UDC 621.396.67 DOI: 10.20535/2411-2976.12025.14-21

MATHEMATICAL MODEL AND METHOD OF MAINTAINING CONNECTIVITY IN A MOBILE NETWORK WITH DIRECTED ACTION SENSORS USING TELECOMMUNICATION AERIAL PLATFORMS AT DIFFERENT LOCATION LEVELS

Ihor O. Sushyn, Olexandr I. Lysenko, Yevhenii M. Tymofeiev, Valeriy I. Novikov

Educational and Research Institute of Telecommunication Systems
Igor Sikorsky Kyiv Polytechnic Institute, Kyiv, Ukraine

Background. In conditions of modern and forecasted natural and man-made emergencies, mobile sensor networks (MSNs) with telecommunication aerial platforms (TAPs) for effective functioning need to have an energy reserve almost an order of magnitude larger than the current energy reserve. Moreover, existing networks of this type have an unacceptably high delay for information transmission, a low speed of its transmission from node to endpoint, and require the use of an extremely large number of telecommunication aerial platforms to maintain continuous connectivity.

Objective. Delay reduction, end-to-end information transmission speed enhancement, and a decrease in the number of TAPs in a mobile sensor network with TAPs, while operating in an emergency zone, where there is no telecommunications infrastructure.

Methods. Analysis of literature and modern research related to the topic of ways to improve and evaluate the effectiveness of mobile sensor networks with telecommunication aerial platforms. Identification of strategies and tools employed by researchers in the creation of mathematical models and methods. Development of a mathematical model that allows modelling both the conditions of existence and absence of connectivity for a mobile-directed action sensor network (MDASN) with TAP at different location levels and energy support, and that computes the numerical values of the vector-criterion components used for quantitative appraisal of the effectiveness of this connectivity. Development of maintaining a MDASN connectivity method using TAP at different location levels that solves the stated multi-criteria problem.

Results. A significant scientific and technical problem was solved regarding the development of a mathematical model and method of using directed action sensors as part of a mobile sensor network using a two-level spatial arrangement of telecommunication aerial platforms with different energy support to maintain this type of connectivity, which allows achieving a reduction in the average delay time during information transmission and telecommunication aero-platforms quantity directly involved in each information transmission session while increasing the average end-to-end information transmission speed.

Conclusions. Based on the obtained results, it can be stated that using the developed mathematical model enables simulation modelling in Matlab computer mathematics system, and method can be used in an expert modelling decision-making system for managing search-and-rescue robots.

Keywords: *mathematical model; method of maintaining connectivity; mobile sensor network; directed action sensors; telecommunication aerial platforms at different location levels; unmanned aerial vehicle.*

Introduction

Advances in mobile ad-hoc network (MANET) technologies have raised the challenge of efficiently establishing data collection and transmission between nodes. To solve these problems, telecommunication aerial platforms are increasingly being used. In turn, ground-to-air networks (GANs) used for rapid response in crisis situations usually include MSN nodes and UAVs of various configurations [1,2,3], as shown in Figure 1.

Primary data is collected using sensor elements integrated into mechanical devices. Such devices can be stationary or mobile, moving autonomously or as part of rescue teams performing search operations in disaster areas. The operating environment for such systems often includes locations (land surface, water areas of seas or oceans) where standard telecommunications infrastructure is absent due to large-scale natural or man-made disasters. Also, it should be noted that sensor nodes and TAPs often demonstrate a high degree of hardware and software interoperability, using identical or compatible hardware and common information exchange protocols. Each network element has its own managing positioning systems and can interact with other network elements. It allows each node to choose the best method to transmit data (sequential, cluster, etc.). The presence of a significant amount of built-in memory in the nodes allows data to be accumulated in the absence of a stable radio connection. Once the connection is established, the collected information is transmitted and/or exchanged according to a predefined algorithm. When clustering is used, nodes can perform various roles, including routing, cluster master node (CMN) functions, multimedia data transmission, and monitoring tasks [1,2,4,5].

