ISSN 1814-4225 (print)
ISSN 2663-2012 (online)

UDC 654.165:621.395.742:621.391.825 **doi: 10.32620/reks.2023.2.13**

Aleksandr SERKOV[1], Oleg KASILOV[1], Bogdan LAZURENKO[1], Volodimir PEVNEV[2], Karyna TRUBCHANINOVA[3]

[1] ***National Technical University "Kharkiv Polytechnic Institute", Kharkiv, Ukraine***
[2] ***National Aerospace University "Kharkiv Aviation Institute", Kharkiv, Ukraine***
[3] ***Ukrainian State University of Railway Transport, Kharkiv, Ukraine***

STRATEGY OF BUILDING A WIRELESS MOBILE COMMUNICATION SYSTEM IN THE CONDITIONS OF ELECTRONIC COUNTERACTION

*The **subject** of research in this article is the process of building a mobile communication system that operates under electronic countermeasures. The **aim** is to develop recommendations for building a wireless mobile communication system that operates effectively in a complex interfering electromagnetic environment. The strategy for building a mobile wireless communication system is based on the use of a grouping of low-altitude UAVs with ultra-wideband signal technology circulating in control and communication channels, with the integration of artificial intelligence elements into its structure. The **objective** of this study is to ensure the stable and secure operation of a wireless mobile communication system despite electronic countermeasures. The **methods** of analytical, temporal positional pulse coding, and fuzzy logical inference were used to make decisions on the transfer of service in the network. The following **results** were obtained. A strategy for building a wireless mobile communication system despite electronic countermeasures has been developed. It is shown that in order to obtain high noise immunity of control and communication channels and to protect information from interception, wireless ultra-wideband communication technology should be used. This will provide large volumes and speeds of information transmission. A technical solution for the design of an ultra-wideband transceiver antenna system is proposed. Moreover, it is recommended to use the results of data processing in a fuzzy decision-making system for the transfer of service between mobile network nodes in conditions of interference. **Conclusions**. The scientific novelty of the obtained results is as follows. The use of ultra-wideband channels makes it possible to increase the number of control and communication channels in a wireless mobile system almost unlimitedly. The preliminary distribution of orthogonal codes between the channels realizes the process of control and communication without the interception of information and mutual interference. The use of the time-position-pulse coding method prevents the occurrence of intercharacter distortions of the encoding ultrashort pulses. This also reduces the level of distortion of information signals caused by multipath propagation, which guarantees the security of information in the system. The use of a fuzzy decision-making system for the transfer of services between mobile network nodes allows dynamically changing the network topology in real time and maintaining high quality of service under electronic countermeasures.*

***Keywords**: mobile wireless network; security; ultra-wideband control and communication channel; radio-electronic countermeasures; fuzzy system.*

Introduction

Motivation. Existing fifth-generation (5G) terrestrial wireless mobile communications technologies have difficulty providing adequate coverage in remote areas and meeting the stringent quality of service (QoS) standards expected of terrestrial networks. To solve the coverage problem, two directions were chosen: the use of a group of satellites or unmanned aerial vehicles (UAVs). The quality of service of the system can be ensured through the use of special types of signals that allow for high noise immunity of control and communication channels and protection of information from interception. Other means of countering electronic interference is the ability to dynamically change the network topology in real time.

State of the Art. Using a satellite constellation to provide broadband is one way to ensure reliable coverage in remote areas. The most famous in this area today is the global Starlink satellite system. Since 2019, SpaceX has launched about 3,500 Starlink satellites, which is about half of the total number of active satellites currently in orbit. It is planned to launch up to 40,000 satellites [1]. One of the advantages of this system is its resistance to electronic countermeasures [2]. This is primarily due to the high density of satellite architecture and software updates [3]. One of the serious disadvantages of this system is the need to use special terminals, as the Starlink system does not allow the signal to be transmitted directly to the phone [4].

An alternative solution is to use of UAVs in the form of atmospheric satellites (with a balloon or aerodynamic type design [5, 6]).

The balloon as an option for using UAVs was implemented by Loon. The control was carried out using an autonomous system that considered the wind speed and direction, could change the flight altitude, and thus could reach a given area [5].

An atmospheric satellite of the aerodynamic type uses solar energy in the air, while flying at night uses the energy accumulated during the day in batteries. The most well-known project of such vehicles is the Solar-Powered Skydweller project, which was launched in 2002. The last test flight was conducted in February 2023. During the initial verification summer tests, the system autonomously controlled the aircraft from takeoff to landing without the participation of a pilot, although there was a safety pilot on board [7, 8].

The advantages of atmospheric satellites are high bandwidth due to the operation of satellites in a wide range of gigahertz frequencies - a satellite can support several thousand voice communication channels, energy efficiency (solar panels), less impact of various atmospheric phenomena on signals between the satellite and the Earth compared to satellite repeaters, lower time delays (up to 150 ms) in data transmission, and lower cost [9, 10].

The disadvantages are the likelihood of mutual distortion of radio signals from ground stations operating at neighboring frequencies, the need to spend time and money to ensure confidentiality of data transmission and prevent the possibility of data interception by third-party stations [10].

The use of a single UAV as a cellular base station in the absence of radio interference will be a fairly effective solution for creating a mobile network. The radius of stable reception will be determined by the UAV's flight altitude and the characteristics of the transmitting and receiving equipment installed on board. At a flight altitude of 50 m and an individual receiver at an altitude of 0 to 2 m, this radius of radio visibility will be 25 to 30 km. However, both UAV and individual transmitting devices cannot provide a signal energy level at such distances that corresponds to stable reception. This radius will be 2–3 times smaller.

The disadvantages of using single low-altitude UAVs as repeaters are their vulnerability to electromagnetic pulses, relatively short flight times, and high probability of control interception.

The use of a group of low-altitude UAVs allows for an expanded coverage area and improved service quality. Each of them is equipped with a switching module, which allows them to coordinate and interact with each other. Moreover, to fully ensure global connectivity in the next-generation wireless air network, it must be combined with ground networks. This creates a hybrid wireless network that can provide users with quality services everywhere and at any time.

