Bieliakov, Robert; Fesenko, Oleksii

Article

FANET management process simulation at the deployment and operation stage

Reference: Bieliakov, Robert/Fesenko, Oleksii (2023). FANET management process simulation at the deployment and operation stage. In: Technology audit and production reserves 5 (2/73), S. 40 - 47.
https://journals.uran.ua/tarp/article/download/290033/283777/669919.
doi:10.15587/2706-5448.2023.290033.

ISSN 2664-9969

UDC 621.396
DOI: 10.15587/2706-5448.2023.290033

**Robert Bieliakov,
Oleksii Fesenko**

FANET MANAGEMENT PROCESS SIMULATION AT THE DEPLOYMENT AND OPERATION STAGE

The object of the study is the process of managing the air network of air communication platforms of the FANET class (Flying Ad-Hoc Network), which is a component of the ground-air communication network, and which is performed on rotary unmanned aerial vehicles (UAVs) of the mini class, at the stage of deployment and operational management. The scientific research is aimed at the managing process formalization of aerial communication platforms of the air communication network in the implementation of two classes of management tasks – the class of traffic management tasks and the class of communication tasks. The analysis of this subject area showed that the management tasks at the stage of deployment and operational management of the air subnet are a multi-parameter optimization task and require the formation of control solutions at the OSI physical, channel and network levels, open systems interaction model. Tasks related to the adaptive management of radio coverage in zones (geographic areas of the area), including the clustering of terrestrial subscribers (communication nodes), were not considered, and relate to processes at the transport and application levels. At the same time, the article shows the mathematical apparatus of the approach to the compensation of the deviations of the trajectory of an unmanned aerial vehicle (UAV) in the conditions of a directional obstacle, which will allow the formation of control solutions for adaptive control, directional patterns at the output of the transmission path. Such compensation is carried out using methods of algorithmic exchange of probes (messages) between the mobile base station and communication platforms with a certain periodicity – solutions at the channel and network levels, as well as the use of Multi User MIMO technologies. This technology allows for information exchange with several client devices at the same time, and not sequentially, sending probes to several spacecraft on one channel, using several transmitting and receiving antennas, and the calculation of channel coefficients allows to estimate the azimuthal angle of deviation and the angle of elevation.

Keywords: *ground-to-air communication network, FANET, objective functions, deployment phase, operational management, prediction, dynamic topology.*

Received date: 16.09.2023
Accepted date: 27.10.2023
Published date: 30.10.2023

How to cite
Bieliakov, R., Fesenko, O. (2023). FANET management process simulation at the deployment and operation stage. Technology Audit and Production Reserves, 5 (2 (73)), 40–47. doi: https://doi.org/10.15587/2706-5448.2023.290033

1. Introduction

In the military sphere, especially in the conditions of a full-scale invasion of the Russian Federation, one of the key tasks is to maintain a stable command of the troops. The information and communication aspect of ensuring this process plays a key role. Today, there are many ways to improve the efficiency (productivity) of information and communication systems (networks), including expanding the range of communication tools of various types and types with different technical capabilities to expand network capabilities and improve the architectural reliability of the network [1].

With the growing practical interest in automating the processes of ensuring information and communication exchange, in connection with the actualization of the value of human life, there is a search for new solutions to decentralize the management process and, at the same time, improve its time characteristics [2].

For decentralization of information exchange, one of the approaches is the use of MANET class networks, which, along with numerous advantages, is a difficult task due to their dynamic nature, high mobility of nodes, limited resources (for example, battery energy, technical characteristics of communication tools, protocols of different levels of the model OSI, etc.), which requires the development of models, methods, techniques, algorithms to improve productivity [3].

Taking into account the high dynamics of hostilities and the need for a quick response to a changing situation, the use of FANET (Flying Ad-Hoc Networks) class networks becomes especially relevant. These networks can serve as an additional level to ensure communication in the interests of officials of ground communication nodes, ensuring fast and reliable transmission (retransmission) of information (messages). Building a new architecture of an information and communication network using FANET requires a complex process of multi-parameter management and optimization [4], which includes setting routing parameters, managing energy consumption, and adapting to changing operating conditions. This not only increases the efficiency of the system as a whole, but also makes it more resistant to various types of failures and attacks.

The application of FANET networks, which are technically a group of air communication nodes (communication aerial platforms – CAP), united in a network, together with the advantages of integration into a ground Ad-Hoc network, requires a detailed study of the peculiarities of their management process. Thus, the FANET management process is carried out according to the relevant target functions at different levels of the OSI model at each of the management stages [4].

Among the stages, the first is the planning stage, the second is network deployment, and the third is operational management. Planning tasks include, in particular, a set of technical and organizational actions aimed at modeling the structure (architecture) of the network, its resources, as well as initial parameters for the predicted normal operation of the system.

At the deployment stage, the classic approach involves collecting data about the operating environment, available node and network resources, forming control influences for the implementation of target functions, analyzing the resource capabilities of performing information exchange tasks at the established level of QoS quality, as well as adjusting the main resources, their preliminary configuration and network preparation.

The stage of operational management combines procedures that ensure the implementation and maintenance of key functions of nodes and the network as a whole.

