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Assessment of Indicators for Updating Adjacency Matrix of Self-Organizing Flying Ad Hoc Network

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ABSTRACT

The concept of a swarm of drones assumes the presence of a wireless ad hoc network, in which drones are network nodes and exchanging information with each other. This article is devoted to studying the behavior of an ad hoc network in a transient mode and assessing the characteristics of updating local adjacency matrices (LAM), which allow network nodes to autonomously form packet transmission routes. Using a simulation model, a comparison was made of two multiple access methods to a common data transmission channel in the process of updating matrices: cyclic and random (slotted ALOHA). The simulation results made it possible to determine areas of their effective application: slotted ALOHA is advisable to use with relatively high probabilities of packet distortion (of the order of 0.1 and higher), a numerous nodes (more than 40), and low network connectivity, and cyclic access (CA) is effective at a low level of distortion. It is shown that the completion of the process of updating adjacency matrices (AM) can be judged by such indicators of the exchange of routing information as the achievement of a certain threshold of the number of transmissions and a decrease in the level of network traffic.

Keywords: Unmanned aerial vehicle; Swarm; Flying Ad Hoc Network; Adjacency matrix; Cyclic access; Slotted ALOHA.

INTRODUCTION

The development of telecommunication technologies and robotics has led to the practical implementation of the concept of a swarm of drones that act in concert and perform a common task. This approach opens up new opportunities and advantages in the field of unmanned systems, as it is shown in the Table 1 (Chen *et al.* 2020).

To perform the target function of the swarm, it is necessary to organize the rapid exchange of information between drones using an appropriate communication network. Since drones are constantly moving in space, the communication network must automatically adjust to changes in their position. In the scientific and technical literature, such networks are called wireless ad hoc networks, in which drones are network nodes and exchanging information with each other (Agrawal *et al.* 2022; Cheng *et al.* 2013). If in wired networks and managed wireless networks data flows are controlled using routers and access points, then in ad hoc networks such control is carried out decentralized using various dynamic routing protocols.

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Table 1. Comparative characteristics of a system with a single drone and a swarm.

Features	Single drone	Swarm
Survivability	Poor	High
Scalability	Limited	High
Speed of mission	Slow	Fast
Autonomy	Low	High
Cost	High	Low
Communication needs	High	Low
Radar cross-sections	Large	Small

Source: Elaborated by the authors.

There are three main types of ad hoc networks: Mobile Ad Hoc Network (MANET) (Gupta *et al.* 2018; Hasan *et al.* 2020), Vehicular Ad Hoc Network (VANET) (Rehman *et al.* 2013; Zeadally *et al.* 2010), and Flying Ad Hoc Network (FANET) (Bekmezci *et al.* 2013; Sahingoz 2014; Sobhy *et al.* 2016). Table 2 (Tareque *et al.* 2015) shows a comparative assessment of these networks according to various criteria, from which it follows that FANET, whose subscribers are unmanned aerial vehicle (UAV), has the most rapidly changing topology. At the same time, the node density in it is low, i.e., subscribers are located at a fairly large distance from each other.

Table 2. 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.

For FANET, as for other types of ad hoc networks, a pressing scientific and technical challenge is the development of routing protocols that quickly adapt to frequent and unpredictable changes in the network topology. There are quite a few approaches to the development of routing protocols in FANET, a detailed review of which is given in (Guillen-Perez *et al.* 2021; Khan *et al.* 2019; Leonov 2017; Mahalakshmi and Nithya 2018; Yadav *et al.* 2015). In this regard, it is also necessary to note the works (Kaur *et al.* 2021; Li *et al.* 2019; Madridano *et al.* 2020; Malecki *et al.* 2021; Wu *et al.* 2022) that consider the issues of adapting a swarm to the failure of individual network nodes and methods of route planning using various algorithms.

Also, a numerous works are devoted to analyze the effectiveness of various routing protocols in FANET. In Kim *et al.* (2023), a study was carried out on the influence on the characteristics of FANET of such parameters as the density of UAV and the speed of their movement for various protocols and mobility models. In Yang and Liu (2019), a FANET network with the Dynamic Source Routing (DSR) protocol operating in conjunction with a continuous Hopfield neural network was simulated. It is shown that the use of artificial intelligence can increase network throughput and reduce the average network delay when transmitting data from

UAV. Modeling the behavior of FANET with Ad Hoc On-Demand Distance Vector (AODV) and Location-Aided Routing (LAR) protocols using the NS2 simulator, carried out in (Kumar *et al.* 2020), made it possible to compare these protocols in terms of the probability of packet delivery, their average delay time and network throughput. In Guillen-Perez *et al.* (2021), a comparative analysis of the probability of packet loss and network throughput of routing protocols Babel (based on distance-vector), Better Approach to Mobile Ad-hoc Networking (BATMAN) and Optimized Link State Routing Protocol (OLSR) was conducted. A similar study was carried out in (Alkhatieb and Felemban 2020) for OLSR, AODV, DSR, Temporally Ordered Routing Algorithm (TORA), and Geographic Routing Protocol (GRP) under different mobility models: Random Waypoint Mobility, Manhattan Grid Mobility Model, Semi-Random Circular Movement and Pursue Mobility Model.