The dynamic characteristics of UAVs, such as speed and acceleration, are variable, allowing them to move in three planes and take up positions at different heights above the ground. In addition, UAVs differ in energy and telecommunications support, which determines their ability to remotely collect and exchange data with elements of wireless sensor network nodes [6,7,8]. With routers on board, TAPs act as key links in data processing and transmission, ensuring their transit to the base station or neighbouring TAPs for further operations. Decentralised control systems built into each network element are an important component of GAN. Such systems provide an opportunity for both centralised coordination of actions to maintain the overall network connectivity and autonomous operation of their segments in the event of a breakdown in communication with the control centre [1-3,9].

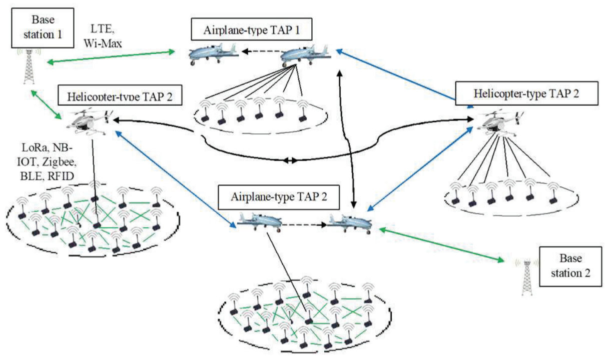

Fig. 1. Structure of a mobile sensor network using telecommunication aerial platforms based on aeroplane and helicopter UAVs, which combines various algorithms and protocols for information exchange

Sequential information exchange requires direct communication with each node, which inevitably leads to the formation of long routes for TAPs [1,10]. Although the elimination of complex data exchange management algorithms makes this method attractive in terms of cost and power consumption of network elements, its practical application is limited by the long data collection time and the significant need for TAP resources. These shortcomings have led to searching for and developing new, more efficient methods. Among them is the proposal to cluster nodes using TAPs that act as self-organised CMNs [5,11]. The implementation of this approach implies that the network control centre receives the coordinates of the nodes, based on which, using algorithms such as k-means or FOREL and their modifications, it calculates the optimal locations for data exchange with the TAP [3,12]. The first is used for optimal clustering of MSN nodes, and the second for forming connectivity between the formed clusters. Also, the telecommunication industry uses new and other advanced algorithms or their combination to solve the connectivity problem and increase the efficiency of its execution, but they can solve them only partially or insufficiently effectively.

In conditions of modern and forecasted natural and man-made emergencies, mobile sensor networks with telecommunication aerial platforms need to have an energy reserve almost an order of magnitude larger than the current energy reserve with which modern MSNs with TAPs are provided.

Modern MSNs with TAPs have an unacceptably high delay time for information transmission, low speed of its transmission from the node to the end point, and require the use of an extremely large number of telecommunication aerial platforms to maintain continuous connectivity.

Therefore, there is an objective necessity for hardware (constructive and algorithmic) improvement of existing mobile sensor networks with telecommunication aerial platforms to reduce information transmission delay time, increase its end-to-end transmission, and reduce the number of directly involved telecommunication aerial platforms (TAPs), taking into account the need for more efficient utilisation of the energy resource available in the network nodes and aboard the TAPs.

Main part

Based on the existing problems, it is proposed to improve the architecture of the existing MSN with TAPs by using a mobile-directed action sensor network with telecommunication aerial platforms at different location levels. Let`s consider its features in more detail (Fig. 2).

Primary information sources at the zero level are sensors equipped with mechanical devices. Current practice suggests that teams arriving at an incident site usually deploy helicopter-type (or, less commonly, airplane-type) TAP. As shown in the corresponding figure, these platforms form the network's first, or tactical, layer. This level provides the local connectivity necessary to collect and exchange information between search and rescue equipment and rescuers. The operating height of such platforms ranges from half a kilometre to several kilometres [13].

