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MODIFYING A METHOD FOR DIRECT DATA COLLECTION BY A TELECOMMUNICATION AERIAL PLATFORM FROM NODES OF WIRELESS SENSOR NETWORKS

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Wireless sensor networks are becoming increasingly important in both the civilian and military fields. The object of this study is the process of collecting data by a telecommunication aerial platform from network nodes under conditions of their remoteness from the telecommunication infrastructure. Most available papers consider a solution to partial problems related to the process of data acquisition by a telecommunication aerial platform: clustering of the network, search for the shortest flight route, minimization of energy costs of nodes, etc. Therefore, an improved method of direct data collection by a telecommunication air platform is proposed, which consistently and comprehensively solves these problems. Unlike existing methods, it takes into consideration several objective functions (optimization of data collection time by a telecommunication air platform and a network functioning time), parameters of the state of nodes and clusters, as well as makes it possible to obtain solutions in real time. A special feature of the proposed method is the search for the optimal solution according to the hierarchy: network – cluster – node. At the network level, the following is optimized: the number of clusters of a certain dimensionality and the trajectory of the cluster flyby. At the cluster level, the points (intervals) of data collection during the freezing (in motion) of the telecommunication air platform and the trajectory of its flight within a cluster are determined. At the node level, its energy consumption is minimized by reducing the distance to the telecommunication aerial platform. The trajectory of the platform within a cluster is calculated according to the developed rule base. The rules implement the method of situational management. The conditions of application are the parameters of the state of the nodes, the solutions are the parameters of the trajectory of a telecommunication aerial platform, and the intervals of data acquisition. The rules take into consideration the priority of the objective functions, the state of the parameters of the cluster nodes, and the previously made basic decision on the trajectory of the flyby. The simulation results show that the application of the method reduces the time of data collection up to 15 % or increases the network functioning time to 17 %

Keywords: wireless sensor networks, clustering, flight path, telecommunication aerial platform, data collection

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1. Introduction

Wireless sensor networks (WSN) are becoming increasingly developed in many areas as part of the Internet of Things: environmental and meteorological monitoring of territories, monitoring the state of forests, fields of agricultural crops, borders, search and rescue, as well as military operations, etc. WSN can be used in remote or inaccessible areas in the absence of any public telecommunication infrastructure, without the possibility of replacing the batteries of the nodes. To collect data from network nodes under those conditions, it is proposed to use telecommunication aerial platforms, which are built on the basis of unmanned aerial vehicles [1, 2].

Autonomous stationary sensor nodes collect and store certain parameters of the zones (objects) of their monitoring. The telecommunication aerial platform (TAP) flies over the territory of the location of WSN nodes along a certain trajectory. When TAP appears in the radio communication zone of the node, it transmits the acquired monitoring data. After flying around the network and collecting data, TAP transfers them to the processing center for further analysis.

A feature of this class of networks is the limited resources of sensor nodes: battery energy (respectively, operating time), processor performance, memory capacity, transmitter power, etc. Modern WSNs can have an impressive dimensionality (hundreds or thousands of sensor nodes). Replacing batteries for such networks becomes impractical or even impossible. Consequently, reducing the energy consumption of sensor nodes is crucial to prolong the time of their operation. In addition, these networks belong to the class of DTN (Delay Tolerant Networks) networks, which are characterized by a delay in acquiring monitoring data [1–4].

Scientific research into tasks for optimizing the time of data acquisition by telecommunication platforms and optimizing the operating time of this class of networks is important. There are a number of papers [1–4] that consider general approaches to the synthesis of the process of data collection by telecommunication aerial platforms from WSN nodes.

It is the development of a method in which all the tasks of data acquisition by a telecommunication aerial platform are consistently solved while minimizing the time of collection and energy consumption of nodes in determining the trajectory of its movement that is a relevant scientific task. Solving the described problem would make it possible to find the parameters for sensor networks and determine the TAP control influences on the nodes, which could increase the time of operation of the network and reduce the time for collecting monitoring data (which is critical, for example, in military applications).

The algorithms of the developed method can be used in specialized software for both the telecommunication aerial platform and the network management center. In general, their use will reduce the total cost of operating a certain class of networks. In addition, in the absence of TAP communication with a control center, it must perform all its functions, which imposes significant restrictions on the computational complexity of the method under conditions of limited TAP energy resource.

2. Literature review and problem statement

Solving the problem of collecting data from nodes by a telecommunication aerial platform when achieving certain objective functions is divided into several tasks: clustering the network, determining the points (intervals) of data acquisition, finding the flight path, etc. That is why most papers focus on solving partial tasks that arise in the process of collecting data from network nodes by TAP. We shall consider papers addressing each subtask, the proposed solutions, and their compliance with the task set.

To reduce the time of data acquisition, most authors propose clustering the network with a telecommunication aerial platform. The problem of WSN clustering belongs to the class of NP complex ones. In works [5–9], the use of many iterative clustering algorithms is proposed. In [5], the algorithm of *k*-means is considered. However, it gives heterogeneous clusters in size, which does not guarantee the creation of a TAP coverage area, therefore it is used only in another class of methods – the method of collecting data by TAP from the main nodes of clusters. In [6], a variation of the genetic algorithm was proposed. However, it has significant computational complexity, its application in TAP with limited computing capabilities will not allow for real-time decisions. In [7], the algorithm for optimizing the swarm of particles PSO (Particle Swarm Optimization) is implemented.

However, that algorithm is very sensitive to the selection of a significant number of configuration parameters and is not applied in real time and can be used for networks of small dimensionality. In [8], the FOREL cluster analysis algorithm (FORmal ELement) is used; it provides an opportunity to optimize the size of clusters according to the coordinates of nodes according to certain objective functions but takes into consideration only the coordinates of the nodes and does not take into consideration their battery condition and data volume. Paper [9] considers the feasibility of creating heterogeneous clusters in terms of minimizing energy costs. However, the proposed clustering does not take into account the dependence of TAP flight path on the energy consumption of the nodes and does not aim to minimize the data collection time.

It is worth noting that papers [5–9] generally consider the tasks of clustering without taking into consideration the peculiarities of TAP data acquisition process, the set of parameters of the state of sensor nodes, the need to achieve a certain or several objective functions.

The next task of data acquisition is the task to calculate the route, or rather the TAP flight path. It can be considered as variants for flying over the entire area of the network [10]. However, the time of data acquisition during the overflight of the area is very large, which requires additional requirements for the characteristics of the aircraft. This method will typically be used in the initial flight around the network, when there is no information about the state of the network nodes.

However, in most papers [11–17], the calculation of the TAP flight route is considered only as a solution to the classic traveling salesman problem, although it is necessary to calculate the flight path and reduce the energy consumption of the nodes. This problem belongs to the NP-complex class. Obtaining an exact solution to a network of significant dimensionality is problematic. Therefore, heuristic algorithms for obtaining an approximate solution are practically used, which have a small computational complexity (meet our requirements). For example, the algorithm of the nearest neighbor [12] does not take into consideration the parameters of the state of the nodes, does not optimize the energy consumption of nodes. The spiral algorithm [13] also does not take into account the state parameters of the nodes and does not minimize the energy consumption of the nodes.

In [14], the FPPWR (Fast Path Planning with Rules) cell algorithm does not take into consideration the parameters of the state of the nodes, does not minimize the energy consumption of the nodes. In [15], the algorithm of the convex shell CHIH (Convex Hull Insertion Heuristic) searches for the shortest TAP flyby route but does not consider the problem of minimizing the cost of energy. This set of iterative algorithms [11–15] is very similar and actually differs in the rule for choosing the next node in the algorithm for constructing a route. For each of them, the length of the constructed route depends on the dimensionality of the network, its type, and location of nodes. There are no obvious advantages of each of them for all types of networks. In addition, no studies have been conducted into their effectiveness in clustered networks (which are actually obtained at the first stage of the method implementation). And in general, they do not solve the issue of TAP interaction with network nodes, namely: the presence of a clustered network, the presence of a set of parameters of the state of nodes, several objective functions, etc.

In [16], the peculiarities of constructing a TAP flight route of an aircraft type (curvature, inertia of rotation) are considered but the issues of taking into consideration the dependence of the energy consumption of nodes on the TAP flight path remained unresolved.

In [17], a genetic algorithm for finding a TAP flight route is proposed. However, its feasibility due to computational complexity can be recognized for networks of small dimensionality. The requirement to make decisions by TAP in real time does not allow its application for solutions to networks of significant dimensionality. In addition, it does not consider taking into consideration the dependence of the energy consumption of nodes on the TAP flight path. In [18], the problem of minimizing the time of data acquisition from all WSN nodes is solved by optimizing the flight route. The route consists of data collection points. As a metric for choosing the route for the flyby of TAP nodes, a convolution of parameters is proposed: the number of nodes for exchange at the point of freezing and the number of nodes that are serviced during the flight. However, this approach provides a significant number of route options and is focused on small-sized networks. Therefore, for networks with a significant number of nodes in clusters, significant time will be spent on its calculation, although in this case the decision should be made in real time. In addition, the problem of optimizing the energy consumption of nodes is not considered by the authors. Paper [19] formulated the problem of reducing energy consumption through network clustering, optimizing the trajectory, and data aggregation. However, the optimization problem is not focused on achieving several objective functions. In [20], the authors considered the problem of optimizing the energy consumption of WSN nodes by optimizing the schedule of node awakening relative to the TAP flight path. However, the authors solve the problem by optimizing only the channel exchange protocol in isolation from the existing set of parameters of the state of nodes and consideration of the problem of minimizing the time of data acquisition.

