Assessment of the availability of communication channels with UAVs

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Abstract
Today, unmanned aerial systems have spread to various spheres of human activity. The use of these systems in the military sphere, agricultural industry, and goods logistics has given a significant impetus to the development of the relevant industries. Unmanned aerial vehicles can operate in two modes: as an autonomous means that performs the assigned task, and in the mode of communication and correction of tasks with a human operator. In the second mode, the critical components are ensuring the availability of the communication channel, its security, and the possibility of correcting distorted information. These factors significantly affect the efficiency of using unmanned systems for their functional purpose. Therefore, this paper considers the task of assessing the availability of a communication channel for the transmission of useful information. The main attention is paid to the new mathematical relations for the assessment of availability and the determination of the statistical characteristics of the obtained estimates.

Keywords
communication channel, UAV, efficiency analysis, availability, mathematical simulation

1. Introduction

The development of technology, science, and engineering contributes to the increasing informatization of human and social activities [1]. Sustainable development and the transition to the Industry 4.0 paradigm make it possible to use new intellectual methods and means of industrial computerization [2, 3].

In the field of robotics and autonomous systems development, new and more advanced machine learning and deep learning methods are currently being used [4]. These methods are based on processing large amounts of data using the CPU and GPU cores and can

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significantly improve the efficiency and veracity of decision-making under conditions of uncertainty.

Unmanned aircraft systems are an integral part of the robotics industry [5]. They must have a set of sensors for spatial orientation, a system for monitoring the parameters of onboard equipment technical conditions, and an adaptation system for adjusting the required tasks [6, 7]. In general, the measured data can be processed both directly by the systems of the unmanned vehicle and in the mode of data transmission and communication with the control center [8].

Today, unmanned aerial systems have spread to various spheres of human activity. The use of these systems in the military sphere, agricultural industry, and goods logistics has given a significant impetus to the development of the relevant industries [9].

According to the Urban Air Mobility (UAM) doctrine, unmanned aircraft systems will be developed and implemented at the level of airspace use in conjunction with civil aviation aircraft. In particular, the principles of organizing passenger and cargo transportation are being developed. Passenger transportation is aimed at reducing urban traffic and increasing the speed of movement of people within a particular city or state. To achieve this goal, such means of air transport evolution as electric vertical take-off and landing (eVTOL) can be used to introduce air taxi services [10]. Cargo mobility applications involve the expansion of logistics services for the delivery of goods in densely populated urban areas through the use of small and medium-sized drones.

The development of the UAM doctrine with its further evolution into Advanced Air Mobility (AAM) requires the creation of the necessary infrastructure at the state level. This infrastructure should be based on the development of technologies and innovations in the field of unmanned systems operation. The infrastructure should include:

1. Areas for basing drones, quadcopters, and other eVTOL vehicles.
2. Operating companies for repair and maintenance.
3. Logistics centers.
4. Airspace control and monitoring centers, including workplaces of unmanned aircraft system operators.
5. Factories producing components, structural elements, and unmanned aircraft systems in general.
6. Training and certification centers.
7. Public administration bodies.

An important element of the implementation of the UAM and AAM doctrines is the development of normative and regulatory documentation. For example, in the United States, the Federal Aviation Administration has developed a document [11] that establishes and describes the specifics of the use of unmanned aircraft systems in urban areas, outlines technologies for collecting, transmitting and processing information, and characterizes the main properties of airspace management.

The development of unmanned aerial systems using drones and unmanned aerial vehicles is already an important sector of the economy [12]. Modern business structures and industrial organizations receive significant profits by using them to increase the productivity of their tasks [13, 14]. According to the most conservative forecasts, the market for UAM and AAM services in the United States alone in 2035 will be approximately $115 billion [15], which will be distributed between passenger and cargo transportation in approximately equal parts.