At the same time, an additional, second level of TAP is needed to broadcast information flows over long distances, particularly to points where general (operational and strategic) decisions are made. Its characteristic feature is a significant altitude, from several to several tens of kilometres. This second layer should be able to interact with both the lower, tactical level of the helicopter-type TAP network and with higher links, such as low-orbit satellites or high-altitude telecommunications platforms (so-called pseudo-satellites). The primary purpose of such an architecture is to guarantee fast data transmission to the main decision-making center or to transmit information directly to this center [13].

Also, levels are determined not only by their spatial location, but also by their equipment and the possibility to be in working state, that is, to perform information exchange with other levels of the network [13].

Typical timeframes for the adequate performance of telecommunications functions for helicopter-type TAPs range from half to several hours. This figure is significantly higher for airplane-type, ranging from one day to several days [13].

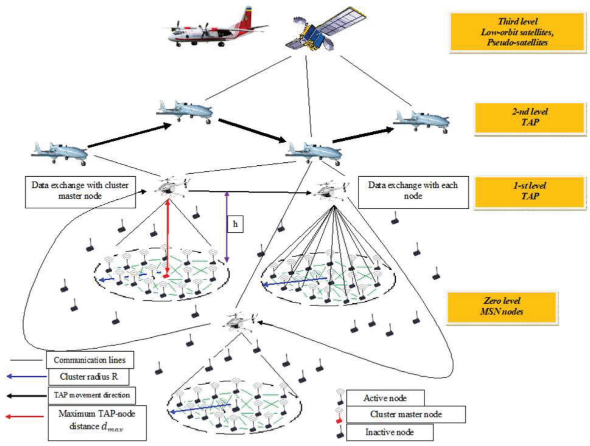

Fig. 2. Structure of mobile-directed action sensors network using two-level telecommunication aerial platforms location

For conducting simulation modelling and comparison of functioning effectiveness for improved network, a multi-criteria mathematical model has been developed. It allows modelling both connectivity existence and absence conditions for a MDASN with TAPs at different location levels and energy support, and that computes the numerical values of the vector-criterion components used for a quantitative appraisal effectiveness of this connectivity.

Values that meet the scalar criteria $Wi(X)$ ($i = \overline{1,11}$) and are integral parts of the vector criterion

$$W(X) = \begin{bmatrix} W_1(X) \\ \vdots \\ W_{11}(X) \end{bmatrix}$$

where X represents the vector of control parameters. Determining whether X resides within the permissible domain G is accomplished by utilising an algorithmically specified model. This model simulates a MDASN incorporating TAPs operating at varying location levels and functioning with diverse energy support mechanisms. (Fig. 3).

Components of control parameter vector X:

- node transmitters power, TAPs on first and second levels;
- node antenna coefficient and spatial beam orientation (azimuth, moon angle);
- operating frequency, bandwidth;
- number and sizes of clusters;
- node sleep time.

The physical context of the problem dictates the necessity of defining the domain G, encompassing all acceptable values for the aforementioned control parameters.

To build a multicriteria mathematical model, the set of criteria $Wi(X)$ ($i = \overline{1,11}$) was determined by selecting from the list of ITU-R methodological guidelines and the tools of the MATLAB software environment:

$W_1(X)$ – information transmission time averaged over sensors number, s;

$W_2(X)$ – information transmission rate averaged over sensors number, bits/s;

$W_3(X)$ – number of directly involved TAPs averaged over sensors number, pcs;

$W_4(X)$ – TAPs maximum number, pcs;

$W_5(X)$ – TAPs median number, pcs;

$W_6(X)$ – TAPs number mode, pcs;

$W_7(X)$ – route length averaged over sensors number, m;

$W_8(X)$ – maximum route length, m;

$W_9(X)$ – minimum route length, m;

$W_{10}(X)$ – median route length, m;

$W_{11}(X)$ – route length mode, m.

