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A MODEL OF SITUATIONAL CONTROL OF THE TELECOMMUNICATION AERIAL PLATFORM FLIGHT TRAJECTORY TO COLLECT DATA FROM NODES OF A WIRELESS SENSOR NETWORK

Романюк В. А., Гримуд А. Г. Модель ситуаційного управління траєкторією польоту телекомунікаційної аероплатформи для збору даних з вузлів безпроводової сенсорної мережі.

Телекомунікаційна аероплатформа на базі безпілотного літального апарата розглядається як перспективна технологія для збору даних у безпроводових сенсорних мережах в умовах відсутності зв'язності між вузлами мереж та будь-якої комунікаційної інфраструктури. Фактично телекомунікаційна аероплатформа виступає в ролі мобільного шлюзу та має можливість збирати дані з декількох вузлів одночасно. Траєкторія його переміщення, локація точок та інтервали обміну даними суттєво впливають на ефективність процесу збору даних. У статті розглядається модель ситуаційного управління побудовою траєкторії польоту для збору даних телекомунікаційною аероплатформою для досягнення певних цільових функцій: оптимізації часу збору даних та часу функціонування мережі.

У роботі класифікована множина ситуацій на мережі та визначені відповідні продукційні правила з побудови траєкторії телекомунікаційної аероплатформи, які реалізують визначену ієрархію прийняття рішень: мережа, кластер, телекомунікаційна аероплатформа, вузол з врахуванням цільових функцій управління. На мережевому рівні застосовується правила визначення кількості та розмірів кластерів, будується базове рішення з визначення точок збору та траєкторії їхнього обльоту. На рівні кожного кластера телекомунікаційна аероплатформа в процесі польоту корегує базове рішення на основі врахування параметрів фактичного стану вузлів кластера. На рівні взаємодії телекомунікаційна аероплатформа – вузол оптимізуються енерговитрати вузла та швидкість передачі даних завдяки зменшенню відстані вузла до телекомунікаційної аероплатформи. Для скорочення перебору правил запропоновані метаправила. Такий підхід дозволяє досягати оптимізації цільових функцій процесу збору даних та забезпечити прийняття рішення в реальному часі. Результати імітаційного моделювання довели можливість зменшення часу збору даних на 10–15 % або підвищення часу функціонування мережі на 12–17 % порівняно з існуючими рішеннями.

Ключові слова: *безпроводова сенсорна мережа, телекомунікаційна аероплатформа, траєкторія польоту, збір даних, база правил, ситуаційне управління.*

V. Romaniuk, A. Hrymud A model of the situational control of the telecommunication aerial platform flight trajectory to collect data from nodes of a wireless sensor network.

A telecommunication aerial platform (TA) based on an unmanned aerial vehicle is considered a promising technology for data collection in wireless sensor networks in the absence of connectivity between network nodes and any communication infrastructure. In fact, TA acts as a mobile gateway and could collect data from several nodes at the same time. The trajectory of its movement, location of points and data exchange intervals significantly affect the efficiency of the data collection process. The article considers a model of situational control of flight trajectory construction for data collection to achieve certain target functions: optimization of data collection time and network operation time.

In the work, a set of situations on the network is classified and corresponding production rules for building a TA trajectory are defined, which implement a defined decision-making hierarchy: network, cluster, TA, node, considering the target management functions. At the network level, the rules for determining the number and size of clusters are applied, and a basic solution for determining the collection points and the trajectory of their flight is being built. At the level of each cluster, the TA adjusts the basic solution during the flight based on considering the parameters of the actual state of the cluster nodes. At the level of TA-node interaction, the energy consumption of the node and the speed of data transmission are optimized by reducing the distance of the node to the telecommunication aerial platform. To reduce the number of rules, meta-rules are proposed. This approach allows you to achieve optimization of the target functions of the data collection process and ensure decision-making in real time. The simulation results proved the possibility of reducing data collection time by 10–15 % or increasing network operation time by 12–17 % compared to existing solutions.

Keywords: *wireless sensor networks, telecommunication aerial platform, UAV trajectory, data collection, rule base, situation control.*

1. Statement of the problem. In recent years, there has been a rapid development of wireless sensor network technologies that are used to solve various problems: monitoring the parameters of objects (territories) for compliance with environmental standards; monitoring the condition of crop fields, forests, product pipelines, power lines, borders; search and rescue and military operations (monitoring the movement of their own and enemy troops), etc.

The peculiarity of wireless sensor networks (WSNs) is the limited resources of sensor nodes in terms of battery power, processor speed, memory capacity, transmitter power, etc. Modern WSNs can have hundreds or thousands of sensor nodes. Certain areas of application of WSNs determine the peculiarities of the placement and functioning of sensor nodes (in remote or disaster-affected areas without any available public telecommunications infrastructure, a significant distance between nodes or terrain does not allow building a coherent network structure, etc.) In these conditions, it is proposed to use telecommunication aerial platforms (TA), which are built based on unmanned aerial vehicles (UAV), as a mobile air gateway to collect data from network nodes [1; 2]. This allows: first, to organize the collection of monitoring data from unconnected network nodes; second, to obtain line-of-sight radio channels to the TA node; and third, to reduce the energy consumption of nodes for data transmission (increase the network lifetime), unlike the classical architecture of building sensor networks.

This raises the scientific task of constructing a trajectory for the overflight of the TA nodes of the network, determining the points (intervals) of data collection to achieve certain target functions: minimizing the energy consumption of nodes (maximizing the network operation time) and/or minimizing the data collection time [3; 4]. Solving this problem will allow to control the parameters of the telecommunication aerial platform and nodes, which will increase the network lifetime and reduce the time of monitoring data collection (for example, this parameter is critical in military applications). Models and algorithms for solving this problem can be used in specialized network management system software.

2. Analysis of recent publications. The solution to the problem of overflight and direct data collection by a telecommunication air platform from each WSN node can be achieved in the following ways (according to these methods, the research is proposed).

