Methods of information systems synthesis

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ALGORITHMS FOR SYNTHESIS OF FUNCTIONALLY STABLE WIRELESS SENSOR NETWORK

Abstract. Research objective. Development of algorithms that allow to implement the synthesis of a functionally stable wireless sensor network. **Subject of research.** Wireless sensor networks, algorithms for the synthesis of a functionally stable network. **Research method**. Algorithmic and numerical analysis of the procedures for performing the synthesis of functionally stable sensor networks. **Research results.** Ensuring the property of functional stability of a wireless sensor network provides a solution to the problem of the influence of destabilizing factors, such as: software and hardware failures, errors, accidental or intentional damage to individual structural elements, their aggregates, communication channels between them, cyberattacks, service failures, etc. Research of existing scientifically based approaches to ensuring the functional stability of wireless sensor networks and its components shows that there is no single general approach to determining the functional stability of a wireless sensor network. Therefore, the work is devoted to solving the current scientific problem of developing an algorithm for searching for the optimal structure of a wireless sensor network. An algorithm for finding a lower bound for the number of removed vertices and an algorithm for finding a lower bound for the number of removed vertices taking into account redundant communication lines have been developed. It has been established that first of all it is necessary to determine the complete set of minimal graph sections and their power. An algorithm for finding the optimal structure of a wireless sensor network has been developed, which consists of nine steps and can be used to synthesize the structure of wireless sensor networks that have the ability to self-organize in order to find its optimal structure. It is shown that the proposed algorithm has a high level of convergence and provides the desired result for a finite number of iterations, which is much better than finite search. The developed algorithm is effective when the dimension of the problem is $n > 20$. The results of solving test problems fully confirm the effectiveness of the algorithm in comparison with the results of the solution by exhaustive search, which confirms the importance of the results obtained. This result can be applied to information systems for production process control and information security systems that have a wireless topology and are under the influence of external and internal destabilizing factors of an impulse nature. The proposed algorithm actually implements the controllability conditions in such a system through monitoring the state of the system and mechanisms for restoring functioning in its optimal perimeter.

Keywords: functional stability; algorithm; wireless network; sensor network; convergence; structure synthesis.

Introduction

Wireless sensor networks (WSNs) are becoming increasingly prevalent across various domains. his growth is driven by ongoing advancements in hardware and software, optimization of data transfer protocols, and enhancements in information security. WSNs are evolving continuously; however, the comprehensive design framework for WSNs—both hardware and software—remains unresolved. As before, the construction and integration of WSNs depends on the features and requirements of operation.

WSNs are increasingly integrated into diverse industries and aspects of human activity each year. This trend is due to the rapid complication of technological processes, the development of production, resource potential management, etc. New practical tasks and theoretical problems related to the applications of wireless sensor networks are constantly emerging. The use of inexpensive wireless sensor devices for monitoring parameters of various nature is constantly expanding the areas of their application. Over the past five years, the rapid growth of the IoT/IIoT device market—where the number of devices has nearly doubled—has significantly contributed to the expansion of WSNs. In fact, such dynamics of growth of this telecommunications sector makes it one of the most relevant areas covered in the global and European research environment. The application of WSNs to solve practical problems in the industrial sector, educational and scientific purposes should provide the necessary, high-quality, more detailed understanding and assessment of complex processes in the most diverse areas of application of modern information technology.

A wireless sensor network is a distributed system for collecting, storing and processing information. Designing and building a monitoring system for sensor nodes that are distributed in space and are constantly exposed to external and internal destabilizing factors is a complex and very costly process.

Analysis of the principles of construction, purpose and technologies used in WSNs today has shown the complexity of integrating and building networks of this type in terms of ensuring the property of functional stability of information systems for managing production processes, information security systems and other systems built on this basis.

Monitoring the proper level of performance of such indicators as reliability, redundancy, survivability, stability of operation and fault tolerance is no longer a sufficient condition for the normal and uninterrupted functioning of wireless sensor networks. That is why the study of additional, but no less important properties of the system, the complexity of which is constantly growing, is a priority task.

Problem statement and its connection with important scientific and practical tasks. Ensuring the functional stability of the WSNs should consist of a comprehensive and deep approach that should take into account the totality of all factors of operation, the possibility of external influence, issues of software and hardware security, the reliability of transmission channels, increasing the coverage area and data transmitted and processed by the system, a possible heterogeneous approach to building a network, etc.

The theory of functional stability [1] proposes analyzing extraordinary system states caused by permissible failures and implementing functionally stable controls to mitigate their effects while maintaining the system's core functionality. Due to this, the redistribution of system resources is ensured to achieve the main goal, even in the presence of failures. The fundamental condition for ensuring the property of functional stability in such a context is the possibility of redistributing available resources within the system. Therefore, the key task is to establish the conditions for the existence of functional stability for WSNs and to apply this property in the conditions of the rapid growth of new tasks that cannot be considered and fully solved exclusively by the traditional properties of complex technical systems that function under the constant influence of destabilizing factors of various nature.

Analysis of recent research and publications. The Kyiv school of cyber-physical systems has significantly advanced the theory of functional stability in complex technical systems. The first results were obtained by Mashkov O.A. in the theory of functional stability for stochastic systems. A method was developed that allows establishing the conditions of functional stability of stochastic systems by analyzing their spectral effects. Further, based on the analysis of transition matrices, a method for ensuring functional stability for discrete systems was developed [2]. It is worth noting that the presence of destabilizing factors of an internal or external nature significantly affects the nature of the system's behavior. Thus, even for systems whose mathematical models can be represented by linear systems, the presence of impulse forces leads to significantly nonlinear, and under certain conditions, even chaotic behavior. This issue has been actively studied recently. In particular, in [3], an apparatus for finding bounded solutions of linear impulse systems was developed. In [4], the authors developed an approach where for a system that is subject to impulse disturbances at unfixed moments of time, a sequence of moments of system destabilization can be constructed. It is shown that the problem of the existence of periodic modes in such a system is reduced to the problem of the existence of a fixed point of the interval reflection into itself.

