Methods for Increasing the Lifetime of Wireless Sensor Networks with Redundant Number of Nodes

Illia Kovalenko[a], Yevhen Stepanenko[b] and Mykola Masesov[a]

[a] *Military Institute of Telecommunications and Information Technologies Named after the Heroes of Krut, Kyiv, 01011, Ukraine*
[b] *Taras Shevchenko National University of Kyiv, Kyiv, 01033, Ukraine*

Abstract

Wireless sensor networks consist of small electronic nodes with integrated functions of monitoring the external space, data processing and transmission. The paper proposes methods of reducing energy consumption of nodes and algorithms for their application to increase the lifetime of wireless sensor networks with redundant number of nodes. The article proposes methods for reducing (redistributing) battery power consumption in order to increase the lifetime of networks with redundant number of nodes by planning and managing the joint operation of network elements at various levels of the reference model of open systems interaction. An algorithm is proposed for the application of the developed methods in accordance with certain criteria (increased load and redundant consumption of the unit's energy resource). With the help of simulation modeling, an assessment of the effectiveness was carried out, which made it possible to conclude that the developed control methods for the WSN increase the network life time up to 15-20% compared to similar methods of this class.

Keywords [1]

wireless sensor network, network nodes, energy resource redundancy nodes, the lifetime of the network

1. Introduction

Modern advances in radio electronics have made it possible to create small-sized, cheap and multifunctional wireless devices (nodes), consisting of a set of monitoring sensors, a microprocessor, a power battery and a transceiver. These nodes are capable of transmitting monitoring data over radio channels, providing network interaction between a plurality of similar nodes and creating wireless sensor networks (WSN). The main properties of WSN are [1]:

- low cost and small dimensions of the unit;
- scalability, fast deployment and initialization;
- automatic configuration and restoration;
- the ability of nodes to carry out primary processing of monitoring data;
- low cost of deployment and maintenance;
- minimum restrictions on the placement of wireless devices;
- fault tolerance of the network in case of disruption of individual connections between nodes or failure of some nodes;
- limited communication and energy resources of the nodes.

These features of the WSN can be effectively used to solve various applied problems related to distributed collection, analysis and transmission of information, for example [2]:

1. Automation of life support processes (monitoring of microclimate, presence of people, etc.);
2. Industrial automation (remote control and diagnostics of industrial equipment, etc.);
3. Defense and security (control of the movement of people and equipment, means of operational communication and reconnaissance, control of the area of the monitoring area and remote observation, assistance in carrying out rescue operations, security and fire alarms, etc.);

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EMAIL: kig777@ukr.net (A. 1); naukaviti@gmail.com (A. 2); masesov@ukr.net (A. 3)
ORCID: 0000-0002-6827-5196 (A. 1); 0000-0003-1993-2441 (A. 2); 0000-0003-4537-4295 (A. 3)

4. Monitoring of the environment (natural processes, pollution, etc.)
5. Healthcare (monitoring the condition of patients, etc.).

Some areas of application of the WSN (especially defense and security) require full coverage of the area of the object by the monitoring zones of the sensors. In addition, to ensure the reliability of monitoring data collection, it is often necessary to overlap the area of the object with monitoring sensors multiple times, ensuring a given degree of connectivity of the network nodes. To do this, before deploying the WSN, planning of the locations of the nodes is carried out. But there are areas of application of the WSN, in which the deterministic deployment of nodes is impractical (or impossible) due to the large time or economic costs of deployment (for example, in the event of hostilities, environmental disasters, in areas of chemical or radiation contamination, hard-to-reach areas, etc.) [3]. In such cases, for the operational deployment of the network, the dispersion of nodes over the monitoring area using aircraft (missiles, guns, etc.) can be used. At the same time, due to the random placement of nodes, it is possible to cover the monitoring area as much as possible with sensors only with the use of a sufficiently large number of nodes (redundancy). Redundancy of the number of nodes (RNN) will provide the required coverage, but will lead to an increase in the number of collisions during transmission due to an increase in the level of mutual interference, data transmission delays, duplication of monitoring information and unnecessary consumption of battery resources for retransmissions.

Each WSN node is equipped with an energy source of limited capacity, therefore, the fundamental requirement for them is to reduce energy consumption to increase the lifetime (LT) of the network. The lifetime of a network is understood as the duration of the network's functioning without loss of connectivity of its elements due to the failure of nodes that have used up their energy resources (battery power) [3]. At present, the universal standard for the construction of WSN is the specification of ZigBee upper layer network protocols, using the IEEE 802.15.4 physical and link layer protocol. It is obvious that the use of standard technology has many advantages (reduction in the cost of the element base, reduction in development time, the ability to combine different networks, etc.). However, the ZigBee specification, due to its versatility, is not optimal for many applications, and its commercial orientation does not provide for the use of the WSN with redundant number of nodes. Therefore, it is necessary to develop methods to reduce the consumption of energy resources of nodes in order to increase the lifetime of the WSN of this class.