1. Flying over the entire territory (area) occupied by the WSN with simultaneous collection of monitoring data from the network nodes. Researchers have analyzed the options for flying over the entire network area [5]: by squares, by spiral, by angle, etc. The purpose of the study is to reduce the length of the flight route and, accordingly, the time of the network flight. However, the time to fly over the entire area of the WSN remains very significant, which imposes additional requirements on the technical characteristics of the aircraft. This method will usually be used during the initial overflight of the network to collect initial information about the parameters of the network nodes (position coordinates, amount of monitoring data, battery power level, etc.)

2. Flying over only certain clusters (zones) of the WSN network in conditions of heterogeneous node placement. To do this, before the TA flight, the ground network control center (GCC) conducts its virtual clustering, determines the points (intervals) of monitoring data collection by the telecommunication air platform in clusters (in the simplest case, the data collection point is the geometric center of the cluster), builds the shortest route to fly around the data collection points.

Under such conditions, in most publications [6-8], the calculation of the TA flight route is considered only as a solution to the classical traveling salesman problem - finding the shortest route between the start and end point of the TA flight with a flight over the data collection points. This problem belongs to the class of NP-hard problems. Obtaining an exact solution for a network of significant dimensionality is problematic. Therefore, in practice, heuristic algorithms are proposed to obtain an approximate solution that have a low computational complexity: nearest neighbor [6], spiral [7], FPPWR (Fast Path Planning with Rules) [8], convex hull CHIH (Convex Hull Insertion Heuristic) [9], etc. However, in such a problem statement, only the shortest flight route is calculated, the state of the nodes' parameters is not considered, and the energy consumption of the nodes is not optimized. Therefore, the application of the shortest path search algorithm can be used for the initial (basic) solution for its further improvement.

In the work [10] study of several strategies for constructing a flight path and collecting data from the TA in a clustered WSN are investigated: flying through the center of the cluster and collecting data during the flight at the closest node-to-AV distance; flying through critical nodes in clusters and collecting data during the flight; flying with hovering at one collection point that minimizes the total energy consumption of nodes, etc. However, the authors do not consider the possibility of building multiple data collection points in a cluster, optimizing exchange intervals, optimizing multiple objective functions.

In research [11], simple heuristics for building a TA trajectory are considered, which try to reduce the data collection time by sequentially adding potentially possible hanging points.

In paper [12], it is proposed to determine the TA data collection points considering the ability of the MAC protocol to change the radio channel bandwidth depending on the radio range. However, these solutions do not consider the ability of the MAC protocol to change the transmission power (reduce the energy consumption of node batteries).

In research [13], a deep neural network is used to find the 3D flight path of the TA to optimize the data collection time and radio channel bandwidth, but the network lifetime is not optimized.

In the work [14], the authors proposed a method of direct data collection of TA from WSN nodes, which allows for multi-criteria optimization of data collection indicators. However, the process of deciding on the flight path for data collection is not disclosed in detail. Therefore, the proposed article develops a decision-making mechanism using a situational management model.

The dynamic formation of clusters and their sizes, the trajectory of TA movement, the location of points and intervals of TA data exchange with nodes significantly affect the efficiency of data collection. However, publications [1-13] do not consider several efficiency criteria, their dependence on a set of parameters of the state of network nodes and clusters, and the trajectory of the vehicle. Thus, the unresolved problem when considering the process of building a TA flight path is to determine the points (intervals) of the data collection trajectory while considering two criteria: minimizing the time of data viewing and maximizing the network operation time.

The aim of the article is to develop a model for situational control to build a flight path for a telecommunication air platform with defining points (intervals) for collecting data from nodes in the WSN to achieve certain object functions.

Summary of the main material.

Problem statement. We consider a wireless sensor network of considerable dimensions (tens, hundreds of sensor nodes) with stationary nodes that are randomly located in a remote area, are not interconnected, and operate in the absence of any public telecommunications infrastructure. Each sensor node has the following main elements: battery, touch sensors, processor, memory, transceiver, antenna, positioning system, and control system. In the process of operation, the node collects and stores environmental parameters (objects of observation) of the monitoring area assigned to it before the TA approaches.

The UAV-based TA has additional equipment to implement the data collection process: a processor, memory, a transmitter, an antenna, a positioning system, and a corresponding control system. The TA flies around the data collection points (intervals) along a certain trajectory, using a directional antenna to form a ground coverage area (radio communication) of the WSN nodes with a radius of R_k (the size of the temporary k-th cluster of the local network). When nodes enter the TA radio connectivity zone, it establishes radio communication with them, determines the exchange schedule, and receives monitoring data from the nodes (Fig. 1).

The planning of temporary network clusters, trajectory and speed of the TA flight, points (intervals) of data collection from nodes, etc. is carried out by the ground-based network control center. The TA control system allows for independent decision-making (on clustering, flight path, data collection points and intervals, etc.) in the absence of communication with the ground network control center.

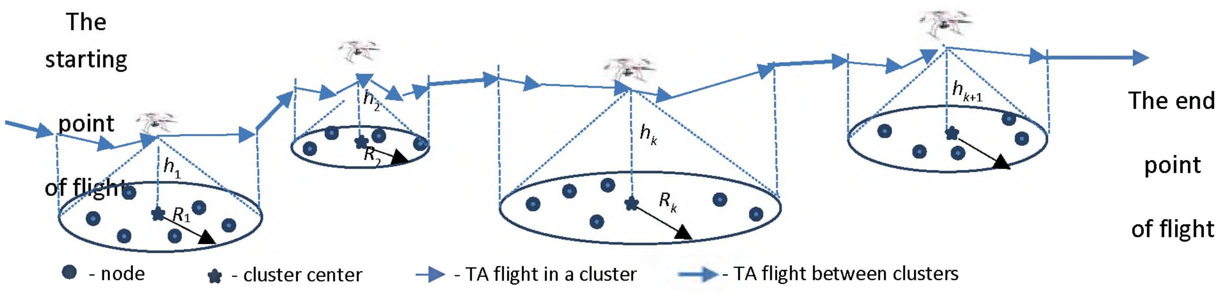


Fig. 1. An example of a TA fly over of cluster nodes through its center

Given:

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

– Technical characteristics of the node - number and types of sensors, battery power level, energy consumption for monitoring environmental parameters for each type of sensor, etc.