In [5], a system analysis was performed and a methodology for ensuring the functional stability of the information system for critical infrastructure objects that are vulnerable to the action of destabilizing factors was proposed. In turn, in [6], a mathematical model of control of a functionally stable technological process of production enterprises in conditions of and changes in the dimension of the control vector was presented.

[7] presents a methodology for evaluating synchronization conditions in telecommunication devices. The architecture of information systems, network resources and network services, and methods for restoring parameters of information objects in a single information space based on computer networks are studied in detail in [8]. In addition, a standard model of the architecture of an enterprise IT infrastructure system is described in [9]. In [10], an algorithm for building effective protection of enterprise information infrastructure from unauthorized access is presented.

Work [11] is devoted to the development of a modification of the method for building energy-efficient sensor networks using static and dynamic sensors. An important component of the development of functionally stable complex technical systems is the provision of stable and protected communication and data exchange subsystems. In [12], a spectral analysis method for determining random digital signals is described. An algorithm for recognizing network traffic anomalies based on artificial intelligence is presented in [13].

It is important to note that many researchers often use the study of patterns in WSNs as a classical optimization problem, that is, they consider the process of determining several solutions for various functions [14–16]. When solving optimization problems, the solution variables are determined in such a way that the information networks work at the best point (mode) according to the optimization criterion. Generally, the optimization problems in information networks are discontinuous, non-differentiable, and multimodal. Therefore, to solve problems that study the problem of self-organization of information networks, it is not worth using classical gradient deterministic algorithms [17–22] or stochastic optimization algorithms, which are known as the so-called metaheuristic algorithms [23–27].

The aim of the paper [28] is to provide energy-efficient routing for mobile nodes in a WSNs using an ontological optimization approach. The approach is based on the use of echolocation to determine the location and representation of cluster nodes near the receiver, which supports optimal energy consumption during simulation.

Researchers in [29], using an innovative approach to combine fuzzy logic and device swarm optimization, proposed an approach for efficient cluster head selection in a WSNs, which ensures the stability of such a network during its intended operation. The paper [30] is devoted to addressing the correlation between the position of a wireless device and signal strength to improve the localization process and controllability in such a WSNs.

To ensure stable operation and improve the performance of the localization procedure in a WSNs, clustering methods are useful, which allow dividing the network into segments that can operate independently, thus reducing communication costs and increasing network throughput by providing distributed computing

[31]. The work [32] is devoted to improving the methodology for assessing the information value of controlled parameters, based on the analysis of the probabilities of the values of controlled parameters falling into subintervals of the interval of possible values for different states of the system. System diagnostics in conditions of a small initial data sample was investigated in [33]. The authors in [34] established the conditions for the functional stability of the network and developed an approach to finding the minimum distance between components as a structure for a quick assessment of the dynamics of network functionality representations. In [35] the authors conducted a stability analysis for control systems with state feedback, created as neural networks with input constraints. Analysis of the obtained results indicates a high interest of researchers in the issue of ensuring the functional stability of complex technical systems. However, research for wireless sensor networks is at the initial stages. Their rapid development requires significant attention to the development of methods and algorithms for detecting and synthesizing wireless sensor networks. This issue is precisely the subject of this work.

Purpose of the work and task statement. Functional stability is ensured by leveraging various types of redundancy – structural, temporal, informational, functional, and load-based—within complex technical systems, particularly in WSNs. This involves redistributing resources to mitigate the effects of emergency situations. At the same time, the issue of developing a mathematical apparatus for modeling the synthesis of functionally stable wireless sensor networks and algorithms for synthesizing BDMs requires detailed attention.

The aim of the work is to develop algorithms that, together, allow us to propose a comprehensive methodology for synthesizing the optimal structure of a wireless sensor network.

Research results

Algorithms for the synthesis of a functionally stable sensor network. Local connectivity between nodes is determined by the availability of network elements and communication channels at any given moment. Therefore, designing and operating complex technical systems requires minimizing the risk of local connectivity disruptions caused by failures or malfunctions. The choice of connectivity characteristics is based on:

- existing indicators of functional stability;
- classification of connectivity characteristics (Fig. 1).

Total connectivity.

In this regard, it is advisable to introduce a new indicator of functional stability – total connectivity (k, ω), where k is the number of elements of the optimal destruction of the ω-connected graph.

Let us introduce some notations and assumptions: ω connectivity is a maximum number of vertex-independent routes between any pair of vertices of a graph; λ connectedness is a maximum number of edge-independent routes between any pair of vertices of a graph; $G[v_x]$ is a set of vertices adjacent to v_x in the graph G; $G^z[v_x]$ is a set of vertices that are at a distance z from the vertex v_x.

We will assume that the graph $G(V, L)$ is ω-connected, *totally connected*, if upon removal of any k $(k < \omega)$ vertices $\{v_i\}$ from the graph any pair of vertices from $(k < \omega)$ vertices $\{v_i\}$ from the graph any pair of vertices from the set $V\backslash(\{v_i\} \cup G[\{v_i\}])$ ω is connected in the subgraph $G'(V\backslash\{v_i\}, L^i)$.

