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Models for ensuring the interconnection of wireless sensor network nodes

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ABSTRACT: The article describes the connection of wireless sensor networks, provides methods for assigning and evaluating the connection, and analyzes the use of connectivity for wireless sensor networks. Connectivity is one of the most important indicators of wireless sensor network (WSN) performance. The Erdesh-Reni model was used as the model for linkage estimation, simulation results are presented. An algorithm is developed that allows you to select positions to add additional nodes to the network. The article explores network connectivity as one of the key performance indicators. The choice of this indicator is based on the fact that the linkage characterizes the possibility of providing data services, ie the availability of services. The obtained results confirm that the Erdesh-Reni theorem can be used to evaluate WSN binding. A study of the probability of WSN binding in a three-dimensional space depends on the radius of contact and the number of nodes revealed the statistical equation of the results obtained from the Erdesh-Reni model. The possibility of using a random graph model for the number of network nodes is analyzed.

KEY WORDS: Wireless sensor network, connectivity, Erdesh-Reni models, unmanned aerial vehicles, data transmission, network connectivity, simulation results, Poisson field, threshold probability.

I. INTRODUCTION

The scope of the WSN is constantly expanding. Today, these technologies are used in everyday life, transport, logistics, housing, security, military Affairs, medicine, and many other areas. With their help, as well as their interaction with other networks, monitoring and management tasks are solved. The use of wireless technologies and self-organization functions in many cases allows you to find quick and effective solutions to such problems of information delivery, which using traditional technologies can not be done, is inefficient or requires significant time[1-4].

The development of concepts of increasingly penetrating sensor networks and the Internet of things (IoT) can be considered as a continuation of the evolution of the WSN. The variety of applications of these technologies requires determining the main indicators of their functioning and methods of evaluation. Different targets of the WSN impose different requirements for certain indicators, for which it is necessary to have methods and models that establish their relationship with the technical parameters of the network and its elements[5-9].

The paper examines the connectivity of the network as one of the main indicators of functioning. The choice of this indicator is due to the fact that connectivity characterizes the very possibility of providing an information delivery service, i.e. the availability of the service.

II. STATEMENT OF THE PROBLEM

The main function performed by the WSN, is the delivery of data. Depending on the final service received by the user, this may be telemetry data or data transmission (DT) of streaming services. Telemetry services cover a wide range of applications such as monitoring environmental parameters, technological processes, geographical coordinates, meter readings of electricity or heat consumption, the state of the human or animal body, and many others. etc. Streaming data transmission services include audio and video transmissions, which can also be implemented on the basis of the WSN when selecting the appropriate radio channel management technology that provides the required bandwidth. Depending on the intended purpose and the service being implemented, network requirements may differ significantly.

From the point of view of probabilistic-time indicators, it is customary to distinguish networks that are tolerant of delays and networks that are tolerant of losses [2]. The tolerance of the network to the value of a certain indicator indicates that it is not of primary importance for a specific target. The main indicators of the quality of WSN

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functioning, as well as indicators of other communication networks, can be divided into three main groups: availability, reliability, and time indicators.
Time indicators include the time to data rate, time and delivery variation (jitter), and throughput. Reliability indicatorsinclude the probability of data loss (loss coefficient), and the probability of errors in the delivered data.
The availability indicators include the probability of availability of the DT service, which in the WSN is largely determined by the relative location of network nodes and is characterized by connectivity (probability of connectivity). Also, the last group should include the lifetime, which in many cases is limited due to the use of non-renewable energy sources[10-13].
Depending on the intended purpose, one of the above-mentioned network quality indicators becomes dominant. For example, for fire safety monitoring, such an indicator of the quality of the function as the message delivery time is critical, and for DT about the readings of energy consumption meters (hot, cold water), the delivery time is less critical. If the network is used for monitoring a certain area, then the coverage indicator is of paramount importance.
For almost all applications, the connectivity indicator plays a significant role. The connectivity of a sensor network refers to the network property, which is the ability to establish a connection between network elements, such as a gateway and any of the network nodes. In sensor networks, heterogeneous connectivity is often found, i.e. a sensor node may have several independent paths connecting it to the gateway. Network connectivity is an important parameter that largely determines the survivability of the network. The loss of connectivity of the nodes in the network cease to perform their functions. It is quite difficult to calculate the connectivity parameters of a real network with a large number of nodes. Various models are used to evaluate connectivity.
Since the options for building a network can be different, it is advisable to characterize connectivity by its probability. The probability of connectivity is one when any node in the network can be connected to any other node in the network[15].