Mathematical model parameters that are considered as constant:

1. Node characteristics (number N_{node}, battery type, its capacity, form factor);
2. TAP characteristics (TAPs number on 1st N_{TAP1} and 2nd levels N_{TAP2}, power source type, speed, flight height or height range);

3. The area where they are located and movement routes;

4. Nodes coordinate and TAPs at the time of information transmission (when considering the quasi-mobility scenario);

5. Data amount (including service data) V_i of i-th node to be transmitted, i=1…N_{node};

6. Topology and routes of data transmission from MSN nodes to the satellite via TAP;

7. Possibilities of interaction between network elements of each level.

Upon completing the stage of formalising the vector of control parameters, the set of criteria and constants of the mathematical model, we will consider the next essential component: an algorithmically deterministic model for calculating scalar criteria. (Fig. 3).

A detailed description of the stages in algorithmically defined model functioning used to calculate the scalar components of the vector criterion is presented in the relevant article [14].

Based on the experience of previous studies and taking into account the degree of importance of local (scalar) criteria used in the mathematical model, we formulate the statement of the multicriteria optimisation problem as follows:

$$\begin{bmatrix} W_1(X) \to \max\limits_{X \epsilon G} \\ W_2(X) \to \min\limits_{X \epsilon G} \\ W_3(X) \to \min\limits_{X \epsilon G} \end{bmatrix},$$

where X denotes a vector consisting of the control parameters, while G represents the region (or set) values considered valid for these parameters.

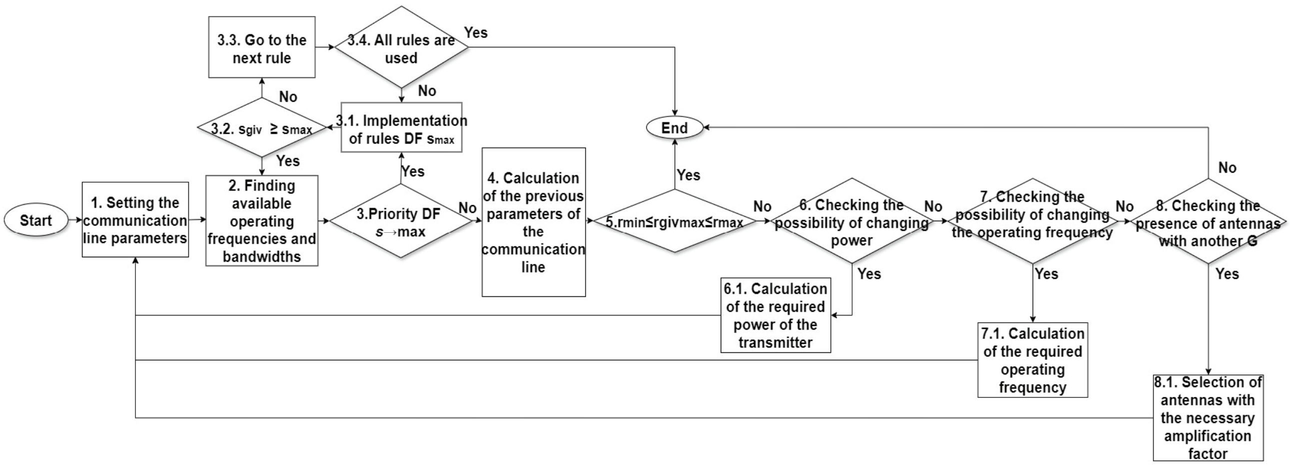

Fig. 3. An algorithmically defined mathematical model for calculating scalar components of a vector-criterion

The mathematical formulation of the multi-criteria optimisation problem faces the challenge of the impossibility of simultaneously achieving an extremum (maximum or minimum) by all local (scalar) criteria at the same permissible values of control parameters, except in ideal cases [15]. This necessitates the choice of the optimality principle, or the so-called method (scheme) of compromise, which would allow us to calculate the optimal solution for a given set of criteria $W_i(X)$ $(\mathrm{i} = \overline{1,3})$. As such, a compromise approach, the method of the leading criterion was chosen, which is widely used in engineering problems [16,17]. To determine the extreme value of the leading criterion, it is recommended to use the Hooke-Jeeves numerical method [17].