The main priority areas for the implementation of the UAM and AAM doctrines in the technical part are as follows:

1. Development of new configurations of unmanned aircraft systems.
2. Development of technologies to increase the capacity of batteries and reduce their discharge rate.
3. Researching the possibilities of using artificial intelligence technology including machine and deep learning.
4. Use of secure, reliable, and high-speed information transmission technologies for communication between the unmanned aerial system and the control center or operator.
5. Development of a maintenance system.
6. Justification of the structure and localization of repair centers.

In general, unmanned aerial vehicles (UAVs) can operate in two modes: as an autonomous means that performs the assigned task, and in the mode of communication and correction of tasks with a human operator [16]. In the second mode, the critical components are ensuring the availability of the communication channel, its security, and the possibility of correcting distorted information. These factors significantly affect the efficiency of using unmanned systems for their functional purpose.

2. State of the art for the problem of research

The equipment of an unmanned aerial vehicle includes equipment for various purposes, namely:

- Aerodynamic equipment that enables UAVs to maneuver in airspace.
- An aerial photography system that is necessary to provide the required information for the UAV operator.
- Electronic equipment that measures navigation parameters, processes flight data and images, and monitors the technical condition of UAV components.
- Electronic means of communication with the command center or UAV operator, which is necessary to transmit information on UAV control, as well as images and flight data.

An analysis of the literature has shown the existence of significant scientific results in the field of improving the quality of information transmission, communication channel security and increasing its bandwidth, and technologies for processing useful information [17, 18]. Let us consider some of them.

Research [19] focuses on the development of a new concept for building a communication channel that takes into account the mobility properties of UAV movement and its shadowing by foreign objects. The authors investigated the efficiency of information transmission when using a shadowed communication channel with double scattering. The model proposed by the authors is based on taking into account the influence of environmental parameters with various interferences. The authors presented analytical relations for estimating the bit error probability for using a BPSK modulation scheme. The obtained formulas were confirmed by the results of statistical modeling and empirical calculations.

The paper [20] discusses the development of an effective strategy for organizing communication with UAVs. According to the authors, the main way to increase the efficiency of information transmission was to find an available repeater in case of data loss over the main communication channel. It was proposed to use another UAV located in the vicinity of the one to which the information was to be transmitted as a repeater. To solve this problem, the authors used linear programming methods to optimize the spectral efficiency of communication channels.

The authors of the paper [21] investigate the problem of synthesizing an optimal resource allocation algorithm to increase the throughput of D2D communication and reduce the probability of losing packets of useful information. The developed algorithm was implemented as an implementation of three steps of the corresponding methodology: 1) use of the k-means clustering method in the variant with fuzzy logic based on navigation information about users of communication channels; 2) using the Kuhn-Munkras algorithm to find the required channel; 3) use of the game model to ensure the required quality of information transmission.

The research [22] focuses on analyzing the availability of 5G communication systems in its application in the space industry. The determination of communication channel availability zones was performed based on the state of the system, cell, and user by using a mathematical tool with point Poisson process models. The availability indicator was determined in the time and space domains. In the temporal domain, availability was defined as the ratio of the average time of one hundred percent information transmission to the total average time of system use during reliable data transmission and loss of communication. In the spatial domain, availability was defined as the ratio of the average coverage area to the total average coverage area and the area without reliable communication.

Publication [23] focuses on the development of an availability indicator model to determine the benefits of using this indicator to determine the quality of a communication channel. The developed model was tested on the example of road transport management, which proved its feasibility as a subsystem for improving the quality of communication in fifth-generation systems.

The paper [24] considers the issue of analyzing the availability of an ultra-reliable communication network by using the classical models of reliability theory extended to the temporal and spatial domains. The authors focus on a multicellular Voronoi cell scenario using the Poisson distribution for nodal infrastructure elements, which allows taking into account user mobility, cellular coverage, and the state and availability of communication channels. In general, the paper proves that better quality of the communication channel can be achieved by implementing new strategies to compensate for the negative effect of the reliability of the system's structural elements.

