Conceptual Model for Ensuring Functional Stability of Wireless Networks*

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Abstract

The article addresses the issue of ensuring the reliability and functional stability of wireless sensor networks under destabilizing factors and enemy countermeasures. The research focuses on developing a methodological approach for creating reliable wireless sensor networks that use audio wave propagation of signals in the air and soil. The study analyzes the key physical aspects of sound waves propagation in various environments and their impact on the performance of sensor networks. Key parameters affecting system functionality are identified, including temperature conditions, air humidity, soil density and composition, elasticity of materials, and more. Existing technologies, such as SOSUS, seismographs and sonars, that use the principles of audio wave propagation are examined. The study explores the optimization problem of designing the structure of wireless sensor networks while considering a range of constraints: probability of connectivity between sensors, communication line lengths, message delay time, bit error rate, data routing setup time, and network node energy consumption. A comprehensive approach is proposed to ensure functional stability by integrating a pseudo-satellite radionavigation system with the wireless sensor network. This integration enhances protection against disruptions and interference and increases the overall reliability of the system. A general model of wireless sensor network operation has been developed, including description of the system's resource set, informational functions and services, structural and parametric system descriptions, and service delivery technology. Particular attention is paid to the relationships between the sets of services and system resources. The results obtained can be used in the design and optimization of wireless sensor networks to ensure their stable operation under active influence from both external and internal destabilizing factors. The proposed approach allows to significantly improve the reliability and functional stability of wireless sensor networks, which is especially important for applications in the military industry and critical civilian systems.

Keywords

Wireless sensor networks, functional stability, reliability, audio wave propagation, structure optimization, pseudo-satellite systems, electronic countermeasures

1. Introduction

The rapid development of wireless sensor networks is one of the trending directions in modern information technology [1,2]. In the early stages, the prototype of modern wireless sensor networks (WSNs) can be considered to be distributed military-technical systems, the development of which was actively carried out at the end of the last century. It is known that sound propagates in the air through the periodic change of density of air molecules. When an object emits sound, it creates zones of increased and decreased pressure, which move in the form of waves. The propagation of sound is affected by: temperature, where higher temperature increases molecular motion and thus the speed of sound (at 20°C, the speed of sound is about 343 m/s); humidity, moist air transmits sound better,

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since water molecules are lighter than nitrogen and oxygen molecules; attenuation, sound waves in the air gradually fade due to friction between molecules (especially at high frequencies).

In the ground, sound propagates in the form of seismic waves, which are the result of soil vibrations. These waves can be both longitudinal (P-waves) and transverse (S-waves). The propagation is affected by the density and composition of the soil - denser materials such as granite transmit sound faster than loose rocks - and elasticity, with more elastic materials (for example, stone) transmit sound better. Notably, sound in the ground attenuates more slowly than in the air, due to lower friction between particles. These physical properties are actively exploited in various technologies, such as SOSUS, seismographs, and sonars. The SOund SUrveillance System (SOSUS), for example, constitutes a global acoustic surveillance network system designed to detect and identify submarines, i.e. it used water as a medium for the propagation of audio waves, it collected and transmitted data via dedicated radio communication channels for subsequent processing. Nevertheless, a persistent challenge lies in ensuring the properties of functional stability and electronic countermeasure resistance of a complex autonomous navigation system in the format of GPS signals and sensor monitoring along the line of contact in active combat conditions.

At the core of this issue is a fundamental contradiction in the requirements for building a functionally stable system, for example, between the requirement to reduce the enemy's impact on the system elements, which can be achieved by increasing the distance to the line of combat contact, and the need to provide the end-users with navigation and reconnaissance information in the area of combat operations. Furthermore, there also exists a discrepancy between the existing scientific and methodological frameworks and the conditions of specific operational scenarios, which requires the development of new models and methods. A partial solution to this problem is the integrated deployment of a pseudo-satellite radionavigation system in conjunction with a wireless sensor network, both of which are designed to be resistant to jamming and interference.