An important property of an optimal solution is its rationality. To achieve this, the criteria $W_i(X)$ $(\mathrm{i} = \overline{4,11})$ must not take values worse than their corresponding constraint levels [15].

A method is proposed to effectively solve the multicriteria optimisation problem and obtain results better than those demonstrated by the prototype system. The essence of the method is to ensure the MDASN connectivity using the optimal location of the TAPs, characterised by different energy support. This approach successfully solves the initial optimisation problem and achieves higher performance.

When developing the proposed method, a constructive algorithmic approach was used to improve existing maintaining connectivity methods [1,2,9,15].

The key element of the first constructive component of the developed method is an innovative proposal for the use of mobile sensors characterized by directed action.

The second constructive key of the proposed method solves the problem of ensuring an extended communication range by introducing a two-level system of telecommunication aerial platforms. The fundamental principle of designing this system is that second-level platforms are developed with significantly higher energy support than first-level platforms. This increased energy support enables second-level platforms to establish and maintain long-term communication sessions with low-Earth orbit satellites or high-altitude telecommunications platforms (pseudo-satellites).

The algorithm underlying the method unfolds through the following stages [13]:

1. The algorithmic procedure for collecting data on the network status initiated by the TAP overflight is similar to the prototype system. However, this stage includes a solution proposed for the first time: using second-level aerial platforms. These platforms actively determine the coordinates of mobile directional sensors using a location method in which the directional sensor antennas function as specialised reflectors of the second-level telecommunications aerial platform's location beam. The results of the overflight are then systematically processed in the control centre.
2. The determination of TAP positioning points at both levels is based on the solution to the multi-criteria problem. The process of calculating these points is implemented in the control centre.
3. The determination of route to TAP positioning points is based on the solution to the multi-criteria problem. The process of calculating these points is implemented in the control centre.
4. The algorithmic procedure for establishing connectivity between specific network components is implemented considering the special properties of directional antennas equipped with network elements, including mobile sensors and TAPs.
5. The algorithmic procedure for data transmission from the nodes (via the TAPs) to the monitoring data collection and processing centre is implemented considering the special properties of directional antennas equipped with network elements, including mobile sensors and TAPs.

Physical content of method stages [13]:

The outcome of the first stage is to obtain comprehensive information, including the total number of nodes, their information exchange capabilities (including transmitter power, antenna types, operating frequencies and bandwidth), and their energy characteristics. The ultimate goal is to form a structured data set that describes each node and each telecommunications aerial platform in detail from the perspective of the control object.

After the primary data is collected, it is analysed in depth. This analysis determines the method of information transmission between different components of the system (from nodes to TAPs, between TAPs of the first and second levels, with the possibility of using clustering and taking into account interaction), as well as the necessary technical characteristics (transmitter power, bandwidth, operating frequencies). The obtained analytical results are directly used to perform the second and third stages, which consist of calculating the optimal positions of the TAPs at both levels and building their routes.

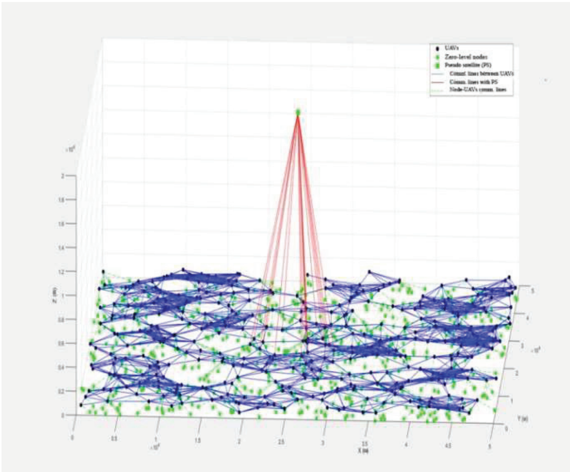

Fig. 4. Graphical illustration of prototype system during one of the experiments performed in the Matlab computer mathematics system