Study [25] uses the probability of channel blocking in cognitive radio systems based on the Markov process theory and risk identification in specially designed software to analyze the availability of a communication channel. A significant part of this study was devoted to statistical modeling, in which histograms for availability were obtained for the case of a binomial distribution for the channel-blocking forecast.

In general, the concept of steady-state availability has been widely studied in the processing of equipment operational data and reliability theories [26, 27]. In the paper [28], statistical models of the steady-state availability for radio electronic equipment are considered. These models were obtained by using the theory of functional transformations of random variables. Steady-state availability models can also be used to analyze the deterioration of the technical condition of equipment [29, 30], and this approach can also be used to analyze the deterioration of the quality of communication channels. In addition, the research [31] proved the hypothesis that it is necessary to apply sequential procedures for the reliability assessment that can allow for faster decision-making on the functional condition of the system. Thus, it can be assumed that the procedures for assessing the quality of a communication channel should also be built according to a sequential scheme for forming sample sets.

It should be also noted that the quality of communication channels can be affected by a variety of factors, such as equipment reliability, lack of sufficient cellular network coverage, interferences and noise, the presence of electronic warfare, the possibility of cyber incidents, and others [32, 33].

Therefore, this paper considers the task of assessing the availability of a communication channel for the transmission of useful information. The main attention is paid to the new mathematical relations for the assessment of availability and the determination of the statistical characteristics of the obtained estimates.

3. Materials and methods

Let's assume that the UAV is used for its intended purpose in the mode of communication with the command-and-control center. The operator directly controls and adapts the UAV to the conditions of the environment. This task is realized by transmitting voice commands from a specified vocabulary. The UAV contains a radio receiving device, where voice commands are decoded and fed to the speech recognition system [34].

Speech control commands must be correctly recognized. The probability of correct recognition depends on numerous factors, including the processing algorithm, the amount of information lost, and thus the quality of the communication channel. In the event of packet loss (degradation of the quality of information transmission), delays occur as the system goes into standby mode to obtain the sufficient information to recognize the commands [35].

Let's consider two approaches to assessing the quality of communication channels. The first approach is based on estimating the amount of transmitted information. The second approach uses estimates of the availability factor as a measure of communication availability.

1. Estimating the amount of information transmitted.

Let the voice commands for controlling the UAV be spoken at a rate of ν (measured in phonemes per second). The amount of information that one phoneme contains is calculated through the entropy

$$I = H(\lambda) = \log_2(m), \quad (1)$$

where m is the number of phonemes in the language of the message. For example, the Ukrainian language has 40 phonemes. For 40 phonemes, we get $H(\lambda) = 5$ bits per phoneme or, taking into account the correlation $H(\lambda) = 3.52$ bits per phoneme.

The speed of information transfer is

$$\nu_{inf} = \nu H(\lambda). \quad (2)$$

The amount of information transmitted in one second is equal to

$$I_T = \nu_{inf} T + I_a, \quad (3)$$

where $T = 1$ second, I_a is the amount of information due to the speaker's authentication. In this case

$$I_a = F_t T \log_2\left(1 + \frac{\sigma_s^2}{\sigma_n^2}\right), \quad (4)$$

where F_t is the frequency band in which the fundamental tone frequency is located (usually, this value is 200 - 250 Hz), $\frac{\sigma_s^2}{\sigma_n^2}$ is signal-to-noise ratio by power.

Taking into account the initially set values, you can get $I_T = 714$ bits.

The codec converts the original information into frames of length $\Delta t = 30\, ms$. Each frame of length Δt contains $I_k = 200$ bits.

The speed of information transmission is $\nu_I = 64000$ bits per second. The amount of output information per 1 second is

$$I_{in} = \nu_I T. \quad (5)$$

In this case, the $I_{in} = 64000$ bit.

