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Fuzzy models of wireless components sensor networks

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ABSTRACT

The article addresses the problem of modeling wireless sensor network components operating under uncertainty and the influence of external factors. The relevance of the research stems from the growing need for reliable and autonomous monitoring and control systems in industrial environments, especially under conditions where wired communication is not feasible or consistent. Classical models with strictly defined input parameters fail to adequately reflect the dynamics and unpredictability of sensor node behavior and communication links, which limits the accuracy of performance assessment and complicates the design of robust systems. The aim of this study is to develop a formalized approach for describing wireless sensor network behavior under uncertainty using fuzzy logic and semantic representation. The proposed solution is based on a generalized modeling framework that utilizes the theory of fuzzy sets and supports both crisp and fuzzy input/output variables. Two universal formulations are introduced: one that models relationships solely between fuzzy variables, and another that links crisp parameters with fuzzy outputs. These models serve as a flexible basis for representing typical processes in wireless sensor networks, where parameters are often only partially known, qualitatively estimated, or described in linguistic terms. Variables are mapped into an orthogonal semantic space, allowing the use of membership functions for further reasoning and integration into ontological structures. Although detailed structural models of sensor nodes and communication channels are not included in this version and will be presented in a separate follow-up study, the current work lays the methodological groundwork for their development. The scientific novelty lies in the creation of a unified fuzzy modeling framework that supports both abstract and data-driven representations of uncertainty in wireless sensor networks. The practical significance is seen in the applicability of the proposed approach to designing adaptive, context-aware sensor networks capable of operating reliably in challenging and resource-constrained environments. The introduced models provide enhanced flexibility, semantic interpretability, and accuracy in representing real-world operational conditions.

Keywords: Wireless sensor networks; fuzzy models; sensor node; communication channel; linguistic variables; orthogonal semantic space; reliability; fault tolerance; fuzzy logic; industrial systems

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INTRODUCTION

Dispatching control and data acquisition systems are part of industrial control systems. They provide control over processes in various industrial sectors, as well as in sectors that constitute critical national infrastructure. The list of such sectors may vary depending on the country, but usually includes those infrastructure facilities that are vital to ensuring the continuity and integrity of basic services used by the state. Partial or complete loss of control in at least one of these sectors can have serious economic or social consequences, and sometimes even lead to the loss of life. Such sectors usually include energy, food, water supply, transport, communications, emergency services, healthcare, the financial sector, government and others.

These systems require uninterrupted and reliable operation, for which it is necessary to receive data from working nodes. Data transmission is usually carried out through existing wired physical networks. However, during emergency situations this can be difficult or even impossible. One way to solve this problem is to organize data collection in such a way that even if physical communication with the object is interrupted or impossible, the data still reaches the desired nodes. These are networks of devices that collect data about the environment and the state of the devices, and also transmit this information to base stations using wireless communication channels.

The main features of sensor networks are:

– lack of wired communication channels;

– information transmission over long distances;

– ease of installation and maintenance;

– low cost of components (installation, operation and maintenance);

– low energy consumption.

These characteristics make WSN indispensable for monitoring and data collection in critical infrastructure facilities, which must operate both in normal and emergency situations. They allow you to receive timely information about the state of these facilities and make operational decisions in case of problems. That is why when designing monitoring and management systems for critical infrastructure facilities, WSN synthesis tasks play an important role.

However, despite the significant advantages of wireless sensor networks, their implementation in critical systems is accompanied by a number of challenges, in particular, related to limited reliability of nodes, instability of communication channels and the influence of external factors that are difficult to predict and formalize in the form of precise numerical parameters. In real operating conditions of such systems, the parameters may be known only partially or described linguistically, for example: “low signal level”, “average load”, “high probability of data loss”. This complicates the process of designing, analyzing and managing sensor networks using traditional methods.

At the same time, existing approaches to the modeling and analysis of wireless sensor networks often rely on deterministic or probabilistic methods that assume the availability of complete and accurate data about network parameters and states. Such assumptions are rarely met in practice, especially under emergency conditions where sensor readings may be delayed, partially lost, or distorted. Moreover, most traditional models lack the means to incorporate linguistic evaluations and qualitative expert knowledge, which are often available and valuable in the domain of industrial control and monitoring. This creates a methodological gap and highlights the need for alternative modeling approaches that are better suited to conditions of uncertainty and incomplete information.

In view of this, there is a need to use fuzzy models that allow working with imprecise, partially known or qualitative variables. The use of such an approach provides flexibility, adaptability and increased compliance with the conditions of the real environment. Further in the article, methods for constructing fuzzy models of the main components of the WSN – the sensor node and the communication channel – are considered, which allow formalizing and evaluating their performance and data transmission efficiency under conditions of uncertainty.

