Algorithms for Adapting Communication Protocols of Fanet Networks

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Abstract: Ensuring the reliability and high throughput of information channels between unmanned aerial vehicles (UAVs) located in different environments and ground control centers requires the development of ad-hoc networks of aircraft (Flying Ad Hoc Network, FANET) that can function in case of accidental movements, switching on and off of network nodes, in case of accidental destructive effects on network nodes, failure of one or more control centers. Unstable operating conditions of the FANET network determine the relevance of adapting network protocols of different levels of the OSI model, while most of the known protocols of wireless ad-hoc networks are optimized for specific operating conditions. An overview of the existing adaptive protocols of the physical, channel, network, and transport levels of ad-hocnetworks is performed. The directions of further work on the development of new adaptive protocols aimed at building FANET networks with improved characteristics are determined.

Key words: Ad-hoc network, unmanned aerial vehicle, UAV, flying ad-hoc network, FANET, adaptation.

1. Introduction

Successful solution of a wide range of different tasks using unmanned aerial vehicles (UAVs) for scientific, military or civil applications requires the development of effective means of communication between UAVs and control centers, as well as individual UAVs. At the same time, the characteristics of wireless communication channels change significantly over time due to the spatial movements of aircraft, so the most widely used hierarchical network technologies are not applicable. The problem of building ad-hoc networks of aircraft (Flying Ad Hoc Network, FANET) that can function in case of accidental movements, inclusions and disconnections of network nodes; in case of accidental destructive effects on network nodes, failure of the existing network infrastructure (one or more control centers) [1]-[7] becomes highly relevant.

A significant number of scientific studies are devoted to the problem of mathematical modeling, practical implementation, and experimental research of FANET protocols that function at various levels of the open system interconnection (OSI) model: physical, channel, network, and transport [8].

The special relevance of the concept of wireless mobile ad-hoc networks (MANET) in general, and FANET in particular, is characteristic of providing information exchange in the course of the following special activities:

- search and rescue operations;
- prevention and liquidation of emergency situations;

- works in conditions of danger of exposure to destructive and damaging factors of natural and man-made nature;

- law enforcement operations;

- protection of important (dangerous) geographically distributed objects;

- counter-terrorism operations;

- tactical-level military operations.

These applications are characterized by complex and unstable network conditions. What determines the relevance of the application of adaptation of network protocols of different levels of the OSI model, while most of the known protocols of MANET are optimized for specific specific operating conditions. Some issues of adaptation of protocols of ad-hoc networks at the physical, channel, network and transport levels remain insufficiently studied:

- at the physical level: adaptive selection of the modulation method and its implementation based on the existing element base;

- at the channel level: multi-parameter adaptation based on joint adjustment of transmission power, bitrate, redundancy of direct error correction, disabling certain types of control frames (transmission request, transmission permission, reception acknowledgement) at low network load to reduce overhead;

- at the network and transport level: selecting the inter-packet interval, retransmission timeout, and the probability of dropping packets while also adjusting the parameters of the lower levels (physical and channel).

The complex nature of the influence of transmission mode parameters on network performance makes it difficult to build analytical models of adaptive protocols and determines the relevance of neuro-fuzzy adaptation at various levels. However, most research is limited to adapting only one of the levels of the OSI model. Known examples of cross-layer adaptations [8]-[25] do not address issues related to physical layer adjustment.

The purpose of this work is to review the existing adaptive protocols of the physical, channel, network and transport levels of ad-hoc networks, as well as to determine the directions for further work on the development of new adaptive protocols aimed at building FANET networks with improved characteristics.

2. Physical Level

For the effective implementation of a FANET, the protocols of the upper layers of the OSI model, requires the use of informed decision on a physical level (choice of structural diagram of a radio transmitter of the UAV and its parameters, method of modulation and signal coding, antenna design). The key factors affecting the physical level of FANET are the multipath model of radio waves [9], [10] and the structure of antennas (directional and omnidirectional) [11], [12].

The functioning of the network is accompanied by the influence of a large number of destabilizing factors of various types, caused by natural and man-made interference, as well as the influence of electronic warfare. Choosing a single type of modulation for a wide range of network conditions seems inefficient. When implementing a UAV transmitter, it is necessary to realize the possibility of changing the main characteristics of the generated signal (the type of modulation and the carrier frequency).

In the frequency range above 1 GHz, several variants of radio transmitters' structural schemes that differ in complexity are currently used: radio transmitters with direct modulation, with direct quadrature modulation, with indirect modulation (superheterodyne), and with a direct digital frequency synthesizer (DDS) [13]. The choice in favor of one of them for implementation as an on-board radio transmitter of the UAV can be made taking into account the following main indicators, which will be listed in order of their significance:

- type of modulation and data transfer rate;

- requirements for the quality of the radio signal, namely the stability of the carrier frequency and the level of spurious spectral components in the output signal;

- energy efficiency (economy) of the radio transmitter as a whole;

- weight and size indicators.