These and several other works analyze the behavior of FANET for various routing protocols, data rates, and models of subscriber behavior in the stationary mode. However, the analysis of FANET characteristics not only in the stationary mode, but also in non-stationary conditions, i.e., when it's topological structure changes, is of great scientific and practical interest. This article is devoted to the analysis of the characteristics of updating local adjacency matrices (LAM), which allow network subscribers to autonomously form packet transmission routes. The need to periodically update information about the current network configuration in LAM is due to the fact that its topology changes due to the mutual movement of UAV. To transmit this routing information, it is necessary to either allocate part of the communication channel capacity (with frequency-division multiplexing [FDM]) or interrupt the transmission of information packets to exchange routing information (with time division multiplexing [TDM]). The purpose of this work is to estimate the time required to update LAM in FANET with TDM when using various algorithms for accessing the communication channel and in the presence of distortions in the transmitted data.

Theoretical basis

The effectiveness of using a UAV swarm is significantly increased when the following basic conditions are met (Campion *et al.* 2018; Chen *et al.* 2020; Pirmagomedov *et al.* 2019): the group is autonomous, i.e., information interaction with a remote-control point is minimal or absent; data exchange within the swarm is carried out using a communication network, the nodes of which are UAV themselves that are part of the swarm.

The presence of a communication network allows each UAV to transmit information to any other UAV in two possible ways: directly via a direct communication channel (we will call such UAV adjacent); by relaying through other UAV if the transmitting and receiving UAV do not have a direct communication channel.

Possible data transmission routes (directly over the forward link or through relay nodes) are determined by the network structure, which is constantly changing due to the movement of UAV relative to each other. Thus, each node must have up-to-date information about the network structure and the ability to route both its own and transit packets. The basis for constructing a route is the LAM (Liu *et al.* 2008; Singh and Sharma 2012), which contains information about the characteristics of communication channels between adjacent nodes (i.e., those that currently have a direct communication channel). The mutual movement of UAV changes the network topology, so there is a need for each node to periodically update information about the current network configuration.

To solve the problem of updating LAM, it is necessary to organize the exchange of this information between network nodes. Since the speed of information transmission over a communication channel is finite, it is necessary to allocate a certain amount of time for TDM or part of the bandwidth for FDM to update the matrices. The lack of clear LAM update frequency criteria can result in: to an unjustified increase in the time allotted for updating matrices, which accordingly reduces the time for transmitting packets; to the premature start of transmission of information packets, which accordingly does not allow LAM to be completely updated.

In both cases, these factors lead to a decrease in the efficiency of FANET operation. Therefore, an urgent scientific and practical task is to estimate the time required to update LAM network with dynamic routing when using various access algorithms.

Below we will consider such a network of N nodes, communication between which is carried out via a radio link with TDM. We will also assume that the communication channel between nodes is half-duplex. The model of such a network can be represented as a graph, the vertices of which are the network nodes, and the edges of the graph model the communication channel between the corresponding nodes (Diestel 2005; Wilson 1996). Since the channels are half-duplex, the edges of the graph are bidirectional.

In the general case, the graph can have markings that reflect the technical parameters of the communication channel: its load, cost, transmission time, etc. In this article, we will only take into account the fact of the presence of a channel between two nodes – there is a direct channel between the corresponding nodes or there is none.

The network graph can be represented as an *NxN* size LAM. The element *M(k,n)* of this matrix is equal to one if nodes numbered *k* and *n* are connected by a channel, and equal to 0 otherwise (Aldous and Wilson 2003). Since the arcs are non-directional, the matrix will be symmetrical. From adjacency matrices (AM), all nodes associated with a selected node can be determined. The procedure for determining connected nodes is iterative, the procedure of which is described below.

We denote by: *A(k)* the set of nodes that are directly connected to node Y_k, by K_{AC} the average adjacency coefficient of nodes, which is defined as the ratio of the number of nodes directly connected to an arbitrary node to the total number of nodes in the network, and by $C_j(k)$ the set of nodes connected to node Y_k at the *j*-th iteration step.

