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Evaluation of Quality of Hidden Transmitters Detection by a Group of Coordinated Unmanned Aerial Vehicles on the basis of Entropy Decrease Dynamics

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ABSTRACT

The article investigates a problem of evaluating the quality of the hidden transmitters search by a group of unmanned aerial vehicles. Suggested method is based on the dynamics of reducing the entropy of the system. The main factors of influence are signs of the presence of a hidden transmitter in a certain sector of the territory, which can be detected by drone sensors. The reliability of the method is proved by modeling different scenarios of the system. It is shown that a system with full communication and control coordination is more efficient than a system that works according to the established search algorithm.

Key words : detection, entropy, evaluation, hidden transmitter, unmanned aerial vehicle.

1. INTRODUCTION

Today, unmanned aerial vehicles (UAVs) or drones are increasingly used to solve various problems. Their ability to move quickly, observe and transmit information and classify targets makes them indispensable in the protection of important infrastructure objects. UAVs are particularly effective when used as part of autonomous groups with centralized control. With this approach, the UAV team can monitor a specific area to find signs of suspicious behavior of potential attackers. One way for terrorists to do this is to monitor an important object using a variety of sensors and transmit information via radio. Since the search for a separate sensor in a large area is associated with the need to involve a large number of personnel and equipment, it is more appropriate to use groups of drones to intercept the radio transmissions of illegal transmitters with the subsequent identification of such devices.

1.1 Problem Statement

The main problem in the use of groups of drones is the coordination of individual UAVs, which should be aimed at maximizing the use of their capabilities in the coordinated work of individuals. The work of flying detectors is mostly not related to the signals themselves, but to individual signal features, which, taken together, will allow you to find the location of the hidden transmitter. In addition, the UAV cannot be in the air for a long time, so the efficiency and consistency of action between drones looking for a hidden transmitter is crucial. Therefore, in the case of UAV group use, the method of searching for hidden transmitters must take into account distributed nature of the group, dynamic of information environment changes over the search area, as well as the capabilities of the drone group control system.

1.2 Related Works Overview

In recent publications, in particular in the article of Il-Kyu Ha and You-Ze Cho [1] three main groups of search methods are mentioned: 1) search methods based on image analysis; 2) methods based on radiation analysis; 3) and probabilistic methods. Methods based on image analysis, such as Abdulla Al-Kaff et al. [2], are undoubtedly promising, but today are quite difficult to implement, as they require significant computing resources on UAV's board. Radiation analysis to search for suspicious objects is more complicated and less popular, so, it needs more in-depth consideration. An example of such a model is given in the publication of O. Laptev et al. [3]. In addition, Savchenko's publications [4] and [5] consider the possibility of weak signals passing through shielding surfaces. Probabilistic methods, such as Il-Kyu Ha and You-Ze Cho [1], are designed to work in an uncertain environment when a source of radiation is found that may not be in the search area. Thus, methods that combine the advantages of radiation search and probabilistic search are more effective for finding hidden transmitters.

A significant number of probabilistic search algorithms are embedded in the UAV motion model. Thus, in the article of O. Permyakov et al. [6] investigates a model of drone group motion for formation of a sertain structure with local self-coordination between agents. In articles of Chenxi Huang et al. [7] and P. Shchypansky et al. [8] the coordinated movement of drones to a specific object, which is given by the probability field is considered. The approach based on probabilistic fields is developed in the work of Steven R. Hansen [9] and is quite effective. As a continuation of the probabilistic approach is the method of potential fields (Changxin Huang [10]), in which each UAV moves along the field gradient.

Planning the work of a group of drones is impossible without the use of GIS (Geo-Information Systems) technologies. Thus, Joao Valente [11] presents a number of technologies for combining cartographic information with visual and probabilistic information from UAVs. This approach is most often considered on the basis of clustering the territory by dividing it into separate sectors, each of which is assigned the appropriate value of detection probability of the object, such as Alexander Fedorov [12] or Myungsoo Jun [13]. Clustering and division into sectors is used both to search for objects and to avoid collisions with other objects during the movement of UAVs, as in the article by Zhong Liu [14]. At the same time, UAV navigation can be provided by satellite radio navigation systems or alternative local navigation systems (Savchenko [15]).

