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# STATEMENT OF THE SCIENTIFIC TASK FOR OPTIMIZING FLIGHT AND CONTROL OF UNMANNED AERIAL SYSTEMS USING AIRBORNE REPEATERS

*The article substantiates and proves the necessity of developing mathematical support for existing and prospective models of weapons and military equipment, namely, class I unmanned aerial systems, for flight optimization and control using unmanned aerial system-based repeaters, which are used to solve the tasks of information and reconnaissance support of troops (forces) of the Armed Forces of Ukraine. It is established that the use of such systems provides information and fire superiority over the enemy during aerial reconnaissance, engagement of their resources, etc. Based on these prerequisites, the paper presents a formalized statement of an important scientific problem, which consists in increasing the efficiency of class I unmanned aerial systems by optimizing the flight route, network topology, us well us energy-efficient control using unmanned aerial system-based repeaters. The authors define "Unmanned aerial systems efficiency" as a comprehensive indicator of multi-criteria optimization of a non-linear compromise scheme, which depends on the values of the complex's probability of being hit, its combat radius, and survivability. A structural and logical scheme of the research is presented, which includes the solution of the following subtasks: analysis of the use of tactical class I unmanned aerial systems, unmanned aerial system-based repeaters, and their routing methods, as well as methods of planning optimal flight routes based on transport problem solving algorithms; optimization of the flight route of class I unmanned aerial systems to bypass their engagement zones; energy-efficient use of tactical unmanned aerial systems based on repeaters. The final scientific result is the developed mathematical support for class I unmanned aerial systems and the verification of its performance. The presented structural and logical scheme allows to systematize the essence and content of the scientific research.*

***Keywords:*** *unmanned aerial system; airborne repeater; efficiency; optimization; multi-criteria evaluation.*

**Problem statement in general terms:** For today, an integral component of modern armed conflicts is the active use of unmanned aviation. As evidenced by the experience of combat operations during the heroic resistance to the armed aggression of the russian federation (rf), there is a steady trend toward the increasing importance of employing unmanned aerial systems (UAS) [1], particularly for aerial reconnaissance, defeat enemy resources, adjusting artillery fire, assessing the outcomes of fire missions, and more.

At assessing combat effectiveness of UAS, their formations or groupings, it is necessary to take into account the specific features of their composition, methods of deployment, flight-technical characteristics, and operational limitations of unmanned aerial system (UAS) [2]. At the same time, rapid technological advancement coupled with improved tactics for using this class of weaponry prompts mutual and swift modernization of countermeasures. Under these conditions, the enemy improves existing countermeasures and develops new ones. Therefore, the task of increasing the effectiveness of UAS is timely, important, and necessary to achieve military superiority over the enemy.

Based on the outlined premises, the purpose of this article is to formalize a scientific problem of optimizing the flight and control of UAS when using UAS-based airborne repeaters.

**Analysis of recent studies and publications:** To date, a number of modern methods for assessing and ensuring an appropriate level of effectiveness of UAS, particularly in the context of group deployment, have been developed and implemented. For instance, in [2], a methodological approach is proposed for determining the combat potentials of systems, their units, and formations, which, unlike existing methods for evaluating the effectiveness of manned aviation, takes into account the specific features of modern UAS.

In [3, 4], the authors developed methods for the combat deployment of military UAS groups within the system "UAS group – enemy countermeasures – target – environment" and substantiated the prospects of combining modern control theory methods with artificial intelligence technologies to build their control systems. In [5], innovative approaches are examined, including generative design, swarm control algorithms, computer vision, and information-extreme learning methods, which contribute to expanding the functional capabilities of UAS.

The results obtained in [6], which involve a comprehensive approach to improving the effectiveness of aerial reconnaissance, can be used in the development of new reconnaissance UAS and in enhancing existing ones to better evaluate the effectiveness of aerial reconnaissance operations.