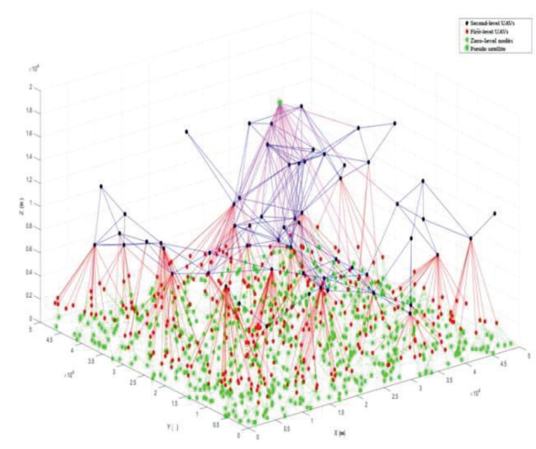

Fig. 5. Graphical illustration of the improved system during one of the experiments performed in the Matlab computer mathematics system

At the fourth and fifth stages, the network is directly operated. This process consists of the following sequential operations: flying UAVs along pre-calculated routes, establishing and maintaining connectivity between all network elements involved (including nodes and UAVs at the first and second levels), and finally, transmitting the received information to the control centre.

The key (critical) element in both the constructive and algorithmic components of the proposed method is the analysis and selection of the hardware for implementing directed action sensors and telecommunication aerial platforms (hardware improvement) [14].

A simulation experiment (Fig. 4) confirms the achievement of better results, which is described in detail in the article [18]. The first three most important criteria were optimized to ensure objective comparison between the proposed MDASN with TAP at different location levels and the known MSN with TAPs – the prototype system. The other eight criteria remained free. This optimization approach was used in the works of previous researchers in the prototype system. Multi-criteria optimization was performed using the leading criterion method. After optimizing the proposed system (MDASN with two-level TAP location with different energy support) and the prototype system (MSN with single-level TAP location with homogeneous energy support) according to the three most important criteria, a multi-criteria comparison was performed for all 11 criteria. A trivial result was obtained - the proposed system prevails in all eleven criteria [18].

Conclusions

The developed mathematical model is aimed at assessing the level of connectivity of mobile sensor network nodes with TAPs. To achieve this goal, the model combines: mathematical models of the directed action sensors functioning, models of the two-level location of TAPs with different energy support, and an algorithmically defined procedure for calculating evaluation criteria.

A new method is formulated to guarantee the connectivity of MSN nodes with TAPs. Its main difference from existing methods is the effective use of directional antennas on sensors and hierarchically deployed TAPs (two-level spatial arrangement with different energy support). This design significantly reduces the average latency of information transmission and minimises the number of TAPs required for one session. At the same time, it increases the average data transfer rate in the MDASN that uses this two-level TAP structure.

References

1. Lysenko, O., Romaniuk, V., Romaniuk, A., Novikov, V., Yavisya, V., Sushyn, I. (2023). The Method of Using a Telecommunication Air Platform as a Flying Info-Communication Robots. In: Ilchenko, M., Uryvsky, L., Globa, L. (eds) Progress in Advanced Information and Communication Technology and Systems. MCiT 2021. Lecture Notes in Networks and Systems, vol 548. Springer, Cham. (pp. 140-149).

2. Lysenko, O., Chumachenko, S., Valuiskyi, S., Yavisya, V., Novikov, V., & Sushyn, I. (2023). Methodological aspects of ensuring state security in the mind hybrid threats. Expert-modelling system decision support for the deployment and management of a wireless sensor network with mobile sensors and telecommunication air platforms in the emergency zone. Vysoka škola bezpečnosneho manažerstva v Košiciach. (pp. 255-270).

3. Sushyn, I., Lysenko, O., Romaniuk, V., Yavisya, V., Kyselov, V., Novikov, V. (2024). UAV Connectivity Maintenance in Wireless Sensor Networks. In: Luntovskyy, A., Klymash, M., Melnyk, I., Beshley, M., Schill, A. (eds) Digital Ecosystems: Interconnecting Advanced Networks with AI Applications. TCSET 2024. Lecture Notes in Electrical Engineering, vol 1198. Springer, Cham. (pp. 843-857).