The main task in this case is to determine the structure of such a network, when removing k nodes in which the given level of connectivity is preserved, except for the unit neighborhood of the removed nodes.

A graph $G(V, L)$ is considered (k, ω)-totally coherent if, after the removal of any k $(k < \omega)$ vertices $\{vi\}$, any pair of vertices from the set $V(\{vi\} \cup G[\{vi\}])$ remain ω-connected in the resulting subgraph $G'(V\{v_i\}, L^i)$.

At the same time for k $(k < \omega)$ vertices $\{v_i\}$ graph $G(V, L)$ any pair of vertices from the set

$$V\backslash(\{v_i\} \cup G[\{v_i\}])$$

ω-combined in a subgraph $G'(V\backslash\{v_i\}, L^i)$.

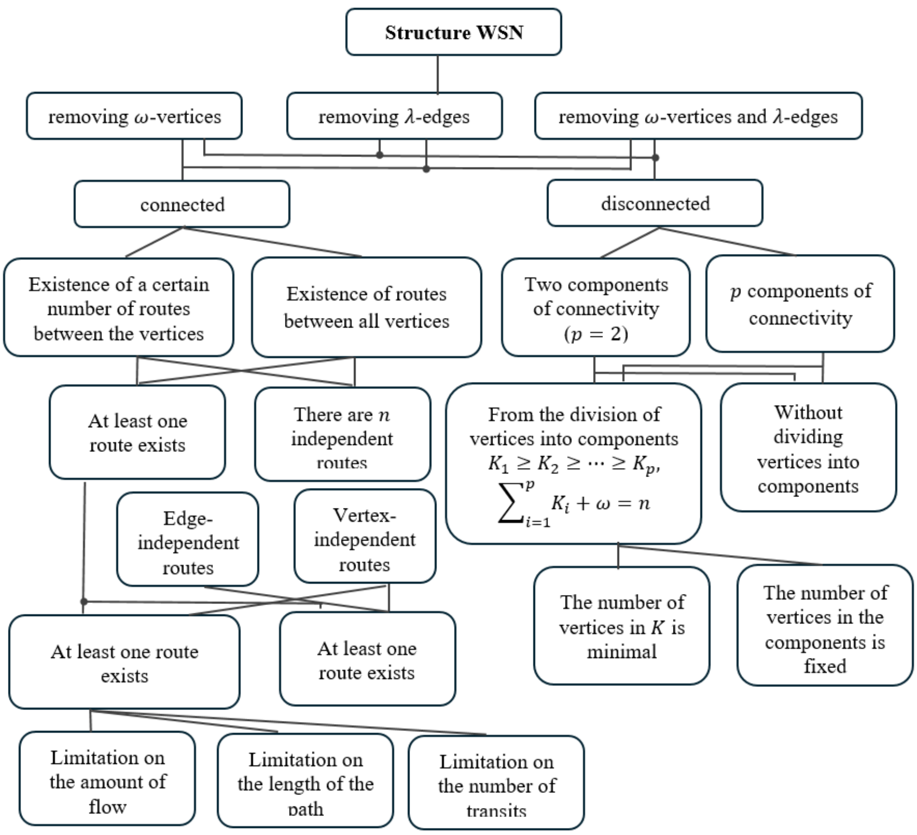

Fig. 1. Classification of connectivity characteristics of wireless sensor network structure

Total costal connectivity. Network design and operation must consider potential functional stability violations caused by element or communication channel failures. The graph $G(V, L)$ ω-connected is called (k, λ)-*totally costally connected*, if upon removal of any k $(k < \lambda)$ edges $\{l_{ij}\}$ in the subgraph $G'(V, L \setminus \{l_{ij}\})$ any two vertices from the set $V \setminus (\{v_i\} \cup \{v_j\})$ λ-intertwining, i.e. λ-edge connected. That is why, when designing a network, one should try to achieve a situation in which, when k communication lines are removed, the system elements remain λ-intertwining.

We will take into account the same indicators of local functional stability of the structure:

1. The number (k, ω) of total connectivity is the maximum number of vertices whose removal together with incident edges does not change the local ω-connectivity of vertices not adjacent to the removed ones.

2. The number (k, λ) of edge total connectivity is the optimal number of edges, which, if removed, does not violate the local λ-connectivity of vertices not incident to the removed edges.

To establish total connectivity in a wireless sensor network, there is a need to check for local connectivity of a large number of vertices, which directly depends on the structure and tasks of the system. The given criteria for total connectivity are designed to solve the following tasks:

1) the structure will be (k, ω)-totally connected if for an arbitrary set of vertices $V' = (v_1, v_2, \ldots, v_k) \subset V$ $(k < \omega)$ in the subgraph $G'(V \setminus V', L')$ any pair of vertices from a subset $G^2[V']$ ω-connected in G';

2) the structure will be (k, λ)-totally edge-connected if for an arbitrary set of edges $L' = \{l_{ij}\} \subset L$, $|L'| = k$, $(k < \lambda)$ in the subgraph $G'(V, L \setminus L')$ any pair of vertices from a subset

$$G\left[\bigcup_{i,j=1}^{k} (v_i \cup v_j)\right],$$

where λ-intertwining in G.

Total connectivity (k, ω) characterizes the maximum possible number of switching node failures, at which the network remains ω-locally connected. Total edge connectivity (k, λ) characterizes the maximum possible number of communication lines, after the failure of which, the network remains λ-locally connected.

The given indicators are designed to identify elements of a wireless sensor network, when they fail, the total connectivity between other elements that are not adjacent to the removed ones is not broken.