III. PROBLEM DECISION

A.CHOOSING A CONNECTIVITY MODEL

To represent the network structure, a graph model is often used, in which network nodes are represented by vertices, and communication lines (channels) are represented by edges. In the WSN model, the presence of an edge between vertices is determined by the location of nodes and the characteristics of their radio communication zones. When modeling WSN, as a rule, a circle of radius R with the center at the node location is used as a model of the radio communication zone. In case of a random location of network nodes, the connection between pairs of vertices is also random and can be described by the probability of a vertex falling into a circle of radius R.
The random nature of the connection between the WSN nodes suggests the possibility of choosing a random graph as its model. There are various models for describing random graphs [6-9]. In the late 50s and early 60s of the XX century, P. erdesh and A. Renyi proposed a model of a random graph, which is described as follows. Let be given a set V_n = { 1,…,n), whose elements are called vertices. A random graph with random edges is constructed on this set. The graph has no more potential edges than C_n^2. Any two vertices i and j are connected by an edge with some probability p $\in$ {0; 1}, which does not depend on the other C_n^2 -1 pairs of vertices.
In other words, the edges appear in accordance with the standard Bernoulli scheme, in which C_n^2 tests and *p* is the "probability of success". Denote by *E* a random set of edges that occurs as a result of implementing such a scheme. Put *G* = (V_n,E*)*. This is the random graph in the erdesh-Renyi model [6]. There are several theorems for this model. One of them describes a method for evaluating graph connectivity.

B.THEOREM

Consider the model *G(n,p)*. Let $p = c\frac{\ln(n)}{n}$. If *c*> 1, the random graph is almost always connected; if *c*< 1, it is almost always not connected. For our case, the main meaning of the theorem is that for *c* = 1, the probability of connectivity of the P_C graph is equal to a certain threshold value. For *c* > 1, the probability of graph connectivity is less than this value, and for *c* < 1, it is greater than it. From the point of view of the problems of building the WSN, the value of C can be judged on the extent to which the connectivity problem is solved.
In this model, there are no restrictions due to the length of the edges, while in the BSS, the maximum possible length of the edge is limited by the value R. For example, for the most common technologies for building sensor networks, such

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as ZigBee (IEEE 802.15.4) and Bluetooth (IEEE 802.15.1), the radius of the nodes is reached from 10 to 100 m, and for Wi-Fi (IEEE 802.1.1 b) technology from 20 to 300 m.Along with the restriction of the edge length, the WSN model also restricts the location of the network nodes.

IV. SIMULATION RESULTS

A simulation model has been developed to study the connectivity of the network under consideration and verify the applicability of the theorem. It generates a specified number of nodes with random coordinates in a bounded 3D area, and then finds the shortest paths between all pairs of nodes using the Floyd algorithm. The model then estimates the percentage of paths found out of the total number of possible paths. The resulting relation is an estimate of the probability of connectivity. The considered area of node placement is a cube (К= 250x250x250 м^3). The flat area (2D) is considered in [10].
We assume that the nodes are distributed randomly, i.e. they form a Poisson field [11]. During the experiment, the number of nodes in the cube varies from 20 to 100. Taking into account the characteristics of the ZigBee and Bluetooth standards, the communication radius is selected from 50 to 100 m. the simulation results are shown in Fig.1.

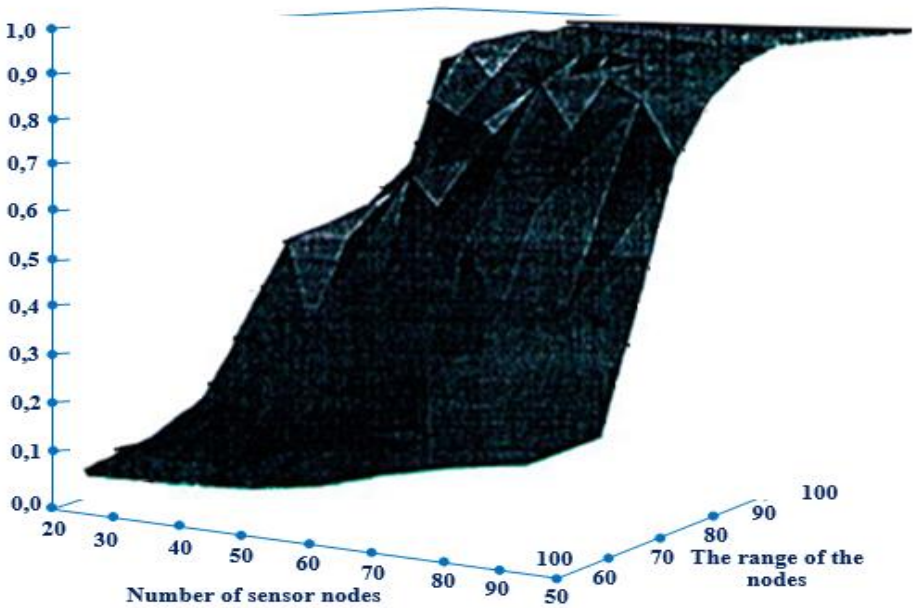

Fig.1. The probability of a tie R bond in the area of limitation with the cube radiusi and n is the dependence on the number of nodes