The basis of the hybrid wireless network is the airborne mobile peer-to-peer network FANET (Flying Ad Hoc Network) [11]. It is a set of UAVs that are connected by communication channels to each other, external ground-based control points, and base stations of ground-based mobile communications. At the same time, each UAV can directly transmit information from the source to the user [12].

A distinctive feature of this system is the concentration of several electromagnetic radiation sources in a limited space, which have a diverse amplitude and frequency range [13]. The presence of such a complex electromagnetic environment complicates the quality of the network [14], causing failures in control systems and communication channels [15]. At the same time, there is a real possibility of unauthorized access to information circulating in the network, as well as the likelihood of unauthorized interception of the UAV control channel by organized electronic countermeasures [16].

Transmitting radio frequency signals to destroy a targeted UAV system is a typical method of counter-UAV warfare, divided into hard and soft jamming according to the degree of damage. Hard jamming refers to the use of powerful RF signals to damage target systems, especially communication-related devices. In [17, 18], the impact of a broadband powerful electromagnetic pulse on UAV components based on a quadcopter UAV was studied and it was indicated that the receiver and GPS are the most vulnerable modules. Soft destruction mainly involves deceiving the target system by transmitting false navigation or interfering with normal communication [19].

Based on the analysis of possible ways to build wireless mobile communication systems, it can be concluded that it is necessary to use a grouping of low-altitude FANET-type UAVs with the use of methods of masking control and information transmission channels to ensure the survivability of the communication system and quality service to subscribers in difficult conditions and remote areas.

The aim of this work is to develop a strategy for building a wireless mobile communication system that works effectively in a complex interfering electromagnetic environment.

Objectives and approach. This paper presents a strategy for building a wireless mobile communication system. It functions effectively under the conditions of electronic countermeasures. This allows us to obtain some advantages that cannot be obtained by traditional methods.

ISSN 1814-4225 (print)
ISSN 2663-2012 (online)

To solve this problem, it is necessary to study:

- features of the FANET network functioning in the conditions of electronic countermeasures
- possible options for ensuring security during information transmission;
- model of the antenna element;
- options for UAV route optimization in terms of network survivability.

1. Features of the FANET network functioning in the conditions of organized electronic countermeasures

Electronic countermeasures systems generate an interfering electromagnetic environment in a specific frequency range. Traditionally, the frequency range from 0.5 to 18 GHz is used. At the same time, the radiation power of organized interference in airborne systems is on average 40–150 W, ground-based systems – 0.5–1 kW, and sea-based systems – 1–10 kW. The main principle used in the development of electronic countermeasures is their ability to create interference that should be 30 dB higher than the signal power used to create the interference. According to the classification of the international standard IEC 61000-2-13 [20], the interfering electromagnetic environment, which in free space has a destabilizing electromagnetic effect on the control and communication channels of UAVs, is more than 100 v/m of the electrical component or 0.27 A/m of the magnetic component [21].

Despite the wide variety of UAV types, their generalized parameters [22] are:

– maximum power of the radiation signal in the control channel – 100 mW;
– typical frequency range – 2.4... 5.8 GHz;
– single pulse width – 0.9 μS;
– inter-pulse interval – 1.2 μS.

The connection of individual devices to a FANET turns it into a complex dynamic system that operates under conditions of significant a priori uncertainty and randomly organizes the interaction of its various components. Due to the high mobility of UAVs in the FANET, the critical factor is the fulfillment of electromagnetic compatibility requirements [23]. At the same time, their movement in three-dimensional space complicates mobility problems because movement leads to disconnection of current users and requires updating the locations of all nodes in the network. Each UAV needs to know the location of other devices in real time, which requires the need to obtain reliable and stable communication between devices to maintain an appropriate level of quality of service (QoS) and quality of experience (QoE) [24].

The analysis of the network's functioning allows us to identify two of its features. The first is the ability to move the UAV automatically according to a predefined programme. The second is the interception of information in digital radio channels.

Moreover, the use of UAV bodies made of composite materials makes them virtually invisible to radar stations. At the same time, the presence of a set of tools for UAV control and potentially vulnerable points in data transmission protocols, software of control, data transmission and navigation systems poses a threat to the security of the wireless network. It depends on the structure of the network and its location in space, the location of users, the length of the access line, the physical and geographical conditions of the area, as well as the ability to provide the user with several routes for information transmission at the same time [25].

2. Security in the FANET network

The main requirements for network information security are to ensure its availability and integrity.

The availability of communications means is the ability to provide the user with the necessary resources of the communications system, the spatial topology of users and the stability of communications elements despite organized electronic countermeasures. Integrity means the ability of the system to counteract unauthorized changes to information and/or restore distorted information within a specified time using built-in means. The most common means of ensuring the integrity of information are methods of interference-resistant coding and concealment of the fact of transmission [26]. Communications availability is the ability to provide a user with the necessary communications system resources. It also ensures the spatial topology of users and the resilience of communication elements despite electronic countermeasures. Integrity is the ability of the system to counteract unauthorized changes to information and/or restore distorted information within a given time using built-in means. The most common means of ensuring the integrity of information are methods of noise immunity coding and concealment of the fact of transmission [26].

The noise immunity of the UAV control system and communication channel is defined as the maximum level of electromagnetic interference at which it maintains the proper quality of operation. Increasing noise immunity is facilitated by coding in the information and control channels. In the presence of external influencing factors, the use of known algebraic, cascade, wrapper, and other codes, as well as methods for their decoding [27], requires redundancy, which leads to a decrease in the information transmission rate. At the same time, the need to increase the transmission rate of control signals in wireless channels requires the use of the widest possible frequency range. Thus, the known methods of encoding information and control signals in wireless UAV channels do not provide the necessary noise immunity, which requires the development of new approaches to solving this problem. The physical limitation of the frequency spectrum has led to the need to use ultra-wideband communication technologies [28].

In wireless control and communication channels, the transmission medium is the physical path between the transmitter and the receiver. In this case, the characteristics of the transmission medium are less important than the bandwidth of the radiation signal. The most common and optimal range is from 1 to 10 GHz. Due to frequencies below 1 GHz there is significant interference from various industrial electronic devices. At the same time, at frequencies above 10 GHz, there is a large absorption of the useful signal by the transmission medium [29].