– Communication characteristics of the node - parameters of the antenna, transmitter, energy consumption per bit of reception and transmission of data for the selected MAC protocol and type of equipment, etc.

– Flight characteristics of the TA - speed, altitude, flight time, the ability to hover and move in space at a constant or variable speed, etc.

– Communication characteristics of the TA - MAC protocol, antenna, transceiver parameters, etc.

Restrictions and requirements:

– The TA flight area has no prohibited zones; the flight trajectory is formed in the form of certain coordinates of points in space (modeling of the TA flight process is not considered).

– Information about the nodes' state parameters (location coordinates, battery energy level, amount of monitoring data) is collected during the initial overflight of the TA network, and then the information about the nodes' state is updated during each round of overflight.

– TAs and sensor nodes have radio equipment with the same MAC protocol, which allows to change the data transmission rate depending on the signal-to-noise ratio ("radio channel range") [2] and to adjust the transmission power (energy consumption for transmission) [14], for example, IEEE 802.11.

– Memory capacity of sensor nodes and telecommunication aerial platform is sufficient to store monitoring data.

– The value of the battery (fuel) energy of the TA is sufficient for a round of network circling.

– The control algorithms implemented by the TA should have a low computational complexity to ensure the real-time data collection process.

It is necessary to: determine the trajectory and flight speed of the TA, the points (trajectory intervals) of TA data collection, the procedure (schedule) of TA data exchange with cluster nodes. At the same time, it is necessary to implement one of the defined objective functions (OF) of data collection management [14]:

– Minimize data collection time T_{col}

$$T_{col} \rightarrow min \tag{1}$$

ensuring a given network operation time $T_{ot} \geq T_{otgiv}$.

– maximum operating time

$$T_{ot} \rightarrow max \tag{2}$$

ensuring a given data collection time$T_{col} \leq T_{col\,giv}$.

– Optimization of both criteria, considering their priority

$$\begin{cases} T_{col} \rightarrow min \\ T_{ot} \rightarrow max \end{cases} \tag{3}$$

– Obtaining an acceptable solution

$$T_{col} \le T_{colgiv} \text{ and/or } T_{ot} \ge T_{otgiv}, \quad (4)$$

with restrictions Ω on:

– Type of TA (rotorcraft); speed, altitude, time and range of TA flight – $v = [v_{min}, v_{max}]$; $h = [h_{min}, h_{max}]$; $t_{fly} \le t_{flymax}$; $L_{fly} \le L_{flymax}$.

– Number of clusters in the network – $1 \le k \le N$.

– Initial energy of the node batteries $e_{min} \le e_i \le e_{max}$ and TA $e_{TA} \le e_{TAmax}$.

– An amount of monitoring data of each i-th node – $V_{dmi} \le V_{dmmax}$.

– Node-TA radio communication range – $d_{i-TA} \le d_{max}$.

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

The solution. To solve the problem in accordance with the objective functions, it is proposed to divide the decision-making process into stages [14]:

– To perform virtual two-step (homogeneous and heterogeneous) clustering of the network and determine the number of clusters $k = 1...K$ of the network, their sizes.

– Determine the hang points Q_k for the collection of TA data from the cluster nodes with coordinates in space $(x, y, h)_k$.

– Calculate the basic (initial) flight route of the TA in the network from the initial position A to the final position B through the data collection points Q_k from the cluster nodes.

– Build the flight path of the TA in clusters with the definition of data collection points (intervals), the schedule of data exchange with nodes by adjusting the base route.

Let's consider in detail the sequence of the hierarchy of the main stages of optimization (Fig. 2).

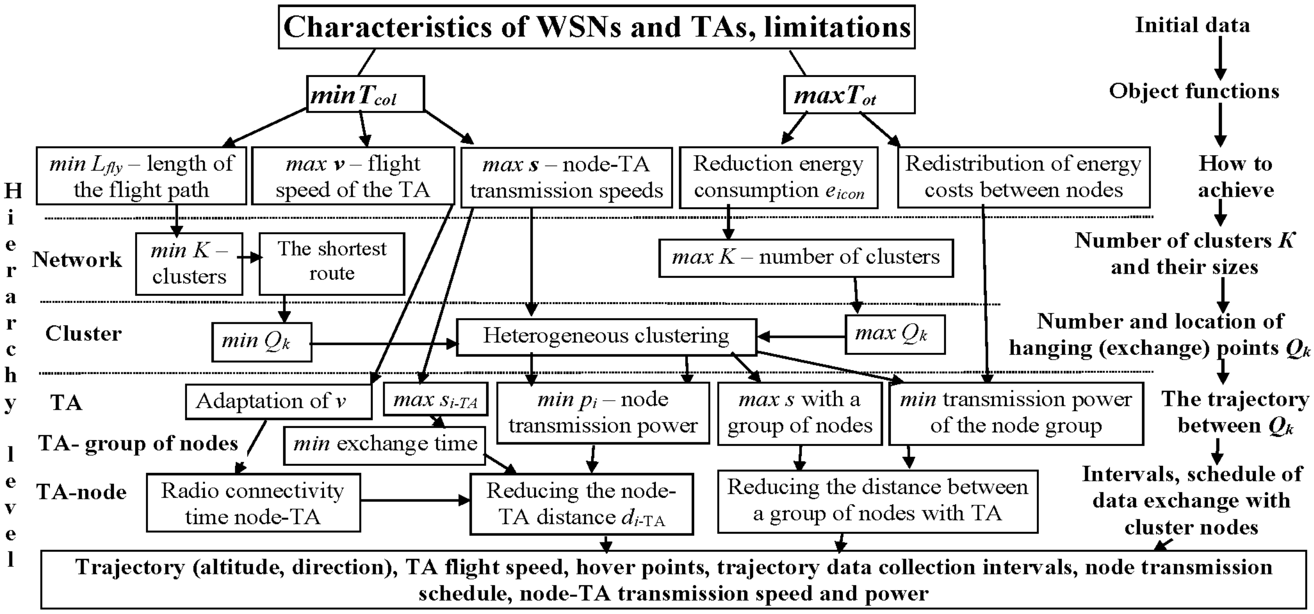


Fig. 2. The hierarchy of the decision-making process for achieving the objective functions

The time of data collection T_{col} by the telecommunication aerial platform from the network nodes depends on the following parameters (5) [14]:

$$T_{col} = f(N, K, TR(St_k), v, V_{dmi}, Q_k, INT_i, s_{i-TA}(d_{i-TA}, MAC), h_k) \quad (5)$$

– Number of nodes $i = 1 ... N$ and coordinates of their location on the territory (x_i, y_i).

