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Computer-Oriented Model for Network Aggregation of Measurement Data in IoT Monitoring of Soil and Climatic Parameters of Agricultural Crop Production Enterprises

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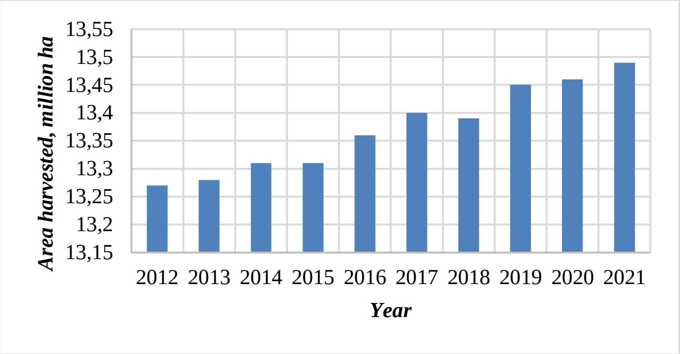
Abstract. Currently, the development and implementation of infocommunication and computer technologies in agricultural enterprises specialising in the cultivation of grain crops allow the enhancement of their efficiency through online monitoring of distributed parameters of soil and climatic growing conditions. This article is focused on developing scientifically based provisions to enhance the efficiency of IoT systems for agrotechnical monitoring through synthesising the computer-oriented model according to the optimality criterion, which considers the simultaneous influence of the following factors: maximum uptime of hardware and software components, maximum network coverage area and minimum number of wireless sensor modules used. The main outcome of the results obtained is the development of the computer-oriented model of the IoT system based on wireless sensor networks and edge-computing techniques. The proposed model implements adaptive switching of wireless data exchange technologies depending on the distance of message retransmission and aggregation of data at the field level of microprocessor devices.

Keywords: monitoring, agriculture, Internet of things, wireless sensor network, uninterrupted operation, coverage area, computer-oriented model.

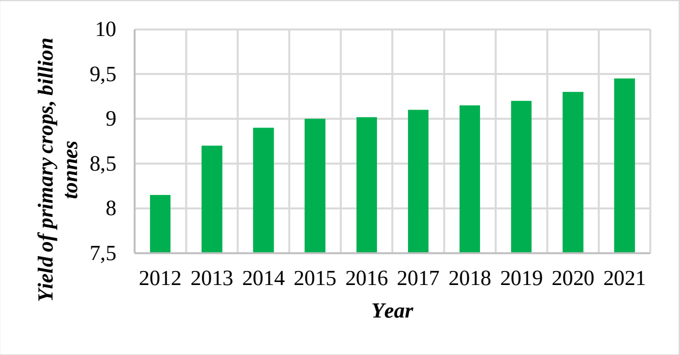
1. Introduction

1.1. Relevance of the research topic

Applied information technologies are a highly efficient tool for monitoring, controlling and diagnosing the current and predicted state of production processes. The implementation of modern information, computing and computer technologies in the production processes of agricultural enterprises of crop production allows for a significant enhancement of their efficiency through online monitoring of a set of distributed physical and chemical parameters related to soil and climatic conditions during their cultivation. This is further supported by automated decision-making based on intelligent software analysis of measurement data. It is worth mentioning that information and computer technologies for agrotechnical purposes are advanced and highly efficient technical systems based on various methods and tools of data collection, network communication and online data transformation. Taking into account the steady dynamics of the cultivated areas for agricultural crops, as well as the volumes of production (WEB, a; WEB, b), as shown in the form of worldwide statistics in Fig. 1, there is a significant relevance to the development, modernisation and improvement of distributed soil and climatic monitoring systems integrated into IoT networks for agrotechnical purposes.



a) Area harvested



b) Yield of primary crops (cereals, fruits, sugar crops, vegetables, oil crops, roots and tubers)

Figure 1. Statistics of yield and area harvested (2021 year – current update of Food and Agricultural Organization (FAO) data)

Therefore, the steady dynamics of cultivated areas for agricultural crops, and the corresponding increase in production volumes necessitate the online detection of soil and climatic parameters at distributed locations and their intelligent processing. It is also worth noting that the expansion of agricultural areas results in a proportional growth of data generated by field-level sensors in IoT systems and networks. Thus, there is a need to develop models for network interaction among functional components in IoT networks integrating algorithms of edge-computing at the field level. This will optimise the overall performance indicators of network operativeness and reliability, as well as comprehensive multi-level data processing. Taking into account the above, it is established that the topic of the article is relevant and the significance of the expected scientific and applied outcomes lies in the design of the applied IoT systems for agrotechnical monitoring through the development of software and hardware solutions for distributed network aggregation of measurement data implementing fog and edge computing techniques.

1.2. Review, comprehensive analysis and logical generalisation of scientific and applied works

One of the modern and efficient approaches to planning agrotechnical operations during sowing and cultivation is the automatic generation of recommendations for agrotechnical activities based on the in-depth processing of measurement data on the dynamics of soil and climatic parameters (such as soil and air temperature and humidity, precipitation, leaf wetness, effective lighting, wind speed and direction), taking into account the types and stages of vegetation of the cultivated crops (Slater et al, 2022; Chia and Lim, 2022; Laktionov et al., 2023*a*; Laktionov et al., 2023*b*). For instance, the authors of the scientific article (Slater et al, 2022) established the patterns of the destabilising impact of climate factors on the quality of wheat growing. In the scientific paper (Chia and Lim, 2022), a correlation was established between air humidity and the length of Lactuca Sativa leaves. In the scientific article (Laktionov et al., 2023*a*), the regularities of the integral influence of temperature and humidity of the greenhouse growing zone on the quality of growing introduced crops were established, and in the scientific article (Laktionov et al., 2023*b*), intelligent computer models of edge transformation of distributed measurement information on soil and climatic parameters were developed based on low-cost microcontroller and sensor technologies. It should be noted that there is a significant body of high-quality results of scientific and applied research on the development of IoT systems for distributed physical and chemical parameters monitoring including those related to agrotechnical purposes. This is evident from the findings presented in Table 1.

