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DIRECT DATA COLLECTION METHOD BY TELECOMMUNICATIONS AERIAL PLATFORMS FROM THE WIRELESS SENSOR NETWORK NODES

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Background. To collect monitoring data from the nodes of the wireless sensor network in the absence of public telecommunications infrastructure, it is proposed to use telecommunications aerial platforms (TA), built on the basis of UAVs. Each telecommunication aerial platform acts as a mobile gateway, dynamically creates virtual clusters in the network, determines the data collection points in the clusters and their flight paths, forms a schedule and exchanges data with cluster nodes depending on their location coordinates relative to the TA flight path, battery power level and volume of monitoring data.

Objective. The aim of the paper is to improve the efficiency of data collection from wireless sensor network nodes by telecommunication aerial platforms.

Methods. Unlike existing data collection methods, the proposed method: uses the FOREL (FORmal ELement) cluster analysis method for clustering the network, new rules for selecting data collection points and rules for data transmission between TA and cluster nodes to achieve the specified target control functions: minimization of TA data collection time, maximization of network operation time, minimization of used TA.

Results. The proposed monitoring data collecting method by TA from the nodes of the wireless sensor network allows increasing the efficiency of achieving a given target control function (reduce the time of data collection, increase the time of network operation, reduce the number of telecommunication aerial platforms used).

Conclusions. The implementation of the proposed method into the specialized software of the wireless sensor network control system will improve the efficiency of the sensor node data collection process by telecommunication aerial platforms.

Keywords: wireless sensor network; data collection method; network clustering; telecommunication aerial platform.

1. Introduction

Wireless sensor networks (WSN) are increasingly being used in various areas of human activity [1 - 3]: monitoring of forests, fields of agricultural crops, oil and gas pipelines, borders, implementation of environmental and meteorological monitoring of areas, search and rescue missions, etc. A wireless sensor network can be designed to operate for months or even years in remote (inaccessible) areas in the absence of common telecommunication infrastructure. The only solution to collect data from the network nodes in these conditions is using of UAV-based telecommunications aerial platforms (TA) [3]. Autonomous stationary sensor nodes monitor the specified parameters of zones (objects) of their coverage, store the received data and when a telecommunication aerial platform appears in the zone of their radio communication transmit the collected data to it.

Let us highlight the main features of this class of networks:

1. Lack of connectivity between nodes or fragments of the network in the absence of common telecommunication infrastructure, which does not allow you to build a classic data collection schemes in the WSN, based on the constructed transmission routes from the sensor nodes to the gateways (base stations).
2. Limited resources of both sensor nodes (in terms of battery power, processor performance, memory, transmitter power, radio channel capacity, etc.) and resources of telecommunication aerial platforms (in time, altitude and speed of flight, energy reserve, transmitter power, memory capacity, etc.)
3. Significant dimensionality of the network (hundreds, thousands of sensor nodes). Replacing batteries for such a large number of nodes may be impractical or even impossible. Consequently, reducing the energy consumption during data collection by sensor nodes is crucial for increasing the lifetime of the network.
4. Delay in receiving monitoring data (DTN class). One way to reduce data collection time is to cluster the network and define data collection points, which can significantly reduce the length of the TA overflight route and, therefore, reduce the data collection time.

The TA can collect data directly from each node in three basic ways of flying the network [4 - 11] :

1. TA overflight each node of the network on the calculated route. The main advantages - low power consumption of nodes for transmission, simplicity of the node's transmission algorithms with TA (in the presence of radio communication with TA, sensor node transmits monitoring data to it) and, therefore, their cheapness. Disadvantage – significant TAs flight time (data collection) and, accordingly, significant collection time of monitoring data, increased requirements to its flight characteristics,
2. The TA trajectory (serpentine, spiral, zig-zag line etc.) overflows the entire network area, which also requires a significant flight and data collection time and relatively high node energy consumption.
3. TA overflight the data collection points. In this case, the network control centre (or the TA control system in the case of autonomous operation) divides it into clusters, calculates TA position in area (in the form of points or trajectory intervals) to collect data from nodes in clusters, builds a route to overfly only collection points. This method allows to significantly reduce the time of TA data collection, reduce the consumption of node batteries, but implies the implementation of appropriate algorithms of interaction between the telecommunication airplane and network nodes.

The methods and algorithms of data collection proposed for today [12 - 25] solve only partial tasks of data acquisition, do not consider features of functioning of this class of networks, multi-criteria character of target functions of network management and require improvement. Most works consider TA overflight of the whole monitoring territory, or consider clustering with "centroid algorithm", according to which data collection points are placed in the area of the greatest accumulation of nodes.

The aim of the work is to improve the methods of direct collection by TA data from WSN nodes, the general directions of the synthesis, which are defined in [26].

2. Statement of objective

Let us formulate a general statement of the problem.

Given: The monitoring area of the wireless sensor network is A;

the number of network nodes ($i = 1 \dots N$)and their location coordinates $(x_i, y_i) \in A$, V_{mdi} - the amount of collected monitoring data for each i-th node, technical (number and types of sensor sensors, battery energy, energy consumption per unit time interval of monitoring each type of sensor node at a certain distance, etc.) and telecommunication characteristics (channel and physical layer protocols, antenna type, transmitter power, power consumption per bit of receiving and transmitting data for the selected protocol and type of communication equipment, etc.) of sensor nodes;

number of telecommunication aerial platforms N_{TA}, technical (speed, altitude, flight time, etc.) and telecommunication (channel and physical layer protocols, antenna type, transmitter power, etc.) characteristics of TA.

Assumptions: the TA data collection process is managed by the ground control centre (GCC); each network node and each TA has its own control systems (CS), which implement the adopted method of data collection and interact with each other and the control centre; TA can perform autonomous data collection in the absence of communication with the ground control centre.