Among the many advantages of DDS over other schemes that are relevant for building UAV radio transmitters are [14]:

- very high resolution in frequency and phase, which is controlled digitally, which makes it possible to accurately set the parameters of the transmitted signals;

- frequency tuning with no phase discontinuity, no spikes or other anomalies associated with the time of establishment;

- the DDS-based architecture, due to the very small frequency adjustment step, eliminates the need for precise adjustment of the reference frequency, and also provides the possibility of parametric temperature compensation;

- digital interface makes it easy to implement microcontroller control;

- for quadrature synthesizers, there are DDS with I and Q outputs that work in concert.

The diagram of a radio transmitter with a DDS is shown in Fig. 1. Indicated: RF i and q - radiofrequency outputs, φ – phase shifter at 90^0, PA – power amplifier, VHF Gen. – very high frequency generator.

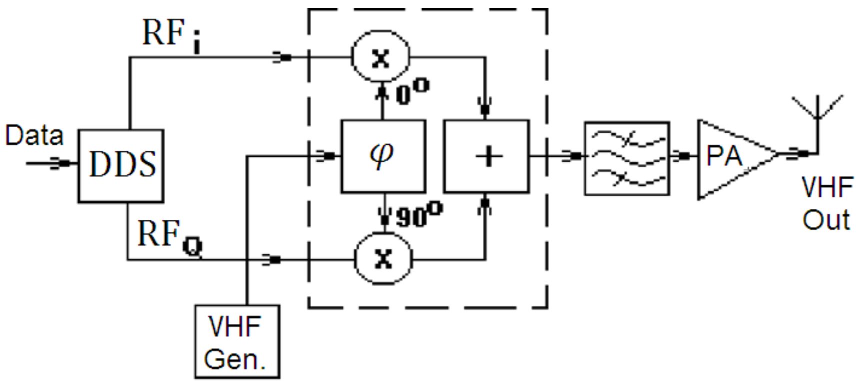

Fig. 1. Diagram of a radio transmitter with a DDS.

The main requirements for the DDS of UAV radio transmitters are:

- multichannel and independent individual channels for simultaneous communication with multiple aircraft, as well as multiple control centers;

- presence of an amplitude register (except for frequency and phase registers);

- convenience of forming signals with different modulation types.

Complex signals are relevant for UAV radio transmitters due to the possibility of increasing noise immunity, which is especially important for the control channel. The easiest way to generate modulated signals in the DDS is to supply them with the appropriate control codes for frequency, phase, amplitude, duration of the signal and the period of its repetition. If it is necessary to generate signals with linear frequency modulation (chirp signals), a speed code accumulator is usually added to the DDS, which provides a linear change in the frequency code [15].

Thus, the existing element base allows to implement the possibility of changing the main characteristics of the generated signal (type of modulation and carrier frequency). However, algorithms for automated adaptive selection of signal parameters in the process of network operation, tested in the MANET in general and FANET in particular, are not currently available.

3. Link Layer

The streaming channel and the UAV control channel have significantly different requirements, and when developing FANET network protocols, they must be considered separately.

3.1. Streaming Information Channel of the UAV

The problems of building communication networks with UAVs are constantly growing requirements for bandwidth at a high cost of frequency resource. This aspect makes it difficult to use the simplest method of multi-channel access - frequency channel separation - and determines the need to develop more complex medium access protocols (MAC) that are effective in the conditions of competition for the transmission environment.

There are various ways to adapt MAC layer protocols:

- various strategies for "handshakes" (exchange of control frames - request for transmission, transmission permission, confirmation of reception);

- adjusting the bitrate [16], transmission power [17], priority of individual frames [18], changing the redundancy of direct error correction [19], a hybrid of content-based and content-free protocols [20];

- automatic combination of MAC protocols to optimize performance under unknown conditions [21].

- adaptation of radiation patterns of network nodes in MAC protocols with directional antennas (Directional MAC, DMAC) [22].

Protocols with directional antennas improve network performance, but are more difficult to implement, since it is also necessary to define information about the position of nodes (Table 1).

Table 1. Comparison between Omnidirectional and Directional Antennas in FANET

Specification	Omnidirectional antenna	Directional antenna
Security	Low	Relatively high
Communication range	Small	Large
Spatial reuse	Low	High
Node location information	Not needed	Needed
Network capacity	Less	More
Latency of data packets	High	Low

The problem is to ensure the speed and stability of the adaptation process when the network conditions change rapidly. The complex nature of the influence of MAC-level parameters on network performance makes it difficult to build analytical models of adaptive protocols and determines the relevance of neuro-fuzzy adaptation at the channel level [23]-[27].

3.2. Control Channel of the UAV

High bandwidth is not required for the UAV control channel, but high reliability is required under the influence of natural and deliberate interference, since the inability to accurately control the UAV is highly likely to cause the aircraft to fail. Therefore, to control the UAV, methods of communication with the expansion of the spectrum due to pseudo-random adjustment of the operating frequency (frequency hop spread spectrum, FHSS) are used, which have increased noise immunity [28]. Nevertheless, scientific research [29] and examples from practice indicate the vulnerability of such systems to suppression, interception and substitution of information messages, so the problem of increasing the security of the UAV control channel remains relevant.