When using ultra-wideband information transmission, a deliberate transformation of relatively narrowband information signals with an effective spectral width Δf to an ultra-wideband signal with an effective spectral width ΔF is performed, provided that the total signal energy E is preserved. In this case, the spectral energy density of the channel signal is deliberately reduced by a factor of $\Delta F/\Delta f$ and will be $\Delta E/\Delta F$. The base of the channel signal also increases in $\Delta F/\Delta f$ times accordingly. The base of an ultrashort pulse signal is the product of the signal duration and its spectral width. The simplest and most convenient method for expanding the signal base is to directly expand the frequency spectrum. The higher the frequency of use, the higher the potential data rate.

Thus, ultra-wideband communication technology is based on the transmission of low-power coded pulses in a very wide frequency band without a carrier frequency. Usually, it is not a harmonic oscillation that is emitted, but an ultra-short pulse, the duration of which is in the range of 0.2 – 2.0 ns, and the period of the pulse sequence is 10 – 100 ns. Usually, such signals are in the form of idealized Gaussian monocycles, the main part of the radiation spectrum of which is located in the frequency range from 1 to 10 GHz [30]. Thus, using a Gaussian monocycle with a duration of 2.0 ns to 0.1 ns, the bandwidth of the power spectrum will be from 500 MHz to 10 GHz, respectively. The signal spectrum will occupy the entire frequency band from 0 to $\Delta F \approx 1/\Delta t$.

In the control and communication channels, information is encoded by time-position pulse modulation. Thus, the shift of a pulse relative to its reference position in the sequence forward sets a zero bit, and backward – a one bit, and the shift time does not exceed a quarter of the pulse duration. One information bit is encoded by a sequence of many pulses (chips) per bit. To separate the information channels, the location of each pulse is additionally shifted by a time proportional to the current value of some pseudo-random sequence. Moreover, the shift time is one to two orders of magnitude higher than the shift in the time modulation. Each of the communication channels is assigned its own expanding code combination, the elements of which make up the orthogonal basis and define the channel code. The information message is restored only if the receiver and transmitter use the same channel code, which increases the noise immunity of signals in a wireless control and communication system. The useful signal is extracted against the background of noise and interference by correlating the received and reference signals. The correlator convolves the received signal with the reference signal. It is an ideal detector for determining the time shifts of received pulses relative to the reference. Thus, when receiving a one, the correlation function is equal to +1, and when receiving a zero, it takes the value –1. In all other cases, the correlation function is 0. Given that one information bit is represented, for example, by 200 ultra-short chips, when they match, they accumulate in the receiver integrator. Thus, the information bit will be detected even if 99 out of 200 chips are lost. The useful signal is extracted from the noise, which in this case significantly exceeds its level in the signal-to-noise ratio. This method ensures that the fact of transmission is concealed.

At the same time, encoding an information bit with a series of ultrashort pulses solves the problem of multipath signal propagation. This is because signals arriving with a time shift due to different paths will be rejected as interference. In addition, the use of a series of ultrashort pulses to encode an information bit makes it possible to eliminate intercharacter interference. Before the next ultrashort pulse from a series of encoding chips arrives, the energy of the previous chip has time to completely dissipate. When emitted, the coded information pulse signals are in a very wide frequency band without a carrier frequency, the requirements for the broadband of the transceiver antennas are basic.

3. Antenna modeling

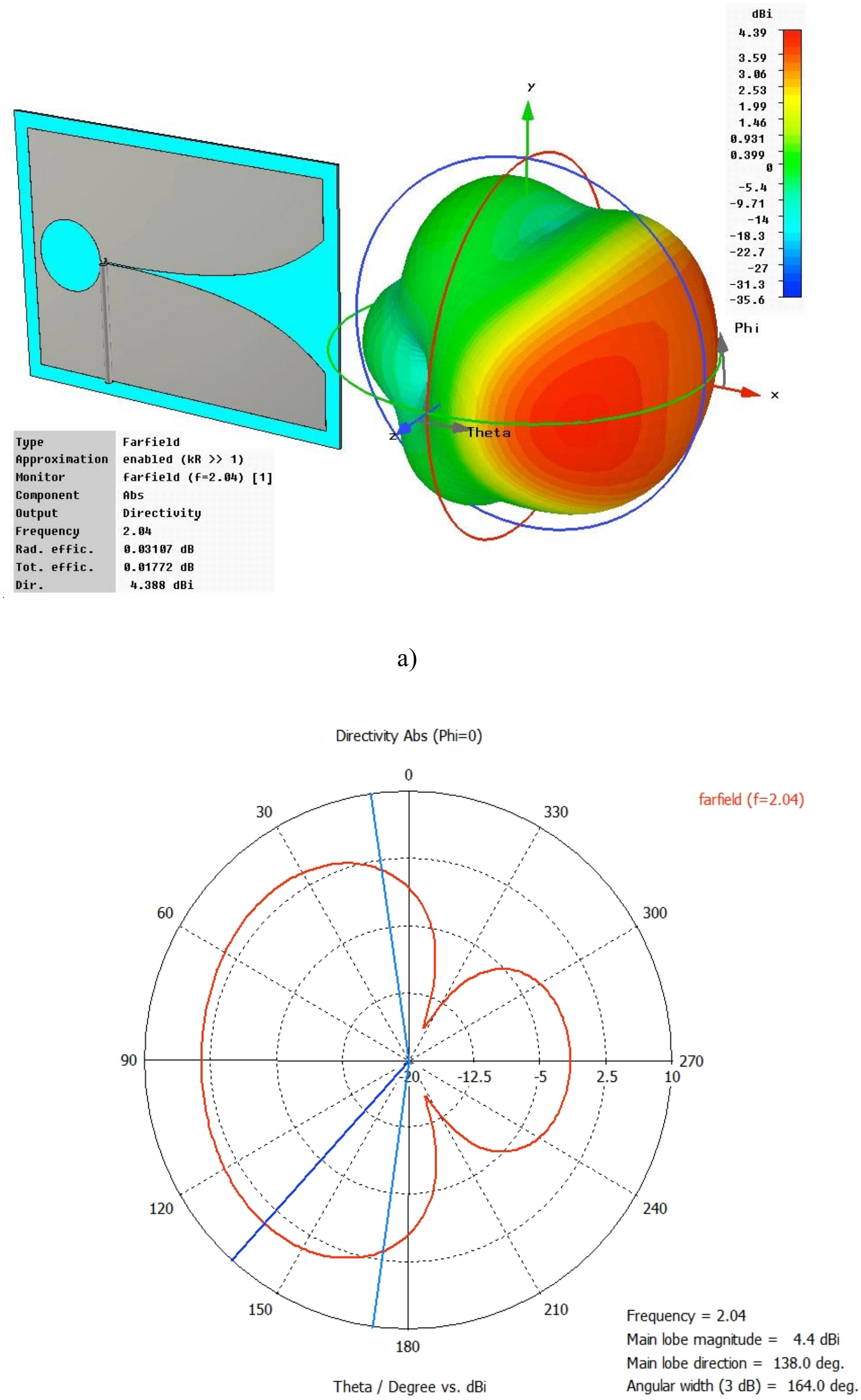
According to the technical characteristics, the most suitable antenna element is the Tapered Slot Antenna (TSA) [31]. The mathematical model of the antenna was created in the CST software environment. The results of modeling its main characteristics are shown in Fig. 1, and the block design is shown in Fig. 2 [32, 33].