Since the nodes of the network form a Poisson field, the probability of the existence of a connection (edge) will be described by the probability of a random point (node) hitting the area bounded by a ball of radius R (Fig. 2):

$$p = \frac{V_{ball}\rho}{n} (1)$$

where p is the probability of nodes falling within the radius of action of the node; $\rho$is the density of network nodes (nodes/m^3); p is the total number of network nodes;$V_{ball} V_{ball} = \frac{4\pi R^3}{3}$m^3; R is the radius of connection of the node.

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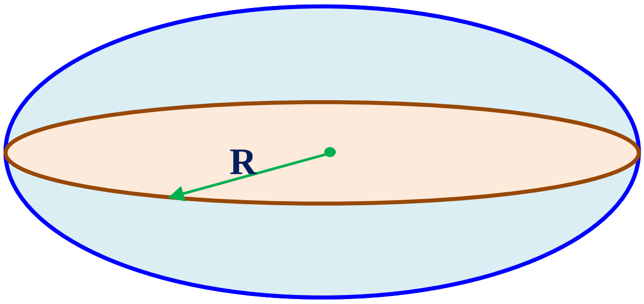

Fig.2. Node communication zone in three-dimensional space

Comparing the value of p with the threshold probability, which we define from the Erdesh-Renitheorem as

$$p_0 = \ln n / n \qquad (2)$$

we estimate the probability of network connectivity for the given parameters R and n. The Approximate value of the probability of connectivity can be obtained using the formula from [9]:

$$p_c = e^{-e^{-c}} \qquad (3)$$

where $c$is a constant from the expression $p_0 = \frac{\ln n + A}{n}$. For c=0, the probability of connectivity $p_c = e^{-1} \approx$ 0,37.

We estimate the dependence of network connectivity on the radius of nodes for a fixed number of nodes. For Fig.3 the dependence of the probability of network connectivity calculated by the simulation method on the radius of network nodes at n = 100 is given. According to the results obtained, the probability of connectivity at this point is 0.34 for R = 52 and 0.55 for R = 54. With linear extrapolation for the probability of connectivity of 0.37, we get R = 52.4.

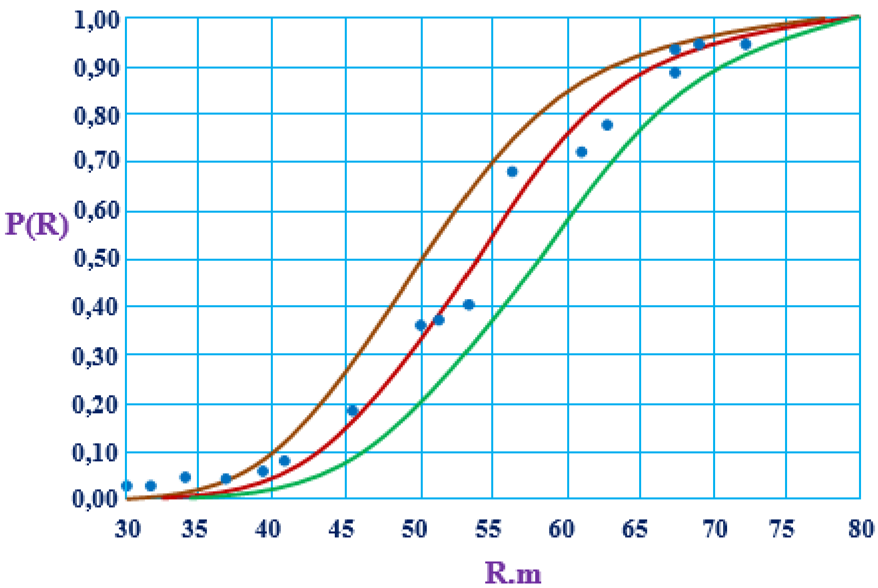

Fig.3. Dependence of the probability of coupling at the radius of the nodes when n = 100 and V=2504 $м^3$in the cube