LITERATURE REVIEW

In works devoted to the design of wireless sensor networks (WSNs), various methods of their construction and various methods of processing information received from network sensors have been proposed.

The study [1] proposes a combined approach to improving energy efficiency in WSN by integrating energy/time splitting methods (SWIPT) with fuzzy logic. The main idea is to use an adaptive clustering mechanism based on two consecutive FLC blocks that take into account node density, distance to the receiver, and residual energy. The uniqueness of the approach lies in dividing packets into information and energy, with subsequent coordinated adjustment of modulation coefficients and power distribution to minimize losses. The efficiency assessment covers classical metrics: network lifetime, throughput, energy consumption, execution time, packet loss/delivery, and encryption/decryption time. The results demonstrate the stable dominance of the proposed FLEE-SWIPT model over others (LEACH, DRR-LEACH, FLCMN, etc.). Value for the article – the source is relevant to the subtopics of energy efficiency, the use of fuzzy systems for decision-making, and can be used in the network structure modeling module or for energy scenario evaluation. Its example of fuzzy rules can be adapted to formalize the energy characteristics of nodes within a multi-level model. Limitations – does not cover security or risk assessment aspects, does not use a semantic or ontological model, but its methodology is well aligned with the fuzzy modeling approaches used in the study. The article [2] considers the use of fuzzy logic in combination with next-generation wireless sensor networks to optimize the operation of HVAC systems in small industrial enterprises. The authors propose a fuzzy control model that allows reducing the energy consumption of air conditioning systems by 30% compared to traditional systems. The main attention is paid to the development of intelligent fuzzy control rules that take into account the variability of temperature and humidity in critical areas of industrial premises. The model is implemented in MATLAB and includes stages of calibration of data from five wireless sensors, which allowed increasing the accuracy of control. The work confirms the feasibility of using fuzzy rules for dynamic control of HVAC systems and demonstrates the improvement of efficiency using the example of scenarios with different energy consumption. The article [3] proposes a fuzzy logic-based protocol for cluster head election in WSNs, incorporating zone division and fuzzy rules to evaluate node efficiency. It also introduces multipath routing for load balancing. Simulations show better energy use and packet delivery. Useful for the research topic – the work contains an example of effective application of fuzzy logic in WSN for decision-making, which is relevant to fuzzy models of sensor components in the target article. Limitations – focus on clustering and routing algorithms, while the model of components (sensors, batteries, etc.) is presented only contextually without formal detail. Article [4] presents a Type-2 Fuzzy Logic-based method for cluster head selection in WSNs, considering node energy, distance to base station, and density. The protocol builds on AOMDV with backup nodes for stability, outperforming LEACH and HEED in experiments. Value for the research topic – the article demonstrates the application of Type-2 Fuzzy Logic for selecting the head node and the optimal route, which is directly correlated with the topic of optimizing WSN elements in the context of fuzzy models. Limitations – the work lacks formalization of fuzzy rules and does not consider the modular structure of WSN components, which reduces the possibility of its integration into a multilevel system description model. The article [5] proposes a multi-criteria routing model for WSN that combines the particle swarm optimization method with fuzzy logic to optimize energy consumption, route reliability, and balanced load. The fuzzy system manages conflicting objectives through rules and membership functions, and particle swarm optimization adapts to network changes. Experiments in NS-3 have shown improvements in network lifetime, residual energy, and a 15-25 % reduction in load variation. A useful source for integration into WSN route optimization and energy management modules using fuzzy models. Limitations – the model does not detail the behavior of individual node components (sensor, processor, battery) and does not take into account their structural interaction. In paper [6] presents an improved UWF-RPL routing protocol for underwater wireless sensor networks that uses fuzzy logic to make path selection decisions. The optimization is based on depth, energy, RSSI to ETX ratio, and delay. The results show reduced latency, improved energy efficiency, and improved packet delivery in dynamic environments. A useful resource for studying the application of fuzzy logic in complex communication environments that can be adapted to models for terrestrial WSNs. Limitations – specificity to the underwater environment limits direct applicability in general WSN component models. The article [7] proposes a hybrid approach to building an intrusion detection system, which combines fuzzy logic, neural networks, and a genetic algorithm. Fuzzi fication is used to process fuzzy input data, an artificial neural network performs classification, and a genetic algorithm optimizes system parameters. This approach allows achieving high attack detection accuracy (up to 97 %) and reduces the level of false positives. A useful source for developing intelligent protection mechanisms in WSN using fuzzy models as part of the risk analysis module. Limitations – focused on the intrusion detection system and does not consider the models of sensor node components or their energy characteristics. Article [8] presents an AHP-M-TOPSIS-based method for optimal node placement in WSNs, considering coverage, connectivity, and energy feasibility. It reduces the number of dead nodes and improves residual energy compared to LEACH and other methods. A valuable source for the network description module – formalizes the procedure for assessing the effective node placement, taking into account energy and topological factors. Does not provide for risk-based assessment or semantic modeling, but can be integrated as part of the structural layer of the ontology. The article [9] proposes an adaptive method for managing the alternation of node activity in Sensor-Actor networks with energy harvesting (EH-SAN), based on fuzzy logic. The model takes into account environmental parameters, battery charge level and time of day to make decisions about node activity. The system provides a balance between network performance and sustainable energy consumption. The simulation results show improved node lifetime, reduced delays and increased energy efficiency. A valuable source for modeling the energy consumption of WSN components taking into account fuzzy control of node operation modes. Limitations - the model is focused on actor networks with energy harvesting, which may require adaptation for classic WSNs without EH components. The article [10] presents an energy-efficient approach to clustering in WSN based on the VIKOR multi-criteria trade-off ranking method. The main attention is paid to the selection of cluster heads taking into account seven conflicting criteria: cluster head coverage, node energy characteristics, connectivity with the sink node, distance to it, and distance to sensor nodes, residual energy and power. The proposed algorithm allows achieving a balance between these criteria and ensuring an optimal cluster structure with increased network lifetime. The source is useful for building a network description module – it describes formal rules for selecting cluster heads based on trade-off analysis. It does not contain a formalization of risks or ontological representation, but its structure can be adapted for the semantic layer of the WSN ontology. In [11], a new approach called Probabilistic Collaborative Event Detection (PCED) for WSN is proposed to improve the accuracy of event detection and reduce the number of false alarms. This system is aimed at environments where accurate and reliable event detection is critical. The PCED system uses a hybrid method that combines probabilistic models and fuzzy logic to process data collected from various sensors, such as temperature, gas, smoke, and light sensors. The data is aggregated through a network structure based on clustering, which improves the quality of information sent to the data center. The probabilistic approach helps to convert sensor readings into probabilistic values, which allows for more accurate and detailed event detection. The system was evaluated using the MATLAB simulation program, showing significant improvements in detection accuracy and reduction of false alarms compared to existing methods. The article [12] proposes a two-level clustering algorithm for selecting cluster heads (CH) in wireless sensor networks. The first level provides the formation of preliminary clusters based on distance and residual energy; the second level refines the cluster structure using neighborhood matrices. The goal is to reduce the overall energy consumption by optimally selecting CHs taking into account topology, range, and load balance. The simulation is performed using the energy consumption per round metric and is compared with LEACH. The results show an improvement in network lifetime and a reduction in CH load. A useful resource for a network description module – demonstrates efficient two-level clustering taking into account local topological and energy factors. Can be adapted to an ontological model to formalize the cluster structure and CH selection criteria.