Thus, the analysis of scientific and practical sources indicates that there is a sufficient amount of scientific, methodological, and practical support for solving tasks related to improving the combat deployment of UAS, particularly with the use of relays. However, the issue of enhancing UAS effectiveness through flight route optimization, network topology design, and energy-efficient control has not received sufficient attention in the scientific literature.

**Formulation of the research task.** To achieve the stated research objective, it is necessary to formalize the scientific task, which consists in improving the efficiency of the Unmanned Aerial System (UAS) by optimizing the transmission power of the communication unit $E_{випр}$, the number of UAS-based relay drones $N_{ретр}$, and the consideration of reconnaissance objects (RO) $N_{ор}$:

$$E^{*}_{БпАК}\left(P_{ураж}, R_{БпАК}, Rel\right) \to \max \tag{1}$$

Due to the reduced probability of being hit $P_{ураж}\left(t_n\right)$, the increased combat radius $R_{БпАК}\left(N_{ретр}\right)$, and the enhanced survivability $Rel\left(E_{випр}, t_n\right)$ over the duration of the flight mission $t_n$.

Constraints and assumptions: depth of the reconnaissance area is 45–50 km; the locations of enemy firepower assets, radar electronic jamming stations, and counter-battery warfare systems are known in advance. The number of relay UAS is up to 5–6. Reconnaissance data were obtained through preliminary monitoring and are considered input data for planning the flight route of the system.

**Main material.** Since the beginning of the full-scale invasion, the use of reconnaissance UAS by the Security and Defense Forces of Ukraine has significantly improved situational awareness and increased the effectiveness of their units' operations.

Currently, there is a trend where the number of detected and confirmed targets exceeds the ability to engage them. Additionally, during the assessment of fire effectiveness, there is an operational opportunity to re-engage the target or redirect fire to another one [7].

However, the enemy still demonstrates a high level of success in countering reconnaissance and strike UAS. This is primarily due to the lack (or inadequacy) of automated tools for flight route planning and ensuring reliable communication during mission execution.

The effectiveness of the systems currently in service and used by units (troops) is significantly reduced because their mathematical support does not meet modern requirements.

