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Evaluation of the energy reserve of communication channels during data transmission using small-sized UAVs in the conditions of smart cities

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Abstract

In this article, the influence of various factors and conditions of data transmission on the energy reserve of radio communication channels with small-sized unmanned aerial vehicles performing flight tasks within the "smart cities" with dense buildings is evaluated using mathematical modeling. It is shown that modern cities of this type, due to the presence of buildings of various height with various reflection coefficients and a significant level of electromagnetic interference, create specific conditions for the propagation of radio waves, forming multipath fields with a complex interference structure and sharp spatial changes in signal levels, which creates a number of issues related to both the quality of communication and its reliability, including, in particular, the determination of energy reserves of radio communication channels. For their quantitative evaluation, mathematical models, typical data transmission parameters and energy characteristics of both unmanned aerial vehicles and ground-based control systems were selected. On their basis, a corresponding study of the energy reserve of the radio communication channel was conducted, and the corresponding conclusions were drawn based on the results of modeling.

Keywords: radio channel, unmanned aerial vehicles, "smart cities", energy reserve of the radio communication channel, loss of radio signal propagation
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1 Introduction

In the theory of communication [9, 12, 11, 4, 21], the concept of a radio channel is important [13, 10, 22, 28], which is usually understood as that part of the communication system that includes the source of information, the encoding and modulation device, the transmitting device, the physical channel (signal propagation medium), the receiver with information processing devices and the receiver of information. The accelerated development and mass use of unmanned aerial vehicles (UAVs) [18, 6, 3, 7, 5] around the world, as well as the rapid development of radio electronics, make it necessary to constantly review the requirements for communication channels both between UAVs and between UAVs and ground control systems (GCC). In particular, this problem is relevant in the design of flying

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ad-hoc networks (FANET) based on UAVs [27, 16, 25, 26, 23]. Thus, to meet the requirements for the bandwidth of communication channels when transmitting both telemetry data and payload data, it is necessary to expand the frequency band of the transmitted signals using spectral-efficient modulation methods, which, in turn, leads to a decrease in the signal-to-noise ratio at the input of the receivers and an increase in the probability of bit error.

When organizing and modeling wireless radio communication channels, it is important to evaluate the characteristics of the signals propagated at any point in space within the entire service area of the communication system. Modern " smart cities " [29, 19, 1, 17, 2, 15, 30] create specific conditions for the propagation of radio waves.

So shadow zones, multiple reflections and scattering of waves form multipath fields with a complex interference structure and sharp spatial changes in the signal level. The multipath nature of radio wave propagation, when waves come to the receiving point from different directions and with different time delays, gives rise to the phenomena of intersymbol interference during the transmission of code sequences. Signal distortions caused by inter-character interference can cause a serious deterioration in the system performance and the quality of high-speed digital data transmission if the delay duration exceeds the character duration.

As a result, any radio path can be represented as a set of several main paths along which the signal from the UAV antenna or GCC reaches the UAV antenna and vice versa. On each of these paths are different objects that affect the propagation of radio waves. In urban conditions, the following main elements can be distinguished:

- guiding structures (avenues, streets, sections of rivers, contact lines of urban electric transport, etc.);
- a separate building or groups of buildings;
- the surface of the Earth and obstacles on it (cars, poles, fences, etc.);
- areas of vegetation (parks, squares, yard plantings, etc.).

Modeling of the influence of these objects on the propagation of radio waves can be carried out in various ways: deterministic, statistical, and combined. The first ones include mainly methods of geometric optics, physical and geometric theories of diffraction, the method of the parabolic equation, as well as numerical methods of electrodynamics. They allow you to calculate the field strength with a high degree of accuracy, but they place high demands on the accuracy of setting the model of the environment. Statistical methods take into account the random nature of the distribution of inhomogeneities of the medium that affect the propagation of radio waves. These methods allow us to predict some of the averaged characteristics of the signals.