2. Purpose of the study

The aim of this research is to develop a concept for functionally stable wireless sensor networks [1], capable of operating under the influence of destabilizing factors that affect signal propagation within the network. This scientific task remains only partially resolved, both at the hardware and software levels. One of the key aspects of solving this scientific task is ensuring the functional stability of wireless sensor networks, which simultaneously guarantees their reliability in the intended context. From a technological standpoint, it is proposed to implement a comprehensive integrated concept involving the joint operation of a pseudo-satellite radionavigation system and a wireless sensor network, both of which are protected against the impact of external and internal destabilizing factors.

3. Overview of results and sources

Numerous studies have been devoted to the investigations of the features of the functioning of complex technical systems under the influence of destabilizing factors. In particular, a systematic analysis of approaches to ensuring the functional stability of information systems within critical infrastructure, as well as methods for designing energy-efficient sensor networks using both static and dynamic sensors are presented in [3,4]. The assessment of functional stability in hierarchical automated control systems and the development of control strategies for automated manufacturing centers to maintain the functional stability of enterprise information systems have been examined in [5-7]. These works have also established the conditions for the practical stability of differential inclusions using Lyapunov functions, as well as for the practical stability of discrete inclusions with spatial components.

Considerable research interest has been directed toward studying the characteristics of signal generation and transmission across networks of various types. In [10], the authors proposed a method for detecting radio signals by estimating the parameters of signals exhibiting inverse Gaussian propagation. Signal processing involving frequency and phase manipulation in telecommunications has been examined in [11]. In [12], a spectral analysis method for identifying random digital signals was developed. A method for testing vulnerabilities in corporate networks using Bernstein transforms, approaches to self-testing and self-diagnosis of modular systems based on the principle of a walking diagnostic kernel, and an algorithm for recognizing network traffic anomalies based on artificial intelligence are presented in [13-15]. In [16], effects that are characteristic of models of the phenomenon of self-excitation of drill string oscillations that can affect wave propagation are studied in detail. Analytical evaluations of the security level in distributed and scalable computer systems and signal smoothing methods in the development of navigation systems are described in [17,18].

An important aspect involves tools that ensure access to networks for a trusted circle of users. Studies [19,20] examine the features of biometric authentication using convolutional neural networks. Studies [21 - 24] are devoted to the development and description of approaches involving modified McEliece and Niederreiter cryptographic coding systems to enhance security, including multi-level authentication and hybrid security systems.

Security models for socio-cyber-physical systems, adaptive resource allocation methods for data processing and security in cloud environments, and information protection techniques within the cyber-physical space have been explored in [25-27]. An intrusion detection model based on an enhanced transformer architecture is described in [28].

At the same time, the existing research lacks a unified conceptual approach to the modeling and formal analytical description of functionally stable wireless sensor networks. Therefore, the following section introduces the authors' approach to the formalization of this problem.

4. Conceptual approaches to the modeling of functionally stable WSNs

The concept of reliability is defined in national standard DSTU 2860-94 as the ability of an object to maintain its capacity to perform the required functions within a specified time interval under the given system parameters. The reliability property should be considered in relation to the intended purpose of the system and its operating conditions.

Reliability is one of the key expected characteristics of modern network technologies. A reliable system is less prone to failures, which in turn enhances its resistance to external disturbances.

Functional stability refers to the property of complex technical systems that enables them to continue performing their core functions (potentially at reduced quality levels) under the influence of internal or external destabilizing factors. It guarantees the system's ability to maintain operational capability even in the presence of partial network component failures.. Functional stability demands that the network be adaptive: able to reallocate tasks and redistribute loads among remaining operational components to recover performance despite the loss of some original capabilities.

Thus, functional stability ensures uninterrupted operation and timely response to crisis conditions, while reliability is more closely associated with preventative design measures. Therefore, reliability is a necessary but not sufficient condition for achieving functional stability. For systems to perform effectively under uncertainty and stress, functional stability must be an integral design objective.

