)\Xi} = \boldsymbol{RD}_{(ml)Gj}\boldsymbol{A}_{\Xi G}^{-1} = \boldsymbol{RD}_{(ml)Gj}\boldsymbol{A}_{G\Xi}, \quad (1)$$

where

$$\boldsymbol{A}_{\boldsymbol{G\Xi}} = \begin{matrix} \\ G_1 \\ G_2 \\ \dots \\ G_g \end{matrix} \left\| \begin{matrix} \xi_1 & \xi_2 & \dots & \xi_\vartheta \\ a_{11} & a_{21} & \dots & a_{\vartheta 1} \\ a_{12} & a_{22} & \dots & a_{\vartheta 2} \\ \dots & \dots & \dots & \dots \\ a_{1g} & a_{2g} & \dots & a_{\vartheta g} \end{matrix} \right\|. \quad (2)$$

In the basic block of modeling the subprocess of determining rational radio communication routes among the set of possible ones, the optimization problem with the objective function (3) is solved:

$$\min_{\xi_i} \sqrt{RD^2_{(k_{ml})\xi_i}(\lambda) + RD^2_{(k_{ml})\xi_i}(\tau) + RD^2_{(k_{ml})\xi_i}(\sigma) + RD^2_{(k_{ml})\xi_i}(p)}, \quad (3)$$
$$\forall(m, l \in [1, M]); \forall(k \in [1, K_{ml}]); \forall(\xi_i \in [\xi_1, \xi_{\vartheta_{ml}}]),$$

with restrictions: $\lambda_{k_{ml}} \le \lambda_{set}$; $\tau_{k_{ml}} \le \tau_{set}$; $\sigma_{k_{ml}} \le \sigma_{set}$; $p_{k_{ml}} \ge p_{set}$; $\lambda^{los}_{(k_{ml})G} \le \lambda^{los}_{set}$.

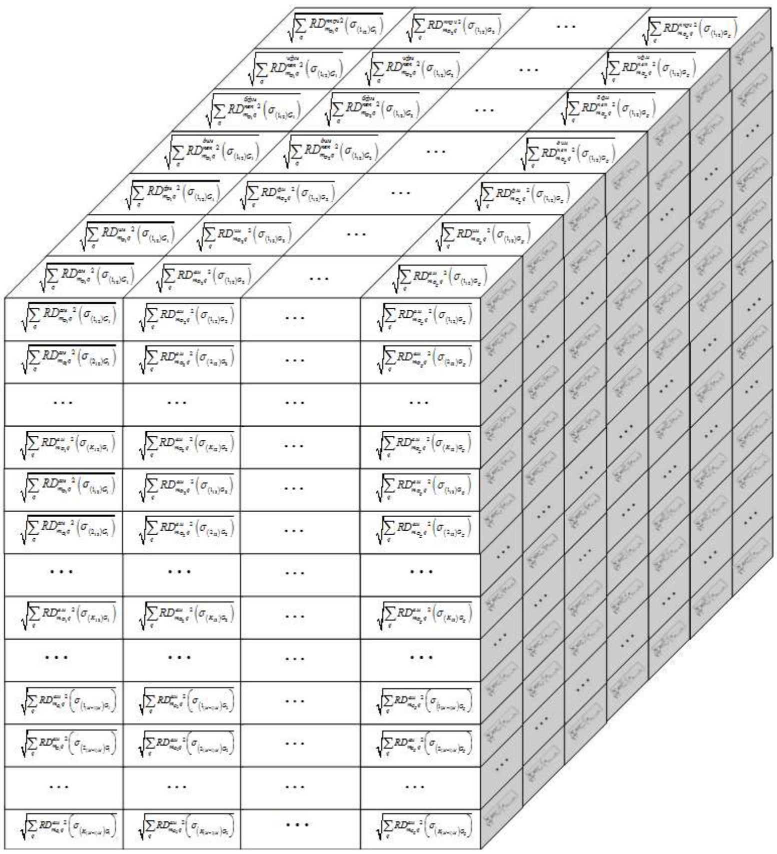

Figure 4 – 3-tensor of intelligence accessibility of individual branches of the network $\boldsymbol{RD}_{(ml)Gj}(\boldsymbol{\Sigma})$

