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ORIGINAL PAPER

Selection of Routing Metrics and Service Channel Characteristics of ad hoc Network for UAV swarm

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ABSTRACT

Swarm technologies for unmanned aerial vehicles (UAV), which represent a qualitatively new level of robotics development, can significantly increase the efficiency of using drones. From the point of view of organizing communications, such a swarm is an ad hoc network, the nodes of which are UAV. A characteristic feature of this network is the frequent change in the network structure due to changes in the position of UAV in space, necessitating the use of dynamic routing protocols when transmitting information within the swarm. This article is devoted to the study of the behavior of a self-organizing radio network, which uses various variants of the algorithm for finding the shortest route distance with reference to the constantly changing network topology. An analysis of the behavior of such a network was carried out using various options for routing metrics: node metrics, characterizing the state of network nodes, and channel metrics, characterizing the state of communication channels between nodes. Particular attention is paid to the impact on network characteristics, primarily the average packet transmission time from source to recipient, the composition of routing metrics, service channel parameters, traffic intensity, and energy parameters of communication channels. The results from modeling allowed drawing conclusions about the feasibility of using various methods for organizing a service channel depending on the volume of transmitted routing information and evaluating the influence of routing metrics on the characteristics of the network in a stationary state and in the process of changing its structure. The approach proposed by the authors for assessing the efficiency of routing in a self-organizing network is applicable not only to UAV, but can be adapted for other unmanned vehicles (ground, surface, underwater) taking into account the peculiarities of their functioning and the propagation of radio waves.

Keywords: Unmanned aerial vehicle; Swarm; Routing metrics; Ad hoc network; FANET; Service channel; Signal-to-noise ratio; Adjacency matrix.

INTRODUCTION

Unmanned aerial vehicles (UAV) have found widespread use in the civilian sector, from light displays to monitoring industrial facilities and conducting search and rescue operations (Arkin 2015; Kostin and Bogatov 2019; Sivakumar and Tyj 2021). In the last decade, swarm technologies have been actively developed: combining UAV into groups ("swarm") to perform a common operational task, for example, monitoring the condition of critical infrastructure facilities. A UAV swarm is an ad hoc network that supports a dynamically changing network configuration (Phadke and Medrano 2022; Ragab *et al.* 2021). In the scientific and technical literature, such networks are called flying ad hoc network (FANET) (Bekmezci *et al.* 2013; Elfaham *et al.* 2016; Sahingoz 2014), so, in the future we will use this abbreviation in relation to UAV swarm communication network. Table 1 shows a comparative evaluation of FANET with similar self-organizing networks with other mobile subscribers: mobile ad hoc network (MANET) and vehicular ad hoc network (VANET) (Tareque *et al.* 2015).

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Table 1. Comparative evaluation of FANET, VANET, and MANET.

Criteria	Ad hoc network types		
	FANET	VANET	MANET
Node mobility	High compactness	Medium compactness	Low compactness
Mobility model	Usually predetermined but special mobility models for independent multi-UAV systems	Steady	Arbitrary
Node density	Low thickness	Medium thickness	Low thickness
Topology change	Rapid and speedy	Average speedy	Slow and steady
Radio propagation model	High above the ground level, LoS is accessible for most of the cases	Close to ground, LoS is now accessible for all cases	Very close to ground, LoS is not accessible for all cases
Power consumption and network lifetime	Needed for mini-UAV, but now needed for small UAV	Not needed	Need of energy efficient protocols
Computational power	Very big	Average	Limited
Localization	GPS, AGPS, DGPS, IMU	GPS, AGPS, DGPS	GPS

Source: Elaborated by the authors. LoS = line of sight.

There are various approaches to solving the problem of constructing FANET, for example, networks of UAV (Bok and Tuchelmann 2011), distributed aerial sensor networks (Rohde *et al.* 2010), UAV ad hoc networks (Cai *et al.* 2013), unmanned aeronautical ad hoc networks (Shirani *et al.* 2012), and others (Sahingoz 2013). One of the current challenges of swarm technology is the development of routing protocols that quickly adapt to frequent and unpredictable changes in the network topology. The success of solving this problem largely depends on the choice of a set of routing metrics: parameters on the basis of which the route is selected. In relation to radio networks, in addition to the main metric (signal power), and others ones are also used: channel load, noise level, and others (Borges *et al.* 2009; Campista *et al.* 2008; Elshaikh *et al.* 2012; Wang *et al.* 2021).