Then you can determine the number of frames that carry information I_{in} as follows

$$N = \frac{I_{in}}{3 I_k}. \quad (6)$$

For the above parameters, we obtain $N \approx 106$.

Then the amount of source information transferred in one frame is

$$I_{kT} = \frac{I_T}{N}. \quad (7)$$

In this case, for the considered numerical example $I_{kT} = 6.74$ bits.

The number of frames that can be lost during information transmission to lose one phoneme is

$$n_l = \frac{H(\lambda)}{I_{kT}}. \quad (8)$$

In this example, this value is 1 frame.

The amount of information that is generated at the output of the packetizer is

$$I_{out} = 2kF_{max}\Delta t N \log_2\big(1 + (6k - 7.2)\big), \quad (9)$$

where k is the number of bits (usually 8), F_{max} is the maximum frequency of the speech signal spectrum in the communication channel.

Another approach to determining the amount of information that will be generated at the codec output is to take into account the signal-to-noise ratio by power

$$I_{out} = 2kF_{max}\Delta tN\log_2\left(1+\frac{\sigma_s^2}{\sigma_n^2}\right). \tag{10}$$

If the range of the speech signal $2x_{max}$ then for the k-bit quantizer we obtain

$$\Delta= \frac{2x_{max}}{2^k}. \tag{11}$$

Let the noise have a uniform distribution, i.e.

$$\sigma_n^2 = \frac{\Delta^2}{12} = \frac{x_{max}^2}{3\cdot 2^k}.$$

Then we have

$$\frac{\sigma_s^2}{\sigma_n^2} = \frac{3\cdot 2^k}{x_{max}^2/\sigma_s^2}.$$

Assuming that the quantization range $x_{max} = 4\sigma_s$we obtain

$$\frac{\sigma_s^2}{\sigma_n^2} = \frac{3\cdot 2^k}{(4\sigma_s)^2/\sigma_s^2} = \frac{3\cdot 2^k}{16} = \frac{3\cdot 2^k}{2^4} = 3\cdot 2^{k-4}.$$

From here we get

$$I_{out} = 2kF_{max}\Delta tN\log_2\left(1+3\cdot 2^{k-4}\right). \tag{12}$$

Thus, the assessment of the amount of information can be used as a measure of the quality of the communication channel, since its decrease to a certain threshold level will be a sign of the inability to recognize the voice control command.

2. Assessment of the availability indicator.

As an assessment of the quality of the communication channel availability indicator, we use the time domain parameter given in [22]. In this case.

$$Q = \frac{\overline{t_{norm}}}{\overline{t_{norm}} + \overline{t_{fail}}}, \tag{13}$$

where $\overline{t_{norm}}$ is the average duration of normal notification transmission in the case of one hundred percent recognition of control commands, $\overline{t_{fail}}$ is the average duration of the communication channel disruption.

Usually, the durations of normal notification transmission and communication disruption are random variables. Therefore, the communication channel quality parameter Q is also stochastic. For its most complete characterization, it is necessary to find or estimate its distribution law.

Let $p(\overline{t_{norm}})$ and $p(\overline{t_{fail}})$ be the probability densities of the average durations $\overline{t_{norm}}$ and $\overline{t_{fail}}$ respectively. Let us define the method of finding the distribution law $p(Q)$.

According to the law of distribution and independence of random variables $\overline{t_{norm}}$ and $\overline{t_{fail}}$, we obtain

$$\int_{-\infty}^{\infty} p(Q)dQ = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} p(\overline{t_{norm}})p(\overline{t_{fail}})d\overline{t_{norm}}d\overline{t_{fail}}.$$

Hence

$$p(Q) = p(\overline{t_{norm}})p(\overline{t_{fail}})\frac{d\overline{t_{norm}}d\overline{t_{fail}}}{dQ}.$$

According to equation (13)

$$\overline{t_{fail}} = \overline{t_{norm}}\frac{1-Q}{Q}.$$

In this case, the first derivative

$$\frac{d\overline{t_{fail}}}{dQ} = -\frac{\overline{t_{norm}}}{Q^2}.$$

Taking into account the positivity of probability and its density, we obtain

$$p(Q) = \int_{-\infty}^{\infty} p(\overline{t_{norm}})p(\overline{t_{fail}})|_{\overline{t_{fail}}=\overline{t_{norm}}\frac{1-Q}{Q}} \frac{\overline{t_{norm}}}{Q^2} dQ. \quad (14)$$

Formula (14) is generalized and describes all possible variants that can occur in a communication channel.