Despite the rather extensive range of tasks currently being solved, many scientific and technical problems associated with the use of UAVs in the conditions of "smart cities" with dense buildings (characterized by the presence of buildings of various height with various reflection coefficients and a significant level of electromagnetic interference) remain unresolved. In particular, such problems include a number of issues related to both the quality of communication and its reliability, including, for example, the determination of the energy reserve of wireless radio communication channels [22], which allows us to assess the reserve for the reliability and reliability of information transmission by communication systems based on UAVs. At the same time, the problem of determining the energy reserve of the communication channel for UAVs is poorly studied and is mainly of a statistical nature, which is due to both the complex picture of the multipath propagation of signals, and the variety of conditions for the propagation of radio waves of different ranges, as well as the complexity of describing the signal-interference situation at the receiving point.

2 Initial data and models for estimating the energy reserve of communication channels during data transmission using small-sized UAVs

As the initial data for estimating the energy reserve of wireless radio communication channels with UAVs, we take the following parameters:

- data carrier frequencies: 433, 868, 1800, 2400 MHz;
- GCC antenna height: from 1 to 50 m;
- UAV flight altitude: 10 up to 120 m;
- distance between the UAV or between the UAV and the GCC: from 10 to 1000 m;
- data transmission conditions: dense development of the "smart city".

The selected frequencies correspond to the generally accepted standards in the world for consumer use of frequency bands without special permits and licenses, belong to the UHF band and provide a good compromise between the range and bandwidth of radio communications; the selected heights of the GCC antennas are typical for communication

Parameter of the UAV transmitter	Carnivore	Phantom 3 Professional	UAV family ZALA
Maximum flight range, m	390-915	2400	2400
Maximum flight altitude, m	10000	2000	5000
Minimum flight altitude, m	2000	300	1000
Radio transmitter power, dBm	35	20	19
Antenna gain, dBi	8	6	-
Antenna gain, dBm	up to –125	-	-100

Table 1: Energy characteristics of small-size UAV transceiver equipment

systems using UAVs in urban conditions, and the flight heights of UAVs are also characteristic of the values regulated when using UAVs in the city.

Modern small-size UAVs (for example, "Carnivora" from the Russian NPF "Mikran", "Phantom 3 Professional" of the Chinese company DJI, "ZALA" of the group of Russian companies ZALA AERO (Table. 1) and others) are characterized by the use of radio transmitters with a power of 15-40 dBm with antenna gain of 1-10 dBi and radio receivers with a sensitivity of minus 90 – minus 125, and the GCC for them (due to the absence of restrictions on weight and size indicators) – slightly better values of these parameters.

Based on the specified maximum range of the UAV (1000 m), for the simulation, we assume the use of a radio transmitter with a power of 20 dBm with an antenna gain of 6 dBi and a radio receiver with a sensitivity of minus 100 dBm on board the UAV. We also assume that for the GCC, the transmitter power will be 30 dBm, the antenna gain - 24 dBi, and the sensitivity of the radio receiver - minus 110 dBm.

The obtained parameters and conditions of data transmission using small-sized UAVs can serve as a basis for modeling and subsequent estimation of the energy reserve of the radio channel in accordance with the generally accepted calculation method described in [8]. According to it, when determining the performance of a radio communication channel, the most interesting parameter is the signal-to-noise ratio, or (E_b/N_0) – the ratio of the bit energy to the noise power spectral density required to obtain a given error probability.

To facilitate the calculation of the limits of the energy reserve of the communication channel M, it is necessary to distinguish between the required ratio $(E_b/N_0)_{need}$ and the real (or accepted) ratio $(E_b/N_0)_{real}$. In this case, the specified reliability of information transmission over the communication channel will be achieved if there is a certain margin, when $(E_b/N_0)_{real}$ will be slightly larger than the demand $(E_b/N_0)_{need}$, and the difference in decibels between $(E_b/N_0)_{real}$ and $(E_b/N_0)_{need}$ gives the desired energy reserve of the communication channel

$$M(\mathrm{dB}) = (E_b/N_0)_{\mathrm{real}}(\mathrm{dB}) - (E_b/N_0)_{\mathrm{need}}(\mathrm{dB}). \tag{2.1}$$

