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# EVALUATING THE FUNCTIONING EFFECTIVENESS OF SENSOR GROUND-TO-AIR NETWORK USING MULTIPLE UAVS LAYERS AND DIRECTIONAL ANTENNAS

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**Background.** Based on the theoretical and practical (using Atoll) calculation of radio communication lines and antenna devices were estimated the main network parameters (throughput, length of the data transmission route, delays, number of network elements) of proposed ground to air network (GAN) architecture.

**Objective**. The purpose of the work is to evaluate the effectiveness of mobile networks with directed action sensors using UAVs at different levels.

**Methods.** Simulation modelling of two mathematical models and their comparison using MATLAB software.

**Results.** It is shown that the throughput decreases with the increase of the data transmission route, while the delay and the number of network elements increase in accordance with the previous study. Changing the location of the nodes also affects the parameters evaluated, so 10,000 measurements were made to obtain the required amount of statistical data. Two mathematical models were created. The first model is based on an existing mobile omnidirectional sensor network using a single UAV layer while the second one is based on a mobile network of directional sensors using two levels of UAVs. In both models, the data was transmitted from the nodes to the pseudo-satellite. In the proposed model, the following average values were achieved: throughput - 852071 bits/s, number of network elements - 4.4, route length - 33673 meters.

**Conclusions.** According to the obtained results, it can be argued that the proposed two-level UAV location model using directional sensors can be effectively used to maintain the connectivity of a mobile sensor network with the achievement of a gain in the evaluated indicators.

***Keywords:*** *ground-to-air network; unmanned aerial vehicle; directed action sensors.*

## Introduction

Mobile sensor networks (MSNs) occupy an increasingly important part of wireless networks every year due to the growing number of military conflicts, disasters of various kinds, etc. They can be characterized as a distributed system of wireless nodes (small in size) capable of self-organization. The main qualities of MSM using telecommunication aerial platforms (TAP) are the ability to monitor various parameters, and exchange information over large areas along routes that pass through other nodes and UAVs to the nearest network element (NE) (e.g., satellite or base station) of public systems or directly to the information processing center. Therefore, their development is relevant, including with the use of TAP, namely the organization and improvement of connectivity between NEs.

In classic MSNs using TAP, sensor nodes are omnidirectional (using the appropriate type of antennas), and unmanned aerial vehicles (UAVs) are located at the same level, but this does not always allow achieving the required throughput or introduces limitations on the length of the route from the sensor (node) to the satellite or base station and other parameters. It is also important to efficiently utilize the available limited UAV resource. Therefore, it is worth considering a mobile network of directional sensors [1,3] with the use of TAP at different levels [2,4], which will improve key parameters.

To evaluate the effectiveness of a ground to air network (GAN), it is important to determine a list of parameters: deployment time, operation, number of required TAPs, percentage of coverage, throughput, delay, etc., as well as input parameters: coverage area, characteristics of transceiver equipment, detailed description of the topology, etc. Based on this, there is a need to develop a methodology for assessing the effectiveness of GANs.

The classic topology of the GAN network consists in the use of omnidirectional nodes at the zero level and UAVs located at the same level. Existing works show that their improvement lies in the introduction of new algorithms for clustering, flying and positioning. In MSNs of this type, nodes can receive and transmit signals in all directions, which allows them to be used in scenarios of rapidly changing events and movement in space, but in this case, energy efficiency remains low or there are limitations in the maximum distance of the communication line or throughput [1,3]. Also, the use of one level of UAVs requires a larger number of them, which is not always possible. Therefore, to address the above shortcomings, MSNs with directional nodes using two or more UAV layers have been proposed [2,4], which allow the use of existing algorithm improvements with different access protocols. However, there is still a need to evaluate and compare them in order to make a decision on their further implementation for further scientific and industrial purposes.

Research and development that improves the connectivity of the network elements of the GAN is an important direction in their development with further implementation in the civilian and military spheres.

Next, the task is to formulate possible parameters for assessing their effectiveness and the corresponding methodology. Therefore, based on existing studies and methods, it is necessary to compare the proposed mobile network of directional sensors using TAPs of different levels of location. To do this, it is necessary to create mathematical models with pre-selected input data that will allow for an experiment (simulation modelling) and draw conclusions.