2. Goals of the article

The article proposes methods for reducing (redistributing) battery power consumption in order to increase the lifetime of networks with redundant number of nodes by planning and managing the joint operation of network elements at various levels of the reference model of open systems interaction.

3. Analysis of recent research and publications

To reduce the energy consumption of nodes in order to increase the lifetime of the network, a variety of appropriate methods have been proposed [4], the classification of which in accordance with the layers of the OSI model is shown in Figure 1. The main methods of saving energy resources of WSN nodes is the organization of operating modes, which implies periodic shutdown of nodes or their transceivers. WSN carry out monitoring data transmission with a specified period and disconnecting nodes (transceivers) after data transmission until the beginning of the next period, which allows to reduce energy consumption, but this raises the problem of organizing interaction between nodes to ensure relay messages in the direction of the gateway with minimum delays. The classical approach to solving this class of problems is the organization of coordinated sleep/wake-up cycles of nodes (transceivers), which introduces delays in the transmission of messages [4].

4. Presentation of the main material

In contrast to the classical approach to organizing sleep/wake-up cycles for the WSN with redundant number of nodes, it is proposed:

1. *At the application level*, disable nodes that duplicate the coverage of the monitoring area. To extend the duration of the network operation, it is proposed to organize the on/off periods of individual

nodes so that at each moment of time a set of nodes is functioning, which is necessary to ensure the specified coverage of the monitoring area.

2. *At the network level,* use an energy-saving routing method that takes into account the periodic operation of multiple redundant nodes, as well as a method for reducing (compressing) the amount of transmitted data due to their redundancy.

3. *At the data link layer,* with increasing data transmission load, use hybrid multiple access (MA) methods (deterministic and random access methods have different efficiency limits depending on the load). For nodes close to the gateway (where the traffic of the entire network is concentrated), in order to reduce the number of collisions in packet transmission and increase transmission rates, it is advisable to use methods of deterministic access to the channel. For nodes remote from the gateway, it is advisable to use random channel access methods that do not require node synchronization.

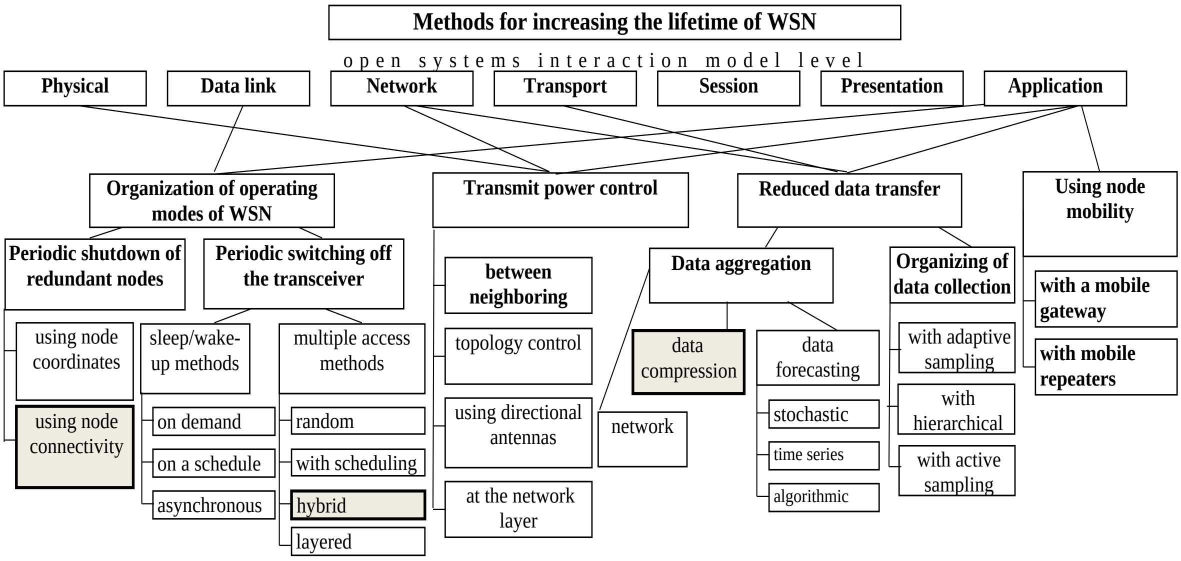

Figure 1: Classification of methods for increasing the lifetime of WSN

Controlling transmission power allows to reduce energy use by reducing transmission power (range). Based on the fact that the WSN nodes are not mobile and route options can be determined in advance, transmission power control is advisable to use at the network level in routing methods.