Provided that the connectivity indicators meet the specified conditions, the structure of the wireless sensor network will be functionally stable:

$$\{\omega(G) \geq 2 \cap k > 1\} \cup \{\lambda(G) \geq 2 \cap k > 1\}. \quad (1)$$

Provided that a lower bound for k is found for a given vertex and edge connectivity, it is possible to verify that the total connectivity condition is satisfied for the structure under study.

Algorithm for finding a lower bound on the number of removed vertices. Let a given ω-connected graph be $G(V, L)$. Let's select a pair of non-adjacent vertices in this graph v_x, v_y and check their ω-connectivity under the condition that the removed vertices are not adjacent to v_x and v_y.

<u>Step 1</u>. Identify $G^2[vx]$ and $G^2[v\text{y}]$ for vertices v_x and v_y.

<u>Step 2</u>. If v_x belongs to $G^2[v_y]$ (v_y accordingly $G^2[vx]$), then

$$\tau := |G[x] \cap G\,[y]|; \quad (2)$$

remove vertices from graph G

$$G[v_x] \cap G\,[v_y]. \quad (3)$$

Go to step 1, otherwise go to step 3.

<u>Step 3</u>. Between the vertices of $G^2[v_x]$ and $G^2[v_y]$ we find the maximum number of vertex-independent chains connecting these sets, moreover, the chains must not intersect even for the final vertices.

<u>Step 4</u>. In $G^2[v_x]$ and $G^2[v_y]$ we choose subsets of vertices v_x and v_y, in which the construction of independent chains begins and ends.

<u>Step 5</u>. For each vertex

$$v_{i\in} G[v_x] (v_j \in G[v_y]) \quad (4)$$

let's find the value

$$d_{v_i} = \tau_{V_x}(v_i) - 1; \quad (5)$$

$$\mathrm{d}_{\mathrm{v_j}} = \tau_{\mathrm{V_y}}(\mathrm{v_j}) - 1. \quad (6)$$

where $\tau_{V_x}(v_i)$ is a number of vertices from V_x, contiguous with v_i,

$$k_x := \min\,(\min(d_{v_i}), |V_x| - (\omega - \tau)),$$

$$k_y := \min\,(\min(d_{v_i}), |V| - (\omega - \tau)),$$

$$k' := \min\,(k_x, k_y).$$

<u>Step 6</u>. Let's find local connectivity $\delta(v_x, v_y)$ between vertices v_x and v_y.

Let us calculate the final values of k for a given connectivity ω between the vertices v_x and v_y

$$k_{x,y} = k' + \left(\delta(v_x, v_y) - (\omega - \tau)\right). \quad (7)$$

Lower bound for the number of removed vertices between vertices v_x, v_y under the conditions of preserving the ω-connectedness of these vertices, we find.

<u>Step 7</u>.

$$k_{x,y} = k' + (\delta(v_x, v_y) - (\omega - \tau)). \quad (8)$$

Algorithm for finding a lower bound for the number of removed vertices, taking into account redundant communication lines. Let a given λ-edge-connected graph be $G(V, L)$. Let's select a pair of non-adjacent vertices in this graph v_x, v_y and check their λ-intertwining.

<u>Step 1</u>. For non-adjacent vertices v_x and v_y we find $G[v_x]$ and $G[v_y]$.

<u>Step 2</u>. Between the peaks $G[v_x]$ and $G[v_y]$ we find the maximum number of λ-edge-independent chains connecting these sets.

<u>Step 3</u>. For each vertex $v_i \in G[v_x]$ ($v_j \in G[v_y]$) let's find the value

$$l_{v_i} = \sigma_{V_x}(v_i) - 1,$$
$$l_{v_j} = \sigma_{V_y}(v_j) - 1.$$

where $\sigma_{V_x}(V_i)$ $(\sigma_{V_y}(V_j))$ is a number of independent chains ending at the vertex v_i (v_j), adjacent to v_i:

$$k_x := \min_i (l_{v_i}),$$
$$k_y := \min_j (l_{v_j}),$$
$$k' := \min(k_x, k_y).$$

Step 4. Let's find the local edge connectivity $\gamma(v_x, v_y)$ between vertices v_x and v_y. Then

$$k_{x,y} = k' + (\gamma(v_x, v_y) - \lambda). \quad (9)$$

Step 5. The estimate k for the entire graph G is calculated by the formula

$$\min_{v_x, v_y \in V} k_{x,y}. \quad (10)$$

Studies of the developed indicators and criteria demonstrate that achieving the highest level of local functional stability of the wireless sensor network structure is possible by increasing the connectivity of the structure by introducing redundant communication lines.

Probabilistic criterion for assessing functional stability. A structure is considered functionally stable if the probability of its failure-free operation meets or exceeds a predefined threshold

$$P(G, \rho) \geq P_{\text{def}}(G, p). \quad (11)$$

When designing and implementing complex technical systems, which in turn include wireless sensor networks, as well as to solve the problems of stability of functioning for such systems, it is customary to use minimal sections. A section of a graph is a set of edges, the removal of which divides a connected graph into two disconnected subgraphs. In fact, the smallest number of edges is a minimal section.

The minimum network cross-section is the smallest set of communication lines whose failure disrupts data exchange, dividing the network into two disconnected segments. The occurrence of such situations due to the influence of external and internal destabilizing factors that disrupt the normal functioning of the system may be due to system and hardware failures, the occurrence of interference of natural or artificial origin, software errors, management, etc. The search for the minimum cross-section of a graph can be carried out using the Stor-Wagner, Karger or Ford-Fulkerson algorithms. As already noted, it is customary to use graph theory for the formal description of wireless sensor networks.