Equation (2.1) is usually represented as an expression containing all the main parameters that affect the reliability of information transmission over the communication channel

$$M(\mathrm{dB}) = EIPR(\mathrm{dBW}) + G_r(\mathrm{dBi}) - (E_b/N_0)_{\mathrm{need}}(\mathrm{dB}) - kT^0\left(\frac{\mathrm{dBW}}{\mathrm{Hz}}\right) - L_S(\mathrm{dB}) - L_0(\mathrm{dB}). \tag{2.2}$$

where EIPR is the effective output power of the transmitting antenna; G_r is the gain of the receiving antenna; R – the bit rate; k - the Boltzmann constant; T_0 - the effective noise temperature (a parameter that simulates the effect of various noise sources and is described by the function of the noise emitted to the antenna and the thermal noise generated at the first stages of the receiver); L_S, L_0 – the losses in the communication channel and the intrinsic noise of the receiving and transmitting equipment.

A simplified model (2.2) is the equation from [20], which is more applicable for practical calculations:

$$M(\mathrm{dB}) = PT(\mathrm{dBm}) + G_R(\mathrm{dB}) + G_T(\mathrm{dB}) - L_S(\mathrm{dB}) - L_0(\mathrm{dB}) - P_S(\mathrm{dBm}), \tag{2.3}$$

where P_T is the transmitted power, G_R and G_T-the gain coefficients of the transmitting and receiving antennas, L_S - the propagation loss of the radio signal, L_0 - the coefficient of system losses not related to propagation (losses in the feeder and connectors of the GCC and UAV, polarization mismatch of the antennas), P_S- receiver sensitivity.

Theoretically, when transmitting data using small-sized UAVs within the line of sight and in the absence of interfering factors, the range of the radio channel energy reserve required for reliable and reliable communication can be tenths of a dB. At the same time, a similar organization of communication in conditions of dense urban development and the presence of an obstacle on the radio wave propagation route requires achieving its values measured in dB units.

To determine the energy reserve of communication channels when transmitting data using UAVs, it is necessary to know one of the most important characteristics of the propagation of radio signals - their attenuation in the communication channel [22, 20, 24, 8, 14], for which it is necessary to choose adequate models describing the propagation loss for data transmission conditions both between UAVs and between UAVs and GCC.

If the characteristics of the radio channel are not specified, then it is generally assumed that the signal attenuates with distance in the same way as when propagating in an ideal free space. In real conditions of radio signal propagation on the ground, the amount of attenuation depends on a set of factors that determine the nature of radio wave propagation, which include:

- reflection of the signal from objects that are larger than the length of the radio wave;

- diffraction of radio waves, which is characterized by the refraction of the radio signal on the propagation path;

- signal scattering, which occurs when there are a large number of objects on the ground that are smaller than the length of the radio wave (for example, deciduous trees);

− the Doppler effect that occurs when moving moving objects (UAVs).

As a result, an accurate analytical calculation of radio signal propagation losses for real data transmission conditions between UAVs and between UAVs and GCC is almost impossible due to the presence of many factors that are difficult to describe mathematically. As a result, the estimation of this propagation parameter is carried out using empirical models developed on the basis of numerous experiments.

First of all, we will choose the signal propagation model for data transmission between UAVs. Based on the fact that data transmission between UAVs will be carried out at a height, as a rule, exceeding the level of urban buildings and structures, and the orientation of streets and re-reflections of radio waves from the walls of buildings are not so significant (in relation to data transmission between UAVs and GCC), in this case, we can assume that these conditions correspond to the case of the presence of a line of sight and we can use the modified empirical formula COST231-Walfisch-Ikegami

$$L = (32,4 + \Delta_1) + 20\lg(f) \ + (20 + \Delta_2)\lg(R) \ , \tag{2.4}$$

where Δ_1 and Δ_2 are the correction factors that take into account the losses on the real radio signal propagation path in urban conditions, R – the distance between the transmitter and receiver, f – the carrier frequency of the propagated signal.