The shape of open slot determines the frequency band. Moreover, the energy pattern of such an antenna is characterized by a narrow main beam and the practical absence of side lobes. However, the preliminary formation of Gaussian monocycle entering the antenna system causes difficulties in matching in a wide frequency band. This manifests itself in the form of re-reflection of individual signal components, which distorts the shape of

ISSN 1814-4225 (print)
ISSN 2663-2012 (online)

Gaussian monocycle. Therefore, the radiation pulse is formed directly in the antenna opening [32].

To do this, the information monopulse signal is split in half. A portion of the signal is sequentially inverted and delayed for a period of time equal to half the duration of the monopulse. Both mono-pulse signals are used to excite two TSA antennas located side by side on a single dielectric base. The electromagnetic fields of both monopulse signals interfere with the equivalent common aperture space of both antennas, creating a bipolar pulse electromagnetic field in it, while eliminating the time gap between the two parts of the radiated field, which is typical for a TSA antenna. Thus, such an antenna in an ultra-wideband communication system is capable of emitting and receiving both an ultra-short unipolar monopulse and a bipolar pulse information signal. This makes it possible to significantly increase (by 3 to 10 times) the range of propagation of pulsed electromagnetic signals.



a)

b)

Fig. 1. TSA antenna geometry, 3-D (a) and 2-D (b) radiation patterns of the antenna at 2040 MHz

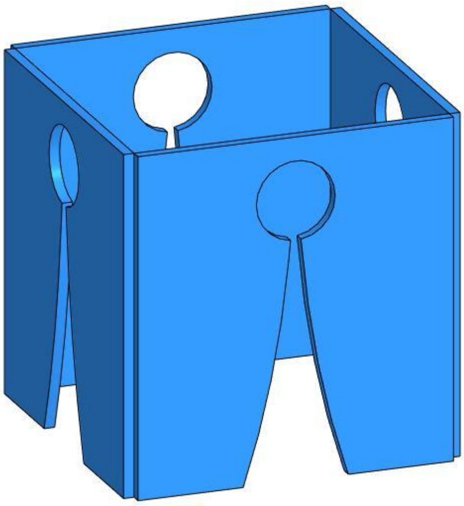


Fig. 2. Design of the antenna unit

4. UAV trajectory optimization in the FANET network

The combination of indicators of the level of mobility, the direction of UAV movement, the bandwidth of communication channels and the indication of the received signal strength make up an integral indicator for making a decision on the transfer of service between devices. Thus, it is advisable to apply an intelligent method of information and service transmission by integrating artificial intelligence elements into a wireless mobile communication network [33].

The optimal routing algorithm provides support for the required noise immunity and quality of information transmission and UAV control functions. Note that the routing protocol cannot be implemented in a simple proactive or reactive way because the UAV wireless network needs to be reorganized repeatedly when the UAV is not operating. In addition, it is difficult to instantly control the transfer of user links from an inactive UAV to an active UAV [34].

A special feature in solving the problem of increasing the interference resistance of a wireless FANET is the method of controlling the trajectories of individual UAVs to create a network configuration that minimizes the impact of electronic interference. The implementation of this method, in particular, provides for the organization of the exit of individual network elements from the interference zone to transmit information to the base station on ground networks.

The basis for organizing a wireless network is the creation of a network that is resistant to electronic interference both within the network and by external ground-based control points. At the same time, the possibility of direct information interaction within the network and with external ground-based control points using ultra-wideband signals are realized.

The restriction on the formation of the optimal route for information transmission within the network is not to exceed the permissible value of the probability of error in the transmission of information between the subscriber and the user along the corresponding route using ultra-wideband technologies.

The FANET network topology model is a graph represented by a number of vertices - communication nodes. The communication channel directly connects nodes i and j creates a branch $\beta^{(i,j)}$. The quality of data transmission by the network branch $\beta^{(i,j)} \in M$ characterizes the probability of information transmission error in the network:

$$P_e^{(i,j)} = P_a^{(i,j)}(0)P_{fa}^{(i,j)} + P_a^{(i,j)}(1)P_m^{(i,j)},$$

where $P_a^{(i,j)}(0), P_a^{(i,j)}(1)$ – a priori probabilities of signal presence and absence;

$P_{fa}^{(i,j)}, P_m^{(i,j)}$ – corresponding probabilities of false alarm and signal miss.

For the optimal receiver, which is built using the criterion of the ideal observer under the conditions of equal values of the a priori probabilities $P_a^{(i,j)}(0) = P_a^{(i,j)}(1) = 0.5$ and the cost of incorrect decisions $C_{01} = C_{10}$, the probability of error in the network guild will be as follows:

$$P_e^{(i,j)} = P_{fa}^{(i,j)} = P_m^{(i,j)} = \left[1 - \Phi_0\left(\frac{q^{(i,j)}}{2\sqrt{2}}\right)\right],$$

where $\Phi(*)$ – the probability integral;

ISSN 1814-4225 (print)
ISSN 2663-2012 (online)

$q^{(i,j)}$ – the signal-to-noise ratio in the guild (i, j) of the network.