## 1. Indicators identification for assessing the work effectiveness of the MSN with TAP

It is important to understand that performance evaluation can be performed in phases: during operational management, configuration changes (ramping up or down), planning, or deployment. Each phase is allocated the necessary time $\mathrm{T}_{neces}$ (a time limit is set), and the efficiency is determined according to the rule $\mathrm{T}_{neces} \rightarrow \min$ або $T \leq \mathrm{T}_{neces}$, the quality of decisions made by the network control center (NCC), resources (nodes, TAPs) and energy consumption. The management system consists of the following subsystems: coverage planning and optimization, telecommunications, and energy management. Accordingly, each of them has certain performance indicators (Table 1).

Table 1

Indicators for assessing the effectiveness of subsystems

| **Planning and optimizing coverage** | **Telecommunications** | **Energy management** |
|---|---|---|
| Deployment time | Connectivity | Energy consumption |
| Percentage of coverage | Throughput | Functioning time |
| Number of nodes | Delay | |
| Number of TAPs | Traffic volume | |
| | Load | |

The first subsystem provides coverage of a certain area, object, settlement, etc. to exchange/collect information such as the status of the monitored object or transfer information to it. The second subsystem should ensure data exchange with nodes and TAPs, including the base station (or satellite), with the required quality. Prior to this process, the network should be deployed with the formation of clusters and points of exchange of information of the UAVs, as well as the flight route. The third subsystem is responsible for the distribution of energy costs between network elements (each of which has its own power source). Its main goal is to increase the lifetime of the network and its elements while maintaining the minimum required quality of coverage and data exchange/collection.

## 2. Methodology for assessing the effectiveness of directed action nodes in ground to air networks using multilevel UAVs

For a rational comparison of the efficiency of the presented telecommunication system, a methodology consisting of four stages has been proposed.

In the first stage, it is necessary to set the parameters of the GAN:

1. NE characteristics: transmitter power $P_{\mathrm{i}}$, operating frequency $f_{\mathrm{p}}$, bandwidth $\Delta f$, antenna type, their gain coefficients $G_{\mathrm{i}}$ based on measurement accuracy, quality of multimedia data transmission, exchange/collection time, completeness of the information received, etc.)

2. Network characteristics: coverage area, number of NEs ($N_{node}$, $N_{\mathrm{TAP}}$), their coordinates, topology (number of clusters and nodes in them, communication lines, algorithm for selecting the cluster master node (CMN), etc.), access protocol, type of service (with or without a guarantee), and operating hours.

3. Characteristics of the method of information exchange/collection, namely: their type (sequentially from each node, from the CMN); the NE that organizes the cluster and manages the network (NCC or TAP or CMN); algorithms for building a flight route (general or local) and clusters based on the

objective function (minimizing the number of TAPs, maximizing network operation time, etc.);

In the second stage, it is necessary to select performance indicators (from Table 1).

The third stage involves the construction of mathematical models of the GAN (one-level with omnidirectional sensors and two-level with directional sensors) and the experiment (simulation modelling).

In the fourth stage, we will obtain the results and dependencies of performance indicators on various network conditions. Based on the above, the last step is to make comparisons and draw conclusions.

## 3. Simulation modelling

For comparison, two mathematical models were built: a one-level model with omnidirectional sensors (Fig. 1,2) and a two-level model with directional sensors (Fig. 3,4). The nodes of the sensor network are located at ground level at a height of up to 1.5 m, and the height of the pseudo-satellite with which UAVs communicate is 20 km. In the one-level model, the UAV's height is up to 1 km. And in the two-level model, the height of the first-level UAV is 1.5-2 km, and the second - 5-15 km. All network elements are randomly located on an area of 50 $km^2$. The number of zero-level nodes $N_{node}$ is 600. UAVs in the one-level model $N_{\text{TAP}} = 400$, in the two-level model – $N_{\text{TAP}} = 360$ (60 of which are located on the second level). The communication range was determined according to the methodology [1] with the IEEE 802.11ax access technology. The maximum flying radius of the first-level UAV is 4000 m, and the second level - 8000 m. The transmitter power of the node is 20 dBm, the UAV of the first level is 25 dBm, the second level is 30 dBm, the operating frequency is 2447 MHz, and the bandwidth is 20 MHz. The antenna gain of the nodes in the one-level model is 5 dBi, and in the two-level model - 17 dBi. The data packet size is 1024 bits.