4.1. Criterion for functional stability of WSNs

Then, having reviewed the key requirements and criteria of functional stability as they directly pertain to wireless sensor networks and account for all the specific features of their operation, we can formulate the problem of WSN structural synthesis as follows:

$$F_{WSN} = f(P_{ij}) \rightarrow \max, \quad i,j = 1,\dots,N, \quad i \neq j; \tag{1}$$

$$C = \sum_i \sum_j C_{ij}(d_{ij}, p_{ij}, h_{ij}) \leq C_+; \tag{2}$$

$$\forall \pi_{ij} P_{ij} \geq P_{\min}; \tag{3}$$

$$\varphi_{ij} \leq p_{ij}; \tag{4}$$

$$\tau_{aver.vel} \leq T_{\max}; \tag{5}$$

$$Err_{ij} < Err_{\max}; \tag{6}$$

$$t_{ij} < t_{\max}; \tag{7}$$

$$E_{ij} < E_{\max}, \tag{8}$$

where N is the number of sensors in the network;

- F_{WSN} is the quality functional, an objective function to be maximized;
- P_{ij} is the probability of connectivity between a pair (i,j) of network sensors;
- d_{ij} is the link distance between sensors (i,j);
- $\tau_{aver.vel}$ is the average message delay between sensors.
- Err_{ij} is the bit error rate between sensors (i,j);
- t_{ij} is the time for establishing a new data transmission route between sensors (i,j);
- E_{ij} is the energy consumption of a link between sensors (i,j).

Expression (1) defines the optimization criterion for the system under study. Actually, when the functional reaches its maximum in practice, this means that the probability of connectivity P_{ij} across the network components is at its highest, meaning that the network has not effectively lost any of its components, can perform its tasks as intended and, therefore, is functionally stable.

Expressions (2) - (8) impose constraints on network parameters for solving the optimization problem. Constraint (2) means that the total costs for the sensor network, taking into account link lengths, bandwidth and transmitted data volume, must not exceed allowable thresholds.

Condition (3) defines the connectivity probability value P_{ij} for all routes in the network. Condition (4) limits the volume of information flow φ_{ij} transmitted through each communication channel with a given bandwidth p_{ij}.

Condition (5) determines the average message delay time $\tau_{aver.vel}$ within the network. Condition (6) determines the acceptable value of the bit error rate Err_{ij} during data transmission between a given pair of vertices, which does not exceed the specified threshold value Err_{max} .

Condition (7) determines the time for establishing a new data transmission route t_{ij} between a given pair of sensors. Condition (8) means the maximum permissible value of energy consumption E_{ij} by a node during the complete cycle of data receiving and transmitting, which must not exceed the threshold of autonomous power usage E_{max} .

Thus, solving the formulated optimization problem yields the optimal structure of a sensor network consisting of N sensors, which satisfies the optimization criterion (1) and constraints (2)–(8). This structure is represented by the adjacency matrix of the graph describing the network topology.

4.2. Comprehensive model of WSN functioning

The system for ensuring functional stability should be created at the design stage of the WSN and must take into account the peculiarities of its architecture and operation under destabilizing external and internal factors. This requirement necessitate the development of a comprehensive model of WSN functioning.

Such a model can be presented in general terms as:

$$G = \langle I, \mu \rangle, \quad (9)$$

where I is the wireless sensor network model; μ is the model of destabilizing factors.

The WSN model can be represented as

$$I = \langle \mathcal{R}, \mathcal{U}, \delta, \eta \rangle, \quad (10)$$

where $\mathcal{R}$ is the set of system resources, , understood as the combination of hardware and software components, auxiliary equipment, system services, and management services; $\mathcal{U}$ is the set of information functions and services provided by the system; δ is the structural-parametric description of the system, which includes the characteristics of resources, their territorial location and methods of interaction; η is the description of the service delivery technology, encompassing user request processing, identification of required resources, and the order of their utilization.

The set $\mathcal{R}$ of WSN resources includes the collection of software and hardware (including auxiliary equipment), system services and management services used to deliver specified information services to end users. The set of resources $\mathcal{R}$ can be represented as: $\mathcal{R} = \{r_1, r_2, \dots, r_n\}$, where r_i denotes a specific resource (hardware, software or other).