At the channel level, hop reservation multiple access protocol (HRMA) is used to implement FHSS [30] with a fixed law of carrier frequency change. The possibility of adapting the protocol to changes in network conditions has not been studied.

4. Network Layer

To find the optimal transmission route in conditions of frequent changes in the network topology due to the connection and disconnection of individual nodes and their movements, it is necessary to develop effective routing protocols at the network level, which differ significantly from similar protocols in hierarchical networks with a constant topology.

The classification of FANET network layer protocols is shown in Fig. 2.

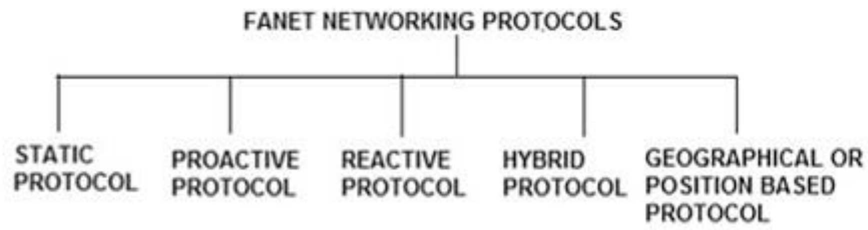

Fig. 2. Classification of FANET network layer protocols.

Proactive protocols build routes between all network nodes in advance and maintain an up-to-date routing table on each node [31], [32]. Because of the high node mobility in FANET, maintaining the routing table as in proactive protocols is not optimal.

Hybrid routing protocols combine the advantages of reactive and proactive routing protocols, but are relatively more difficult to implement. Routing efficiency in such protocols is reduced due to the need to divide the network structure into clusters. One of the most famous hybrid protocols is HWMP (Hybrid Wireless Mesh Protocol).

Protocols that use location data of network subscribers (georouting protocols) show better results when used for FANET, especially in networks with high node density (for example, the GPSR – Greedy Perimeter Stateless Routing Protocol [33]).

To improve the reliability of a network with a small number of UAVs, it is recommended to use georouting protocols in combination with proactive protocols (for example, the routing protocol using a directional antenna DOLSR – Directional Optimized Link State Routing Protocol) [34]. Using directional antennas reduces the number of transit nodes and, as a result, reduces latency, which is an important criterion for the FANET network.

Existing solutions cannot meet all FANET requirements, so developing new routing protocols for FANET is relevant.

5. Transport Layer

The classic protocol for reliable data transfer in wired networks is the Transfer Control Protocol (TCP) from the TCP/IP Protocol stack. Poor TCP performance in ad-hoc netwworks was confirmed by analysis and simulation [35]-[42] and is caused by the following reasons:

1) errors related to conflicts and collisions;

2) disadvantages related to node mobility in MANET;

3) inability to handle the flow of unordered packets;

4) high power consumption.

To eliminate the shortcomings of the TCP Protocol in MANET, a protocol with adaptation to packet loss is proposed, which reacts to the state of the channel and dynamically selects the data transfer rate [43]. This is done by monitoring the state of the protocol buffer, packet queues, and step-by-step transmission. At the same time, the protocol does not use feedback, thus avoiding additional complexity and unnecessary overhead.

Joint architecture for unmanned systems for military, civil, and commercial applications (JAUS) [44] supports the AS5669A standard, which makes it possible to use efficient transport protocols with their own packet format and semantics, in particular JSerial, which supports variable-length data packets at low throughput via a serial channel.

The use of a neuro-fuzzy approach for adaptive selection of parameters for packet data transmission (inter-packet interval, retransmission timeout, packet drop probability) was performed in the work [45]. According to the simulation results, the new approach significantly reduces the average packet delay in channel queues, minimizes the number of retransmissions, reduces the delivery time of messages of a specified size (up to 10.9 %), and increases the amount of data transmitted (up to 11.2%) in the MANET.

6. Conclusion

The complex and unstable operating conditions of the FANET network determine the relevance of adapting network protocols of different levels of the OSI model, while most of the known protocols of wireless ad-hoc networks are optimized for specific operating conditions. An overview of the existing adaptive protocols of the physical, channel, network, and transport levels of ad-hoc networks is performed. Based on the analysis, further work directions on the development of new adaptive FANET communication protocols with improved characteristics are determined as follows:

- at the physical level: adaptive selection of the modulation method and carrier frequency of UAV transmitters based on direct digital frequency synthesizers;
- at the channel (especially, MAC) level: independent multiparametric adaptation of two UAV channels – the streaming channel and the control channel;
- at the network and transport level: testing the method of neural fuzzy selection of packet transmission parameters (inter-packet interval, retransmission timeout, packet drop probability) in FANET networks);
- joint adaptation of several levels of network interaction.

The complex influence of network interaction parameters on network performance makes it difficult to build analytical models of adaptive protocols and determines the relevance of the development and application of neuro-fuzzy adaptation at separate levels (physical, channel, network, transport).

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Gleb S. Vasilyev investigated the channel layer protocols and wrote the paper, Dmitry I. Surzhik and Igor A. Kurilov conducted the research related to the physical level of FANET, Oleg R. Kuzichkin analyzed the protocols of network and transport levels; all authors had approved the final version.

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