Let the characteristics of the communication lines be equivalent $p(e_j) = p_j$, where $j = 1, \ldots, m$, p_j is a probability of having a working communication channel, i.e. edges e_j. In this case, the probability of failure of the communication channel e_j is equal to

$$q(e_j) = q_j = 1 - p(e_j) = 1 - p_j,$$

at $j = 1, \ldots, m$. Thus, the probability of network failure at equal values of the reliability of the communication line $(1 - p)$ is calculated by the formula

$$\bar{P}(G, \rho) = k_1(1 - \rho) + k_2(1 - \rho)^2 + \cdots +$$
$$+ k_{m-1}(1 - \rho)^{m-1}. \quad (12)$$

For a visual perception of the definition and explanation of the nature of the change in the probability of network failure, we will conduct a simulation. The simulation was conducted to determine the probability of network failure. The simulation results are presented in Fig. 2. The simulation demonstrates that as the reliability of working channels increases, the rate of decrease in network failure probability slows down.

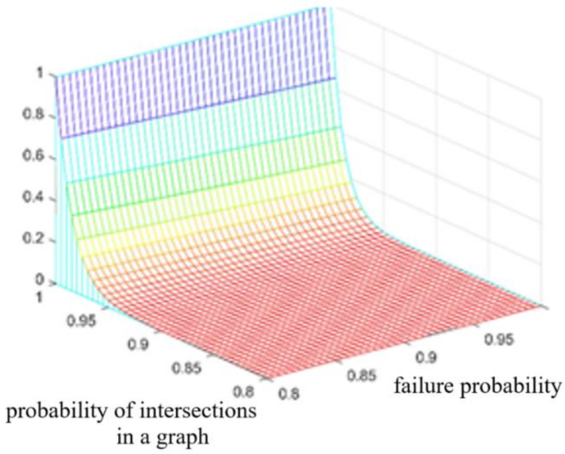

Fig. 2. Network failure probability graph

As can be seen from the graph shown in Fig. 2. the probability of failure the probability of network failure at equal values of the reliability of the communication line depends on the number of sections in the graph. With "ideal" reliability the probability of failure of the entire network is straight to zero. The obtained graphical simulation results correspond to the physical aspect of the network properties, which confirms the adequacy of the simulation.

The next step in the investigation is to determine the probability that the graph G will be connected. The probability will be calculated by the formula:

$$P(G, \rho) = 1 - k_1(1 - \rho) - \cdots -$$
$$- k_{m-1}(1 - \rho)^{m-1}, \quad (13)$$

where k_1 is a number of sections per edge, k_{m-1} is a number of sections along the $(m-1)$-th edge, $k_i(1 - p)^i$ is a probability of failure of all sections with dimension and edges.

Each term in formula (13) determines the probability of failure of a section with dimension u, i.e. failure of both communication channels, and the probability of failure of the network is defined as the sum of the probabilities of realization of the sections.

The first term of the series determines the probability of failure realized by sections consisting of one edge, the second term determines the probability of failure realized by sections consisting of two edges, etc. The first non-zero term determines the probability of failure realized by minimal sections.

Let us conduct a mathematical modeling of this process. The modeling results are shown graphically in Fig. 3.

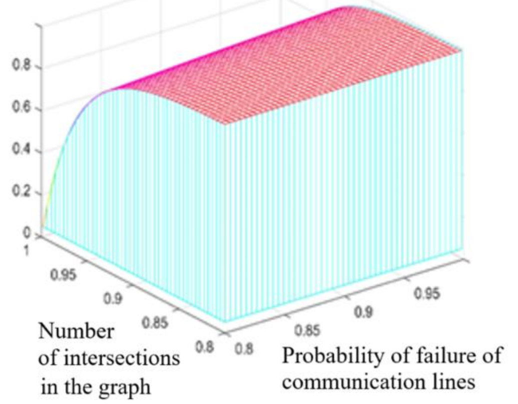

Fig. 3. Graph connectivity probability graph

The graph shows that increasing cross-sections significantly enhances the probability of graph connectivity, aligning with real-world observations and validating the simulation.

Despite the fact that in practice each communication channel has a different probability of failure, these probabilities are slightly ($\pm 10^{-3}$-10^{-4}) differ from each other. Since the probability of the communication channel being operational has a value close to unity, and the probability of failure is close to zero, then the relation holds

$$q^r >> q^{r+1}. \qquad (14)$$

The value of expression (13) is the first non-zero term $k_s(1-\mathrm{p})^s$ of the series, where k_s is a number of minimal intersections of a graph whose dimension is equal to s. Thus, to determine an approximate estimate of the functional stability of the network, while obtaining a small error, it is necessary to determine the complete set of minimal sections of the graph model of the system under study in accordance with its characteristics: if the edges of the graph are equally reliable, then the characteristic of the section is its dimension s, and for a loaded graph the section is characterized by the superposition of the weight of its edges - the weight dimension of the section. Thus, the indicator of the probability of connectivity of the graph model of the network, taking into account (14), will be determined by the formula

$$P(G,p) \approx 1 - k^s q^s. \quad (15)$$

Thus, to calculate an approximate estimate of the functional stability of the network, it is necessary to determine the complete set of minimal graph sections and their power (Fig. 4).

