Method for Ensuring Survivability of Flying Ad-hoc Network Based on Structural and Functional Reconfiguration

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Abstract. Self-organizing flying ad-hoc networks are increasingly used to solve the tasks of recording, storing and transmitting data in space. In some cases, such networks are implemented on a hierarchical basis (mesh topology) and are specialized. These networks are rather volatile since the failure of one of the nodes can disrupt the entire network, and the time it takes to reconfigure the network may be too long. The survivability of the network is an important aspect of the main function (goal achievement) performance reliability. The network has to perform the main function throughout the operating time. During and after the impact of adverse factors, in order to perform the main function, the network has to restore its functions in a minimum time. A characteristic property of a natural or techno-productive negative influence is its low predictability, suddenness, instantaneous distribution, the chance of damaging network nodes, low probability of failure of the network nodes outside the scope of the factor. The goal of survivability is to perform a target function in the event of a malfunction or network failure and the possibility of complete timely recovery in the case of a failure. The article is devoted to the development of a method for ensuring the survivability of flying ad-hoc network. Effective ways to ensure the survivability of the network in adverse conditions is the application of reconfiguration scenarios, redistribution of functions in the network among nodes, temporary self-isolation of nodes, etc. The proposed method is based on the use of the strategy of structural and functional network reconfiguration. This strategy is based on the aggregate-decomposition approach to network nodes. Experimental studies show that the probability of maintaining the functionality of the network when using the strategy of structural and functional reconfiguration increases the probability of performing the main function during the influence of the negative factor up to 15% and after it - up to 45%. The analysis of the obtained results shows that additional experimental research is needed to accumulate statistical information for modification of the method in the context of the introduction of self-learning elements.

Key words: survivability, flying ad-hoc network, reconfiguration, data transmission.

1 Introduction

Lately most innovations have been appearing in high-tech areas such as biomedical engineering, robotics, infocommunication technologies and artificial intelligence systems. This is quite a logical movement, since many points of contact of directions generate new vectors in the development of science and technology, which led to the massive use of embedded systems, which are the main component of information systems. This is the result of combining technologies of different directions [1]. Demand for the embedded systems is steadily increasing, and together with this, requirements for products on their base are also growing.

The high complexity and rapid development of the elemental base of the embedded systems leads to an increase in the level of abstraction, at which most of design decisions are taken. This requires extensive use of simulation, methods for mathematical analysis and formal verification of models of embedded systems.

An example of the above-mentioned systems is a self-organizing network based on the unmanned aerial vehicle known as a flying ad-hoc network (FANET). Many works [2-5] are devoted to the subject of FANETs, which give a detailed description of the basic principles of design, development and operation of FANETs. Fig. 1 shows one of the possible options for implementing systems, subsystems, classes, types, and components. It should be noted that the problem of external negative influence on the hardware component of the embedded system is considered in this paper. Problems of software deflection due to existing information "viruses" are not considered in this paper. The problem associated with the powerful external influence of microwave radiation on the hardware component of the embedded system or radio suppression of FANET nodes.

The study of FANET operation is directly related to the structural dynamics of various nature caused by changes in the parameters and state of nodes (UAVs) of the network at different stages of their life cycle under the influence of objective and subjective factors [6]. The natural hazards (lightning, temperature anomalies) as well as technical and industrial activities (electromagnetic pollution, damage), which lead to critical situations and failure of the network in general, represent a particular danger to the functioning of the FANET. In these conditions, one of the most important strategic directions for the development of embedded systems is ensuring the continuity of technological processes of the FANET and increasing functional resistance to failures in the network.

Such an option for managing the structure of objects as a structural and functional reconfiguration of an existing topology of the FANET has become widespread in practice when solving the problems of ensuring the survivability of embedded systems in the theory of structural dynamics management [7].