Based on the comprehensive analysis and generalisation of the prior information (see Table 1), the following findings were established: wireless sensor network technology is utilised for building the physical layer of IoT systems; LoRa, ZigBee, 4G LTE and BLE technologies are used for network data transmission and routing; cloud computing technology is used for addressing the tasks of measurement data transformation and analytics; the synthesis of structural and algorithmic organisation of wireless sensor networks for agrotechnical purposes is predominantly carried out based on a single-factor approach, considering criteria such as energy efficiency or network coverage area.

Therefore, the analysis and logical generalisation of known scientific and applied research results in the field of online IoT monitoring of distributed objects, taking into account specific characteristics of agricultural enterprises of crop production as monitoring objects, have allowed to identify the scope of questions requiring further investigation in this article: substantiation of the optimal topology of wireless sensor network (field-level data aggregation) within field locations, considering the integral influence of criteria such as uptime of hardware and software components and coverage area of the infocommunication network; substantiation of basic network data exchange technologies during the transfer of various hierarchical levels within the IoT system; development of software and algorithmic solutions of the field-level transformation of measurement data enabling the transition to edge-computing technology without a fundamental change in the architecture of currently used IoT networks.

Table 1. The results of comprehensive analysis and logical generalisation of scientific and applied findings regarding the construction of distributed online monitoring IoT systems

The research subject	Used technologies	Reference source
System of measurement control and diagnostics of electrical objects	WSN, DPM	Damodaram et al., 2023
A probabilistic model of wireless sensor network taking into account criteria of network communication quality and coverage area	WSN	Hossain and Mishra, 2014
Model for constructing a wireless sensor network considering the optimisation of criteria of efficiency and security of information message routing	WSN	Ganesh and Amutha, 2012
Development of a generalised functional diagram of the WSN of the IoT agricultural monitoring system	WSN	Cao et al., 2017
Geometric models for wireless sensor network construction for agricultural monitoring purposes based on multi-parameter optimisation	WSN, GA	Kaiwartya et al., 2016
Hardware and software solution of IoT intelligent system that encompasses data collection, network communication and cloud-based processing of measurement data on agrotechnical monitoring	WSN, PLC, LoRa	Saban et al., 2023
Analysis of network scenarios of measurement data exchanging during IoT agrotechnical monitoring	WSN, LPWAN, LoRa	Pagano et al., 2023
The structural and algorithmic organisation of wireless system on microclimate parameters monitoring in greenhouses	WSN, ZigBee	Alqahtani, 2022
Analysis of current trends in building IoT systems using wireless sensor networks	WSN, ZigBee	Nourildean et al., 2022
IoT system of forest fire detection with optimised energy consumption indicators	WSN, Bluetooth, LoRa, LTE	Khan, 2023
Concept of creating network models based on data from open sources	WSN, WANET, MANET	Musznicki et al., 2022
Analysis of architectural solutions for building IoT systems with embedded AI algorithms for smart cities	ICT, AI	Alahi et al., 2023
Methods for assessing the quality of signals in wireless sensor networks based on ML algorithms for greenhouse monitoring conditions	WSN, ML, ZigBee	Kochhar et al., 2022
Methods and interfaces for power consumption optimisation in wireless sensor networks	WSN, LPWAN	Alaerjan, 2023
Development of architecture and software and hardware solution of agrotechnical monitoring based on wireless sensor network and MQTT network protocol	WSN, MQTT	Syafarinda et al., 2018

Thus, conducting research in the aforementioned directions will contribute to the improvement of existing systems of online IoT monitoring of soil and climatic parameters in agricultural crop production enterprises by optimising the processes of data aggregation, network communication and data transformation in accordance with the scientific and applied principles of fog and edge computing technologies, specifically, the capability to process a significant amount of time- and space-distributed measurement data at the field level using low-cost microcontrollers.

1.3. Aim, object, subject and structure of the article

The main aim of the article is to develop scientifically substantiated principles for improving the efficiency of IoT systems on agrotechnical monitoring through the synthesis of structural and algorithmic organisation of wireless networks and intelligent sensor integration based on criteria such as maximum coverage area and the maximum probability of uninterrupted operation of the network organisation of the IoT system, as well as minimum sensor nodes used. The object of research is informational processes of wireless aggregation, network communication and embedded data processing in agrotechnical monitoring. The subject of research is computer-oriented models for constructing IoT systems and networks in agrotechnical monitoring. The structure of the article is as follows: the second section contains information on the used methods, approaches and means employed in the research; the third section highlights the main scientific and applied results; the fourth section substantiates the suggestions for future investigations; the fifth section presents the key conclusions; Appendix A presents the software components.

1.4. Expected scientific and applied impact

The scientific and practical value of the research results in this article lies in the synthesis of a structural and algorithmic organisation of the IoT system on agrotechnical monitoring, which incorporates distributed data aggregation, reliable network communication and embedded data processing at the edge of the network. The proposed computer-oriented model of the IoT system is based on WSN and edge computing techniques and, unlike previously known models, implements adaptive switching of wireless data transmission technologies based on the distance of message sending (receiving) and statistical analysis of measurement data at the level of intelligent sensors.

2. Approaches, methods and means of the research

2.1. Generalised research approaches

The main results of the research were achieved using the following approaches and methods: comprehensive analysis and logical generalisation of known research results in the field of IoT monitoring; probability and reliability theory of technical systems; computer modelling of information and communication systems; synthesis and analysis of the structural and algorithmic organisation of distributed infocommunication systems.

The research results obtained and presented in this article are a logical continuation of the authors’ own theoretical and experimental studies in the development of intelligent IoT monitoring systems for agricultural objects, which are reflected in the following scientific publications (Laktionov et al., 2019; Laktionov et al., 2020; Laktionov et al., 2021). The authors of the scientific article (Laktionov et al., 2019) introduced a technique for intelligent processing of distributed measurement data for monitoring the climate of agricultural facilities, which enable them to communicate with a remote cloud server. In the scientific article (Laktionov et al., 2020), a structural and algorithmic organisation of an intelligent climate data monitoring system based on low-cost sensor and microprocessor technologies was proposed. The results of experimental investigations and evaluation of the main technical and functional characteristics of the prototype of a computerised weather station are presented in (Laktionov et al., 2021).

The validation of the obtained results was performed by testing the computer model of the synthesised structural and algorithmic organisation of the IoT system for agricultural monitoring using the CupCarbon simulation software.