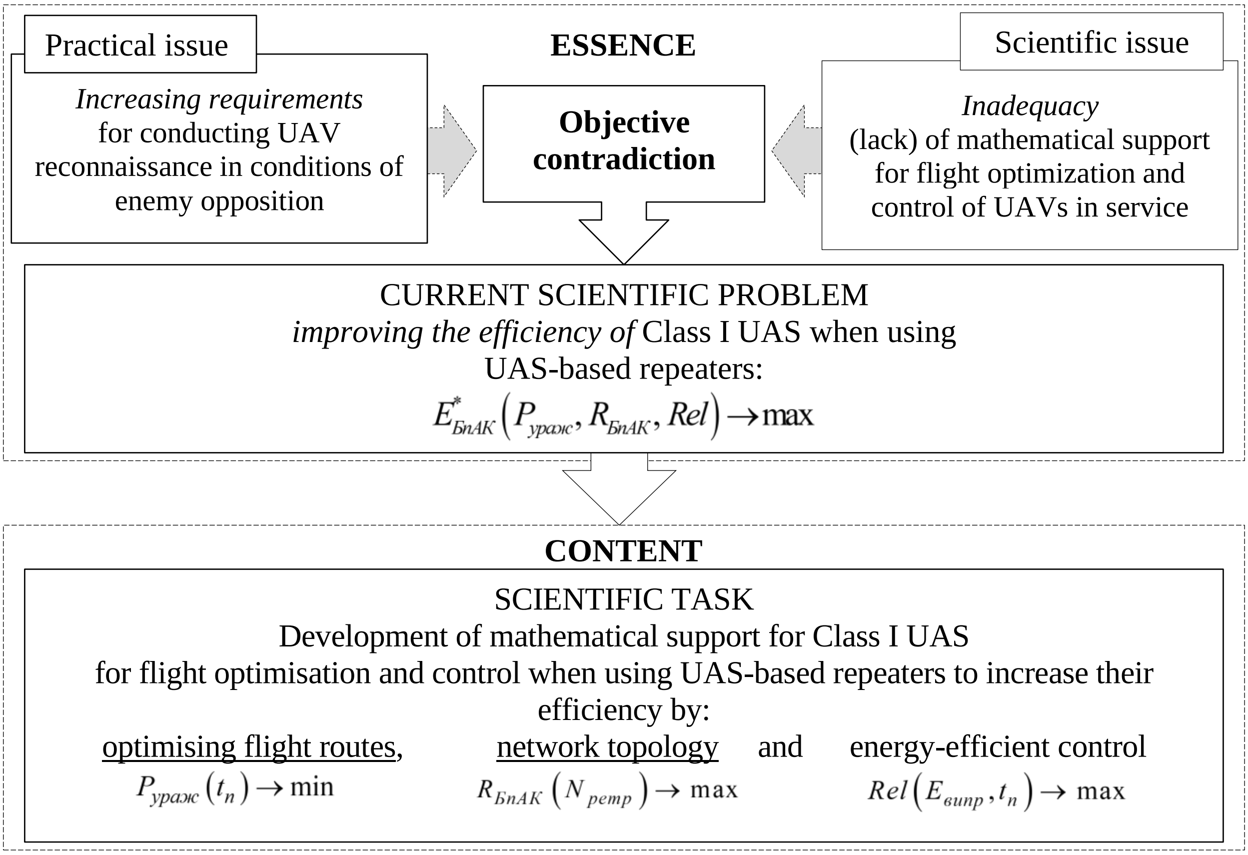



*Figure 1. The essence and content of the scientific task*

In addition, the functional and combat capabilities of UAS are limited by their flight-technical and energy characteristics. Therefore, at present there is an objective contradiction between the imperfection (or absence) of the mathematical support of existing models and the requirements for conducting reconnaissance at the current stage (see Figure 1).

Taking into account the classical definition of efficiency as the ratio between the result or effect of a weapon system (complex) performing a task and the costs involved, in this article the efficiency of a UAS will be understood as a comprehensive indicator (1) of multi-criteria optimization of a nonlinear compromise scheme [8].

$$E^{*}_{БпАК} = \arg \quad \max \begin{cases} P_{ураж}(t_n) & \rightarrow \quad \min; \\ R_{БпАК}(N_{ретр}) & \rightarrow \quad \max; \\ Rel(E_{випр},\ t_n) & \rightarrow \quad \max, \end{cases} \tag{1}$$

Its value depends on the probability of being hit, the combat radius, and survivability. Therefore, $E^{*}_{БпАК} \in [0;1]$ consider it as an integral parameter that reflects the optimal balance between resource expenditures $\{E_{випр}, N_{ретр}, t_n\}$ and the achieved operational results $\{P_{ураж}, R_{БпАК}, Rel\}$. In the case of multi-criteria evaluation of alternatives, it becomes necessary to obtain not only an analytical (quantitative) but also a qualitative assessment. For this purpose, the obtained UAS efficiency value must be normalized and compared with the normalized fundamental scale. The interval normalized scale of the indicator $E^{*}_{БпАК}$ is presented in Table 1, which show depends of its qualitative  and corresponding quantitative estimates (values).

*Table 1*

Interval-normalized efficiency scale of UAS

| Quality category | Intervals of the standardised fundamental scale | Degree of optimality (suboptimal / optimal) |
|---|---|---|
| Unsatisfactory | 0,0–0,2 | Suboptimal |
| Low | 0,2–0,4 | |
| Satisfactory | 0,4–0,5 | On the verge of uncertainty |
| Good | 0,5–0,7 | |
| High | 0,7–1,0 | Optimal |

To address the scientific task (see Figure 1), a structural and logical scheme of the research process was developed (Figure 2). This scheme makes it possible to systematize the content of each stage and the solution of partial tasks.