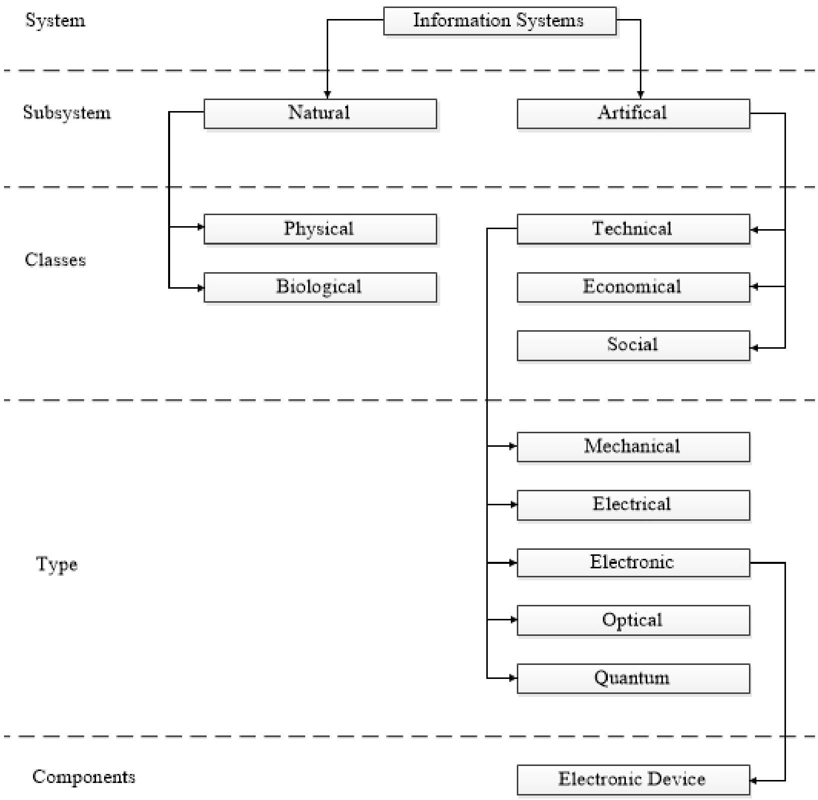

Fig. 1 Scheme of the IS structure

The reconfiguration of the FANET topology means the process of changing its structure in order to preserve and further restore (increase) the level of network performance or to ensure a minimum reduction in the network efficiency under degradation of its functions [8]. At the same time, the survivability of the system means its ability to adapt to new unforeseen conditions of operation, withstand unwanted external influences while realizing the main function [9].

This work is devoted to the development of the FANET survivability ensurance in adverse conditions, which is based on the structural and functional reconfiguration of the FANET topology.

2 Analysis of Known Solutions

In the article "Routing protocols in wireless networks" [10], the authors focus on examples of implementing reactive, proactive, and hybrid protocols in solving the problem of optimal construction of data transmission paths between FANET nodes as well as to ensure survivability of the network as a whole. The problem of influence of the dynamics in distance change between the nodes during FANET movement in space (including nodes-participants of the network) on the reconfiguration of the FANET topology is considered from the perspective of searching for optimal data transmission routes. It is argued that in the case of using proactive protocols, there is a need for the regular transmission of service information between FANET nodes to update routing tables and to continuously change the role of nodes. The authors emphasize that in quite dynamic FANETs, there is a problem of buffer overflow for the parameter of sequence numbers of network topologies, the time of their search increases. This is critical for a FANET with fast-changing topology. When using reactive protocols, such as Dynamic Source Routing (DSR), there may be an unreasonable increase in the size of data packet for long routes or an increase in a new address format (IDs), as in IPv6. It is also noted that the general problem of hybrid protocols and georouting protocols lies in the narrow specialization and complexity of their implementation [11, 12].

Based on suggestions of the authors on the possibility of a rotary choice of solutions for improving the survivability of a specialized FANET, other shortcomings can be distinguished. First, the FANET can be operated using protocol support within a single protocol family. Creating a FANET that could use a variety of tools in different protocols requires the creation of a complex statistical apparatus, the mechanisms of semantic analysis and the use of self-learning methods [13]. Complication of the system leads to a significant increase in the reaction time on factors, the probability of false positives also increases.

Secondly, each of the protocol types has its disadvantages under conditions of different densities and speeds of nodes. For example, proactive protocols are characterized by advantages over reactive ones in time of rerouting in case of a node failure. In proactive protocols, this process takes place in advance, taking into account prognostic models - it is only necessary to read the scenario of the route from the table, while reactive protocols need to send a broadcast request and expect a response from the recipients. Permanent broadcasting reduces the bandwidth of the FANET for useful data transmission. In addition, hybrid protocols can significantly reduce routing efficiency due to network clustering.