In [21], the process of collecting data from the main nodes of clusters, which are located on hilly terrain, is considered. Determining the data collection point from TAP above the main node occurs at a point in space with a maximum signal/noise ratio, but the whole set of state parameters of the nodes is not taken into consideration, the presence of several objective functions of the data acquisition process is not considered. In [22], the heuristics for building a TAP flight path through the center of the cluster are studied. However, the authors do not consider the possibility of constructing several data collection points in a cluster, which could provide an opportunity to reduce the time of data exchange and implement it in the proposed method. In [23], the authors propose increasing the throughput of the data collection process by TAP during its flight based on the division of the network into priority exchange zones, according to which TAP plans to exchange data. That is, the researchers optimize data exchange parameters only by improving the MAC protocol. Optimization of the TAP flight path depending on the state of the nodes, optimization of energy consumption of nodes is not considered. In [24], the authors consider a metric for selecting the main nodes of clusters, which determines the distance to the TAP flight path. The decision to select the main node of the cluster is made by exchanging service messages between the cluster nodes. In the proposed method of direct acquisition, the decision to adjust the flight path is made by TAP based on taking into consideration several parameters of the state of the node, including the distance between the node and TAP. That will make it possible for TAP to make decisions on multicriterial optimization. In [25], the problem of minimizing the number of TAPs when collecting data from WSN is considered, but the set of parameters of the state of the nodes is not taken into consideration, the presence of other objective functions was not considered. In [26], a data collection solution with a time limit for data acquisition is proposed, network clustering is based on the k-means algorithm, a flight route search using learning. However, the study does not take into consideration the set of parameters of the state of nodes and the problem is reduced only to single-criteria optimization (minimization of energy consumption of nodes).

However, papers [5–26] solve only partial problems of data collection (clustering the network, finding the shortest route, minimizing the energy consumption of nodes, etc.). That is, they are not a comprehensive solution to the problem of data acquisition by a telecommunication aerial platform from WSN nodes. They do not take into account several criteria of the data collection process, their dependence on the set of parameters of the state of nodes and clusters of the network and the TAP trajectory.

Thus, an unresolved task when considering the process of collecting data by TAP from WSN nodes is a comprehensive solution to all stages of data acquisition (clustering, points and intervals of data collection, TAP flight path) with simultaneous consideration of two criteria: minimizing the time of data collection and maximizing the time of operation of the network. The method makes it possible to maximize the time of operation of the network, minimize the time of data acquisition by improving clustering algorithms, search for points (intervals) of data collection, build a trajectory of TAP flyby and exchanging data with nodes.

3. The aim and objectives of the study

The aim of this study is to develop a modified method for directly collecting data by TAP from WSN nodes of considerable dimensionality. The application of the method makes it possible to increase the efficiency of TAP data acquisition process: minimize data collection time and/or maximize the time of network operation.

To accomplish the aim, the following tasks have been set:

– to develop algorithms for network clustering by a telecommunication aerial platform and determining data collection points from cluster nodes;

– to build a method for constructing a trajectory of the flyby and data exchange by a telecommunication aerial platform with cluster nodes;

– to develop an algorithm for the modified method of direct data acquisition by a telecommunication aerial platform from wireless sensor network nodes.

4. The study materials and methods

We have considered WSN of considerable dimensionality. Stationary sensor nodes are randomly distributed in a limited area, have the same resources, are equipped with a positioning system (for example, GPS). Each node monitors and stores data on environmental parameters (objects of observation). When TAP arrives in the radio communication zone of the node, it sends the collected monitoring data to the TAP.

Initial data:

– the monitoring area of WSN nodes – S; the number of network nodes $i=1... N$, the coordinates of their location on the ground $(x_i, y_i)\in S$; the volume of collected monitoring data by the i-th node – V_{dmi};

– technical characteristics of the node – quantity, types of sensors, initial battery energy, unit energy consumption for monitoring for each type of sensor;

– telecommunication characteristics of the node;

– the protocols of channel and physical levels, type of antenna, transmitter power, energy consumption per bit of data reception and transmission for the selected MAC protocol and type of communication equipment, etc.;

– the technical (speed, altitude, flight time, etc.) and telecommunication (exchange protocols, antenna type, transmitter power, etc.) characteristics of TAP.

The network node and each TAP have their own control systems (CS) that implement a specific method of data acquisition and interact with each other. TAP has the ability to move in three dimensions at a constant or variable speed at a limited height and a limited time. Due to a directional antenna, TAP forms a ground coverage area (radio connectivity) with a radius R, the size of which depends on the TAP flight height, transmitter power, interference level, characteristics of transceivers, MAC protocol, etc.

Limitations:

– features of the construction of the flight path for an aircraft-type TAP [16] (a significant turning radius and inertia compared to the TAP of rotary type) are not considered;

– information on the parameters of the state of the nodes (location coordinates, battery energy level, monitoring data) is collected during the initial TAP overflight of the network; subsequently, information on the status of the nodes is updated during each round of the flight;

– TAP and sensor nodes have radio tools with the same exchange protocols (for example, IEEE 802.11) with a set of exchange speeds at a certain radio communication range;

– sensor nodes, TAP have amounts of memory, which are enough to store monitoring data;

– planning the flight path and the order of node flyby is carried out by the ground control center, its adjustment depending on the situation on the network is carried out by TAP;

– the TAP control system makes it possible to take decisions independently (on clustering, flight path, points and intervals of data acquisition, etc.) in the absence of connectivity with the ground network control center;

– algorithms that are implemented by TAP should have little computational complexity;

– the TAP energy is enough to carry out a round of network flight.

It is required, in accordance with the objective functions:

– to determine the number of clusters $k=1...K$ in the networks, their sizes;

– to determine the position in space $(x, y, h)_k$ of points Q_k of hanging (data acquisition) by TAP from cluster nodes;

– to calculate the basic TAP flight route in the network from the starting position A to the final B through the points of data collection Q_k from the cluster nodes;

– to identify additional collection points (when TAP hovers) and flyby strategies (St_k): TAP flight path in clusters and trajectory intervals (when TAP flies) of data collection by TAP within a cluster, the order (schedule) of data exchange between TAP and cluster nodes.

At the same time, it is necessary to implement the objective control functions (OCF) specified by the ground network control center for data acquisition, taking into consideration their priority [8]:

– minimizing or ensuring a given time of data collection T_{col},

$$T_{col} \to \min \text{ or } T_{col} \le T_{colgiv}; \quad (1)$$

– maximizing or reaching a given time of network operation (T_{fun}),

$$T_{fun} \to \max \text{ or } T_{fun} \ge T_{fungiv}. \quad (2)$$

Consider limitations Ω for:

– the type of TAP (aircraft or rotary); the TAP flight speed, altitude, time and range – $v=[v_{\min}, v_{\max}]$; $h=[h_{\min}, h_{\max}]$; $t_{fl} \le t_{fl\max}$; $L_{fl} \le L_{fl\max}$;

– the number of clusters in the network – $1 \le k \le N$;

– the energy of batteries of nodes and TAP $e_i \le e_{\max}$, $e_i \le e_{TA\max}$;

– the volume of monitoring data of each i-th node – $V_{dmi} \le V_{dmmax}$;

– the range of the radio communication channel node-TAP – $d_{i\text{-}TA} \le d_{\max}$;

– the radius of the coverage area (cluster) – $R_{\min} \le R \le R_{\max}$.

Let us consider in more detail the expressions for calculations and ways to achieve the objective control functions (OCFs) for TAP data acquisition process.

The time of data collection by TAP from WSN nodes during its clustering depends on (3):

$$T_{col} = f\left(n, K, L_{tn}, v, V_{dmi}, Q_k, INT_i, t_{coli}, h_k, St_k\right); \quad (3)$$

– the number of nodes $i=1...N$ and their location on the ground $(x_i, y_i) \in S$;

– the quantities $k=1...K$ of clusters (according to the accepted clustering algorithm), their area, dimensionality, relative location;

– the lengths of the TAP flight path in the network and $L_{tn}=l_{tin}+l_{tbe}$, where l_{tin} – the length of the flight path in clusters, l_{tbe} – between clusters;

– the TAP flight speed v, which changes v_{in} in and between clusters v_{be};

– the volumes of monitoring data V_{dmi} in the network nodes;

– the number and location of data acquisition points Q_k in space $(x, y, h)_k$ of each cluster when TAP hovers;

– the length and placement (spatial and temporal) intervals INT_{and} of TAP flight path for collecting (exchanging) data in motion with each i-th node;

– the time of data acquisition (exchange) by TAP with each i-th node t_{coli};

– flight altitude h_k;

– the strategy St_k of TAP flyby and exchange with the nodes of each k-th cluster;

– the limitations Ω of the resources of nodes and TAP.