2.2. Structural and algorithmic description of the computer-oriented model

The developed hardware and software solution for online IoT monitoring of soil and climatic parameters of agricultural enterprises of crop production is based on the WSN technology using a star-of-stars topology (see Fig. 2). In such an architecture each functional block ‘local field's infocommunication infrastructure’ represents a location (a specific fragment in Fig. 3) that aggregates data from end-nodes (a set of intelligent sensors for soil and climatic parameters) using ZigBee wireless technology (Type A). Afterwards, the aggregated data from Type A network nodes, which have undergone preliminary statistical transformation within the corresponding Type B network nodes (temporal and spatial averaging) are transmitted to the base station (Type C) of the field's network infrastructure using LoRa technology. The base station (Type C network node) performs the following functions: the formation of a local database for measurement observations, intelligent data analysis with the capacity to predict the impact of soil and climatic parameters on the quality indicators of agricultural crops, coordination of network protocols and transmission of information messages (processed data) to the cloud server using Internet communication technology (for instance LTE). In this architecture (see Fig. 2), the cloud server acts as an IoT platform that provides access to the visualisation of measurement information on remote user devices. The aforementioned wireless infocommunication technologies were chosen based on typical indicators of coverage area, energy consumption and data encryption algorithms.

Thus, the functional chain of information message routing using the proposed architecture (see Fig. 2) and the structural and algorithmic organisation of the IoT system for agricultural monitoring (see Fig. 3) is shown in Fig. 4.

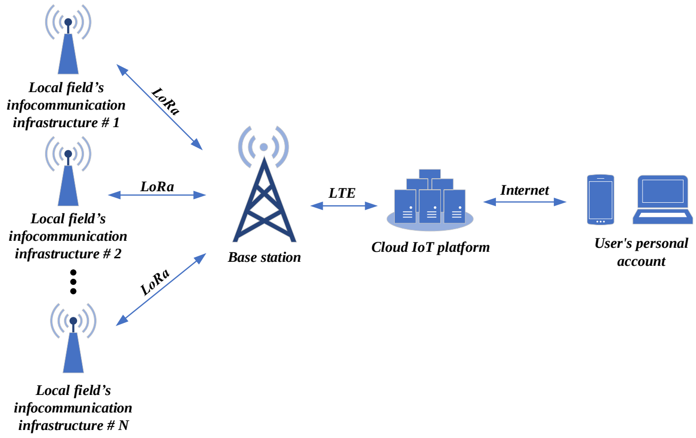


Figure 2. The proposed architecture of the IoT infrastructure for agricultural monitoring

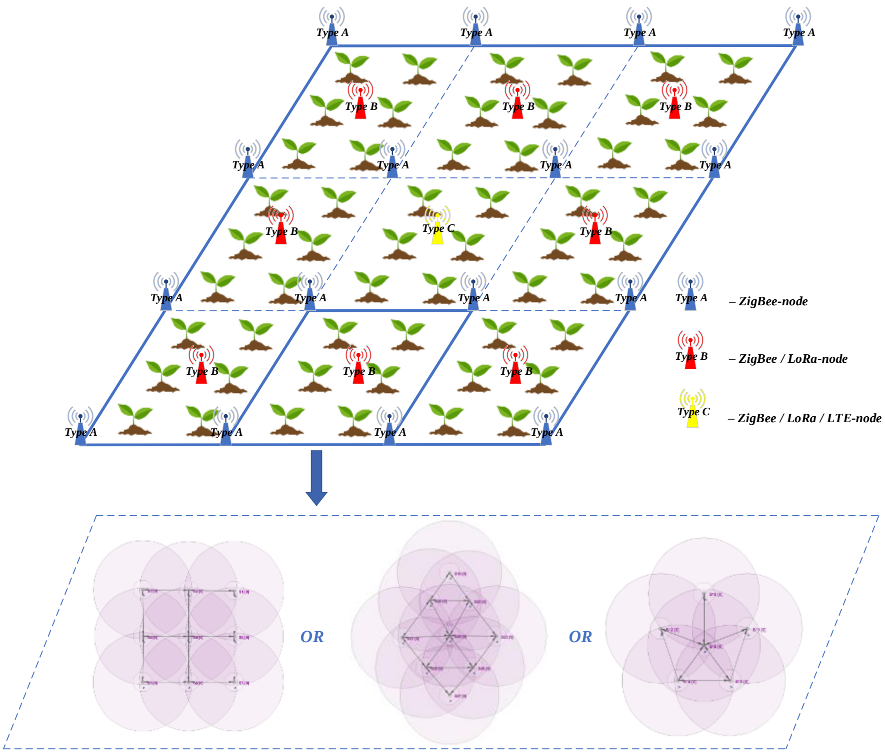


Figure 3. Detailed structural and functional organisation of the infocommunication infrastructure of the IoT system on agricultural monitoring

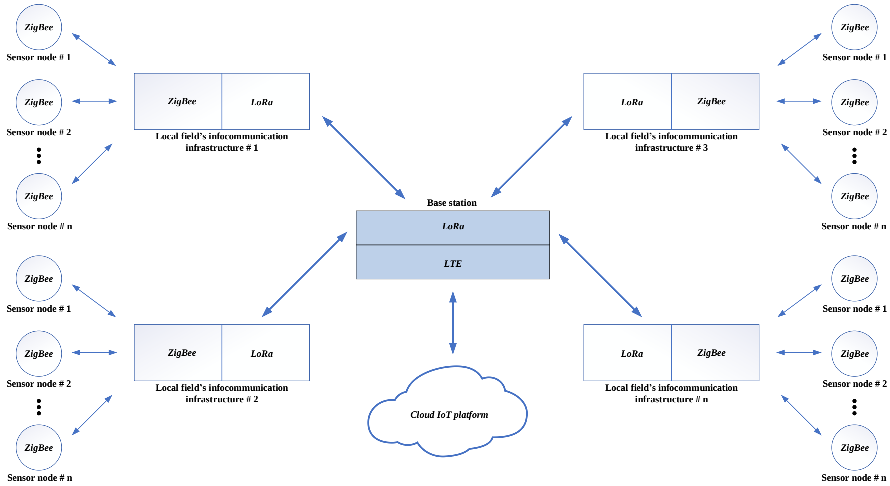


Figure 4. The functional chain of using network technologies

It should be noted that the possible variants of geometric models for the sensor nodes placement (see Fig. 3) were determined through an analysis of research results discussed in the scientific article (Kaiwartya et al., 2016). In this article, the authors conducted a study on the multicriteria optimisation of geometric models of building a network organisation for agrotechnical purposes. However, it should be noted that the authors of this article took into account solely the performance indicators of the network: total coverage area, effective coverage area, net effective coverage area, net effective coverage area ratio, total non-overlapped coverage area, total overlapped coverage area and quality of connectivity. Given the depth and quality of the research results presented in (Kaiwartya et al., 2016), it should be emphasised that, given the fact that the designed system involves practical implementation on the basis of low-cost software and hardware solutions, these findings require further enhancement by taking into account the factor of WSN component uptime, as well as the specific types of network technologies on which the IoT system is built. Therefore, the presented structural and functional organisation of the IoT system's infrastructure requires further research to substantiate the optimal geometric model for sensor node placement based on criteria such as reliability and coverage area.