Another feature of the application of the UAV group is the need for information exchange and prediction of the behavior of individual agents. The issues of modeling information exchange are considered in sufficient detail in the publication [16], and the method for predicting behavior in the publication [17]. At the same time, the influence of these factors on search efficiency requires additional research.

Obviously, the effectiveness of the search for hidden transmitters will strongly depend on the number of UAVs, the option of using the system (centralized or decentralized control, communication between individual drones, etc.). Therefore, the evaluation of the effectiveness of the search method should be considered on the basis of individual scenarios of their application. In this case as the main information can be a priori probabilities of transmitters in a particular sector, taking into account the parameters of the territory, because the more complex the terrain, the easier it is to hide both the sensor and the transmitter.

Thus, the scientific literature offers a large number of search methods based on individual features of the problem to be solved. At the same time, the choice of a particular method is determined by its quality, because the UAV has limited resources and cannot cover large areas during the flight. When looking for hidden transmitters, it is necessary to take into account their small size and erratic mode of operation, when the detection of such a transmitter will be carried out not by the direction of the signal itself, but only by concomitant factors. Such features include the characteristic insignificant traces on the ground which in themselves do not indicate the presence of the transmitter, but unambiguously identify it at their significant concentration in a certain area. Therefore, the task of a priori evaluation of the quality of search methods and conditions is relevant.

The purpose of the article is to develop a method for assessing the effectiveness of the search for hidden transmitters by a group of unmanned aerial vehicles and to study the results of modeling the system for individual typical situations of application.

2. METHODOLOGY FOR ASSESSING THE QUALITY OF UAV GROUP USE

To develop a methodology for evaluating the effectiveness of the group of search drones, it is necessary to introduce some assumptions:

1) to perform the task of finding hidden transmitters, a group of 3–6 drones is formed, one of which is determined by the group coordinator (Figure 1).

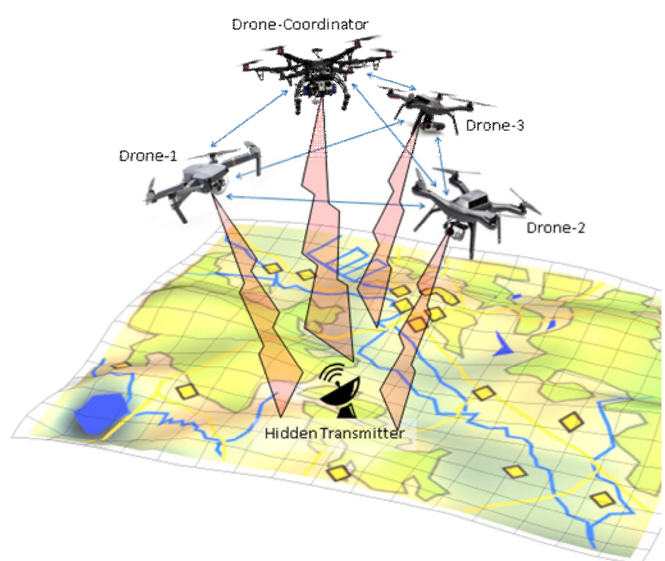

Figure 1: Coordinated group of drones

The task of search drones is to find the object of radiation (transmitter), or signs of its presence in a certain area and transmit this information to the drone coordinator. The task of the coordinating drone is to manage the activities of the search drones by redirecting them to those sectors where the object is most likely to be found. In addition, the drone coordinator has the opportunity to work as a regular search drone and communicate with the ground commander;

2) each drone has on board equipment for visual and radio scanning of the territory with recognition of the characteristic features of the transmitter;

3) each UAV has the ability to communicate with other UAVs on a separate channel, exchanging information about its location, detected objects (signs), and receive commands from the coordinator drone.

As a result of using the UAV group, the required amount of information is obtained, which a priori exists in the system. Therefore, the assessment of the quality of the drone group as a dynamic information system can be done by determining the dynamics of change in the entropy of the system over time to reduce it to a level that will make the necessary decision about the presence or absence of a hidden emitter.

The information field of the UAV group application is a set of separate elements (sectors) $R=\{R_i \mid i=1,...,n\}$, each of which can be estimated using the indicator of the impact on the search task (Figure 2). Another 7 – 10% of the territory will show signs of a hidden transmitter - that is, it can be detected by UAV direction finding. The rest of the territory will not have any characteristic features.