There is a large number of publications in the scientific and technical literature devoted to the development of routing protocols in self-organizing networks; a detailed review of which is given in Leonov (2017). Recently, many new approaches to solving these problems have appeared. For example, in Madridano *et al.* (2020), the issues of adapting UAV swarm to changes in environmental conditions or technical malfunctions of individual members of the swarm are considered. The work of Li *et al.* (2019) describes a method for planning the route of a swarm of UAV with implementation on the robot operating system (ROS) platform. Issues of planning UAV routes using the Deep-Sarsa algorithm, built on the basis of a neural network and allowing building a route avoiding obstacles, are considered in Luo *et al.* (2018), Małecki *et al.* (2021), and Wu *et al.* 2022). In Kaur *et al.* (2021), a modification of the well-known firefly algorithm (Yang 2010) is proposed, aimed at reducing the number of transitions between FANET network nodes based on the Gauss Markov mobility model. Issues of optimizing UAV swarm routes based on the genetic algorithm and its modifications are discussed in Haghighi *et al.* (2020). A large number of publications in the scientific and technical literature are devoted to the problems of using artificial intelligence to control the routing of a swarm of UAV; a detailed review of which is given in Puente-Castro *et al.* (2022).

The list of publications on this topic is not limited to these works; due to the limited scope of the article, the authors did not set themselves the task of reviewing new approaches to organizing routing in FANET. However, despite their diversity, these protocols typically use various variations of the algorithm for finding the shortest route distance with reference to the network topology and location of network nodes. The class of such algorithms includes the following (Jacquet *et al.* 2001; Ogier *et al.* 2004; Perkins and Belding 1999; Rathi and Singh 2015; Razgulyaev 2008):

- Distance vector algorithm, in which each node has complete information about the network topology but collects routing information only from neighboring (adjacent) nodes;
- Link state routing algorithm, in which periodic distribution of information about the state of connections with neighboring nodes is carried out;

- Source-based routing algorithm, in which the choice of route is determined by the sending node, while the packet contains the full route to the recipient node.

Despite the large number of publications on assessing the effectiveness of various routing protocols, the issues of analyzing the behavior of FANET in conditions of non-stationarity that arise when the network structure changes remain practically unexplored. Considering the fact that in FANET the movement of UAV relative to each other occurs with high intensity (which is confirmed by the data in the table above), solving this problem is an urgent scientific and technical problem. This work, which is a development of the article by Borodin *et al.* (2017), is devoted to studying the behavior of FANET in stationary and transient modes and assessing the influence of routing metrics (nodal and channel), characteristics of the service channel, traffic intensity, and energy parameters of communication channels on the efficiency of its functioning.

The relevance of the task of choosing routing metrics and options for organizing a service channel is due to the fact that:

- Routing metrics are indicators that can be measured and on the basis of which an optimal route can be built (indicators of route optimality can be different parameters: network delay, number of hops, route cost, etc.);
- Distribution of routing information, on the basis of which the route for transmitting information from the source to the recipient is built, is carried out via a service channel; therefore the efficiency of updating routing information in network nodes largely depends on the choice of the option for organizing the service channel.

The study of the influence of the type of routing metrics on network characteristics (primarily network delay) in conditions of non-stationary network behavior during the restructuring of the network structure is of great scientific and practical interest. As noted above, the scientific and technical literature has quite fully studied the behavior of FANET with dynamic routing a stationary mode, for example, Borodin *et al.* (2024). However, the authors are not aware of any publications that have studied the transient mode of operation of FANET when the network topology changes (the number of UAV and/or their relative position), which determines the relevance and novelty of the results obtained in this article.

The research was carried out within the framework of a grant from the Russian Science Foundation for the development of control models in heterogeneous networks, and the proposed approach is applicable to almost any mobile subscriber. The choice of UAV as a mobile subscriber is due to the fact that they are widely used in traditional areas such as logistics, environmental and industrial monitoring, search and rescue operations, etc. (Arkin 2015; Kostin and Bogatov 2019; Sivakumar and Tyj 2021). In addition, UAV have recently found applications in completely new areas: monitoring crop diseases, landslides, mountain ranges, etc. (Ahmadi *et al.* 2022; Yun 2023). At the same time, the introduction of ground, surface, and underwater unmanned vehicles is progressing at a high pace. The authors believe that their proposed approach, with minimal changes, can be adapted to assess the efficiency of routing for these mobile subscribers, taking into account the characteristics of radio wave propagation, the presence of opaque and partially transparent screens, the use of other multiple access methods, etc. In addition, according to the authors, the results obtained can be used to organize dynamic flow control in an integrated communication network with UAV (Chechin *et al.* 2023).

The material is presented in the following sequence:

- Theoretical basis, which provides the main calculated relations;
- Methodology, which describes the FANET network structure model, organization of the routing process in it, and service channel model;
- Results, in which there are modeling results, influence of metrics, options for organizing the service channel, and energy of communication channels on the characteristics of a network with dynamic routing is assessed;
- Discussion, in which a mechanism for combined transmission of metrics data in information packages is proposed and analyzed.

THEORETICAL BASIS

As a telecommunications network that supports communication between UAV in a group, we will consider a radio network with packet switching and random access using the slotted ALOHA protocol (Abramson 1970; Black 1987; Roberts 1975).