Let us briefly review all the stages. To solve the first partial task, it is necessary to analyze: the use of Class I UAS during combat operations; countermeasures against the enemy's use of such systems; methods for planning optimal UAS flight routes based on algorithms for solving the transportation problem; the use of aerial relays and methods for their routing.

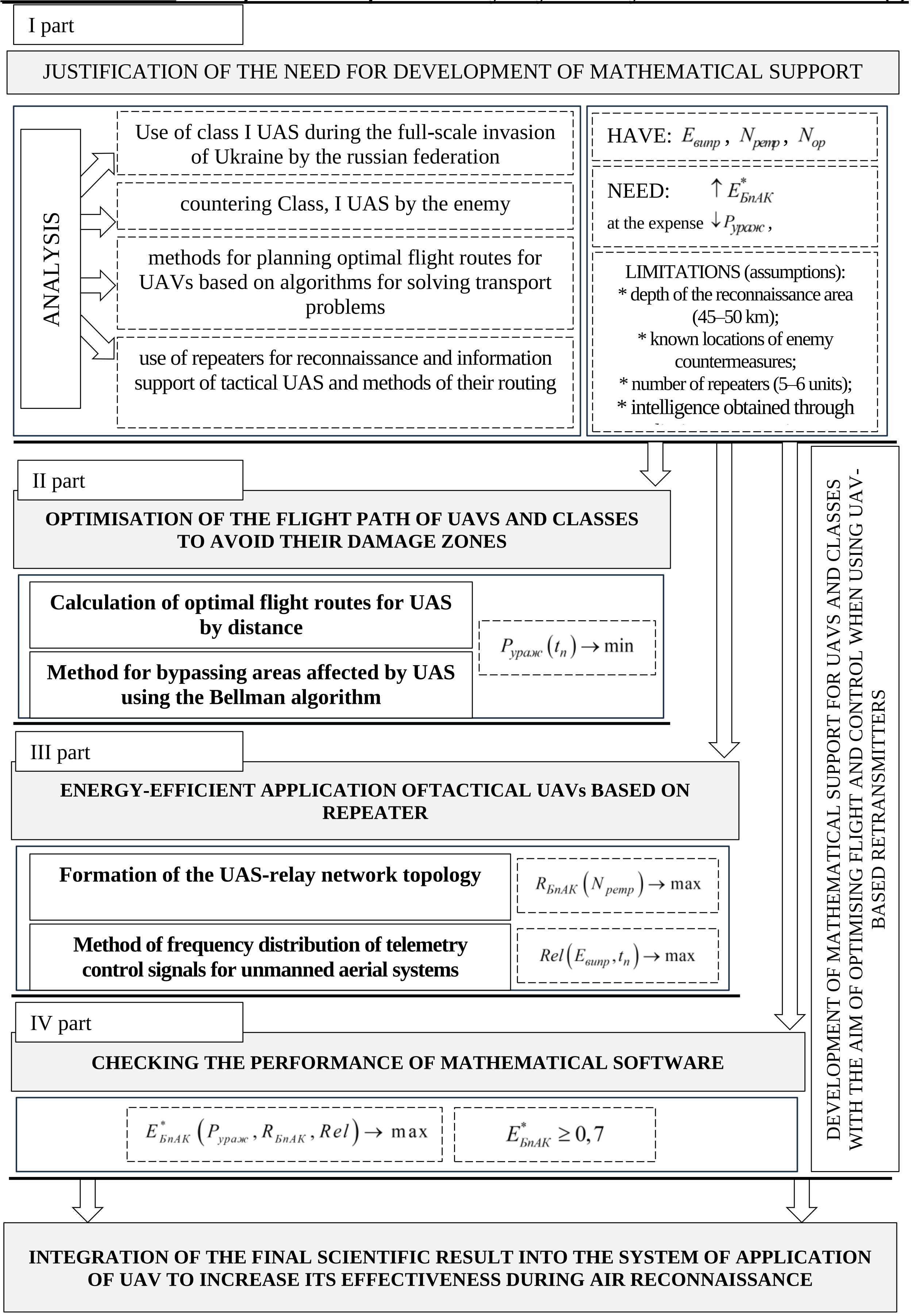
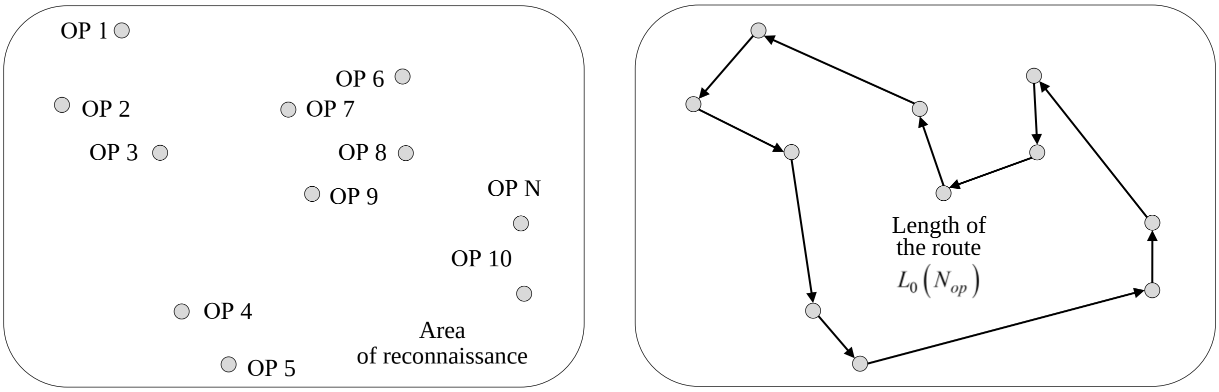



