ISSN: 0974-5823 Vol. 7 No. 1 January, 2022

International Journal of Mechanical Engineering

Modeling radio signals propagation losses during data transmission using unmanned aerial vehicles

Surzhik D.I. [1,2], Kuzichkin O.R.[2], Vasiliev G.S.[2], Kurilov I.A.[1], Kharchuk S.M.[1]

[1]Vladimir State University named after Alexander Grigoryevich and Nikolai Grigorievich Stoletovs, Vladimir, 600000, Russia

[2]Belgorod State Research University, Belgorod, 308015, Russia

Abstract: Models of radio signal propagation losses during data transmission using unmanned aerial vehicles (UAVs) are obtained in this work. The features of the organization of radio communication channels based on wireless self-organizing networks using unmanned aerial vehicles are considered. It is noted that in such networks it is possible to carry out information transmission, both in the air-to-air mode and in the air-to-ground mode, it has been determined that the best communication option is to carry out data transmission in free space, which is difficult to achieve in practice, especially in conditions of dense urban development, in connection with which radio communication channels using UAVs are generally described by a multipath model of radio wave propagation.The well-known models of losses during the propagation of radio signals are considered, for which the main advantages and disadvantages are determined. To estimate propagation losses during data transmission between UAVs, it is proposed to use a modified free-space loss formula, supplemented by correction factors; for data transmission between UAVs and ground control systems - generalized Xia-Bertoni models adapted taking into account the peculiarities of data transmission by means of coefficient inversion.The initial data are selected for estimating the propagation losses of radio signals during data transmission using unmanned aerial vehicles. With their use, a study was carried out of the influence of the main operating factors on the quality of information exchange, both between individual unmanned aerial vehicles and between unmanned aerial vehicles and ground control systems; the corresponding conclusions were drawn from the simulation results.

Keywords: unmanned aerial vehicles, "smart cities", wireless self-organizing networks, multipath signal propagation, direct and indirect visibility, propagation loss.

Introduction

Unmanned aerial vehicles (UAVs) [1-3] are artificial mobile flying objects that do not have a pilot and crew on board and are capable of independently purposefully moving in the air to perform various functions autonomously or through remote control. Historically, military UAVs were the first to appear, however, starting in the 2000s, the active development of civilian UAVs and their introduction into various spheres of human activity began. Their use seems to be especially promising in the conditions of modern "smart cities" [4-9], the management of urban development of which is based on advanced information and telecommunication and technological solutions, which makes it possible to provide residents with more comfortable and safe living conditions, as well as to ensure autonomous work and interaction of all components of the urban economy.

However, despite a fairly wide range of tasks to be solved using UAVs (providing communications, conducting monitoring work, etc.), many technical problems associated with their use remain unsolved. One of these problems is their use in urban environments with dense buildings, characterized, in particular, by the presence of buildings of various storeys with various reflection coefficients and a significant level of electromagnetic interferences. In this aspect, a number of issues related to both the quality of communication and ensuring its reliability are becoming relevant for solving.

These parameters largely depend on the amount of attenuation (propagation loss), which is one of the most important characteristics of the propagation of any signal (especially in wireless radio communication channels). The importance and relevance of solving the problem of estimating the propagation losses of radio signals is determined both by the lack of adequate mathematical models in relation to data transmission using UAVs, and by the complex picture of the multipath propagation of signals, the variety of real conditions of propagation of radio waves of various bands, as well as the complexity of describing the signal-interference situation at reception.

Features of the organization of radio communication channels using unmanned aerial vehicles

One of the options for using small-sized UAVs in the conditions of "smart cities" is the organization on their basis of wireless self-organizing networks and their special case - self-organizing networks of aircraft (Flying Ad-Hoc Network, FANET) [10-12]. At the same time, in such networks, it is possible to transfer information both in the air-to-air mode (between UAVs within the established network) and in the air-to-ground mode (between individual UAVs and software and hardware ground control systems, GCS).At the same time, the distinctive features of the organization of such communication channels from the classical model of interaction between the base station and mobile nodes are:

- the heights of the GCS antennas can be several times lower than the heights of typical antennas of base stations of data transmission systems due to the features of organization of FANET networks;
- the flight altitudes of small-sized UAVs, legally regulated in many countries when used within the city, are standardly divided into two ranges: the first - from 0 to 60 m and intended for low-speed localized traffic in sparsely populated areas of cities and the second - from 60 to 120 m - for high-speed traffic in densely populated areas, with heights above 120 m, as a rule, it is considered to be a no-fly zone. The structure of the airspace for UAV flights in urban areas is illustrated in Figure 1.