2.3. Theoretical and applied foundations of criterion-based synthesis of the IoT system

The algorithm for evaluating the effectiveness of geometric models of the wireless sensor network of the investigated IoT system for agrotechnical monitoring (see Fig. 3) is based on the task of maximising a two-parameter objective function:

$$F = optimum\left(S_{cover\ norm}, P_{uptime}\right) \to \max , \tag{1}$$

where: F – the objective function of the two-parameter optimisation; $S_{cover\ norm}$ – the normalised value of the total coverage area; P_{uptime} – the probability of uninterrupted operation.

In this article, for a more meaningful analysis of the effectiveness of WSN construction using a specific geometric model, the normalised value (2) of the coverage area to the number of deployed wireless modules was proposed as the first criterion when evaluating efficiency (1).

$$S_{cover\ norm} = \frac{S_{cover}}{n}, \tag{2}$$

where: $S_{cover\ norm}$ – the normalised value of the total coverage area; S_{cover} – the total coverage area; n – the number of wireless modules that form the corresponding geometric model.

The total coverage area of the WSN geometric model can be accurately calculated according to the following formulas (Kaiwartya et al., 2016):

$$S_{cover} = \begin{cases} \left(\frac{7\pi}{3} + 2\sqrt{3} + 4\right) \cdot r^2 \ \ // \ \ \textit{for square pattern} \\ \left(\frac{11\pi}{3} + 8\sqrt{3}\right) \cdot r^2 \ \ // \ \ \textit{for rhombus pattern} \\ \left(\frac{9\pi}{4} + 6.13\right) \cdot r^2 \ \ // \ \ \textit{for pentagon pattern} \end{cases}, \tag{3}$$

where: r – the wireless module range.

As the second criterion for the two-parameter optimisation of efficiency (1), the probability of uninterrupted operation of the WSN based on a specific geometric model (square, rhombus or pentagon pattern) is proposed to be used. This criterion can be calculated using the following algorithm.

Each local geometric model of the field-level data aggregation, from a network organisation perspective, consists of a set of transmitters (see Fig. 3, Type A) and one receiver (see Fig. 3, Type B). The probability of failure (occurrence of a non-operational state) of at least one of the transmitter nodes in the network structure can be found based on the disjunction of failure probabilities of individual transmitters. The final form of expression (4) was obtained by transforming the disjunctive form into the conjunctive form using De Morgan's rule:

$$\begin{gathered} Q_{transmitter} = q_1 \text{ or } q_2 \text{ or ... or } q_m = \overline{\overline{q_1} \text{ and } \overline{q_2} \text{ and ... and } \overline{q_m}}, \\ \textit{where } q_i = 1 - p_i \end{gathered} \tag{4}$$

where: $Q_{transmitter}$ – the probability of transmitters failure; q_i – the probability of the i^{th} transmitter failure; p_i – the probability of faultless operation of the i^{th} transmitter; i – the index of the transmitter; m – the number of transmitters (Type A devices) in the corresponding geometric model.

The next step is converting the logical operations in (4) into algebraic operations, namely: the ‘and’ operation was replaced by algebraic multiplication, and the inversion operation was replaced by (1–q_i). In addition, when obtaining (5), it was considered that the transmitters are built on identical devices that are put into operation simultaneously, hence satisfying the condition $q=q_i$. Thus:

$$Q_{transmitter} = 1-(1-q)^m . \tag{5}$$

The complete failure state of the network organisation refers to the simultaneous failure of the receiver (Type A) and at least one of the transmitters (Type B). This assumption is valid for networks built on self-organising ZigBee technology. Thus, the probability of a failure state occurring in the sensor network with the corresponding topology can be calculated using the Boolean conjunction operation according to the formula:

$$Q_{total} = Q_{receiver} \text{ and } Q_{transmitter} , \tag{6}$$

where: Q_{total} – the probability of the network organisation being in a failure state; $Q_{receiver}$ – the probability of the receiver (Type B) failure; $Q_{transmitter}$ – the probability of the transmitters (Type A) failure.

After equivalent transformations of logical operations in (6) into algebraic ones, as well as taking into account that the receiver has an identical circuit implementation to the transmitters (the difference is only in embedded software, moreover, the structure and complexity of the code are approximately the same, with the difference being only in the sequence and number of calls to the corresponding functions, so the probability of software errors of the transmitter and receiver can be taken as equal in a certain approximation), the condition $Q_{receiver} \approx q$ is satisfied because the receiver and transmitters in this article are considered as integrated hardware and software solutions. Therefore, the probability of network organisation failure can be calculated using the following formula:

$$Q_{total} = q \cdot \left(1-(1-q)^m\right). \tag{7}$$

Based on (7), the probability of uninterrupted operation of a specific geometric model of the wireless sensor network can be calculated using the formula:

$$P_{uptime} = 1-Q_{total} = 1-q \cdot \left(1-(1-q)^m\right). \tag{8}$$

Therefore, based on the analysis of (8), it is established that the criterion for the reliable operation of IoT system for soil and climatic parameters monitoring is a nonlinear function that depends on the number of edge functional elements of the wireless sensor network (sensor node).