*Figure 2. Structural and logical diagram of the research*

The result of this stage is the justification and proof of the necessity of developing appropriate mathematical support, as well as the formulation of the research task.

The second subtask is the development of an optimization method for the flight route of the UAS (Unmanned aerial system), which will ensure a reduction in the probability of its destruction. Let's specify the sequence of its solution in detail.

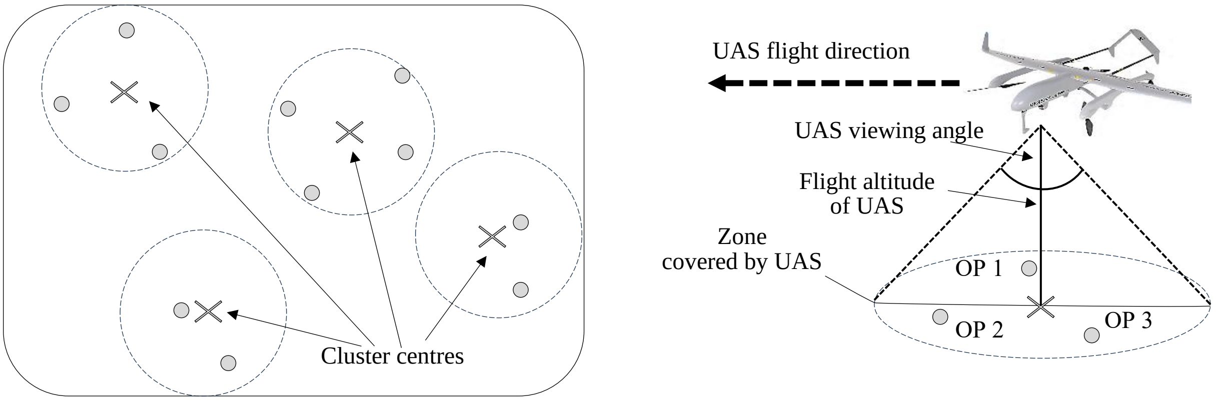
The input data are the operational route (OR) (see Fig. 3a), obtained during the previous monitoring. The optimal route is sought using a genetic algorithm, considering its advantages identified through analysis (see Figure 3b).