Formalized statement of the discrete optimization problem with Boolean variables. We need to find the optimal vector $X^* = (x_1^*, \dots, x_n^*)$, such that

$$F(X) = C \cdot X = \sum\nolimits_{j=1}^{n} c_j \cdot x_j \to \min, \;\; X \in \mathbb{R}^n,$$

$$x_j \in \{0,1\}, \qquad j = 1, \dots, n \qquad (16)$$

under restrictions $A \cdot X \le B$ and

$$\sum\nolimits_{j=1}^{n} a_{ij} \cdot x_j \le b_i, \;\; i = 1, \dots, m, \;\; j = 1, \dots, n, \;\; (17)$$

where X is a state vector of dimension n, consisting of Boolean variables; any variable x_j characterizes the presence of communication lines between the corresponding nodes; $F(X)$ is a quality functional that characterizes the main optimization indicator; $C = (c_1, \dots, c_n)$, $c_j > 0$ is a vector of constant coefficients of dimension n; $A = ||a_{ij}||$ is a rectangular matrix of dimensionality constraint coefficients $m \times n$; $B = (b_1, \dots, b_m)$ is the vector of the right-hand sides of the constraints. Partial l-solution $(1 \le l \pounds n - 1)$ of problems (16), (17) is any ordered set called $X' = \left(x_1', \dots, x_l'\right)$, consisting of fixed l variables.

Subsystem $(l+1)$-th order for partial l-solution $X' = (x_1', \dots, x_l')$ is called a system of linear inequalities in unfixed variables $x_{l+1}, \dots, x_m$, which is obtained by transformation from (17).

$$\sum\nolimits_{j=l+1}^{n} a_{ij} \cdot x_j \le b_i - \sum\nolimits_{j=1}^{l} a_{ij} \cdot x_j',$$

$$i = 1, \dots, m, \qquad x_j \in \{0,1\}. \qquad (18)$$

Before executing the algorithm for finding the optimal solution, an auxiliary matrix $Z = ||z_{ij}||$ with dimension is calculated $m \times n$.

$$z_{ij} = \sum\nolimits_{k \in I_{ij}^-} a_{ik}\,, \qquad i = 1, \dots, m, \qquad (19)$$

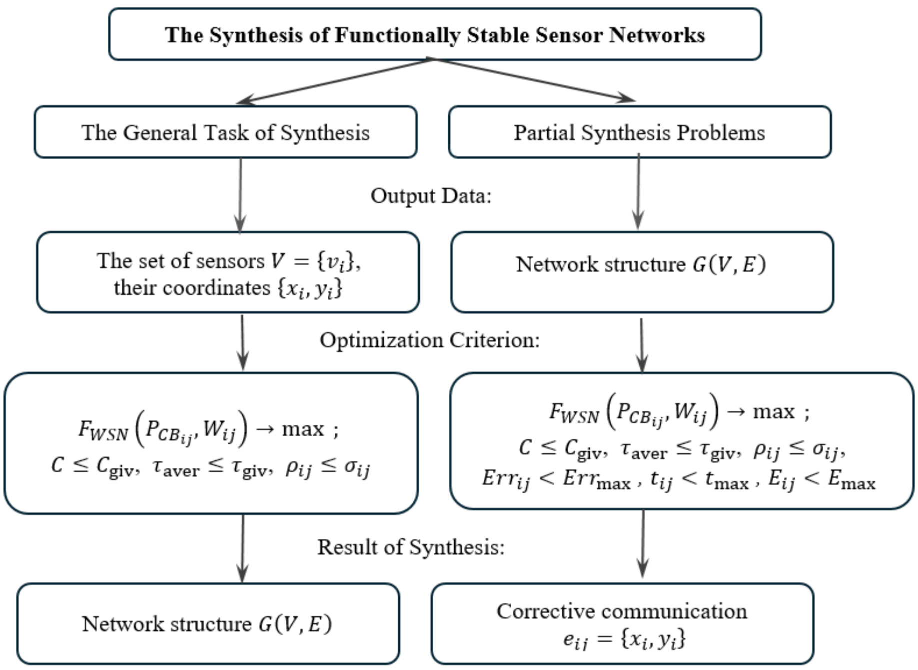

Fig. 4. Characterization of problems of synthesis of functionally stable wireless sensor networks

where I_{ij}^{-} is a subsets of indices of negative elements of matrix A satisfying the conditions:

$$I_{ij}^{-} = \{k\}/a_{ik} < 0,$$

$$k \in \{j, \dots, n\}, \qquad i = 1, \dots, m.$$

Description of the algorithm for finding the optimal structure of a wireless sensor network (Fig. 5).