Thus, at the first step we have $C_1(k)= A(k)$. At the second step, the set $C_2(k)$ of nodes connected to node *K* will be equal to the set of connected nodes in the previous step (i.e., the set $C_1(k)$) combined with the set of nodes that are directly connected to these nodes, i.e.:

$$C_2(k) = C_1(k) \bigcup_n A(n), n \in C_1(k) \tag{1}$$

Continuing for *j* = 2,3, … we obtain the following expression for the set C_j at the *j*-th iteration step can be defined as follows:

$$C_j(k) = C_{j-1}(k) \bigcup_n A(n), n \in C_{j-1}(k) \tag{2}$$

where $\bigcup_n$ is the sign of the union of sets A(i), i changes from 1 to n.

We note an important property of undirected graphs. We denote by *R(k,n)* the relation of connectivity between nodes Y_n and Y_k (Chekuri *et al.* 2011). This relation is symmetrical because the communication channels are bidirectional. In addition, it is transitive, i.e., if the condition *R(k,n)* and *R(n,l)* are true, then *R(k,l)*. It is also obvious that each node is connected to itself, i.e., *R(k,k)* is true. The presence of these three properties shows that the connection relation is an equivalence relation (Engelking 1977; Kolmogorov and Fomin 1976). In turn, this means that the entire set of network nodes can generally be represented as a set of areas, in each of which the nodes are interconnected. Nodes belonging to different areas are not connected to each other.

We will call a network fully connected if all its nodes are connected, i.e., there is a path from any network node to any other. Otherwise, the network will be called partially connected. In what follows, we will only consider only a fully connected network.

An important consequence of this result is that the sets C_j defined by Eq. 2 are monotonically increasing and, due to the finite number of nodes, the sequence $\{C_j\}$ is bounded (Eq. 3):

$$C_1(k) \subset C_2(k) \subset \ldots \subset C(k) \tag{3}$$

where *C(k)* is a limit set.

Therefore, the number of iterations *r* can be defined as follows (Eq. 4):

$$r = min\ J{:}\ C_{j+1} = C_j \tag{4}$$

The relations (2)-(4) obtained above allow, firstly, to establish the existence of a route between arbitrary nodes and, secondly, to determine all the shortest routes between these nodes. The presented algorithm is used in a simulation model to construct the optimal route between the packet source and the receiver.

METHODOLOGY

The complexity of the processes occurring in FANET does not allow the use of analytical methods to calculate its characteristics and necessitates the use of simulation modeling (Kleinrock 1976). Well-known modeling packages, such as General Purpose *Simulation* System (GPSS) (Schriber 1974), OPNET (Mittal 2012), NS2 (Issariyakul and Hossain 2009), and a number of others, do not fully take into account the main features of FANET, particularly the rapid variability of the network topology and the presence of dynamic routing. Therefore, the authors refined the simulation model for sensor networks, a detailed description of which is given in Borodin *et al.* (2023), taking into account the variability of the network structure (movement of subscribers in space), the presence of packet distortions, multiple channel access methods, and a number of other parameters.

This model consists of three functional blocks: a block for setting initial data for modeling, a modeling block, and blocks for processing and displaying simulation results.

The block for setting initial data for modeling corresponds to the Open Systems Interconnection model (OSI) and sets the values of the input parameters in all levels of this model.

At the Physical layer, the following main parameters are defined: number of network nodes; energy potentials of the radio link; number of transmission channels, methods of sealing and fixing channels; models for calculating the probability of packet distortion.

The following parameters are defined at the Link layer: access methods; packet acknowledgment methods; operation algorithms and service channel parameters.

The Network layer defines composition of metrics for packet routing, parameters of network structure changes (various mobility models for UAV), and routing methods.

The Transport layer defines structure of the transmitted messages and the method of splitting the message into packets and redundancy options for channels for data exchange between nodes.

At the layer of Application Processes are set characteristics of the message source (intensity of message flow, distribution of message size, and distribution of time between adjacent packets in a message); for each source of messages, the recipient node of the corresponding message is indicated.

The process of modeling in the modeling block is carried out by events on a given time interval of the network operation. It is possible to study stationary and non-stationary processes of network behavior with a given allowable statistical error.

The model allows determining the statistical characteristics of the following quantities: packet transmission waiting time in the node; packet transmission time over the network from the source to the consumer; packet retransmission time and number of retransmissions; probability of packet loss, etc.

The model includes mechanisms for recognition of the network transition to an unstable state, reduction of modeling time and obtaining express results, optimization of network parameters, and display during the simulation of the network parameters.