To assess the efficiency of such a network, we will use the average time it takes to transmit a packet over the network from outgoing node *A* to incoming node *B*. We will also assume that communication between nodes is carried out via a two-channel radio link, which contains:

- Information channel designed to transmit target information;
- Service channel intended for sending routing information about the state of nodes (node metrics) or about the state of communication channels between nodes (channel metrics).

As an information channel, we will consider a half-duplex channel with time multiplexing and random access using the slotted ALOHA protocol. Networks with random access are characterized by the appearance of collisions of simultaneously transmitted packets, and a handshake mechanism is used to control the network when a collision occurs. In this case, the channel is divided into a sequence of slots, the duration of which is sufficient to transmit one information packet and transmit a positive response receipt from the destination node. If a receipt is not received, the sending node decides that a collision has occurred and retransmits the packet.

To calculate the probability of packet distortion due to mutual overlaps, we will use the following model. Let each node radiate a signal isotropically, meaning it has an antenna with a spherical radiation pattern and the signal is radiated equally in all directions, at wavelength λ, and the radiation power is equal to P_{rec}. Then, at a distance r from the node, the signal power will be equal to (Pestryakov and Kuzenkov 1985):

$$P_s = \left(\frac{\lambda}{r}\right)^2 \cdot \mathrm{P}_{rec}, \tag{1}$$

The input of the receiver of node *B* receives a useful signal from node *A* (transmitting packets for node *B*), as well as signals from other nodes that interfere with the useful signal. We will also assume that additional noise of power P_{ns} is received at the input of the receiver of node *B*.

The total interference power at the input of the receiver of node *B* is equal to:

$$P_i = \mathrm{P}_{ns} + \textstyle\sum_{\kappa} \mathrm{P}_{sk} = \mathrm{P}_{ns} \cdot (1 + \sum_{\kappa} \mathrm{P}_{sk} / \mathrm{P}_{ns}) = \mathrm{P}_{ns} \cdot (1 + \sum_{\kappa} h_{\kappa}), \tag{2}$$

where $P_{s\kappa}$ and h_{κ} are, respectively, the signal power from the *K*-th node and the signal-to-noise ratio at the point under consideration, while the summation occurs over all nodes transmitting their packets simultaneously with node *A*.

Let r_s be the radius of the service area of an arbitrary node. Let us denote by h_s the signal-to-noise ratio at the boundary of the node's service area.

Then, Eq. 1 can be written in the following form:

$$P_s = \left(\frac{\lambda}{r}\right)^2 \cdot \mathrm{P}_{rec} = \left(\frac{\lambda}{r_s}\right)^2 \cdot \left(\frac{r_s}{r}\right)^2 \cdot \mathrm{P}_{rec} = \mathrm{P}_{cs} \cdot \left(\frac{r_s}{r}\right)^2, \tag{3}$$

where P_{cs} is the signal power at the border of the service area.

Substituting Eq. 2 into Eq. 3 we get:

$$P_{\text{п}} = \mathrm{P}_{ns} \cdot (1 + \sum_{\kappa} \mathrm{P}_{sk} / \mathrm{P}_{ns}) = \mathrm{P}_{ns} \cdot (1 + \frac{\mathrm{P}_{cs}}{\mathrm{P}_{ns}} \sum_{\kappa} \left(\frac{r_s}{r_{\kappa}}\right)^2) = \mathrm{P}_{ns} \cdot (1 + h_s \cdot \sum_{\kappa} \left(\frac{r_s}{r_{\kappa}}\right)^2).$$

Thus, the signal-to-interference ratio for receiving node *B* is:

$$h_B = \frac{P_B}{P_п} = P_{cs}(r_s/r_{AB})^2 \cdot (P_{ns} \cdot (1 + h_s \cdot \sum_к \left(\frac{r_s}{r_{KB}}\right)^2))^{-1} = \frac{h_s \cdot (r_s/r_{AB})^2}{1+h_s \sum_к (r_s/r_{KB})^2}. \quad (4)$$

The last expression uses the following notation: h_B is the signal/noise ratio (potential) at the considered point in space (at the input of the receiver of node *B*), r_{AB} is distance from node A to the considered point in space (node *B*), and r_{KB} is the distance from the transmitting node to the considered point in space (node *B*).

The found potential value can be used to determine the probability of packet collision under the condition of simultaneous emission of several nodes. Particularly with optimal signal reception with an active pause and known parameters, the probability of bit distortion is equal to (Pestryakov and Kuzenkov 1985):

$$Q = 1 - F(\sqrt{h}),$$

where

$$F(u) = 1/\sqrt{2 \cdot \pi} \int_{-\infty}^{u} exp(-x^2)dx.$$

We will consider the bit distortions in the packet to be independent, and we will assume that code error correction methods are not used. Then the probability Q_{pack} of distortion of a packet containing *L* bits will be equal to:

$$Q_{pack} = 1 - (1 - Q)^L$$

Thus, the mutual overlap of several packets due to their simultaneous transmission by different sources leads to distortion of the received packet with probability $Q_{pack} < 1$. In traditional random access models, it is assumed that when packets overlap, distortion occurs with probability one. Taking into account the parameters of the radio channel, the location of sources, and recipients of information packets allows for a more accurate determination of the characteristics of the network. This result will be used further when modeling routing processes to calculate the probability of packet distortion at the boundary of the node's adjacency region.