Ordering the set of edges included in the route, $\mu(i, j) = (\beta_1, \beta_2, ..\beta_R)$ between subscriber i between subscriber j we obtain the probability of error on the route $\mu(i, j)$:

$$P[\mu(i, j)] = 1 - \prod_{r-1}^{R} (1 - P(\beta_r)), \qquad (1)$$

where R – the number of graph branches included in the route $\mu(i, j)$;

$P(\beta_r)$ – probability of information transmission error along the edge β_r.

The rule for choosing the optimal route when transmitting information from subscriber i to user j will be as follows:

$$\begin{gathered} \mu(i, j) = s \Leftrightarrow \\ \Leftrightarrow P_s[\mu(i, j)] = \min\{P_k[\mu(i, j)]\}, k = 1, S, \end{gathered} \qquad (2)$$

where S – the set of possible data transmission routes s between subscriber i and user j.

At the same time, the network performance indicator is used to measure the compliance of the probability of information transmission error along the route with the required acceptable value.

$$P[\mu(i, j)] \le P^E,$$

where P^E – the acceptable value of the error probability.

Relations (1), (2) define the rule for the formation of the optimal route of information transmission within the network. High mobility of FANET network elements increases the delay in information transmission and complicates the decision-making process of connecting a device to the current or another access point and creating an optimal route by transferring service to communication channels with higher quality.

The organization of suppression of FANET communication channels is usually carried out by means of a movable jammer. The spatial branching of network elements creates a different distance of each element to the jammer, which causes a different signal to noise ratio at the input of UAV receivers. This ratio allows the formation in real time of the current optimal data transmission route with the minimum possible errors.

The criterion for deciding whether to handover service is usually the power of the received signal [35]. However, this single criterion for selecting a route for information transmission in the network can lead to service disruptions because it can direct the route to an overloaded part of the network with low bandwidth. Thus, to guarantee continuous connectivity and quality of service in a mobile wireless network, a comprehensive criterion should be applied that additionally takes into account both the direction and speed of UAV movement, the bandwidth of communication channels, and the level of battery power. The use of a fuzzy system for making a decision on the transfer of service with a logical inference system allows for the evaluation and generation of output data for decision-making. In fuzzy systems, the results are classified in the range from 0 to 1. A value of 0 means absolute impossibility, and a value of 1 means full correlation. The output of the fuzzy system indicates the probability that the mobile device starts the service transfer process. In general, if the user has high mobility and a high level of received signal strength, there will be no handover process

For example, suppose that the system uses fuzzy logic and considers three input parameters. It processes them, evaluates them, and generates output data for decision-making. For example, the first one is related to the speed of the UAV. The faster it is moving, the less time it will be connected to the access point. Therefore, we divided the first parameter into three groups of linguistic values: slow (0-1.5 m/s), moderate (1.5-2.5 m/s) and fast (2.5-4 m/s). The second set of parameters relates to the level of the received signal. The linguistic values of the received signal are divided into three groups: weak (from -120 to -100 dB), moderate (from -100 to -70 dB) and strong (> -70 dB). The third set of parameters considers UAV's flight range. This determines how long the UAV can operate. This parameter helps to avoid unnecessary transmissions to UAVs that cannot complete the task. For this parameter, you can use the following sets of values: low (0-10 minutes), medium (10-20 minutes) and high (20-30 minutes) battery level. Thus, all these sets of parameters are part of a common logical conclusion. The service is transferred when the value of the logical conclusion is equal to or greater than 0.6.

In this case, an additional means of increasing the level of network interference protection is to control the trajectories of individual UAVs to create a network configuration that minimizes the impact of interference. In this case, it is advisable to choose the UAV that is most suitable for transferring control to it while moving with the organization of the exit of individual network elements from the zone of influence of electronic interference to transmit information to the ground network.

Given the use of ultra-wideband technologies in FANET communication channels, when the useful signal is below the noise level [36], the quality of the communication channel is simply the level of electromagnetic radiation, which, according to the developers of electronic countermeasures systems, should be 30 dB higher than the useful signal. Due to the high mobility of UAVs in a FANET, updating the location of all network nodes is a critical factor. Network devices must know the locations of other elements in real time.

Thus, in addition to using GPS, which sends location information on the average once per second. UAVs should send their location data at a shorter interval than GPS, which requires high-bandwidth communication channels.

Conclusions

The use of NSS technology in the control and communication channels of a FANET network allows for obtaining some advantages that cannot be obtained by traditional methods. In particular, this applies to improve the quality of wireless network channels. The expansion of the communication channel bandwidth and transition to broadband channels allows for an almost unlimited increase in the number of communication channels. Having previously distributed modulation codes among the channels, they operate without intercepting UAV control, information, and mutual interference.

An important indicator characterizing the efficiency of wireless mobile communications systems is the high potential specific density of data and information transmission. It is determined by the value of the total data transmission rate per square meter of the working area, which is currently about 1 Mbps/m2. The proposed and substantiated method of using short information pulses-chips allows avoiding inter-character distortion due to the dissipation of the energy of the received pulse before the next one arrives. This also reduces the level of distortion of information signals caused by its multipath propagation. The method of pulse formation proposed in this paper involves the use of an antenna with an expanding slot, in the opening of which a radiation pulse is directly formed. This study shows the results of modeling the proposed type of antennas and presents their characteristics. The use of this type of antenna can significantly increase (by a factor of 3–10) the propagation range of pulsed electromagnetic signals.

A characteristic feature inherent in control and communication systems based on ultra-wideband signals is the low probability of detecting both the fact of temporary establishment of communication channels and the impossibility of intercepting UAV control channels. It is also possible to operate simultaneously and without interference in the same frequency range of both traditional narrowband communication systems and systems with UWB signals. The levels of information and control signals do not exceed the noise level in the operating frequency range. At the same time, reducing the power and radiation level of electromagnetic fields guarantees the fulfillment of electromagnetic compatibility requirements at all stages of the development and implementation of a wireless mobile network FANET.

In the context of organized electronic countermeasures, the proposed method of determining the optimal routing by controlling the trajectories of individual UAVs to create a network configuration that minimizes the impact of interference contributes to increasing the level of network security. At the same time, the most suitable UAV is automatically selected in real time and control is transferred to it with the organization of its exit from the zone of influence of electronic interference to transmit information to the ground network.