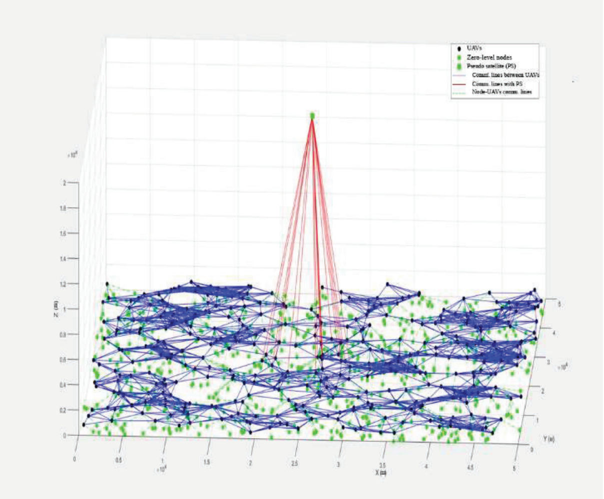

Fig. 1. One-level GAN model with omnidirectional nodes (3D visualization)

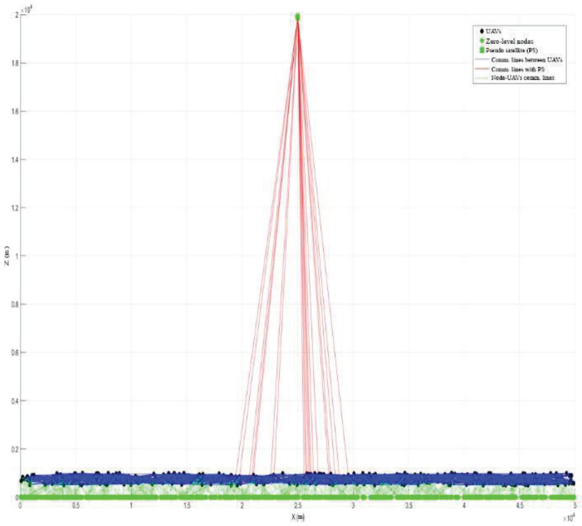

Fig. 2. One-level GAN model with omnidirectional nodes (2D visualization)

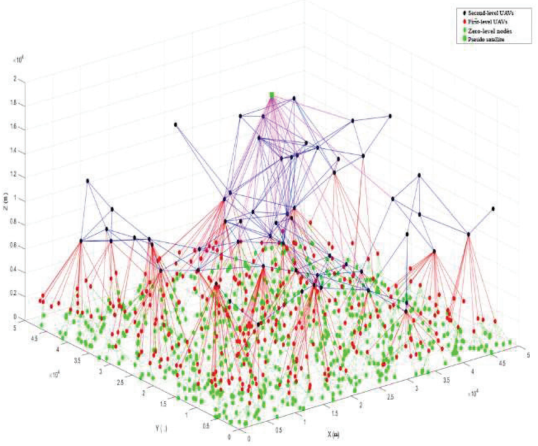

Fig. 3. Two-level GAN model with directional nodes (3D visualization)

Fig. 4. Two-level GAN model with directional nodes (2D visualization)

The main nodes of the cluster are the first-level UAVs, which establish communication with the available zero-level nodes in the range. In the one-level model, the first-level UAVs also communicate with the closest UAVs to maintain connectivity, and in the two-level model, the second-level UAVs (they are the CMNs for the first-level UAVs). The efficiency of the improved model was evaluated by the following parameters: route length, number of network elements, average throughput, and delay from the zero-level node to the pseudo-satellite. To calculate these indicators, we will use the methodology proposed in the research [1] and the specifications of the IEEE 802.11ax standard in the MATLAB software package. The number of measurements is 10000.