Reducing the number of clusters k reduces the length L_{tn} of the TAP flight route (respectively, flight time) but increases the energy consumption of sensor nodes and exchange time (decreases the transmission rate of the MAC protocol) due to an increase in the distance in the node-TAP radio channels. An increase in the number of clusters will lead to an increase in the length of the route, a decrease in the node-TAP exchange time, and the energy consumption of the nodes. There is a certain optimum of the number of clusters k, their size, and the location of TAP collection points Q_k in it, which determines the compromise between the time of data acquisition by TAP and the time of operation of the network.

The total time T_{col} of TAP data collection in the network (4) according to a certain TAP flight path consists of the flight time between clusters $t_{fbe}^{k,k+1}$, the flight time in clusters t_{fin}^{k} (with or without data acquisition from nodes in motion), and data collection (exchange) time t_{colh}^{k} when hovering at the corresponding collection points Q_k of clusters, $k=1...K$:

$$T_{col} = \sum_{k=0}^{K-1} t_{fbe}^{k,k+1} + \sum_{k=1}^{K} t_{fin}^{k} + \sum_{k=1}^{K} t_{colh}^{k} \to \min. \quad (4)$$

The flyby time between clusters is determined by the ratio of path length to flight speed: $t_{fbe}^{k,k+1} = l_{tbe}^{k,k+1} / v_{fbe}^{k,k+1}$. Usually, between clusters, TAP flies at maximum speed $v_{fbe}^{k,k+1} = v_{\max}$.

The flyby time within a cluster is determined by $t_{fin}^k = l_{tin}^k / v_{fin}^k$.

In this case, the time of collection (exchange) of data by TAP from the j-th node t_{colj} (Fig. 1) should be less than or equal to the flyby time of TAP over this node t_{flj} with radio connectivity support (7) [2, 3, 8]:

$$t_{colj} \le t_{flj},\ t_{colj} = l/v = 2\left(\sqrt{d_{\max}^2 - h^2}\cos\alpha\right)/v,$$

$$t_{colj} = s\left(d_{j-TA}\right)/\left(V_{dmj} + V_{stj}\right), \quad (5)$$

where l is the length of the route of TAP movement within radio communication with node j, v is the flight speed, $d_{\max}$ is the maximum range of radio communication, $t_{colj}=INT_j/v$, where INT is the length of the exchange trajectory interval.

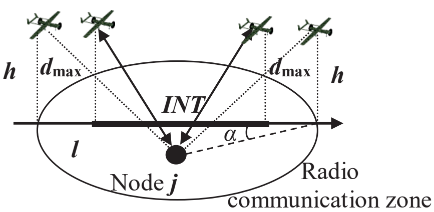

Fig. 1. Parameters of the flyby by a telecommunication platform of node j

The time of collection (exchange) of data t_{colj} depends on the rate of transmission s in the radio channel (which is determined by the distance $d_{i\text{-}TA}$ between the j-th node and TAP, the parameters of the radio channel, and the characteristics of the MAC protocol), and the volume of monitoring data V_{dmj} and V_{stj} of service traffic.

That is, TAP, after entering radio communication with the j-th node, receives the actual value V_{dmj} and selects the speed of movement, the height to ensure the required time of collection of a certain amount of data t_{colj} (6):

$$v \le 2\left(\sqrt{d_{\max}^2 - h^2}\cos\alpha\right)\left(V_{dmj} + V_{stj}\right)/s\left(d_{j-TA}\right). \quad (6)$$

The time of data acquisition t_{colh}^k from n_k nodes when TAP hovers at the collection points Q_k of the k-th clusters is equal to:

$$t_{colh}^k = \sum_i^{n_k} t_{coli}. \quad (7)$$

It is possible to use several basic strategies of TAP flight and data collection within a cluster: only when hovering at certain points in space and collecting data from all nodes of the cluster, a flight without hovering and collecting data at flight path intervals, and hybrid.

The operating time T_{col} of a network depends on the time of operation of its nodes and can be determined by [8]:

a) the time (or number of rounds of TAP overflight and nodes NR_{net} of the network of stable network operation before the first node fails:

$$T_{fun} = \min_i t_{funi} \text{ or } NR_{net} = \min_i NR_i, i = 1 \ldots n, \quad (8)$$

where t_{funi} – operating time (the number of rounds of flyby NR_i) of the i-th node until the battery energy is consumed.

The total number of rounds of the flight by TAP of the network of the i-th node is equal to:

$$NR_i = e_{i0} / e_{coni}, \quad (9)$$

where e_{i0} is the initial energy of the i-th node, e_{coni} is the average energy consumption of the node for the main operating modes for one round of flight: monitoring of objects, reception and transmission of data from TAP, standby mode (10):

$$e_{coni} = e_{moni}\left(r_{moni}, p\right)t_{moni} + e_{rcb}V_{rci} + e_{tri}V_{tri} + e_{sli}\left(t_{sli}\right), \quad (10)$$

$$e_{trb} = \alpha + \beta d_{i-TA}^2, \quad (11)$$

where e_{moni} – the energy consumed by the i-th node per unit of monitoring time at a given monitoring radius r_{moni} of the node, t_{moni} – monitoring time, p – the type of sensor; e_{rcb} and e_{trb} – energy spent on the bit of receiving and transmitting data of the received MAC protocol; V_{rci}, $V_{tri}=V_{dmi}+V_{sti}$ – volumes of receiving and transmitting data taking into consideration monitoring data V_{dmi} and service traffic V_{sti}; $e_{sli}(t_{sli})$ – energy consumed during sleep, α, β – coefficients, $d_{i\text{-}TA}$ – the distance between the node and TAP;

b) by dependence of the average battery energy consumption per data collection $\overline{e}_{coni}$ or the percentage of node failures $n_{failure}$ relative to the number of rounds of TAP flyby.

An increase in the operating time of nodes and the network as a whole can be carried out by reducing the energy consumption of nodes or redistributing costs between them. From the standpoint of data acquisition, a decrease in node energy costs can occur by reducing the transmission power due to a decrease in the distance $d_{i\text{-}TA}$ between the node and TAP. This is achieved by optimizing the number of clusters, the number of nodes within a cluster, the diameter of the cluster, the TAP trajectory, the position of the exchange points (intervals).

In addition, the cluster flyby and data exchange strategy should take into consideration:

– relative location of nodes and trajectory (data exchange at points that are closer from the node to the TAP trajectory);

– the available energy of the nodes (more energy – spend more);

– the critical energy of the node (the trajectory is adjusted – it is planned to fly around the depleted nodes at a minimum distance);

– the amount of node monitoring data (selection of the TAP collection point, which is closer to the node).

This logic is taken into consideration further in the relevant rules for building a flight strategy.

The presence of several objective control functions leads to the tasks of multicriterial optimization. In general, the number of OFs, their priority, restrictions will be determined by the network administrator in each case of the situation. Since in the initial data it is possible to streamline OFs by importance, we shall solve the problem of multicriterial optimization using the lexicographic method.

To assess the effectiveness of the proposed methods and algorithms, their simulation was carried out. For this purpose, a simulation program was developed in the C# environment. The initial data for modeling are the parameters of the network, nodes, TAP, algorithms that implement the process of collecting data by TAP (defined at the beginning of chapter 4). Algorithms for clustering and determining collection points, an algorithm for finding the shortest flight route of network clusters, the process of making a decision and building a flight path in a cluster, determining the intervals of the collection trajectory, etc. have been implemented by software. The calculation of performance indicators for the data collection process for each round of TAP flight was carried out in accordance with (4), (8).

Studies of the effectiveness of the proposed method in comparison with the hybrid method [8] with different initial data were carried out: network dimensionality, the number of clusters (TAP coverage zones), the number of nodes within a cluster, the volume of monitoring data in nodes, options for constructing flyby routes, node flyby strategies within a cluster, etc. The number of runs of the model was 700 rounds of flight, which satisfied the specified accuracy and reliability of the results. The simulation results are given in chapter 5.

5. Methods and algorithms for direct data collection by a telecommunication aerial platform from wireless sensor network nodes

5. 1. Development of algorithms for network clustering by a telecommunication aerial platform and determining data collection points from cluster nodes

The development of algorithms for clustering a wireless sensor network and determining monitoring data collection points by a telecommunication aerial platform from cluster nodes is carried out to achieve the objective functions.

In contrast to existing solutions [8], it is proposed to implement two-step (homogeneous and heterogeneous) clustering of the network. At the first step, homogeneous clusters are built, in the second step – their consolidation or enlargement depending on the objective control functions (1), (2) and the state of the clusters (the number, parameters of nodes, and their relative location).

The problem of network clustering belongs to the class of NP-complete. Obtaining an accurate solution to networks of large dimensionality requires considerable time and computing resources that are limited in TAP. Therefore, in practice, heuristic methods are used. For uniform clustering of the network, it is proposed to use the iterative FOREL cluster analysis algorithm [27]. Unlike existing algorithms for covering points on a plane with circles of radius R (random, greedy, etc.), it allows one to adapt the size of the TAP coverage area R. In addition, the FOREL algorithm makes it possible to find the minimum (required) number of clusters and data collection points in the network according to a specific objective function.