– Number of $k = 1 ... K$ clusters, their area, number of nodes n_k, relative positioning.

– Trajectory *TR* of the TA flight in the network defined by the strategy St_k overflight and data collection from the nodes of each k-cluster (in-flight and/or hover data collection, one or more hover points in the cluster, etc.).

– Flight velocity of the TA v.

– The amount of monitoring data V_{dmi} in the network nodes.

– Number of data collection points Q_k with coordinates in space $(x, y, h)_k$ in each k-th cluster when the TA hangs.

– Location of intervals in space and time $INT_i = \{(x, y, h)_{begin}, (x, y, h)_{finish}, t_{begin}, t_{finish})\}_i$ flight trajectories of UAVs, which are defined for data collection (exchange) in motion with i-th node.

– Transmission speed of the MAC protocol $s_{i-TA}(d_{i-\text{TA}}, MAC)$, which depends on the distance $d_{i-\text{TA}}$ and parameters of the radio channel (signal-to-noise ratio), transmitter, receiver, antennas, etc.

– flight altitudes h_k, restrictions Ω resources of nodes and TAs.

Reducing the number of clusters k in the network reduces the length of the TA flight route (respectively, the flight time), but leads to an increase in the energy consumption of sensor nodes (due to the increase in the node-TA distance) and an increase in the node-TA exchange time (decreases the transmission rate of the MAC protocol). And vice versa. An increase in the number of clusters leads to an increase in the length of the TA flight route, but reduces the node-TA distance and, accordingly, reduces the node-TA exchange time and node energy consumption. That is, there is a certain optimum of the number of clusters k, their sizes, the location of points Q_k in them, and the intervals INT_i of TA data collection, which determines a compromise solution with respect to the objective functions.

That is, reducing (minimizing) data collection time T_{col} can be achieved by (Fig. 2):

– Reducing the length of the flight path (reducing the number of clusters and building the shortest route to fly around them).

– Increasing the speed of movement of TAs (determining the maximum v_{max} flight speed of TAs between clusters and, if there is no connectivity between nodes in the cluster, adapting v in clusters to the time required to exchange data with nodes).

– Increasing the transmission rate in the radio channels TA-node s_{i-TA} by reducing the distance TA-node d_{i-TA} (this is provided by the MAC protocol), i.e., by bringing the TA trajectory points closer to node i.

The increase in the network operation time T_{ot} can be achieved by:

– Reducing the energy consumption of nodes (reducing the transmission power of a node) by reducing the TA-node distance

$$d_{i-TA} = g(K(R_k), n_k, TR_k, Q_k, INT_i),$$

which is achieved by optimizing the number of clusters K (coverage area size R_k), the number of nodes in the k-th cluster n_k, the trajectory TR_k , the position of points Q_k (intervals INT_i) of the exchange.

– Redistribution of energy consumption between nodes competing for transmission (if a node has a higher battery energy level, then it should consume more energy).

In addition, when determining the trajectory of the cluster nodes and data exchange, it is necessary to consider:

– The relative position of the nodes relative to the trajectory (it is advisable to exchange data in the nearest intervals of the TA's flight path from the node).

– Critical energy level of the node's battery (plan to fly over "exhausted" nodes at a minimum distance).

– The amount of node monitoring data – selecting the point (interval) of trajectory collection that is closer to this node.

The achievement of the objective functions occurs sequentially at the following hierarchy levels: network, cluster, TA, group of nodes, and individual node. At the network level, performance indicators are optimized by determining the number of clusters and their sizes (by determining the flight height or hover of the TA), and by building the shortest flight route.

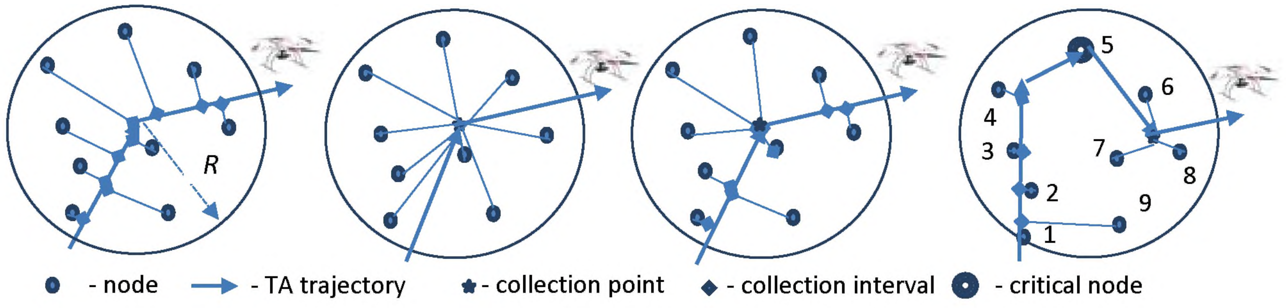
At the cluster level, the number and coordinates of hover points (intervals), the strategy for flying over them and collecting TA data are determined. Possible strategies are shown in Fig. 3 [10; 14].

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

– Energy consumption of each cluster node for data collection (transmission and reception) $e_{\text{con}i}$, total energy consumption of cluster nodes $E^k_{\text{con}} = \sum_{i \in k} e_{coni}$ [14].

– Time of data collection in the cluster t^k_{col}, which is determined by the flight time and hover time of the TA.