Thirdly, there are no algorithms for network operation in the case of instant degradation or radio suppression of nodes in the FANET in the epicenter of the negative external influence factor. Since the time of the negative external factor influence is less than the time necessary for an adequate response of the FANET to make a decision on the reorganization of the topology or the change of the functioning protocols in order to ensure the survivability of the network, the protocols described in the work, in fact, are meaningless, and achievement of the target function is in jeopardy.

In the article "Viability of wireless communication networks in conditions of emergency sutation" [14], the authors substantiate the thesis that the most effective way to ensure the functioning of amobile communication network in the conditions of the adverse factors is to increase the intensity of service by operating nodes, i.e. searching of functions of the damaged non-operaring nodes by working nodes; increasing the number of communication channels in a damaged cluster of nodes is proposed to be carried out at the expense of redistribution of the released radio frequency resource; transition to the use of other frequency channels. In the final part, the authors conclude that the proposed solution can be used as an additional measure when the FANET falls into the zone of negative external influence of the damage factors.

The disadvantage of this method is the emergence of a significant problem, which consists in solving the problem of eliminating interference of radio signals.

In the paper "Peer selection algorithm in flying ad hoc networks" [15], the authors propose a comprehensive solution to ensure the survivability of the UAV self-organizing network at the expense of: a data transfer method at the application level of the OSI model; an algorithm for selective retransmission request at the application level of the OSI model (AL-ARQ); an algorithm for route selection; an algorithm for choosing an assistant node using the "greedy" criterion; a criterion based on the relative speeds of the nodes. The solution is proposed for the use in the FANET under conditions of radio interference and possible external factors of node damage.

This solution is effective for highly specialized tasks of guaranteed data streaming. Multipath redundancy, permanent reconfiguration of the topology can be realized on the FANET by distributing identical data and forecasting models, collecting and processing static information in various ways. The proposed network encoding also makes the entire process secure. However, the effectiveness of the proposed solution in case of changing the network environment requires additional studies.

3 Rationale for Application of FANET Topology Structural and Functional Reconfiguration

The structural and functional reconfiguration of the FANET is aimed at changing the network topology and performance characteristics of its technical and organizational subsystem to eliminate the effects of various destructive influences and should take into account the possibility of flexible redistribution of a function, a task and a goal performed by the FANET among the valid nodes with taking into account admissible functioning of the FANET with the worst quality indicators within the allowed limits. During the reconfiguration of topology, the FANET may be located in one of the states $G = \{G_v, v=1, 2, ..., m\}$. Changing states may be caused not only by failures of certain nodes or communication channels, but also by critical situations when only one node of the FANET can remain functioning. For a formal description of possible situations, let us consider some assumptions:

- The feature of the problem statement of structural and functional reconfiguration to ensure the survivability of the FANET is connected to the fact that a set of partial solutions $Q(G_v) = (Q_1(G_v), Q_1(G_v), ..., Q_n(G_v), ..., Q_N(G_v))$, $n \in \hat{N} = \{1, 2, ... N\}$ of the FANET performance quality of service in the state of G_v can be divided into two groups of indicators according to the following scheme (Figure 2).

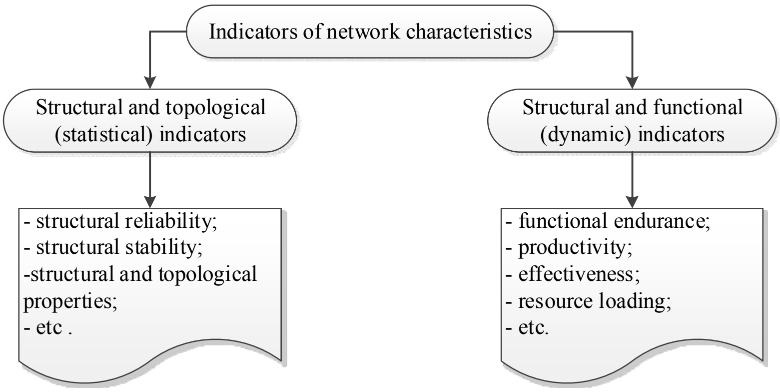

Fig.2. Schematic diagram of FANET characteristics.