Blocks for processing and displaying modelling results form given statistics based on the obtained results (distribution laws, average values, dispersions, etc.) and display the obtained results in the form of graphs and tables.

Below there is a brief description of the main results obtained using this model: multiple access methods and the process of updating AM used to organize efficient dynamic routing in the network.

Methods for accessing the information transmission channel between UAV

When conducting research, we will consider the following two options for multiple access to the data exchange channel between UAV: cyclic access (CA) with TDM and random synchronous access – slotted ALOHA.

In the first case, deterministic access to the channel is carried out and each UAV is allocated one time interval (slot), during which it completely transmits AM data. Time slots follow each other, with each slot assigned to one specific UAV. With random synchronous access, the channel is divided into successive slots, the duration of which is sufficient to transmit data about AM. Each UAV randomly selects a slot to transmit AM information. If multiple UAV select the same slot, a data collision occurs and the corrupted data is not retransmitted (an uncorrupted transmission is possible on the next data transmission).

This article does not discuss the technical aspects of organizing a synchronous radio channel for data exchange between UAV, since solving this problem is the subject of a separate study.

Description of the process of updating LAM

To build an optimal route, each node must have LAM that is identical to the network (actual) AM. The algorithm for each node to form its own LAM is described below. It is assumed that the total number of nodes is *N* and each node has its own number in the network (from 0 to N-1).

At the initial moment, each network node has its own (local) 0 LAM, i.e., all elements of these matrices are equal to 0. As information is received from other nodes, LAM is updated to fully match the network matrix. The formation of LAM is carried out as follows. An arbitrary node of Y_K network sends a broadcast routing message containing the number of this node. This message is received by all nodes that node Y_K is connected to. Each Y_L node that received this message updates its LAM. In it, in particular, units appear at the intersection of the *K*-th column and the *L*-th row (*L* is the number of the receiving node).

Next, each node determines the change in its LAM that occurred after receiving the message from node Y_K. This change contains those connections between nodes that were not previously marked in LAM of the corresponding node. If the changes are non-0, then the node broadcasts a message containing LAM changes and its number.

Messages are transmitted to adjacent nodes, and this procedure is repeated cyclically. Thus, in one cycle, a message containing LAM change is transmitted from one node. In this case, nodes transmit their messages in response to an incoming message only if the received message leads to a change in their internal LAM. In accordance with the described algorithm, the process of updating matrices ends after the completion of changes to LAM.

When studying the efficiency of data transmission in FANET, the following key indicators of the LAM update process are of particular interest: share of adjacency areas – the number of nodes for which all adjacent nodes are defined in relation to the total number of nodes; share of created LAM – the number of nodes for which LAM is fully defined in relation to the total number of nodes; distribution function of the number of transmissions in which the node has completely determined LAM; and network traffic – the number of nodes transmitting LAM update messages in relation to the total number of nodes.

The next section of the article provides some numerical simulation results that allow us to assess the impact of data transmission network parameters (including the probability of data corruption) on the above indicators. It identifies areas of effective application for each of the considered access method and proposes indicators for determining whether the LAM update process has been completed.

RESULTS

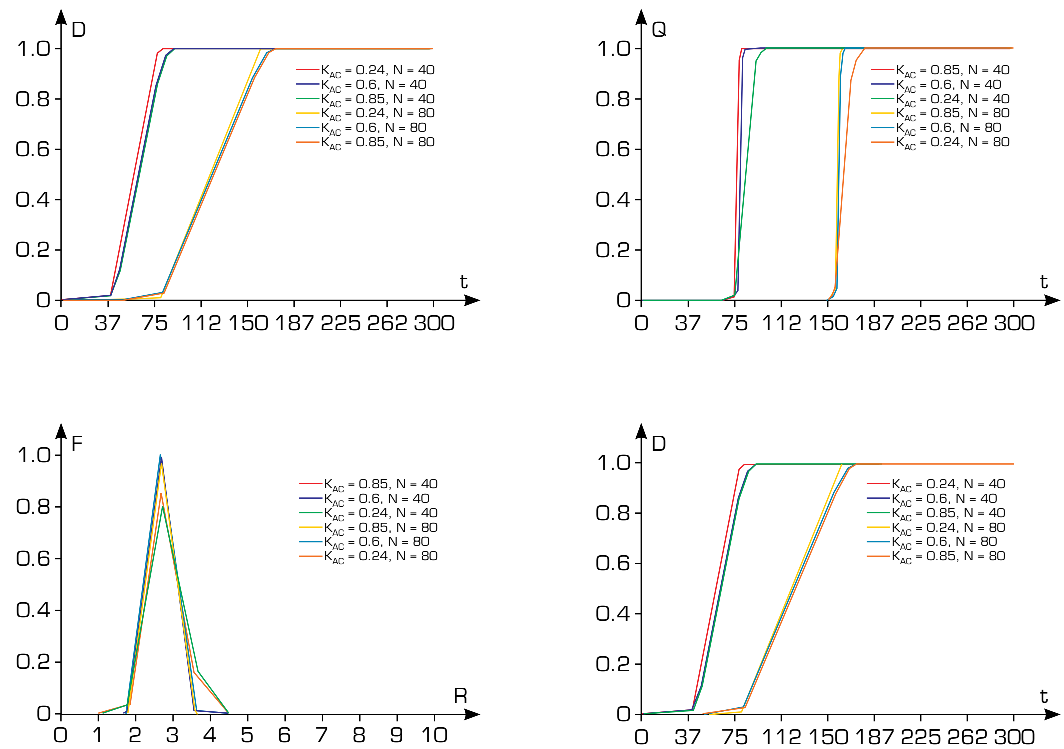
Description of the process of updating LAM