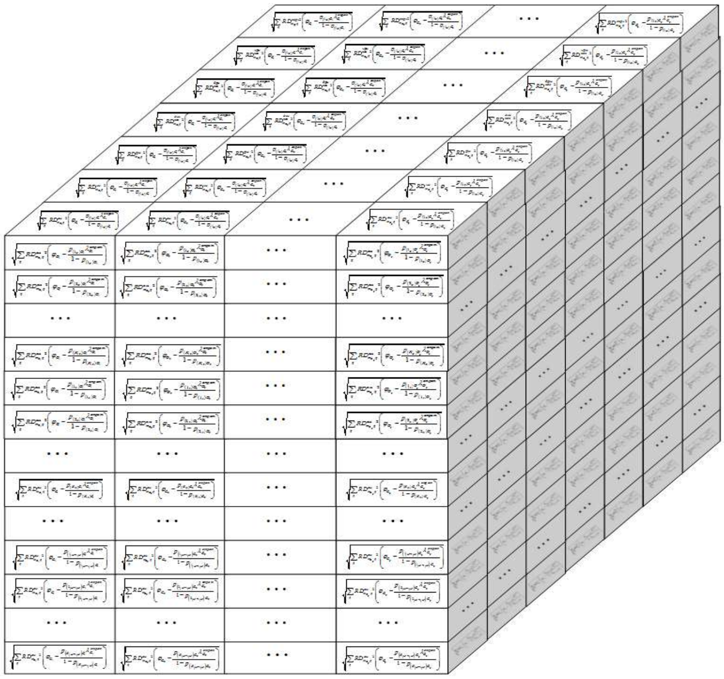

Figure 5 – 3-tensor of intelligence accessibility of individual branches of the network $\boldsymbol{RD}_{(ml)Gj}(\boldsymbol{P})$

At the same time, for each information direction in the radio communication system, such rational routes for the transmission of partial information streams are selected, which have the minimum total intelligence availability with restrictions on the intensity of radio communication, average delays of information packets and their dispersion, the probability of timely delivery of information packets in the network, and the intensity of packet losses. The result of solving the optimization problem (3) is conveniently presented in Table 1.

Table 1 – Rational Radio Communication Routes

Information direction	Partial information flow k_{ml}	Rational route of information exchange $\xi_{rat}^{k_{ml}}$	Estimated reconnaissance accessibility of the route $RD_{(k_{ml})}$	Estimated intensity of information exchange on the route $\lambda_{(k_{ml})}$	Estimated delay in information delivery $\tau_{(k_{ml})}$	Estimated deviation from the average delay in information delivery $\sigma_{(k_{ml})}$	Estimated probability of timely delivery of information $p_{(k_{ml})}$
12	1_{12}	$\xi_{rat}^{1_{12}}$	$RD_{(1_{12})}$	$\lambda_{(1_{12})}$	$\tau_{(1_{12})}$	$\sigma_{(1_{12})}$	$p_{(1_{12})}$
	2_{12}	$\xi_{rat}^{2_{12}}$	$RD_{(2_{12})}$	$\lambda_{(2_{12})}$	$\tau_{(2_{12})}$	$\sigma_{(2_{12})}$	$p_{(2_{12})}$
	…	…	…	…	…	…	…
	K_{12}	$\xi_{rat}^{K_{12}}$	$RD_{(K_{12})}$	$\lambda_{(K_{12})}$	$\tau_{(K_{12})}$	$\sigma_{(K_{12})}$	$p_{(K_{12})}$
13	1_{13}	$\xi_{rat}^{1_{13}}$	$RD_{(1_{13})}$	$\lambda_{(1_{13})}$	$\tau_{(1_{13})}$	$\sigma_{(1_{13})}$	$p_{(1_{13})}$
	2_{13}	$\xi_{rat}^{2_{13}}$	$RD_{(2_{13})}$	$\lambda_{(2_{13})}$	$\tau_{(2_{13})}$	$\sigma_{(2_{13})}$	$p_{(2_{13})}$
	…	…	…	…	…	…	…
	K_{13}	$\xi_{rat}^{K_{13}}$	$RD_{(K_{13})}$	$\lambda_{(K_{13})}$	$\tau_{(K_{13})}$	$\sigma_{(K_{13})}$	$p_{(K_{13})}$
…	…	…	…	…	…	…	…
(M – 1)M	$1_{(M-1)M}$	$\xi_{rat}^{1_{(M-1)M}}$	$RD_{(1_{(M-1)M})}$	$\lambda_{(1_{(M-1)M})}$	$\tau_{(1_{(M-1)M})}$	$\sigma_{(1_{(M-1)M})}$	$p_{(1_{(M-1)M})}$
	$2_{(M-1)M}$	$\xi_{rat}^{2_{(M-1)M}}$	$RD_{(2_{(M-1)M})}$	$\lambda_{(2_{(M-1)M})}$	$\tau_{(2_{(M-1)M})}$	$\sigma_{(2_{(M-1)M})}$	$p_{(2_{(M-1)M})}$
	…	…	…	…	…	…	…
	$K_{(M-1)M}$	$\xi_{rat}^{K_{(M-1)M}}$	$RD_{(K_{(M-1)M})}$	$\lambda_{(K_{(M-1)M})}$	$\tau_{(K_{(M-1)M})}$	$\sigma_{(K_{(M-1)M})}$	$p_{(K_{(M-1)M})}$