At the levels of TA-group of nodes, TA-node, the distance is determined (actually, the trajectory points are adjusted), which allows optimizing the time of exchange between them and energy consumption.



a *b* *c* *d*

Fig. 3. Main options for flight strategies and data collection from cluster nodes:
a – data collection during the flight of the TA through the center (center of mass) of the cluster;
b – data collection only when the TA hovers in the center (center of mass) of the cluster;
c – data collection during the flight and with hovering at one point (center) – a hybrid strategy;
d – data collection in flight and several hovering points (proposed strategy)

To reduce the options for searching and reduce the time for finding a solution along the trajectory of flying over the nodes and collecting data, it is proposed to use the situational control method. The essence of situational management is reduced to the transformation of state information (current situation) $S^{current}$ into a controlling influence U_z, that brings the control object to a new state S^{new} ($S^{current} \rightarrow U_z \rightarrow S^{new}$), where $z = 1 \ldots Z$ – a set of controlling influences. For this purpose, a limited number of situations S (a set of parameters of network states, clusters, TAs, nodes) is formed and classified, a certain set of controlling influences U_z and an appropriate base of product-type decision-making rules is developed: **IF <condition>, THEN <action>** [14] (Fig. 4).

According to the objective functions, the rules are divided into:

– On the network – minimum or limitation of data collection time T_{col}, maximum or achievement of a certain network operation time T_{ot} (1)–(4).

– in the k-th cluster – minimum data collection time t^k_{col}, minimum energy consumption of nodes E^k_{con};

– in the i-th node – minimum time of collection (exchange) with TA $t_{coli-TA}$, minimum energy consumption $e_{coni-TA}$.

By network, cluster, TA, node status parameters that determine the situation on the network:

– Parameters of the WSN, TA, nodes, number of clusters, their area, number of nodes in a cluster, their relative location, data collection parameters (collection time, operation time), etc.

– A set of parameters of the cluster nodes (energy, data volume, relative location).

– Location of the nodes relative to the flight path of the TA in the cluster.

– Node status parameters (coordinates, battery power, amount of monitoring data).

– Parameters of node exchange with TA (time, energy consumption of the node), etc.

– Node status parameters: battery power level, amount of monitoring data, location.

In terms of controlling influence, it is possible to determine (change): the number of clusters (by changing the altitude of the TA, the antenna pattern), the location of hovering and data collection points, the strategy of flying around the cluster nodes, the flight path, the TA-node exchange intervals on the path, the transmission power of the nodes, the TA flight speed on certain parts of the path, etc.

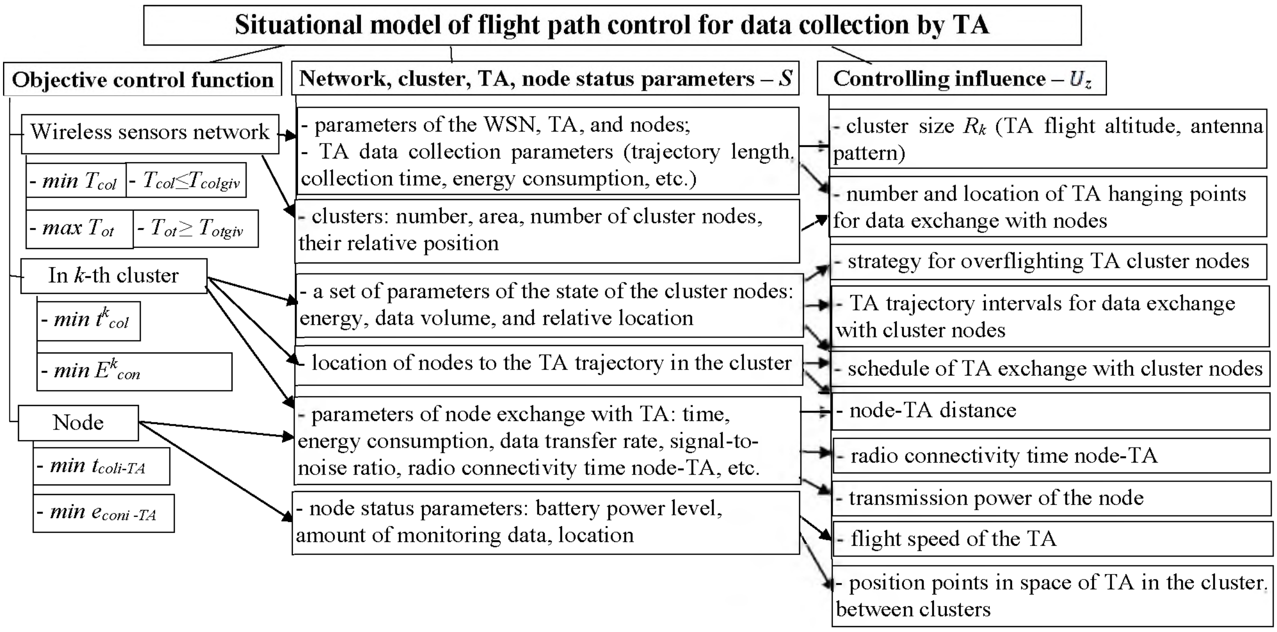


Fig. 4. Scheme of the situation management model

Let's consider several general rules for determining the flight path and data exchange, which are conditionally divided into groups (for determining the number and size of clusters, data collection points (intervals), trajectory correction, redistribution of energy consumption of nodes, etc.) that implement the corresponding control objectives (1)–(4) [14].

The rule for determining the number of clusters: IF the object function T_{col}→min (T_{ot}→max), THEN increase (decrease) the size and number of clusters.

The rule for determining hang points for data collection: IF there are clusters of nodes in the cluster (loaded or with low battery energy), THEN determine the TA hang point for collecting data from these cluster nodes, which minimizes the exchange time or energy consumption of these nodes.

The rule for correcting the flight path TA: IF it is necessary to reduce the transmission time in the node-TA radio channel and/or reduce the energy consumption of the node, THEN it is necessary to place (move) the TA trajectory points closer to the node.

The rule to reduce and equalize transmission costs: IF multiple nodes are competing for exchange intervals with the TA, THEN determine the closest INT exchange interval on the TA's flight path to the node with the lower battery energy.

Rules for determining the number and location of hover points, exchange intervals, overflight and exchange strategies in the cluster:

IF the object function T_{col}→min, the number of nodes in the cluster is small (medium) and the amount of data is insignificant, THEN determine the basic strategy (TA flight through the center of the cluster with the definition of exchange intervals on the flight path) (Fig. 5*a*).