The results of modeling the process of updating matrices in the absence of distortions in the transmitted data are shown in the Fig. 1, where the following symbols are given: D is the proportion of certain adjacency areas; Q is the share of created LAM; F is the distribution function (histogram) of the number of gears; S is the network traffic; and R is the number of gears.

Graphs depicting dependence of LAM update indicators are plotted against the current execution time of the matrix update task. As a unit of time in these and the following graphs, a time slot is selected, within the boundaries of which information is transmitted between nodes, and K_{AC} adjacency coefficient and the number *N* of network nodes are parameters.

The obtained results lead to drawing an important conclusion that the number of data transmissions before a complete LAM construction is practically independent of the number of nodes and the network adjacency coefficient. As depicted in Fig. 1, the average number of gears does not exceed three, and the dispersion of the distribution of the number of gears is small and amounts to 0.1-0.2 from the average value. This allows concluding that one of the possible indicators that determine the completion of LAM update data transfers can be such a parameter as reaching a certain threshold of the number of transfers.

After the LAM update is completed, the network continues to transmit data for a certain time, but this does not lead to a change in LAM. Therefore, another indicator of the completion of updating LAM is a decrease in network traffic. Additionally, the update time of LAM is an almost linear function of the number of nodes and weakly depends on the adjacency coefficient. Figure 1 shows that for two values of *N* (40 and 80), the time to construct the matrix in the second case is approximately two



Source: Elaborated by the authors.

Figure 1. Change in LAM update rates over time (proportion D of certain adjacency areas, share Q of created LAM, distribution function F of the number of gears, network traffic S) in the absence of transmission distortion.

times longer. As the calculation results showed, such a dependence of the matrix update time on the number of network nodes is also valid for other values of *N*.

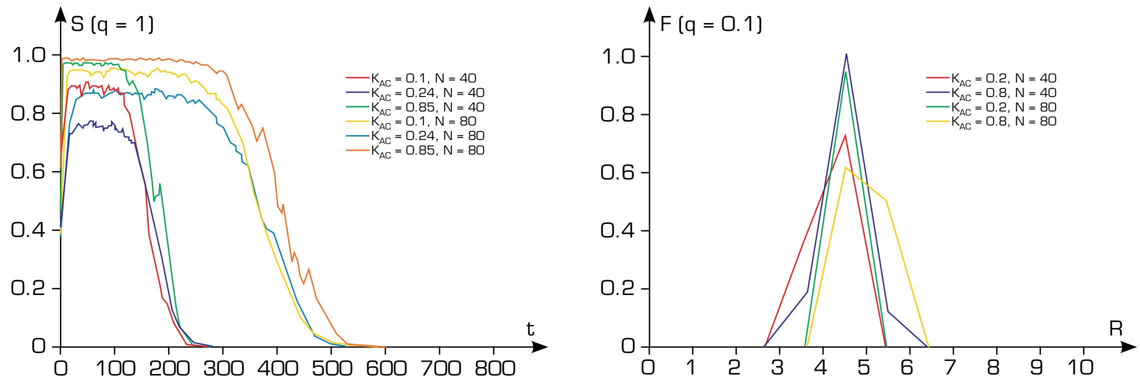
Analysis of network traffic over time shows that in the initial section all transmitted messages are significant, i.e., containing new information to update AM. This suggests that when forming AM, access via dedicated channels is effective, since it is in this case that the data transmission channels are fully loaded.

Now we consider the characteristics of updating matrices in the presence of distortions in transmitted data caused by noise and interference.

