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Wireless Sensor Network based Forest Fire Early Detection Systems: Development and Implementation

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ABSTRACT The article is devoted to the development of a monitoring system based on wireless sensor networks. The purpose of the article is to implement a system for environmental monitoring using wireless sensor networks, as well as to solve the problem of covering the area with this network. Wireless sensor networks and their involvement in environmental monitoring are investigated and interactions between wireless networks and data communication protocols are described. The monitoring system is considered and analyzed. An experiment is conducted in which it has been checked at what maximum distance the temperature parameters can be transmitted, the experiment is conducted with and without interference. Routing algorithms for how they work and how parameters (temperature) are transmitted from sensors to the server are considered. A terrestrial monitoring system layout for environmental monitoring is investigated and developed based on Zigbee wireless sensor network construction technology, given that it can be added to this network new units or their replacement. The Mesh topology is selected and the separate physical devices that are the nodes of this network are identified. Nodes are also designed, using modules from Digi called XBee as a base station for Arduino sensors and as a ZigBee data base. These nodes are investigated for noise immunity and stability using flame, smoke and temperature sensors. The study found that XBee nodes are very unstable working near Wi-Fi routers and interfering in the form of forest. The conclusion about the result of the experiment is formulated, as well as how the system can be further upgraded, which can be added and what parameters can be observed. The proposed method for the location of the ground forest fire monitoring system's equipment ensures full control and the flame detection preciseness.

KEYWORDS monitoring; wireless sensor network; forest fire; ZigBee technology; a covering; universal system.

I. INTRODUCTION

IN the world, the problem of forest fires has reached a high level of criticality in recent years. The loss of forests is not just a loss of the green massif, but also serious changes in the level of reservoirs, rivers, the activation of erosion processes, the reduction of oxygen in the air and the increase of the radiation background on the planet [1].

According to the State Statistics Committee of Ukraine, the largest number of forest fires occurred in Kyiv last year - 207. In the Kyiv region, 139 fires occurred in the year, in the first five there were Southeastern regions - Kherson (184), Dnipropetrovsk (177) and Zaporizhzhya regions. (109). The total amount of damage caused to Ukraine by forest fires is 8.6 million UAH. The most traditional method of detecting fires is the visual detection by people of specialized structures - towers. The present method has been used for more than a hundred years with minor improvements related to the use of communications (radios, cellular communications, etc.) and optical visual control devices (binoculars, telescopes, etc.) [2]. Ideally, the detection of fire is as follows: on a specialized rig (intended for long stay on it person) on a special site is a person. A significant disadvantage is the high cost of the tower, as the tower must be specially equipped for permanent stay on it. For example, the cost of a tower intended only for the placement of equipment is 5000 UAH ($185) per meter height, the cost of a fire tower is more than 25000 UAH ($925) per meter [3]. For this reason, fire towers have not been installed for more than 15-20 years, and most of them can no longer be used due to emergency technical condition.

According to the World Fire Statistics, if we take countries that number more than 1,000 deaths a year through fire, heat or hot substances, A total of about 138,000 people died in 2015 in such countries [4]. Growth in the number of the high level indexed publications on forest fires and remote sensing during the last ten years is in four time [5].