IF the object functionT_{ot}→max, a large number of nodes in the cluster, their data volume is significant, THEN cluster the cluster with the definition of additional hang points (Fig. 5*b*).

Rule for shortening the trajectory length in a cluster (Fig. 5*c*): IF the objective function T_{col}→min, the i-th node is at a considerable distance from the TA flight path, has a significant battery level and a small amount of data, THEN plan the TA exchange with node i in motion.

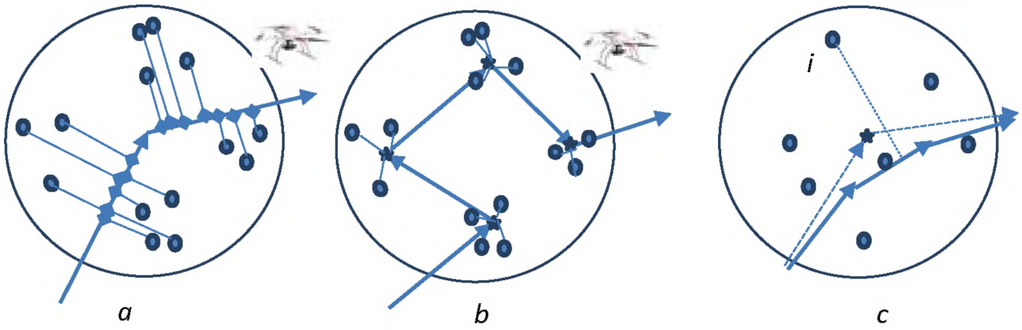


Fig. 5. Variants for implementing the rules for building a flight path and collecting TA data

The rule for maintaining "critical" nodes: IF a node has a critical battery level (significant amount of data) and is a significant distance from the TA flight path, THEN change the TA flight path to reduce the distance from that node.

To reduce the list of possible variants of the TA flight trajectory and determine the points (exchange intervals), a set of meta-rules is proposed that determine the priority sequence of rules for achieving the target function according to its priority. Let's consider a few [14].

Metarule 1: IF the objective function is T_{col}→min, THEN (the problem is reduced to a single-criterion optimization) finding:

– The maximum number of network clusters;

– Set the basic trajectory of the TA through the center of the clusters, find the shortest path (use the shortest path search algorithm) to fly around the centers.

– Determine possible additional TA collection points (hang-ups) according to the position and amount of data in the cluster nodes (grouping of nodes with a significant amount of data), recalculate the shortest path.

– Determine the strategy of flying around the cluster nodes.

– Set the maximum speed of TA movement in the cluster (which meets the requirements for TA data exchange with cluster nodes).

– Calculate the intervals and schedule of node transmissions during the flight of the TA, considering the state of the nodes using rules that are focused on increasing the transmission rate in the radio channel.

Metarule 2: IF T_{col}→min and T_{ot}→max, the first OF takes precedence over the second, THEN (lexicographic optimization method):

– Find a certain significant number of network clusters.

– Determine the collection points (hang-ups) of TA according to the priority of the OF.

– Determine the strategy for flying around the cluster nodes.

– Calculate the TA trajectory through the collection points.

– Calculate the intervals and schedule of node transmissions during the flight at a minimum distance, considering the available energy of the nodes.

The proposed situational model is realized by the interaction of algorithms in the GCC, control systems of the TA, and nodes. The network management cycle consists of the following stages: collecting data on the state of network nodes (performed by the TA in the next round of overflight), analyzing and identifying the state of the network, searching and making decisions, implementing the decision during the overflight.

In accordance with the OF, the GCC solves the following main tasks:

– Network clustering, optimization of the number and size of clusters.

– Calculation of the number and coordinates of data collection points (hovering) of the TA.

– Determination of the strategy for overflight and data collection of TAs in clusters.

– Calculation of the TA flight trajectory with the determination of its intervals and exchange schedule.

In the absence of radio communication between the TA and the GCC, the control tasks are performed by the TA in an autonomous mode. The diagram of the generalized algorithm for implementing the model, which is part of the method of direct data collection by the TA [14], is shown in Fig. 6. Let us consider the main steps of the method.

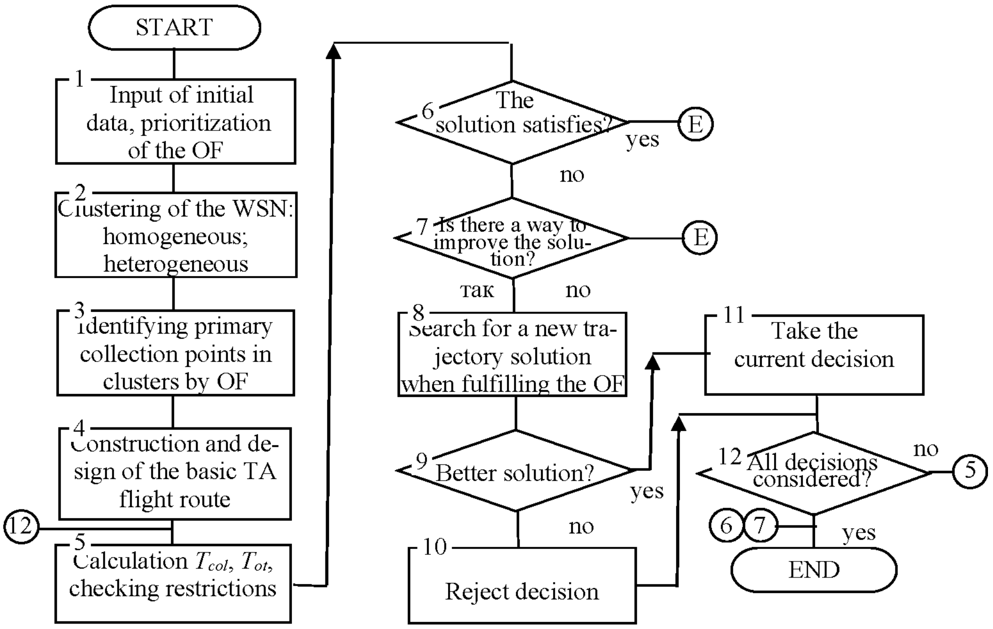


Fig. 6. Schematic algorithm for finding a solution along the flight path and data collection

Step 1. Collection and entering data (according to the task).