METHODOLOGY

Due to the fact that an analytical study of the characteristics of FANET is not possible, and the use of well-known modeling packages (GPSS, OPNET, NS2, and others) does not fully account for its features, the authors improved the simulation model for sensor networks (Borodin *et al.* 2023), taking into account the speed of movement of subscribers, their number and location in space, energy of channels, intensity of network traffic, routing algorithms, and a number of other parameters (options for organizing a service channel and distributing metric information).

One of the important points when developing a FANET simulation model is the choice of a mobility model that describes the movement of mobile subscribers and how their location changes over time. The UAV swarm simulation model was based on a mobility model based on random walk (Chiang and Shenoy 2004; Zhang *et al.* 2015). This model is characterized by such parameters such as random walk, random waypoint, and random direction. In other words, the mobile node moves from its current location to a new location, randomly choosing a direction. Random walk is a memory-less mobility pattern, which in some cases leads to unrealistic movements, such as sharp turns. Therefore, when developing the UAV swarm model, the principle of collision avoidance, first proposed by Craig William Reynolds (1987), was additionally used.

The following basic assumptions were used in the modeling:

- Communication between UAV is carried out using a radio network with packet switching and random access using the slotted ALOHA protocol;

- All UAV have a limited power transmitter, so the service radius (the maximum distance at which data exchange between UAV is possible) is also limited;
- Routing is carried out by each UAV based on the routing information contained in its local adjacency matrix (AM);
- Local matrices are updated using information transmitted from neighboring UAV via the service data channel;
- Route selection is based on routing metrics;
- Routing matrices are updated dynamically when the network topology changes;
- The speed of movement of UAV was chosen in such a way that the time between adjacent moments of change in the network topology was greater than the time for updating the adjacency matrices.

Below is a brief description of this model, as well as the routing algorithm and the service channel model.

Network structure model

The process of modeling the network structure is carried out as follows:

- The area where nodes are located (square, cube, etc.) of the unit area (volume) is determined;
- Then the coordinates of each node are randomly formed within the location area.

To determine routes, we introduce the concept of an adjacency area (service area). The adjacency region of node *A* contains those nodes for which the probability of distortion of a packet transmitted by node *A* does not exceed a specified value. We will call nodes located in the service area of a node adjacent to this node. In a route, neighboring nodes are always adjacent.

When modeling the movement of nodes, the coordinates of each node receive small random increments. The degree of similarity between the original and displaced network topologies is the relative number of changed links between nodes.

The network structure model is represented as a square AM (Liu *et al.* 2008) with the dimension *NxN*, where *N* is the number of nodes in the network. Element *M(k,m)* of this matrix is a multicomponent quantity and determines, particularly, the adjacency of nodes m and *k*, the distance between nodes, coordinates of nodes, value of the node metric, and communication channel between nodes. Each node contains its own local AM, the elements of which reflect the amount of information available to a particular node. Routing is performed by each node using its own local AM, which gradually updates its contents as metric information is transmitted.

Organization of the routing process

Routing is carried out based on the routing information received by each node from neighboring nodes via the service data channel. The routing task is to determine the sequences of relay nodes for packet transmission and select the optimal sequence.

When forming a packet, node *A*, which is the source of information, writes into the packet the number of node *B*, which is the recipient of the information. Next, before transmitting the packet, node *A*, using its local AM, determines the list of shortest (i.e., containing the minimum number of relay nodes) routes to node *B* and for each route determines the value of its metric. After this, the route whose metric has an extreme (usually minimum) value is selected. If there are several routes with the same metrics, then one route is selected randomly. The address of transit node *C* (the first node of the selected route), to which this packet is sent, is written into the packet. After receiving the packet, node *C* compares the end node address and its own address:

- If the node that received the packet is transit (i.e., the addresses do not match), then the packet is queued and awaits transmission, then the routing process is repeated;
- If the addresses match, this means that node *C* is the final node of the route (node *B*) of this packet, so, node *C* removes the packet from the network.

Next, the following nodal metrics characterizing the state of the node are analyzed:

- "queue": total length of the queue of nodes included in the selected route;
- "load": total load of nodes included in the route;
- "number of repetitions": total number of repeated transmissions of packets by nodes included in the route;
- "distortion probability": probability of packet distortion along the route;
- "queue1": queue length of the first network node along the route (node *C*);
- "load1": load of the first network node along the route (node *C*);

- “number of repetitions1”: number of repeated transmissions of the first network node along the route (node *C*);
- “random selection”: random number of the relay node (node *C*).