Depending on the location area, the number of nodes, their physical and communication parameters, features of the terrain, obstacles and distance from other network elements, the number of communication platforms and their initial position, which is the «zero» position, to implement the operational management process, is determined at the planning stage. The main difficulty of returning the CAP to the «zero» position is the presence of directional influences on the CAP's control channels, which significantly affect the accuracy of positioning and increase the deviation of the CAP from the initial hovering point.

Articles [5–8] show that the process of flight path correction is mostly carried out at the expense of high-cost inertial navigation systems and additional correction channels, including GPS signals.

Articles [9, 10] show the use of neural network algorithms to increase the accuracy and speed of operation of the intelligent flight control system developed on the basis of Kalman filtering algorithms.

However, in the conditions of directed interference from the enemy's means of radio-electronic warfare, which can lead to the disappearance of signals from the global navigation satellite system, and in the conditions of restrictions on increasing the technological composition of the CAP, it is necessary to search for new scientific and technical solutions for the formation of additional control channels of the CAP at the stage deployment without changing the composition of communication tools and without using additional technical solutions.

Thus, *the aim of the research* is to investigate the possibility of implementing an additional CAP control channel at the stage of deployment in autonomous flight mode, the essence of which is the process of reducing the deviation from the target trajectory of the «zero» CAP hang point of the FANET network in conditions of sudden disappearance of GPS signals.

2. Materials and Methods

In general, to manage the CAP group of the air network, it is necessary to implement the performance of the target functions of two classes:

– the first – U_{com} – a class of communication component management goals;

– the second – U_{traj} – the class of CAP movement control objectives:

$$U(t)=\left\{U_{com}(t),U_{traj}(t)\right\}. \quad (1)$$

In the article, processes of subsystems of routing management, load, mechanisms of access to the channel resource of subnetworks (transport tasks) are considered tangentially, as they relate mainly to the class (set) of operational management tasks. The main task of the article is the formalization of the ground-to-air network (GAN) management process in general, and the air sub-network at the deployment stage.

For a further description of the management process at the stage of deployment and operational management, let's define the output data generated as a result of the planning stage of FANET application as part of the MANET – FANET ground-air communication network.

Communication network parameters: the network is represented by a directed graph $G^{\psi}=(V^{\psi},E^{\psi})$, with a set of vertices $V^{\psi}=\{v_i\}$ and a set of edges $E^{\psi}=\{(v_i,v_j)\}$, $i,j=\overline{1,N_{\psi}}$, $\psi=\overline{1,3}$ (1 – network of mobile users of ground communication network, 2 – a network of mobile base stations, 3 – a network of air-level nodes on a CAP). N_{ψ} is the total number of communication nodes of the ψ-th level. For G^2, $i,j=\overline{1,N_2}$ mobile base stations act as ground control points of FANET subnets.

Node parameters: each communication node is equipped with a battery whose capacity at each moment of time t cannot be higher than some maximum value $e_{bi}(t)\le e_{bimax}$. Communication nodes have the ability to change the transmitter power depending on the situation $p_i^{\psi}(t)\le p_{max}$ – transmission power of the i-th node. Also, the receiver of each mobile node is characterized by a sensitivity threshold of p_s, which determines the minimum power of the signal $p_i^{\psi}(t)$, which can be received by the node.

Each node is equipped with a MU-MIMO transceiver and a 2×2 MIMO antenna device. The network movement parameters G^1 of mobile users (mobility metrics) are determined according to the mobility model [3]. The initial position of mobile base stations (topology G^2-network) is determined by the criterion of radio accessibility (by signal level, line of sight, etc.) to the FANET subnet (zone, group) and acts as a ground control point of the FANET network (topology G^3-networks). As part of each mobile node, an intelligent control system functions for the formation of control decisions and forecasting of the space of states.

Parameters of information exchange: at the stage of deployment of the FANET air network, the number of recipients in each session is determined by the number of CAPs included in each MBS (multicast transmission); at the $m_{MBS_aCAP_b}$ deployment stage – the route between the MBS-sender and the spacecraft-addressee for the transmission of the spacecraft coordination probe; $m_{CAP_aMBS_b}$ – the route between the CAP-sender and the MBS-addressee for transmitting the probe of the current state of the CAP; $m_{CAP_aCAP_b}$ – useful information exchange route G^3-network; m_{ab} is the route between the sending node and the destination node, which consists of h relay intervals $h=\overline{1,N_\Psi-1}$.

Assumptions and limitations: the GAN management principle is mixed (decentralized in the process of exchanging useful information), with the possibility of manual monitoring and management (exchange of service information): $N_\Psi \le 80$, $N_2 \le 2$, $N_3 \le 8$. Each terrestrial communication node has a forecast of information about the state of neighboring nodes, as well as the dynamic nature of their functioning (frequent changes in topology are caused by the mobility of all nodes), a set of parameters that determine the state of the communication node and GAN, $X(t)=\{x_f(t)\}, f=\overline{1,F}$. The UAVs are assembled on rotor-type UAVs that move at a constant speed, the dependence of the battery discharge on the increase in speed is linear. MBS are equipped with high-precision topographic reference equipment. CAPs are equipped with an inertial navigation system and GPS receivers for correcting control influences with GNSS reference parameters to reach the given hovering coordinates calculated at the planning stage and reduce the positioning deviation at the operational control stage. During CAP operation, GPS correction channels may be under the influence of the enemy's radio-electronic warfare in the form of spoofing and jamming attacks.