3. Research results

3.1. Results of criterion-based synthesis of the IoT system

When evaluating the performance criteria of the synthesised IoT system for agricultural monitoring the following assumptions were made:

– the maximum range of typical ZigBee modules (WEB, c) compatible with budget microprocessor devices for field conditions is equal to 100 m;

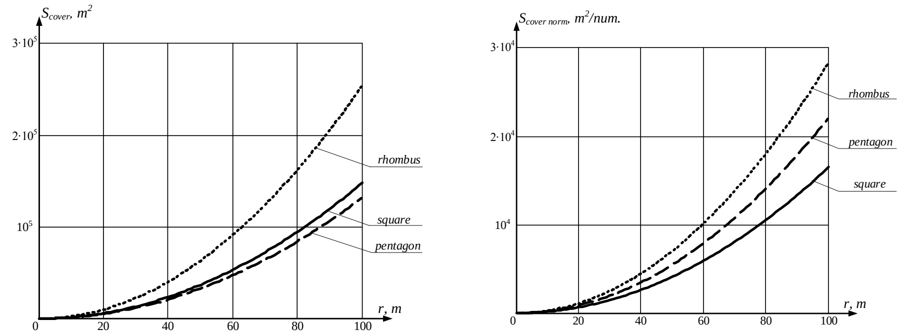
– the maximum range of typical LoRa modules (WEB, d) compatible with budget microprocessor devices for field conditions is equal to 15 km;

– ZigBee modules are considered as integral microprocessor devices built on a semiconductor component basis when analysing the probability of failure;

– the dynamic range of variations in the probability of failure of ZigBee modules was determined based on experimental research conducted by the authors of the article (Conti and Orcioni, 2020) and ranges from 0.01 rel. un. to 0.1 rel. un. corresponding to a service life of 5 years in accordance with the normal distribution law.

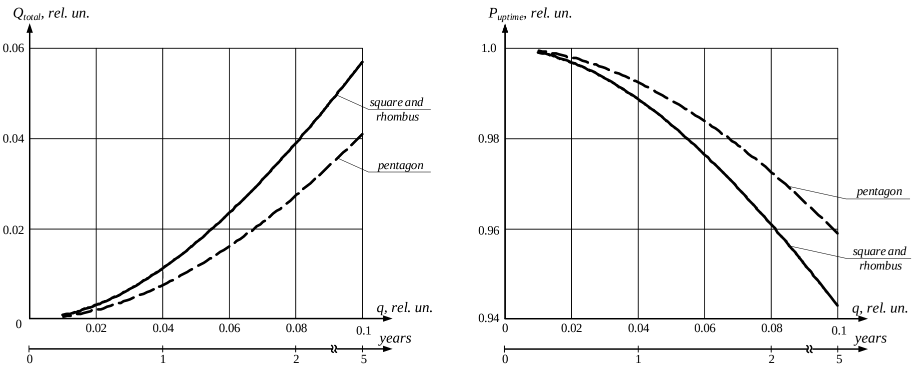
The graphical results of assessing the coverage area and its normalised value, depending on the wireless module range for different types of geometric models of WSN construction, calculated using formulas (2) and (3) are shown in Fig. 5. The curves given in Fig. 5a show the dependence of the total coverage area (S_{cover}) of the field on the change in the wireless module range of one wireless module (r), which is part of the corresponding geometric model. The range of variation of the wireless module range, in this case, was chosen by analysing the technical documentation of typical ZigBee modules (WEB, c). To objectively assess the effectiveness of a geometric model that can be used to construct a wireless sensor field network, the coverage area was limited to the number of sensors within each model. This approach indirectly considers the hardware cost of the IoT network components, as presented in Fig. 5b.

The graphical results of the reliability indicators assessment for the investigated geometric models of field-level sensor network in the IoT system for agricultural monitoring calculated using formulas (7) and (8) are shown in Fig. 6. This plot is presented in two versions (Fig. 6a – failure probability, Fig. 6b – probability of uninterrupted operation) for a more ergonomic perception of the calculation results. It is worth noting that failure probability and probability of uninterrupted operation are inversely related and are equally used in the theory of reliability of technical systems.



a) Coverage area b) Normalised value of coverage area

Figure 5. The coverage area of the investigated wireless sensor network models



a) Failure probability b) Probability of uninterrupted operation

Figure 6. Reliability indicators of the investigated wireless sensor network models

The summarised analysis results of the evaluated effectiveness criteria of the investigated IoT system are shown in Table 2. The probability of uninterrupted operation is calculated based on a period of continuous operation over a 5-year period.

Table 2. Quantitative evaluations of the effectiveness of the IoT system for agricultural monitoring

Parameter / Model	Normalised value of the total coverage area ($S_{cover\ norm}$)		Probability of uninterrupted operation (P_{uptime})	
	Maximum value, m^2/num.	Relative deviation, %	Maximum value, rel. un.	Relative deviation, %
Square	$1.64 \cdot 10^4$	–41.8	0.943	–1.67
Rhombus	$2.82 \cdot 10^4$	0	0.943	–1.67
Pentagon	$2.20 \cdot 10^4$	–22	0.959	0

The analysis of the data presented in Table 2 based on the two-parameter optimisation objective function (1) of the structural and algorithmic organisation of the investigated IoT system for soil and climate parameters monitoring in crop farming allowed the following conclusions to be drawn. According to the partial criterion of the normalised value of the total coverage area, the most optimal model is the rhombus pattern ($S_{cover\ norm}$=$2.82 \cdot 10^4$ m^2/num.), while according to the criterion of the probability of uninterrupted operation, the most optimal is the pentagon pattern (P_{uptime}=0.959). In this article, the compromise of finding the optimal value of the two-criteria function was solved as follows. The $S_{cover\ norm}$ for the pentagon pattern is 22 % lower than that of the rhombus pattern, and the P_{uptime} for the pentagon pattern is 1.67 % higher than that of the rhombus pattern. Assuming equal weighting of the normalised value of the total coverage area criteria and probability of uninterrupted operation the most efficient geometric model for constructing the WSN is the rhombus pattern. Therefore, the functional nodes (Type A sensor nodes) should be arranged according to the rhombus pattern within a single functional field segment (local field's infocommunication infrastructure) with subsequent data aggregation occurring at the base station as shown in Fig. 3. The number of such field segments can be determined based on the total area of specific agricultural crop field being monitored, as the ratio of the total field area to the area covered by a single field segment (the maximum value of $2.54 \cdot 10^5$ m^2, this value was determined from the plot in Fig. 5a – the local maximum for the rhombus pattern).