Reducing the use of energy resources by reducing the amount of data (aggregation) occurs by reducing the redundancy or loss of accuracy in collecting monitoring data with the introduction of transmission delays for data processing. The WSN with redundant number of nodes is used to improve the reliability and quality of coverage of the area of the monitoring object, therefore, in these networks, it is advisable to use aggregation methods at the network level at individual nodes with increased energy use to prevent their failure if other energy saving methods are ineffective. To reduce the amount of data, it is advisable to use their correlation (temporal, when the data does not change over time, and spatial, when the data from neighboring nodes coincide). The author analyzed the methods for increasing the lifetime of the WSN from the point of view of the expediency of their application in networks with redundant number of nodes, and the following methods of controlling the WSN were proposed:

1) an energy-saving method for controlling the WSN with redundant number of nodes at the application and network levels of the OSI model (*MC* WSN *ENN*);

2) an energy-saving control method of the WSN with redundant number of nodes at the link layer of the OSI model - an energy-saving method of multiple access to the channel (*EMMA* WSN *ENN*);

3) an energy-saving method of data aggregation in the WSN with redundant number of nodes (*EMDA* WSN *ENN).*

The developed methods can be used both separately and in addition to each other in accordance with the following algorithm for choosing a set of applied methods for the WSN with *ENN* (Figure 2):

1) if the number of nodes is redundant $\xi \geq 1{,}5$, the gateway initiates the use of *EMC WSN ENN* ($\xi = N / N_н$, N – the total number of nodes, $N_н$ – the number required to ensure the specified coverage);

2) with an increase in the total load on the gateway and nodes close to it to the values of the resistance boundary (critical increase in collisions) for random multiple access methods $G^{\mathrm{rc}} = \arg\max_G \left(S(G)\right)$ (G – the total load on the node, S – the average transmission speed of the node) [2], the gateway initiates the use of *EMMA WSN ENN*;

3) in case of a threat of loss of network connectivity due to the exhaustion of energy resources by individual nodes, *EMDA* WSN *ENN is* used for them.

Let's consider the proposed methods separately.

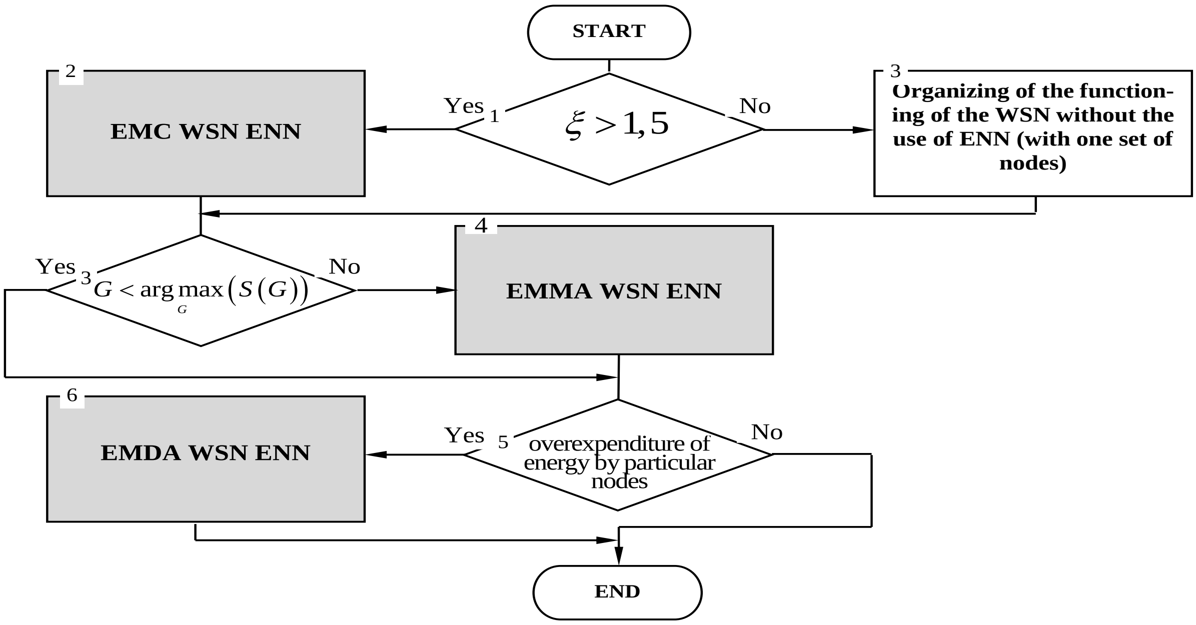

Figure 2: Algorithm for choosing a set of applied methods for increasing the lifetime of a WSN with ENN