Information about node state parameters (location coordinates, battery energy level, amount of monitoring data) is collected during the initial overflight of the TA network, later information about node state is updated during each overflight of the network.

Necessary:

1. Determine the number of clusters k, their sizes R_k, coordinates of data collection points $(x, y, h)_k$ TA from cluster nodes (TA position in the space).
2. Calculate the route (trajectory) of the TA flight in the network from its initial position to the final one through the data collection points from the cluster nodes.
3. Calculate the flight path, the points (intervals) of the TA data collection trajectory in the cluster, the order (graph) of TA data transmission with the nodes of the cluster.

In this case, it is necessary to implement the target control functions (TSC) specified by the network control centre:

minimizing or ensuring a given time of data collection (T_{dc})

$$T_{dc} \rightarrow \min \text{ or } T_{dc} \leq T_{dcgiv}, \quad (1)$$

maximizing or ensuring a given time of network operation (T_{op})

$$T_{op} \rightarrow \min \text{ or } T_{op} \geq T_{opgiv}, \quad (2)$$

minimizing or using a given number of TA (N_{TA})

$$N_{TA} \rightarrow \min \text{ or } N_{TA} \leq N_{TAgiv}, \quad (3)$$

at restrictions Ω on:

type of TA - airplane or rotary;

time, speed, altitude and length of the TA flight – $T_{fl} \leq T_{fl\max}$, $v = [v_{\min}, v_{\max}]$, $h = [h_{\min}, h_{\max}]$; $L_{fl} \leq L_{fl\max}$;

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

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

radio channel range $d \leq d_{\max}$ and transmission speed $s_{i-TA} \leq s_{\max}$ (determined by the MAC protocol);

the volume of node buffers and TA – $V_{buf} \leq V_{bufnode}, \sum_{i=1}^{N} V_{bufi} \leq V_{bufTA}$;

quality of service requirements - to collect monitoring data from all nodes in the network.

The presence of several target control functions (expressions 1 – 3) leads to the problem of multi-criteria optimization, which can be solved by methods: the main indicator, concessions, etc.

3. Stages of the method

The method of direct collection data by TA from the nodes of the network assumes the following steps of operation (Table 1):

1. Network clustering - building clusters and finding data collection points from TA nodes of the network (initially one collection point per cluster).

To reduce the flight time the network is divided into a minimum number of clusters, to increase the functioning time of the nodes are built clusters with a minimum power consumption of nodes to transmit data with the TA.

2. Construction the basic (shortest) route of TA flight from the starting point to the end point of the flight through the data collection points in the clusters (to minimize the TA flight time).

3. Construction the TA flight path in clusters and selection transmission points (intervals) on it to achieve the specified target network control functions.

The basic flight route in clusters is adjusted and additional data collection points (intervals) are determined according to the proposed rules that implement the specified target functions of network management.

Scheduling TA transmissions of nodes in a cluster (defining a schedule of node transmissions in a cluster) to reduce collection time, redistribute battery power consumption between nodes (proposed modification of the IEEE 802.11 protocol). Let's consider each of the stages of the method of direct TA data collection from network nodes in more detail.

Table 1

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

Stages of the method	Existing solutions	New (proposed) solutions
1. Network clustering.	Algorithms for covering points in the area with circles (random, greedy, centroid, etc.), algorithms for cluster analysis (*k*-means).	FOREL cluster analysis algorithm.
2. Construction the shortest flight path between cluster centres.	Algorithms for solving the traveling salesman problem (full brute force, heuristic, genetic, etc.).	The algorithm is chosen based on the accuracy and time requirements for obtaining the TA flight path.
3. Calculation of TA flight path, transmission points (intervals) in clusters.	The flight path is built through the centre of the cluster, the data collection point is the centre of the cluster.	Rules for constructing the trajectory in a cluster and calculating collection points to achieve given target network control functions.
4. Scheduling by TA the nodes transmissions in clusters.	Existing protocols (e.g., IEEE 802.11).	Trajectory-position model of TA data transmission with cluster nodes (IEEE 802.11 modification).

3.1. Calculation models for TA data collection time and network operation time

Splitting the network nodes into clusters and defining TA data collection points in the area above the clusters allows reducing the length of the TA flight route. However, the cluster area (TA coverage area - Θ), their number (k) and size (R_k) must be determined by the target network control functions, which are set by the network operator. So, increasing the size of TA coverage area (cluster) reduces the number of clusters and, accordingly, reduces the number of collection points (at the initial stage of the solution it is considered that one cluster - one collection point), which leads to a reduction of the route length of TA coverage and, accordingly, reduction of data collection time. However, this solution increases the distance between TAs and cluster nodes, which leads to an increase in energy consumption of nodes and TAs for data transmission and, accordingly, a decrease in the time of network operation and vice versa. Therefore, in order to make a clustering decision, the network control centre needs to have models for calculating the network uptime and network operation time.

The TA data collection time (T_{dc}) in one round of network flight will be equal to the total time of its flight (T_f) which is determined by the sum of TA flight times in each k-th cluster t_{fk} and the sum of the TA times between clusters $t_{fk,k+1}$ (depending on route lengths l and TA flight speed v)

$$T_{dc} = T_{fl} = \sum_{k=1}^{K} t_{fl,k} + \sum_{k=1}^{K-1} t_{fl,k+1} = \sum_{k=1}^{K} \frac{l_k}{v_k} + \\ + \sum_{k=1}^{K-1} \frac{l_{k,k+1}}{v_{k,k+1}},$$

where $k = 1 \ldots K$ is the number of clusters in the network, l_k and v_k $(l_{k,k+1} v_{k,k+1})$ are the route length and speed of TA flight in the k-th cluster (between k and $k+1$ clusters).