The algorithm for achieving network objective functions works iteratively as follows. The initial size of the cluster (TAP flight altitude) is determined. To achieve OF (1), the TAP flight altitude increases, which leads to an increase in the size of the cluster, a decrease in their number, and a reduction in the length of the flight path. However, the energy consumption of nodes for the TAP transmission process increases due to an increase in distance. Conversely, it is done to achieve OF (2).

The size of the coverage area by a telecommunication aerial platform $R=\sqrt{d_{\max}^2-h^2}$ depends on the height of its flight, the radiation pattern of the antenna, the maximum range of radio communication between the node and TAP in the assumption of the boundary model of the radio channel when satisfy the *SNR* signal/noise ratio in the channel. An example of different values of the size of the radio communication zones R depending on the TAP flight height h when using sector antennas and the maximum transmission range $d_{\max}$=250 m is shown in Fig. 2 [8].

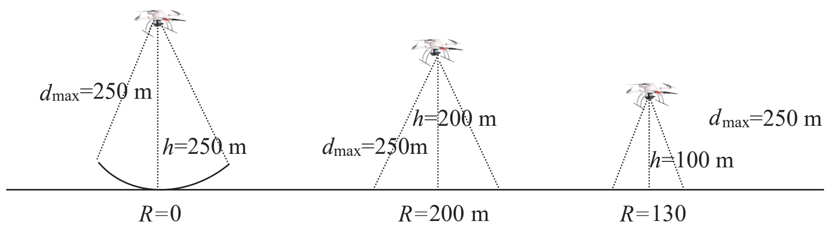

Fig. 2. Dependence of the size of the radio communication zone R on altitude h

The advantages of the FOREL algorithm include the ability to change the number of clusters depending on the value of R, the convergence of the algorithm, which increases with increasing R, insignificant computational complexity – $O(N^2)$.

As a result of the clustering algorithm, the WSN will be divided into a certain number of cluster sizes of the same size in accordance with the priority of the objective function. In the second step of clustering, heterogeneous clustering is carried out taking into consideration the set of parameters of each cluster (size, number of nodes, data volume, battery energy level, relative location) to meet certain objective functions. For example, for:

– reduction of data collection time, reduction of energy consumption of nodes for transmission (by reducing the distance between nodes with TAP) – additional clustering of clusters with a maximum number of nodes or nodes with a significant amount of monitoring data is carried out;

– reduction of the length of the trajectory of the flyby (by reducing the points of the TAP flyby) – clusters with a small number of nodes are destroyed by redistributing them between other clusters;

– reducing the energy consumption of nodes for transmission – the size of the cluster is reduced by reducing the TAP flight altitude.

Fig. 3 shows the results of our simulation of the process of homogeneous (*a–d*) and heterogeneous (*e–h*) clustering of WSN for N=100 nodes with R=80, 100, 150, 190. Designation: a dot is a sensor node, a circle with a thin line is the process of cluster formation, a circle with a thick line is a formed cluster.

The problem of selecting the primary points of data collection by TAP is stated as follows: to find the optimal position of TAP hovering in space $Q_k^*=\left(x_k^*,y_k^*,h_k^*\right)$ above the k-th cluster of the area s_k, with nodes $i=1...n_k$, $i\in s_k$ with known volumes of monitoring data of each i-th node V_{dmi}, which minimizes the time of data acquisition within a cluster t_{colh}^k (12) or the total energy consumption of the cluster E_{conh}^k nodes (13):

$$t_{colh}^k=\min_{Q_k\in Z}\sum_{i=1}^{n_k}t_{coli}^k=$$

$$=\min_{Q_k\in Z}\sum_{i=1}^{n_k}\left(\left(V_{dmi}+V_{sti}\right)/s\left(d_{i-TA}\right)\right), \qquad (12)$$

$$E_{conh}^k=\min_{Q_k\in Z}\sum_{i=1}^{n_k}\left\{e_{trb}\left(d_{i-TA}\right)\left(V_{dmi}+V_{sti}\right)+e_{rcb}V_{rci}\right\}, \qquad (13)$$

under restrictions. Namely, the zone of TAP possible location – Z (in which radio connectivity with cluster nodes is maintained) parameters of the MAC protocol (the volume of service traffic, the speed of data transmission in the radio channel at certain distances, energy consumption per bit of transmission and data reception) and the volume of received data.

Objective functions (12), (13) are non-convex and may have local minima. Known methods have considerable computational complexity, so an iterative algorithm is used to calculate the approximate position of TAP to achieve a specific objective function [28]. Its computational complexity is $O(n_{point}n^2)$, where n is the number of nodes within a cluster, n_{point} is the number of possible points of TAP placement.

The decision to select certain data collection points (when hovering) in clusters will be made according to the priority of the objective function:

– a geometric center of the cluster, if the priority of OF (1) is due to the reduction of the flight route;

– the center of «mass» of the cluster, if OF (2) is a minimum average transmission energy within a cluster with the assumption of the same amount of monitoring data in the nodes – the result of the algorithm of homogeneous clustering;

– a collection point, which minimizes the average power of cluster nodes – priority of OF (2) with known data on the volume of monitoring data (13);

– a collection point, which minimizes the time of data collection – priority of OF (1), (12).

5. 2. Development of a method for constructing a trajectory of the flyby and data exchange by a telecommunication aerial platform with cluster nodes

The TAP flight path in the network is divided into a flight path in and between clusters. It is proposed to minimize the time of data collection by TAP in the network to build its basic flight route using algorithms for finding the shortest path (solving the traveling salesman problem). The traveling salesman problem belongs to the class of NP-complete. Therefore, in practice, heuristic algorithms are used that provide an approximate solution but have little computational complexity.

To build a flight route in a clustered network (between data collection points), studies were conducted on the effectiveness of heuristic algorithms proposed by researchers for WSN: the nearest neighbor [12], in a spiral [13], in squares FPPWR [14], CHIH [15].

For this purpose, a set of algorithms for finding the shortest path in the C# environment for a clustered network of dimensionalities N=100, 200, 500 nodes was implemented. According to the FOREL algorithm, the network was clustered into k=7–17 clusters (by changing the TAP flight altitude), the routes of the TAP flyby were built according to certain algorithms for finding the shortest path. Visualization of the results of the work of various algorithms is shown in Fig. 4.

The results of the study (Fig. 5) made it possible to estimate the length of the route depending on the number of clusters (collection points) for different algorithms. The method of complete brute force makes it possible to obtain solutions for networks that have up to 10 clusters.The simulation results demonstrated the efficiency of the Convex Hull Insertion Heuristic algorithm for a clustered network (up to 15 % shorter route).

Fig. 6 shows the result of the algorithm for finding the shortest route CHIN in a clustered network with R=100, 150, and 190.

However, the resulting trajectory of the TAP network flyby does not take into consideration the real state of the nodes, which can change significantly during the last round of the flyby. Further improvement of the primary strategy along the TAP flight path should correspond to the priority of the objective control functions and take into consideration the state of the nodes within a cluster (battery energy level, monitoring data volume, their relative location, etc.).

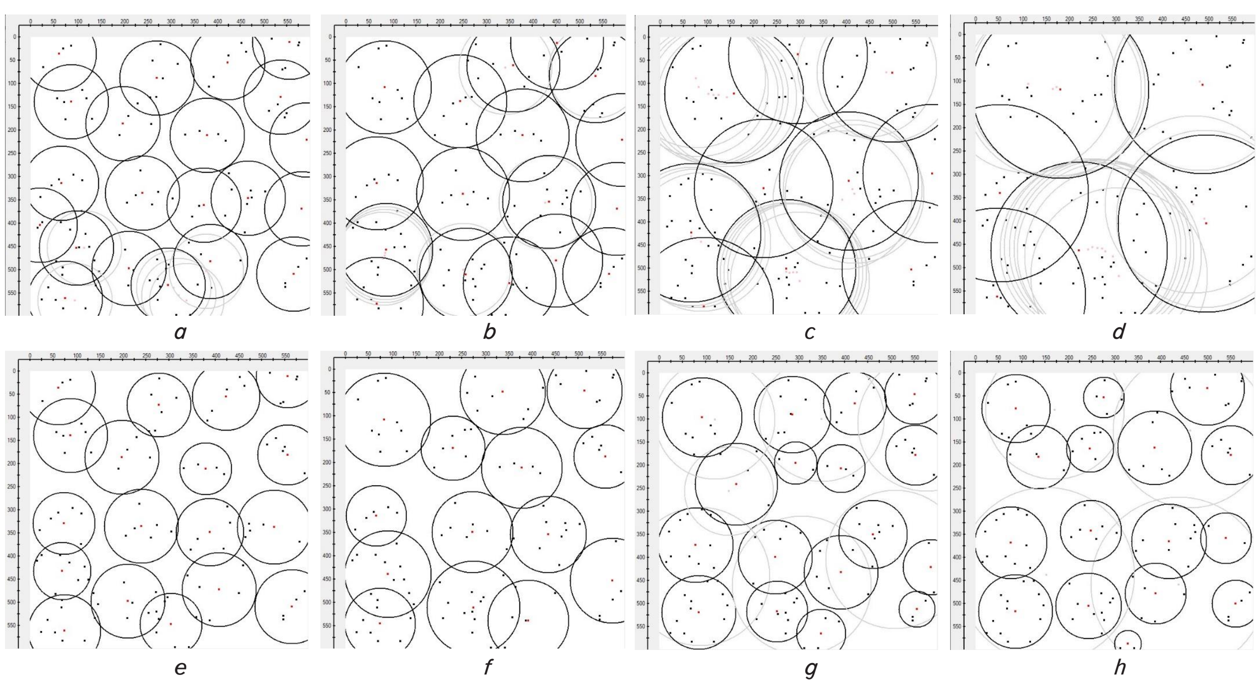

Fig. 3. Options for clustering a wireless sensor network: *a* – R=80; *b* – R=100; *c* – R=150; *d* – R=190; *e* – objective function (1); *f* – objective function (2); *g* – objective function (1) and objective function (2); *h* – objective function (1) and objective function (2)