Let's consider a simplified version. Let's assume that a certain strategy for the UAV's operation has been determined. Under this strategy, the amount of information is measured and then compared to a certain acceptable threshold. At the same time, let the UAV monitoring system archive events and historical data based on flight information. In case of unsatisfactory quality of the communication channel, the UAV should return to the last point of its route, where the communication was at a satisfactory level. After that, a new UAV trajectory can be recalculated to avoid the prohibited areas of no or poor communication level.

For this strategy, the assessment of statistical characteristics of availability indicator will be simplified, as we can assume a constant duration of the outage. That is

$$\overline{t_{fail}} = t_{fail} = const.$$

With this in mind, let's write down

$$\int_{-\infty}^{\infty} p(Q)dQ = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} p(\overline{t_{norm}})d\overline{t_{norm}}.$$

Hence.

$$p(Q) = p(\overline{t_{norm}})\frac{d\overline{t_{norm}}}{dQ}.$$

According to equation (13)

$$\overline{t_{norm}} = \overline{t_{fail}}\frac{Q}{1-Q}.$$

In this case, the first derivative

$$\frac{d\overline{t_{norm}}}{dQ} = -\frac{\overline{t_{fail}}}{(1-Q)^2}.$$

Taking into account the positivity of probability and its density, we obtain

$$p(Q) = \frac{\overline{t_{fail}}}{(1-Q)^2} p(\overline{t_{norm}})|_{\overline{t_{norm}}=\overline{t_{fail}}\frac{Q}{1-Q}}. \quad (15)$$

The resulting model (15) is simplified because it does not take into account the reliability of the equipment. For the specified UAV control strategy, in this case, the unmanned system will strive to return to its launch point along the reverse trajectory.

It should be noted that obtaining the final statistical models using formulas (14) and (15) is a difficult task. For more reasonable conclusions about the availability of the communication channel, it is necessary to conduct real experiments and accumulate training datasets.

In general, the use of steady-state availability as an indicator of communication channel availability allows us to apply effective and well-researched methods of the theory of reliability and equipment operation to improve the efficiency of information transmission and assess their quality.

4. Results and discussions

This section of the article is devoted to a demonstration example based on Monte Carlo simulation.

At the first stage of the modeling, datasets with an exponential distribution law were generated for the duration of normal communication (Figure 1).

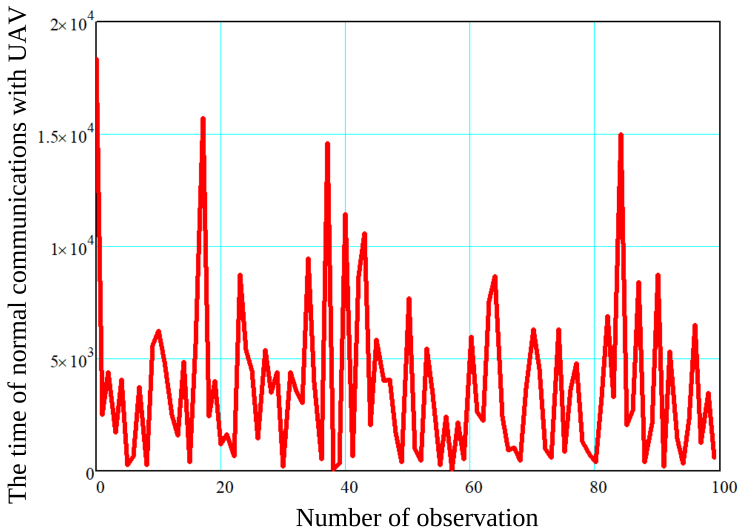

Figure 1: The realization of random variable time of normal communications.