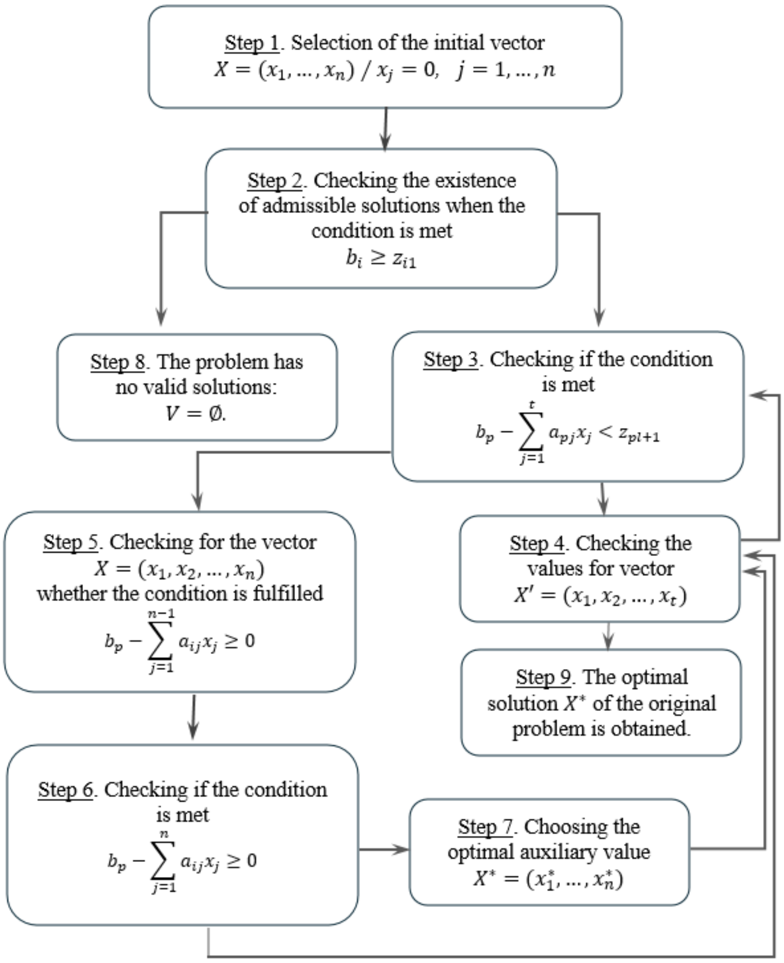

Fig. 5. Algorithm for finding the optimal structure of a wireless sensor network

<u>Step 1</u>. Select the lexicographically minimal zero vector:

$$X = (x_1, \ \dots, \ x_n)/x_j = 0, \quad j = 1, \dots, n,$$

which is taken as the basis for searching for the optimal solution. We assume $t := 1$.

<u>Step 2</u>. Checking for the presence of admissible solutions. If for all $i = 1, \dots, m$ the condition is satisfied $b_i \geq z_{i1}$.

Go to step 3. Otherwise, go to step 8.

<u>Step 3</u>. The vector under investigation $X = (x_1, x_2, \dots, x_n)$, in which everyone $x_j = 0$ at $j > t$. Changing l from t to $n-1$, we find $l' = \min\{l\}$, in which the subsystem $(l'+1)$-th order for partial l'-solution has no solution: if for at least one $p = 1, \dots, m$ the condition is met

$$b_p - \sum_{j=1}^{t} a_{pj} x_j < z_{pl+1}. \qquad (20)$$

The following actions are performed: relies $l' := 1$; $t := l'$; vector is truncated X to the length t: $X' = (x_1, x_2, \dots, x_t)$; it is concluded that X' does not satisfy the constraint (17) and all possible additions of it to the complete vector X also do not satisfy the constraint (20); go to step 4. If condition (20) is not satisfied for all $l = t, \dots, n-1$, it is concluded that the vector $X = (x_1, x_2, \dots, x_{n-1})$, can be included in the set V and the transition to step 5 is performed.

<u>Step 4</u>. If all $x_j = 1$ in the vector under study $X' = (x_1, x_2, \dots, x_t)$ then go to step 9.

Otherwise, a new lexicographic value of the vector X'' is determined for the vector $X' = (x'_1, x'_2, \ \dots, x'_t)$.

If $x'_t = 0$, then we put $x''_t := 1$. If $x'_t = 1$, then we calculate $k = \max\{j\}/j \in \{1, \dots, t\}$, $x'_j = 0$ (that k is an index of the rightmost zero in the vector X').

We assume $x''_k := 1$; $x''_j := 0$ for $j = k+1, \dots, t$; $t := k \dots$. After obtaining a new lexicographic meaning X'', we pad it with zeros to the length $n-1$ and we obtain the vector under investigation X. Go to step 3.

<u>Step 5</u>. Checking the membership of the studied vector $X = (x_1, x_2, \dots, x_{n-1})$, with addition $x_n = 0$ of the set of feasible solutions V: if for all $i = 1, \dots, m$ the condition is met

$$b_i - \sum_{j=1}^{n-1} a_{ij} x_j \geq 0. \qquad (21)$$

A conclusion is drawn as to which solution is being investigated $X = (x_1, x_2, \dots, x_{n-1}) \in V$ and proceed to step 7. If condition (20) is not satisfied for at least one $i = 1, \dots, m$, then proceed to step 6.

<u>Step 6</u>. Checking the membership of the studied vector $X = (x_1, x_2, \dots, x_{n-1})$ with addition $x_n = 1$ of the set of feasible solutions V: we accept $x_n := 1$; if for all $i = 1, \dots, m$ the condition is satisfied

$$b_i - \sum_{j=1}^{n} a_{ij} x_j \geq 0. \qquad (22)$$

A conclusion is drawn as to which solution is being investigated $X = (x_1, x_2, \dots, x_{n-1}, 1) \in V$ and proceed to step 7. If condition (20) is not satisfied for at least one $i = 1, \dots, m$, we accept $t := n-1$ and go to step 4.

<u>Step 7</u>. Upon receipt of an acceptable solution $X^* = (x_1^*, \dots, x_n^*)$ we remember it as optimal. If the admissible solution X^* is obtained for the first time, an additional constraint is introduced into the system of constraints (22)

$$\sum_{j=1}^{n} c_{ij} x_j \leq b_{m+1}. \qquad (23)$$

where $$b_{m+1} = \sum_{j=1}^{n} c_{ij} x_j^* - \delta,$$

δ as a minimal increase in the functional when changing the vector X in one digit

$$\delta = \min\{|c_i - c_j|\} \text{ для } i, j = 1, \dots, n; \ i \neq j.$$

The constraint coefficient matrix A is adjusted: $(m+1)$ rows are added $a_{m+1,j} := c_j$, $j = 1, \dots, n$.

The matrix Z is adjusted: $(m+1)$ rows are added

$$z_{m+1,j} := 0, \qquad j = 1, \dots, n.$$

We increase the value of m by one: $m := m + 1$.