Thus, on the basis of the research presented in this article, it is possible to develop a strategy for building a wireless mobile communication system under the conditions of electronic counteraction.

This primarily involves the use of a group of low-altitude UAVs, each of which can communicate with base stations on the ground and other UAVs. This strategy involves the rotation of aircraft in case of malfunction, possible damage, and need for recharging.

The second element of the strategy is the use of methods to hide the transmission of information and control signals, which are realized through the use of ultra-wideband signal and noise immune coding. To implement this method, it is proposed to use an antenna, the modeling results of which are presented in this article.

The next element of the strategy is the UAV flight route management system, which makes real-time decisions to change the flight route depending on the situation with obstacles, technical conditions, and possible malfunctions of the UAV.

Obviously, the use of UAVs leads to the need to solve some tasks that are not considered in the proposed work. Such tasks include the selection of UAV models that will provide the required quality of communication channels, ensuring timely withdrawal from the group and replacement of certain UAVs depending on their technical condition, organization of countering electronic warfare, and much more, which is part of the organization of the data transmission network.

Contributions of authors: review and analysis of references, formulation of the purpose and tasks of research, formulation of conclusions – **Bogdan Lazurenko**; development of conceptual provisions and methodology of research – **Aleksandr Serkov, Volodimir Pevnev, Karyna Trubchaninova**; development of mathematical models and analysis of research results – **Oleg Kasilov**.

All authors have read and agreed to the published version of the manuscript.

ISSN 1814-4225 (print)
ISSN 2663-2012 (online)

References

1. Starlink's performance in Ukraine has ignited a new space race. *The Economist*. Available at: https://www.economist.com/leaders/2023/01/05/starlinks-performance-in-ukraine-has-ignited-a-new-space-race (accessed January 12, 2023).

2. Watling, J. and Reynolds, N. *Ukraine at War. Paving the Road from Survival to Victory*. Royal United Services Institute for Defence and Security Studies, 2022. 24 p.

3. Simonite, T. How Starlink Scrambled to Keep Ukraine Online. *Wired*. Available at: https://www.wired.com/story/starlink-ukraine-internet/ (accessed May 11, 2022)

4. *Use, shcho potribno znaty pro Starlink* [Everything you need to know about Starlink]. Available at: https://l-a-b-a.com/uk/blog/3317-vse-chto-vam-nuzhno-znat-pro-starlink (accessed January 11, 2023).

5. *Project Loon*. Available at: https://x.company/loon/ (accessed January 11, 2023).

6. *Facebook's Aquila drone completes its second test flight, lands well this time*. Available at: https://techcrunch.com/2017/06/29/facebooks-aquila-drone-completes-it-second-testflight-lands-well-this-time/ / (accessed January 11, 2023).

7. *Solar Impulse - Around The World To Promote Clean Technologies*. Available at: https://aroundtheworld.solarimpulse.com/our-story/milestone-feasibility-study (accessed January 11, 2023).

8. Warwick, G. *Solar-Powered Skydweller Completes First Autonomous Flights*. Available at: https://aviationweek.com/aerospace/aircraft-propulsion/solar-powered-skydweller-completes-first-autonomous-flights (accessed February 7, 2023).

9. *What is Network Latency and Why Does It Matter?* Available at: http://www.telecomstalk.com/wp-content/uploads/2012/08/white-paper_latency-matters.pdf (accessed February 7, 2023).

10. Melnykov, S. V., Volkov, A. Ye., Korshunov, N. V. and Hryshchenko, Yu. Yu. Zastosuvannya bezpilotnykh lital′nykh system yak mobil′nykh kompleksiv radiozv″yazku [Using Unmanned Aerial Systems as the Mobile Radio Communication Complexes]. *Upravlyayushchiye sistemy i mashiny – Control Systems and Computers*, 2017, no. 5(271), pp. 54-61. DOI: 10.15407/usim.2017.05.054.

11. Ayass, T., Coqueiro, T., Carvalho, T., Jailton, J., Araújo, J. and Francês, R. Unmanned aerial vehicle with handover management fuzzy system for 5G networks: challenges and perspectives. *Intell Robot*, 2022, vol. 2, iss. 1, pp. 20-36. DOI: 10.20517/ir.2021.07.

12. Kravchenko, V. and Serkov, O. *Radioelektronni zasoby borot'by, prydushennya ta sylovoho urazhennya* [Radio-electronic means of combat, suppression and force defeat]. Kharkiv, Madrid Printing House Publ., 2022. 422 p.

13. Panchenko, S., Serkov, O. and Trubchaninova, K. *Teoriya i praktyka elektromahnitnoyi sumisnosti telekomunikatsiynykh system* [Theory and practice of electromagnetic compatibility of telecommunication systems]. Kharkiv, USURT, 2020. 249 p.

14. Berdnyk, S., Gomozov, A., Gretskih, D., Kartich, V. and Nesterenko, M. Approximate boundary conditions for electromagnetic fields in electrodmagnetics. *Radioelektronni i komp'uterni sistemi – Radioelectronic and computer systems*, 2022, no. 3(103), pp. 141-160. DOI: 10.32620/reks.2022.3.11.

15. Makarov, S. A., Chekunova, O. M. and Beliak, S. P. Metodyka otsinky zavadostiykosti systemy zv"yazku povitryanykh syl [Methodology for assessing the interference resistance of the air force communication system]. *Systemy ozbroyennya i viys'kova tekhnika – Weapon systems and military equipment*, 2020, no. 1 (61), pp. 128-135. DOI: 10.30748/soivt.2020.61.15.

16. Zinchenko, A. O., Pikul, R. V., Zinchenko, K. A., Liubarchuk, K. V., Yusukhno, Ye. A., Maksimenko, O. M., Sokil, Yu. M. and Ryndin, Yu. I. Metodychnyy pidkhid z otsinky efektyvnosti systemy zv"yazku spetsial'noho pryznachennya [A methodical approach to evaluating the effectiveness of a special purpose communication system]. *Systemy upravlinnya, navihatsiyi ta zv"yazku – Control, navigation and communication systems*, 2020, vol. 1, no. 59, pp. 132-136. DOI: 10.26906/SUNZ.2020.1.132.