The regularity between groups can be described as $\hat{N}_{str} \cup \hat{N}_{fun} = \hat{N}$ under $Q_n(G_v)$, $n \subset \hat{N}_{str} \subseteq \hat{N}$, $n \subset \hat{N}_{fun} \subseteq \hat{N}$;

- The FANET operation in each of the G_v states is determined by the set of operating and non-operating functional nodes. We will consider those nodes that are not able to perform operations of storing, receiving, transmitting, processing and protecting information resources as non-operating; the nodes performing at least one of these operations will be considered as partially operating;
- structural and functional reconfiguration of the FANET topology occurs under the assumption that a critical situation, unlike a failure (possible or predicted event), is an event that is possible but not probable or its probability is very small and can not be reasonably evaluated during the design of FANET. In other words, the reasons for the emergence of critical situations, as a rule, do not obey probabilistic statistical laws and have a multi-aspect and multifactorial nature;
- analysis of the structural dynamics of the FANET shows that its structures do not change continuously under the influence of various causes, but maintain the stability of the topology at certain time intervals.

Obviously, the value of the partial parameters $Q_n(G_v)$, $n = \{1, 2, \ldots N\}$ as a function of the FANET in each of the G_v states depends on the set of non-operating, partially operating and operating nodes; distribution of operations of processing, storage, reception and transmission of information; redistribution of these operations between the FANET operating or partially operating nodes.

Proceeding from the theory of system survivability, one of the objectives of managing the structural dynamics of the FANET is to provide the maximum possible performance level of the network and its nodes at every moment of time. This goal is achieved by targeted external influence on the degradation process of the FANET in such a way as to eliminate or reduce the possibility (probability) of FANET transitions to the unwanted state, and to manage the processes for updating the FANET.

An important condition for developing a FANET survivability method is to analyze and evaluate its topology. To do this, the theory of structures taxonomy can be applied based on such concepts of homogeneity, equality and monotony [7]. In this approach, it is assumed that the topology of the network is homogeneous if all the functional nodes included in it are identical; and heterogeneous if at least one of its node is different from all others. A FANET structure is considered to be equival if the loss of one of the nodes results in an equal significant loss of any other, and vice versa, the structure is unequal if the individual nodes of the FANET are of great value compared to others. Considering this property, we must further investigate the criticality of input nodes by their functional features. Detection of critical elements contributes to the optimization of the functional policies of other nodes that play the key role in ensuring the reliability, security and survivability of the FANET. The criticality of node failure is considered as a complex property, for the evaluation of which it is expedient to use such partial quality indicators as: failure probability; severity of failure consequences; stability of a node to the influence of external adverse factors; reservation ability; cluster rebuilding; possibility to control node state; duration of failure risk existence; node self-isolation; ability to localize a failure.

This analysis has shown that the model of the FANET functioning can be represented by a structural scheme, a fault and event tree, a connectivity graph, etc. But such a model can describe functioning of a monotone network only. In monotone models, it is impossible to take into account conflicting relationships and relationships between functional nodes: for example, in some configurations, such connections increase the efficiency of the FANET operation while in others they decrease. Such a model can not be operated if there are nodes, which simulnataneously increase, for example, reliability or security, and the others are the cause of failures or critical situations, that is, they have the opposite, harmful effect on the security of the FANET as a whole.

4 Algorithmic Support

Figure 3 shows a general view of the algorithm that implements the above principles. It is important to emphasize that there are a number of additional steps that are not given in Figure 3. These, in particular, are: research tasks on monotony, homogeneity, equivality of FANET structures based on the policy of functional definitions of the basic configuration; assessment of node failure criticality; parametric synthesis of the initial structural architecture of the FANET; multicriteria analysis of node failure criticality; analytical and simulation modeling of the conditions of structural and functional reconfiguration; constructing classes of equival structural reconfiguration scenarios and isolating reference scenarios.