Service channel model

We consider the following two options for organizing a service channel through which metric information about the state of nodes and the state of channels is sent.

In the first option, the exchange of such routing information is carried out by nodes over a dedicated (for example, frequency) service channel, which is allocated a certain share of D_{sl} from the total channel capacity. This exchange is carried out simultaneously with the transmission of information packets. For example, if the channel capacity is C, then the service channel capacity is CD_{sl}, and the information channel capacity is $C(1\text{-}D_{sl})$. As shown by experiments with a simulation model, for a wide range of network parameters, the optimal value of D_{sl} is approximately 5%.

In the second option, the entire channel capacity is allocated for the transmission of routing information, but at the same time, the transmission of information packets is periodically interrupted for a time interval T_{ob}, during which the routing information is updated. The repetition period is chosen equal to $T_{pb} = T_{ob}/D_{sl}$.

Distribution of metric information about the state of nodes is carried out in a cyclic mode sequentially by all network nodes. In the first option, such distribution is carried out in parallel with the transmission of information packets; in the second option, it occurs only in designated time intervals.

Let the sequence $\{A_1, A_2, A_3, \ldots, A_N\}$ determine the order in accordance with which nodes A_i transmit metric information, while at the initial moment t_0 of the network operation, each node has only information about its own state. At time t_0 of the first routing information update cycle, node A_1 transmits the current metric state to all adjacent nodes. Then, at subsequent moments of time (cycles) of the first cycle $t_1, t_2, \ldots, t_{N-1}$ the corresponding nodes $(A_2, A_3, \ldots A_N)$ transmit to all adjacent nodes information about their own state and information about the state received at the time of transmission from other nodes. In the second and subsequent cycles, each node transmits only information from the nodes that arrived during the time between the current and previous transmission. Each node transmits state data to new nodes.

The algorithm for sending metric information about the state of channels between nodes, as well as sending information about the network structure, has much in common with the previous algorithm and is as follows. In the first cycle, each node *A* generates a reference signal, which arrives at the corresponding clocks to all available nodes *B*. We assume that the received signal can be used to estimate the characteristics of the corresponding communication channel between nodes *A* and *B* (for example, the distance between nodes). Thus, each node accumulates information about the characteristics of the channels connecting it to other nodes. This information is transmitted to other nodes in the next transmission cycle for this node. To reduce the amount of transmitted information in clock cycles in the following cycles, each node transmits only the information that was received during the time between the current and previous transmission.

RESULTS

Service channel modeling results

When carrying out the modeling, the following parameters were used as characteristics of the service channel:

- Share of D_{sl} from the total packet transmission rate (channel capacity);
- Time t_p for sending metrics to all network nodes.

Preliminary studies have shown that for a wide range of changes in the initial data, the optimal value of $D_{sl} \approx 5\%$. Therefore, this D_{sl} value was used in further modeling.

During the modeling, it was assumed that the metric is encoded in one byte, and the transmission of metric information is carried out in standard IP packets with a service part size of 28 bytes. It was also accepted that when transmitting routing information, the volume of the packet is equal to the volume of the information packet.

Because the main results of modeling the service channel are presented in a fairly complete form in Borodin *et al.* (2015), this article presents only the main conclusions from the experimental results. One of these important results is the fact that the amount of information transmitted (and therefore the time of distribution) about the state:

- All nodes (channel metrics) are proportional to the square of the number of nodes in the network;
- Channels (channel metrics) are proportional to the cube of the number of nodes in the network.

For practically important cases (for example, when the number of nodes is several dozen or more), the transmission time of channel metrics is several tens or hundreds of windows (slots). This means that distribution can only be carried out if the entire information channel is provided, i.e., when using the second option for organizing a service channel.

Thus, the organization of the service channel significantly depends on the choice of metrics used. The transmission of routing information simultaneously with the transmission of information packets is advisable when its volumes are relatively small, for example, when sending node tags. If there is a large amount of routing information, it is necessary to use interruption in the transmission of information packets.

In radio networks, routing is primarily based on calculating the energy of communication channels between nodes, so, it is necessary to at least have information about the distance between nodes or their coordinates. Distribution of coordinates can be performed simultaneously with the distribution of other nodal metrics and takes relatively little time.

If the nodes do not have technical means that allow them to determine their coordinates, then it is necessary to send out the channel parameters, namely the distances between the nodes. In this case, the volume of routing information increases N times and to distribute it, it is necessary to forcibly interrupt the transmission of information packets for the time required to distribute the corresponding information.