If a repeated admissible solution X^* is obtained, then the right-hand side of constraint (23) is corrected and replaced by the value

$$b_m = \sum_{j=1}^{n} c_{ij} x_j^*.$$

This allows us to exclude solutions that belong to the set V and do not belong to the set of optimal solutions. We assign $t := n - 1$ and go to step 4.

Step 8. The problem has no feasible solutions – a set $V = \emptyset$. The algorithm stops working, the problem has no solutions.

Step 9. The algorithm is finished. The optimal solution X^* of the original problem is the last.

The proposed algorithm Fig. 5 can be used to synthesize the structure of wireless sensor networks that have the ability to self-organize, in order to find its optimal structure. According to the given algorithm, a simulation of the search for an optimal solution was carried out. The analysis showed that the proposed algorithm has a fairly high level of convergence, as well as a finite number of iterations, which in turn depends on and determines the total time of its execution, respectively, on the number of constraints, relative to the functioning of the system being analyzed.

Conclusions

This study redefined total and total edge connectivity to address challenges in sensor network synthesis. The task of determining the criteria for total connectivity was solved. The need to determine a lower bound for k for a given vertex and edge connectivity was justified, which allows checking the fulfillment of the total connectivity condition for the studied structure. Two algorithms were developed: one for determining the lower bound of removed vertices and another incorporating redundant communication lines The study of functional stability highlighted the necessity of identifying the complete set of minimal graph sections and their weights. Taking into account the considered limitations and assumptions, an algorithm for finding the optimal structure of a wireless sensor network has been developed, which consists of nine steps and can be used to synthesize the structure of wireless sensor networks that have the ability to self-organize, in order to find its optimal structure.

The analysis demonstrated that the proposed algorithm achieves a high level of convergence with a finite number of iterations. Its execution time is directly influenced by the number of constraints and the system's complexity, relative to the functioning of the system being analyzed. Compared to exhaustive search, this algorithm is particularly effective for problem dimensions exceeding n>20. The results of solving the test problems completely coincide with the results of the exhaustive search solution, which confirms the reliability of obtaining new results. The presented algorithms allow us to determine the overall indicator of the functional stability of the system under study. The findings can be applied to information systems for production process control and information security, particularly in wireless topologies subject to external and internal destabilizing factors of a pulsed nature. The proposed algorithm ensures system controllability by monitoring its state and restoring functionality within an optimal operational perimeter.

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Алгоритми синтезу функціонально стійкої бездротової сенсорної мережі

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Анотація. Мета дослідження. Розробка алгоритмів, які у дозволяють реалізувати синтез функціонально стійкої бездротової сенсорної мережі. **Предмет дослідження.** Бездротові сенсорні мережі, алгоритми синтезу функціонально стійкої мережі. **Метод дослідження.** Алгоритмічний і чисельний аналіз процедур виконання синтезу функціонально стійких сенсорних мереж. **Результати дослідження.** Забезпечення властивості функціональної стійкості бездротової сенсорної мережі забезпечує вирішення проблеми впливу дестабілізуючих факторів, таких як: програмні та апаратні збої, помилки, випадкові або навмисні пошкодження окремих структурних елементів, їх сукупності, каналів зв'язку між ними, кібератак, відмов в обслуговувані тощо. Дослідження існуючих науково-обгрунтованих підходів забезпечення функціональної стійкості бездротових сенсорних мереж та її компонентів свідчить, що не існує єдиного загального підходу до визначення функціональної стійкості бездротової сенсорної мережі. Тому робота присвячена вирішенню актуального наукового завдання розробки алгоритму пошуку оптимальної структури бездротової сенсорної мережі. Розроблено алгоритм знаходження нижньої оцінки числа видалених вершин та алгоритм знаходження нижньої оцінки числа видалених вершин з урахуванням надлишкових ліній зв'язку. Встановлено, що насамперед необхідно визначити повну сукупність мінімальних перерізів графа і їх потужності. Розроблено алгоритм пошуку оптимальної структури бездротової сенсорної мережі, який складається з дев'яти кроків та може бути застосований для синтезу структури бездротових сенсорних мереж, які мають здатність до самоорганізації, з метою пошуку її оптимальної структури. Показано, що запропонований алгоритм має високий рівень збіжності та за скінченне число ітерацій забезпечує потрібний результат, що значно краще скінченного перебору. Розроблений алгоритм є ефективним при розмірності задачі $n > 20$. Результати рішення тестових задач цілком підтверджує ефективність алгоритму у порівнянні з результатами розв'язку повним перебором, що й підтверджує важливість отриманих результатів. Даний результат можна застосовувати і інформаційних систем управління виробничими процесами та систем інформаційної безпеки що мають бездротову топологію та які перебувають під дією зовнішніх та внутрішніх дестабілізуючих факторів імпульсної природи. Власне запропонований алгоритм реалізує умови керованості у такій системі через моніторинг стану системи та механізми відновлення функціонування в її оптимальному периметрі. **Висновок.** Результати представленого дослідження дозволили адаптувати визначення тотальної та тотальної реберної зв'язності для завдань синтезу сенсорних мереж. Представлені у роботі результати можна застосовувати і інформаційних систем управління виробничими процесами та систем інформаційної безпеки що мають бездротову топологію та які перебувають під дією зовнішніх та внутрішніх дестабілізуючих факторів імпульсної природи. Запропонований у роботі алгоритм реалізує умови керованості у такій системі через моніторинг стану системи та механізми відновлення функціонування в її оптимальному периметрі.

Ключові слова: функціональна стійкість; алгоритм; бездротова мережа; сенсорна мережа; збіжність; синтез структури.