17. Zhang, J., He, Y. and Pan, X. Vulnerability Analysis of UAV against Mesoband Electromagnetic Pulse. *J. Proj. Rocket. Missiles Guid*, 2020, vol. 40, pp. 110-115.

18. Wang, T., Peng, S. and Wang, G. Analysis of the Interference Mechanism of High PRF Pulse Jamming to the Front End of GPS Receiver. *J. Air Force Early Warn. Acad.*, 2021, vol. 35, pp. 248-253.

19. Zhang, X., Bai, Y. and He, K. On Countermeasures against Cooperative Fly of UAV Swarms. *Drones*, 2023, vol. 7, iss. 3, article no. 172. DOI: 10.3390/drones7030172.

20. *IEC 61000-2-13:2005. Electromagnetic compatibility (EMC) – Part 2-13: Environment – High-power electromagnetic (HPEM) environments – Radiated and conducted*. International Electrotechnical Commission, 2005. 40 p. Available at: https://webstore.iec.ch/publication/4131 (accessed February 7, 2023).

21. United States Federal Communications Commission (FCC). Decision No. FCC 02-48 of 14/02/2002. Available at: https://transition.fcc.gov/Bureaus/Engineering_Technology/Orders/2002/fcc02048.pdf. (accessed January19, 2023).

22. Zuo, Z., Liu, C., Han, Q.-L. and Song J. Unmanned Aerial Vehicles: Control Methods and Future Challenges. *IEEE /CAA Journal of Automatica Sinica*. 2022, vol. 9, no. 4, pp. 601-614. DOI: 10.1109/JAS.2022.105410.

23. Noorwali, A., Javed, M. A. and Khan, M. Z. Efficient UAV communications: recent trends and challenge. *Computers, Materials & Continua,* 2021, vol. 67, iss. 1, pp. 463-476. DOI: 10.32604/cmc.2021.014668.

24. Harmuth, H. F. *Nonsinusoidal Waves for Radar and Radio Communication*. New York, Academic Press Publ., 1981. 396 p.

25. *Enhanced LTE support for aerial vehicles.* 3GPP Portal. Available at: https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=3231. (accessed January 19, 2023).

26. Pevnev, V., Frolov, A., Tsuranov, M. ad Zemlianko, H. Ensuring the Data Integrity in Infocommunication Systems. *International Journal of Computing,* 2022, vol. 21, iss. 2, pp. 228-233. DOI: 10.47839/ijc.21.2.2591.

27. Tkachov, V., Kovalenko, A., Kuchuk, H. & Ni, I. Metod zabezpechennya zhyvuchosti vysokomobilʹnoyi komp'yuternoyi merezhi [Method of ensuring the survivability of highly mobile computer networks]. *Suchasni informatsiyni systemy – Advanced Information Systems.* 2021, vol. 5, iss. 2, pp. 159-165. DOI: 10.20998/2522-9052.2021.2.24.

28. Serkov, A., Kravets, V., Yakovenko, I., Churyumov, G, Tokariev, V. & Namnan, W. Ultra-Wideband Signals in Control Systems of Unmanned Aerial Vehicles. *10th International Conference on Dependable Systems, Services and Technologies (DESSERT'2019),* June 5-7, 2019, Leeds, United Kingdom, 2019, pp. 25-28. DOI: 10.1109/DESSERT.2019.8770039.

29. Minoli, D. *Innovations in Satellite Communications and Satellite Technology*. *The Industry Implications of DVB-S2X, High Throughput Satellites, Ultra HD, M2M, and IP*. John Wiley & Sons, Inc., Hoboken, New Jersey, 2015. 420 p. Available at: https://data.kemt.fei.tuke.sk/DigitalnaTelevizia/prednasky/Prednaska_DTV_7_11_17/eBooks%20(12-03-2015)/adn8c.Innovations.in.Satellite.Communication.and.Satellite.Technology.pdf (accessed January 19, 2023).

30. Saad, W., Bennis, M., Mozaffari, M. & Lin, X. *Wireless communications and networking for unmanned aerial vehicles.* Cambridge, Cambridge University Press Publ., 2020. 249 p. DOI: 10.1017/9781108691017.

31. Wolff, C. *Tapered Slot Antenna (Vivaldi- Antenna).* Available at: https://www.radartutorial.eu/06.antennas/Tapered%20Slot%20Antenna.en.html (accessed February 7, 2023).

32. Serkov, O. A., Lazurenko, B. O., Pevnev, V. J., Tkachenko, V. A. & Kharchenko, V.S. *Sposib peredachi informatsiyi nadshyrokosmuhovymy impul'snymy syhnalamy* [The method of transmitting information using ultra-broadband pulse signals]. Patent UA, no. 123519, 2021.

33. Panchenko, S. V., Serkov, O. A., Trubchanynova, K. A., Kurtsev, M. S. & Lazurenko, B. O. *Nadshyrokosmuhova antena z merekhtlyvoyu polyaryzatsiyeyu ta sposib yiyi zbudzhennya* [Ultra-wideband antenna with flickering polarization and method of its excitation]. Patent UA, no. 126475, 2022.

34. Khan, M. A., Qureshi, I. M., Safi, A. & Khan, I. U. Flying Ad-Hoc Networks (FANETs): A Review of Communication architectures, and Routing protocols. *First International Conference on Latest trends in Electrical Engineering and Computing Technologies (INTELLECT), Nov. 15-16, 2017,* Karachi, Pakistan, 2017, pp. 1-9. DOI: 10.1109/INTELLECT.2017.8277614.

35. Serkov, A., Tkachenko, V., Kharchenko, V., Pevnev, V., Trubchaninova, K. & Doukas, N. Method of Increasing Security of Spatial Intelligence in the Industrial Internet of Things Systems. *24th International Conference on Circuits, Systems, Communications and Computers (CSCC'2020), July 19-22, 2020,* Platanias Chania Grete Island, Greece, 2020, pp. 283-289. DOI: 10.1109/CSCC49995.2020.00058.

36. Saeed, A. S., Younes, A. B., Cai, C. & Cai, G. A survey of hybrid unmanned aerial vehicle. *Progress in Aerospace Sciences*, 2018, vol. 98, pp. 91-105. DOI: 10.1016/j.paerosci.2018.03.007.

