On how to model and investigate the interaction of mobile network nodes with a limited number of mobile access points

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Abstract. This paper investigates a new way to position unmanned aerial vehicles, that act as routers, to allow subscribers to access a communication network. In my model, the subscribers move along known trajectories in sparsely populated areas. To solve this problem, I developed a software to simulate how the subscribers move. I also developed an optimization algorithm that maximizes my custom objective function, where the function sums the probabilities for the subscribers to access the network.

Introduction. One of the modern and very promising technologies to provide communication for subscribers or groups of subscribers in sparsely populated areas are unmanned aerial vehicles (UAVs). These vehicles act as access points and routers in the communication network; the network devices and battery power supplies are attached to the drone's body [1,2,3]. This allows you to very quickly deploy a communication network in almost any conditions. The advantages of this method include ease of organization, independence from the landscape, the ability to flexibly adapt to route changes and high mobility. It should be noted that this method also has a number of significant drawbacks: the high cost of devices, limited UAV carrying capacity, limited battery capacity and operating time, sensitivity to weather conditions, and navigation complexity. Limitations on the weight and size of the network devices require low-power, short-range versions of them. We can partially compensate for this disadvantage, if we quickly position the network devices.

Due to these features, the UAV-equipped network often covers the operational territory only partially. When we deal with incompletely covered territory, the network devices interfere less with each other since they are far apart from each other. It becomes more important to correctly position the access points. The areas where the subscribers concentrate most are prioritized (binding to traffic) to provide communication in any key points. One can solve this problem by different means. We need significant investments of time and money to develop such models for a specific task, to conduct research and measurements on the ground, to obtain the testing equipment, etc. The experience with such problems can be used to model rapid deployment networks. The listed tasks have a number of common features: how to use wireless technologies, to count the subscriber mobility, to place the access points, to bind the movement trajectory. We need a universal tool to quickly model and evaluate the efficiency of a rapidly deployed network, to take into account the peculiarities of each specific task. These tasks become really pressing in an emergency and we need to quickly adapt to different conditions [4,5,6].
Let us list the main features of the tasks to design rapidly deployable networks and distinguish the tasks from other wireless network design tasks:

- complexity and variety of functioning conditions;
- high requirements for equipment reliability;
- relatively small number of users and their low density;
- limited number of network equipment;
- long distances between subscribers and devices;
- unstable network coverage;
- tests are complex to formalize;
- great variety and influence of individual conditions;
- different requirements and quality criteria.

In addition to the listed tasks, related to the organization of communication networks, there is also a complex task to control the UAVs. The main ways to control the UAVs are as follows: an operator fully manually controls the UAV, the UAV moves along a pre-planned route, the UAV is semi-automatically controlled, for example, automatically takes-off and lands on command from a ground post, the UAV moves to a given target, the UAV uses intelligent control systems to perform assigned tasks, etc. For more details on the control methods, see [7, 8].

1. Problem statement

In this paper, we propose a method for finding the optimal route for UAV movement in order to provide communication to subscribers traveling along a known route at a known speed. When the number of devices is greater or equal to the number of subscribers, the solution to the problem is trivial — drones follow the subscribers. If there is a shortage of sets of network equipment based on UAVs, the solution is no longer obvious [9,10,11].

Moving drones along the routes calculated by the program can be dangerous due to the appearance of obstacles unknown to the system. This control may be appropriate when working in an open area where the probability of obstacles is very low. Or you can use the results of the simulation as recommendations, complementing them with known navigation methods.

It is assumed that the operational drones can communicate with the control center from any point on the route. Various network architectures using UAVs are possible, and their consideration is beyond the scope of this article [12, 13, 14].

To set the problem and build the model, we take into account how a tourist (or a rescuer) group moves along routes in mountainous areas. This choice was made in connection with the actual tasks of providing communication during various events in non-populated mountain areas, for example, for organizing the movement of tourist groups, providing communication for rescue expeditions, etc.

The essence of the proposed solution is to create a special software module that allows you to simulate the movement of subscribers along routes in a known area and use an algorithm to find optimal routes for network devices. Before launching the UAV or to adjust the route, the initial data is set, based on them, a simulation model of the movement of subscribers in the area is created, the optimization algorithm searches for the recommended position of the drone at each moment of time, and tables of results are formed based on the simulation.