4. Lysenko, O., Chumachenko, S., Tachinina, O., Tureichuk, A., Novikov, V., & Sushyn, I. (2022). Justification of the requirements for the sensor network of information support of the environmental safety system of a distributed man-made object. In Conference Proceedings of the 15th Annual International Scientific Conference «SECURITY FORUM 2022» (pp. 114–123).

5. Lysenko, O., Sushyn, I., Romaniuk, V., & Novikov, V. (2021). The Improvement Direct Method for Collecting Monitoring Data from the Wireless Sensor Network Nodes with their Clustering by Telecommunications Aerial Platforms. In 2021 IEEE International Conference on Information and Telecommunication Technologies and Radio Electronics (UkrMiCo) (pp. 123–126). IEEE.

6. Lysenko, O., Tachinina, O., Kirchu, P., Ponomarenko, S., Kutiepov, V., & Sushyn, I. (2023). Approach for determining the influence of UAV spatial motion parameters on the characteristics. Information processing in control and decision-

making systems. Problems and solutions. NU «OMA». (pp. 34-58).
7. Tachinina, O., Lysenko, O., Alekseeva, I., Sushyn, I., & Novikov, V. (2022). Method of Algorithmic Correction of Dynamic Properties of Special-Purpose Electric Drive. In 2022 IEEE 3rd KhPI Week on Advanced Technology (KhPIWeek) (pp. 263–266). IEEE.
8. Tachinina, O., Lysenko, O., Alekseeva, I., Novikov, V., & Sushyn, I. (2021). Methods for Parametric Adjustment of a Digital System and Precision Automatic Stabilization of an Unmanned Aerial Vehicle. In 2021 IEEE 6th International Conference on Actual Problems of Unmanned Aerial Vehicles Development (APUAVD) (pp. 76–79). IEEE.
9. Chumachenko, S., Lysenko, O., Tachinina, O., Furtat, O., Furtat, S., & Sushyn, I. (2023). Method of collecting information on the condition of critical infrastructure objects from wireless sensor network nodes. Challenges and threats to critical infrastructure. NGO Institute for Cyberspace Research. (pp. 171-178).
10. Popescu, D., Stoican, F., Stamatescu, G., Chenaru, O., & Ichim, L. (2019). A survey of collaborative UAV–WSN systems for efficient monitoring. Sensors, 19(21), 4690.
11. Ho, D.-T., Grøtli, E. I., Sujit, P. B., Johansen, T. A., & Sousa, J. B. (2015). Optimization of wireless sensor network and UAV data acquisition. Journal of Intelligent & Robotic Systems, 78(1), pp. 159–179.
12. . Ho, D.-T., Grotli, E. I., & Johansen, T. A. (2013). Heuristic algorithm and cooperative relay for energy efficient data collection with a UAV and WSN. In 2013 International Conference on Computing, Management and Telecommunications (ComManTel) (pp. 346–351). IEEE.
13. Sushyn, I., & Butkevych, H. (2023). Methodology for assessing the connectivity of wireless sensor network nodes when using a multilevel network of telecommunication aeroplatforms. Scientific notes of Taurida National V.I. Vernadsky University series «Technical Sciences», 34 (73)(6), pp. 39–46.
14. Sushyn, I., та Lysenko, O. (2024). Universal method of data transmission using directed action sensors. Scientific notes of Taurida National V.I. Vernadsky University series «Technical Sciences», 35 (74)(2), pp. 6–14.
15. Romaniuk, V., Lysenko, O., Romaniuk, A., Novikov, V., & Guida, O. (2021). Methods of gathering information from a node of wireless sensor networks with intelligent adaptive information and telecommunication flying robot. Scientific notes of Taurida National V.I. Vernadsky University series «Technical Sciences», 32 (71) (2 (Part 2)), pp. 25–35.
16. Romaniuk, A. (2017). Nodal objective control functions of the wireless sensor networks for critical infrastructure monitoring. Scientific notes of Taurida National V.I. Vernadsky University series «Technical Sciences», 28 (67)(2), pp. 49–54.
17. Lysenko, O., Tachinina, O., Yavisya, V., Novikov, V., & Sushyn, I. (2024). Digital automatic control systems for telecommunications. Igor Sikorsky Kyiv Polytechnic Institute.
18. Sushyn, I., & Lysenko, O. (2024). Evaluation of method effectiveness for maintaining connectivity in a mobile network with directed action sensors using telecommunication aerial platforms at different location levels. Scientific notes of Taurida National V.I. Vernadsky University series «Technical Sciences», 35 (74) (5 (Part 1)), pp. 71–78