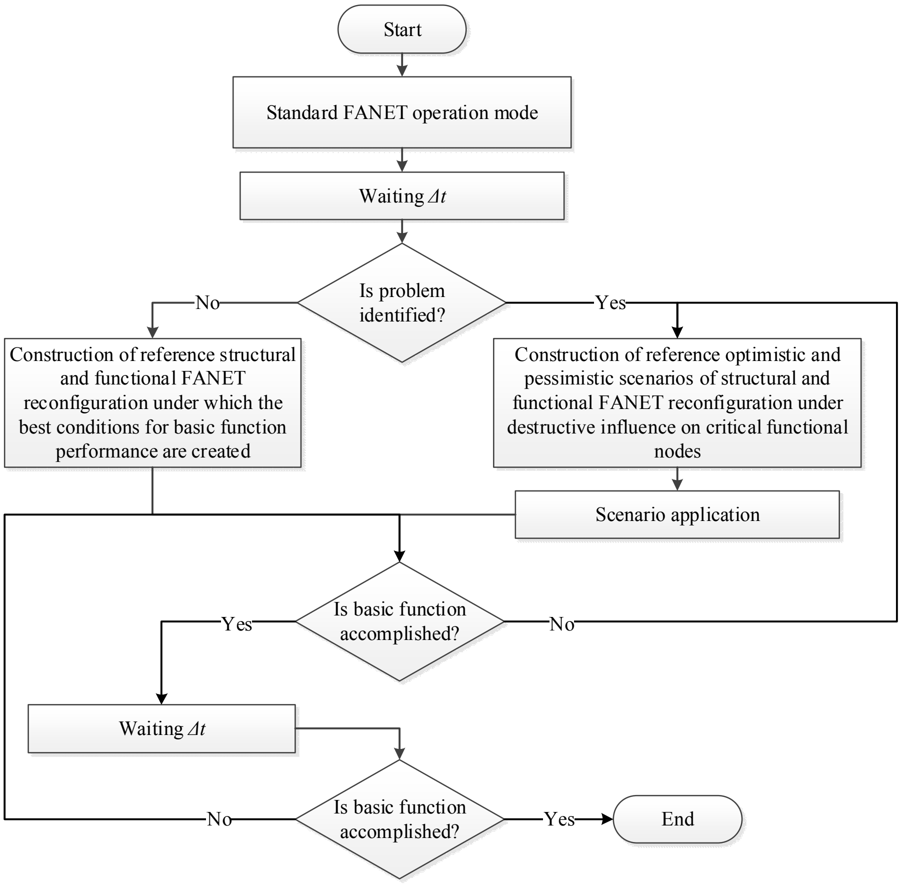

Fig.3. Block diagram of supporting algorithm

5 Simulation Modeling

In the simulation modeling, authors-initiated scenarios for the operation of a group of mobile objects [6, 16] and known software models [17] are used, taking into account the developed algorithmic design.

Let one of the FANET nodes B be connected to the control node A, to which all the collected data are sent. Control node A carries out a control over the FANET and monitors the state of its nodes. The interaction of the FANET nodes is based on the mesh principle [18, 19]. The FANET continuously transmits a data flow. The most stringent requirements for the quality of service, equipment and parameters of the FANET are renderd by nonelastic kind of data. Therefore, in order to improve the efficiency of the FANET, it is advisable to take into account the features of such data.

The model uses physical 802.11 technology at physical and channel levels. The Yans software package is applied as a simulator, which uses the Monte Carlo method.

One of the factors that determines the degree to which the FANET simulation model is based on mobile nodes is the choice of an adequate model for location of mobile network devices. In the process of choosing a mobility model, the following points are usually taken into account: the desire to adequately consider the features of the movement of nodes from the point of view of their impact on the aspects of traffic transmission in the network; the need to consider resource constraints and the impact of the detailed description of the movement on the complication of the FANET model in general; the ability to take into account the requirements for reconfiguring the FANET topology in case of a failure of the nodes with the help of the chosen system of parameters. In the framework of this work, the well-known Gaussian-Markov model of nodes mobility is used [17]. This model is the one with memory, that is, the current position of the node in it takes into account its position in the previous step. The movement of mobile nodes in a model is limited to the zone of action of the coordinating node A, where the node changes the direction of its movement after reaching its boundaries. The advantage of the model is the formation of movement trajectories smoothed in speeds and directions, the ability to vary the parameters of movement and the degree of non-determinism of the model, for example, for optimal accounting the influence of external factors that cause deviation of the node from the calculated lanes.