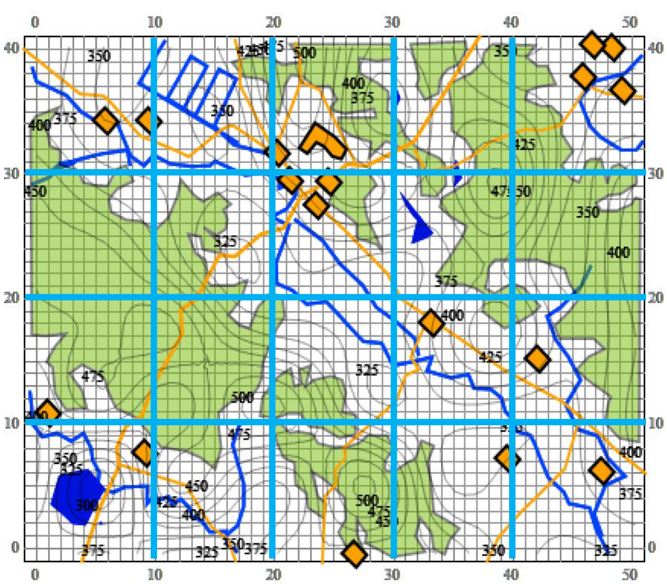

Figure 2: Information field of UAV group application

Therefore, each square of the district can be in one of three states with probabilities, respectively $p_1=0.02$ – the presence of the transmitter, $p_2=0.08$ – the presence of signs of the transmitter (signal direction), $p_3=0.9$ – the absence of the transmitter and its features. However, these probabilities do not take into account parameters of the area, which has a significant impact on the distribution of such squares on the territory.

To take into account the impact of the terrain, we will use the indicators of the impact of the territory $h_R \to [0,1]$, which, in essence, determine the information picture of the impact of the objects of the territory on the task of finding a transmitter. Under certain conditions, the value h_R can be interpreted as the probability of an event, which is the presence of a transmitter (or the ability to receive its signal) in a single square, taking into account the terrain. In this case, the value of the first-order entropy for one individual sector R can be determined as follows

$$H_1^R=-\left(\frac{\left(p_1+\frac{p_1}{p_1+p_2}h_R\right)}{2}log_2\frac{\left(p_1+\frac{p_1}{p_1+p_2}h_R\right)}{2}+\right.$$
$$+\frac{\left(p_2+\frac{p_2}{p_1+p_2}h_R\right)}{2}log_2\frac{\left(p_2+\frac{p_2}{p_1+p_2}h_R\right)}{2}+$$
$$\left.+\frac{\left(p_3+(1-h_R)\right)}{2}log_2\frac{\left(p_3+(1-h_R)\right)}{2}\right).$$

The essence of this approach is that instead of "pure" probabilities of the states of the sectors $p_i, i=1...n$, some average values of probabilities are taken, calculated on the basis of knowledge of the impact of the territory h_R in the appropriate ratios (Figure 3). The total entropy of the whole system will be the sum $H_1^S=\sum_R H_1^R$ of the entropies of all sectors. The entropy field (Figure 3) expresses the degree of assessment of the territory in terms of the possible location of hidden transmitters. In this case, the task of the UAV group in reconnaissance will be to reduce the entropy, especially in those areas where it is the greatest $H_1^R \to max$.

Thus, to determine the information picture of the territory as the main indicator of control by the UAV group, it is advisable to use the first-order entropy. Since the purpose of the UAV group is to obtain the required amount of information (entropy reduction), the total entropy of the system will be a monotonically decreasing function of time. The time required to decide on the presence or absence of a hidden transmitter will be defined as the period of time during which the entropy of the system will decrease to the required value.