Task: to carry out the synthesis of a mathematical model of the radio connectivity of air nodes of the communication network at the stage of deployment, which, taking into account the situation $X(t)$ that has developed in the zone G^Ψ-network, will allow the following management decisions to be made on the physical $W_{ph}(t)$, and channel $W_{ch}(t)$, and network $W_{net}(t)$ levels of the OSI model, which will correspond to the system objective function:

$$W^*(t)=\arg \underset{W_{ph},W_{ch},W_{net}(t)\in\Omega^\Psi}{opt} U^\Psi\left(X^\Psi(t),W_{ph},W_{ch},W_{net}\right),\forall,$$
$$\forall Z_{i,j}=1, i,j\in N_\Psi, i\ne j, \quad (2)$$

where

$$X^\Psi(t)=\begin{Bmatrix} pos_i(t), p_{ij}(t), p_{s_i}, BER_{\xi_{ij}}(t), \\ m_{ab}, e_{bi}(t), \xi(t), Pr_{\xi ij} \end{Bmatrix}, \quad (3)$$

and will make it possible to minimize the energy resource costs of mobile nodes and ensure the specified quality of service of the ξ-th type of traffic on the transmission route m_{ab} while fulfilling the restrictions on the resources of communication aerial platforms and the accuracy of the assessment and forecast of their positioning:

$$\Omega=\begin{Bmatrix} \min \Delta pos_i(t), p_{s_i} \le p_{ij}(t) \le p_{i\max}, \\ BER_{\xi_{ij}}(t) \le BER_{allow\xi}(t), e_{bi\min} \le e_{bi}(t) \le e_{bi\max}, \end{Bmatrix} \quad (4)$$

where $W_{ph}(t)$ is a set of control decisions of the nodal control system at the physical level of the OSI model regarding the selection of optimal transmission power values $P(t)=\{p_{ij}(t)\}, i,j\in N_\Psi$ in radio channel *ij*, and allocation of useful information from the periodic exchange of coordinate information from MBS along the route $m_{CAP_aMBS_b}$ and $m_{CAP_aCAP_b}$; $W_{ch}(t)$ is a set of control decisions at the channel level of the OSI model regarding the selection of intervals for sending coordination probes (service information) and transmission of useful information (ξ-th type of traffic); $W_{net}(t)$ is a set of control decisions at the network level of the OSI model regarding selection of optimal transmission routes $M(t)=\{m_{ab}(t)\}, a,b\in N_\Psi$ between sender nodes a and destination b or intermediate nodes i and j on route m_{ab}; e_{bimin} is the minimum permissible capacity of the battery, which is necessary to ensure the transmission of streaming traffic in the volume defined within the current connection; $Pr_{\xi ij}$ is the priority of the ξ-th type of traffic in channel *ij*.

To describe the deployment process, it is necessary to define the scenario according to which the processes will be considered (Fig. 1).

At the planning stage, the initial coordinates of some geographically defined area (zone) of the CAP network are calculated to ensure the quality of a given level of GN information exchange. Next, let's consider scenario 1 – the process of deploying the FANET network:

1. Communication aerial platforms take turns, with a time interval of t=2 sec from CAP1 to CAP4 according to the given coordinates of the trajectory, gain the set hovering height h (Fig. 1).

2. At some point in time, the GPS signals disappear, and the flight path is corrected on the radio channel.

Unmanned aerial vehicles (CAP) are equipped with a transceiver, with a 2*2 antenna system, MU-MIMO technology, an inertial navigation system and a receiver of GPS signals from the global navigation satellite system.

The role of the control point of the air network is performed by the mobile base station – MBS (Fig. 1), which is equipped with high-precision topographical equipment, MU-MIMO communication equipment, and a GPS receiver.

The process of implementation of movement management goals (1) in scenario 1 is carried out at the expense of the inertial navigation system with GPS correction. However, in the event of the disappearance of such signals at the system input, the UAV navigation system is usually equipped with additional sources of reference signals to correct the flight route through control channels. For example, in [11], the implementation of the transition to manual control via an optical channel is shown, but this option requires additional equipment for control at night, and complex image recognition algorithms in the case of automatic correction. In [12], an implementation with additional laser equipment is shown for correcting the height h of the drone, which in practice is not sufficient for correcting the coordinates (x, y) in the vertical plane. In [7], one of the ways to implement the process of automatic UAV flight control in conditions of disappearance of GPS signals for up to 300 sec is shown, due to the correction of navigation data with pseudo-reference data obtained by using the MELM multi-level extreme machine learning algorithm and an advanced filtering Madgwik algorithm.

In addition, at the channel and network level, it is possible to apply special protocols, such as Direct-MAC [13], where service information about the state of neighboring air nodes, including their coordinates, on which the correction takes place, is exchanged due to request probes along the coordinate axes in the horizontal plane, but the height correction is not described in the article.

At the same time, at the physical level when applying MU-MIMO technology, it is possible not only to adaptively control the directional pattern in order to increase the channel bandwidth, but also to adaptively control the radio frequency resource.