To reduce the flight time between clusters, the TA flight speed is set to maximum $v_{\max}$. In clusters, the TA flight speed is calculated as the maximum possible under the condition of ensuring connectivity and guaranteeing the collection of all data from all nodes of the cluster. Note that the TA flight speed in the cluster can be: constant or variable (adapted to the necessary time of data collection from specific nodes of the cluster to reduce the time of flight in the cluster).

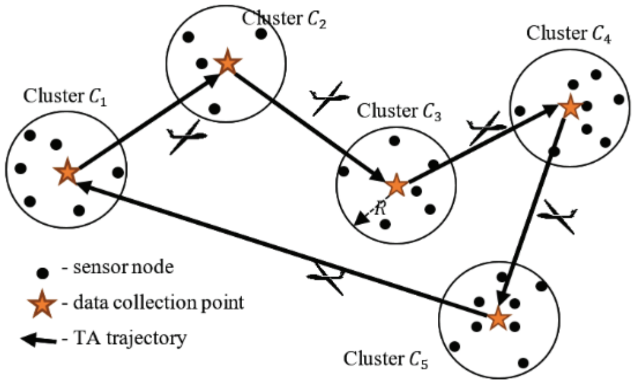

Fig. 1. Variant of clustering of the network and the route of TA overflight of the data collection points

To guarantee the quality of service, the TA data collection time from each *i-th* node $t_{dc(i-\mathrm{TA})}$ must not exceed the time of radio communication $t_{rc(i-\mathrm{TA})}$ for TA overflight over this node (Fig. 2)

$$t_{rc(i-\mathrm{TA})} = \frac{l}{v} = \frac{2\sqrt{d_{\max}^2 - h^2} cos\alpha}{v} \geq t_{dc(i-\mathrm{TA})} = \\ = \frac{V_{dci} + V_{oti}(PR)}{s_{i-\mathrm{TA}}(d_{(i-\mathrm{TA})}, PR)} \quad (4)$$

where l is the length of the flight path; v is the flight speed on this section; $s_{i-\mathrm{TA}}$ is the data transmission speed in the $i-\mathrm{TA}$ radio channel, which depends on the selected PR protocol and the distance $d_{i-\mathrm{TA}}$ between the i-th node and TA, V_{dci} is the amount of collected monitoring data by the i-th node, V_{oti} is the amount of overhead traffic of the protocol used.

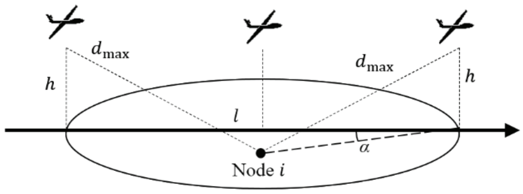

Fig. 2. Illustration of the radio communication time calculating of the i-th node with TA

The data collection time T_{dc} from nodes of the TA network for one round of overflight depends on the route length L_f and the flight speed v of the platform. The length of the initial basic flight route L_{bfl} (between the centres of clusters) TA depends on the number of clusters K and their location on the ground, coordinates of data collection points $(x, y, h)_k$ of each k-th cluster and the adopted algorithm for calculating the shortest flight route (Alg)

$$T_{dc} = \frac{L_{fl}}{v};\ L_{bfl} = f\ (K, (x, y, h)_k, Alg), k = 1 \ldots K \ (4).$$

In turn, the flight path in the cluster may differ from the baseline trajectory in accordance with the accepted rules of flying around the nodes of the cluster.

The network operation time T_{op} depends on the operation time of its nodes and can be estimated by the stable operation time (network operation time until the failure of the first node) or by the percentage of failed nodes at a certain round of TA overfly.

The number of rounds of TA network flying is: $NR = \frac{e_{i0}}{e_i}$, where e_{i0} is the initial battery energy of the node, e_i is the energy consumption of the node for the main modes of operation (monitoring, TA data reception and transmission, sleep) in one round of TA flying:

$$e_i = e_{imon} + e_{irc} + e_{itr} + e_{isl} = \\ = e_{mon}(r_{imon}, t_{imon}) + e_{trb} V_{tri} + \\ + e_{rcb} V_{rcj} + e_{sl}(t_{isl}), e_{trb} = \alpha + \beta r_{ij}^2, \\ e_{mon} = f(r_{mon}, p),$$

where e_{trb} and e_{rcb} are the energy consumed per bit of transmitting and receiving data; V_{tr}, V_{rc} are the volumes of transmitted and received data (considering monitoring data V_{mon} and service traffic V_s); α, β are coefficients, r_{ij} is the distance between nodes i and j; e_{mon} energy consumed by i-th node per unit of monitoring time at a given radius of node monitoring r_{mon}, t_{mon} - monitoring time, p - type of sensor; $e_{sl}(t_{sl})$ is the energy consumed for node sleep time.

If $NR \geq NR_{giv}$, then the network satisfies the time requirement, otherwise the GCC produces control actions to achieve the target function (splits the network into more clusters, changes the trajectory of the TA flight, etc.).

3.2.The FOREL cluster analysis algorithm

The problem of network clustering belongs to the class of NP-complete, obtaining the exact solution for large-dimension networks requires significant computational resources, so it is reasonable to use heuristic methods. In contrast to existing algorithms coverage of points on the area by circles of radius R (random search, greedy algorithm, etc.) for network clustering it is proposed to use iterative algorithm of cluster analysis FOREL (FORmal ELement) [27]. It allows finding minimum (necessary) number of clusters and data collection points in the network at the expense of TA coverage size R (adjusting TA flight height).

The FOREL cluster analysis algorithm solves the clustering problem by minimizing the total quadratic deviation of cluster nodes from the centres of mass of these clusters.