3.2. Computer model of hardware and software of the IoT system

To validate the obtained results from the criterion synthesis of the structural and algorithmic organisation of the investigated IoT system for soil and climatic parameters monitoring, a computer model of the hardware and software was developed (see Fig. 7). When developing and testing the corresponding model, the number of functional blocks (local field's infocommunication infrastructure) was chosen equal to 4, covering a field area of approximately 100 ha.

In the provided model (see Fig. 7): the node SINK_70 (located at the centre of the model) serves as the base station (see Fig. 3, Type C), the nodes S_28, S_36, S_49 and S_61 (located at the centres of the rhombuses) function as devices for local data aggregation and preliminary statistical data processing (see Fig. 3, Type B), all other nodes represent models of intelligent sensors of physical and chemical parameters (see Fig. 3, Type A). Furthermore, as mentioned earlier, each of these functional nodes represents a hardware and software solution operating on a specific network technology (see Fig. 4). In the CupCarbon software, the configuration of these functional blocks was done using software tools in the form of SenScript blocks. The developed software components for the respective functional nodes in the model are shown in Appendix A.

The main purpose of the computer experiment in the CupCarbon simulation environment was to validate the network interaction of wireless sensor nodes operating on the appropriate network technologies (see Fig. 4) and arranged in the specific topology (see Fig. 3) based on the rhombus pattern (see Fig. 7). During the validation of these computer models, the following parameter settings were configured: the maximum range of ZigBee modules was 50 m (average dynamic range) and the maximum range of LoRa modules was 7500 m (average dynamic range). The probability of hardware and software components failure was taken into account in the corresponding SenScript blocks by using the 'kill' operator, which imitates the exit of WSN modules from the operational state with a present probability. The numerical value of the probability of WSN modules failing to operate was taken to be 0.057, which corresponds to the worst-case scenario, taking into account the lifetime of 5 years. It is also worth noting that the characteristic features of the terrain and weather conditions affecting the functioning of the IoT system were not taken into account in this computer experiment. This omission stemmed from the functional limitations of the modelling environment and will be addressed in further research.

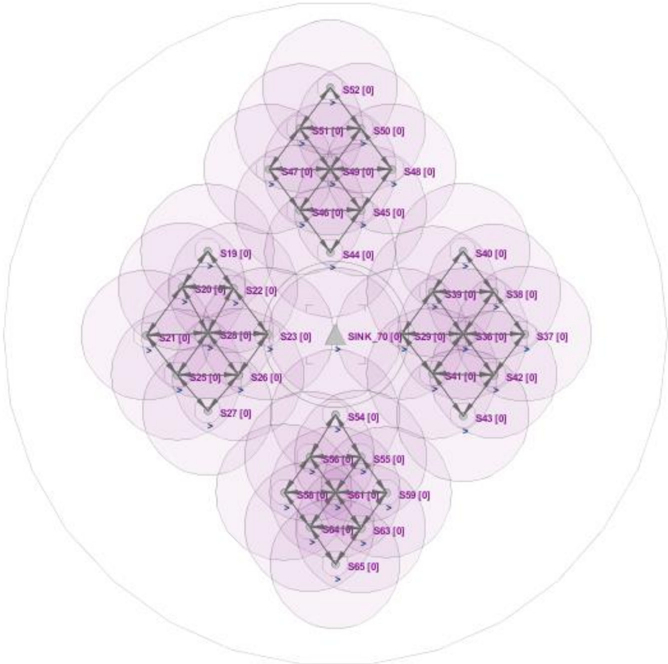
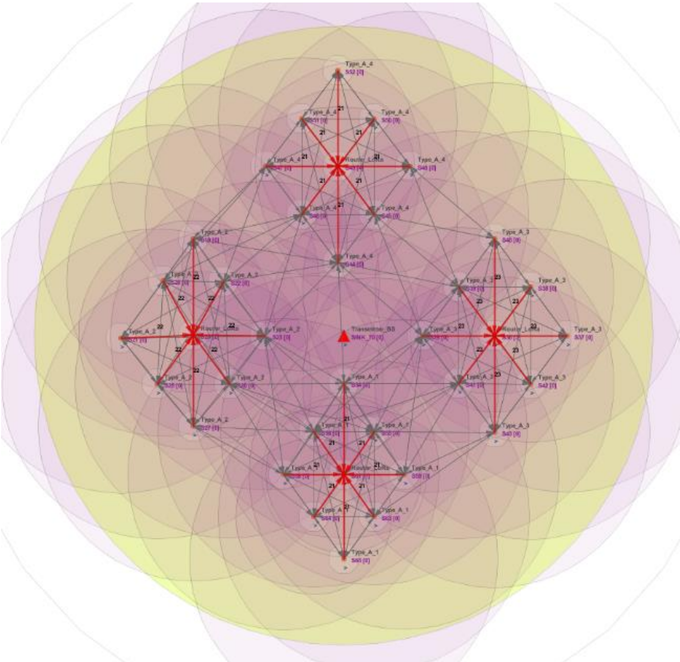


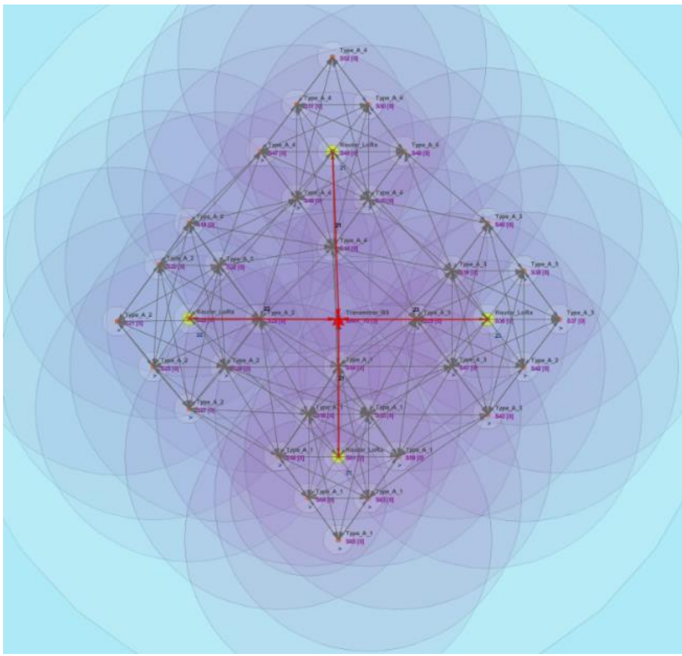
Figure 7. The developed imitation computer model of the WSN-assisted IoT system on agricultural monitoring using the CupCarbon software