According to (2), the threshold probabilityp_0=0,046, and the probability of hitting the ball for this radius by (1) is 0.039. The difference between these values is 15%. The simulation results were approximated using the S-curve:

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$$\tilde{p_c}(P) = \frac{1}{1 + e^{-\frac{R - r_0}{b}}}$$

where R and r_0 are parameters obtained by numerically approximating the curve to the simulation data. For fig.3 the upper and lower bounds of the confidence interval are given for the 5% significance level. The confidence interval includes the theoretical point p_0, according to the theorem and approximation (3).
Thus, the results obtained allow us to assert that, despite the limitations noted, the erdesh-renya theorem is applicable for estimating the connectivity of the WSN.
It is obvious that the use of a random graph model for WSN is appropriate if the number of network nodes is large enough. With a small number of nodes, the network structure can often be described geometrically and does not require the use of probabilistic methods. When investigating the applicability of the random graph model to describe the connectivity of the network, a simulation was performed that estimated the standard deviation (SD) of connectivity. For fig.4 shows the dependence of the network connectivity probability on the number of network nodes.
As can be seen from the above figure, the SD, and hence the error of the connectivity estimation, decreases as *1/n*. It is maximal at a small *n*, and stabilizes at *n*>50at the level of 20% of the estimated value. Thus, for a relatively small number of network nodes, the error in estimating connectivity using the random graph model may be too large. For practical calculations, if the number of nodes is 50 or more, the error is quite small (less than 20%).

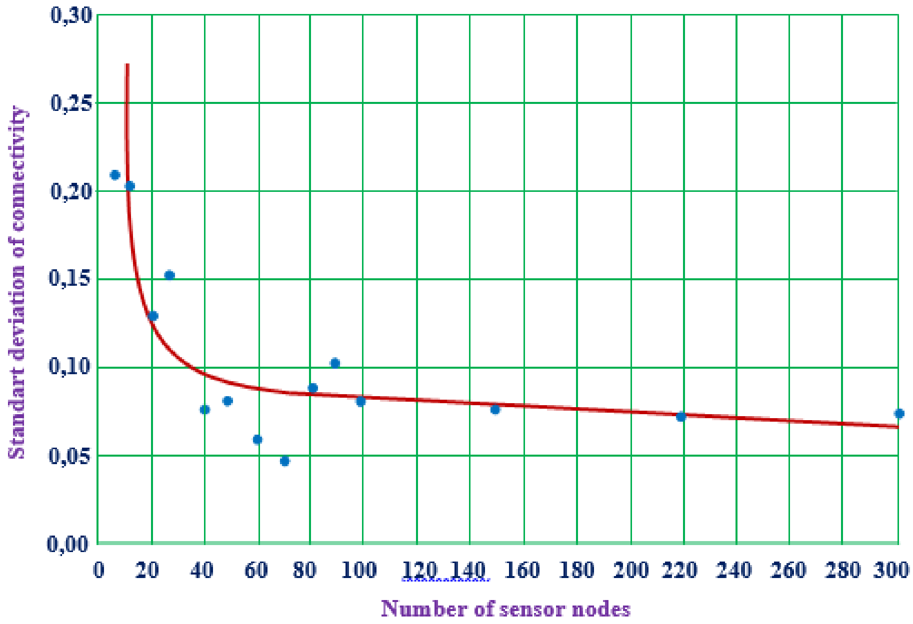

Fig. 4. Dependence of the standard deviation (SD) of the network connectivity probability on the number of network nodes

When the probability of network connectivity p is less than the threshold probability p_0, the network splits into clusters. To ensure cluster connectivity, you need to increase the communication radius R or the number of network nodes. In particular, unmanned aerial vehicles (UAVs) can be used to solve the problem of connectivity.

V. CONCLUSION

When establishing WSN on many randomly located nodes, a random graph model can be used to describe it. The likelihood of edges in modeling WSN by random graphs is defined as the probability of the node falling into the communication radius and depends on the nature of the nodes being placed in the service zone. The results of simulation of the WSN by node random displacement (Poisson field) have shown that the probability of network

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Vol. 7, Issue 5 , May 2020

connectivity depends on the number of nodes, the radius of the communication, and can be described by the Erdesh-Renitheorem. A study of the probability of WSN binding in a three-dimensional space depends on the radius of contact and the number of nodes revealed the statistical equation of the results obtained from the Erdes-Rene model. The analysis of the probability of applying a random graph model to the number of nodes showed that the error of estimating the linkage decreases with the increase of n by the law of about 1/n. When $n > 50$, the evaluation of connectivity is less than 20%, which is permitted in most practical cases.

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