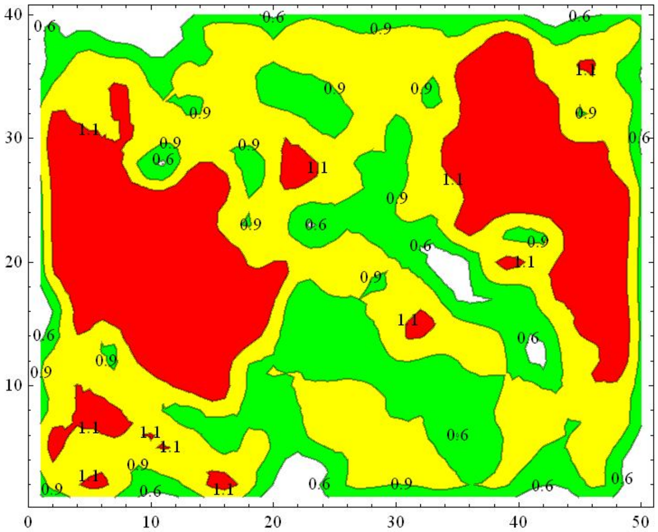

Figure 3: Distribution of the entropy field (*bits*) in the territory

3. RESEARCH OF QUALITY OF A GROUP OF UAVS APPLICATION BY RESULTS OF SIMULATION

In accordance with the proposed method of assessing the quality of the search, the purpose of simulation is to find the time dependences of the UAV group. For the computational experiment, an area 15x20 km of rugged terrain was selected (Figure 2), which is divided into 2000 squares (400x400 m), forming 20 control sectors. Four UAVs are searching in this area, one of which is endowed with coordination functions. Such approach allows the group to search for suspicious objects in a coordinated manner, as the drone coordinator is able to receive information about suspicious signs (weak radiation) from other members of the group and coordinate the work of the whole group based on this information.

The work of the model is as follows. Immediately after the launch of the drones, the drone coordinator analyzes the available information on the territory of the district and determines the sectors of the priority survey, after which it distributes the search drones into sectors. The drones are deployed to their sectors, where they are inspected, and they exchange information about the state of each sector both with each other and with the coordinator drone. The coordinating agent sends the received information to the head, who makes the decision. Depending on the conditions of a particular model, communication can be permanent, stochastic, or limited. The surveyed sector reduces its entropy to 0, while also reducing the total entropy of the system. The graph in Figure 4 shows one of the implementations of the search process.

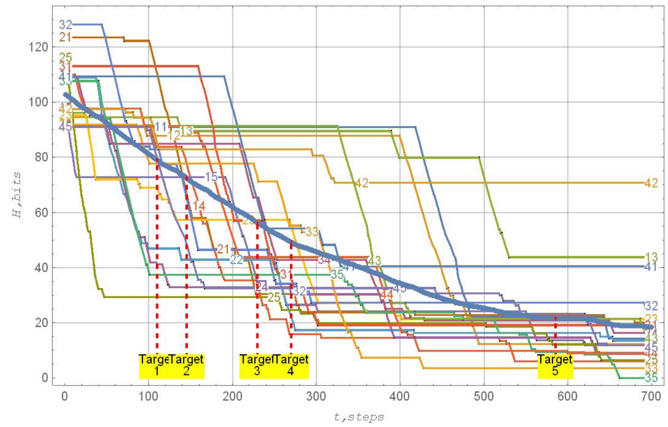

Figure 4: Dynamics of decreasing entropy for sector

In Figure 4 thin lines indicate the dynamics of decreasing entropy of each sector, bold line - the average entropy of the system, as the arithmetic mean entropy of all sectors. The moment of decision-making is considered to be the moment of target recognition (hidden transmitter).

To analyze the behavior of the system, we highlight the most typical scenarios that will determine the parameters of the simulation:

Scenario 1. Full connection with coordination. All drones in the system can exchange search results without hindrance. Messages are not distorted or lost.

Scenario 2. Stochastic connection with coordination. In the process of information exchange between search drones, messages may be lost. The probability of receiving a message depends on the distance between the agents. The probability of communication between the coordinator drone and the ground commander is assumed as 1.

Scenario 3. Limited connection with coordination. Search drones only communicate with the coordinating agent and do not exchange messages. The other parameters of the model are similar to scenarios 1 and 2.

Scenario 4. Full connection without coordination. Search drones operate according to their algorithms without receiving control messages from the coordinator drone. The coordinator drone operates as a search drone. Information to the supervisor comes from search drones. The other parameters of the model are similar to scenarios 1–3.

Scenario 5. Without communication and without coordination. Search drones operate autonomously and their movement is determined by the underlying motion algorithms. The results of the search drones are transmitted directly to the manager.