The article [13] discusses methods for optimizing routing in WSN with an emphasis on balancing energy consumption, reducing delays, and improving throughput. The authors analyze classical approaches to routing and propose a hybrid strategy that takes into account the residual energy of nodes, placement density, and topological features of the network. The main focus is on increasing efficiency through adaptive route selection based on local information. A useful source for a data transmission optimization module in WSN that can complement fuzzy route selection models by taking into account energy criteria. Limitations – the lack of use of fuzzy logic or other intelligent methods limits the relevance to the topic of fuzzy component models. The article [14] proposes a model for energy-efficient data transmission management in a sensor network for precision agriculture based on software-defined networks (SDN). The architecture takes into account the characteristics of sensors, loads, data types, and energy parameters when making routing decisions. The authors have developed a special algorithm taking into account the priority of data and the residual energy of nodes, which allows optimizing energy consumption and ensuring high-quality transmission of important information (for example, soil or moisture parameters). A valuable source for expanding the network description module – demonstrates the integration of energy parameters into routing taking into account the type of data and application in agriculture. The approach can be adapted to industrial WSMs. Limitations – the model does not include semantic formalization or the use of ontology’s, but demonstrates the potential for integration with intelligent control and decision-making systems. The article [15] proposes a novel algorithm NDGAI (Novel Data Gathering Algorithm using Artificial Intelligence) for efficient data collection in wireless sensor networks. The approach combines artificial intelligence methods, in particular, modified clustering (gap statistics + EM), fuzzy logic for cluster leader selection, and a hybrid PSO-ABC algorithm for mobile collector route optimization. The proposed architecture takes into account energy indicators, topology, and dynamic characteristics of the network to minimize energy consumption and increase network lifetime. A valuable resource for modeling fuzzy systems in WSM – demonstrates a comprehensive approach to combining fuzzy logic and AI-based optimization algorithms for data transmission control. Consideration of residual energy, node location, and topology is a relevant example for inclusion in