Let us formulate the problem to be solved. The terrain is defined as a surface in Cartesian coordinates with dimensions $x_0$ by $y_0$ by $z_0$. On the orthogonal projection of the surface on the horizontal plane, $k$ routes of subscribers are set as segments defined by two points. For each subscriber, the movement speed $v_j$, $j \in [1, k]$ is set constant relative to the plane. Subscribers move cyclically from the first point to the second and back. There are $n$ UAVS with a radius of action $R_i$, $i \in [1, n]$. We need to find an UAV route $(x_i(t), y_i(t))$ to provide the highest possible level of access for all subscribers during the period of time $T$. This time may be during daylight, or when the drones operate without recharging. We also need to place the network equipment to ensure the maximum level of network availability for the subscribers.
The probability of access of the j-th subscriber to the i-th UAV at time t is given as follows:

\[ p_{ij} = e^{-d_{ij}^2}, \quad d_{ij} = (x(t)_j - x(t)_i)^2 + (y(t)_j - y(t)_i)^2, \]  

(1)

where \( x(t)_j \) and \( y(t)_j \) are the coordinates of the j-th subscriber at time t.

Choosing an objective function under these conditions is a non-trivial task. One possible solution is to use the average probability of access to the subscriber network at time t. But this approach has a number of disadvantages:

1) if the subscriber is close to the network device, the possibility to access the network will be equal to 1, and, from the simulation point of view, it would not make sense to block access to the areas of different network devices, but in practice there are many additional parameters in the model that we do not take into account. Real values of probability will be lower and the overlap areas may be useful.

2) Based on the practical goals and features of a specific task, additional weight factors can be added to the target function, for example, the priority of subscribers or time intervals, when it is particularly important to communicate. When we use access probability, we don’t add coefficients.

Taking into account the above-mentioned features, the target function was chosen as a composite indicator \( w \), the value of which affects both the reliability of the network and the probability of subscriber access to it. The obtained probability values are summed for each of the subscribers and for each access point. In other words, if one subscriber can connect to three access points at once, all three values will be taken into account in the calculation:

\[ w = \sum_{i=1}^{n} \sum_{j=1}^{k} p_{ij}, \]  

(2)

where \( n \) is the number of access points, \( k \) is the number of subscribers, and \( p_{ij} \) is the probability of j-th subscriber accessing the i-th access point. The value of this indicator does not have an explicit physical interpretation, but it makes it possible to compare different options. Testing the model using this target function has revealed the following drawback: it is effective to move all unmanned aerial vehicles along the same route when the network access areas are completely blocked, but this clearly contradicts the practical significance. To eliminate this drawback, another function was added to the model to push network devices away from each other. Its parameters are selected empirically. They are not taken into account when we calculate the values of the target function, but they affect the movement of the network device attached to the UAV. A graphical representation of the program is shown in Fig. 1-2.
2. Description of the program.

The terrain is depicted using a gradient transition from green in the lowlands to red at higher elevations. The trajectories where the subscribers move are indicated by segments, subscribers – by points on the segments, access points – by circles with a point in the center. Fig. 1 indicates the start of the simulation, Fig. 2 – some time after the simulation starts. When we start the simulation, subscribers move from the starting points of the route, where the points are set in the configuration file, and UAVS start from a certain limited area, also set in the settings. This may be the operation headquarters, for example. When subscribers move, the access points continue to move along their path to places, where there is the highest possible level of communication. Terrain tracking in the system allows you to select coordinates along the z axis. When testing the algorithm, an automatically generated terrain with known heights was used. To construct a relief based on topographic maps is a separate problem that undoubtedly requires a solution.

For clarity and convenience of studying the proposed configurations, a three-dimensional representation is implemented with the ability to rotate the image and change the angle of inclination (Fig. 3).

After performing the simulation, the user receives recommended travel routes for communication nodes attached to the UAV and information about the level of communication provided at any time for each of the subscribers. In addition to the graphical representation of the model, data tables that are compatible for processing with table processors are used to analyze the results obtained. The results are displayed as a list of time values and coordinates of UAV placement. It is possible to display both two and three coordinates. The expediency of setting the height of the UAV placement based on modeling is controversial, since the real terrain is planned to be set in the program using a map that clearly does not show any buildings, trees, or other obstacles. In this regard, it may be safer to use laser or other sensors to determine the required height. A fragment of the table with data records is shown in Table 1. The table contains the record number, the simulation time, the coordinates of all subscribers (these data are not the result of modeling and are directly calculated from the initial conditions, but are necessary for interpreting the results), the coordinates of all unmanned aerial vehicles, the access level provided to each subscriber at the time under consideration, and the distance to the nearest access point. The simulation time is specified in the software, but it is synchronized with the real time of the subscribers movement by the speed of their movement.
### Table 1. Information about simulation results