As the simulation results showed, the presence of distortions during data transmission, provided that each node transmits data about LAM only if there are changes in its LAM, leads to the impossibility of completely constructing LAM. These changes themselves are formed based on data received from other nodes. If there are no errors during transmission, then with probability one all changes will sooner or later reach all nodes. However, in the presence of distortions, there is always the possibility that any node will not receive all changes to LAM of other nodes and, as a result, will not be able to fully form its LAM.

In this regard, in the presence of distortions, it is advisable to use another mechanism for updating matrices, in which each node transmits its data regularly without taking into account changes in LAM in relation to the previous transmission. The results of modeling the process of updating matrices in the presence of distortions and using such LAM update mechanism are shown in the Fig. 2. During the simulation, the assumption was made that each message could distorted with probability *q*, with distortions occurring independently of each other.

The results suggest that LAM update time in the presence of distortions depends on the number of network nodes and weakly depends on the adjacency coefficient. Experiments were also carried out with the model for various values of *q*, which showed that the effect of interference significantly affects LAM update time and the number of transmissions before LAM is completely updated. Moreover, the greater the amount of data distortion, the greater the increase in LAM update time and the number of transmissions. In other words,



Source: Elaborated by the authors.

Figure 2. Change in LAM update rates (proportion D of certain adjacency areas, share Q of created LAM, distribution function F of the number of gears, network traffic S) in the presence of transmission distortions.

a non-linear relation can be traced, for example, when q doubles, LAM update time and the number of transmissions increase from three to five times depending on the value of q. Generally, the average number of transmissions before a complete update of LAM per node does not exceed 10, with the coefficient of variation weakly depends on the probability of distortion and does not exceeding 0.15.

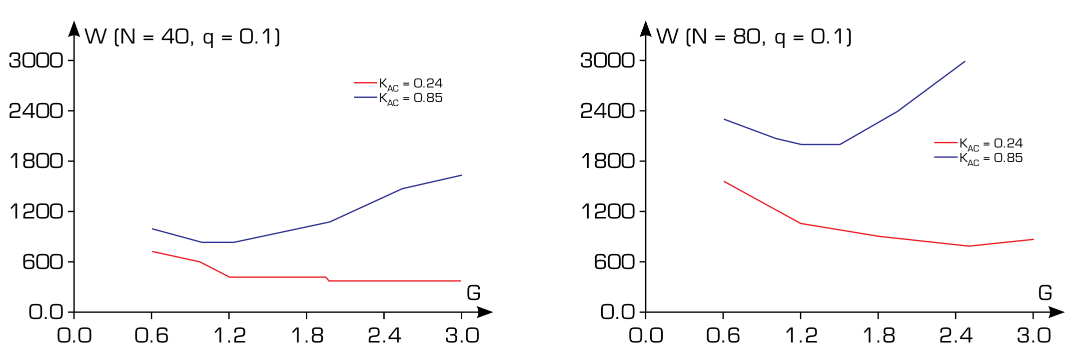
It should also be noted that with a high probability of corruption, a decrease in network traffic is no longer an indicator of the completion of LAM update, as was observed in the case of no corruption. LAM are formed during the entire transmission of significant messages.

Random access (RA) LAM update rates

Since in some cases the use of CA may not be possible, it is advisable to use slotted ALOHA without handshake as an alternative (Abramson 1970; Tobagi 1982). In this case, time windows (slots) are continuously transmitted over the channel, with sufficient duration for packet transmission. A network node with a packet to transmit randomly selects a slot and transmits its packet there. Since the slot selection mechanism is random, collisions may occur due to the simultaneous transmission of packets by two or more nodes in the same slot, leading to packet loss.

During simulation, it was assumed that the network contains N nodes connected to each other by a duplex data exchange channel. The transmission of packets by nodes is carried out in broadcast mode without acknowledgment and each node transmits messages after a random time with an exponential distribution. The total traffic (message flow from all nodes) was assumed to be Poisson, with an intensity per slot is equal to G.

Simulation results are depicted in the Fig. 3, where W is the average LAM update time normalized with respect to the duration of the time slot for data transmission.



Source: Elaborated by the authors.

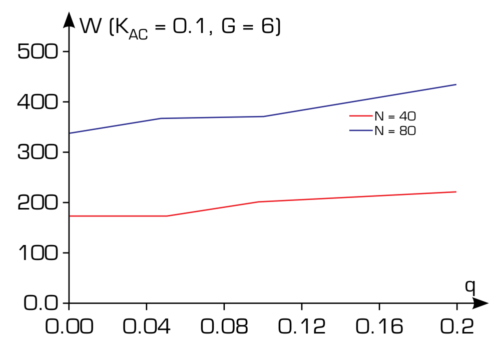
Figure 3. Change in LAM update time from the size of G of total network traffic with the RA and different number values of N (40 and 80) of network nodes.