Additionally, in order to compare the proposed models with existing control systems, three more were added to the identified situations, which are based on the model of the first scenario, but taking into account the possibility of death of search drones. Such situations may arise in the case of the use of "non-intelligent" models: search by specific sectors (spatial distribution of drones). These situations differ only in the probability of death of drones in the event of a direct hit in the sector occupied by the transmitter.

Scenario 6. Search by sectors with 1% death. In case of hitting the target sector the drone loses its ability to work with a probability of 0.01.

Scenario 7. Search by sectors with 5% death. Similar to scenario 6, the ability to work is lost with probability of 0.05.

Scenario 8. Search by sectors with 10% death. Similar to scenario 6, the ability to work is lost with probability of 0.1.

The simulation determines the main parameters by which the quality of decision-making is assessed: the number of recognized targets (the target can be recognized by the manager as a result of accumulation of sufficient information from search agents) and the recognition time of a given number of targets (1 to 6). The maximum number of targets is 6. The maximum number of simulation steps is limited to 700 steps.

The simulation results are given in Table 1. Analyzing the simulation results, we can see that the most effective in terms of the number of defined targets and search time is scenario 1, which reflects the ideal case when agents are in full contact with each other and their work is coordinated by the coordinator drone. The first target was identified in step 105, and all 6 targets were identified in 351 steps of the system. The worst case in a coordinated system is in the absence of communication between search agents (scenario 3), when the first target is searched in 120 steps, and for six purposes it is necessary to perform 485 steps of the system.

Table 1: Average values of the number of targets and moments of targeting (steps) depending on the parameters of the models

№	Simulation parameters	Average number of targets	The average search time (steps) for a given number of targets					
			1	2	3	4	5	6
1.	Full connection with coordination	5,68	105	135	182	238	294	351
2.	Stochastic connection with coordination	4,96	118	148	199	259	323	397
3.	Limited connection with coordination	4,28	120	156	221	300	387	485
4.	Full connection without coordination	4,04	137	180	251	340	456	596
5.	Without communication and without coordination	3,20	266	321	384	455	528	–
6.	Search by sectors with 1% death	5,28	117	159	231	320	412	552
7.	Search by sectors with 5% death	4,35	143	194	265	358	460	632
8.	Search by sectors with 10% death	3,44	162	218	312	434	580	–

In the case of a system without coordination (scenarios 4 and 5) to find the first target requires 137 and 266 steps respectively, for a fully connected system and a system without communication, and for six targets requires 596 steps in the case of full communication and more than 700 steps in case of no connection. These values emphasize the importance of ensuring the connectivity of its individual elements (drones) and the importance of managing drones, which in themselves do not have general information, but act situationally, depending on the conditions around them.

To compare the UAV group search method with traditional control systems, let's consider scenarios 6 - 8, which simulate traditional approaches to managing groups of objects, the main of which is to determine each agent a certain sector of responsibility without further situational control. In this case, the drone will not be able to recognize the target and may find itself in a situation that will lead to its death.

The death of one drone means that the other drones must take more steps to reduce the entropy of the system, which will generally increase the search time. Thus, with the probabilities of death of 0.01, 0.05 and 0.1, the time to find the first target will be 117, 143 and 162 steps, respectively, and the search for all targets will be 552, 632 and more than 700 steps, respectively. So, as we can see, the multi-agent approach with communication and coordination is more effective than traditional methods of UAV group control.

To determine the quantitative characteristics of the efficiency of the developed system, consider the dynamics of changes in the average entropy of sectors in different situations. Figure 5 shows graphs of changes in the average entropy of sectors for situations from 1 to 8 and, in addition, shows the situation of "ideal search" (№ 9), which shows the option when drones systematically survey a given area without any idea of search objects and without using available information about the area.