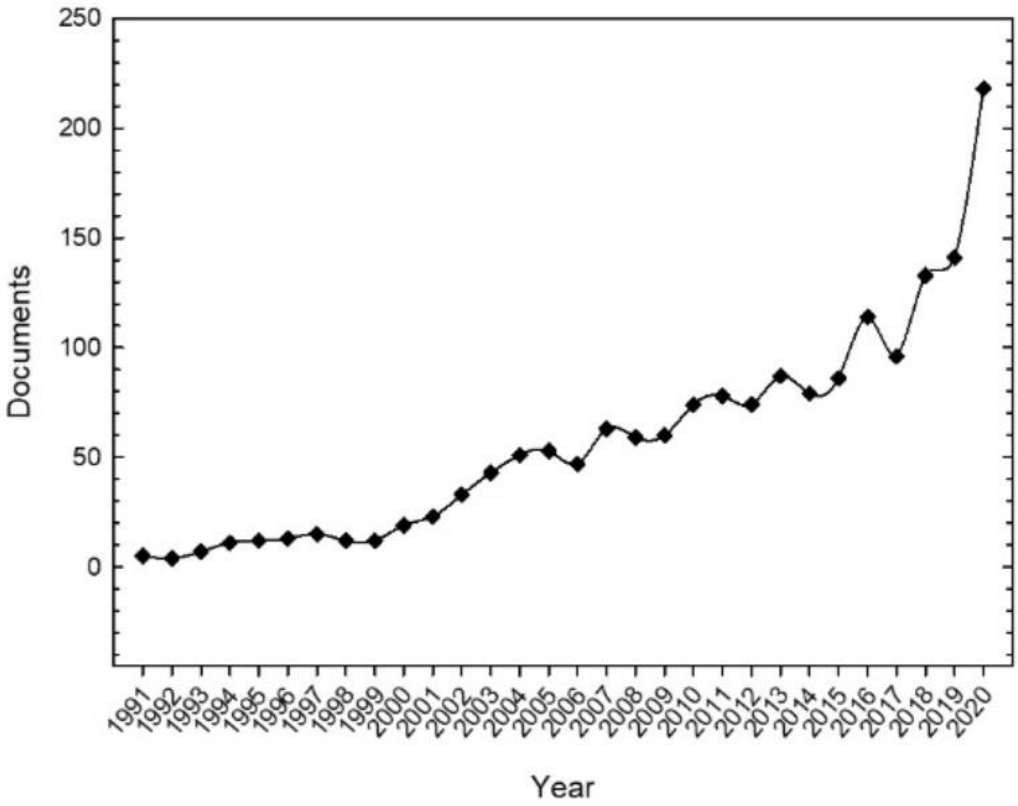

Figure 1. Growth in the number of publications on forest fires and remote sensing available in the Scopus database [5]

In the article, the authors propose to consider algorithms and methods for covering the forest area with sensors, designing a wireless sensor network that will transmit data to the server with the help of ZigBee technology. This sensor network enables the detection of fire and the location of the fire. The versatility of this sensor network will also be considered [6].

Therefore, the purpose of this work is to create a wireless sensor network, to design a method of covering the area with sensors that, using the technology of ZigBee, will transmit data. This sensor network allows you to determine the presence of a fire and the location of a fire.

The main provisions of this article are outlined as follows. Section 2 describes related methods for early detection of wildfires. The methods and algorithms for forest area coverage by sensors are presented in Section 3. Section 4 shows the design of the wireless sensor network, also discusses the routing algorithm and data transmission protocols and the conducted experiment. The versatility of the system is outlined in Section 5. Conclusions and prospects for future research are outlined in Section 6.

II. RELATED WORKS

Additionally, azimuth circle is applied to the site to determine the direction. In the visual detection of fire, the observer determines the direction of the fire using the azimuth circle and reports this direction to the control center by means of communication. The control center determines with which towers another fire can be detected and communicates with another observer, who also detects the fire and determines the direction to it.

Then in the control center, using known directions from the towers to the fire, determine the location of the alleged fire and take measures to eliminate it. The main disadvantage of this method of detection is the need to constantly use human labor at each point of the tower, throughout the fire season (to ensure promptness) and limit the monitoring area to the number of towers installed.

Another method of detecting fires is the detection of fires from the air, from aircraft. Pilot on the aircraft (light aircraft, helicopter) with some frequency fly around the fire-hazardous area, in the visual detection of fire navigator determines its coordinates and transmits to the control center information about the detected fire. The main advantage of this method is the ability to monitor any even the most remote and wild territory. The main disadvantage is the very high cost of flying hours over 10,000 UAH ($370). In addition, specially trained personnel are required. It is also impossible to continuously monitor a large area, which can be a cause of late fire detection.

Unmanned aerial vehicles are gaining some popularity, which can reduce the cost of a flight a little but does not eliminate the problem of untimely detection. The cost of an unmanned aircraft of imported production is ~ $ 1,000,000.

There is also a satellite monitoring system. Specialized satellites in non-geostationary orbits produce images of the Earth's surface in the IR range. Based on the difference between the surface temperature of the earth and the temperature of the fire, it may be possible to determine its location. The picture is transferred to special centers from where interested users can receive all data through the Internet.

The advantages of this method include the automation of the process of obtaining data, the distance of the method, the ability to monitor any area, easy access to information through the Internet. The disadvantages of satellite monitoring include the large area of the minimum detected fires, which ranges from 1 to 50 hectares, the low frequency of data acquisition (several times a day) and the strong influence of weather conditions. In windy weather, delaying the detection of even a small fire can have serious consequences and increase the cost of eliminating it [8].