The minimization function is defined as follows

$$M = \sum_{k=1}^{K} \sum_{x_j \in S_k} \left(x_j - \mu_k\right), \quad (5)$$

where K is the number of clusters; S_k is the set of nodes of the k-thcluster; μ_k is the coordinates of the centre of mass of the k-thcluster; x_j is the coordinates of the j-thnode, $\left(x_j - \mu_k\right)$ is the distance between the cluster node and the centre of mass of that cluster.

In two-dimensional area, each node is considered a point on the area with coordinates $\left(x_j, y_j\right)$. The coordinates of the centre of mass of the k-thcluster are determined according to the expression

$$x_k^{\mu} = \frac{1}{n_k} \sum_{k=1}^{n_k} x_j \ , \ y_k^{\mu} = \frac{1}{n_k} \sum_{k=1}^{n_k} y_j. \quad (6)$$

Each node is characterized, in addition to the coordinates, also by the "mass" m_j, the centre of mass of the cluster is defined:

$$x_k^{\mu} = \frac{1}{m_k^{\Sigma}} \sum_{j=1}^{n_k} m_j x_j \ , y_k^{\mu} = \frac{1}{m_k^{\Sigma}} \sum_{j=1}^{n_k} m_j y_j,$$

$$m_k^{\Sigma} = \sum_{j \in S_k} m_j. \quad (7)$$

The FOREL algorithm specifies the cluster size (coverage area size $R = f(h, d_{\max}, \gamma)$ by the telecommunications aerial platform), which depends on its flight altitude (h), the maximum range of radio communication between the node and TA ($d_{\max}$), the antenna radiation pattern (γ).

The FOREL clustering algorithm consists of the following steps:

1. Specified area boundaries, coordinates of objects (points) $I = \{I_1, I_2, \dots, I_n\}$ and maximum cluster size R, cluster number ($k = 1$).

2. A random point m_k in *a* given area is selected. At the initial stage this point is taken as the centre of mass of the cluster.

3. All nodes that are at a distance not greater than $R$from point $m_k$are assigned to belong to this cluster.

4. To create a cluster, the centre of mass m_k' is calculated according to expressions (6) or (7).

If the obtained coordinates of the centre of mass m_k'coincide with the coordinates of point m_k, then it is considered that the k-th cluster is found, all nodes of this cluster are denoted by the cluster number and are excluded from further consideration. Then proceed to step 5 - search for the next cluster.

If the coordinates of the centre of mass m_k' do not coincide with the coordinates of point m_k, then we take $m_k = m_k'$, skipping to step 3.

5. Check whether there are nodes that do not belong to clusters. If there are no such nodes (i.e., all clusters are defined), then go to step 6. If there are such nodes, then go to step 2 (search for the next cluster).

6. Output the data about nodes belonging to clusters and coordinates of their centres of mass. End.

Note. When searching for another cluster it may turn out that there are no nodes at a distance smaller than the value R from the selected centre of mass. In this case a new centre of mass is randomly chosen. A generalized scheme-algorithm of FOREL functioning is shown in Fig. 3.

It should be noted that the problem of clustering in two-dimensional area can also be solved in three-dimensional area, in the case where the network nodes are located not on a flat surface, but on a real terrain.

As a result of the algorithm, the network at a certain value of R will be divided into a certain number of clusters. By increasing the value of R and executing the algorithm, we can achieve a decrease in the number of clusters (TA data points) and vice versa. The advantages of the FOREL algorithm are: the possibility to change the number of clusters depending on the R value; the convergence of the algorithm, which increases with increasing R; low computational complexity $- O(n^2)$. Disadvantage: the result depends on the initial solution (to improve it, it is necessary to perform several runs of the algorithm with different input data and choose among them the best one to satisfy a certain target control function).

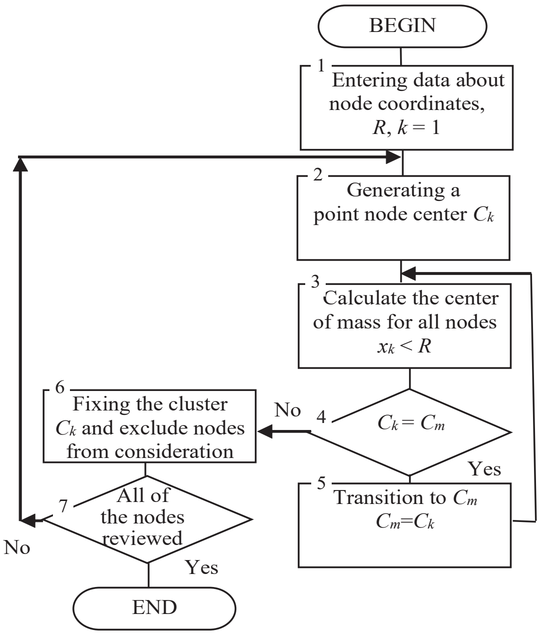

Fig. 3. Scheme-algorithm of FOREL functioning

Fig. 4 shows the results of clustering simulation FOREL algorithm for networks with 50, 100, 200 nodes.