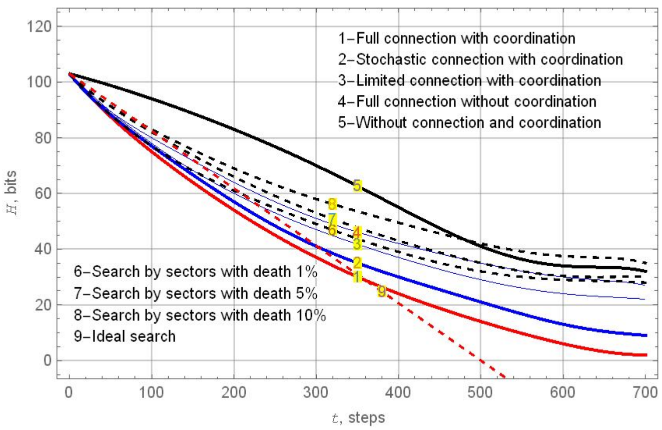

Figure 5: Comparison of entropy change by scenarios 1 – 9

The best results are still observed in scenario 1 – full connection with coordination, and the worst in situation 5 – without connection and without coordination. The difference in the dynamics of entropy change of these two scenarios can be estimated as the difference between the areas of the figures bounded by the abscissas of the start time (t_0 = 0) and the end time ($t_{\max}$ = 700) of the operation, and by the ordinates – curves 5 and 1.

As a result of calculations under the given conditions we receive value $E_1^5(t_0, t_{max}) = 41{,}6\%$. That is, the introduction of mechanisms of information exchange and coordination (intellectualization of information support) in the system increases its efficiency by 41.6%.

Comparing similar situations 1 and 9, we can see that in the initial stages of the search, the developed system gives an increase in efficiency of 8.56%, however, starting from step 360, the ideal search has the advantage that in 500 steps 4 agents could completely inspect 2,000 squares. However, in this case, the drones would be forced to explore the sectors with targets, which would inevitably lead to the possibility of their death, which in the "ideal" case is not allowed. That is, the two ideal cases almost compensate for each other over long periods of time.

However, to get a real picture of efficiency, it is necessary to compare more realistic scenarios. Comparative estimates for scenarios 2, 6, 7, 8 indicate an increase in efficiency for the following options, respectively: $E_2^8(t_0, t_{max}) = 28{,}1\%$; $E_2^7(t_0, t_{max}) = 21{,}8\%$; $E_2^6(t_0, t_{max}) = 16{,}5\%$. That is, depending on the chosen application, the use of a coordinated group of UAVs can improve the efficiency of decision-making time by 16 – 28%.

Also, it can be seen that efficiency estimates were obtained for the maximum simulation time periods. For practical evaluation, it is more interesting to know the dependence of efficiency on the operating time of the system. By modeling the dependence of functions $E_1^5, E_1^9, E_2^8, E_2^7, E_2^6$ on a period of time $[0,700]$, we obtain Figure 6, which shows that with increasing application time, the efficiency of the system increases monotonically, except for the comparison of two "ideal" situations 9 and 1, which, in fact, reflect the limit cases of the study.

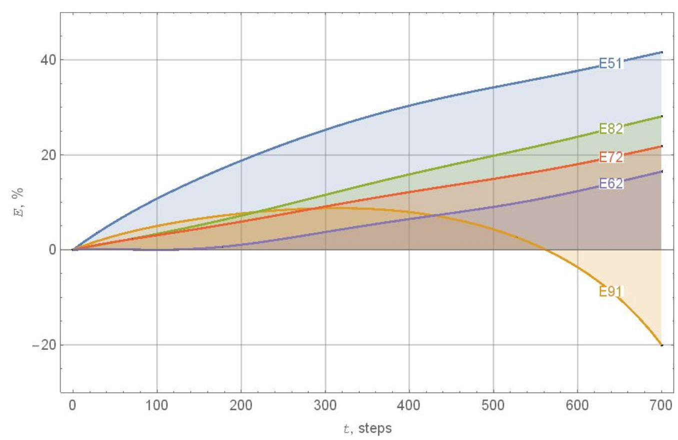

Figure 6: Dependence of efficiency on system operation time

4. CONCLUSION

Thus, the proposed method for assessing the quality of UAV search for hidden emitters based on the calculation of the dynamics of entropy reduction of the system allows to quantify the main parameters of the system (quality and efficiency of search) and indicates the possibility of implementing a multiagent approach to build promising automated systems on UAV base.

The results of modeling the application of the system in different situations confirm the basic laws of control in distributed systems and show the importance of communication and coordination between individual drones. Thus, with reliable communication and coordination, the efficiency of the search system increases by 40 – 42% compared to the uncoordinated actions of the UAV group.

The direction of further research in this area may be a wide range of issues to assess the effectiveness of the UAV groups in different scenarios of hidden transmitters.

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