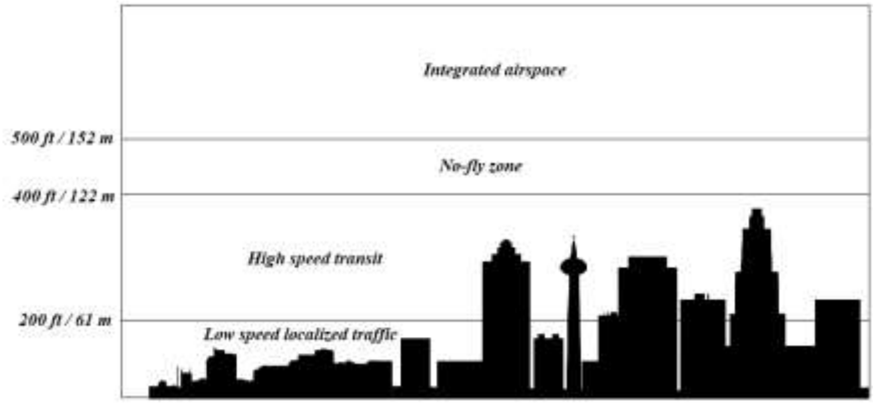


Figure 1 - The structure of the airspace for UAV flights in urban conditions

The best option for communication between the UAVs, as well as between the UAVs and the GCS is the implementation of data transfer in free space. In this case, it is possible to realize the communication with high speed and low losses. Within the framework of the free space model, it is assumed that the propagation medium is homogeneous, and the signal energy depends only on the distance between the transmitter and the receiver and decreases in inverse proportion to its square. At the same time, the maximum distance of radio visibility between the UAVs, as well as between the UAVs and the GCS, depends on the flight altitude of the UAVs and the elevation of the GCS antennas.

However, in practice, data transmission in free space is difficult to achieve, especially when operating wireless communication systems in dense urban areas, and therefore radio communication channels using UAVs in the general case should be described by a multipath model of radio wave propagation, taking into account the phenomena of re-reflection, scattering and diffraction.

The reflection effect occurs when an electromagnetic wave collides with an obstacle that is much larger than the wavelength. In urban environments, radio waves can be reflected off the walls of buildings.

The diffraction effect occurs when the propagation path between the transmitter and receiver is covered by an obstacle with dimensions that are large in relation to the signal wavelength, which leads to the formation of secondary waves behind the obstacle. In urban environments, radio waves are diffracted from the edges of buildings, cars, and many other objects.

The scattering effect occurs when the propagating signal strikes an object that is on the order of the signal wavelength or less, resulting in re-emission of signal energy in all directions. In urban environments, scattering of radio waves can occur on lamp posts, road signs, trees, etc.
In addition, another of the characteristics of a multipath communication channel is signal propagation loss, which can be caused by a decrease in the power of the useful signal, an increase in noise power, or the power of signals interfering with the useful signal.
As sources of reducing power of the desired signal can act as losses associated with the restriction of the communication channel bandwidth, the effect of intersymbol interference, intermodulation distortion, the polarization loss, spatial loss, an adjacent channel interference, modulation losses own receiver noise, loss in antenna feedlines and a series of others. Atmospheric and galactic noises and, what is especially important, industrial noise can be noted as sources of noise power increase.