4.1. An energy-saving method of control of the WSN with ENN at the application and network levels of the OSI model

When analyzing the existing methods for increasing the lifetime of the WSN, the advantages of the EECCR methods (An Energy-Efficient m -coverage and n -connectivity Routing Algorithm Under Border Effects in Heterogeneous Sensor Networks [7]) and ECR (An Energy Conserving Routing Algorithm for Wireless Sensor Networks [8]) were determined. These methods are aimed at providing m-fold coverage of the monitoring area and n-fold connectivity of network nodes and, according to the simulation results, show the best results of the network lifetime. The author identified the shortcomings of these methods and proposed an improved method [5]. In the proposed method, new algorithms have been developed for determining the available number of subsets of redundant nodes, the deployment and operation of the WSN with an excess number of nodes.

The essence of the method:

at the stage of network planning, the available number of subsets of nodes is first determined, each of which can provide a given coverage of the monitoring area; and then the total number of WSN nodes is divided into a certain number of sets of nodes that will operate at different periods of time and provide m-fold coverage of the area of the monitoring area by sensors and n-fold connectivity;

at the initial stage of operation, the routes of message transmission from each node in the direction of the gateway are determined, taking into account the periods of operation of the WSN and the use of energy resources by the nodes, and some nodes are included in different subsets to ensure network connectivity;

after determining the routes, data is transmitted in the direction of the gateway (when switching sets, the routes are adjusted depending on the consumption of energy by individual nodes).

To determine the minimum number of nodes that should provide a given coverage of the monitoring area, the analytical model of the WSN was used.

WSN model with redundant number of nodes: N nodes are randomly evenly distributed in the monitoring area with radius R; $S_\Omega \to \infty$ and $N \to \infty$, but at a separate point $N / S_\Omega = const$; with node density - a random variable (Poisson law with an intensity distribution N / S_Ω; use M types of nodes, number of nodes of i -th type – $\rho_i N$ ($0 \le \rho_i \le 1$, $1 \le i \le M$, $\sum_{i=1}^{M} \rho_i = 1$); monitoring radius of type i node – $r_{\text{м}i}$, maximum transmission radius of type i node – $r_{\text{п}i}$; $\forall i, j \in M$, $r_{\text{м}i} < r_{\text{м}j}$, if $i < j$; the network is represented as a graph $G = (V,E)$.

It was proved that for the described WSN model with redundant number of nodes at $R >> \max(r_{\text{м}i})$, $R >> \max(r_{\text{п}i})$, $i \in (1..M)$ the ratio of the area of m-fold coverage S_{Ω_m} to the area of the monitoring area S_Ω and the probability of n-fold connectivity of nodes $P(G,n)$ for the used WSN model are [5]:

$$\frac{S_{\Omega_m}}{S_\Omega} = 1 - \sum_{x=0}^{m-1} \sum_{n_1+\ldots+n_M=x} \frac{1}{\prod_{i=1}^{M} n_i!} \times \sum_{k=0}^{M} \left(\prod_{i=1}^{M} \left(\frac{\rho_i N r_{\text{м}i}^2}{R^2} \right)^{n_i} e^{\left(-\frac{\rho_i N r_{\text{м}i}^2}{R^2} \right)} \right),$$

$$P(G,n) \ge \left(1 - e^{-\frac{N\left(r_{\text{п}}^{\min}\right)^2}{R^2}} \sum_{x=0}^{n-1} \left(\left(\frac{N\left(r_{\text{п}}^{\min}\right)^2}{R^2} \right)^x / x! \right) \right)^N . \tag{1}$$

The method includes the following sequence of steps:

1. Determination of the required number of sets of WSN nodes and the time periods of their functioning.

A feature of the proposed method is its application in case of redundancy of nodes $\xi \in [1,5..2), [2,5..3)$, $\xi = N / N_{mn}$ (N_{mn} – is the required number of nodes to ensure the specified characteristics of the network). For this, it is proposed to increase the number of subsets of nodes $N_{\text{м}}$ and their periods of operation N_T. In this case, each node will correspond to several periods of turning on and off. So for $\xi \in [1,5..2)$: $N_{\text{м}} = 3$, $N_{\text{м}} = 3$, the number of nodes turning on period $N_{T\,on} = 2$. For $\xi \in [2,5..3)$ $N_{\text{м}} = 5$, $N_T = 5$, $N_{T\,on} = 2$. To determine the required number of subsets of nodes $N_{\text{м}}$ and periods N_T, it is proposed to use the developed algorithm using dependencies (1) 0.