The coefficient Δ_1 values are usually in the range from 0 to 10.2, and the $\Delta_2$values are in the range from 0 to 6.

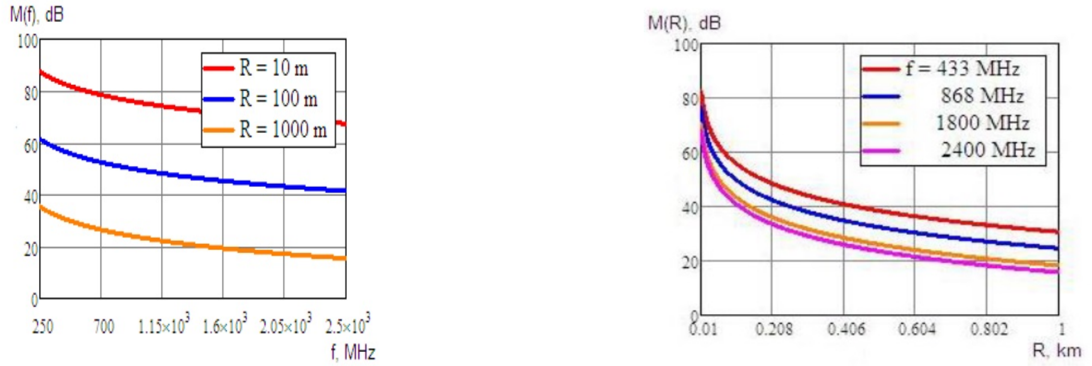
Next, we will select the signal propagation model for data transmission between the UAV and the GCC. In this variant, the case of the location of the base and mobile stations outside the line of sight ("non line of sight", NLOS) is possible, which is more complex. In this case, the value by which the power of the received signal decreases during the passage of the route depends on the propagation losses in free space without obstacles, the losses on the side of the mobile station caused by the scattering of the radio signal when reflected from the surface of buildings, and the estimate of the amount of losses caused by repeated re-reflection and scattering of the radio signal from the roofs of houses.

In this regard, and also in view of the peculiarities of the spatial location of the UAV relative to the GCC, in this case, we can apply the adapted Xia-Bertoni model.

Then, for the flight height of the UAV above the average level of the roofs of buildings, the value of the average losses on the route is determined as

$$L = -10\lg\left(\left(\frac{\lambda}{4\pi R}\right)^2\right) \ -10\lg\left(\frac{\lambda}{2\pi^2 r}\left(\frac{1}{\theta} - \frac{1}{2\pi + \theta}\right)^2\right) \ -10\lg\left(2,35^2\left(\frac{\Delta h_{\mathrm{UAV}}}{R}\sqrt{\frac{b}{\lambda}}\right)^{1.8}\right) ; \tag{2.5}$$

where λ is the wavelength, $\Delta h_{\mathrm{UAV}} = h_{UAV} - h_r$ – difference of heights between the UAV and mid-level roofs, $\theta = arctg\,(2\Delta h_{\mathrm{GS}}/w)$ – the angle of incidence of the refracted beam to the antenna of the ground station, $\Delta h_{\mathrm{GS}} = h_r - h_{GS}$ – height difference in the average level of rooftops and antennas of ground station, w is the average width of the streets



(a) (b)

Figure 1: Dependence of the energy reserve of the communication channel during data transmission between UAVs on the carrier frequency of the transmitted radio signal (a) and the distance between the transmitting and receiving nodes of the communication network (b).

(typically 15-30 m), b – average interval between blocks (typically about 40-80 m), $r = \sqrt{\Delta h_{\mathrm{GS}}{}^2 + x^2}$ – distance from point of deflection of a beam to the ground station antenna.