Step 2. A 2-stage clustering of the network is implemented to achieve the specified OFs:

– homogeneous clustering of the network – finding a certain number of clusters using the FOREL (FORmal ELement) cluster analysis algorithm by applying a rule base to adapt the coverage radius *R*.

– heterogeneous clustering – clustering (splitting) of clusters according to the rule base, the priority of the OF and the relative position of clusters and the state of nodes in clusters.

Step 3. Determination of primary (base) TA data collection points in each cluster according to the analytical models proposed in [14].

Step 4. Building the basic route of the TA flight along the identified data collection points by searching for the shortest path (for example, Convex Hull Insertion Heuristic [8; 14]).

Step 5. Calculation T_{col} and T_{ot} [14], checking the restrictions Ω.

Step 6. If the data collection parameters of the resulting solution meet the requirements, then it's over, otherwise, proceed to the next step.

Step 7. Identification the network state, check if the rule base can be used (to improve the solution). If yes, then proceed to step 8, otherwise – the end.

Step 8. Search for a new solution for the flight path and data collection using a rule base to achieve the defined objective functions.

Step 9. Evaluation of data collection performance, checking the Ω constraints. Checking the quality of the solution in comparison with the basic (previous) one.

If the solution is better, then accept the decision (block 11), otherwise reject it (block 10).

Step 10. Check verification: all solution options have been considered (block 12). If so, then it's over, otherwise – go to step 5.

Fig. 7 shows an example of the application of the situational model of controlling the TA trajectory for data collection in a cluster compared to the basic TA trajectory with data collection in flight through the center of the cluster. The initial cluster C, obtained as a result of homogeneous clustering of the network for the implementation of a certain OF, is divided into seven heterogeneous clusters based on the analysis (identification) of the state of the nodes $\{c_1, \dots, c_7\}$. Each of these clusters has its own strategy for flying over and collecting data (for example, with in-flight collection and hovering – for clusters c_1, c_3, c_5, c_6; for c_5 – flying over each critical node; for c_2 – during the flight not through the center, etc.).

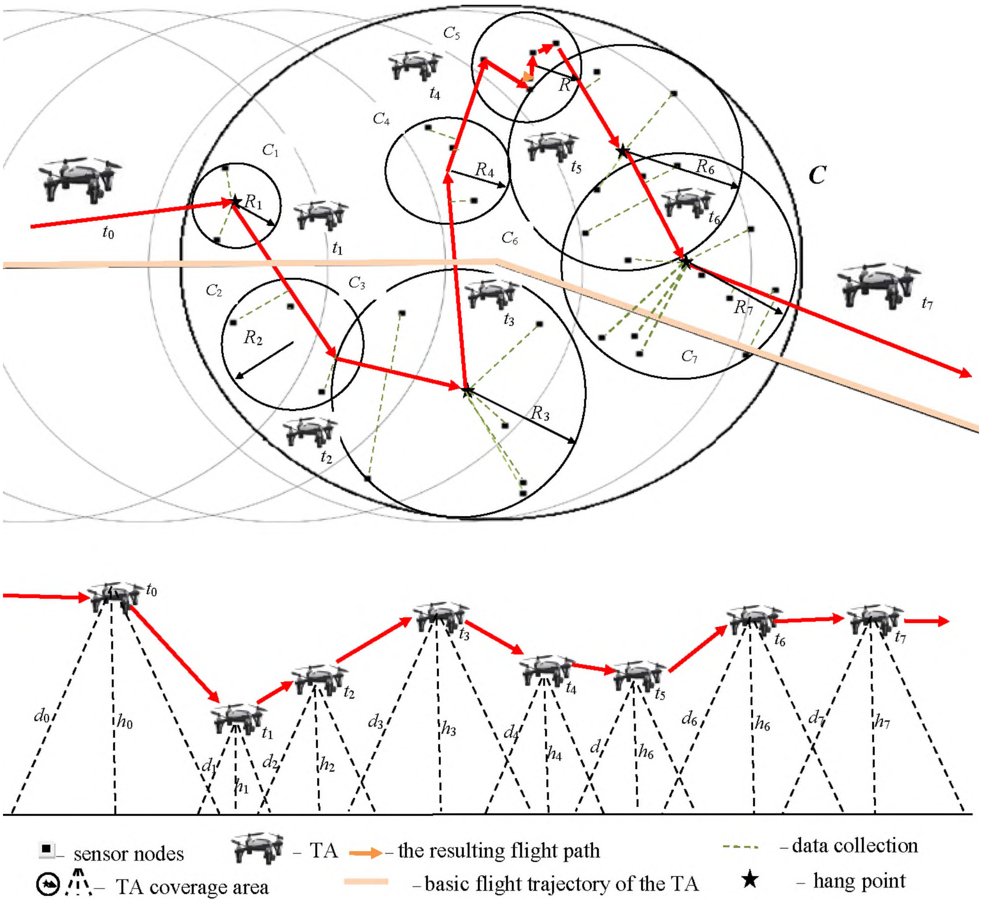


Fig. 7. Decision on the trajectory and points (intervals) of data collection by a telecommunications aerial platform using the situational management model