Models of propagation loss of radio signals in wireless communication channels

Let us consider the known models of losses during the propagation of radio signals [13-25], which will allow us to determine the most optimal of them in relation to communication channels using UAVs.
In general, the full characteristics of the propagation of electromagnetic waves can be obtained by solving the Maxwell equations under certain conditions, which reflect the physical characteristics of the obstructing objects. At the same time, good practical results are obtained by taking into account the relief of the underlying surface on the basis of the physical principle of Huygens-Kirchhoff.
However, since in practice these calculations are difficult to perform, and in many cases there are no necessary parameters for this, approximation methods are often used to obtain signal propagation characteristics that do not require solving complex equations.
First of all, consider the ideal case - the attenuation of a radio signal when propagating in free space - Figure 2.

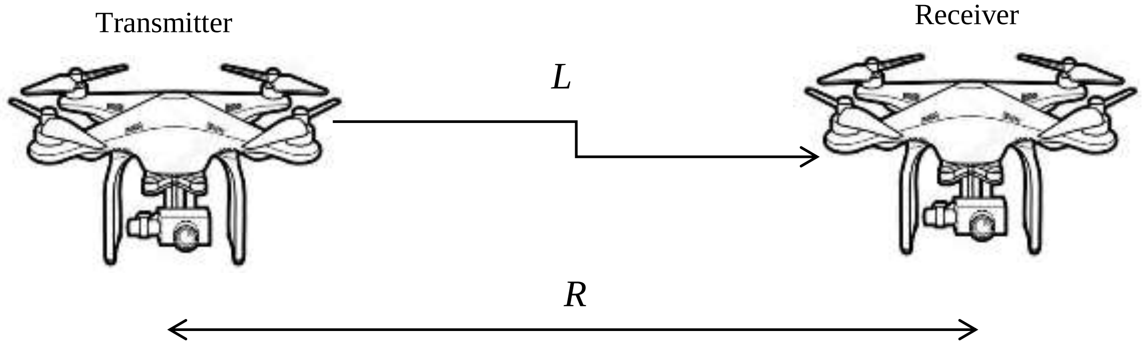


Figure 2 - Radio channel for data transmission in free space

This model assumes that the area between the transmitter and receiver is free of objects that can absorb or reflect radio frequency energy. In addition, it is believed that in this case, inside this area, the atmosphere is homogeneous and acts as a non-absorbing medium, and the earth is infinitely far from the propagated signal [23]. In this case, the propagation loss in free space, expressed in dB, is defined as

$$L = 32{,}4 + 20\lg(f) + 20\lg(R), \qquad (1)$$

where R is the distance between the transmitter and the receiver, f is the carrier frequency of the propagated signal.
For most real channels, in which signals propagate in the atmosphere near the earth's surface, this model does not adequately describe the channel behavior. In addition, this case does not take into account such a common effect as large-scale fading, reflecting the loss in the channel due to the propagation of radio waves over long distances in the presence of various objects along the path. Propagation losses taking into account this type of fading were experimentally measured in Tokyo by Okumura for a large number of antenna heights and coverage distances and were taken into account by Hata when drawing up parametric formulas as a function of the distance between the transmitter and receiver, presented, for example, in [23].
However, in practice, in real conditions of propagation of radio signals on the ground, the amount of attenuation depends on a set of factors that determine the nature of radio wave propagation - Figure 3. As a result, an accurate analytical calculation of the propagation losses of radio signals for real conditions of data

transmission using UAVs is practically impossible due to the presence of many factors that are difficult to describe mathematically. As a result, this propagation parameter is estimated using empirical models developed on the basis of numerous experiments.