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energy-adaptive models in WSM. Limitations – the model does not contain an ontological formalization of knowledge or semantic description of processes, but is clearly structured for integration into intelligent decision-making modules in critical WSN applications. Article [16] presents a system for detecting excess substances in water channels using data fusion from wireless sensors and a fuzzy interface algorithm. Sensor readings are aggregated and processed with fuzzy logic to assess water quality under uncertainty. A useful source for modeling the process of collecting and aggregating data from sensors using fuzzy logic – can supplement the section on processing fuzzy input parameters in the article. Limitations – the model is focused on a specific application task (hydroecological monitoring) and does not cover the general structure or components of a sensor node. The article [17] proposes a Coverage and Connectivity Maintenance – Optimal Adaptive Learning protocol that provides effective coverage and connectivity maintenance in resource-constrained WSNs. The main idea is to autonomously train sensor nodes to choose an operating mode (active/sleep) to minimize the number of active nodes in each scheduling cycle while maintaining full coverage and connection to the base station. The method is implemented in the MatLab environment and tested against existing methods (K-CCA, LA-PC), which demonstrated an increase in network lifetime and a decrease in the number of active nodes while maintaining the quality characteristics of the coverage. A useful source for the network description module – demonstrates the possibility of using machine learning to optimize the coverage and structure of active nodes in dynamic conditions, taking into account the holistic topology. Limitations – lack of formalization of risks or semantic descriptions, but potentially suitable for expanding intelligent functions in a multi-level ontology of WSN state analysis. In [18], a model for assessing and predicting the level of security of a wireless network using fuzzy logic is proposed. The indicators “possibility”, “intent” and “capability” are combined with the Random Forest and Rough Set methods to increase accuracy. A useful source for the risk assessment module – demonstrates the prediction of the level of threats with a formalized assessment based on fuzzy logic. Limitations – the model is focused on general networks, without taking into account the specifics of industrial WSN and semantic integration. Article [19] presents a fuzzy logic-based method for non-uniform clustering in WSNs, improving CH selection and including isolated nodes. Enhances network lifetime and builds on LEACH for homogeneous networks. A useful resource for the clustering module in WSNs – demonstrates an improvement over the standard LEACH approach using fuzzy rules for full node coverage. Limitations – the work is focused on homogeneous networks without considering node heterogeneity or risk-oriented scenarios, and does not include semantic or ontological formalization. Article [20] introduces a hybrid EERR-RLFL protocol for WBANs, combining fuzzy logic and reinforcement learning to optimize routing based on link quality. Simulations show reduced packet loss and improved uptime. A valuable resource for fuzzy models in dynamic networks with heterogeneous nodes. Limitations: focus on WBANs, but the approach is adaptable to industrial WSNs. The article [21] presents an energy-saving clustering algorithm for WSNs based on fuzzy logic. The main idea is to use computational intelligence methods to select cluster heads based on energy parameters and distance to events. Fuzzification of parameters allows local decisions to be made on forwarding and merging data, which are then transmitted to the base station. The proposed approach demonstrates the extension of the network lifetime using the last alive node (LND) criterion. A valuable source for demonstrating the application of fuzzy logic in energy-efficient clustering of WSNs. It can be used to build a cluster optimization module within the ontological model. Article [22] presents FRINA – a fuzzy logic-based routing algorithm for data aggregation in WSNs. It optimizes aggregator selection, routing, and energy use via an adaptive aggregation tree. The approach effectively balances energy consumption across nodes while maintaining reliable data delivery. An important source for demonstrating the role of fuzzy logic in data aggregation and routing problems in WSNs. It can be used to extend the route structure description module in the ontological model. In [23], a strategy for directed recharging of nodes in WRSNs using fuzzy logic is proposed. The priority of nodes is determined by the residual energy, the distance to the charger, and the network density. The improvement of the energy balance and the extension of the network operation time are shown. Useful source for the energy management module – demonstrates the optimization of the recharging process using fuzzy logic. Limitations – the model covers only recharging, without considering risks, routing, or semantic integration. In the article [24], an improved routing protocol for underwater WSN based on fuzzy logic was developed. The complexities of the underwater environment are taken into account: delays, data loss, energy constraints. The fuzzy system selects the transmitter according to three parameters: distance, residual energy, and connectivity index. Simulation in MATLAB showed an increase in performance and energy efficiency. It demonstrates the adaptation of fuzzy logic to complex environments, can be applied to industrial WSN with complex topology. Risks or threats are not taken into account – limited application for full security analysis. The article [25] examines the main areas of application of WSN in the military, medical and industrial spheres, as well as the types of threats that may arise in these environments. The authors classify attacks by levels: physical, network and logical, and describe the requirements for data protection (confidentiality, integrity, availability, authenticity). Cryptographic protection methods are discussed, as well as secure routing protocols. A useful source for the risk analysis module – contains a clear classification of threats, protection principles and application areas. Limitations – overview nature without specific mathematical models or implemented structures of WSN components.