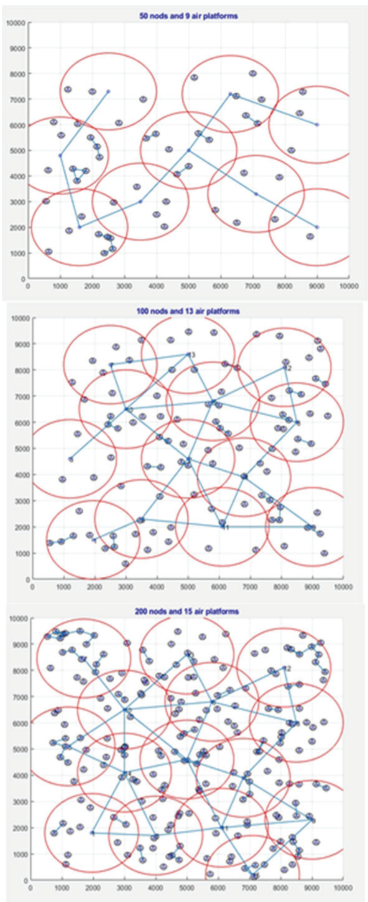

Fig. 4. Results of network clustering by FOREL algorithm

3.3. Construction the basic route by TA for network gathering points

The basic flight route of TA (its length L_{bfl}) from its initial position to the final one through the cluster centres can be constructed by one of the known methods (algorithms) of construction of the shortest path (solution of the traveling salesman problem): full brute force, linear integer programming, branches and borders, greedy heuristic, genetic, etc. [4 - 10, 28 - 30]. The problem belongs to the class of NP-complete. The number of iterations of the algorithm increases significantly with increasing the dimensionality of the network. Obtaining the exact solution for a high-dimensional network is problematic. That's why in practice the methods of obtaining an approximate solution are used. Among the greedy algorithms, the cheap inclusion method is the best in terms of the quality of solution optimality, but it requires maximum computational labour intensity. The least computationally intensive of the greedy algorithms is the nearest-neighbour method. The method consists of the following: nodes are sequentially included in the route, and each next node, which is included in the route, should be close to the last selected node among all others, not yet included in the route. The choice of one or another algorithm will be determined by the accuracy and time requirements to obtain a solution with limitations on the computing power of the hardware.

3.4. Calculation of data collection points (intervals) in the cluster and TA flight path

As the initial variant of the TA flight path in the cluster is taken the basic flight route, calculated at the previous stage (flying around the clusters centres of mass). In addition to calculating the TA flight route, the TA flight altitude (hovering) is important, which determines the size of the coverage area, the distance between the node and the TA. An increase of TA flight altitude leads to an increase of: its fuel (energy) consumption, the energy consumption of nodes for the process of transmission to the TA due to the increase of distance between them, and an increase in the area of coverage and, accordingly, the number of nodes connected with the TA. And vice versa. In addition, the limiting increase in the range of radio communication $d_{\max}$ is limited by the low power of the transmitters of sensor nodes. An example of different values of the size of radio communication zones R from the TA flight altitude h with using of sector antennas and the transmission range $d_{\max} = 250$m are shown in Fig. 5. Therefore, the TA flight altitude must be optimized considering the target functions of network control and limitations on its resources.

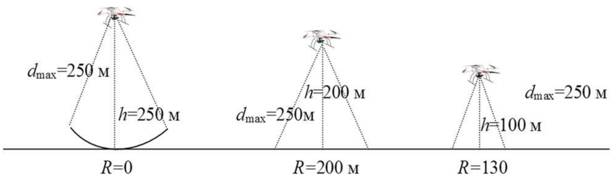

Fig. 5. Dependences of the size of the radio-communication zone R nodes on the TA flight altitude h at $d_{\max}$= 250 m.

Data collection from cluster nodes can be performed during its flight, when it is hovering in the collection point (for rotor-type TA), as well as a combination of these methods.

Let us consider *models for selecting transmission points between TA and cluster nodes when it hangs* to achieve a given target control function.

The problem is formulated as follows: find the positions of TA w^*over the cluster of area Θ with n nodes, which minimizes the time of data collection in the cluster (eq. 8) or provides a minimum of the total energy consumption of cluster nodes E_{cl} for known volumes of data monitoring of each i-th node V_{imd} the volume of overhead traffic V_{iot} (eq. 9)

$$t_{dc} = min \sum_i^n \frac{V_{imd}+V_{iot}(PR)}{s_i(d_{i-\mathrm{TA}},PR)}, \quad (8)$$

$$E_{cl} = \min \sum_i^n e_i(d_{i-\mathrm{TA}},PR)\big(V_{imd} + V_{iot}(PR)\big), \quad (9)$$

with limitations on the TA flight altitude – $h_{\min} \leq h \leq h_{\max}$, the zone of possible TA movement $\Theta_{pm} \in \Theta$, the transmission rates in the radio channel at different distances $s_i(d_{i-\mathrm{TA}},PR)$ (determined by the characteristics of the transmission protocol, the values of the node energy consumption per transmission bit, $\forall i \in \Theta,\ i = 1 \ldots n$.

With the known TA flight altitude (h), the antenna directional pattern (γ), the radius R_{tr} of the circle of possible TA movement, at which all nodes will be covered by this TA is determined: $R_{tr} = R_{cov} - d_{00j}, \forall j \in \Theta$ (Fig. 6).

The target functions (8, 9) are nonconvex and may have local minima. Known solution methods have considerable computational complexity. Therefore, we propose to use an iterative algorithm to calculate an approximate solution by setting the values of TA position coordinates in the form of a lattice. The algorithm calculates t_{dc} and E_{cl} at certain TA positions within the circle of possible displacement and selects the position that gives the optimal value.

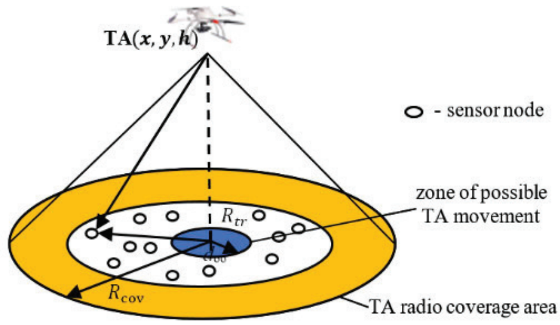

Fig. 6. The cluster and the zone of possible TA relocation

The algorithm for calculating t_{dc} and E_{cl} in a cluster consists of the following steps.