In the last few years, video monitoring systems designed to detect wildfires are beginning to emerge. The main feature of the video monitoring system is the high degree of automation and the ability to use cheap and simple rigs.

Existing systems are rotary cameras mounted on towers from the video image to the operator's console, which should be located near the video monitoring post.
This approach does not allow you to determine the coordinates of the fire. It is also not feasible to scale such a system; in fact, at every monitoring point, the customer must keep a person who will carry out visual control (Fig. 2) [9, 10].

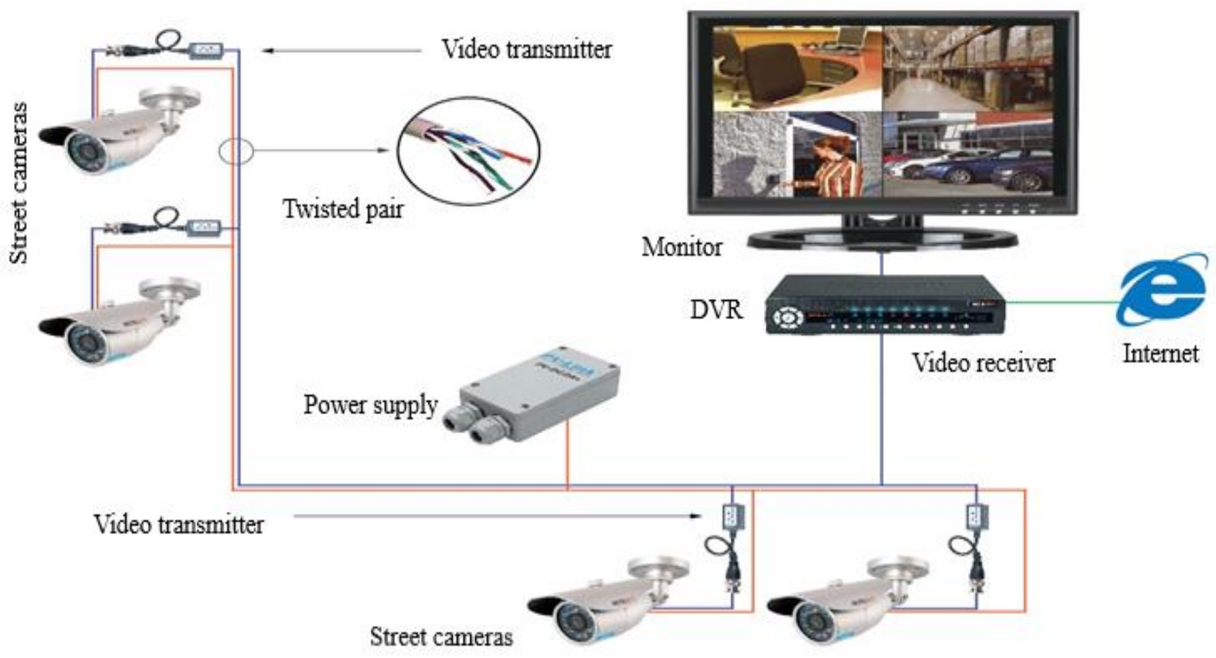

Figure 2. Forest fire early detection system with CCTV cameras [11]

Other studies present modern systems for monitoring and detecting fires based on the use of stationary sensors. In particular, technologies for detecting forest fires based on wireless sensor networks (WSN) were proposed in studies [12, 13]. Space satellite based monitoring systems for detecting fires and agriculture related monitoring are described in [14].

The ground systems for forest fire monitoring require a special approach to design that would, first of all, ensure the rapid and precise flame detection, as well as the full control of forest sites. There is an active growth of the design approaches to the ground systems for the forest fire monitoring based on wireless video-monitoring and sensor network technologies.

III. METHOD AND ALGORITHM COVERAGE

There is a big variety of possible placing of centers of the circles to cover the defined area. Combinations of circles with 2 or 3 different radii are possible. Let us look at the system of the covering based on the equal radius circles. There are two ways to arrange the circles to cover the defined plane based on a square (Fig. 3) and an equiangular triangle (Fig. 4) [15].