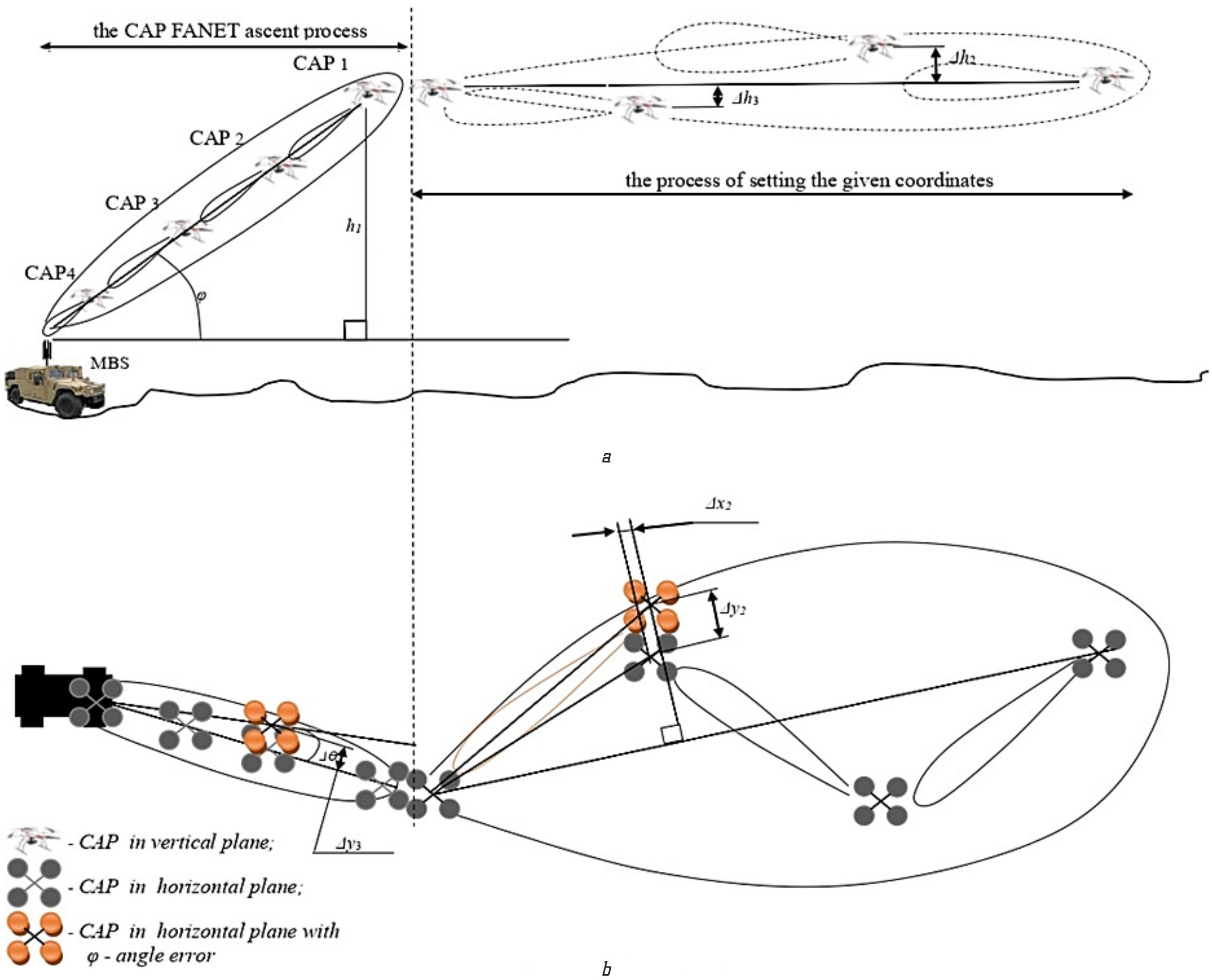

Fig. 1. The process of deploying a FANET subnet: *a* – vertical plane; *b* – horizontal plane

The authors were inspired by the experience of using directional antennas in radar, when the spatial coordinates of an object are determined with high accuracy due to the analysis of tension levels in the vertical and horizontal planes [14]. At the same time, the channel bandwidth due to MIMO technology is more than enough to implement the exchange of service information, and the use of existing Kalman [15] or Madgwik [7] filtering algorithms will allow prediction of CAP deviation based on received signals.

Each message on the receiving side of each communication aerial platform equipped with a 2×2 MIMO antenna on the UAV is received and a channel matrix (5) is formed, on the MBS with a 4×4 system – (6).

When receiving a CTS signal, the $\mathbf{CH}_{CTS}^{CAP1}$ channel matrix for each communication aerial platform can be defined as:

$$\mathbf{CH}_{CTS}^{CAP1}=\begin{pmatrix} r_{11}^{CAP1} & r_{12}^{CAP1} \\ \vdots & \vdots \\ r_{41}^{CAP1} & r_{42}^{CAP1} \end{pmatrix}, \quad (5)$$

where r_{11}^{CAP1} – represents the channel coefficient from the i-th transmitting antenna of the base station to the j-th receiving antenna on the CAP (CAP1). After receiving the signal, the CAP sends an RTS in response:

$$\mathbf{CH}_{RTS}^{MBS}=\begin{pmatrix} r_{11}^{MBS} & \dots & r_{14}^{MBS} \\ r_{21}^{MBS} & \dots & r_{24}^{MBS} \end{pmatrix}. \quad (6)$$

Thus, with each periodically sent CTS, the orientation angles will be adjusted (Fig. 1), by processing data from the channel matrix and synchronizing with the Euler CAP angles. Mathematically, the channel matrix element $r_{ij}^{a}, (a=\overline{MBS,CAP})$ can be expressed:

$$r_{ij}^{a}=\alpha_{ij}e^{j(\omega t+\varphi_{ij})}, \quad (7)$$

where α_{ij} is the attenuation coefficient between the i-th transmitting antenna and the j-th receiving antenna; ω – angular frequency of the signal; t – time; φ_{ij} – phase shift between the i-th transmitting antenna and the j-th receiving antenna.