The set U of information services refers to the collection of system operations executed in response to a set of user requests for access to the resources of the information system. The structural-parametric description of the system δ includes a description of the computer system topology, resource parameter specifications, their territorial location and methods of interaction between the resources. The set of services $\mathcal{U}$ can be represented as: $\mathcal{U} = \{u_1, u_2, \dots, u_m\}$ where u_j is a specific information service.

The structural-parametric description of the system δ defines a system of relations on the set $\mathcal{R}$ of WSN resources. This can be represented as a graph or an adjacency matrix: $\delta: \mathcal{R} \times \mathcal{R} \to \{0,1\}$ where $\delta(p_i, p_j) = 1$, if resources p_i and p_j interact, otherwise $\delta(p_i, p_j) = 0$.

The description of the information service delivery technology η includes the structure, content and characteristics of user request flows for information access, as well as technological chains used to process these requests, including procedures for request identification, resource selection for service execution, and the rules for resource utilization. This can be formalized as a function that determines what resources are needed for each type of service: $\eta: \mathcal{U} \rightarrow 2\mathcal{R}$ where $\eta(u_j) \subseteq \mathcal{R}$ is the set of resources that are needed to provide service u_j.

The relationship between the sets of services $\mathcal{U}$ and the set of system resources $\mathcal{R}$, respectively, is defined by the mapping η for the particular information system under study. The dependency between the set of services $\mathcal{U}$ and the set of resources $\mathcal{R}$: for each type of service $u_j \in \mathcal{U}$ there is a certain set of resources $\eta(u_j)$ that are needed for its implementation. This can be written as: $\forall u_j \in \mathcal{U}, \exists \eta(u_j) \subseteq \mathcal{R}$.

The availability of system resources can be described by the function $\mathcal{A}: \mathcal{R} \rightarrow \{0,1\}$, where: $\mathcal{A}(p_i) = 1$ if resource p_i is available, $\mathcal{A}(p_i) = 0$ if resource p_i is not available.

For each user request q, there exists a specific service u_j that the system must provide. This can be described as the function: $f: \mathcal{Q} \rightarrow \mathcal{U}$, where $\mathcal{Q}$ is the set of user requests and $f(q)$ is the service that corresponds to the request q.

While processing a request q, the system uses certain set of resources. This can be described by a complex function that combines f and η: $g: \mathcal{Q} \rightarrow 2\mathcal{R}$, $g(q) = \eta(f(q))$, where $g(q)$ is the set of resources that are needed to process the request q.

For optimal resource utilization, an objective function can be introduced, which either minimizes the total resource consumption or maximizes the system performance: Objective function: $\mathcal{Z}(\mathcal{R}, \mathcal{U}, \delta, \eta) \rightarrow \mathcal{R}$. For example, minimizing the request processing time or minimizing the number of resources used.

Thus, the mathematical model of the WSN describes the interaction between resources, services, system structure, and service provision technology. The key components of the model are the sets $\mathcal{R}$ and $\mathcal{U}$, the functions δ and η, as well as the functions that define the availability of resources and service requests processing.

By specifying various parameters of the components, the mathematical model makes it possible to obtain the optimal structure of an integrated sensor network. The model supports integration across resources, services, system structure and service delivery technology. For example, Fig. 1 shows a bipartite graph of resources and services for 15 sensors.

The given Fig.1. reflects the relationship between physical resources and system functions. Two groups of nodes are depicted.

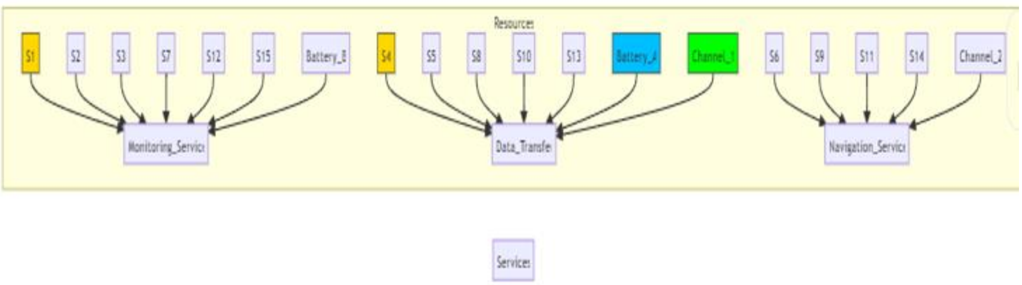

Figure 1: Bigraph of resources and services

The first left group (resources):

- sensors (S1, S2, S3 ...);
- energy (Battery_A, Battery_B ...);
- communication channels (Channel_1, Channel_2 ...).

