Adaptation of the parameters of the physical layer of data transmission in self-organizing networks based on unmanned aerial vehicles

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Abstract
The article discusses the features of adaptation of the parameters of the physical layer of data transmission in self-organizing networks based on unmanned aerial vehicles operating in the conditions of "smart cities". The concept of cities of this type is defined, the historical path of formation, the current state and prospects for further development in the aspect of transition to "smart cities" of the third generation are shown. Cities of this type are aimed at providing more comfortable and safe living conditions for citizens and autonomous automated work of all components of the urban economy. The perspective of the development of urban mobile automated technical means of infocommunications is shown, one of the leading directions of which is the creation and active use of wireless self-organizing networks based on unmanned aerial vehicles. The advantages of using small-sized unmanned aerial vehicles for organizing networks of this type are considered, as well as the range of tasks to be solved in the conditions of modern "smart cities". It is shown that for the transition to self-organizing networks in the conditions of "smart cities" of the third generation, it is necessary to ensure the adaptation of various levels of OSI network models to dynamically changing operating conditions, which is especially important for the physical layer. To maintain an acceptable level of the value of the bit error probability when transmitting command and telemetry data, it is proposed to adaptively change the coding rate depending on the signal-to-noise ratio at the receiver input (or on the number of channel decoder errors), and when transmitting payload data, it is also proposed to adaptively change the coding rate together with the choice of modulation methods that differ in energy and spectral efficiency. As options for the practical implementation of these solutions, it is proposed to use an approach based on the principles of neuro-fuzzy control, for which examples of determining the boundaries of theoretically achievable efficiency are given.
Key words:
“smart cities”, self-organizing networks, unmanned aerial vehicles, OSI network model, physical layer, neuro-fuzzy control, energy efficiency, spectral efficiency.

1. Introduction

According to statistics, today 55% of the world's population lives in cities, and according to projected estimates, this share by 2050 could reach 68%. As a result, modern cities are constantly forced to face ever new challenges of a social, economic, environmental, energy and transport nature.

In such actively changing conditions, there is a gradual revision of approaches to the management of urban development, which increasingly relies on advanced information and telecommunication and technological solutions, which allows us to call cities that use these principles, the term “smart” [1-6].

A distinctive feature of cities of this type is to provide residents with more comfortable and safe living conditions, as well as to ensure autonomous operation and interaction of all components of the urban economy due to:
- use of advanced solutions in the field of energy supply and energy saving;
- effective management of water resources;
- integration into a unified management system of engineering and information systems of structures;
- use of information and communication technologies for solving a wide range of tasks;
- introduction of intelligent transport systems.

Historically, the concept of a “smart city” was formed in the early 2000s and was based on the advanced technological and infrastructural innovations of that time (large data centers, smart sensors, automated power grids, etc.). The further vector of development of this concept was aimed not only at ways of using smart technological solutions, but also at actively involving residents in their development in order to obtain a certain degree of interest and demand on their part.

The widespread use of these solutions made it possible by the end of the 2000s to classify the first generation of "smart cities", characterized by a high level of technological orientation to increase their sustainability, viability and manageability. This stage is associated with mass electrification and re-equipment of the physical infrastructure of cities, the introduction of isolated IT solutions, the formation of semi-automatic urban infrastructures.

Further advances in technology have led to the current phase of the development of second-generation

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smart cities, called high-tech managed cities. This type of cities is characterized by the presence of a primary digital urban infrastructure through the introduction of Internet of Things technologies, 3G / 4G networks, broadband and mobile Internet access, and is also qualitatively distinguished by the widespread use of advanced technologies in order to improve the quality of life of citizens and solve health problems, transport, environment and ecology. As a result, a modern smart city is not just a municipality with a well-developed technological infrastructure, but also a space in which a person's life takes on a new quality thanks to smart solutions. Thus, according to a study of modern cities, conducted by the McKinsey Global Institute (MGI) [1], it was found that the introduction of modern solutions for "smart cities" has provided a number of positive results, in particular:

- to reduce mortality by 8-10%;
- to increase the responsiveness to emergency situations by 20–35%,
- to reduce the average time of citizens on the way to and from work by 15–20%;
- to reduce morbidity by 8-15%;
- to reduce the total energy consumption by 30%;
- to increase the efficiency of water use by 20%;
- to reduce greenhouse gas emissions by 10-15%.
- to reduce the crime rate by 30%.