The reviewed studies demonstrate a wide range of approaches to solving the problems of energy efficiency, data transmission reliability, clustering, and decision-making in wireless sensor networks (WSNs). A significant portion of the literature focuses on the application of fuzzy logic in routing and clustering protocols, which provides adaptability, lower computational complexity, and energy-aware decisions. Several works incorporate multi-criteria decision-making techniques (e.g., TOPSIS, VIKOR, AHP) to enhance the selection of cluster heads or node deployment strategies. Others explore integration with intelligent control systems, software-defined networks, or reinforcement learning, broadening the scope of WSN applications, including in industrial and agricultural domains.

However, despite the diversity of methods, most publications address isolated aspects of WSN operation – energy conservation, topological optimization, or local decision-making – without offering a unified architectural framework. Semantic modeling and ontology-based formalizations are rarely applied, and in many cases, the heterogeneity of node types or communication protocols is not explicitly considered.

The reviewed sources provide a comprehensive basis for the development of fuzzy models in WSNs and confirm the relevance of clustering, energy modeling, and intelligent routing. The originality of this study lies in combining fuzzy decision models with formal ontology-based descriptions, allowing a structured integration of heterogeneous parameters into an intelligent WSN framework.

PURPOSE AND OBJECTIVES OF THE REASEARCH

The purpose of this research is development generalized models for description behavior and sensory status nodes and channels wireless communication sensor networks (WSN) in conditions uncertainty. Research aimed at taking into account specifics industrial environments where complete, accurate, and deterministic information about parameters components is often unavailable. Thanks to application apparatus unclear logic and linguistic modeling, proposed approach allows to increase accuracy and flexibility evaluation performance and reliability elements of WSN.

To achieve this purpose is defined such main task:

– analyze limitation traditional deterministic models that used in WSN, especially in cases unreliable or part famous data;

– to develop fuzzy model for evaluation efficiency and reliability of the sensor node, taking into account probabilities rejections its main components (sensor, processor, receiver and source) power supply);

– build a fuzzy model of the communication channel based on key performance characteristics, such as throughput ability, aging information, downtime and readiness;

– to introduce linguistic formalization key parameters using orthogonal semantic space and functions belongings for incoming and outgoing variables;

– demonstrate applicability developed models in scenarios that imitate real industrial conditions with high level uncertainty.

The research results are aimed at forming the basis for creating an intelligent sensor network management system capable of independently adapting to changes in the environment and the level of threats.

GENERALIZED SYSTEM MODELS WITH CLEAR AND FUZZY INPUT AND OUTPUT PARAMETERS

Let us consider some technical system as a complex one, which has a set of input P_X and output

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P_Y parameters, i.e. This schema is the structure of an ontology metamodel related to risk assessment in WSN for industry.

The schema uses the following key modules:

$$\begin{aligned} &P = \{p_i\}_{i=1..N_P} = P_X \cup P_Y \\ &P_X = \{x_i\}_{i=1..N_X}, P_Y = \{y_j\}_{j=1..N_Y}, \\ &N_X + N_Y = N_P \end{aligned} \qquad (1)$$

where: N_X is the number of input parameters; N_Y is number of output parameters; N_P is the number of all system parameters.

There is usually some relationship between the input and output parameters, which reflects the influence of the values P_X on P_Y.