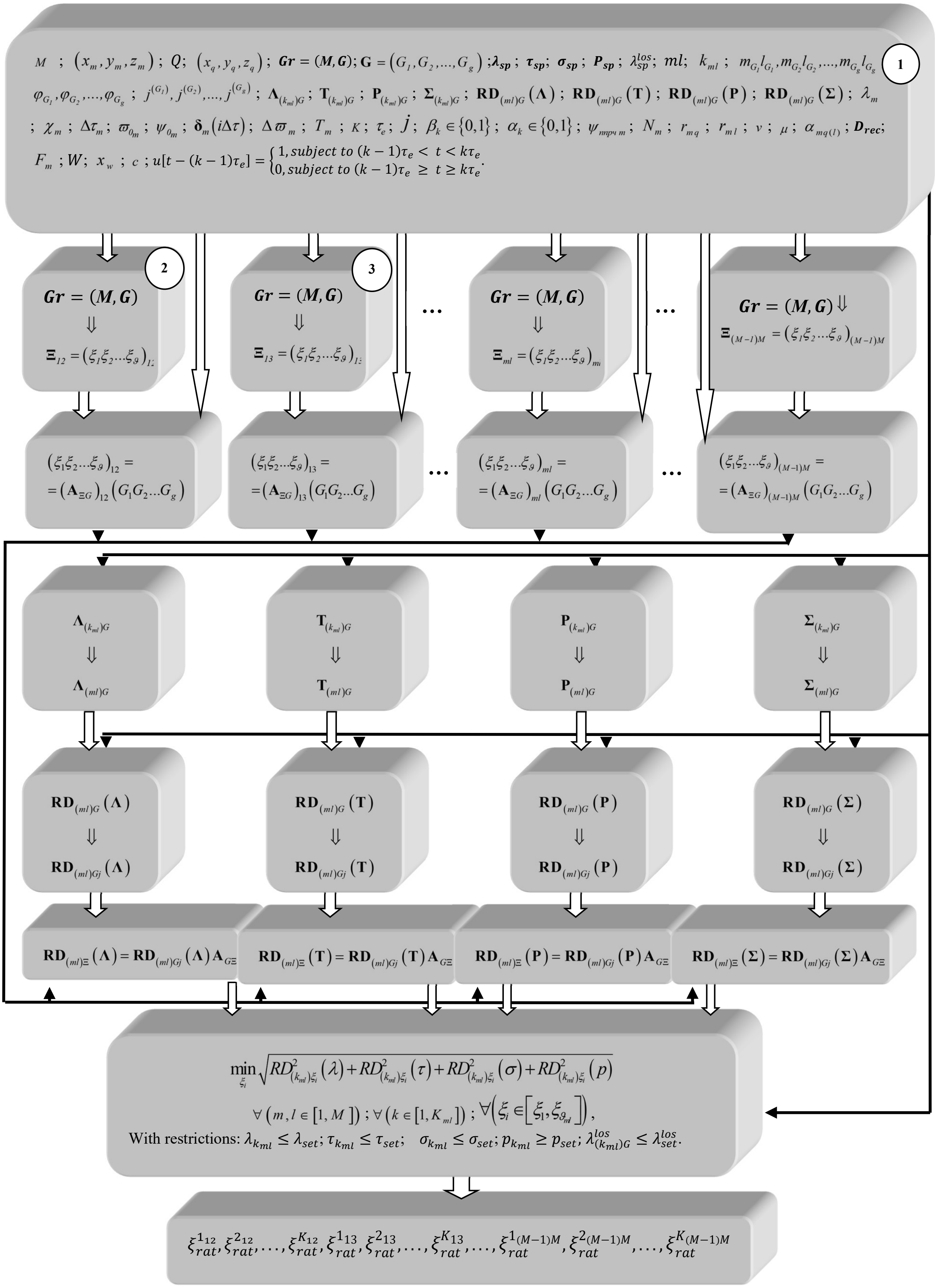

Figure 6 – Block diagram of the mathematical model of the functioning of the automated military radio communication system in the process of its protection from radio reconnaissance by radio communication