2. Distribution of WSN into sets of nodes with separate periods of operation.

The random distribution of the total number of nodes into subsets in the WSN with redundant number of nodes, which is used in the previous methods, can lead to a decrease in the real coverage of the area of the monitoring area in certain periods of the network operation. It can also lead to an overconsumption of the energy resource of nodes in individual zones of the network due to their constant inclusion (when assigning the same set numbers to neighboring nodes) [5]. This is especially applicable to nodes that are in the immediate vicinity of the gateway and relay data across the entire network. In the proposed method, in contrast to the previous ones, a uniform distribution of nodes into subsets and periods of operation is proposed using the developed algorithm [5]. An example of the distribution of nodes into subsets is shown in Figure 3a.

3. Organizing of routing of messages in the WSN (determination of routes) taking into account: periods of functioning of the WSN with ENN; use of energy resources of nodes; uniformity of load on nodes close to the gateway; restoration of connectivity in case of failure of individual nodes. To perform these functions, it is proposed to use the developed routing algorithm [8]. When constructing routes to ensure connectivity, some nodes can be included in different subsets (Figure 3b).

4. Ensuring routing of data collection messages and their transmission along designated routes in the direction of the gateway in accordance with the periods of network operation. At this stage, the network is periodically reconfigured in accordance with the proposed algorithm [9].

The advantages of the developed method:

- the possibility of using the method with redundancy of nodes (the previous methods were used with integer values of redundancy $\xi = 2,3,4,\ldots$);

- a more uniform distribution of nodes into sets with the exclusion of the possibility of including a group of neighboring nodes in one set (which is possible with a random distribution of nodes into sets);

- ensuring the minimum number of functioning nodes close to the gateway, restoring network connectivity in the event of failure of its individual elements;
- using the lowest possible transmission power (transmission power control at the network layer);
- the use of a multi-parameter routing metric that takes into account the transmission power, the number of retransmissions, the remaining battery charge, and distance from the gateway (when used for relaying nodes from another set).

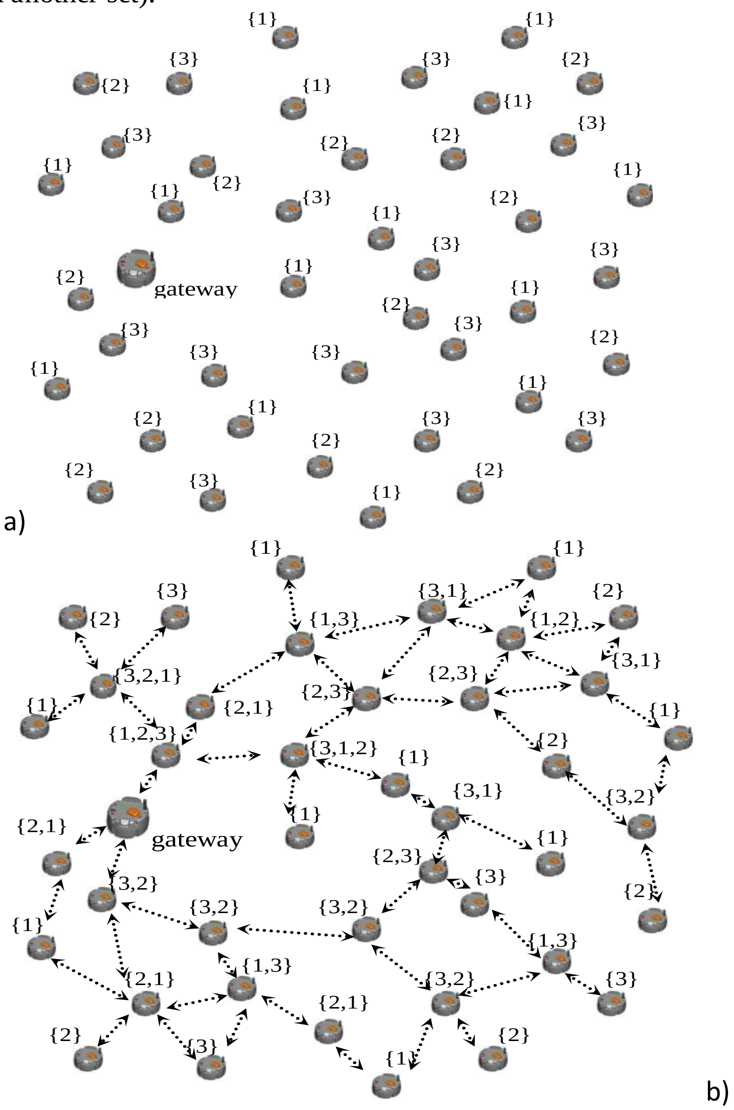

Figure 3: Dividing nodes into subsets for sequential functioning

4.2. An energy-saving control method for the WSN with ENN at the data link layer of the OSI model

For small values of the load in the WSN, it is advisable to use random multiple access methods. For example, the dependence of the average transmission speed of a node on network traffic for flexible carrier sense multiple access [1]:

$$S = \frac{k^2 G e^{-k^2 G(ak+2m)}}{k^2 G(1+2ak) + e^{-k^2 G(ak+2m)}} \quad (2)$$

where a, k, m – are the network parameters that affect the intensity of collisions due to hidden terminals and depend on the characteristics of the WSN [11].