The developed computer model of hardware and software of the IoT system for soil and climatic parameters monitoring was tested using the CupCarbon software, as shown by the graphical results in Fig. 8. The following geometric notations are shown in Fig. 8: purple circles (see Fig. 8a and 8b) are the coverage areas of the respective Type A wireless modules using ZigBee technology; yellow circle (see Fig. 8a) is the coverage area of the Type C module in passive mode; blue area (see Fig. 8b) is the coverage area of Type B (LoRa transmitter mode) and Type C (LoRa receiver mode) modules; a fragment of the light green circle (see Fig. 8c) – the coverage area of the Type C module when switching to LTE technology; grey lines show the areas of potential communication of wireless modules; red lines simulate the paths of directed data transmission between wireless modules by the corresponding identifiers, as described in more detail in the program code (see Appendix A). During the development process, it was considered essential to position all Type A nodes equidistantly from the corresponding Type B rhombus centre to achieve direct communication via ZigBee technology, eliminating the need for additional retransmitters.

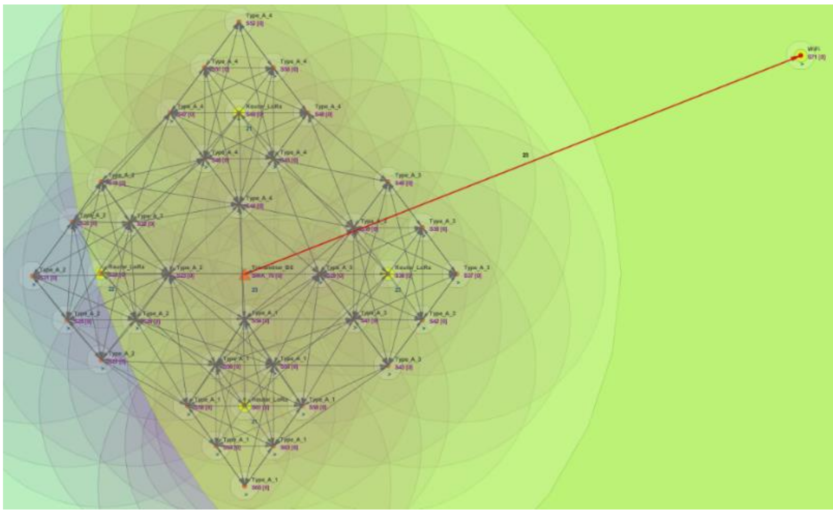
The validation of the developed computer model (see Fig. 8) has confirmed the functionality and effectiveness of the synthesised structural and algorithmic organisation of the IoT system. This fact was established through the detection of information messages at the corresponding functional nodes of the model, which execute algorithms for wireless network data sending / receiving. It should also be noted that the developed model serves as a functional and algorithmic basis for designing an experimental prototype of the investigated IoT system. Therefore, this computer model requires further research in the priority areas as described in detail in Section 4.



a) The result of the transmission of informational messages from the Type A functional nodes to the Type B nodes



b) The result of the transmission of informational messages from the Type B functional nodes to the Type C node (base station)



c) The result of the transmission of informational messages from the Type C functional node to a remote cloud server

Figure 8. Graphical results of the validation of the IoT computer model of the agricultural monitoring system

The validation of the developed computer model (see Fig. 8) has confirmed the functionality and effectiveness of the synthesised structural and algorithmic organisation of the IoT system. This fact was established through the detection of information messages at the corresponding functional nodes of the model, which execute algorithms for wireless network data sending / receiving. It should also be noted that the developed model serves as a functional and algorithmic basis for designing an experimental prototype of the investigated IoT system. Therefore, this computer model requires further research in the priority areas as described in detail in Section 4.

4. Discussion and suggestions for future investigations

The main scientific and applied effect of the results obtained in this article lies in the development of the theory for the designing and utilisation of wireless IoT systems for agricultural monitoring. The development of the investigated theory specifically focuses on the aggregation of distributed edges and exchange of measurement data within a wireless network. This effect was achieved through the development of the computer-oriented model of the IoT system for soil and climatic parameters monitoring of agricultural objects. The developed model is based on the optimised structural and algorithmic organisation that considers the partial criteria of maximum hardware and software component uptime and maximum coverage area with a minimum set of wireless sensor modules. The model developed serves as a structural and algorithmic foundation for the design of a prototype of the corresponding IoT system intended for agrotechnical monitoring.

The investigated model made it possible to assess the probability of fault-free operation of the wireless network organisation of the IoT system, the coverage area during wireless data exchange, taking into account the number of WSN modules involved, with the possibility of proportional scaling of the system aligned with the actual area of agrotechnical crop production facilities. The model implements algorithms of online detection, multi-level network data exchange, formation of a local database of monitoring results, as well as transmission of information messages to a remote cloud server via the Internet. Further development of the theory of constructing IoT systems for agricultural monitoring based on the results of this article involves research in the following prioritised directions:

1. Substantiation of hardware components for system construction. As a result of the conducted research, it was determined a priori that: Type A functional nodes represent intelligent sensors (consisting of sensors connected to a budget microcontroller coupled with Xbee wireless communication module), Type B functional nodes represent intelligent sensors with more advanced functionality (consisting of sensors connected to a more advanced microcontroller that performs statistical computations in quasi-real-time mode, coupled with both Xbee and LoRa wireless communication modules), Type C functional node represents an IoT gateway that performs functions such as data aggregation, network protocol transformation, intelligent computing, as well as local and remote routing of information messages.
2. Integration of routing software components with intelligent data processing software tools in order to support automatic decision-making techniques for agricultural practices.
3. Testing the interaction algorithms of the developed computer-oriented model with remote IoT platforms for remote monitoring of detected soil and climatic parameters.
4. Experimental refinement of the calculated values of the parameters of the probability of uninterrupted operation and failure probability, while taking into account the negative impact of environmental factors and the actual technical and functional characteristics of the hardware and software components of the IoT system.
5. Implementation of the hardware and software solution of the IoT system prototype based on the developed computer-oriented model and its long-term experimental testing aimed at optimising the structural and algorithmic organisation of the IoT system and adapting it to various deployment and usage conditions, in particular, the consideration of the actual terrain and the impact of destabilising factors (climatic and technogenic) on the quality of wireless data exchange.