| n | Time | People Coords | Node Coords | Signal Power | Dist To Nearest Node |
|---|------|---------------|-------------|-------------|----------------------|
|   |      | Person 0     | Person 1    | Person 2    | Node 0  | Node 1  | Pers 0 | Pers 1 | Pers 2 | Pers 0 | Pers 1 | Pers 2 |
| 0 | 0.00 | 500; 000;    | 200; 000;   | 1000;       | 1213;   | 2325;   | 1,351 | 1,593 | 1,079 | 401   | 548   | 687   |
| 1 | 1.06 | 569; 1059;   | 1116; 235;  | 701; 799;   | 1287;   | 1836;   | 1,868 | 1,481 | 1,611 | 368   | 595   | 559   |
| 2 | 2.04 | 1634; 1113;  | 1224; 1449; | 710; 907;   | 1283;   | 1855;   | 1,86 | 1,3487| 1,572 | 403   | 673   | 741   |
| 3 | 3.03 | 1698; 1168;  | 1333; 1666; | 731; 1183;  | 1283;   | 1842;   | 1,869| 1,19  | 1,632 | 444   | 911   | 702   |

3. Interpretation of the results.

If the modeling time is long, the tabular representation of the obtained data is too large to be presented in the article and can be difficult to interpret. Based on the obtained data, you can form more visual representations, as, for example, in Fig. 4. The graph shows straight-line routes of movement of subscribers and the curved trajectory of the UAV. At first glance, it may seem that a given cyclical movement of subscribers along the routes back and forth will lead to periodization of the UAV movement, but this does not happen over a practically significant time interval due to the difference between the speeds and routes of subscribers. The developed functionality of the program provides the ability to set curved routes in the form of several segments, priorities of subscribers, restrictions on the maximum speed of UAV movement, requirements for their return to the base for charging after a certain time interval, and other restrictions necessary for solving specific practical problems. At the moment, setting these limits is only possible by upgrading the program code and requires knowledge of the system.

![Fig. 4. Trajectories of the network devices placed on the UAVs](image)

In the graph above, it is convenient to analyze the UAV trajectories proposed by the system, but it is not clear what level of access is provided and at what time intervals stable communication sessions
are possible for subscribers. For these purposes, it is convenient to use the graph of the network access level versus time (Fig 5). Values higher than one mean that the subscriber is located within the access radius of at least two network devices and the probability of stable communication is higher, even taking into account the influence of a large number of factors not accounted for by the system. When analyzing this schedule, you can select the optimal hours for communication sessions for each of the subscribers, and decide whether to use such a network in these conditions. If most of the time the level of access to the network for most subscribers is significantly lower than one, this may mean that it is pointless to organize the network in these conditions and, for example, it is necessary to attract additional equipment.

![Fig. 5. The signal level vs time for the subscribers](image)

The advantage of the proposed method is ease of use, low computing power and, consequently, high speed of the system, visual interface, and the ability to flexibly configure the system for real-world conditions. You can also enter additional parameters, such as subscriber priorities and additional fixed access points. The absence of the need to read and process information from UAV sensors and cameras in real time is also an advantage of this method. It should be noted that the presented system has a number of significant drawbacks. First of all, the uncertain accuracy of the results obtained, i.e. the quality of the optimization algorithm depends on the performance of the device used and the speed of modeling, there is no ready-made tool and an unambiguous decision on how to measure the quality of the proposed solution. It is possible to partially compensate for this disadvantage by saving the route of the movement and then iterating it in search of the best solution. Another disadvantage is the primitive and poorly functional user interface, the need to manually set a large amount of source data, the complexity of working with the program, and the need for additional processing of the received data. The user interface is limited to viewing configurations in 2d or 3d views and displaying result tables. The graphs shown in the article are generated by transferring data to a table processor. We set the settings and enter the input data via the configuration file (JSON format); this procedure requires experience and qualifications. The interface is expected to be improved.

To be able to use the system in practice, it is necessary to implement the possibility of reading and using existing topographic maps to read the terrain and software implementation of taking into account the features of the terrain during signal propagation.
The software application was developed in the Microsoft visual studio environment in C++. One of the areas of practical application of the described type of networks is search and rescue, research or sports events held in mountainous areas. Due to the terrain features, the population density in such areas is very low, which makes it impractical to install cell towers that are sufficient to cover the territory with a mobile network and Internet access. The developed software product is focused on rapid assessment of the network usage capability in specific conditions, which will allow for more frequent and efficient use of rapid deployment wireless networks. This will reduce the number of events that are not connected, and improve communication and coordination between participants, as well as between participants and rescue services and, if necessary, experts. All of the above will reduce the time needed to deal with the consequences of emergencies in sparsely populated areas and improve the safety of events [15, 16].