The graphs of the corresponding dependencies $S(G)$ for different variants of values a, k, m are presented in Figure 4 [1]. It can be seen that the dependence $S(G)$ has a pronounced maximum - the resistance limit at $G = G^{\mathrm{rc}} = \arg\max_{G}\left(S(G)\right)$, after which there is a sharp drop in the transmission rate due to an increase in the number of collisions. This dependence is typical for all methods of random access to the channel [12]. Obviously, if $G > G^{\mathrm{rc}}$, the use of these methods is impractical.

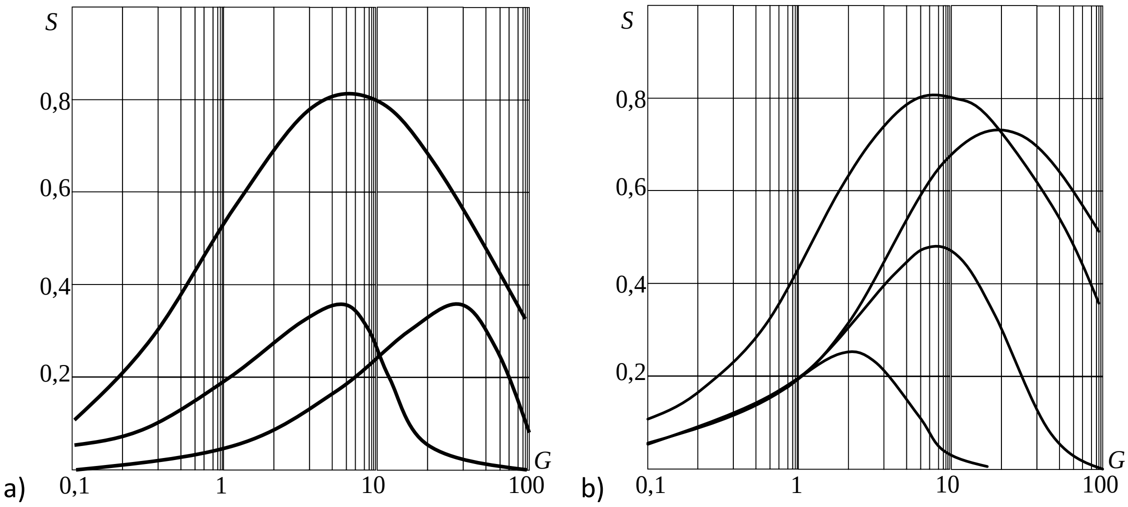

Figure 4: Dependence of the data transfer rate on the load for random methods of multiple access

The essence of the method.

To increase the lifetime of the WSN with increasing traffic in the network $G \geq G^{\mathrm{rc}}$ it is proposed to create a zone of deterministic multiple access (ZDMA) to the channel around the gateway [6]. The method proposes to introduce two time periods of functioning, respectively deterministic and random access (Figure 4a). For remote nodes that are not part of the ZDMA, it is proposed to organize access to the channel using one of the existing random multiple access protocols. For ZDMA, scheduling of time intervals is carried out for each node, which is based on information collected from child nodes about the workload, the working cycle of the parent node and the dedicated parent node of the working cycle for the current node [13]. During the organizing of random access to the channel of remote nodes, the nodes of the deterministic access zone are in sleep mode and vice versa. The boundary nodes of the deterministic channel access zone operate in two periods: during the random access period they are in the mode of receiving data from remote nodes, and during the deterministic period they transmit data towards the gateway.

The use of two types of multiple access will allow combining their advantages, reduce the consumption of energy resources of traffic-loaded nodes, and simplify the synchronization of remote network elements. The maximum number of retransmissions *i* in ZDMA defined as $\max(i)$, where $G_i > G_i^{\mathrm{rc}}$, $G_i^{\mathrm{rc}} = \arg\max_{G_i}\left(S(G_i)\right)$, where G_i – traffic to nodes *i* relaying gateway to or exceeding a predetermined relatively to the level collisions.

The advantages of the developed method:

- the use of ZDMA allows to increase the bandwidth of the network without complicating its synchronization;
- inclusion of nodes in the zone of deterministic access, initiated by the border node of the ZDMA;
- adjusting the schedules of time intervals when switching sets of redundant nodes;
- adaptation of the schedule of time intervals when changing workloads;
- the developed method allows the use of data aggregation mechanisms (proposed below) at the border nodes of the ZDMA without introducing additional delays due to aggregation;
- managing the size of the ZDMA with aggregation of data at the border nodes is an additional way to control the energy consumption of the nodes close to the gateway.