Assessing the influence of metrics and energy of communication channels on the characteristics of a network with dynamic routing

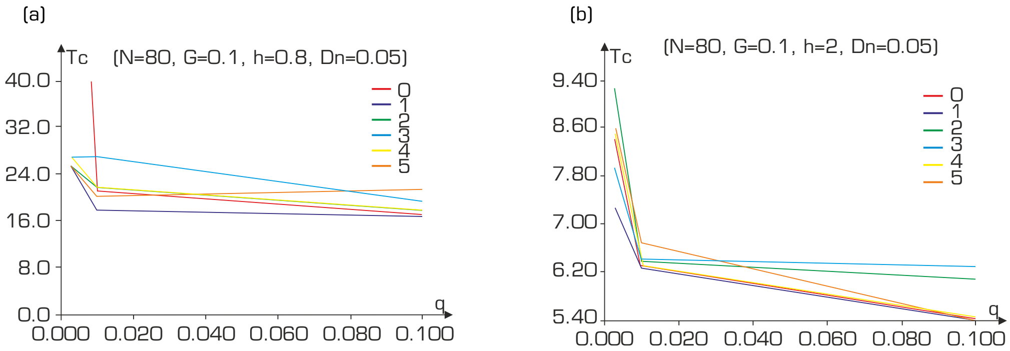
Before moving on to the modeling results, we introduce the following notation that will be used in the text and graphics:

- T_c is the average time of packet transmission over the network from source to recipient, normalized by slot duration;
- q is the probability of packet distortion at the boundary of the node's adjacency region (distortion only from noise is taken into account without considering collisions from other nodes);
- G is the total traffic of all network nodes: the average number of packets transmitted per slot (window);
- N is the number of network nodes;
- h is the value of the channel potential (signal-to-noise ratio) at the boundary of the area located from the most distant node;
- D_n is the degree of difference between the original and shifted network structures (relative number of changed channels between nodes);
- t is the network operating time (modeling time), normalized to the slot duration.

Since the efficiency of information exchange in FANET is one of the main characteristics, when carrying out modeling, the greatest interest is in studying the influence of metrics and energy of communication channels on the time of packet transmission over the network. As noted above, this work considers two classes of metrics: node metrics, containing information about the state of network nodes, and channel metrics, containing information about the state of channels between network nodes.

In Figs. 1–3, there are the dependences of the average time of packet transmission over the network for the case of sending nodal metrics for the following parameter values specified in the technical specifications of the grant: N = 80; G = 0.1; q = 0.003-0.1; h = 0.8-4.

In Fig. 1, there are graphs of the dependence of *Tc* on the channel energy for various metrics, where the following notations are adopted: 0 – "queue"; 1 – "queue1"; 2 – "loading"; 3 – "loading1"; 4 – "random selection"; and 5 – "probability of distortion". As it follows from the given dependencies, with increasing channel energy (increasing h), the time for transmitting packets over the network decreases. This also reduces the degree of dependence of network efficiency on the type of routing metric. For channels with low energy (Fig. 1a), the difference between the maximum and minimum transmission time is 150-200%, and with higher energy (Fig. 1b) it is about 20%.



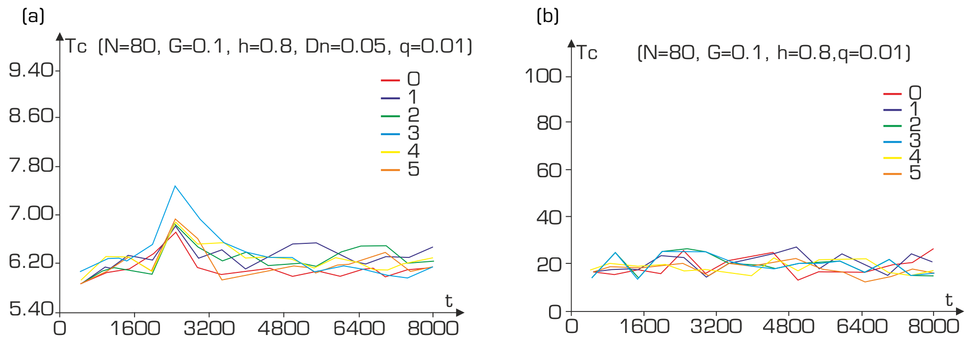
Source: Elaborated by the authors.

Figure 1. Dependence of normalized network transmission time on the type of routing metric: (a) channels with low energy; (b) channels with high energy.

The effectiveness of most of the presented metrics significantly depends on the channel parameters. If we combine the modeling results, it turns out that for a wide range of changes in channel characteristics, subject to the above restrictions, the optimal metric is "queue1" (the length of the queue in the first network node along the route). With other sets of initial data, this metric often turned out to be the best.

To clarify the nature of the impact of metrics on network efficiency, the dependences of operating efficiency on time were determined. In Fig. 2 there is the dependence of the packet transmission time over the network depending on the operating time, while the operating interval from approximately 1,000 (t = 1,000) to 8,000 slots (t = 8,000) was selected for analysis. At the same time, two modes of transmitting information about the network structure are considered: the interruption mode (Fig. 2a) and the continuous mode, in which the transmission of service information is carried out simultaneously with the transmission of information packets (Fig. 2b). The gradation of the graphs is explained by statistical errors in the tests.