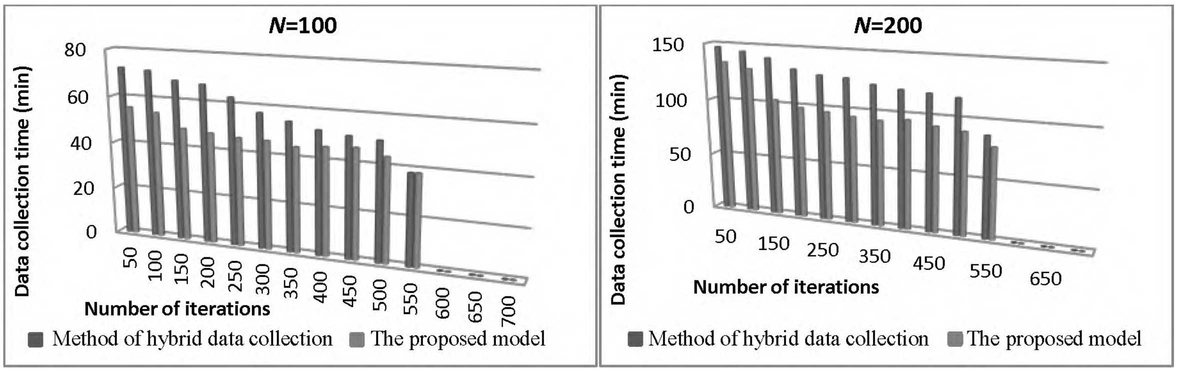
To evaluate the effectiveness of the proposed model, we developed a simulation program in C#. The input data for the simulation are the parameters of the network, nodes, TAs, algorithms and rules that implement the TA data collection process. Programmatically implemented:

- A network clustering algorithm and a model for determining collection points.
- An algorithm for finding the shortest route to fly around the CHIH network clusters.
- The decision-making process (according to the situational model and a certain rule base) on the flight path in clusters for data collection, etc.

The effectiveness of the proposed model was studied in comparison with the hybrid strategy of in-flight data collection through the cluster center [10] with different initial data: network dimension, number of clusters, number of nodes in a cluster, amount of monitoring data in nodes, etc. In the process of modeling, the energy consumption of nodes is calculated according to the cost model given in [14], and the data collection time is calculated.

Initial data for modeling: nodes are randomly placed on a plane of 6000×6000 m; number of nodes $N = 100, 200, 500$; $e_0 = 0.1\,J$, $d_{max} = 250$ m, $h = 50 \ldots 250$ m, $v = 0 \ldots 10$ m/s, MAC-protocol – IEEE 802.11g, $V_{dmi} = 0.1 \ldots 1$ Mb, energy consumption for transmission bit, etc.

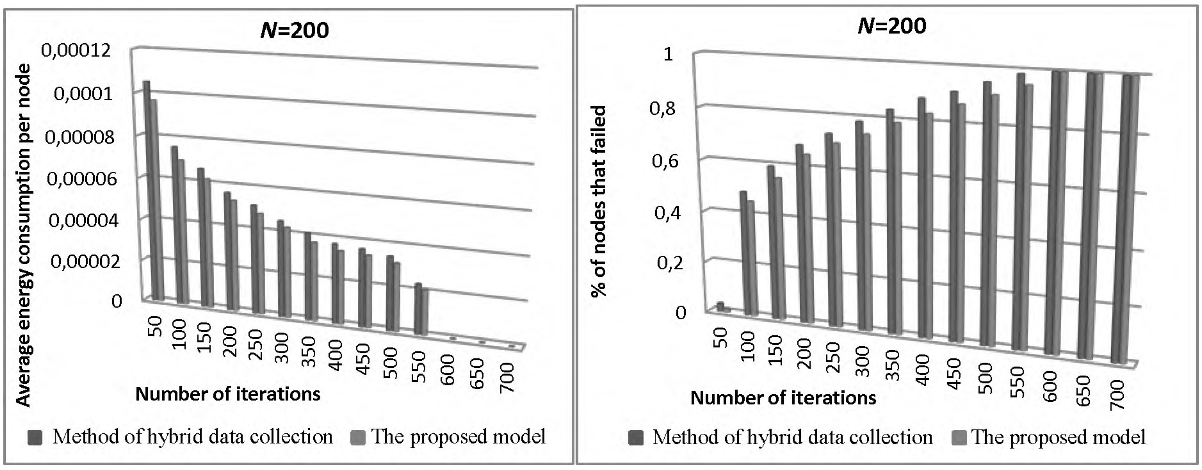
Fig. 8 shows the dependence of the data collection time T_{col} of the model in comparison with the hybrid method [10] at different numbers of nodes in the cluster $N = 100, 200$. The data collection time of the proposed model is 10–15 % less compared to the hybrid collection method [10].



a *b*

Fig. 8. T_{col} dependence at different number of network nodes:
$a - N = 100$; $b - N = 200$

Fig. 9 shows the dependence of the average node energy consumption and the percentage of failed nodes on the number of rounds of circling for a network with $N = 200$ nodes. The average energy consumption of nodes (Fig. 9*a*) in the proposed model is 10 % lower compared to [10], so the percentage of failed nodes (Fig. 9*b*) in the proposed model is lower, which correspondingly increases the network lifetime by 12–17 %.



a *b*

Fig. 9. Dependence of the energy costs and of the percentage of failed nodes on the number of flight rounds

The results of modeling the model of situational control of the flight path and data collection of the TA [13] in comparison with the hybrid method [10] showed that the time of data collection from the TA nodes is reduced by 10–15 % or the network operation time is increased by 12–17 % when certain restrictions are met. It is important to note that the proposed model can be used in special software of the data collection management system. The low computational complexity of the model allows its application in real time.

Conclusions. The developed model of situational control of the flight trajectory and data collection from nodes by a telecommunication aerial platform is implemented in the method of direct data collection by TA [14]. The novelty of the situational control model is the hierarchy of decision making: network, cluster, TA, node, considering the target control functions. At the network level, rules for determining the number and size of clusters are applied; a basic solution is built to determine the collection points and their flight paths. At the level of each cluster, during the flight, the TA adjusts the basic solution considering the parameters of the actual state of the cluster nodes. At the level of TA-node interaction, the node's energy consumption and data transmission rate are optimized by determining the node-TA distance. For each set of situations on the network, in the cluster, and on the node, a corresponding set of rules has been developed. Meta-rules are proposed to reduce the number of solution options. This approach allows us to achieve optimization of the objective functions of the data collection process and ensure real-time decision-making. The results of simulation modeling of the situational management model have proven the possibility of reducing the data collection time by 10–15 % or increasing the network operation time by 12–17 % compared to existing solutions.

The direction of further research is the use of deep learning neural networks to develop appropriate control actions along the flight path to collect TA data from the WSNs.

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