From Fig. 1, it is possible to determine the calculated coordinate z, which will correspond to the actual height of the CAP lift:

$$h=d\cdot\sin(\varphi), \quad (8)$$

where $d=10^{\left(\frac{L(d)-L_0-20\log_{10}(f)}{20}\right)}$ – distance between antennas base station and CAP antenna in meters; $L(d)$ – signal attenuation in decibels at distance; L_0 – attenuation constant, depends on antenna configuration; f – signal frequency in Hz; φ – elevation angle at CAP (9).

Azimuthal θ and elevation angle φ can be determined from the coefficients of the channel matrix [16]:

$$\varphi = \arccos\left(\frac{\sum|h_{ii}|}{2\sqrt{\sum|h_{ji}|^2}}\right), \quad (9)$$

$$\theta = \arctan\left(\frac{\sum\Im\left(h_{ij}h_{ji}^*\right)}{\sum\Re\left(h_{ii}h_{jj}^*\right)-\sum\Re\left(h_{ij}h_{ji}^*\right)}\right). \quad (10)$$

Based on (8)–(10), it is possible to calculate the actual x and y coordinates, which is graphically displayed in Fig. 1.

To determine the position of the CAP (UAV) in space relative to the MBS, matrix operations are used: $\mathbf{x}_{lCAP} = (x_l, y_l, z_l)$ is the CAP vector in the local coordinate system, and $\mathbf{x}_{gMBS} = (x_g, y_g, z_g)$ – MBS position vector in the global coordinate system (based on GPS).

The relationship between the vectors can be expressed through the rotation matrix **Rot** and the displacement vector **Div**:

$$\mathbf{x}_{gMBS} = \mathbf{Rot}\mathrm{x}_{lCAP} + \mathbf{Div}. \quad (11)$$

The rotation matrix **Rot** consists of three orthonormal columns that represent the directions of the axes of the local coordinate system in the global coordinate system, $\mathbf{Rot} = [u_x \quad u_y \quad u_z]$; the displacement vector **Div** is equal to the difference between the start of the local coordinate system and the start of the global coordinate system $\mathbf{Div} = \mathrm{o}_{gMBS} - \mathrm{o}_{lCAP}$.

For the reverse transformation from global coordinates to local coordinates, it is necessary to multiply both parts of the equation by $\mathbf{Rot}^{\mathrm{T}}$ (the transposed rotation matrix) and subtract **Div**:

$$\mathbf{x}_{lCAP} = \mathbf{Rot}^{\mathrm{T}}\left(\mathbf{x}_{gMBS} - \mathbf{Div}\right). \quad (12)$$

At the second stage – the scenario of functioning in the defined zone (district) in order to ensure radio coverage and the quality of information exchange of ground communication nodes; implementation of air communication nodes (CAP) rotation algorithms. At this stage, the location adaptation process follows the same principle described above.

3. Results and Discussion

To investigate the feasibility of the proposed approach, simulation modeling was conducted on real data.

Input data for simulation:
– number of KA: 4 units;
– simulation time: 20 minutes;
– CTS sending interval: 30 s.

Characteristics of the CAP communication equipment:
– encryption algorithm – AES256;
– channel speed – 100+ Mbps;
– output power – 1 mW – 10 W;
– bandwidth – 20 MHz;
– receiver sensitivity: –99dBm@5MHz BW;
– frequency band: 2400 – 2500 MHz;
– battery capacity: 48 W;
– antenna type: 2 omni-antennas, the directional pattern is adaptive;
– in the horizontal plane – up to 117 degrees; in the vertical plane up to 40 degrees;
– MIMO technologies: Spatial Multiplexing, Space-Time Coding, TX Eigen Beamforming, RX Eigen Beamforming.

Characteristics of MBS communication equipment:
– encryption algorithm – AES256;
– channel speed – 100+ Mbps;
– output power – 1 mW – 8 W;
– bandwidth – 20 MHz;
– sensitivity: –102 dBm@5 MHz BW;
– frequency band: 2400–2500 MHz;
– battery capacity: 43 W;
– antenna type: 4 omni-antennas, adaptive pattern;
– in the horizontal plane – up to 170 degrees; in the vertical plane up to 40 degrees;
– MIMO technologies: Spatial Multiplexing, Space-Time Coding, TX Eigen Beamforming, RX Eigen Beamforming.

Type of messages:
– RTS – request probe;
– CTS – response probe;
– DATA – useful information package;
– ACK – a receipt for receiving a package.