From the graphs shown in Fig. 2a, it follows that at the moment the structure changes, the network moves from a stationary state to a non-stationary one. While in this state, information about the new network structure is exchanged between nodes and the packets that have accumulated during this time are dissolved. Then the network returns to a stationary state.



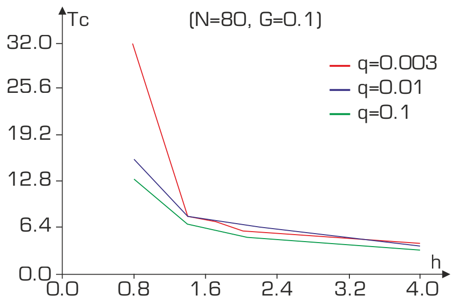
Source: Elaborated by the authors.

Figure 2. Dependence of the normalized network transmission time on the operating time for various types of metrics: (a) channels with low energy; (b) channels with high energy.

With the accepted initial data, the influence of the metric on the average time of packet transmission over the network in stationary sections is insignificant, while the difference in metrics mainly manifests itself in the section where the network structure changes.

If the transmission of routing information occurs over a dedicated service channel in parallel with the transmission of information packets, then transient processes caused by the restructuring of the network structure are less noticeable (Fig. 2b).

As the potential of radio channels decreases, the efficiency of the network also decreases; in particular, the time of packet transmission increases. This conclusion is illustrated in Fig. 3, which shows the dependence of Tc on the energy potential for various values of probability q for the "queue1" metric.



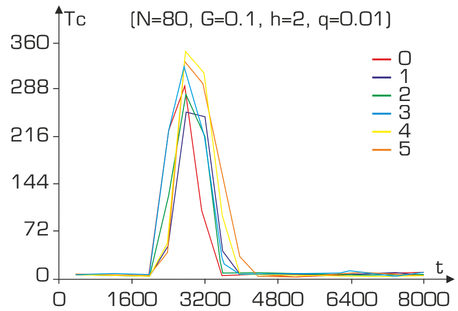
Source: Elaborated by the authors.

Figure 3. Dependence of packet transmission time on the energy potential of the radio channel.

The parameters of the radio channel affect the transmission time only at relatively low values of the potential and probability of packet distortion at the boundary of the adjacency region. As the signal-to-noise ratio increases, this dependence decreases and at a certain value (for the examples under consideration at $h > 2$), it practically disappears. The obtained result can be explained by the occurrence of additional traffic, which loads the network and leads to a deterioration in its performance. If we increase the potential or expand the area of contiguity of nodes (increasing the probability q), then the number of relays will decrease, and in the limit, we will obtain a network in which all nodes are adjacent. In such a network, there is no additional traffic, as a result of which its characteristics reach the maximum possible value.

Let us now consider the behavior of the network when transmitting channel metrics when the routing information contains parameters of communication channels between nodes. As it was noted earlier, a similar situation arises if each node can only determine the distance to other nodes.

In Fig. 4, there are typical dependences of the average delay time of packets in the network on the operating time for various types of metrics.



Source: Elaborated by the authors.

Figure 4. Network transmission time when sending channel parameters.

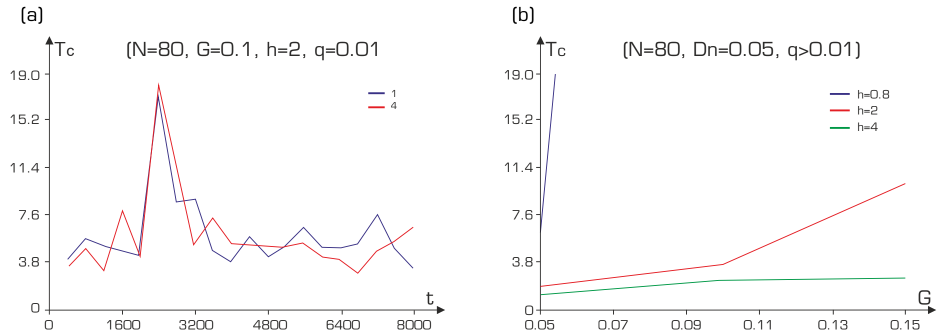
From the modeling results, it follows that the network characteristics when transmitting channel metrics do not differ qualitatively from the option of transmitting nodal metrics (Fig. 2). In stationary sections, when the network structure does not change (t < 1,600, t > 4,500), the influence of metrics on its characteristics is practically absent. Their influence on the packet transmission time is manifested mainly in non-stationary operating mode when restructuring the network structure (1,600 < t < 4,500).

DISCUSSION

Analysis of the results shows that the sharp decrease in the efficiency of FANET operation is mainly caused by long-term (hundreds or more slots) interruptions in its operation. To eliminate the interruption, the authors propose one of the possible solutions to this problem: a mechanism for combined transmission of metrics data, including channel metrics.