Analysis of the results shows that LAM update time significantly depends on the value of G network traffic, while there is an optimal traffic value at which the update time is minimal. For a fixed value N of the number of nodes, as the network adjacency coefficient increases, the optimal value of traffic decreases. It should also be noted that with $K_{AC} < 1$, the total traffic may well be greater than one, while network congestion is not observed.

Comparative analysis of the dependencies presented in the Figs. 1 and 3 shows that LAM update time with RA and no errors is considerably greater than the update time with CA.

It should be noted that with RA, the matrix update time decreases as the adjacency coefficient decreases. This is due to the fact that high network connectivity also means a high probability of message collision, which leads to an increase in matrix update time. This circumstance indicates that RA is advisable to use at low K_{AC} values.

Figure 4 shows the dependence of the average LAM update time for the adjacency coefficient $K_{AC} = 0.1$ on the probability of distortion for various values of N and the optimal network traffic value.

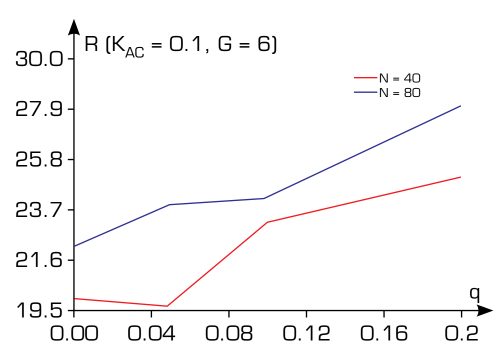


Source: Elaborated by the authors.

Figure 4. Average LAM update time versus corruption probability.

If during CA distortions significantly affect LAM update time, then RA is much less sensitive to distortions. This trend is also true for the number of transmissions for updating LAM, which is illustrated by the dependences of the average number of transmissions for RA on the value of q shown in the Fig. 5.

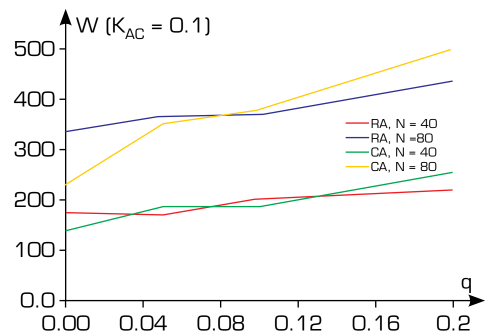
The average number of transmissions per network node with RA (Fig. 5) significantly exceeds the similar characteristics when using CA (Figs. 1 and 2). Moreover, additional studies have shown that the coefficient of variation in the number of transmissions does not exceed 0.15 and almost coincides with this characteristic of CA.



Source: Elaborated by the authors.

Figure 5. Dependence of the average number of transmissions for LAM update on the probability of distortion at the optimal traffic value.

Also, the simulation results showed that the lower the adjacency coefficient, the smaller the difference in the characteristics of networks with RA and CA. To confirm this fact, the Fig. 6 shows the dependences of the average LAM update time for RA and



Source: Elaborated by the authors.

Figure 6. Comparative characteristics of the average LAM update time with RA and CA.

CA with the adjacency coefficient $K_{AC} = 0.1$ and various values of the number of nodes and the probability of packet distortion.

A comparison of network characteristics with RA and CA shows that with a low adjacency coefficient, RA provides better performance, and the greater the number of nodes and the greater the probability of distortion, the higher the difference.

DISCUSSION

The simulation results showed that LAM update time depends almost linearly on the number of network nodes: the more there are, the longer the matrix update procedure. As a discussion, the authors propose one of the possible options for reducing their update time through network segmentation.

The following approach is proposed. The original network is divided into P_1 subnets, each of which has the same number of nodes. Each of these subnets is in turn divided into P_2 subnets. Through M partitions (M is the partition depth) we obtain that each subnetwork contains N/P nodes, where $P = P_1 * P_2 * \ldots * P_M$ ("*" sign means multiplication).

The process for updating AM would proceed as follows: first, the matrices of nodes included in subnets of depth M are updated; then the matrices of subnets at level M-1 are updated, etc.