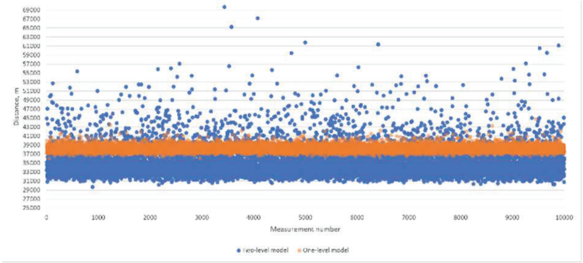

Fig. 5. Measurement of average route length

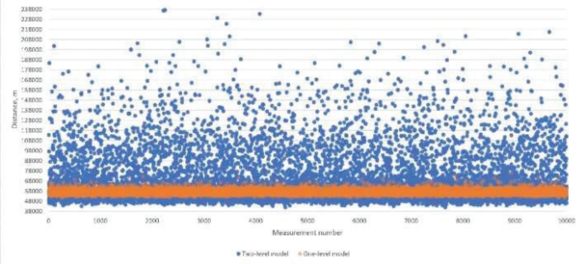

Fig. 6. Measurement of maximum route length

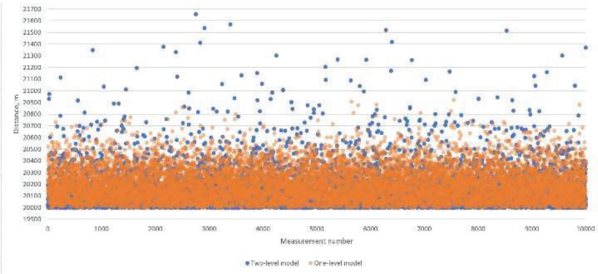

Fig. 7. Measurement of minimum route length

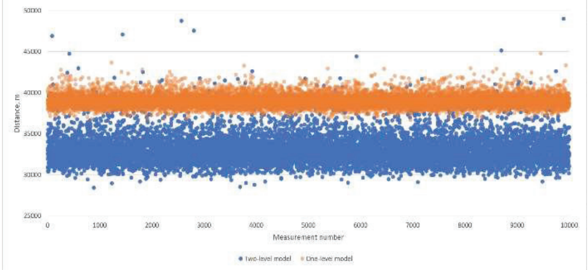

Fig. 8. Measurement of median route length

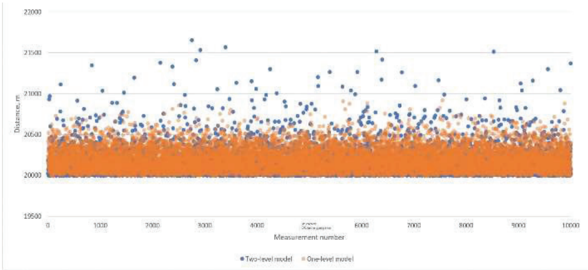

Fig. 9. Measurement of mode route length

Fig. 5-9 show the results of simulation modelling for the route length: average, maximum, and minimum values, as well as their mode and median. Based on the results, we can conclude that the route distance in the improved (two-level) model is 1.5-15.2% shorter (in terms of mode, median, and mean).