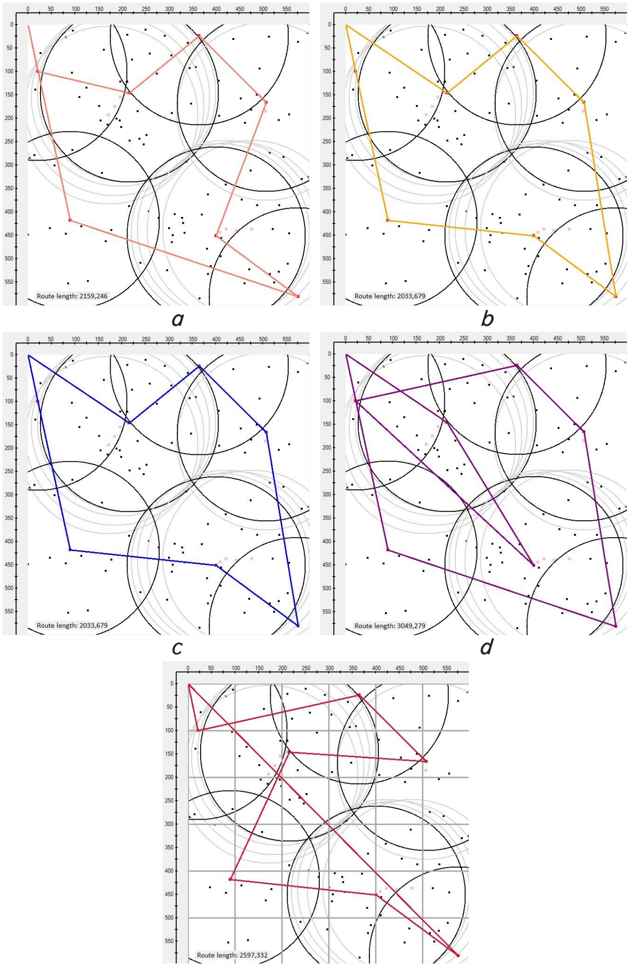

Fig. 4. Simulation results of algorithms for finding the shortest flight route of a telecommunication aerial platform in a clustered network: *a* – the algorithm of the nearest neighbor; *b* – Convex Hull Insertion Heuristic algorithm; *c* – the algorithm of complete brute force; *d* – the algorithm in a spiral; *e* – Fast Path Planning algorithm with Rules

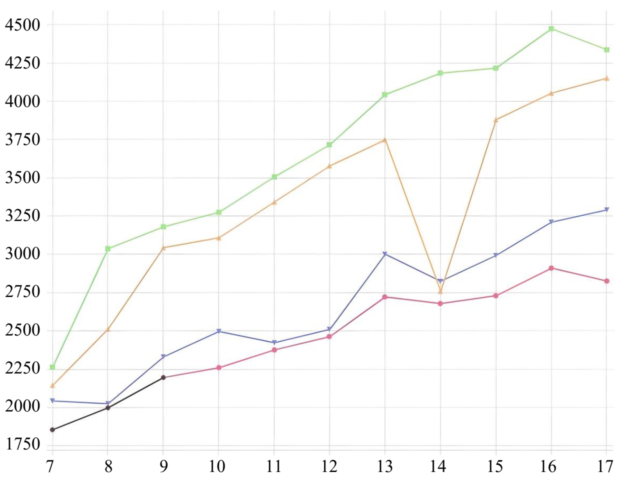

Fig. 5. The results of modeling algorithms for finding the shortest path: black color – the algorithm of complete brute force; red color – the Convex Hull Insertion Heuristic algorithm; blue color – the algorithm of the nearest neighbor; brown color – the algorithm in a spiral; green color – Fast Path Planning with Rules algorithm

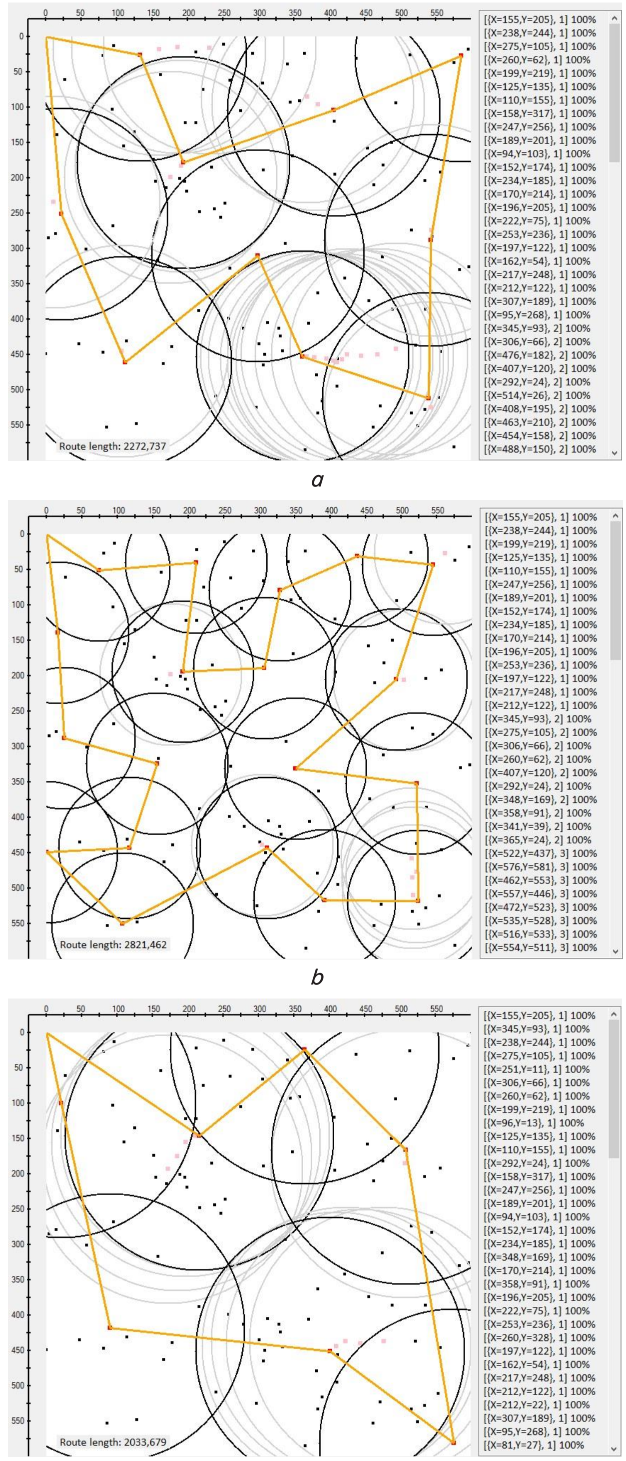

Fig. 6. Results of the convex Hull Insertion Heuristic route search algorithm implementation: *a* – R=100; *b* – R=150; *c* – R=190

Under the flyby strategy of the k-th cluster St_k we mean determining:

a) the way of flying around the clusters by TAP:

– only when hovering – selection of the cluster hovering point depending on the objective control function and the state of the nodes (data volume, battery energy, distance) – models for calculating TAP positioning within a cluster (12), (13) are used;

– only with a flyby – selection and calculation of time intervals of the trajectory and the schedule of exchange of nodes that are closer to the TAP flight path;

– hybrid (flight with data exchange and hovering with data exchange);

b) rules of priority access for exchange with TAP under the conditions of their competition (to draw up a schedule of transfers between the nodes of the cluster and TAP);

c) a TAP flight speed (constant or adaptive) to ensure sufficient time for data acquisition during the flight in the radio connectivity zone of the node (6);

d) taking into consideration the requirements for the quality of service: with a guarantee of service for all nodes of the cluster, with a limit on the maximum maintenance time of the cluster (node);

e) a TAP flight path within a cluster by adjusting the base route, for example, in cases of the presence of critical nodes (with extremely low battery energy or with a very large amount of data, etc.).

Fig. 7 shows the main options for strategies: data collection during the flight through the center of the cluster (Fig. 7, *a*); data collection only at the hovering point (Fig. 7, *b*); hybrid method – data collection during flight and at the point of hovering (Fig. 7, *c*); a change in the base trajectory and collection point (for example, to maximize the time of network operation, the trajectory is built to service critical node 5, units with low battery energy 1–4, the point of hovering and exchange near the accumulated nodes 6–8 with a significant amount of data) was determined (Fig. 7, *d*).