In covering T1, any three pair-wise adjacent lattice knots are vertices of an equiangular triangle (Fig. 4) with the side $R\sqrt{3}$ and the circles with the centers on the vertices are crossed in a unique common point. In covering S1, four pair-wise adjacent knots are square vertices (Fig. 3) with the side $R\sqrt{2}$ and the circles of radius R with the centers on the vertices are crossed in a unique common point.

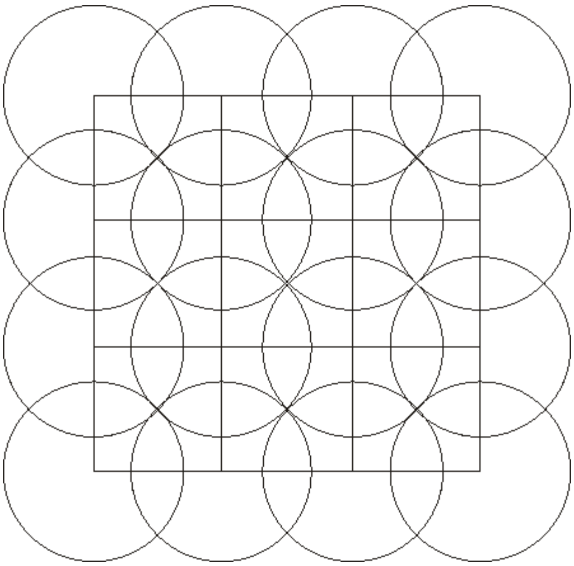

Figure 3. Covering of a plane with the equal radius circles based on the square (S1)

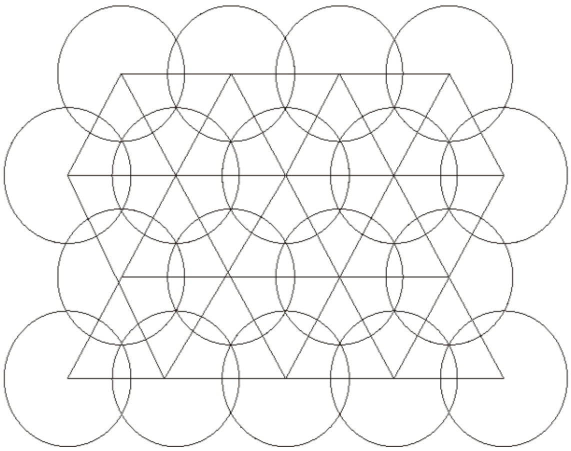

Figure 4. Covering of a plane with the equal radius circles based on equiangular triangle (T1)

The least dense coating T1 of a plane with equal radius circles [16], i.e., a covering of a plane with equal radius circles based on an equiangular triangle is known. The density of coverage of T1 – the ratio of the total area Sf of all parts of circles in a tile to the tile area Sf is equal to [17]:

$$D_{T1} = \frac{Sf_{T1}}{Sp_{T1}} = \frac{\pi R^2/2}{3R^2\sqrt{3}/4} = \frac{2\pi}{3\sqrt{3}} \approx 1{,}2091\,, \qquad (1)$$

and the density of coverage of S1 is equal to:

$$D_{Q1} = \frac{Sf_{Q1}}{Sp_{Q1}} = \frac{\pi R^2}{2\pi R^2} = \frac{\pi}{2} \approx 1{,}5708\,. \qquad (2)$$

The minimum number of circles N, sufficient for a covering of area S with the equal radius circles $R << S$, satisfies to the ratio

$$\frac{N\pi R^2}{S} = \frac{2\pi}{\sqrt{27}} \approx 1,2091.$$

Hence, the density of coverage of the area with the equal radius circles cannot be less than

$$\frac{2\pi}{\sqrt{27}} \approx 1,2091.$$

There is a problem of a rectangular area covering with circles, with detour of forbidden sites (ravines, rivers, lakes, roads, bogs, etc.), based on the technology of block structures given in work [18]. The further development of the algorithms offered in this work is the solution to a problem of covering for areas of any configuration with regards to forbidden sites and priority zones.