A block diagram of a mathematical model of the functioning of an automated military radio communication system in the process of its protection from radio intelligence by radio communication along rational routes with low intelligence availability can be presented in Figure 6. Block diagram number 1 contains the basic unit for obtaining and analyzing information on the current state of radio communications, enemy radio intelligence systems, physical and geographical conditions in the operational area as a medium for the propagation of electromagnetic waves; Numbers 2 – 5 contain the components of the basic block of modeling the subprocess of formation of possible radio communication routes by decomposing the graph $\boldsymbol{Gr} = (\boldsymbol{M}, \boldsymbol{G})$ into a set of its simple chains $\Xi = \xi_1 \xi_2 \ldots \xi_9$ for each information direction *ml*; Numbers 6 – 9 contain the blocks of formation of the basis **G** to basis conversion tensor$\boldsymbol{\Xi}$; Numbers 10 – 13 contain the components of the block formation of 2-tensors of quality indicators generalized to all information directions of the radio communication system radio communication; Numbers 14 – 17 contain the components of the block for the formation of 3-tensors of intelligence accessibility of individual branches of the structure of the radio communication system depending on the quality indicators of the intelligence accessibility tensors of individual branches into 2-tensors of intelligence accessibility of radio communication routes for all information directions; Number 22 is the basic block simulation of the subprocess of determining rational radio communication routes among the set of possible ones; Number 23 is the block for the formation of rational radio communication routes with low intelligence availability.

Conclusions

The article first to develop a mathematical model of functioning of the automated system of military radio communication, which: takes into account the process of its protection from radio intelligence by radio communication along rational routes with low intelligence availability; is built on the basis of tensor dependencies of the intelligence availability coefficients of individual direct radio communication lines on the indicators of the quality of information exchange in the elementary basis of the structure of the automated military radio communication system with their subsequent transformation to tensor dependencies of the intelligence availability coefficients of radio communication routes, which ensured the consideration of multipath packet routing, which is implemented in modern and future automated systems military radio communications, not only for reasons of optimal use of the resources of the military radio communication system, but for reasons of finding a compromise between the values of the coefficients of intelligence accessibility of radio communication routes and the values of indicators of its quality. In addition, it ensured the receipt of rational radio communication routes in the automated military radio communication system.

The results obtainedare the scientific basis for the further development of a systematic approach to the development of theoretical and practical foundations for the creation of mathematical models of the processes of functioning of automated systems of military radio communication in the conditions of their protection from radio intelligence.

In further research, it is planned to improve the algorithms for the formation of 3-tensors of intelligence accessibility of individual branches of the structure of the radio communication system, depending on the indicators of the quality of radio communication.

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РОЗРОБЛЕННЯ МАТЕМАТИЧНОЇ МОДЕЛІ ФУНКЦІОНУВАННЯ АВТОМАТИЗОВАНОЇ СИСТЕМИ ВІЙСЬКОВОГО РАДІОЗВ'ЯЗКУ У ПРОЦЕСІ ЇЇ ЗАХИСТУ ВІД РАДІОРОЗВІДКИ РАДІООБМІНОМ ЗА РАЦІОНАЛЬНИМИ МАРШРУТАМИ

Наведено загальні положення і розкрито сутність підходу до побудови математичної моделі функціонування автоматизованої системи військового радіозв'язку у процесі її захисту від радіорозвідки радіообміном за раціональними маршрутами. Розглянуто основні складники математичної моделі функціонування автоматизованої системи військового радіозв'язку у процесі її захисту від радіорозвідки радіообміном за раціональними маршрутами з низькою розвідувальною доступністю. Запропоновано загальну структуру математичної моделі функціонування автоматизованої системи військового радіозв'язку у процесі її захисту від радіорозвідки радіообміном за раціональними маршрутами.

Показано, що у базовому блоці моделювання підпроцесу визначення раціональних маршрутів радіообміну серед множини можливих здійснюється розв'язування оптимізаційної задачі, результати розв'язання якої для зручності подано у вигляді таблиці. Отримано аналітичні вирази для тензора третього рангу (3-тензора) розвідувальних доступностей окремих гілок структури системи радіозв'язку.

Ключові слова: *модель, математичне моделювання, автоматизовані системи, військовий радіозв'язок, маршрути інформаційного обміну, коефіцієнт розвідувальної доступності, навчальна матеріально-технічна база, підготовка військ, тренажерна база, тренажерний комплекс, штучний інтелект, алгоритми функціонування, захист від радіорозвідки.*

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