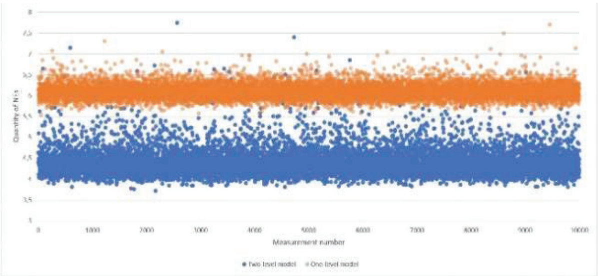

Fig. 10. Measurement of average number of NEs

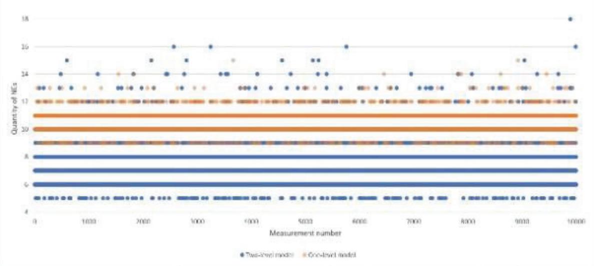

Fig. 11. Measurement of maximum number of NEs

Fig. 12. Measurement of median quantity of Nes

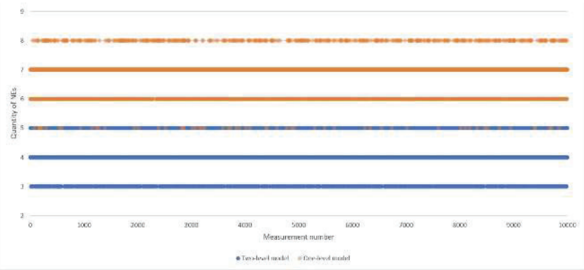

Fig. 13. Measurement of mode quantity of NEs

Fig. 10-13 show the results of simulation modelling for the number of network elements on the route from the zero-level node to the pseudo-satellite inclusive: average, maximum, values, as well as their mode and median. The minimum values for the one-level model are 2, and for the two-level model - 3. Based on the results, we can conclude that the number of NEs in the improved (two-level) model is 20-43% lower than in the above model.

The results of average throughput and delay values (Fig. 14,15) from nodes to the pseudo-satellite were also obtained. The advantage obtained in the two-level model is 41 and 29 percent, respectively. Next, we should pay attention to the dependence of the average throughput, average delay, and number of NEs on the distance (Fig. 16-18). From the dependence shown in Figure 16, it can be concluded that the throughput decreases with increasing distance, which coincides with the calculations in the Atoll software package [1]. And the dependencies in Fig. 17,18 show an increase in the delay and the number of NEs with increasing distance, respectively. The summary of simulation results for both models and their comparison are given in Table 2.

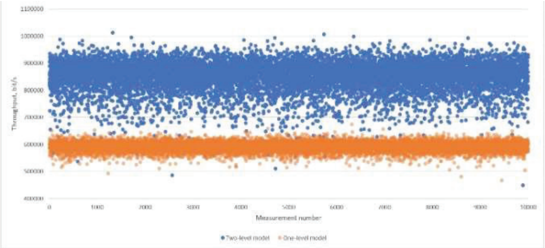

Fig. 14. Measurement of average throughput

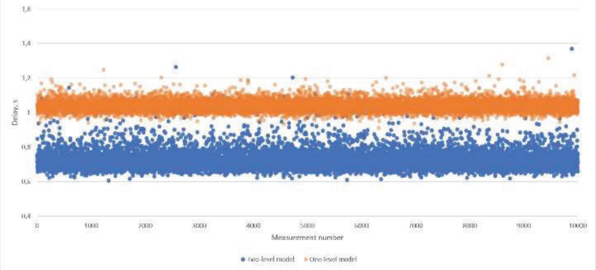

Fig. 15. Measurement of average delay

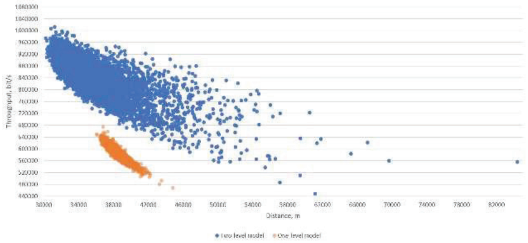

Fig. 16. Dependence of average throughput on average distance

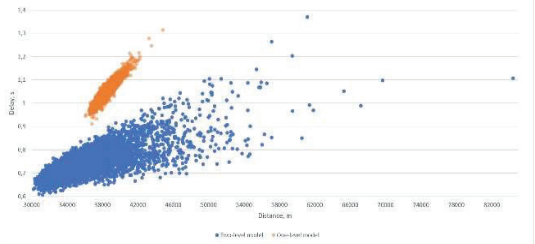

Fig. 17. Dependence of average delay on average distance

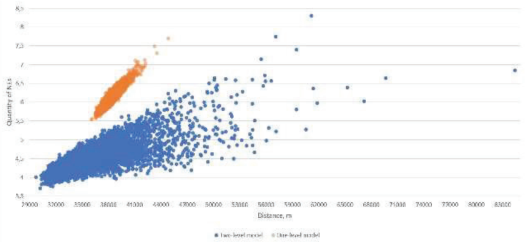

Fig. 18. Dependence of average number of NEs on average distance

Table 2

Summary of simulation results

| Indicator | One-level model | Two-level model | Difference, % |
|---|---|---|---|
| Average route length, m | 37649,13 | 33673,45 | 10,55 |
| Maximum route length, m | 58340,52 | 62871,89 | -7,77 |
| Minimum route length, m | 20397,6 | 20075,12 | 1,58 |
| Median route length, m | 38413,1 | 32561,065 | 15,23 |
| Mode of route length, m | 20397,6 | 20075,12 | 1,58 |
| Average quantity of NEs | 6,04 | 4,351 | 28,04 |
| Maximum quantity of NEs | 10 | 8 | 20 |
| Minimum quantity of NEs | 2 | 3 | -50 |
| Median quantity of NEs | 6 | 4 | 33,33 |
| Mode quantity of NEs | 7 | 4 | 42,86 |
| Throughput, bits/s | 602846,77 | 852071,01 | -41,34 |
| Total delay, s | 1,02 | 0,72 | 29,25 |