At the first stage the circle is replaced with a square K_{ij} which party is equal to $a = R\sqrt{2}$ where R – radius of the circle. All area S breaks into squares K_{ij}. The centers of the squares form a two-dimensional array of points M_{ij} being the centers of the circles which circumscribe the squares. Centre coordinates K_{ij} at known radius of a circle allow to determine the coordinates of vertices of the square easily. Splitting passes by definition of the size of area S across dXS which is equal to a difference between the maximum value of coordinate X of the range setting S and its minimum value (Fig. 5). The vertical size dYS can be determined similarly. An equiangular triangle with the side $R\sqrt{3}$ has been chosen to arrange the centers of the circles in the covering.

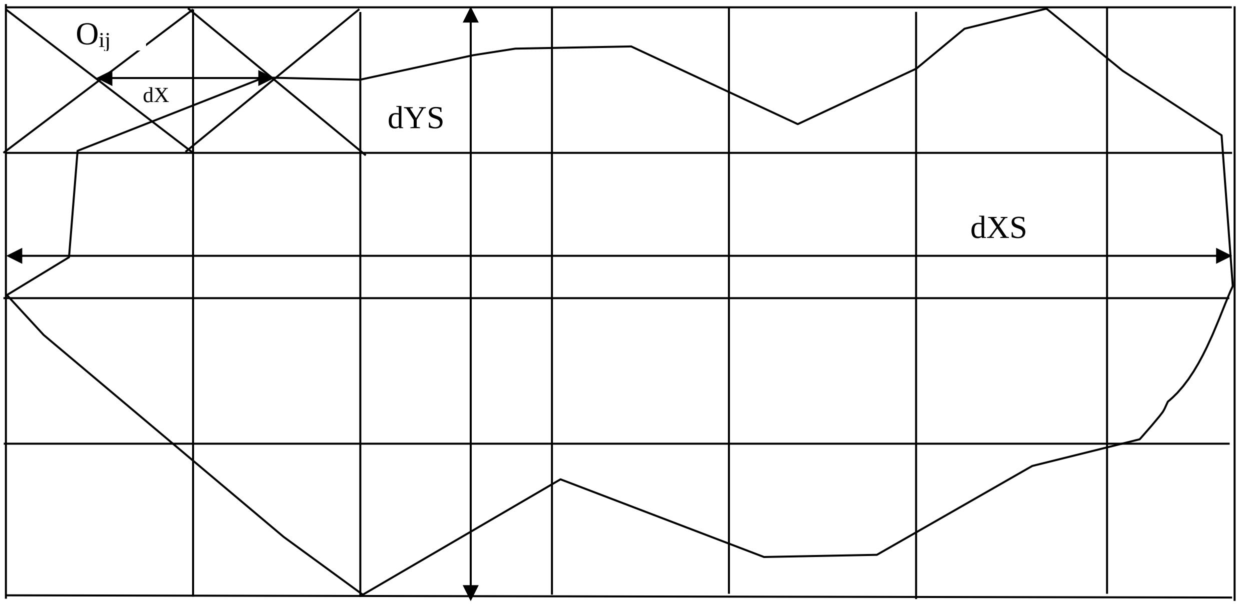

Figure 5. Splitting of the area into blocks-squares

The coordinates $M[xD, yD]$ of the square centers should be defined after a formation of the two-dimensional array. The Y-coordinate is constant for lines, and the X-coordinate belongs to columns. The first center coordinates are defined by formula:

$$X = MinX + corect\,, \tag{3}$$

$$Y = MinY + corect\,, \tag{4}$$

where

$$corect = R^2 - \frac{dX^2}{4}\,, \tag{5}$$

and $MinX, MinY$ are the minimum coordinates of the range which defines S. The X-coordinates of the M array are increased by dX in the lines, and Y-coordinates are increased by dY in the columns. After the array is filled out, an alternating shift of the X-coordinates equal to $\frac{dX}{2}$ is made for lines. Thus, we achieve the placement of the triangle vertices.

The following step of the algorithm is about a removal of the centers which do not belong to S or belong to prohibited zone. This problem can be solved in several steps.

Consecutive checking is made if the point O_{ij} stays in the area S. In case if S does not contain the given point, it is defined as "Out of a zone". In case if any O does not belong to area S, the shortest distance d from the point O_{ij} to borders S is defined, and if $d < R$, then O_{ij} is moved to the nearest point of the area S.