In Fig. 7, the following designations are used: a dot – a node, a solid thin line – radio channel node-TAP, an asterisk – a data collection point; a diamond – a data collection interval; a directed line – a direction of TAP movement TA; an enlarged dot is a critical node.

The latter strategy is implemented in the proposed method.

The result of each strategy in the *k*-th cluster is estimated by a set of parameters:

– cost energy of the node of each cluster node for the collection (transmission and reception) of data e_{coni}, the total cost energy of the cluster nodes E^k_{con} according to (10), (11), (13);

– the time of data collection within a cluster t^k_{col}, which is determined by the flight time (depends on the length of the trajectory and adaptive TAP flight speed for data exchange according to expression (8)) and the hovering time in the presence of collection points (7), (12).

The best solution from *m* flyby strategies in a cluster is determined by each OF (14) or a lexicographical method is used for multicriterial optimization:

$$St^*(t_{col}) = \arg\min_{m\in M} St_m(t_{col})$$

or

$$St^*(t_{fun}) = \arg\min_{m\in M} St_m(E_{con}). \quad (14)$$

To reduce the options for brute force and reduce the time to find a solution for the optimal strategy of node flyby and data collection within a cluster, it is proposed to use the method of situational management.

That is, a limited number of situations are formed (a set of parameters of the states of the cluster elements), a set of control actions, and an appropriate base of decision-making rules of the production type is developed: IF <condition>, THEN <action> [29] (Fig. 8).

According to the objective functions, the rules are divided as follows:

– network ones – minimum or limit of the time of data collection T_{col} (1), maximum or achievement of a certain time of operation of the network T_{fun} (2);

– in the *k*-th cluster – minimum time of data collection t_{col} within a cluster, minimum energy of node costs within a cluster;

– in a node – minimum time of collection (exchange), minimum energy consumption.

Based on control parameters:

– the number of clusters, cluster area, number of nodes within a cluster, their relative location;

– a set of parameters of cluster nodes (energy, data volume, relative location);

– location of nodes relative to the TAP flight path and within a cluster;

– parameters of the state of the nodes (battery energy, data volume);

– parameters of node exchange with TAP (time and energy of node costs);

– trajectory parameters (direction and height).

By control action – determining (change) the position, direction, and altitude of TAP flight, transmission power, antenna radiation pattern, TAP hovering point (redistribution of distance between cluster nodes and TAP), basic trajectory for changing the distance between TAP and node during flight, etc.

Let us consider several general rules for determining the strategies for flyby and exchanging data, which are conditionally divided into groups (by defining collection points, adjusting the trajectory, redistributing cost energy, etc.) that implement the corresponding control goals.

Rule for defining hovering points for data collection:

IF there are sets of nodes within a cluster (loaded or with low battery energy), THEN determine the TAP hovering point to collect data from these cluster nodes according to expressions (12) or (13).

Rule for adjusting the basic trajectory:

IF it is necessary to reduce the transmission time in the node-TAP radio channel and/or reduce the energy consumption of the node, THEN it is necessary to place (move) the TAP flight path closer to the node.

The rule for reducing and equalizing energy costs for the transmission of competing nodes:

IF multiple nodes compete for exchange intervals with TAP, THEN prioritize and determine the *INT* exchange interval on the TAP flight path and the node that has the minimum battery energy.

Rule for servicing critical nodes:

IF the node has a critical battery energy level (a significant amount of data) and it is at a considerable distance from the TAP flight trajectory, THEN change the TAP trajectory and reduce the distance to the node.

To reduce the sorting of possible variants of the TAP flight path and determine the points (exchange intervals), a set of meta rules is proposed, which determine the priority sequence of rules for achieving the objective function according to its priority. Consider some of them.

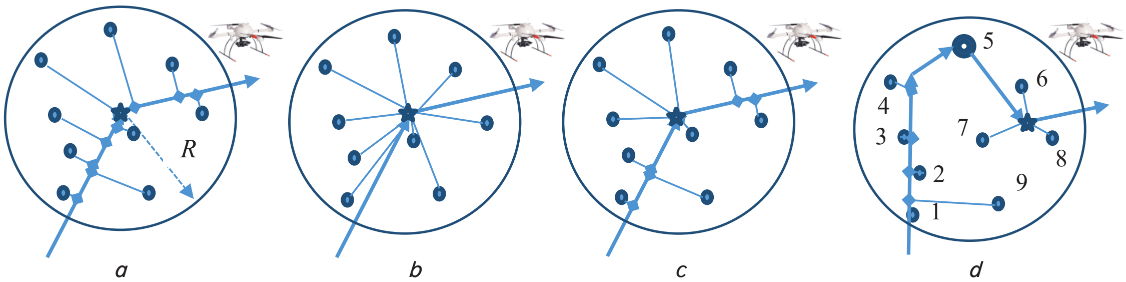

Fig. 7. Key options for flight strategies and data collection by a telecommunication aerial platform in a cluster

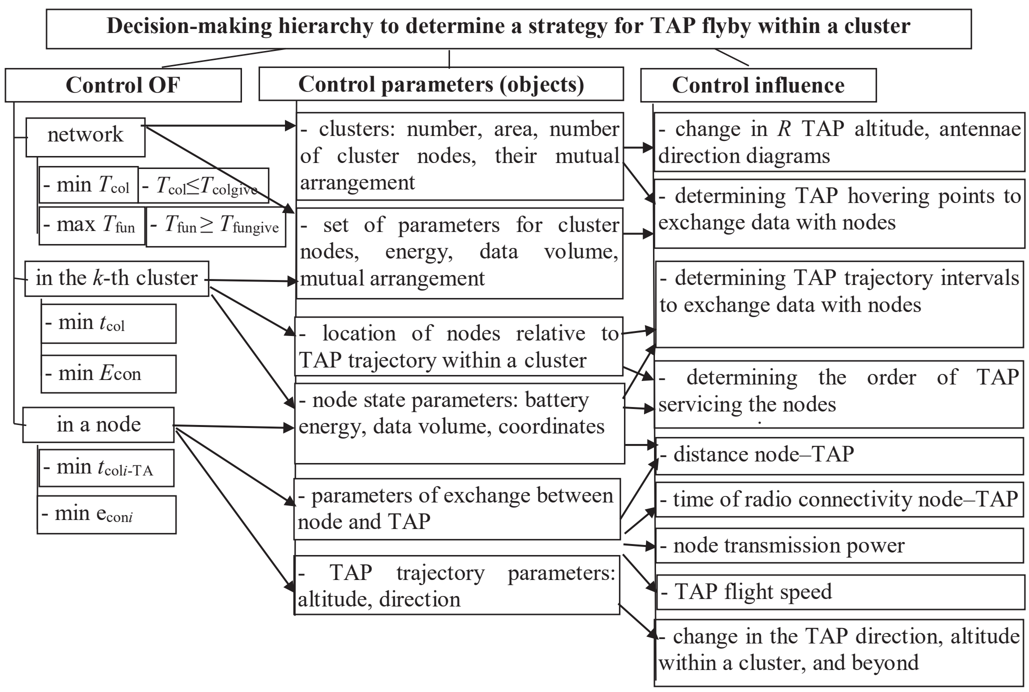

Fig. 8. Decision-making process to determine a cluster flyby strategy

MetaRule1: IF OF T_{col}→min, THEN (the problem is reduced to single-criteria optimization) it is required to:

– find the maximum number of network clusters, set the TAP trajectory through the cluster center;

– set the maximum speed of TAP movement within a cluster (which meets the requirements for data exchange between TAP and nodes);

– calculate the intervals and schedule of transmissions of nodes during the flight, taking into consideration the state of the nodes using rules that are focused on increasing the transmission speed in the radio channel;

– determine the collection points (hovering) according to (12).

MetaRule2: IF T_{col}→min and T_{fun}→max, the first OF takes precedence over the second, THEN (lexicographic optimization method):

– find a certain small number of network clusters;

– determine the points of collection (hovering) according to (12);

– set the TAP trajectory through the collection points;

– calculate the intervals and schedule of transmissions of nodes during the flight at a minimum distance, taking into consideration the available energy of the nodes.

5. 3. Development of an algorithm for a modified method of direct acquisition of data from a wireless sensor network nodes by a telecommunication aerial platform

To solve the problem of developing a modified method for collecting data from WSN nodes by TAP in order to achieve certain objective functions, the method given in [8] is taken as a basis.

The method used consists of the following successive main stages (Table 1): clustering of the network and selection of exchange points between TAP and nodes; the construction of the shortest route for flying around collection points; the construction of the flight path and the order of data exchange with nodes in clusters.

The general algorithm for the functioning of the method is implemented on the basis of the hierarchy of interaction of data acquisition algorithms, which are incorporated in the network control center (NCC), TAP control systems, and control systems of network nodes.

The network management cycle consists of the following stages: collecting data on the status of network nodes (carried out by TAP in the next round of the flight), analyzing the state of the network, making a decision, and implementing the decision.