## Conclusions

The article proposes a methodology that describes an approach to assessing the effectiveness of MSN and a rational comparison of the proposed model with the existing one. It consists of four stages, namely: setting the input parameters of network elements and the network as a whole, selecting available performance indicators, building mathematical models based on the specified information, and obtaining results with the preparation of the necessary dependencies.

A list of indicators for assessing efficiency in each of the network management subsystems (coverage planning and optimization, telecommunications, and energy management) was identified.

Two mathematical models are presented: An omnidirectional MSN using a one-level of TAP and a directed MSM using a two-level TAP. The results of simulation modelling of the proposed and existing models are obtained, on the basis of which visual representations and comparisons are built in the form of a family of graphs and a general table. We also present the dependence of the average values of delays, throughput, and number of NEs on the average route length.

The obtained results show that the route distance in the improved (two-level) model is 1.5-15.2% shorter (by the mode, median, and average indicators) and 7.8% longer by the maximum indicator. The number of NEs in the improved model is 20-43 percent lower by the considered indicators (except for the minimum number of NEs, where it is 3), and the advantage in average throughput and delay is 41 and 29 percent, respectively.

In general, we can see an increase in throughput in the presented model on average, a decrease in the required number of network elements (TAPs) and the length of the route from the node to the pseudo-satellite. However, the minimum required number of TAPs (including the pseudo-satellite) in the proposed model is one unit more (which is its necessary condition for functioning), and in a small number of measurements the average route length in the proposed model is longer than in the existing one, which is due to the location of network elements (TAPs and sensors) at a considerable distance from each other. The scientific novelty is to test the effectiveness of the first proposed improved method of maintaining the connectivity of a mobile sensor network, which can be used for further scientific and industrial purposes.).

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## Оцінка ефективності функціонування сенсорної наземно-повітряної мережі з використанням декількох рівнів БПЛА та спрямованих антен

**Проблематика**. На основі теоретичного та практичного (з використанням Atoll) розрахунку ліній радіозв'язку та антенних пристроїв були оцінені основні параметри мережі (пропускна здатність, довжина маршруту передачі даних) запропонованої архітектури бездротової наземно-повітряної мережі.

**Мета**. Метою роботи є оцінка ефективності мобільної мережі сенсорів спрямованої дії з використанням БПЛА різнорівневого розташування.

**Методи**. Імітаційне моделювання двох математичних моделей та їх порівняння за допомогою програмного забезпечення MATLAB.

**Результати.** Показано, що пропускна здатність зменшується зі збільшенням маршруту передачі даних, тоді як затримка і кількість елементів мережі зростають відповідно до попередньо проведеного дослідження. Зміна розташування вузлів також впливає на оцінювані параметри, тому для отримання необхідного обсягу статистичних даних було проведено 10 000 вимірювань. Було створено дві математичні моделі. Перша модель базується на існуючій мобільній мережі сенсорів всеспрямованої дії з використанням одного рівня БПЛА. Друга - на основі мобільної мережі сенсорів спрямованої дії з використанням двох рівнів БПЛА. В обох моделях дані передаються від вузлів до псевдосупутника. У запропонованій моделі були досягнуті такі середні значення: пропускна здатність - 852071 біт/с, кількість елементів мережі – 4.4, довжина маршруту - 33673 метри.

**Висновки.** Виходячи з отриманих результатів можна стверджувати, що запропонована дворівнева модель розташування БПЛА з використанням сенсорів спрямованої дії може бути ефективно використана для підтримки зв'язності мобільної сенсорної мережі з досягненням виграшу в показниках, що оцінювалися.

***Ключові слова:*** *наземно-повітряна мережа; безпілотний літальний апарат; сенсори спрямованої дії.*