Сушин І.О., Лисенко О.І., Тимофеєв Є.М., Новіков В.І.

Математична модель та метод підтримки зв’язності мобільної мережі сенсорів спрямованої дії з телекомунікаційними аероплатформами різнорівневого розташування

Навчально-науковий інститут телекомунікаційних систем КПІ ім. Ігоря Сікорського, м. Київ, Україна

Проблематика. В умовах сучасних та прогнозованих на майбутнє природних та техногенних надзвичайних ситуацій мобільним сенсорним мережам (МСМ) з телекомунікаційними аероплатформами (ТА) для ефективного функціонування необхідно мати енергетичний запас майже на порядок більший ніж енергетичний запас. Також існуючі мережі даного типу мають недопустимо великий час затримки для передачі інформації, малу швидкість її передачі від вузла до кінцевого пункту, вимагають використання надзвичайно великої кількості телекомунікаційних аероплатформ для неперервної підтримки зв’язності.

Мета досліджень. Зменшення часу затримки, підвищення швидкості передачі інформації з кінця в кінець та зменшення кількості ТА в мобільній сенсорній мережі із ТА при умові її функціонування в зоні надзвичайної ситуації, коли відсутня телекомунікаційна інфраструктура.

Методика реалізації. Аналіз літератури та сучасних досліджень пов’язаних з тематикою способів вдосконалення та оцінки ефективності мобільних сенсорних мереж з телекомунікаційними аероплатформами. Визначення підходів та інструментів, які використовувалися у роботах дослідників для створення математичних моделей та методів. Розробка математичної моделі, яка дозволяє моделювати як умови існування, так і відсутності зв’язності мобільної мережі сенсорів спрямованої дії (МССД) з ТА різнорівневого розташування та енергетичного забезпечення, а також обчислювати чисельні значення складових векторного критерію, за якими можна виконати кількісне оцінювання ефективності цієї зв’язності. Розробка методу підтримки зв’язності ММССД із використанням ТА різнорівневого розташування, який розв’язує поставлену багатокритеріальну задачу.

Результати досліджень. Було розв’язано важливу науково-технічну задачу щодо розробки математичної моделі та методу використання сенсорів спрямованої дії у складі мобільної мережі сенсорів та дворівневого просторового розташування телекомунікаційних аероплатформ із різним енергетичним забезпеченням для підтримки такого типу зв’язності, який дозволяє досягти зменшення середніх значень часу затримки при передачі інформації та кількості безпосередньо задіяних телекомунікаційних аероплатформ в кожному сеансі передачі інформації, а також збільшення середньої швидкості передачі інформації з кінця в кінець.

Висновки. Виходячи з отриманих результатів можна стверджувати, що за допомогою розробленої математичної моделі можна виконати імітаційне моделювання в системі комп`ютерної математики MATLAB, а метод може бути використаний в експертно-моделюючій системі прийняття рішень для керування пошуково-рятувальними роботами.

Ключові слова: *математична модель; метод підтримки зв’язності; мобільна сенсорна мережа; сенсори спрямованої дії; телекомунікаційні аероплатформи різнорівневого розташування; безпілотний літальний апарат.*

Received by the Editorial Office
May 6, 2025

Accepted for publication
June 9, 2025