Table 1

Stages of implementation of the method of direct data collection from network nodes

Stages of the method	Existing solutions	New (proposed) solutions
Network clustering	Algorithms for covering nodes with circles of radius R (random, greedy, k-means, etc.)	2-step clustering: – homogeneous (FOREL); – heterogeneous (proposed heuristic rules)
Selection of primary flight points (data collection) by TAP in the cluster	Data collection point by TAP: – the geometric center of the cluster; – the center of «mass» of the cluster	Selection of the TAP collection point depending on the state of nodes in the cluster and OF: – the minimum energy of node transmissions; – minimum collection time
Construction of the shortest route between data collection points	A set of algorithms for solving the traveling salesman problem	Convex Hull Insertion Heuristic Algorithm for Clustered Network
Selection of overflight strategy and TAP data exchange with nodes in the cluster	The trajectory runs through the center of the cluster, the exchange points are the closest to the TAP flight trajectory	The decision on the TAP trajectory takes into account the state of the nodes and the cluster and is carried out using the appropriate rule base to achieve the objective functions

NCC solves the following main tasks:

– clustering of the network, optimization of the number and size of clusters according to OF;

– calculation of the number and coordinates of collection points (TAP hovering);

– calculation of the TAP flight path, determining exchange intervals;

– determines the priority of TAP flight strategies in clusters according to OF.

In the absence of radio communication between TAP and NCC, its tasks are assigned to TAP.

The scheme of the generalized algorithm for the implementation of the method is shown in Fig. 9. Consider its main steps:

– step 1. Data are collected and entered (according to the statement of the problem);

– step 2. A 2-stage clustering of the network is being implemented to achieve OF:

a) homogeneous clustering of the network – finding a certain number of clusters using the FOREL algorithm to achieve OF by adapting the radius R of the coverage;

b) heterogeneous clustering – consolidation or partitioning of clusters in accordance with the rules, priority of OF, and the real position and state of clusters and nodes;

– step 3. Determining primary collection points (TAP position in space): one in each cluster according to models (12), (13);

– step 4. Construction of a basic TAP flight route at certain collection points by searching for the shortest path using Convex Hull Insertion Heuristic;

– step 5. Calculation of T_{col} according to (3) to (7) and T_{fun} (8) to (11), checking the limitations Ω;

– step 6. If the solution satisfies, then the end, otherwise – the transition to the next step;

– step 7. Calculation of the minimum flight time and data collection t_{flmin} and the maximum operating time t_{funmax} of the network;

– step 8. Verification: it is possible to optimize according to OF.

If so, then proceed to step 9, otherwise – terminate;

– step 9. Search for a new solution to the flyby strategy by applying the rule base;

– step 10. Check the quality of the solution.

If the decision is better, then – make a decision (unit 11), otherwise discard;

– step 11. Verification: all solutions are considered.

If so, then terminate, otherwise proceed to step 9.

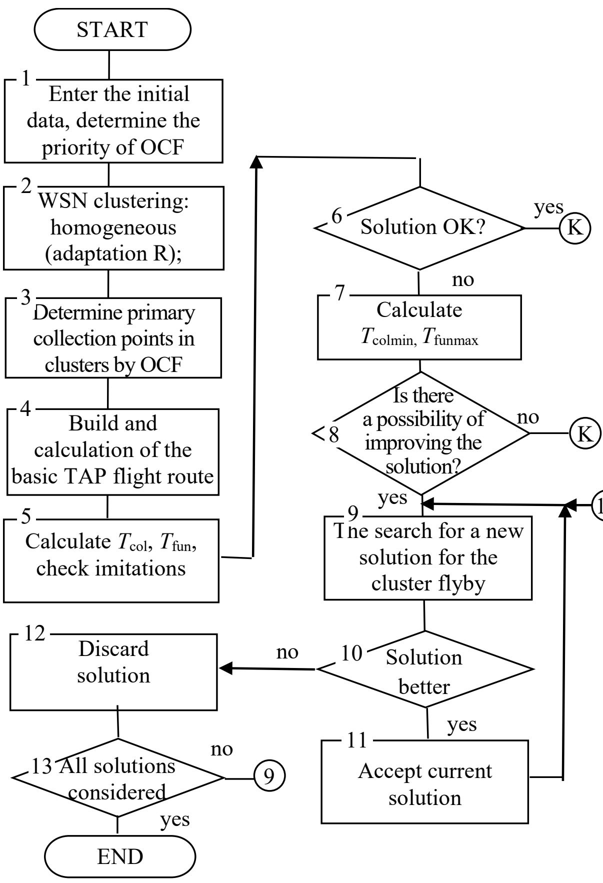

Fig. 9. Scheme-algorithm for the implementation of the developed method of data collection

To assess the effectiveness of the proposed method, a simulation model of the process of collecting TAP data from WSN nodes (created in the C# environment) was developed. The logic of the model corresponds to the algorithm for implementing the proposed method and includes the following steps:

– generation of coordinates of a given set of nodes on a certain plane;

– 2-step clustering of a wireless sensor network and determining the primary points of hovering (data exchange) between TAP and the nodes of the cluster;

– construction of the basic shortest route in the network between exchange points according to the Convex Hull Insertion Heuristic algorithm;

– construction of the TAP flight path between clusters and in clusters by adjusting the base route in accordance with the proposed rules (heuristics) in order to implement the objective functions;

– determining the speed and altitude of TAP flight, intervals and schedule of data transmission between TAP and nodes within a cluster in accordance with the proposed rules;

– adjustment of cluster flyby parameters (trajectory, speed, collection points, etc.) according to the base of rules and objective functions.

Next, the flyby of WSN nodes by TAP is modeled and calculations of the energy consumption volumes of the nodes are carried out according to the flow model, which is given in [5, 9], and the time of data collection is calculated.

Initial data for modeling: nodes are randomly placed on the plane S=600×600 arbitrary units (Fig. 10); number of nodes N=100, 200, 500; e_0=0.1J, $d_{\max}$=250 m, h=50–250 m, $v_{\max}$=0–10 m/s, NR_{giv}=700, MAC protocol – IEEE 802.11g, V_{dmi}=100 Kb, energy consumption per transmission bit, etc.

The studies into the effectiveness of the proposed method in comparison with the hybrid method [8] with different initial data were carried out: the dimensionality of the network, the number of clusters, the number of nodes within a cluster, the volume of monitoring data, options for constructing flyby routes, strategies for flying around nodes within a cluster, etc.

Fig. 10 shows the dependence of the time of data collection T_{col} of the improved method compared to the hybrid method [8] with a different number of nodes within a cluster N=100, 150, 200. The time of data acquisition in the proposed method is 10–15 % less compared to the hybrid method of data collection [8]. At the same time, with an increase in the number of rounds of TAP flight (iterations), the difference in the collection time between the methods becomes smaller due to the faster failure of the network nodes for the method [8].

Fig. 11 shows the dependences of the average energy consumption of a node $\overline{e}_{coni}$ and the percentage of inoperable nodes $n_{failure}$ on the number of flyby rounds NR for a network with N=200 nodes. The average energy consumption of nodes (Fig. 11, a) in the proposed method is 10 % lower compared to [8], therefore the percentage of failed nodes (Fig. 11, b) in the proposed method is smaller, which accordingly increases the time of network operation by 12–17 %.

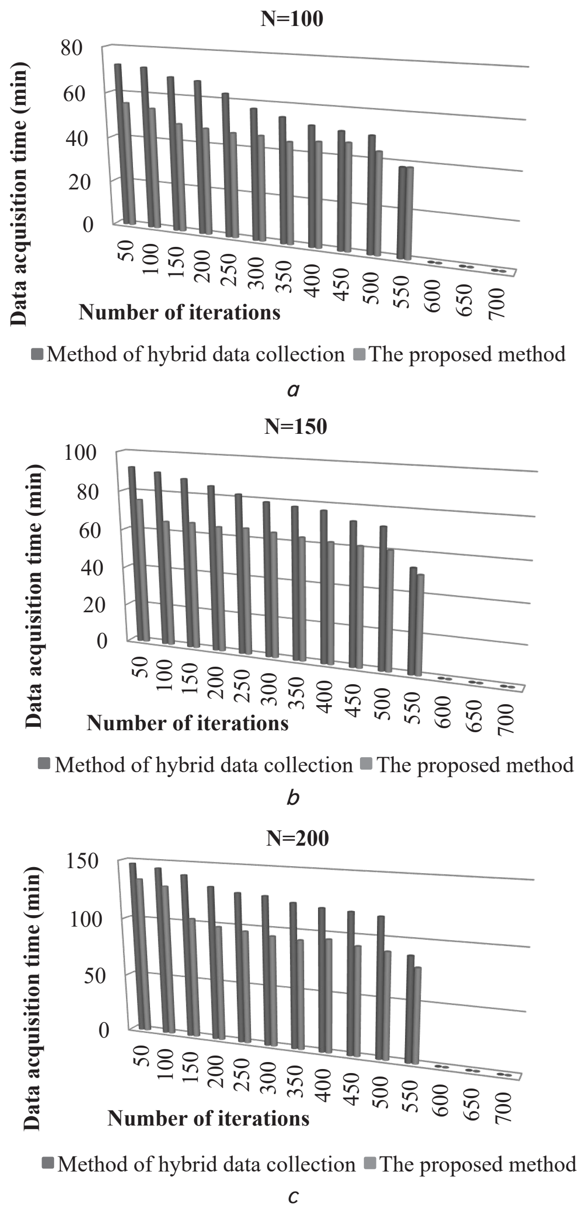

Fig. 10. Dependence of data collection time with different number of network nodes: a – N=100; b – N=150; c – N=200