Thus, all the area of S is covered. For any O should check if each point O_{ij} belongs to the area Z_j, where Z_j - the first prohibited area $j = \overline{1,n}$. If the statement is true, O_{ij} is defined as "forbidden". For $\forall O \in Z_j$ the arrangement scenario for the square in the prohibited zone is defined. The point O_{ij} is moving out in the case "a" (Fig. 6). If $R << S$, the point O_{ij} is transferred to the vertices, lying out of Z_j or to the square sides center in the cases "b", "c" and "d" (Fig. 6).

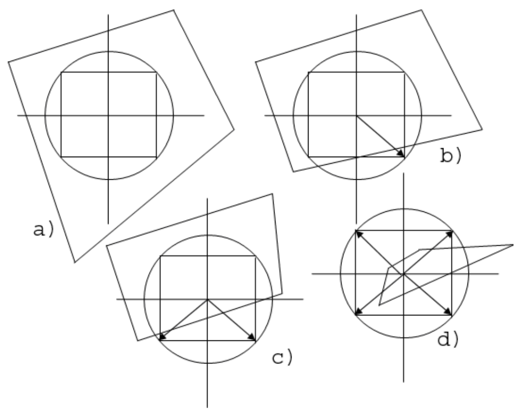

Figure 6 – Example of placing of the center O_i in Z_j : a – completely in zone; b, c – partially in zone; d – center only.

Otherwise, the point O_{ij} is moving to the nearest point of the area S. As a result, we received the area S with a set of prohibited zones Z that is completely covered with the circle of radius R with an exception of the prohibited zones. Then the whole area is checked upon the presence of the uncovered sectors. If such sector is detected, an additional center O_{ij} is added [19].

IV. DESIGNING A WIRELESS SENSOR NETWORK

WSN are usually deployed for control or monitoring over a long period of time (several months or years) in which case frequent replacement of power sources (batteries) in hundreds of sensor devices is not feasible and appropriate [20].

Thus, the energy consumed by each sensor node in the network is one of the limitations that must be considered when designing WSN as this factor affects the life of the sensor system and its components.

Only one module should act as the network coordinator, because it will transmit data from the sensors to the network or to the local server [21].

To ensure such maximum efficiency, the sensor unit needs to be in sleep mode for more than 90 percent of working time and "wake up" only according to the schedule or in connection with forced activation [22].

Since ZigBee protocols allow such sensor networks to be created, they have been chosen for the project [23].

A. ROUTING ALGORITHM

The basic routing algorithm on ZigBee networks – "Ad hoc On Demand Distance Vector" (AODV) is based on the concept of route vector when each router participating in a route request broadcast from a specific source to a specific destination creates its own record in the itinerary table. This entry shall at least contain a "logical distance" from the request source and the address of the previous router [24].

The parameters are transmitted from the sensor to the server as follows. The Arduino Uno is coupled to sensors temperature (t) and smoke (ϕ). The Xbee module connects to the Arduino Uno and with the help of at commands. The Arduino instructs the Xbee module to send data to the ZigBee coordinator and the coordinator sends the data to the server. Mesh topology is an ideal network connectivity topology because it has high reliability and resiliency [25].

Fig. 7 shows how parameters from sensors can be transferred to the server.

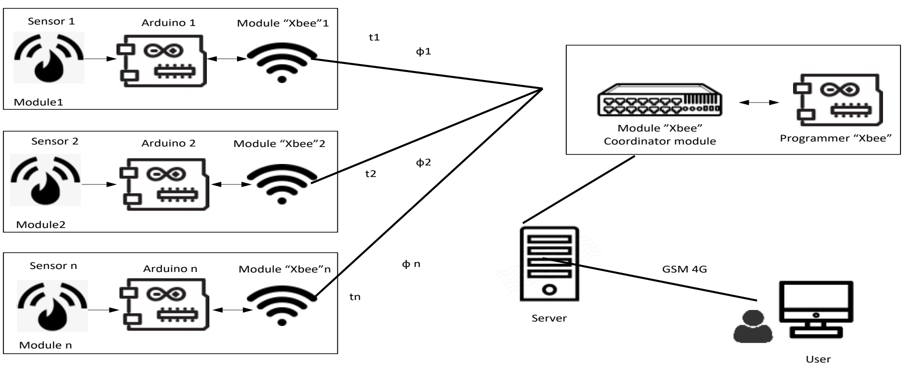

Figure 7. The process of transferring parameters from sensors to the server

B. DATA TRANSFER PROTOCOLS

Networked devices communicate with each other using their own protocols, according to their needs and performance level. To facilitate integration with the Internet of Things, IPv4, IPv6-base protocols are developed and adapted to the requirements of the new type of networks.