Conclusion
In this report, the author presented a new method to find optimal routes that mobile UAV-equipped teams can utilize. The author has shown how relevant this problem is and presented the examples of how to use the program. Finally, the model and the results were analyzed. The proposed solution can be used to organize a communication network in sparsely populated areas with complex terrain. The results obtained are of practical and scientific significance, but the task is not completely solved. To be used in real-world problems, further research is required: we need to find methods to verify the correctness of results and guaranteed quality of the solution, to develop a module to analyze how signals propagate depending on the terrain, to add the ability to read maps for terrain formation, to expand the number of factors taken into account, and to update the user interface. The results obtained can be adapted to other tasks, such as monitoring moving objects, organizing security systems, etc.

References

[1] Chertova O G and Chirov D S 2019 Building a reference communication network based on small-sized unmanned aerial vehicles with no ground infrastructure // Science-intensive technologies in space research of the earth. No. 3. pp. 60-70.

[2] Melnikov A V, Gaidai V A and Rogozin E A 2017 Construction of the optimal flight path of an unmanned aerial vehicle when performing the search task //Bulletin of the Voronezh institute of the ministry of internal affairs of Russia, no. 1, pp. 351-55.

[3] Dinh Ch Z and Kirichek R V 2017 Approaches to the organization of mobile heterogeneous gateways based on unmanned aerial vehicles //Actual problems of infotelecommunications in science and education (apino 2017) pp. 260-65.

[4] Ivanov R E, Mukhtarov A A and Pershin O Yu 2019 The problem of optimal placement of a given set of base stations of a wireless communication network with a linear topology

[5] Tsarev F N 2008 Joint application of genetic programming, finite state machines and artificial neural networks for building a control system for an unmanned aerial vehicle // Scientific and technical bulletin of information technologies, mechanics and optics. No. 53.

[6] Andrusenko J, Kas W T and Ward J R 2009 Modeling of wireless networks and modeling tools for developers and developers //Journal of IEEE communications magazine. t.47. No.3. pp.120-27.

[7] Budimir D and Shelkovnikov B N 2001 Cad for designing broadband wireless access // 5th int. conf. on telecommunications in modern satellite, cable and radio broadcasting service. Telsiks 2001. Collection of scientific papers (cat. No. 01ex517). - IEEE, - vol. 2. - pp. 525-28.

[8] Ivanova I A, Nikonov V V and Tsareva A A 2014 Ways to organize the management of unmanned aerial vehicles //Actual problems of humanities and natural sciences. No. 11-1. – pp. 56-63.

[9] Blinova O V, Vaskovsky S V and Farkhadow M P 2018 Evaluation of the reliability of the communication system with mobile nodes. // Sensors and systems. 2018. No. 5. pp. 3-8.

[10] Blinova O V, Vaskovsky S V and Farkhadow M P 2017 The relationship of mobile
subscribers and stationary communication nodes with known traffic characteristics // Sensors and systems. 2017. No. 3. pp. 3-8.

[11] Blinova O V, Vaskovsky S V, Vorontsov Yu A and Farkhadov M P 2015 Information system with mobile communication nodes // Sensors and systems. No. 12 (198). pp. 24-28.

[12] Down R and Scheinert S 2006 Internet base station: pat. 7117015 USA.

[13] Hannikainen M, Hamalainen T D and Vanhatupa T 2007 Genetic algorithm for optimizing node placement and configuration for wlan planning // 4th int. symp. on wireless communication systems. IEEE, 2007. - pp. 612-16.

[14] Kaspryk M Z and Otto K 2013 Wireless communication device for emergency situations: application pat. 13708911 USA.

[15] Balitsky V S, Kaverny AV, Krivenkov M V, Korvyakov P V, Lazutin V A, Okorokov Yu A and Vergelis N I 2010 Mobile video monitoring and communication station.

[16] Dalmasso I, Galletti I, Giuliano R and Mazzeng F 2012 Wimax networks for emergency management based on unmanned aerial vehicles IEEE First AESS European conf. on satellite telecommunications (ESTEL). – IEEE, 2012. – pp. 1-6