The ns-3 simulation system has been chosen as the basic tool for simulation modeling [17]. The total time of FANET simulation is 200 s. The transfer of useful data and the exchange of official information between nodes begins in the interval between the 10th and 11th seconds and lasts until the end of the simulation. Traffic transmission is simulated by the flow of JUDP datagrams at the data transfer rate of 1024 Mbit/s. To simulate the flow at the output of the node B, the sequence of packets of fixed length is set to 1024 bits. When simulating, nodes move randomly in the area of 500x500 m; the number of nodes is 11 (1 control node (A), 1 node (B), 3 relay nodes - (C), 6 data logger nodes (D)); node movement speed - up to 20 m/s; transmitter power - 8 dBm; routing protocol - AODV. The basic FANET topology is shown in Figure 4. At the 25th and 100th seconds in the FANET two nodes are lost: the relay node and the data logger node.

As a result of the experiment, the dependence of the intensity of data entry on node A on time (Fig. 5) was obtained. Descriptive part of events in different time intervals is shown in Table. 1

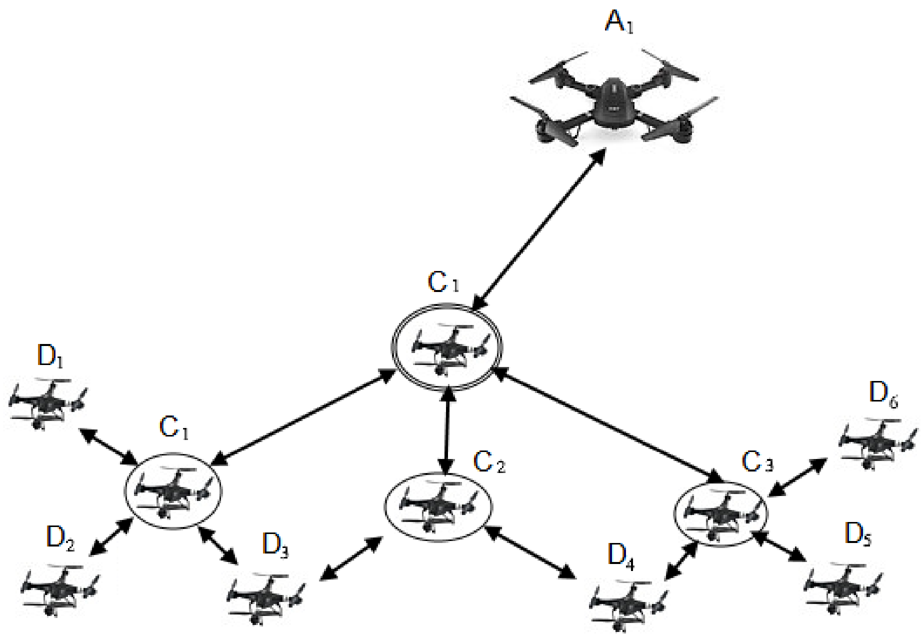

Fig.4. The basic topology of the FANET under study.