At the moment, the average use of smart solutions in cities such as Hong Kong, Dubai, Mexico City, Moscow, New York, Sao Paulo, Seoul, Singapore and Shanghai exceeds 30%, and the utilization rate of the most popular smart technologies in each of these megalopolises reaches 70–80% [1].

Modern smart city systems provide collection, storage and processing of received data, industry and cross-industry analytics, and some of them allow predicting the development of situations and the behavior of individual objects of physical infrastructure, technical systems and social conglomerations, as well as the city as a whole as a global distributed multi-level system and the massive use of infocommunication technologies leads to the optimization of various urban processes.

According to experts, the subsequent development of "smart cities" in these areas will allow the transition to highly intelligent integrated cities of the third generation. It is predicted that their main distinguishing features will be the digital transformation of various spheres of human life and the formation of a fully autonomous integrated automated intelligent urban infrastructure.

The key in this aspect are advanced mobile automated technical means of infocommunications, as well as machine learning technologies and decision-making mechanisms.

1.1. Self-organizing networks based on unmanned aerial vehicles

One of the promising directions for the development of infocommunication technologies in the conditions of modern "smart cities" is the creation and active use of wireless self-organizing networks and their special case - self-organizing networks of aircraft (Flying Ad-Hoc Network, FANET) [7,8]. These networks are intended for network interaction using small unmanned aerial vehicles (UAVs) [9-11]. A feature of these data transmission networks is their variable topology, the absence of a permanent structure and the possibility of high-quality communication between mobile objects. In this case, it is possible to transfer information both between UAVs within the organized network, and between individual UAVs and software and hardware ground control systems (GCS) or satellites (Figure 1). As a result, with such an approach to organizing a network, each of its participants must simultaneously be both a transmitter of their own messages and a relay of information from other nodes, and for the interaction of network nodes outside the limits of radio visibility, the organization of data transmission routes is required. In this case, the determination of which node needs to send data should be made dynamically based on the connectivity of the network.

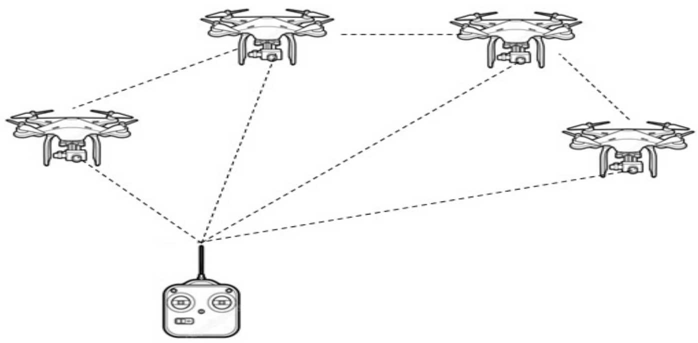

Fig. 1. The principle of organizing a self-organizing wireless network based on UAVs

The use of small-sized UAVs as part of the self-organizing wireless networks allows for scalability and rapid recovery of the core network due to the ability to quickly create additional nodes, as well as to ensure optimal coverage of the serviced area by moving network nodes in the air, taking into account urban development and takeoff to the maximum allowed altitude. Other advantages of using UAVs for organizing data transmission include the complete or partial elimination of the human factor, which allows minimizing the risk of loss of human resources while performing the assigned task and excluding the possibility of a threat to human life, as well as the possibility of equipping the network node with additional onboard load - technical equipment, including in itself various sensors, different-range cameras, etc.

The indicated advantages of the organization of the UAV-based self-organizing wireless networks make it possible to solve with their help a wide range of tasks [12-14] in the conditions of both modern “smart cities” and, in the future, “smart cities” of the third generation.

Equipping UAVs with specialized software and hardware supporting high-speed data transfer in real time, as well as video streams and high-resolution photographic images opens up prospects for using UAVs in the field of providing:

- access of citizens to high-speed Internet;
- video broadcasts of various events from crowded places;
- shooting topographic plans and maps, creating three-dimensional terrain models;
- monitoring of significant infrastructural, administrative and cultural sites;
- monitoring the location and movement of emergency vehicles, special equipment and public transport; collecting information about city traffic jams;
- monitoring of environmental pollution, prevention or reduction of the consequences of accidents; surveying the terrain in emergency zones without risk to life and health of people;
- search for people stuck on the roofs of houses and skyscrapers during floods and other natural disasters;
- public safety in order to prevent intrusions into private territory, pursuing targets, receiving signals from panic buttons and emergency calls with automatic location of the subscriber, conducting search and rescue operations, etc., which can significantly reduce the level of crime and the risk of terrorist attacks, improve coordination of actions of law enforcement agencies and emergency services.