In the case when the flight height of the UAV is comparable to the roof level, the loss of radio signal propagation is defined as

$$L = -10\lg\left(\left(\frac{\lambda}{2\sqrt{2}\pi R}\right)^2\right) - 10\lg\left(\frac{\lambda}{2\pi^2 r}\left(\frac{1}{\theta} - \frac{1}{2\pi+\theta}\right)^2\right) - 10\lg\left(\left(\frac{b}{R}\right)^2\right), \tag{2.6}$$

and in the case when the flight height of the UAV is below the roof level as

$$L = -10\lg\left(\left(\frac{\lambda}{2\sqrt{2}\pi R}\right)^2\right) - 10\lg\left(\frac{\lambda}{2\pi^2 r}\left(\frac{1}{\theta} - \frac{1}{2\pi+\theta}\right)^2\right)$$
$$-10\lg\left(\left(\frac{b}{2\pi\left(R-b\right)}\right)^2 \frac{\lambda}{\sqrt{\Delta h_{\mathrm{UAV}}{}^2 + b^2}}\left(\frac{1}{\varphi} - \frac{1}{2\pi+\varphi}\right)^2\right), \tag{2.7}$$

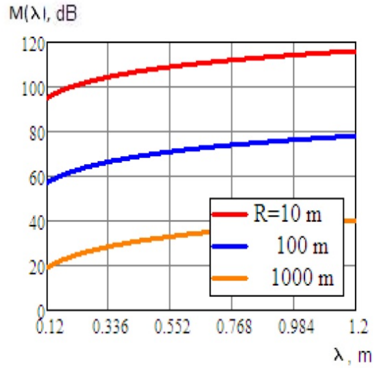
where $\theta = arctg\left(\Delta h_{\mathrm{UAV}}/b\right)$.

This model allows us to take into account a number of additional parameters and thus ensure greater accuracy of the calculation. It is based on the equations of wave optics and considers various mechanisms of propagation of radio waves in urban conditions: propagation in free space, diffraction at the edges of the roofs of buildings, reflection from the walls of buildings. When the base station antenna is located above the average level of the roofs of buildings, two beams come from the base station to the mobile station: one-as a result of diffraction at the edge of the roof of the building, the other-after re-reflection from the wall. Despite the fact that this model does not take into account a number of important parameters (the type of building materials, the orientation of streets, etc.), it provides a fairly simple and convenient way to obtain preliminary estimates of the level of average losses in the communication channel.

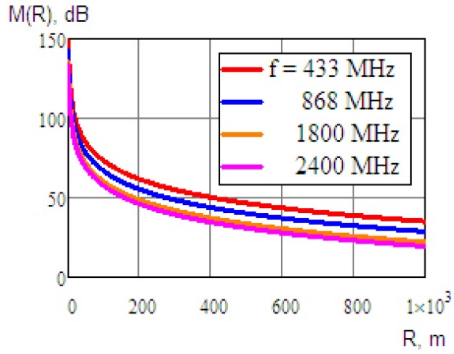
3 Simulation of the energy reserve of the communication channel during data transmission between unmanned aerial vehicles

Figure 1 shows the results of modeling the energy reserve of the communication channel during data transmission between UAVs, depending on the carrier frequency of the transmitted radio signal, as well as on the distance between the transmitting and receiving nodes of the communication network. In Figure 1(a) the red color shows the relationship for a communication range of 10 m, blue-for a communication range of 100 m and orange, for a communication range of 1000 m; in Figure 1(b) in red - the dependence for the carrier frequency of 433MHz, in blue - for the carrier frequency of 868MHz, in orange-for the carrier frequency of 1800 MHz and in pink-for the carrier frequency of 2400 MHz.