RPL (Routing Protocol for Low Power and Lossy Networks) is a simple protocol for providing status data for low-power and unreliable networks. Not only does RPL provide cost-effective routing for micro devices with limited power supply, but it also supports a variety of uses for networks with "smart" objects: Multipoint-to-Point Traffic (MP2P), Point-to-Multipoint Traffic (P2MP), Point-to-Point Traffic (P2P) [26].

6LoWPAN (IPv6 standard over Low power Wireless Personal Area Network) [27] allows devices to obtain their own IPv6-based IP address and is used to easily integrate technology into existing networks.

C. EXPERIMENT

The experiment was conducted in the forest and in the field in order to observe the transmission of parameters with obstacles (in the forest) and without the interference (in the field)

An XBee Series 2 programmer and module was connected to a computer that acts as a server to which temperature and smoke data should be received. We also connected a temperature and smoke sensor to an Arduino Uno board and a battery powered XBee Series 2 module.

Equipment:

XBee Series 2 modules, programmer, DHT11 temperature and temperature sensor, Arduino Uno board, computer or power cable, power bank (used in experiment but could use other power source).

During the experiment it turned out that without interference, the transmission of parameters is as follows, the result of measurement without interference is shown in Table 1.

Table 1. The result of the experiment without interference

Distance (meters)	Delay
10 - 30	Within normal limits
43	5 seconds
55	15 seconds
60	1 minutes
62	The data transfer does not occur

Interference transfer is as follows. Interference measurement result is shown in Table 2.

Table 2. The result of the experiment with interference

Distance (meters)	Delay
10	Within normal limits
20	5 seconds
25	30 seconds
30 - 40	1 minutes
62	The data transfer does not occur

The experiment was carried out in the area of trees and solid bushes.

The proposed methods and the developed tools provide improving the completeness and the preciseness of the ground forest fire monitoring systems.

V. SYSTEM VERSATILITY

This system consists of a sensor network, which in turn consists of temperature sensors, and a server to which data arrives, which are subsequently displayed on the site map. Replacing sensors with sensors of a different type will not lead to a breakdown of the application. Thus, we can say about the universality of the considered system and its use not only for early detection of forest fires, but also for automation of air humidity measurement for meteorologists and even for automation of the protection of strategically important objects using motion sensors.

Figure 8 shows an example of covering an area of arbitrary configuration with circles, taking into account the restricted areas for the placement of wireless sensor network equipment.

Figure 8. Coverage of the resulting area with circles (sensor range 50 m)

VI. CONCLUSIONS

The article is devoted to the development of a monitoring system based on wireless sensor networks. Wireless sensor networks and their involvement in environmental monitoring are closely monitored. It is described how wireless networking and data communication protocols interact.

A coverage algorithm is developed with an accuracy of 100 percent. This accuracy was achieved due to the successful passage of the test algorithm associated with areas of increased danger and with zones with a ban on the placement of sensors. In these additional scenarios, the algorithm checks the area for the presence of forbidden zones or zones with increased danger and adds an additional center, that is, it adds another node of the sensor network. Thus, covering the entire desired area, without leaving any piece of land without observation and evaluation.

As a result of the research, a mock-up of a terrestrial monitoring system is developed for eco-logical monitoring based on wireless technology of building Zigbee sensor networks, taking into account the fact that new nodes may be added to this network or their replacement may be complete. The Mesh topology is selected and the distributed physical devices that are the nodes of this network are identified.

Nodes are designed to be used as a base station for Arduino sensors and in some ZigBee database transmission modules from Digi called XBee.

Data on nodes for noise immunity and stability are investigated using flame, smoke, and humidity sensors. The study found that XBee nodes are very unstable working with Wi-Fi routers and interference. Also, in the course of the experiment, it can be concluded that sensor networks can be used not only for the system of early detection of wildfires as the transmission of the main parameters: temperature and smoke to the server. Sensor networks can also be used to monitor any other environmental processes such as weather monitoring, environmental monitoring, and prevention of natural disasters.

In the future, we plan to implement a device to increase the reliability of each node of the network. This will reduce the number of nodes due to the reduction of high-risk areas. It will also be necessary to further improve the coverage algorithm for devices for reliability.

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