*а)* *б)*

*Figure 3. Route search using a genetic algorithm:*
*a) input data; b) result*

To optimize the route for the operational route (OR), clustering is performed based on the UAS's coverage zone metric (see Figure 4a), taking into account its flight altitude and viewing angle (see Figure 4b).

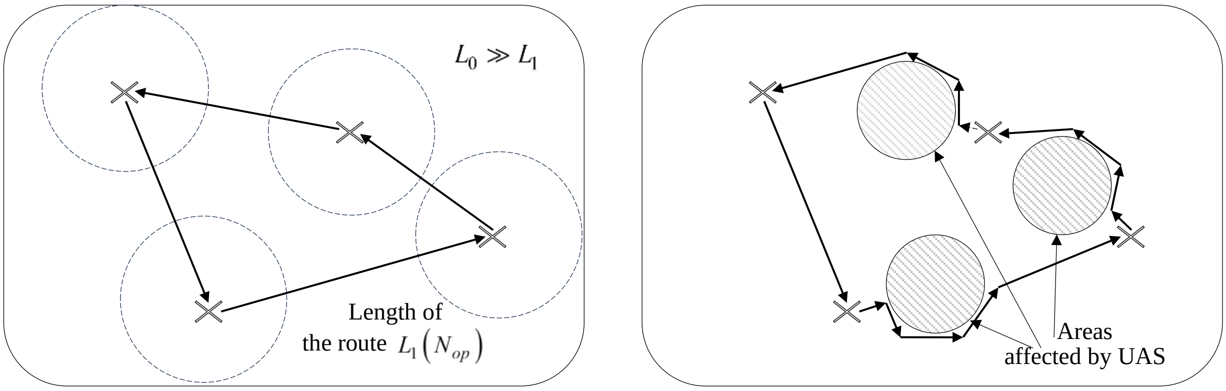



*a)* *b)*

*Figure 4. Clustering of the operational route (OR):*
*a) result; b) explanation of the concept*

Subsequently, the route search is conducted based on the centers of the obtained clusters (see Figure. 5a).

Based on the defined constraints and assumptions for executing the task, namely the availability of information regarding the locations of enemy countermeasures of the UAS (UAS defense means), as well as their tactical-technical characteristics, we identify the hazardous zones for performing the flight mission [9]. Under these conditions, a new flight route is plotted by circumventing these zones. The most effective solution in this case is to search for the optimal route using Bellman's algorithm (see Figure 5b).




*a)* *b)*

*Figure 5. Route search:*
*a) using a genetic algorithm based on cluster centers;*
*b) using Bellman's algorithm for circumventing attack zones*

The achieved result of solving this partial task—calculating the optimal flight routes for the UAS (Unmanned aerial system) using a genetic algorithm based on cluster centers, as well as circumventing attack zones—will significantly reduce the route length (flight time) and, consequently, lower the probability of the complex's destruction.

The next partial task involves energy-efficient deployment of tactical UAS, which includes forming the topology of the UAS-Repeater network (see Fig. 6) and developing a method for frequency distribution of control signals for the telemetry of the complex (see Figure 7).