1. Calculate possible movement zone of the TA (Fig. 7). Determine the set of possible TA positions in the middle of the possible movement zone in the form of a spatial grid (Fig. 7).
3. Calculate at each point of the grid the values of t_{dc} and E_{cl}.
4. Select the grid point with the minimum value - the desired TA position.

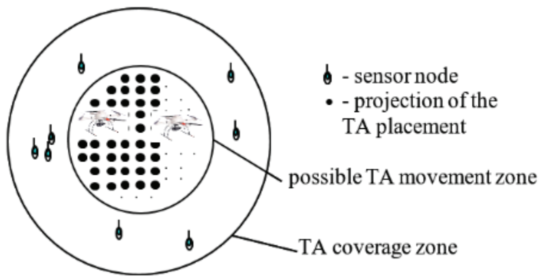

Fig. 7. Points of possible TA placement

Note that the flight time in each k-th cluster t_{flk} will be determined by the sum of the flight times along the route *r* in the cluster and the hover time (data collection) at the data collection point: $t_{flk} = t_{flkr}+t_{dck}$.

Consider *the rules for selecting transmission intervals between* the TA (aircraft- or rotor-type) and cluster nodes on its flight path to achieve the given target control functions.

The following rules for assigning (adding) transmission intervals are suggested to reduce the energy consumption of node batteries when collecting TA data in a cluster.

1. On the TA flight path, assign a data transmission interval between the node and TA, setting the minimum distance between them (Fig. 8, nodes *b* and *c*):

IF $t_{dci} \leq \Delta t_{rci}$ (the time of TA data collection from node *i* is no longer than the time of radio communication with it), THEN - on the TA flight path select the transmission intervals at the closest distance between the node and the TA,

OTHER - calculate the necessary flight speed to ensure radio communication with the TA according to to expression (4) and apply the rule again.

2. From the set of nodes competing to transmit TA data and having different battery energy levels, assign the closest TA path interval for transmission to the node with less battery energy (Fig. 8).

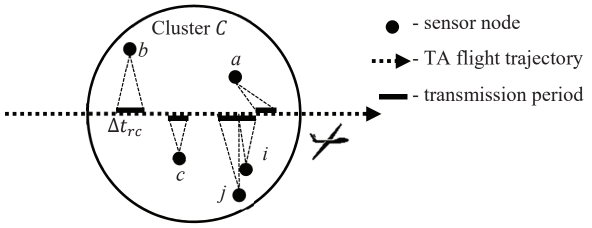

Fig. 8. Illustration of the construction rules TA transmission intervals with cluster nodes

IF several nodes are competing for data transmission with the TA, THEN - the node with the lower energy level should be assigned the highest priority for transmission at the interval closest to the TA flight path (in Fig. 8 if $e_i < e_j < e_a$, then the priority $i \succ j \succ a,\ i,j,a \in C$).

3. Set the minimum (within specified limits) flight height h of TA in the cluster, sufficient to cover a given set of cluster nodes (the goal is to reduce energy costs by reducing the distance between cluster nodes and TA).

4. Set the transmission power level between the node and the TA to a minimum level that is sufficient to provide the specified transmission speed at a given distance.

5. Adjust the basic flight path (between cluster centres) of the TA in the cluster to fly around nodes with critically low battery power at the lowest possible altitude.

6. Cooperative operation of nodes [22]. In the presence of connectivity between nodes in the cluster, form real miniclusters with the designation as the main nodes that are closer to the TA flight path. In the minicluster the shortest transmission routes from nodes (with metrics: minimum transmission power, residual battery energy of the node), remote from the TA flight path, to the node closer to the flight path are constructed (Fig. 9). Prior to TA approach, the main node (the one closest to the TA flight path) collects data from its minicluster nodes.

7. If there are nodes in the cluster with a significant amount of monitoring traffic, to partition the cluster into subclusters to serve loaded nodes with the correction of the TA trajectory.

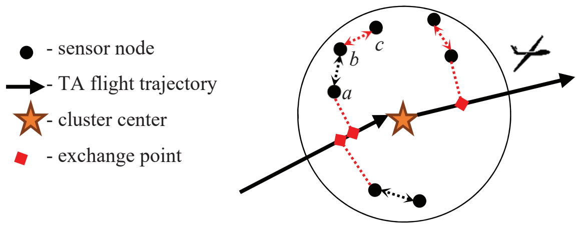

Fig. 9.Formation of miniclusters

3.5. Trajectory-positional model of TA data transmission with cluster nodes

The analysis of existing MAC protocols proposed for WSN showed their insufficient efficiency for data collection from nodes of TA network [31 - 33]. We propose a trajectory-position model of data transmission in the radio channel between TA and cluster nodes, which considers their state (location coordinates, battery energy level, the amount of monitoring data) and the trajectory of movement (hover positions) of the telecommunications airplane, to ensure the maintenance of nodes. The trajectory model is implemented in a hybrid (decentralized / centralized) protocol of data transmission between nodes and TA, consisting of 4 main stages: initialization of TA transmission with sensor nodes, transmission by cluster nodes of requests for transmission with TA, scheduling of transmissions of sensor nodes of the telecom aerial platform, direct transmission of node monitoring data with TA.

1. *Initialization of exchange.* The TA periodically broadcasts a service message about its presence (PR) (Fig. 10). Nodes that are in radio communication with the TA receive the PR and go into active mode.