Received 24.01.2023, Accepted 20.05.2023

СТРАТЕГІЯ ПОБУДОВИ БЕЗПРОВІДНОЇ МОБІЛЬНОЇ СИСТЕМИ ЗВ'ЯЗКУ В УМОВАХ РАДІОЕЛЕКТРОННОЇ ПРОТИДІЇ

Олександр Серков, Олег Касілов, Богдан Лазуренко, Володимир Пєвнєв, Карина Трубчанінова

Предметом дослідження в статті є процеси побудови системи мобільного зв'язку, що працює в умовах радіоелектронної протидії. Мета – розробка рекомендацій щодо побудови безпровідної мобільної системи зв'язку, що ефективно працює у складній завадовій електромагнітній обстановці. В основу стратегії побудови системи мобільного безпровідного зв'язку покладено використання угруповання маловисотних БПЛА з застосуванням технології надширокосмугових сигналів, які циркулюють в каналах управління та зв'язку із інтеграцією до її структури елементів прийняття рішення . Завдання дослідження полягає в забезпеченні усталеної та безпечної роботи безпровідної мобільної системи зв'язку в умовах організованої радіоелектронної протидії. В роботі використовувалися методи аналітичного, часового позиційно-імпульсного кодування та нечіткого логічного висновку для прийняття рішень щодо передачі обслуговування у мережі. Отримані наступні результати. Розроблена стратегія побудови безпровідної мобільної системи зв'язку в умовах радіоеле-

ISSN 1814-4225 (print)
ISSN 2663-2012 (online)

ктронної протидії. Показано, що для отримання високої завадостійкості каналів управління і зв'язку та захисту інформації від перехоплення слід застосовувати технологію безпровідного надширокосмугового зв'язку, яка дозволяє забезпечити великі обсяги та швидкості передачі інформації. Запропоновано технічне рішення щодо конструкції надширокосмугової приймально-передавальної антенної системи. Причому, рекомендовано використовувати результати обробки даних у нечіткій системі прийняття рішень для передачі обслуговування між вузлами мобільної мережі в умовах завад. Висновки. Наукова новизна отриманих результатів полягає в наступному. Використання каналів із надширокою смугою частот дає можливість практично необмежено збільшити кількість каналів управління та зв'язку у безпровідній мобільній системі. Попередній розподіл між каналами ортогональних кодів реалізує процес управління та зв'язку без перехоплення інформації та взаємних завад. Використання методу часового позиційно-імпульсного кодування запобігає виникненню міжсимвольних спотворень кодуючих надкоротких імпульсів. При цьому також знижується рівень спотворень інформаційних сигналів, які викликані його багатопроменевим розповсюдженням, що гарантує безпеку інформації в системі. Використання нечіткої системи прийняття рішень у випадку передачі обслуговування між вузлами мобільної мережі дає змогу у режимі реального часу динамічно змінювати топологію мережі та підтримати високу якість обслуговування в умовах радіоелектронної протидії.

Ключові слова: мобільна бездротова мережа; надширокосмуговий канал управління та зв'язку; радіоелектронна протидія; нечітка система.

Серков Олександр Анатолійович – д-р техн. наук, проф., проф. каф. систем інформації, Національний технічний університет «Харківський політехнічний інститут», Харків, Україна.

Касілов Олег Вікторович – канд. техн. наук, доц., проф. каф. систем інформації, Національний технічний університет «Харківський політехнічний інститут», Харків, Україна.

Лазуренко Богдан Олександрович – асп. каф. систем інформації, Національний технічний університет «Харківський політехнічний інститут», Харків, Україна.

Пєвнєв Володимир Яковлевич – д-р техн. наук, доц., проф. каф. комп'ютерних систем, мереж і кібербезпеки, Національний аерокосмічний університет ім. М. Є. Жуковського «Харківський авіаційний інститут», Харків, Україна.

Трубчанінова Карина Артурівна – д-р техн. наук, проф., проф. каф. транспортного зв'язку, Український державний університет залізничного транспорту, Харків, Україна.

Aleksandr Serkov – D.Sc. (Technical Sciences), Full Professor, Professor of Information Systems Department, National Technical University "Kharkiv Polytechnic Institute", Kharkiv, Ukraine,
e-mail: aleksandr.serkov@hotmail.com, ORCID: 0000-0002-6446-5523, Scopus Author ID: 8345715900,
Researcher ID: AEQ-1018-2022, https://scholar.google.com.ua/citations?hl=ru&user=CnNlKC8AAAAJ.

Oleg Kasilov – PhD (Technical Sciences), Associate Professor, Professor of Information Systems Department, National Technical University "Kharkiv Polytechnic Institute", Kharkiv, Ukraine,
e-mail: o.kasilov@hotmail.com, ORCID: 0000-0002-8524-2345, Scopus Author ID: 55976743600,
https://scholar.google.com.ua/citations?hl=ru&user=Wn7VwbYAAAAJ.

Bogdan Lazurenko – PhD student of Information Systems Department, National Technical University "Kharkiv Polytechnic Institute", Kharkiv, Ukraine,
e-mail: torroloco789@gmail.com, ORCID: 0000-0002-1914-7091, Scopus Author ID: 57539418400,
https://scholar.google.com.ua/citations?hl=ru&user=xpzxw-kAAAAJ.

Volodimir Pevnev – D.Sc. (Technical Sciences), Associate Professor, Professor of Computer Systems, Networks and Cybersecurity Department, National Aerospace University "Kharkiv Aviation Institute", Kharkiv, Ukraine,
e mail: v.pevnev@csn.khai.edu, ORCID: 0000-0002-3949-3514, Scopus Author ID: 57194525720,
Researcher ID: AAB-7309-2021, https://scholar.google.com.ua/citations?hl=ru&user=s3unWIAAAAAJ.

Karyna Trubchaninova – D.Sc. (Technical Sciences), Full Professor, Professor of Transport Communication Department, Ukrainian State University of Railway Transport, Kharkiv, Ukraine,
e-mail: karyna.trubchaninova@kart.edu.ua, ORCID: 0000-0003-2078-2647, Scopus Author ID: 57208109791,
Researcher ID: AAE-5845-2022, https://scholar.google.com.ua/citations?user=tFdGngkAAAAJ.