4.3. An energy-saving method of data aggregation in the WSN with ENN

Data aggregation methods introduce additional delays in data collection and processing. Therefore, it is advisable to use them on individual nodes to extend the duration of their operation in order to increase the network lifetime. When analyzing the methods for increasing the lifetime of the WSN, the advantages of the DyDAP method (A Dynamic Data Aggregation Scheme for Privacy Aware Wireless Sensor Networks) [14], which ensures a decrease in the amount of transmitted data during congestion on network nodes were determined. On its basis, an improved method of aggregating WSN data with redundant number of nodes is proposed to reduce the use of energy resources of nodes.

For the WSN with redundant number of nodes, data aggregation is supposed to be used in two cases, shown in Figure 5. In the first case, it is proposed to use it at the border nodes of the ZDMA (Figure 5a), which receive and transmit data at different periods of the network operation with the ZDMA. Time separation of reception and transmission allows one to apply data aggregation without introducing additional delays. In the second case, data aggregation is applied to nodes overloaded with relaying. Figure 5b shows an example in which nodes 1 and 2 relay data to the entire "detached" subnet and, therefore, can quickly deplete their energy resources and fail, which will lead to a loss of network connectivity. If it is impossible to apply other methods of reducing the use of energy resources (in this case, due to the peculiarities of the location of the nodes), the network lifetime can be extended only by reducing the amount of data transmitted from the subnetwork using their correlation (with an acceptable loss of their accuracy).

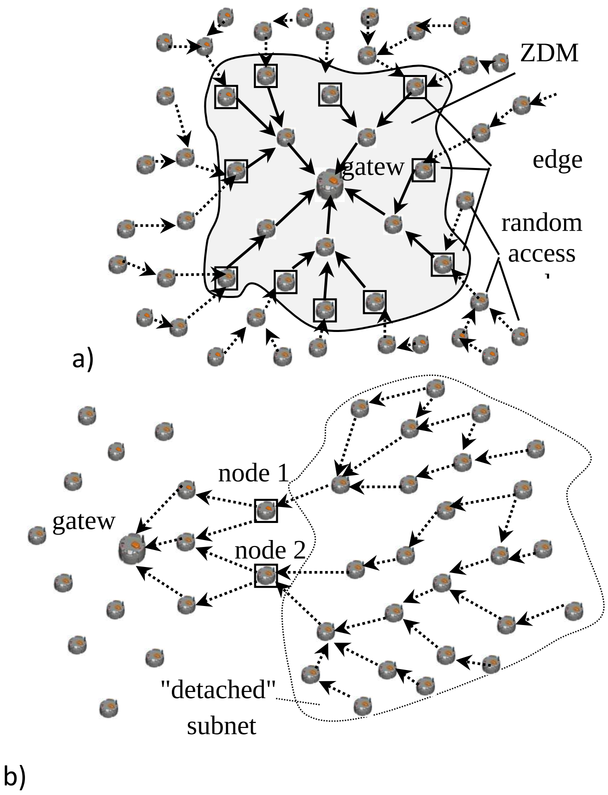

Figure 5: Application options for the data aggregation method

The essence of the method.

In the proposed method, the data volume is reduced by creating dynamic data transmission queues with the given characteristics on individual network nodes at the gateway command: the maximum length of the transmission queue and the limitation of message transmission per unit of time. With an increase in transmission queues due to a sharp increase in traffic or when the number of transmissions is limited (to extend the duration of the operation of an individual node), the possibilities of reducing the amount of data due to the spatial and temporal correlation of individual messages increase. At the node, data processing is carried out and only data that have changed over a certain period are transmitted towards the gateway, while data from a group of neighboring nodes are averaged and transmitted in one aggregated message (Figure 6a-c).