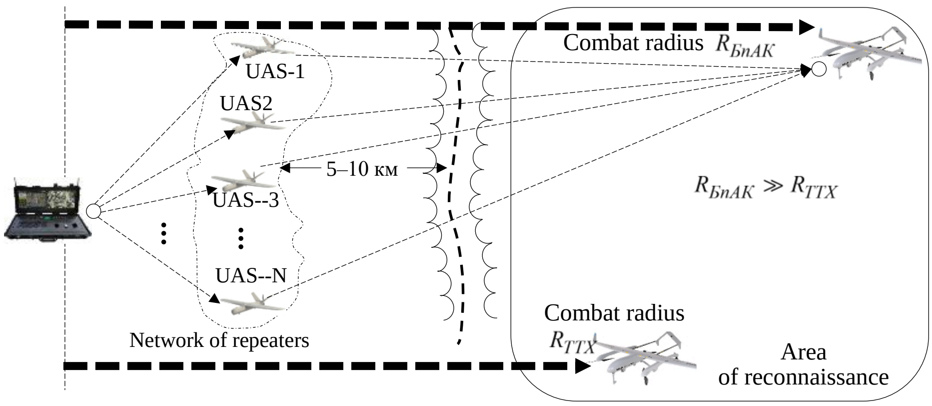



*Figure 6. Formation of the UAS-Repeater network topology*

The formation of the repeater network topology based on UAS is carried out to ensure reliable and efficient communication under complex terrain conditions, long distances, and active electronic countermeasures by the enemy. Utilizing this approach will significantly increase the combat radius compared to the tactical-technical characteristics of the complex.

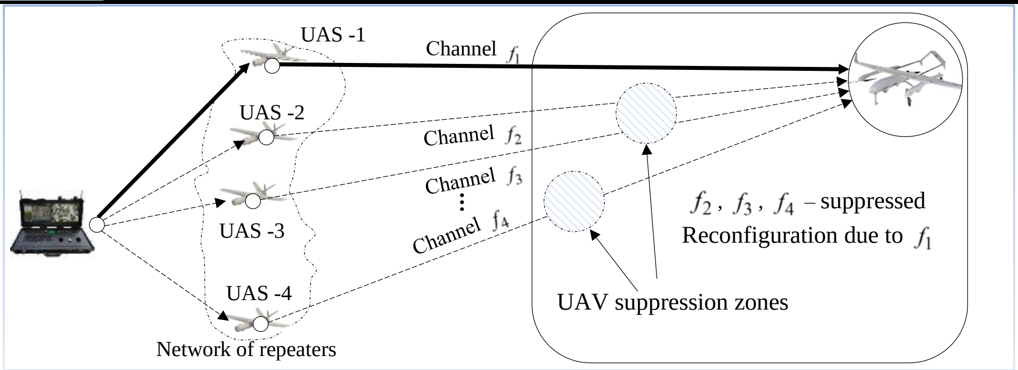



*Figure 7. Frequency distribution of UAS control signals*

Figure 7 illustrates a variant of the frequency distribution of UAS control signals. In the event of successful suppression of UAS $(f_2, f_3, ..., f_4)$ control frequencies by the enemy, the communication network "UAS – Repeater – Ground Control Station" is reconfigured using known routing algorithms and protocols. In this case, the closest and energy-accessible repeater to the reconnaissance UAS (UAS reconnaissance system) is UAS-1, with a communication channel operating at a frequency of $f_1$.

This approach allows for minimizing signal power, reducing energy consumption of the UAS-repeater and reconnaissance UAS, which in turn ensures increased survivability of the complex.

Thus, the scheme presented in this article demonstrates an effective approach to solving an important scientific task, which involves developing mathematical support for a first-class UAS reconnaissance system with route optimization and control during the use of UAS-based repeaters to enhance its effectiveness.

**Conclusions**

The article presents a formalized formulation of the scientific task of optimizing flight and control of a first-class UAS reconnaissance system during the use of UAS-based repeaters, which is modern, necessary, important, and practical.

To improve the efficiency of the UAS reconnaissance system, a mathematical support has been proposed, the structural and logical scheme of which includes solutions to the following partial tasks: optimization of the complex's flight route to circumvent attack zones, and energy-efficient application of the UAS reconnaissance system based on UAS repeaters. Further research will focus on developing the appropriate mathematical support to implement the scientific task outlined in this publication and achieve the corresponding objectives.

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