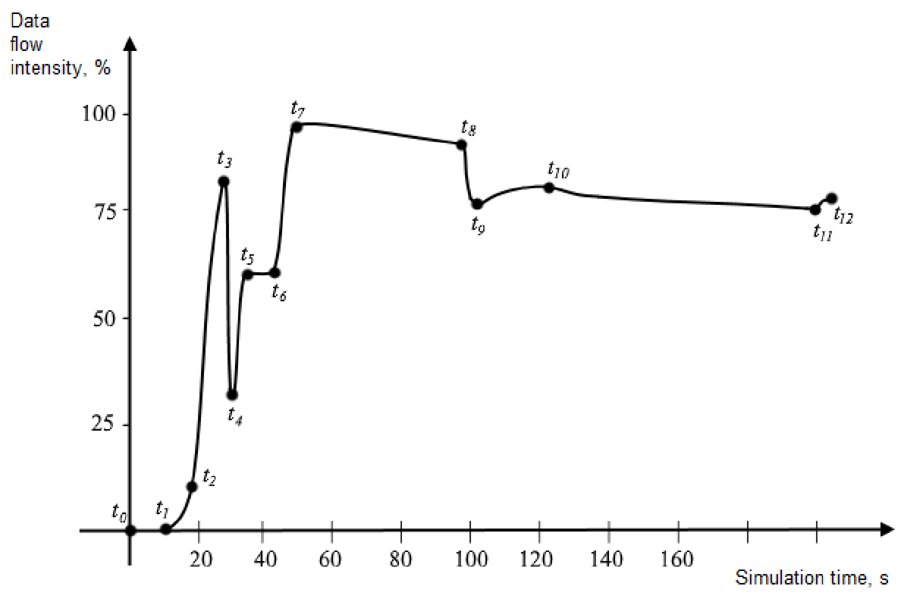

Fig.5. Structural diagram of network characteristics.

Table 1. Events in the FANET during the experiment

Time range		Event
Δt_1	0-10 s	Deploying the FANET.
Δt_2	11-18 s	Setting up the basic FANET configuration, constructing a routing table.
Δt_3	19-25 s	Data transmission.
Δt_4	25-30 s	Failure of node the C_3. FANET assessment of a situation.
Δt_5	30-34 s	Reconfiguration of data flows between the nodes D_4–C_2.
Δt_6	35-42 s	Movement of node the C_2 to the point of the former node C_3
Δt_7	43-50 s	Data transmission under the new configuration.
Δt_8	51-100 s	Reducing the intensity of the flow of service data.
Δt_9	101-102 s	Failure of the node D_6. FANET assessment of a situation.
Δt_{10}	103-121 s	Change location of the nodes D_4 and D_5.
Δt_{11}	122-187 s	Data transmission under the new configuration. Reducing the intensity of the service data flow.
Δt_{12}	187-200 s	Broadcast message about the return of nodes to the base.

Structural and functional reconfiguration, according to the algorithmic description, should take several seconds, however, the abnormal failure rates of the packet transmission on the curve lasted up to 4 seconds (Δt_5). At node speeds of about 10 m/s, this is explained probably due to the inability to instantly reach the required position, taking into account the density and mobility of the nodes, or the long connection when the node-data logger is released from the zone of direct reach to the relay node.

Based on the graph (Figure 4), we can conclude that the use of structural and functional reconfiguration, in general, leads to a significant improvement in the quality of transfer of non-elastic traffic from the nodes of the FANET.

It should be noted that in this experiment, even with the highest value of the number of nodes, the percentage of service traffic is less than 5%. This may be, first of all, due to the fact that the FANET model developed in this study is rather simplified compared to the actual FANET and does not consider the presence of “background” data from other nodes as well as service information that is not related to routing.

6 Conclusions and Recommendations

The analysis of the FANET topology reconfiguration to ensure its survivability is relevant nowadays. Existing formulations of the task of reconfiguration are characterized by high dimensionality and do not take into account most of the operations. In order to consider the features of the FANET management, general and partial requirements for the development of new principles, models, methods and techniques of multicriteria assessment, analysis and selection of structural and functional reconfiguration of the FANET topology are formulated and substantiated. The analysis of these requirements allowed formulating the direction of the aggregate-decomposition approach to solving the problem of structural and functional reconfiguration of the FANET topology.

The simulation results of FANET showed that the developed method is working and provides data transmission in case of a failure of network nodes. At the same time, there is a need to refine algorithmic supporting in order to approximate it from theoretical calculations to the real FANET. This can be achieved by entering service data from other nodes, accounting for non-routing service traffic, applying data of Big Data class, etc [20]. As a mobility model, it is recommended to use a more organized algorithm for nodes. For example, enter a task for nodes B to correct the position of nodes D. It is desirable to introduce routing protocols more adapted to FANETs into the simulation model.

The research is carried out within the framework of the implementation of the fundamental research work "Creation of Scientific and Methodological Foundations for Ensuring Survivability of Network Information Exchange Systems in Conditions of External Influence of High-frequency Microwave Radiation" on the basis of the educational and scientific Laboratory of Reconfigurable and Mobile Systems of the Department of Electronic Computers in Kharkov National University of Radio Electronics.

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