In addition, small UAVs with the ability to lift an additional payload can be used in the service sector for the delivery of urgent mail, food, transportation of small-sized cargo, and in emergency situations - for supplying people with first aid kits, communications and food.

1.2. Adaptation of the physical layer of the OSI network model of self-organizing networks based on unmanned aerial vehicles

Despite the high level of efficiency of information exchange in the process of ensuring communication between UAVs and ground control systems, for the transition to self-organizing networks in the conditions of third generation “smart cities”, it is necessary to ensure the adaptation of various levels of their OSI network models to different conditions of networks functioning. This problem is based on a variety of options for networks operation and a huge number of tasks solved with their help, which, accordingly, leads to the presence of various and sometimes contradictory requirements for the data transmission process [15-20].

At the same time, it is necessary to note the particular importance of ensuring the adaptation of the OSI network model at the physical level, since one of the trends in the development of modern data transmission networks is the constantly growing requirements for the data transfer rate, which are implemented by technical solutions at this particular level. In addition, the task of adapting this level is complicated by the fact that modern UAVs contain, as a rule, two radio transmitters on board: a transmitter of command and telemetric information - to ensure reliable communication with other UAVs and GCS for controlling single and group flights, as well as the operation of an onboard equipment and payload transmitter - for direct high-speed transmission of information received using the target equipment [17]. As a result, the typical requirements for the first transmitter are the data transmission rate measured in tens of Kbit/s and the bit error rate of no more than 10^{-6}, for the second - the data transfer rate, measured in tens of Mbit/s and the bit error rate of no more than 10^{-3} [17].

As adaptively changeable parameters of UAV radio transmitters, we can consider a set of various characteristics [21-23] determined at the physical layer of the OSI network model: modulation type, encoder type and coding rate, system bandwidth, data transmission rate, transmitter output power and others.

It is proposed to consider the signal-to-noise ratio (SNR) at the input of the UAV receiver or the number of errors of the channel decoder as a parameter with respect to the values of which the adaptation of the physical layer can be carried out. Since in communication systems command and telemetry data must be transmitted with minimal losses and high priority, it is proposed to use as an adaptively variable parameter of UAV radio transmitters the coding rate by a constant method (for example, with convolutional coding or the Reed-Solomon coding) when changing the SNR of the receiver to maintain an acceptable level of the bit error probability. So, for example, a low SNR at the receiver input will

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dictate the need to reduce the coding rate and, accordingly, will keep the probability of bit errors at a given level by increasing the redundancy of the transmitted information and vice versa.

This solution can be projected on cases of transmission of low-priority payload data. In addition, depending on the SNR level, an alternative or additional optimization of the energy efficiency of data transmission can be carried out due to the adaptive choice of modulation methods that differ from each other in spectral efficiency and, accordingly, in the data transmission rate. So for cases of low SNR at the input of UAV receivers (caused, for example, by the impact of significant electromagnetic interference in a given frequency range or an increase in the distance between network nodes between themselves or the GCS [20, 21]), one type of modulations can be used, and for high SNR - others.

For a high-quality implementation of the proposed solutions for adapting the physical layer of the OSI network model, it is necessary to use modern approaches based on machine learning technology and automated decision-making mechanisms. As such approaches, for example, one can consider the use of algorithms of fuzzy logic and/or artificial neural networks [24-26]. The application of these principles to the solution of the considered adaptation problems [27-29] will ensure ultra-high speed of decision-making when the conditions for the propagation of radio signals between UAVs and GCS are changed, as well as provide high resistance to noise in the input data, which is extremely important for wireless data transmission and systems operation communication in the presence of natural and artificial interference.