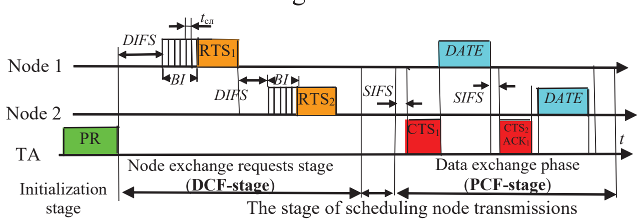

Fig. 10. Functioning of the proposed protocol

2. *Transmission by nodes of request to transmission* (RTS) *from TA* (decentralized by cluster nodes) information about their state: coordinates, battery energy and volume of monitoring data. In contrast to the IEEE 802.11DCF protocol, the output interval for request transmission (t_{rt}) between cluster nodes is introduced, depending on the distance between the node and the TA trajectory (priority in service in the cluster is

given to nodes that are at the greatest distance from the TA trajectory of flight [31]).

3. *TA scheduling of transmissions by cluster nodes (centralized by TA).*

After processing received transmission requests from cluster nodes, TA calculates flight path and graph of node transmissions in the cluster (sequence of time intervals Δt_{tri} for each i-th node in the cluster on TA flight path). For this purpose, TA uses the following input data: position of the node and TA in the cluster, amount of monitoring data, distance to the node and signal level from the node (determines the rate of transmission in the radio channel and energy consumption of the node), size of the cluster, battery energy level, transmission time, location of the node relative to the flight path. The priority of transmitting nodes in the TA cluster will be determined based on the hierarchy of target control functions by rules (p. 3.4), which can determine the speed, altitude and trajectory of TA movement in the cluster.

4. *Data transmission (by TA permission)*. The TA sequentially transmits a confirming transmissions (CTS) message to each node in the cluster and performs the data transmission.

3.6.A generalized algorithm for implementing the TA data collection method

The general algorithm of the method is implemented based on the hierarchical interaction of algorithms embedded in the network control centre, the TA control system and the network node control system.

The main functions of the network control centre are: collecting data on the state of the network, its analysis, decision-making and implementation. The main stages of GCC management are:

1. Planning. At this stage clustering of the network, selection of collection points, calculation of the basic flight route, calculation of the flight time for one TA, calculation of the network operation time, formation of the plan for using TA (or group), TA flight management.

To achieve the target control functions, the NCC optimizes the number, size of clusters, determines collection points or transmission trajectory segments, adjusts the basic movement route, and determines the priority of rule application depending on the target control functions.

2. Deployment. Preparation for the TA flight to collect data is carried out.

3. Operational management of the TA flight and data collection processes, correction of decisions made at the planning stage, considering the real situation on the network.

The scheme of the generalized algorithm for implementing the method is shown in Fig. 11. Let us consider its main steps.

1. Data collection and input (according to point 2): parameters of the network, nodes, TA; initial and final flight point, limit values T_{dcgiv}, T_{flgiv}; target control functions (1 - 3) and their priority, etc.

2. Clustering of the network (finding, using the FOREL algorithm, the minimum number of clusters and collection point coordinates for a given value of cluster size R);

3. Construction of the base route of the TA flight according to the obtained collection points by the known method of finding the shortest route (solution of the traveling salesman's problem).

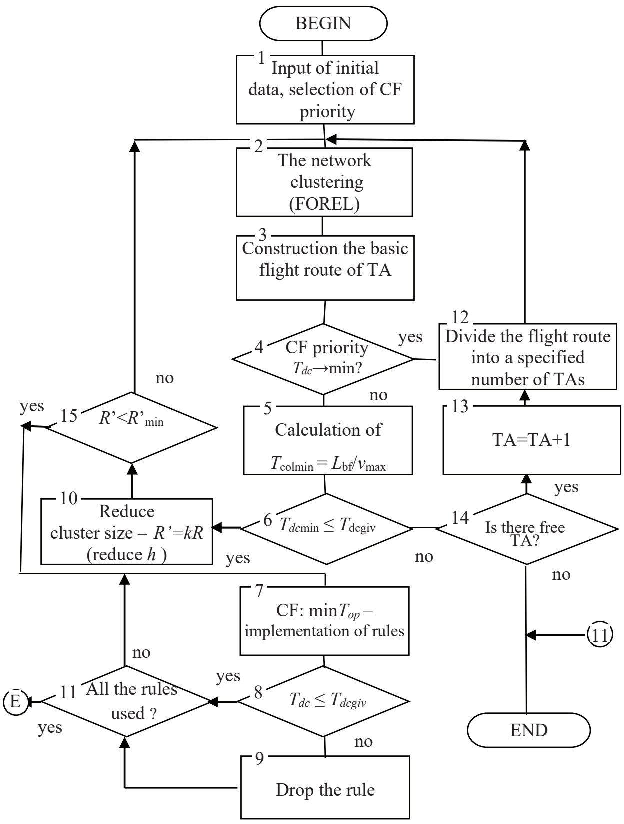

Fig. 11. Scheme-algorithm of method implementation

4. Check (block 4): IF the priority of the target function $\min(T_{dc})$, THEN - divide the flight route of one TA into independent routes for all TA. Transition to block 2.

5. Determination of the minimum time of data collection by one TA (block 5): $T_{dc\text{giv}} = L_{flb}/v_{\max}$.

6. Check the data collection time requirement:
IF $T_{dc\min} \le T_{dcgiv}$
THEN$R' = kR$ - reduce R (height h) (block 10);
IF $R' < R'_{\min}$ (block 15) then go to block 7.

ELSE $R = R'$, go to block 2;

ELSE if there are no free TAs (block 14)

THEN TA=TA+1 (block 13), divide the route by the new number of TA (block 12) and execute the algorithm for each subnet, go to block 2.