Let us display it as follows:

$$P_Y = F_P(P_X) \qquad (2)$$

At the same time, we take into account that not all parameters can be described using clear quantities. Some parameters, due to their inaccuracy, qualitative nature or incompleteness of the data, can be described only using the theory of fuzzy sets. In this case, all parameter sets can be conditionally divided into subsets of parameters with a clear description $\overline{P}$ and a subset of parameters with a fuzzy description P. Then, in the general case, all parameter sets of the system can be written in the following form:

$$\begin{aligned} &P = \overline{P}_X \cup P_X \cup \overline{P}_Y \cup P_Y, \\ &\overline{P}_X = \{\overline{x}_i\}_{i=1..\overline{N}_X}, P_X = \{\tilde{x}_i\}_{i=1..\tilde{N}_X}, \\ &\overline{P}_Y = \{\overline{y}_i\}_{i=1..\overline{N}_Y}, P_Y = \{\tilde{y}_i\}_{i=1..\tilde{N}_Y}, \\ &\overline{N}_X + N_Y = N_X, \overline{N}_Y + N_Y = N_Y. \end{aligned} \qquad (3)$$

where: $\overline{P}_X$ is the set of distinct input parameters; P_X is a set of fuzzy input parameters; $\overline{P}_Y$ is a set of clear initial parameters; P_Y is a set of fuzzy output parameters.

We define for each fuzzy parameter $\{p_i\}_{i=1}^{N}$ a complete orthogonal semantic space (COSS). To do this, on the set of parameter values D_i,=1,…,N, where N is the number of fuzzy parameters of the system, we define a set of variables $\{p_{ic}^{k}\}_{k=1}^{K_i}$, where

$$\begin{cases} p_{ic}^{1} = \min\limits_{D_i}(p_i) \\ p_{ic}^{K_i} = \max\limits_{D_i}(p_i) \end{cases}, i = 1,...,N.$$

The set of fuzzy values $D_i = \{p_i^k\}_{k=1,...,K_i}$, where K_i is the number of fuzzy values accepted by the ith parameter, is defined in the form of fuzzy numbers by the triangular membership function μ_i^k by the relations:

$$p_i^k \Rightarrow \mu_i^k(p_i^`) = \begin{cases} 1, p_i^` = p_{ic}^1 \\ \dfrac{p_i^` - p_{ic}^2}{p_{ic}^1 - p_{ic}^2}, p_{ic}^1 < p_i^` < p_{ic}^2 \\ 0, p_i^` \ge p_{ic}^2 \end{cases}$$

$$p_i^k \Rightarrow \mu_i^k(p_i^`) = \begin{cases} 0, p_i^` \le p_{ic}^{k-c}, p_i^` \ge p_{ic}^{k+1} \\ \dfrac{p_i^` - p_{ic}^{k-c}}{p_{ic}^{k} - p_{ic}^{k-c}}, p_{ic}^{k-c} < p_i^` < p_{ic}^{k} \\ 1, p_i^` = p_{ic}^{k} \\ \dfrac{p_i^` - p_{ic}^{k+c}}{p_{ic}^{k} - p_{ic}^{k+c}}, p_{ic}^{k+c} < p_i^` < p_{ic}^{k+1} \end{cases}, k = 2,...,K_i - 1 \qquad (4)$$

$$p_i^{K_i} \Rightarrow \mu_i^{K_i}(p_i^`) = \begin{cases} 0, p_i^` \le p_{ic}^{K_i-1} \\ \dfrac{p_i^` - p_{ic}^{K_i-1}}{p_{ic}^{K_i-1} - p_{ic}^{K_i}}, p_{ic}^{K_i-1} < p_i^` < p_{ic}^{K_i} \\ 1, p_i^` = p_{ic}^{K_i} \end{cases}$$

where $i = 1,...,N_P$. Membership functions μ_i^k are definite on some interval $(p_{ic}^{k-1}, p_{ic}^{k+1})$.

To use (4) in describing the membership function of fuzzy parameters of the system, we define some mathematical operations that can be performed on these fuzzy quantities.

Let us denote by some fuzzy numbers with a membership function of the form (4):

$$x = \{x_b, x_c, x_e\}$$
$$y = \{y_b, y_c, y_e\}$$
$$\tilde{z} = \{z_b, z_c, z_e\}.$$

These fuzzy numbers are used to represent linguistic variables, where uncertainty is modeled using triangular membership functions, enabling a more intuitive and structured way to handle imprecise information. Taking into account the triangular form of the membership function, it becomes possible to define the core mathematical operations in an explicit form, which in turn facilitates both the implementation of computational procedures and the analytical processing within fuzzy logic-based inference frameworks:

$$\begin{aligned}
\tilde{z} &= x + y = \{x_b + y_b, x_c + y_c, x_e + y_e\} \\
\tilde{z} &= x - y = \{x_b - y_e, x_c - y_c, x_e - y_b\} \\
\tilde{z} &= x \times y = \{x_b \times y_b, x_c \times y_c, x_e \times y_e\} \\
\tilde{z} &= \frac{x}{y} = \{\frac{x_b}{y_e}, \frac{x_c}{y_c}, \frac{x_e}{y_b}\}
\end{aligned} \quad (5)$$

In the general case, for fuzzy values of the parameter y_i, as a result of certain actions on the parameters with sets P_X, we will obtain our own COSS, which will not coincide with any of the fuzzy values y_i^k from COSS D_i.