5. Conclusions

This article solves the relevant scientific and applied problem of substantiating the principles of synthesis of the structural and algorithmic organisation of IoT systems for agricultural monitoring of open-field crop objects.

The structural and algorithmic organisation of the IoT system proposed in this article unlike existing ones is synthesised taking into account the integral impact of the criteria related to the number of wireless network modules, coverage area and probability of uninterrupted operation of the network organisation of WSN modules.

The study in this article is focused on selecting the optimal geometric model of the wireless sensor network of the IoT system. The optimality criteria takes into account simultaneous influence of the following parameters: maximum uptime of hardware and software components, maximum network coverage, and minimum number of wireless sensor modules used. The following geometric models were analysed: square, rhombus and pentagon. Based on the integral criterion of maximising the coverage area, the probability of failure-free operation and minimising the number of wireless sensor nodes used, the rhombus pattern proved to be the most optimal. The normalised value of the coverage area to the number of deployed wireless module was calculated – $2.82 \cdot 10^4$ m^2/num. and the reliability of the WSN structure over five years of operation was determined – 0.943.

The developed and validated computer-oriented model of the software and hardware implementation of the agricultural monitoring IoT system is based on multi-level data exchange algorithms using ZigBee and LoRa technologies. It includes the transmission of statistically processed data to a remote cloud server via the Internet. In addition, the developed model provides for the possibility of local microprocessor transformation of measurement data, which correlates with modern trends in fog and edge computing. However, it is worth noting that the developed model requires additional improvement through long-term experimental tests in real production conditions in order to take into account the destabilising impact of climatic and technogenic factors on the estimated technical and functional characteristics of the IoT system.

Additionally, the imitation computer model of the network data exchange for soil and climatic parameters monitoring was developed and validated using the CupCarbon software. The results of the computer experiment demonstrated the adequacy of the proposed structural and algorithmic organisation of the investigated IoT system in terms of the objective performance of multi-level data transmission algorithms using ZigBee, LoRa and Internet technologies. The developed model of wireless data exchange is based on the principle of addressable directed network exchange of measurement data, which minimises the negative impact of radio transmission collisions and duty cycles when scaling the developed WSN network.

The conducted research provided the foundation for the set of priority directions for further investigation of the developed computer-oriented model of the IoT system. These directions aim to enhance existing approaches to the construction of applied infocommunication technologies for online monitoring in agricultural applications.

List of abbreviations:

AI	Artificial Intelligence
BLE	Bluetooth Low Energy
DPM	Dynamic Power Management
FAO	Food and Agricultural Organization
GA	Genetic Algorithm
ICT	Information and Communication Technologies
IoT	Internet of Things
LoRa	Long Range
LPWAN	Low Power Wide Area Network
LTE	Long Term Evolution
MANET	Mobile Ad-Hoc Network
ML	Machine Learning
MQTT	Message Queuing Telemetry Transport
num.	Number of Wireless Devices
PLC	Programmable Logic Controller
rel. un.	Relative Unit
WANET	Wireless Ad-Hoc Network
WSN	Wireless Sensor Network

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Appendix A – SenScrip blocks

For Type A functional components:

```
loop

/* reading values from sensors, the number of operators for
data reading is determined by the number of sensors
connected to each wireless node (Type A) */

areadsensor T // temperature
areadsensor W // humidity
areadsensor E // effective lighting
areadsensor R// precipitation
getpos pos_A// reading transmitter’s coordinates

/* data transmission to Type B module, addressed delivery
to the module located at the centre of the corresponding
rhombus was used for data transmission, the transmission
was performed using the identifier MY depending on the
device's location to which the data is being sent S_61 –
MY=1, S_28 – MY=2, S_36 – MY=3, S_49 – MY=4) */

kill 0.057 // simulation of WSN modules failure
for i 1 4 1 // cyclic data transmission
send T 0 i
delay 1000
send W 0 i
delay 1000
send E 0 i
delay 1000
send R 0 i
delay 1000
send pos_A 0 i
set i i+1
end
delay 60000 // the transmission period is set to 1 minute
```

For Type B functional components:

```
loop
wait // waiting for data to appear

// setting up ZigBee data receiving technology

kill 0.057 // simulation of WSN modules failure
radio "radio1"
```

```
read T // reading temperature data
printfile T // writing temperature value to file
read W // reading humidity data
printfile W // writing humidity value to file
read E // reading effective lighting data
printfile E // writing effective lighting to file
read R // reading precipitation data
printfile R // writing precipitation to file
read pos_A // reading the coordinates of data transmitter
printfile pos_A // writing coordinates to file
delay 1000

// setting up LoRa data transmission technology

radio "radio2"
/* CupCarbon does not allow implementing a file reading
function so during the network simulation the data in the
file was averaged autonomously and assigned to respective
variables (TT, WW, EE, RR) for testing the corresponding
model */

set TT 21
send TT // sending averaged temperature data
delay 1000
set WW 83
send WW // sending averaged humidity data
delay 1000
set EE 8932
send EE // sending averaged effective lighting data
delay 1000
set RR 2
send RR // sending averaged precipitation data
delay 1000

// reading and sending the coordinates of data transmitter
getpos posLoRa
send posLoRa
delay 60000 // the transmission period is set to 1 minute
```

For Type C functional component:

```
loop
wait

// setting up LoRa data transmission technology

kill 0.057 // simulation of WSN modules failure
radio "radio2"
read TT // reading temperature data
```

```
printfile TT // writing temperature value to file
read WW // reading humidity data
printfile WW // writing humidity value to file
read EE // reading effective lighting data
printfile EE // writing effective lighting to file
read RR // reading precipitation data
printfile RR // writing precipitation to file
read posLoRa // reading the coordinates of data transmitter
printfile posLoRa // writing coordinates to file
delay 1000

/* Setting up Internet connectivity technology for data
transmission to cloud server */

radio "radio3"
send TT
delay 1000
send WW
delay 1000
send EE
delay 1000
send RR
delay 60000 // the transmission period is set to 1 minute
```

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