The essence of the combined transmission of metrics is that the transmission of metrics is carried out in an information package. When the network structure changes, only the addresses of adjacent nodes are recorded in AM of each node. Distribution of information about adjacent nodes is carried out in the usual way by interrupting the functioning of the network, while each node *A*, using its local matrix, determines the route to destination node *B*. If node *B* is adjacent, then the packet is transmitted directly to this node. If node *B* is not adjacent, then node *A* determines a route to node *B*, selects adjacent node *C* and addresses the packet to that node. Previously, metric information about node *A* and the communication channel between nodes *A* and *B* (or *C*) is recorded in it. Thus, when a packet is transmitted, all nodes that received the packet also receive information about the state of the nodes through which the packet passed and the corresponding channels. This information is recorded in each node's local AM. The use of the mechanism of combined transmission of metrics data described above leads to the fact that in the process of transmitting information packets, the local adjacency matrices of nodes are gradually filled.

Typical characteristics of network transmission time for the combined method using additionally two different metrics ("random selection" and "queue1") are shown in Fig. 5, from which it follows that both metrics provide almost identical network characteristics. This statement, as shown by the modeling results, is also true for other types of metrics.



Source: Elaborated by the authors.

Figure 5. Characteristics of the combined method of transmitting routing information: (a) random selection; (b) queue1.

Comparison with the results obtained earlier shows that when distributing metric information about channels, the combined transmission method is significantly more effective than the interrupt transmission method, while its characteristics are comparable to those of separate transmission of node parameters. The results obtained show that the combined method is an effective means of distributing routing information, especially with low traffic and relatively high energy levels of communication channels.

As directions for further research on the topic of the article, the authors consider it relevant to solve the following problems:

- Analysis of FANET characteristics with other radio access protocols (CSMA/CD, CSMA/CA);
- Assessment of the impact on the network characteristics of the speed of movement of nodes;
- Study of network characteristics with heterogeneous traffic;
- Influence of environmental conditions on network characteristics;
- Influence on the characteristics of the network of external organized interference.

CONCLUSION

This paper analyzes the influence of the choice of routing metrics and the method of organizing the service channel on the efficiency of a self-organizing radio communication network of UAV swarm. The results of the studies showed that the organization of the service channel significantly depends on the choice of routing metrics used, among which the authors considered the following:

- Nodal metrics characterizing the state of the node;
- Channel metrics characterizing the state of communication channels between nodes.

In the case of node metrics, the volume of transmitted information (and, accordingly, time of their distribution) is proportional to the square of the number of nodes in the network, and, in the case of channel metrics, it is proportional to the cube of the number of nodes in the network. Thus, the smallest amount of sent routing information corresponds to the case of nodal metrics. However, in a number of cases, it is necessary to transmit channel metrics along with the state of the nodes, which leads to a significant increase in the volume of transmitted information.

The option for organizing a service channel depends on the volume of transmitted routing information. When the volume is small (for example, when transmitting nodal metrics), a dedicated channel can be used through which routing information is sent simultaneously with the transmission of information packets. If the volume of data is large (for example, when transmitting channel metrics), it is necessary to interrupt the transmission of information packets while routing information is being sent.

It is shown that the influence of routing metrics is most critical in conditions of non-stationary network behavior, particularly during the restructuring of the network structure. In stationary sections, there is a weak dependence of the network's efficiency on the type of metrics.

To increase the efficiency of the network when transmitting channel metrics, the authors proposed a variant of the combined mode, in which the transmission of metrics is carried out in an information packet. As the results of simulation modeling have shown, the combined method provides high efficiency over a wide range of changes in traffic and channel energy.

CONFLICT OF INTEREST

Nothing to declare.

AUTHOR CONTRIBUTIONS

Conceptualization: Borodin V, Selin A, Kolesnichenko V, and Kalyagin M; **Data curation:** Borodin V, Selin A, Kolesnichenko V, and Kalyagin M; **Formal analysis:** Borodin V, Selin A, Kolesnichenko V, and Kalyagin M; **Acquisition of funding:** Borodin V, Selin A, Kolesnichenko V, and Kalyagin M; **Research:** Borodin V, Selin A, Kolesnichenko V, and Kalyagin M; **Methodology:** Borodin V, Selin A, Kolesnichenko V, and Kalyagin M; **Project administration:** Borodin V, Selin A, Kolesnichenko V, and Kalyagin M; **Supervision:** Borodin V, Selin A, Kolesnichenko V, and Kalyagin M; **Validation:** Borodin V, Selin A, Kolesnichenko V, and Kalyagin M; **Writing - Preparation of original draft:** Borodin V, Selin A, Kolesnichenko V, and Kalyagin M; **Writing - Proofreading and editing:** Borodin V, Selin A, Kolesnichenko V, and Kalyagin M; **Final approval:** Borodin V.

DATA AVAILABILITY STATEMENT

All data sets were generated or analyzed in the current study.

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