Thus, to calculate a new fuzzy value of the output parameter based on the transformations of fuzzy inputs, a composition operation is applied that integrates multiple neighboring values. This is particularly relevant when the resulting fuzzy value does not correspond to any of the predefined fuzzy terms in the system. The applied approach allows capturing gradual transitions and uncertainties across the parameter space, enhancing the expressiveness of the fuzzy model. The expression for determining the ratio of the obtained value to all possible fuzzy values is given by:

$$\begin{aligned}
y_i &= \min_k \Xi(y_{ic}^{k+1}, y_{ie}, y_{ic}^{k-1}, y_{ib}, y_{ic}^k, y_{ic}) \\
&= \min |y_{ic}^{k+1} - y_{ie}| + |y_{ic}^{k-1} - y_{ib}| + |y_{ic}^k - y_{ic}|
\end{aligned} \quad (6)$$

where (y_{ib}, y_{ic}, y_{ie}) is a fuzzy triangular number y_i.

The COSS defined in this way allows us to proceed to the consideration of specific functions, the general description of which is given by formula (2).

Next, we will consider a model for calculating the characteristics of a system with clear and fuzzy input and output parameters.

Let the given set be incoming parameters $X_1 = \{x_{ij}\}$, $X_2 = \{x_{km}\}$, $A_1 = \{a_{ij}\}$, $A_2 = \{a_{km}\}$, $X_1 \subset P_X$, $X_2 \subset P_X$, $A_1 \subset \overline{P}_X$, $A_2 \subset \overline{P}_X$ and the output parameter $y \in P_Y$, the value of each fuzzy parameter is determined by the membership function of type (4), and the clear parameters are some numbers:

$$x_{ij} = \{x_b^{ij}, x_c^{ij}, x_e^{ij}\} \in P_X$$
$$x_{lm} = \{x_b^{lm}, x_c^{lm}, x_e^{lm}\} \in P_X$$
$$A_1, A_2 \subset \Re$$
$$y = \{y_b, y_c, y_e\} \in P_Y,$$

where $\Re$ is the plural real numbers.

Let us consider the case when the mapping (2) has the following form. This expression models the aggregation of fuzzy input parameters using weighted coefficients, ensuring that each contribution is properly normalized.

It enables a balanced combination of heterogeneous data sources with varying degrees of influence:

$$y = \frac{\sum_i \prod_j a_{ij} x_{ij}}{\sum_l \prod_m a_{lm} x_{lm}} \quad (7)$$

Next, we will consider a model for calculating the characteristics of a system with fuzzy input and output parameters.

Let there be given a set of input parameters $X = \{x_i\}$, $X = P_X$ and an output parameter $y \in P_Y$, each parameter is fuzzy and its value is determined by the membership function of the COSS of type (4).

Then each parameter will be defined by three values: $x_i = \{x_{ib}, x_{ic}, x_{ie}\}$, $y_i = \{y_{ib}, y_{ic}, y_{ie}\}$, $z_i = \{z_{ib}, z_{ic}, z_{ie}\}$.

Consider the case when the mapping (2) has the following form:

$$y = \prod_{i=1}^{n} x_i \quad (8)$$

Expression (11) is a model for calculating the characteristics of a system with fuzzy input and output parameters.

Received models calculation we will be used when building models of WSN components.

CONCLUSIONS AND PROSPECTS OF FURTHER REASERCH

This study provides a systematic and generalized approach to the formal modeling of wireless sensor network (WSN) components functioning under conditions of uncertainty, incompleteness, and qualitative data. The proposed methodology focuses on constructing mathematical models that incorporate both crisp and fuzzy parameters, thereby overcoming the limitations of conventional deterministic approaches. By doing so, the framework becomes applicable to a broad range of practical WSN configurations, including those used in industrial, environmental, and infrastructure monitoring scenarios.

A central contribution of the work is the development of formalized mappings between input and output parameters through the use of fuzzy membership functions and fuzzy arithmetic. These mappings make it possible to process linguistic inputs – such as “low connectivity,” “high energy consumption,” or “medium reliability”– and transform them into quantifiable outputs that preserve semantic meaning. This capability is critical for analyzing WSNs deployed in real-world environments, where data precision is often compromised due to measurement error, noise, or incomplete observations.

The proposed models are not confined to specific hardware layouts or communication standards. Instead, they define a flexible foundation for representing both functional behavior and semantic interpretation in a uniform mathematical framework. By supporting fuzzy logic operations, the models allow for gradual reasoning and uncertainty-tolerant decision-making, which are essential features for modern adaptive sensor networks.