The total matrix update time will be proportional to (Eq. 5):

$$t = N/P + P_1 + P_2 + \ldots + P_M \tag{5}$$

The update time takes a minimum value if (Eq. 6):

$$P_1 = P_2 = \ldots = P_M = \sqrt[M+1]{N} \tag{6}$$

Substituting (Eq. 6) into (Eq. 5) we obtain the following expression for the minimum update time (Eq. 7):

$$t_M = (M+1)\sqrt[M+1]{N} \tag{7}$$

The resulting expression determines the minimum LAM update time at the partition depth M. Differentiating (Eq. 7) with respect to M and equating the derivative to 0, we obtain an estimate for the optimal partition depth equal to (Eq. 8):

$$M_{ipt} = \ln N - 1 \tag{8}$$

And finally (Eq. 9):

$$t_{min} = \sqrt[\ln N]{N} \ln N = e \ln N \tag{9}$$

The obtained result shows that in this case the dependence of the update time is a logarithmic function of N, i.e., depends much less on the number of nodes than in the absence of segmentation.

As directions for further research into the efficiency indicators of routing methods in self-organizing networks, the authors consider it relevant to solve the following problems: assessment of the impact of failure of individual network nodes on its connectivity and, accordingly, on the time of updating routing information; development of routing algorithms and assessment of routing quality with partial correspondence of LAM to the network AM; development of methods for generating AM taking into account the actual route traveled by the packet from the source to the location; assessment of the influence of the speed of node movement on LAM update time; assessment of the influence on the network characteristics of the characteristics of radio wave propagation in various environments and in the presence of screens (opaque or translucent).

CONCLUSION

The article studies the characteristics of updating LAM in FANET, the presence of which allows each UAV to autonomously form message transmission routes. An approach is proposed to the formation of LAM in the process of multiple exchanges between UAV, which are FANET nodes.

To assess LAM update performance, a simulation model has been developed that adequately reflects such main features of FANET, such as high UAV mobility and the rate of change in network topology, the presence of dynamic routing, multiple channel access methods, and a number of other parameters.

An analysis of FANET characteristics was carried out using two mechanisms for accessing a common data transmission channel in the process of updating matrices: deterministic (CA) and RA. For these two access methods, the behavior of the network is considered in the absence and presence of distortions in transmitted messages.

As follows from the simulation results described in the Results section, with CA and no distortion, the update time of local matrices is an almost linear function of the number of nodes and weakly depends on the adjacency coefficient. In the presence of distortions, LAM update time depends on the number of network nodes and weakly depends on the adjacency coefficient. Moreover, with an increasing q of message distortion, a nonlinear increase in LAM update time and the number of transmissions is observed.

It also follows from the simulation results that with RA and no errors, LAM update time is considerably longer than with CA. The presence of distortions leads to deterioration of network characteristics (increase in time and number of transmissions for updating LAM) with RA, although this tendency does not appear as sharply as with CA.

A comparative analysis of modeling results for cyclic and RA has shown that in the absence of distortions (or with a small amount of distortion), CA provides higher efficiency compared to RA. RA is advisable to use with relatively high probabilities of data corruption (of the order of 0.1 and above), a numerous nodes (more than 40) and low network connectivity.

One of the important results of the work is the identification of indicators (reaching a certain threshold of the number of transmissions, reducing the level of network traffic), by which one can judge the completion of the LAM update process. However, this statement is true mainly for CA with a sufficiently small amount of message distortion.

An option has been proposed to reduce the update time of LAM through FANET segmentation, which is especially effective with a numerous network nodes.

CONFLICT OF INTEREST

Nothing to declare.

AUTHOR CONTRIBUTIONS

Conceptualization: Borodin V, Kolesnichenko V, and Kovalkina N; **Methodology:** Borodin V, Kolesnichenko V, and Kovalkina N; **Software:** Borodin V, Kolesnichenko V, and Kovalkina N; **Validation:** Borodin V, Kolesnichenko V, and Kovalkina N; **Formal analysis:** Borodin V, Kolesnichenko V, and Kovalkina N; **Investigation:** Borodin V, Kolesnichenko V, and Kovalkina N; **Resources:** Borodin V, Kolesnichenko V, and Kovalkina N; **Data Curation:** Borodin V, Kolesnichenko V, and Kovalkina N; **Writing - Original Draft:** Borodin V, Kolesnichenko V, and Kovalkina N; **Writing - Review & Editing:** Borodin V, Kolesnichenko V, and Kovalkina N; **Visualization:** Borodin V, Kolesnichenko V, and Kovalkina N; **Supervision:** Borodin V, Kolesnichenko V, and Kovalkina N; **Project administration:** Borodin V, Kolesnichenko V, and Kovalkina N; **Funding acquisition:** Borodin V, Kolesnichenko V, and Kovalkina N.

DATA AVAILABILITY STATEMENT

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

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