The following initial parameters were used in the modeling:

- The average duration of normal communication is 1 hour.
- The average duration of a communication disruption is 50 seconds.
- The volume of observation is 100.
- The number of epochs is 200.

The resulting implementation of a one-time assessment of the availability of communication channels using formula (13) is shown in Figure 2. During the simulation, it was taken into account that the sum of exponential random variables is described by a chi-square distribution. Figure 3 shows the simulation results for 200 epochs. The visual good correlation of the experimental histogram with the result of using formula (15) was confirmed by calculating Pearson's consistency criterion.

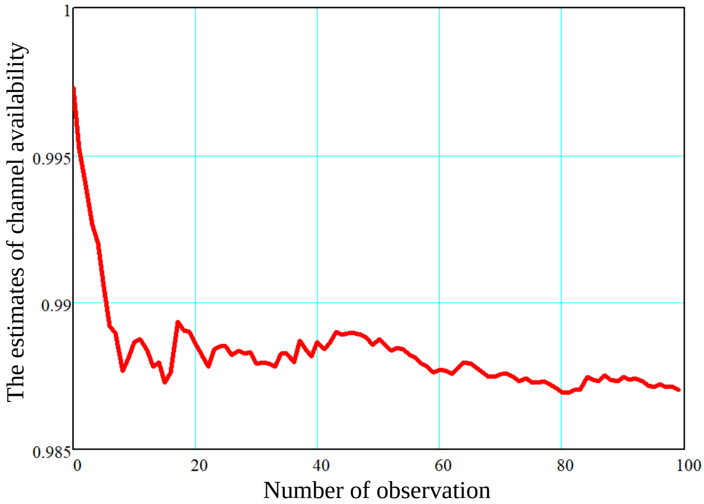

Figure 2: The estimates of channel availability.

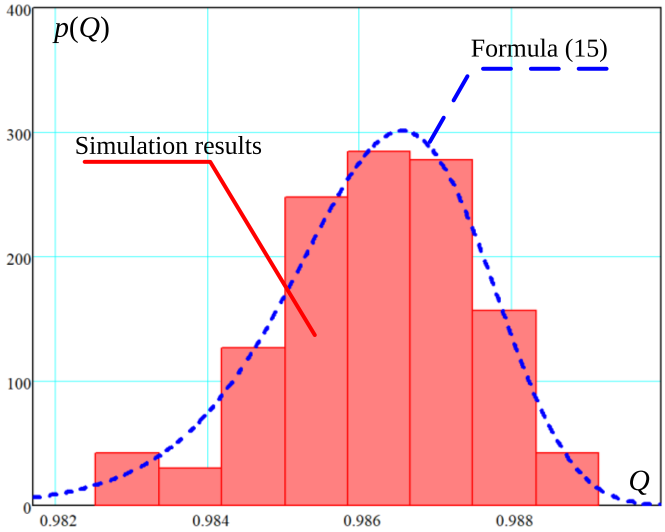

Figure 3: The comparison of simulation results and equation using formula (15).

5. Conclusions

The paper is devoted to the peculiarities of assessing the quality of communication with UAVs. The main quality indicators are the amount of information required to recognize individual phonemes of the control signal and the availability indicator based on the use of the steady-state availability, which is widely used in reliability theory.

To determine the amount of information required, a step-by-step methodology for calculating this indicator is presented. To evaluate the availability, analytical relations for the statistical characteristics of the model in the time domain were obtained using the mathematical models of probability theory. To confirm the analytical relations, the simulation was carried out. Further research will be aimed at improving the accessibility model and taking into account all the constituent elements of the communication channel.

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