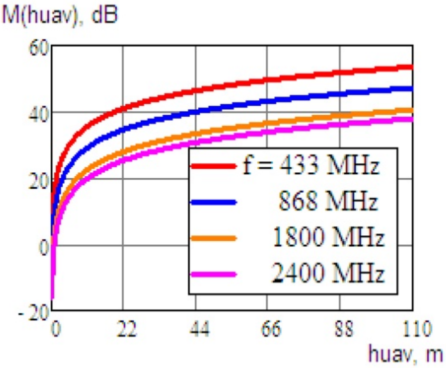
As an example, Figure 2 shows the results of modeling the energy reserve of the communication channel during data transmission between the UAV and the GCC, depending on the wavelength of the transmitted radio signal (in



(a)



(b)



(c)

Figure 2: The dependence of the energy reserve of the communication channel during data transmission between the UAV and the GCC on the wavelength of the transmitted radio signal (a), the distance between the transmitting and receiving nodes of the communication network (b) and the difference in the height of the UAV antenna and the average roof level (c).

meters), the distance between the transmitting and receiving nodes of the communication network (in meters) for the case when the flight height of the UAV is higher than the average level of the roofs of the buildings of the "smart city", as well as on the difference in the height of the UAV antenna and the average level of the roofs. In this case, the following values of the urban environment parameters were used for modeling: h_{GCC}= 10 m, h_{UAV} = 60 m, w = 22.5 m, b = 60 m. Color designations of curves for Figure 2(a) are similar to those previously adopted for Figure 1(a), and for Figure 2(b) and (c) are similar to those used for Figure 1(b).

A graphical comparison of the values of the energy reserve of the radio communication channel when transmitting data between small-sized UAVs and GCC in real conditions for different flight altitudes of UAVs is shown in Figure 3, where the curves for flight altitudes above the roof level are shown in red, blue-at the roof level and orange-below the roof level.

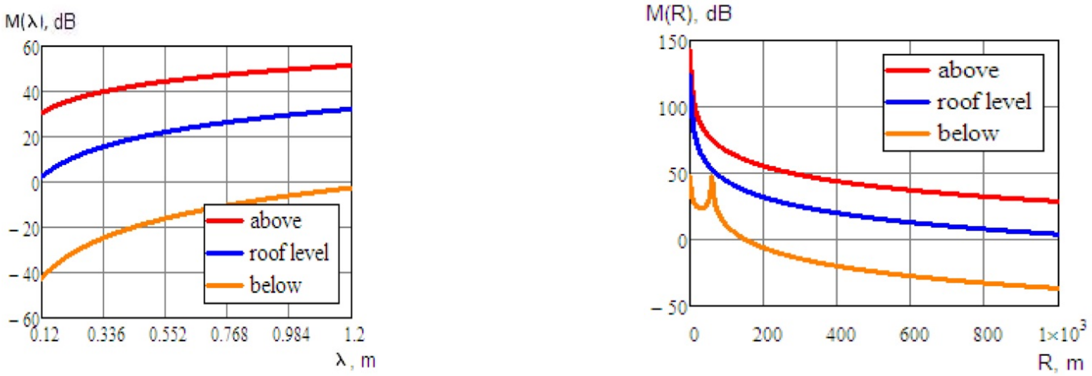
4 Conclusion

Based on the results of the analysis of the mathematical expressions used to calculate the energy reserve of the communication channel and the propagation losses of radio signals during data transmission between the UAV and between the UAV and the GCC, as well as the simulation results, it was found that:

- due to the lower number of re-reflections of radio waves during data transmission between UAVs, this type of communication is generally characterized by a greater amount of energy reserve and, consequently, greater reliability and reliability of data transmission than the communication channel between the UAV and the GCC;

- an increase in the height difference of the UAV antennas and the average roof level leads to an increase in the values of the energy reserve of the radio communication channel;

- the energy reserve of the communication channel for both scenarios of data transmission linearly depends on the



(a) (b)

Figure 3: Dependence of the energy reserve of the communication channel during data transmission between the UAV and the GCC on the wavelength of the transmitted radio signal (a) and the distance between the transmitting and receiving nodes of the communication network (b) for different flight altitudes.

energy parameters of the receiving and transmitting equipment of both the UAV and the GCC (transmitted power, the gain of the transmitting antennas and the sensitivity of the radio receivers);

- with an increase in the carrier frequencies (a decrease in the wavelengths) of data transmission and the communication range, a decrease in the energy reserve of the radio communication channel is observed.

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