Fig. 2 shows graphical flight path models of the FANET sub-network based on GPS data and inertial navigation system operations using a real data set and CAP with the following characteristics:
– airframe: 4510 – type of aircraft, quadcopter;
– hardware: PX4_FMU_V3 (V30) – the name and version of the hardware platform that controls the aircraft;
– software Version: v1.3.6 (075ab724) – the name and version of the software used to control the aircraft;
– branch: ff-release/hotfix3 – the repository from which the software was downloaded;
– OS Version: NuttX, v7.28.0 – the name and version of the operating system running on the hardware platform;
– estimator: EKF – an algorithm for estimating the state of a UAV, which uses data from sensors to determine its position, speed, orientation;
– logging Start: 09-26-2023 02:34 – start time of flight data recording;
– logging Duration: 0:11:16 – duration of flight data recording;
– aircraft UUID: 000100000000303239353439511500490029 – unique identifier;
– distance: 4000.0 m – the distance flown by the aircraft;
– max Altitude Difference: 45 m – the maximum height difference between the highest and lowest points of the flight;
– average Speed: 3.8 km/h – average flight speed;
– max Speed: 8.5 km/h – maximum flight speed;
– max Speed Horizontal: 8.5 km/h – maximum horizontal flight speed;
– max Speed Up: 4.3 km/h – the maximum vertical speed of ascent during data recording;
– max Speed Down: 3.8 km/h – maximum vertical descent speed;
– max Tilt Angle: 17.1 deg – the maximum tilt angle of the aircraft;
– max Rotation Speed: 113.7 deg/s – the maximum rotation speed of the aircraft.

Description of the data (log file) used as a reference trajectory:
– *imestamp_time_utc*: is a UTC timestamp that indicates when the data was collected;
– *usec_lat, lon, alt_ellipsoid_s*: location data in degrees of latitude, longitude and altitude above the ellipsoid;

– *variance_rad_eph, ephv, hdop, vdop, noise_per_ms*: parameters that contain information about the accuracy and reliability of measurements. In particular, *hdop* and *vdop* – these are the horizontal and vertical components of positioning accuracy;
– *jamming_indicator, vel_m_s, vel_n_m_s, vel_e_m_s, vel_d_m_s, cog_rad*: speed, angle of direction of movement;
– *timestamp_time_relative, heading, heading_offset, fix_type, vel_ned_valid, satellites_used*: additional options that include information about relative time, direction of travel, type of location determination, number of satellites used for location determination, and simulated loss of GPS signals.

At the moment of sudden disappearance of the global positioning system signal to determine the estimation of the positioning of the unmanned aerial vehicle, i. e. (speed and position of the CAP), the Kalman filtering algorithm is used to predict the position of the CAP in space relative to the reference coordinates of the MBS.

To model the FANET network, object-oriented programming was used, i. e., the extension of CAP properties due to additional calculations (5)–(12).

The purpose of the simulation is to adaptively correct the navigation data (CAP positioning) relative to the reference point of the MBS during the disappearance of GPS signals to maintain the connectivity of the FANET network.

It is necessary to emphasize that the process of processing navigation data and all computational operations of the multidimensional matrix of CAP states and the calculation of covariance coefficients take place at the ground mobile base station.

The simulation results are shown in Fig. 3.

In the course of the study, a multi-parameter FANET control model was developed, which functions as part of a promising ground-air Ad-Hoc communication network using optimization methods. One of the key advantages of using networks of this class is the ability to function in conditions of a high degree of dynamics of topology change. The proposed mathematical model allows: to take into account the uncertainty of the dynamic topology of the air communication network, to take into account the limited quantitative resource of communication aerial platforms on unmanned aerial vehicles, which is calculated at the planning stage and cannot be situationally increased, to adaptively manage energy resource costs.

The advantages of this research are: taking into account the influence of directed attacks of electronic warfare means on the process of deployment and entering into communication, while this process is considered as a system objective function of functioning at three levels of the OSI model – physical, channel and network, in addition, the proposed the navigation data correction approach does not require additional technical equipment and devices (channels). The shortcomings of the study include: the need to investigate the quality of communication services to nodes (mobile users) of the terrestrial network, namely – route capacity, delay time, jitter, etc.

Further expansion of the mathematical model of the ground-air communication network, taking into account the transport and application level, for the purpose of managing load, topology, and security in the complex during operational management should be considered as the direction of further research.