ELSE IT'S OVER;

7. Implementation of rules (block 7) according to p. 3.4 on reduction of energy consumption of nodes, construction of the trajectory of the TA flight in the cluster with check on fulfilment of the requirement on data collection time (block 8).
8. If all the rules are checked for feasibility, then END, otherwise go to block 7.

Since the network manager determines the preference of optimization criteria, the multi-criteria optimization problem will be solved using the method of successive concessions (trade-offs).

In case of priority of the target function $\min(T_{\text{col}})$ (block 4), the algorithm divides the overflight route among all TAs. Initial clustering of the network is performed with the maximum value of the cluster radius ($R = R_{\text{max}}$), to obtain the minimum number of clusters. Then, when $T_{dc} \leq T_{dc\text{giv}}$ is satisfied, we try to reduce the energy consumption of the nodes by reducing the transmission power by reducing R and applying the corresponding cluster energy reduction rules. Minimizing the number of involved TAs is solved by adding only one platform at a time when the given constraints are satisfied.

To assess the effectiveness of the algorithm, its software implementation in the C# environment was carried out. Experiments and obtained dependences: the data collection time, the time of network operation on the dimensionality of the network, the number of nodes in the cluster when using the proposed algorithm for data collection.

Simulation results have shown that the proposed method allows gaining 10 - 15% gain in network monitoring data collection time (due to the reduction of data collection points), and to increase network operation time (due to new rules for nodes in clusters) by 12 - 17% compared to existing methods of direct TA data collection.

4. CONCLUSION

An improved method for direct collection of monitoring data from wireless sensor network nodes using TA is proposed, which allows realizing various target functions of network management: to minimize data collection time, to maximize network operation time, to minimize the number of TAs. The proposed method can be used in the special software of the control system of data collection in the WSN with the use of TA.

In what follows, we will propose to solve the network clustering problem and to construct routes to fly around data collection points with a given set of TA at their location in different points at the beginning of the flight.

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Романюк А.В, Самберг А.

Метод безпосереднього збору даних телекомунікаційними аероплатформами з вузлів безпроводових сенсорних мереж

Проблематика. Для збору даних моніторингу з вузлів безпроводової сенсорної мережі без наявності телекомунікаційної інфраструктури загального користування запропоновано використовувати телекомунікаційні аероплатформ (ТА), які побудовані на основі БПЛА. Кожна ТА виступає в ролі мобільного шлюзу, динамічно створює віртуальні кластери в мережі, визначає точки збору даних в кластерах і траєкторії їх обльоту, формує графік та здійснює обмін даними з вузлами кластера в залежності від їх координат розташування щодо траєкторії польоту ТА, рівня енергії батарей і обсягу даних моніторингу.

Мета дослідження. Підвищення ефективності процесу збору даних з вузлів безпроводової сенсорної мережі телекомунікаційними аероплатформами.

Методика реалізації. На відміну від існуючих методів збору даних запропонований метод: використовує метод кластерного аналізу FOREL (FORmal ELement) для кластеризації мережі, нові правила вибору точок збору даних і правил обміну даними між ТА і вузлами кластера для досягнення різних цільових функцій управління (мінімізація часу збору даних ТА , максимізація часу функціонування мережі, мінімізація кількості використовуваних ТА).

Результати дослідження. Запропонований метод збору ТА даних моніторингу з вузлів бездротової сенсорної мережі дозволяє підвищити ефективність досягнення заданої цільової функції управління: зменшити час збору даних, збільшити час функціонування мережі, зменшити число використовуваних телекомунікаційних аероплатформ.

Висновки. Реалізація запропонованого методу в спеціалізоване програмне забезпечення системи управління безпроводової сенсорної мережі дозволить підвищити ефективність процесу збору даних збором даними з сенсорних вузлів телекомунікаційними аероплатформами.

Ключові слова: безпроводова сенсорна мережа; метод збору даних; кластеризація; телекомунікаційна аероплатформа.

Романюк А.В, Самберг А.

Метод непосредственного сбора данных телекоммуникационными аэроплатформами с узлов беспроводных сенсорных сетей

Проблематика. Для сбора данных мониторинга с узлов беспроводной сенсорной сети без наличия телекоммуникационной инфраструктуры общего пользования предложено использовать телекоммуникационные аэроплатформы (ТА), построенные на основе БПЛА. Каждая ТА выступает в роли мобильного шлюза, динамически создает виртуальные кластеры в сети, определяет точки сбора данных в кластерах и траектории их облета, формирует график и осуществляет обмен данными с узлами кластера в зависимости от их координат расположения относительно траектории полета ТА, уровня энергии батарей и объема данных мониторинга.

Цель исследования. Повышение эффективности процесса сбора данных с узлов беспроводной сенсорной сети телекоммуникационными аэроплатформами.

Методика реализации. В отличие от существующих методов сбора данных предложенный метод: использует метод кластерного анализа FOREL (FORmal ELement) для кластеризации сети, новые правила выбора точек сбора данных и правил обмена данными между ТА и узлами кластера для достижения различных целевых функций управления (минимизация времени сбора данных ТА, максимизация времени функционирования сети, минимизация количества используемых ТА).

Результаты исследования. Предложенный метод сбора ТА данных мониторинга с узлов беспроводной сенсорной сети позволяет повысить эффективность достижения заданной целевой функции управления: уменьшить время сбора данных, увеличить время функционирования сети, уменьшить число используемых телекоммуникационных аэроплатформ.

Выводы. Реализация предложенного метода в специализированное программное обеспечение системы управления беспроводной сенсорной сети позволит повысить эффективность процесса сбора данных с сенсорных узлов телекоммуникационными аэроплатформами.

Ключевые слова: беспроводная сенсорная сеть; метод сбора данных; кластеризация; телекоммуникационная аэроплатформа.