1.3. Study of the potential for adaptation of the physical layer of the OSI network model of self-organizing networks based on unmanned aerial vehicles

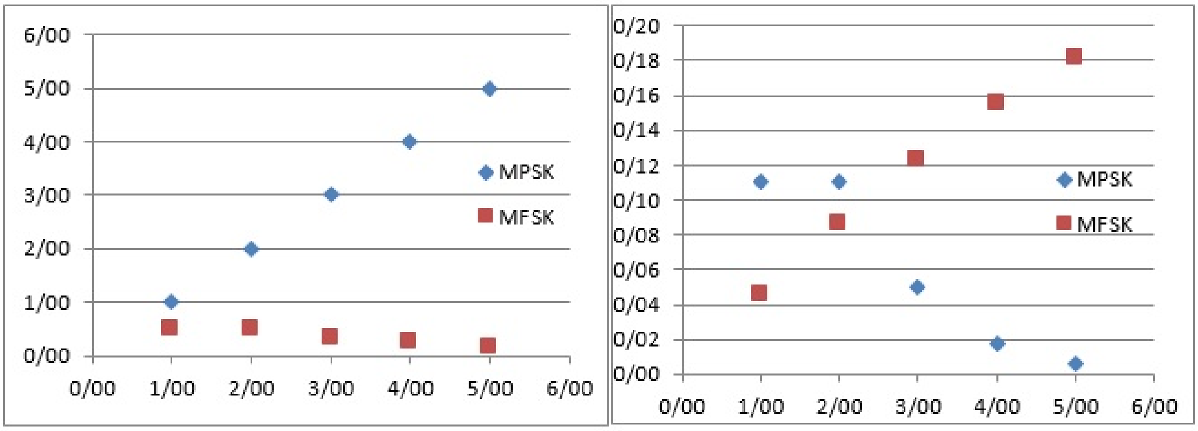
To assess the prospects of the proposed solutions for the use of fuzzy logic algorithms and artificial neural networks for adapting the physical layer of the OSI network model in order to improve the reliability and speed of information exchange in self-organizing networks based on UAVs, a quantitative study of the influence of modulation and coding methods on the energy and spectral efficiency of data transmission was carried out.

The modeling was based on mathematical expressions given and described in detail in [30, 31]. As an example, Table 1 shows the results of calculating the values of the energy efficiency $\beta = \mathrm{N}_0/\mathrm{E}_b$ (where N_0 is the one-sided spectral power density of the additive white Gaussian noise, E_b is the signal energy per bit of information) and the spectral efficiency $\gamma = R_b/\mathrm{B}_w$ (where R_b is the speed data transmission, B_w - signal spectrum width) data transmission using non-orthogonal and orthogonal modulations MPSK and MFSK. In this case, the fixed value of the data transmission rate was 9.6 Kbit/s, the bit error rate (BER) 10^{-5}, and the number of bits k associated with the set of characters of the alphabet M as $M = 2^k$ was used as a variable parameter.

Table 1

k		1	2	3	4	5
γ	MPSK	1,00	2,00	3,00	4,00	5,00
	MFSK	0,5	0,5	0,33	0,25	0,156
β	MPSK	0,11	0,11	0,05	0,02	0,01
	MFSK	0,046	0,087	0,123	0,155	0,182

Based on the values from this table, graphical dependencies are built, shown in Figure 2.



a) b)

Fig. 2. Dependences of spectral (a) and energy (b) data transmission efficiency on the number of bits *k* when using MPSK and MFSK modulations

2. Conclusion

From the obtained graphical dependencies it can be seen that for each of the modulation methods considered, the payment for increasing the energy efficiency of data transmission is a decrease in the spectral efficiency, which is realized in this case by expanding the data transmission frequency band (since in this example the data transmission rate is taken constant). In this case, the nature of the dependences of the spectral and energy efficiency of data transmission on the number of bits k for MPSK and MFSK modulations is the opposite (determined by the peculiarities of their formation), which makes it possible to effectively use each of these modulation methods in the presence of various restrictions introduced in FANET communication networks (for example, transmission power or bandwidth).

Analyzing the results obtained, we can conclude that the successful adaptation of the physical layer of the OSI network model to various conditions of the functioning of self-organizing networks based on the neuro-fuzzy approach will significantly increase the reliability and efficiency of information exchange in the process of providing communication using wireless self-organizing networks based on UAVs, which can be seen as a prerequisite for the transition of modern "smart cities" to third generation "smart cities".

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