An important advantage of the presented approach is its compatibility with ontological modeling. The use of orthogonal semantic spaces (OSS) enables the inclusion of fuzzy variables in a machine-interpretable structure, making the models suitable for integration into semantic decision-support systems. This opens the door for applications in intelligent control, predictive diagnostics, and automated risk analysis in WSN infrastructures.

It should be noted that this article deliberately omits detailed models of internal WSN components– such as the failure mechanisms of sensor nodes and the physical-layer properties of communication channels. These aspects will be addressed in a follow-up study focused specifically on the structural decomposition of WSN elements and their fuzzy modeling. The models currently presented serve as an abstraction layer that defines a universal framework onto which these specialized models will be integrated.

In line with this modular strategy, future research will pursue several important directions:

– extending the current framework to incorporate the topological structure of the network, including dynamic interconnections and routing paths that evolve over time;

– developing a rule-based system for assessing the criticality of individual nodes, with outputs that can be used for risk assessment, prioritization of network maintenance, and security evaluation;

– smplementing adaptive routing algorithms that leverage fuzzy estimates of residual energy, link reliability, and node availability, allowing for decentralized and context-aware path selection.

From a practical perspective, the benefits of the proposed fuzzy modeling approach are significant. It enhances the quality of decision-making under uncertainty, enables early-stage fault detection, supports the construction of predictive and preventive control mechanisms, and lays the groundwork for robust network self-organization. The integration of fuzzy reasoning into WSN modeling is a decisive step toward developing sensor networks that are not only intelligent and scalable but also resilient to the noise and variability that characterize real-world deployment environments.

Thus, the research contributes both to the theoretical understanding of fuzzy modeling in sensor systems and to the advancement of practical tools for next-generation intelligent WSN design.

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Нечіткі модулі компонентів бездротових сенсорних мереж

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АНОТАЦІЯ

У статті розглядається проблема моделювання компонентів бездротових сенсорних мереж, що функціонують в умовах невизначеності та впливу зовнішніх факторів. Актуальність дослідження зумовлена зростаючою потребою у надійних та автономних системах моніторингу й керування в промисловому середовищі, особливо за умов, коли дротовий зв’язок є неможливим або нестабільним. Класичні моделі зі строго визначеними вхідними параметрами не здатні адекватно відображати динаміку та непередбачуваність поведінки сенсорних вузлів і каналів зв’язку, що обмежує точність оцінки їх працездатності та ускладнює проєктування надійних систем. Метою цього дослідження є розробка формалізованого підходу до опису поведінки бездротових сенсорних мереж в умовах невизначеності з використанням апарату нечіткої логіки та семантичного представлення. Запропоноване рішення ґрунтується на узагальненій моделювальній схемі, що базується на теорії нечітких множин і дозволяє опрацьовувати як чіткі, так і нечіткі вхідні та вихідні змінні. Представлено два універсальні варіанти формулювання моделей: один описує взаємозв'язки виключно між нечіткими параметрами, інший – пов'язує чіткі вхідні значення з нечіткими виходами. Такі моделі слугують гнучкою основою для представлення типових процесів у бездротових сенсорних мереж, де параметри часто є лише частково відомими, якісно оціненими або описаними лінгвістично. Змінні відображаються в ортогональному семантичному просторі, що дозволяє використовувати функції належності для подальшого логічного виведення та інтеграції в онтологічні структури. Попри те, що детальні структурні моделі сенсорних вузлів та каналів зв'язку не включено до цієї версії роботи та будуть представлені в окремому подальшому дослідженні, представлена методологія створює концептуальну основу для їх розробки. Наукова новизна полягає у створенні уніфікованого підходу до нечіткого моделювання, який підтримує як абстрактне, так і даноорієнтоване представлення невизначеності в бездротових сенсорних мережах. Практична цінність полягає в можливості застосування запропонованого підходу під час проєктування адаптивних, контекстно-орієнтованих сенсорних мереж, здатних надійно функціонувати в умовах підвищеної складності та обмежених ресурсів. Запропоновані моделі забезпечують підвищену гнучкість, семантичну інтерпретованість і точність у відображенні реальних умов експлуатації.

Ключові слова: бездротові сенсорні мережі; нечіткі моделі; сенсорний вузол; канал зв'язку; лінгвістичні змінні; ортогональний семантичний простір; надійність; відмовостійкість; нечітка логіка; промислові системи

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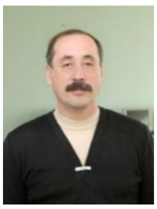

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