The second, right group (services):

- monitoring (Monitoring_Service).
- data transfer (Data_Transfer).
- navigation (Navigation_Service).

Edges connect resources with services (for example, S1 → Monitoring_Service, Battery_A → Data_Transfer).

A comparative table of existing and proposed wireless sensor networks is given in Table. 1

Table 1
Comparison table of existing and proposed wireless sensor networks

Metrics	Traditional WSN	Integrated system
Scalability	Adding new sensors requires separate resources	Ability to add sensors without increasing the number of batteries / channels
Energy consum-ption	High due to duplication of resources	Optimized (shared batteries, adaptive control)
Complexity	Easy setup, but limited flexibility	Complex integration, but high adaptability

As can be seen from the data presented in the table, the proposed mathematical apparatus for ensuring the reliability of wireless sensor networks makes it possible to construct a reliable network while achieving advantages over existing solutions in terms of adaptability, the ability to add sensors without increasing the number of batteries, and optimizing energy consumption, which is very relevant in modern conditions.

5. Conclusion

The study addresses a highly relevant scientific and applied problem: ensuring the functional stability of wireless sensor networks (WSNs) under challenging operational conditions, including destabilizing environmental factors and active adversarial interference. A comprehensive approach is proposed, based on the integration of audio-wave signal propagation technologies through air and soil with pseudo-satellite radionavigation systems. This methodology enhances the network's resilience to external impacts and ensures the reliable operation of critical systems in real-time.

An analysis of the physical aspects of acoustic wave propagation in various media revealed its dependence on temperature, humidity, soil density, and material elasticity. These parameters significantly affect signal transmission quality in WSNs, particularly under external interference. Compared to traditional radio-wave technologies, acoustic wave propagation offers higher resistance to electromagnetic disturbances, making it a promising solution for both military applications and civil critical infrastructure systems.

Special attention is given to the formalization of the optimization problem for WSN structure design, which takes into account a set of parameters: node connectivity probability, communication channel length, message latency, bit error rate, energy consumption, and route recovery speed. The introduction of an objective function aimed at maximizing functional stability allows for the synthesis of an optimal network topology that balances operational efficiency with economic feasibility. The outcome of solving this optimization problem is an adjacency matrix of the network graph, which defines the optimal sensor placement and their interconnections.

The key achievement of the research is the development of a comprehensive WSN operational model that considers interactions among resource sets, information services, and destabilizing factors. The model encompasses a structural-parametric system description, service delivery technologies, and adaptation mechanisms to changes in the external environment. Central role in this model is played by the integration of a pseudo-satellite navigation system, which provides an alternative data transmission channel in the event of failure of primary network components. This significantly enhances redundancy and the system's self-recovery capability, which is critical for deployments in combat zones or areas affected by natural disasters.

The proposed approach demonstrates advantages over existing SOSUS technologies, seismographs and sonars, which are limited by specific conditions of use. It provides flexibility in designing networks adapted to different wave propagation environments, as well as integration with modern electronic warfare systems. Moreover, the focus on energy efficiency extends the autonomous operational lifespan of the sensors, which is particularly important for military and industrial applications.

Thus, the obtained results offer substantial practical potential for building reliable WSNs capable of operating under extreme conditions. Future research should focus on experimental validation of the proposed models, optimization of routing algorithms, and the development of hardware and software tools for implementing this approach. This will contribute not only to solving the scientific challenge of ensuring functional stability but also to the creation of next-generation wireless sensor networks for both strategic defense applications and the civil sector.

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Declaration on Generative AI

The authors have not employed any Generative AI tools.

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