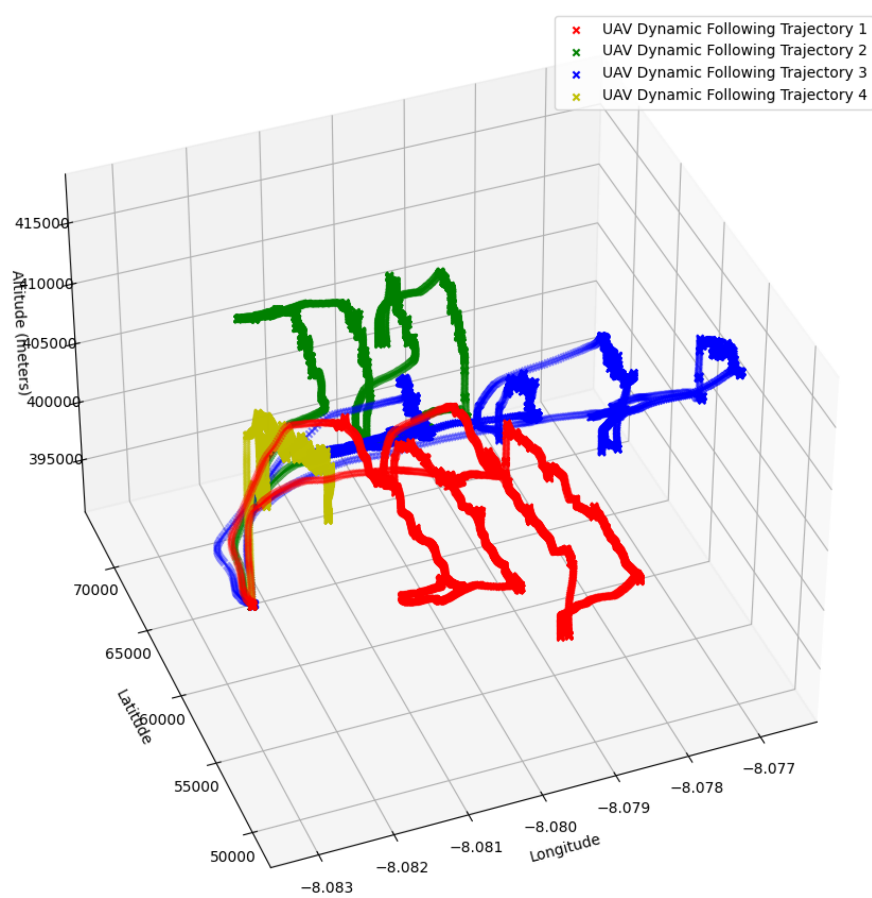

Fig. 2. The process of forming CAP reference trajectories (GPS available)

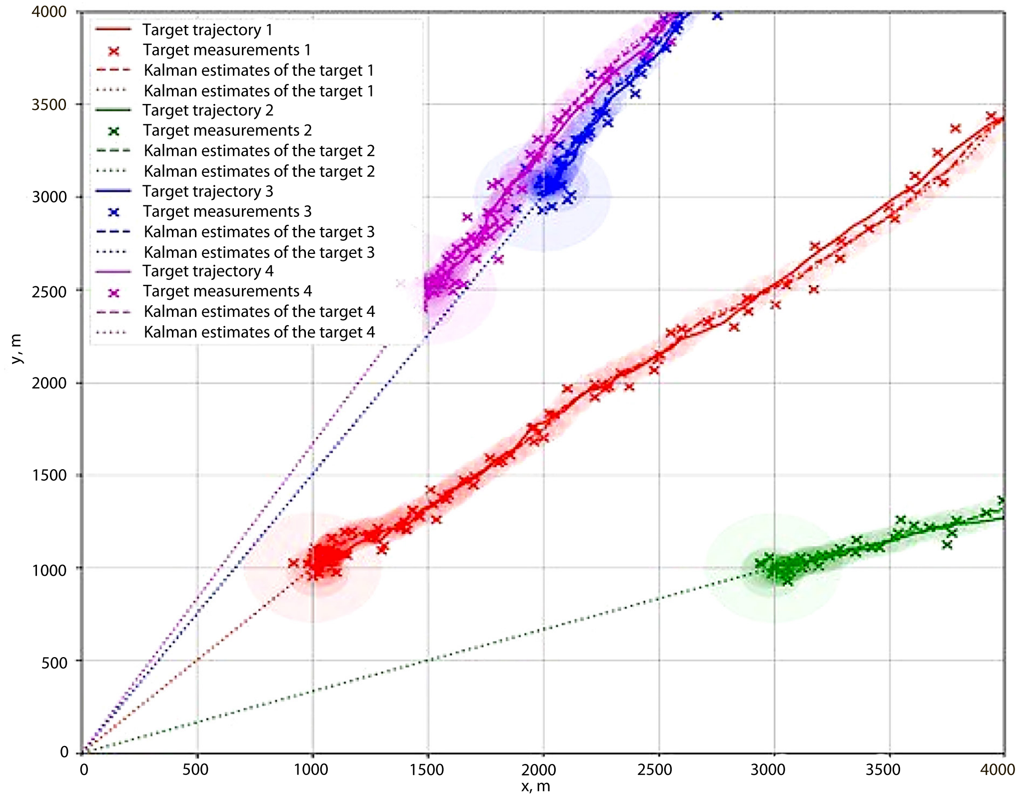

Fig. 3. Plot of trajectories, measurements, estimates and predictions for each UAV target (without GPS, time scope – 20 min)

4. Conclusions

1. The research developed a mathematical model of the deployment and operational management of the FANET network, which is one level of the ground-air communication network.

2. The novelty of the proposed model consists in:

– taking into account directed attacks by means of radio-electronic warfare aimed at blocking GPS correction channels;

– a comprehensive solution for optimizing the target function of network management at the physical, channel and network levels of the OSI model;

– use of MU-MIMO technologies to highlight useful positioning information and simultaneously reduce the volume of service information.

3. The specified model is proposed to be implemented:

– at the planning stage (to confirm theoretical calculations of network and node resources; planning the deployment and operation of communication forces and means;

– in software (development of intelligent control systems) for operational management of the ground-air communication network.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

Financing

The research was performed without financial support.