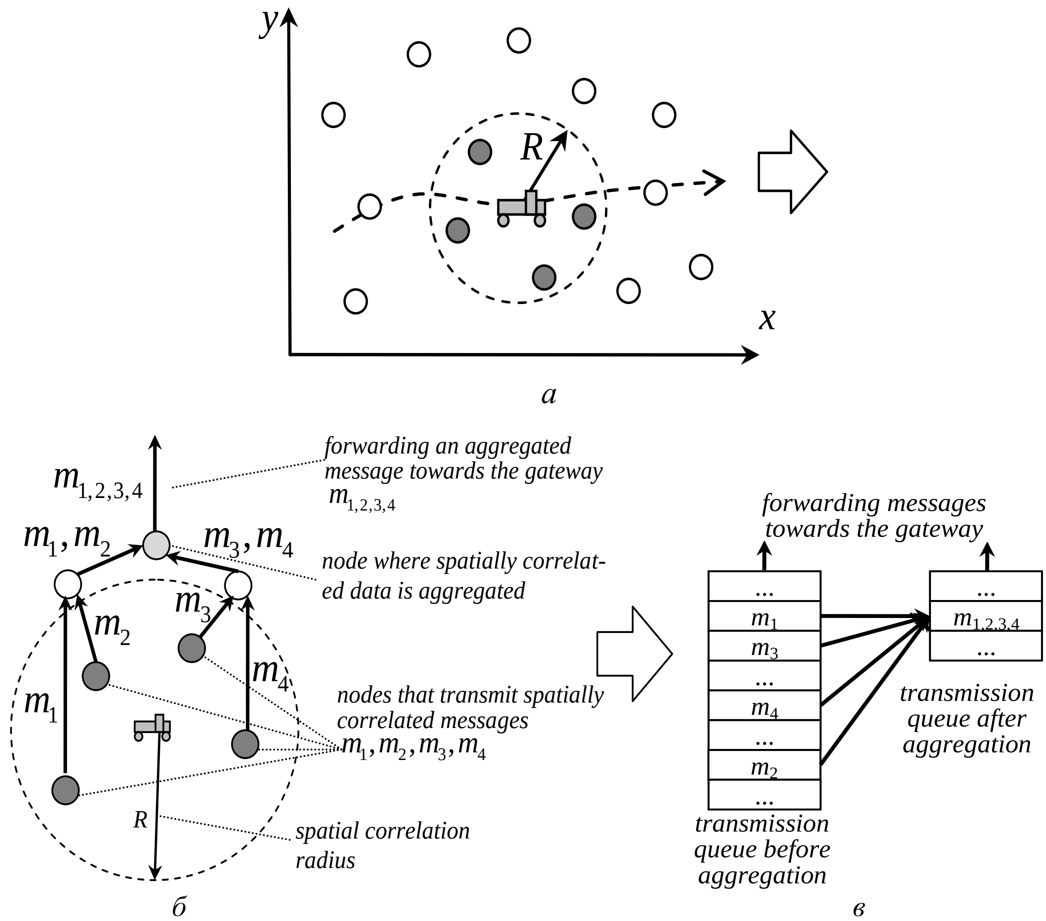

Figure 6: Generating an aggregated message

The advantages of the proposed method:

- use of the method at separate nodes overloaded with relaying to prevent their failure from exhaustion of energy resources and loss of network connectivity;
- the use of ZDMA at the edge nodes to increase the network lifetime;
- control of data aggregation using the maximum queue length for each node and limiting the number of transmissions per unit of time;
- data reduction using temporal correlation;
- reduction of the volume of transmitted data due to the use of different message formats;
- use of several transmission queues of different priority.

Efficiency mark.

To assess the effectiveness of the proposed methods, the WSN simulation model was used. As an indicator of efficiency, it was proposed to use the duration of the network operation until the depletion of the energy resource of at least one node. For simulation, the software package The Network Simulator [15] was used. The functioning of the WSN model depends on many parameters: requirements for the coverage of the monitoring area, the spatial dimensions of the network, monitoring and transmission radii, energy models of nodes, as well as the physical and channel layer protocols involved, etc. A simplified WSN model was used using standard physical and link layer protocols (802.11). At the same time, the results were obtained that allowed us to conclude that the proposed methods allow increasing the network lifetime up to 15-20% compared to similar ones. In addition, the method of increasing the lifetime of the WSN due to the excess number of nodes makes it possible to improve the percentage of real coverage of the area by monitoring zones up to 10%.

5. Conclusions

The article proposes methods for increasing the lifetime of the WSN with redundant number of nodes at different levels of the model of interaction of open systems and algorithm for the application of the developed methods in accordance with certain criteria (increased load and redundant consumption of the unit's energy resource). With the help of simulation modeling, an assessment of the effectiveness was carried out, which made it possible to conclude that the developed control methods for the WSN increase the network life time up to 15-20% compared to similar methods of this class. During the research, it was determined that the data collection model of the WSN with one gateway imposes restrictions on the possibility of evenly distributing the load on the nodes of the WSN to extend the time of its operation. Concentration of traffic leads to increased load on nodes close to the gateway and to their premature failure. It is possible to extend the duration of the functioning of the WSN in such conditions only by aggregating data with a loss of their accuracy. In the future, it is proposed to develop methods for controlling the consumption of energy resources of the WSN with redundant number of nodes and several gateways, which will extend the life of the network without losing the accuracy of the collected data.

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