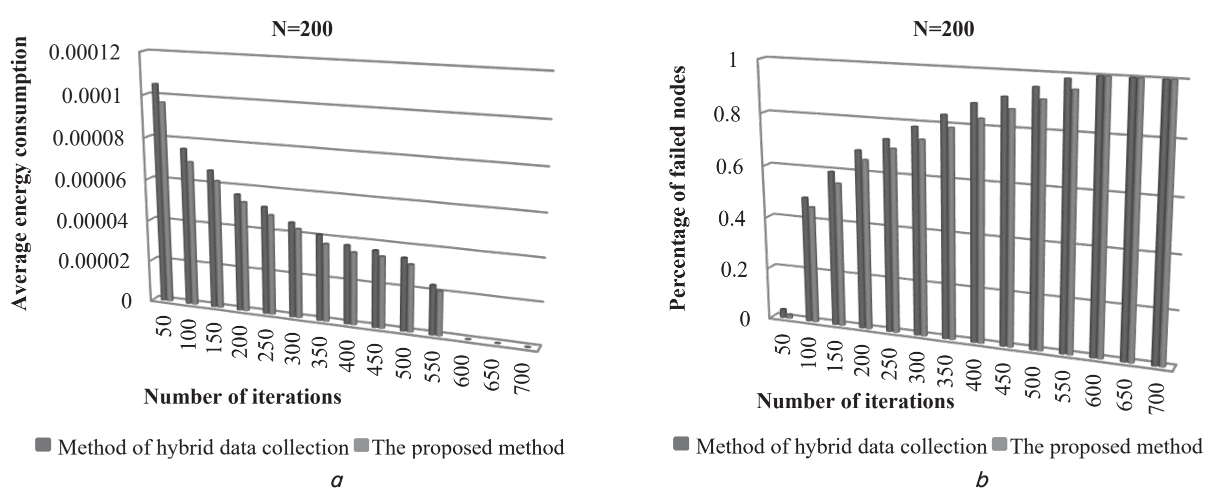

Fig. 11. Dependence of indicators on the number of flyby rounds: a – $\overline{e}_{coni}$; b – $n_{failure}$

The simulation results of the modified method of data collection by TAP in comparison with the existing method showed that the time of data acquisition from the nodes by TAP at the same time decreases by 10–15 % or increases the operating time of the network by 12–17 % when certain restrictions are met.

6. Discussion of results of studying wireless sensor network settings using the modified method of data collection

The main differences between the proposed method and the existing ones [3–9, 18–23] at different stages of its functioning are given in Table 1.

At the first stage (network optimization), in contrast to existing approaches [3, 5–10] where only homogeneous clustering is carried out (in [8], by the FOREL algorithm), it is additionally proposed to carry out heterogeneous clustering.

Our result makes it possible to take into consideration the parameters of the state of the nodes of each cluster, the relative location of the clusters (Fig. 3), to make a decision on the exclusion of the cluster or its additional partitioning. This makes it possible, depending on OF, to reduce the energy consumption of the batteries of the nodes (Fig. 11, *a*) by reducing the size of the cluster or reducing the time of data acquisition through its destruction (Fig. 11, *b*).

The disadvantage of the clustering algorithm is the dependence of the result of work on the initial solution. Therefore, to improve the result, it is necessary to perform several runs of the algorithm with different options for the initial solutions and choose the best one to meet the objective function. The direction of its improvement may be to remove the restriction on the boundary model of the radio channel and take into consideration the set of its parameters of the physical level.

At the second stage of the method, an algorithm for finding data collection points by TAP in the space of each cluster is determined, which, unlike the existing ones [3–10, 22], takes into consideration the actual amount of data, the available energy of the batteries of the nodes within a cluster and the parameters of the MAC protocol. This allows one to minimize the average energy consumption of cluster nodes or to minimize the time of data exchange. This becomes possible due to finding the optimal position of TAP in the space above the nodes of the cluster according to the priority of the objective function. The insignificant computational complexity of the proposed algorithm $O(n_{point}n^2)$ allows TAP to use it in real time. The accuracy of the solution on TAP positioning depends on both the number of potential collection points n_{point} and the parameters of the MAC protocol (a radio communication range and the set of transmission speeds, energy consumption per bit). Therefore, in practical application, it is necessary to take into consideration the parameters of the MAC protocol.

At the third stage of the method, in contrast to studies reported in [11–15] that employ classical approaches to solving the traveling salesman problem in WSN (Fig. 4), the proposed method of constructing a TAP flight path takes into consideration the parameters of the state of the nodes and the dependence of the energy consumption of nodes on the TAP flight path. The novelty of this approach is the search for a trajectory, which is divided into two consecutive steps: network and cluster optimization. This makes it possible at the first step to obtain the shortest routes in the network at collection points in clusters by using the CHIH algorithm [15] (Fig. 6), which showed the best results for clustered networks (Fig. 5). In the second step – to build strategies for the flyby by TAP of cluster nodes, which makes it possible to achieve objective functions taking into consideration the state of the nodes. This becomes possible through the use of the method of situational management (Fig. 6), which meets the requirements for its application: a significant number of situations (states) within a cluster and a relatively small number of control actions. To find a solution for choosing node flyby strategies (Fig. 7), an appropriate database of rules has been developed. The determined hierarchical nature of the adoption of the OF implementation (Fig. 8) made it possible to implement optimization by levels (network – cluster – node). This made it possible to develop meta rules that reduce the number of options for constructing a trajectory and the time to develop a solution. Solutions are produced according to the hierarchy and priority of OF (lexicographic method of optimization).

When constructing the trajectory of the flyby by TAP, we managed to significantly reduce the energy consumption of the nodes (Fig. 11) and increase the operating time of the network compared to the previously proposed method (Fig. 10).

To apply the results of the study and for the correct construction of TAP trajectory, it is necessary to take into consideration the following limitations: the area of WSN territory should be significantly larger than the area of the TAP coverage zones; the absence of prohibited flight areas for TAP; the possibility of placing sensors at different heights due to the peculiarities of the terrain; the features of movement of TAP of the aircraft type.

To advance the method proposed, we plan the following:

– to use several TAPs to build a trajectory and collect data in the network from sensor nodes;

– to conduct research on the method of data acquisition for WSN with mobile nodes;

– to apply artificial intelligence methods to implement the process of building a TAP trajectory and collecting data (designing an intelligent robot platform).

It is important to note that the proposed method can be used in special software for a control system of the telecommunication aerial platform and the network management center. In addition, its computational complexity allows the application of TAP on a real-time scale. It should be noted that the proposed direct data acquisition by TAP from nodes significantly reduces the requirements for hardware resources of nodes (compared to the method of collecting data from the main nodes of clusters) and, accordingly, significantly reduces their cost.

7. Conclusions

1. We have improved the algorithms for clustering wireless sensor networks by telecommunication aerial platforms and determining data collection point. The clustering algorithm makes it possible to form optimal network parameters (the number of clusters and their sizes) to achieve certain objective functions. The novelty of the developed algorithms is the two-stage clustering of the network to determine the position of a telecommunication platform within a cluster space. At the first stage, network optimization of the size and dimensionality of clusters according to the

coordinates of node placement (homogeneous and heterogeneous clustering) is carried out. At the second stage – the proposed model of optimal positioning of the telecommunication aerial platform in clusters, which, unlike the existing ones, takes into consideration the state of the nodes and achieves optimization of the time of collection of nodes within a cluster or the energy consumption of its nodes.

2. A method for constructing the flight path of a telecommunication aerial platform and exchanging data with nodes has been developed. Unlike existing methods, it implements a certain hierarchy of decision-making. At the network level, a well-known iterative algorithm for finding the basic shortest flight route of a telecommunication aerial platform of network clusters is used. At the cluster level, to adjust the basic solution, the telecommunication aerial platform takes into consideration a set of parameters of the actual state of nodes and clusters. At the node level, energy costs are minimized by reducing the distance to the telecommunication aerial platform. This makes it possible to minimize the length of the flight path, the energy consumption of the batteries of the nodes for data transmission. A feature of the method is the use of the situational control method for making decisions on the flight path using the developed rule base. This approach makes it possible to achieve optimization of the objective functions of the data acquisition process and ensure real-time decision-making.

3. We have developed an algorithm for the modified method of direct data collection by telecommunication aerial platforms from wireless sensor network nodes of considerable dimensionality. Distinctive features of the method built are a certain integral sequence of optimization stages: during clustering, in determining the points (intervals) of data acquisition, in building a flight path. The result is achieved through a step-by-step multicriterial optimization by levels of hierarchy (network, cluster, node) taking into consideration the objective functions of managing the data collection process. Simulation results showed a decrease in data collection time by 10–15 % or an increase in the network operation time by 12–17 % while meeting resource constraints.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

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