Data availability

The manuscript has no associated data.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

References

1. Dakov, S., Dakova, L. (2019). Improving the reliability of software-defined network. *Information Systems and Technologies Security, 1 (1),* 66–78. doi: https://doi.org/10.17721/ists.2019.1.66-78
2. Thamizhmaran, K. (2020). Performance of Mobile Ad-Hoc Network. *Journal of VLSI Design and Signal Processing, 6 (2),* 22–25. doi: https://doi.org/10.46610/jovdsp.2020.v06i02.005
3. Bieliakov, R., Fesenko, O. (2023). Mobility model of a special purpose terrestrial communication network. *Computer-integrated technologies: education, science, production, 51,* 130–138. doi: https://doi.org/10.36910/6775-2524-0560-2023-51-17
4. Romaniuk, V. A., Bieliakov, R. O. (2023). Objective control functions of FANET communication nodes of land-air network. *Computer-integrated technologies: education, science, production, 50,* 125–130. doi: https://doi.org/10.36910/6775-2524-0560-2023-50-19
5. Menna, B., Villar, S., Acosta, G. (2019). Navigation System for MACÁBOT an Autonomous Surface Vehicles Using GPS Aided Strapdown Inertial Navigation System. *IEEE Latin America Transactions, 17 (6),* 1009–1019. doi: https://doi.org/10.1109/tla.2019.8896824
6. Munguía, R. (2014). A GPS-aided inertial navigation system in direct configuration. *Journal of Applied Research and Technology, 12 (4),* 803–814. doi: https://doi.org/10.1016/s1665-6423(14)70096-3
7. Bieliakov, R. O., Radzivilov, H. D., Fesenko, O. D., Vasylchenko, V. V., Tsaturian, O. G., Shyshatskyi, A. V., Romanenko, V. P. (2019). Method of the intelligent system construction of automatic control of unmanned aircraft apparatus. *Radio*

Electronics, Computer Science, Control, 1. doi: https://doi.org/10.15588/1607-3274-2019-1-20

8. Delamer, J.-A., Watanabe, Y., Chanel, C. P. C. (2021). Safe path planning for UAV urban operation under GNSS signal occlusion risk. *Robotics and Autonomous Systems, 142,* 103800. doi: https://doi.org/10.1016/j.robot.2021.103800
9. Li, Q., Li, K., Liang, W. (2023). A zero-velocity update method based on neural network and Kalman filter for vehicle-mounted inertial navigation system. *Measurement Science and Technology, 34 (4),* 045110. doi: https://doi.org/10.1088/1361-6501/acabde
10. Bi, S., Ma, L., Shen, T., Xu, Y., Li, F. (2021). Neural network assisted Kalman filter for INS/UWB integrated seamless quadrotor localization. *PeerJ Computer Science, 7,* e630. doi: https://doi.org/10.7717/peerj-cs.630
11. Park, K.-S., Kim, S.-H., Guerra Padilla, G. E., Kim, K.-J., Yu, K.-H. (2018). Operational Performance Evaluation of Remote Controllers for Manual Control of UAV. *Journal of Institute of Control, Robotics and Systems, 24 (4),* 315–320. doi: https://doi.org/10.5302/j.icros.2018.18.8001
12. Nguyen, M. D., Le, L. B., Girard, A. (2022). Integrated UAV Trajectory Control and Resource Allocation for UAV-Based Wireless Networks With Co-Channel Interference Management. *IEEE Internet of Things Journal, 9 (14),* 12754–12769. doi: https://doi.org/10.1109/jiot.2021.3138374
13. Khan, M. A., Qureshi, I. M., Khan, I. U., Nasim, A., Javed, U., Khan, W. (2018). On the Performance of Flying Ad-hoc Networks (FANETs) with Directional Antennas. *2018 5th International Multi-Topic ICT Conference (IMTIC).* doi: https://doi.org/10.1109/imtic.2018.8467274
14. Zhang, L., Tao, C., Yang, G. (2011). Wireless Positioning: Fundamentals, Systems and State of the Art Signal Processing Techniques. *Cellular Networks – Positioning, Performance Analysis, Reliability.* doi: https://doi.org/10.5772/14841
15. Fakharian, A., Gustafsson, T., Mehrfam, M. (2011). Adaptive Kalman filtering based navigation: An IMU/GPS integration approach. *2011 International Conference on Networking, Sensing and Control.* doi: https://doi.org/10.1109/icnsc.2011.5874871
16. Li, J., Zhang, X. (2014). Two-dimensional angle estimation for monostatic MIMO arbitrary array with velocity receive sensors and unknown locations. *Digital Signal Processing, 24,* 34–41. doi: https://doi.org/10.1016/j.dsp.2013.08.005

✉***Robert Bieliakov,*** *PhD, Associate Professor, Scientific-Organizational Department, Military Institute of Telecommunication and Information Technologies named after the Heroes of Kruty, Kyiv, Ukraine, e-mail: france417@gmail.com, ORCID: https://orcid.org/0000-0001-9882-3088*

Oleksii Fesenko, *Lecturer, Department of Technical and Metrological Support, Military Institute of Telecommunication and Information Technologies named after the Heroes of Kruty, Kyiv, Ukraine, ORCID: https://orcid.org/0000-0002-2114-5327*

✉*Corresponding author*