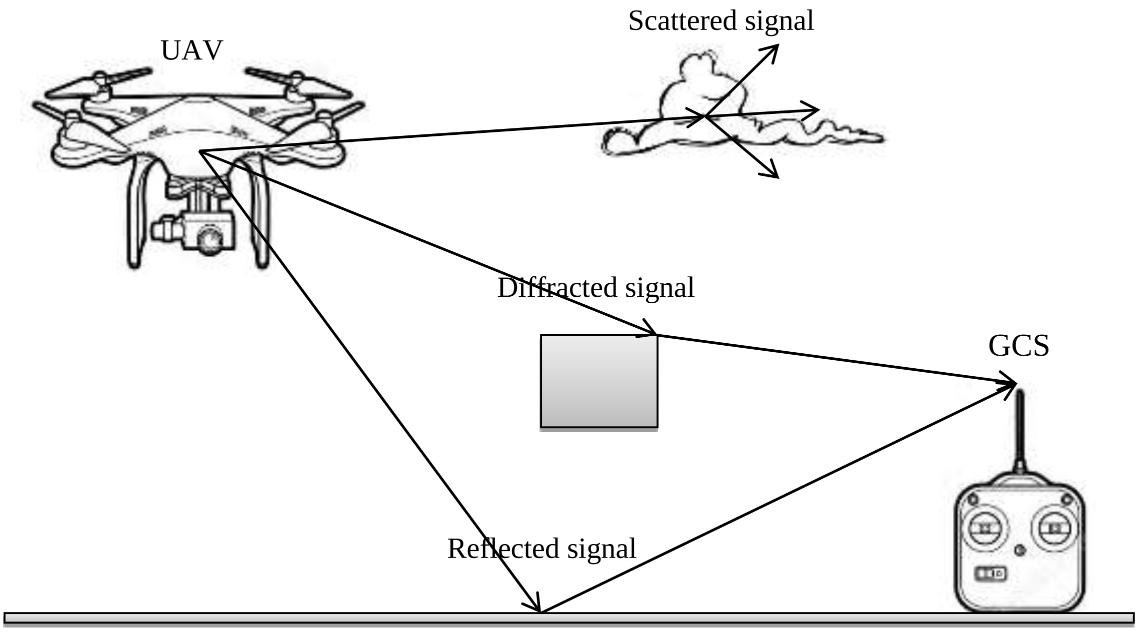


Figure 3 - Radio channel for data transmission in real conditions

The most common empirical model for describing propagation losses during data transmission in real conditions is the use of the Okumura-Hata model [19, 22, 25], based on a graphical or analytical approximation of the results of experimental measurements. A set of empirical formulas and correction factors obtained as a result of such an approximation makes it possible to calculate the average losses for various types of terrain: typical urban areas, suburban areas and open areas. In most cases, these formulas quite accurately (with a maximum error of about 1 dB) correspond to the experimental data under the following conditions: the carrier frequencies during data transmission do not exceed 1500 MHz, the base station antenna height is from 30 to 400 m, the mobile station antenna height does not exceed 10 m, the distance between the antennas of the base and mobile stations does not exceed 80 km [19, 22].

Scientific and technical studies within the framework of the European Union project COST (Cooperation for Scientific and Technical Research) allowed this model to be extended to the carrier frequency range 1.5-2 GHz and it was called the modified Okumura-Hata model or the COST231-Hata model, presented, for example, in [25].

The main disadvantages of these models are that they are not suitable for assessing signal attenuation at distances less than 1 km, they do not take into account the specifics of the FANET communication network deployment (street width, etc.) and they cannot be used to assess signals propagation along streets with high buildings.

A number of additional parameters are taken into account in the Walfisch – Ikegami and Xia – Bertoni models [19, 25]. These models are based on the equations of wave optics and consider various mechanisms of radio wave propagation in urban environments: propagation in free space, diffraction at the edges of roofs of buildings, reflection from the walls of buildings. Despite the fact that these models do not take into account a number of parameters (for example, the type of building materials from which urban buildings and structures are built), they are a fairly simple and convenient way to estimate the level of average losses in wireless communication channels implemented in real urban conditions and can serve as a basis for the development on their basis of models of propagation losses in communication channels using UAVs.

Modifications of propagation loss models taking into account the peculiarities of data transmission using unmanned aerial vehicles

Based on the above analysis, we will modify the known models of radio signal propagation in relation to data transmission between UAVs and between UAVs and GCS.

Based on the conditions for data transmission using UAVs in urban development, the models of radio signal propagation losses in free space in this case cannot be applied due to not taking into account in this case the real operating conditions of the communication channel. In addition, due to the fact that data transmission can be carried out at a short distance (less than 1 km), as well as with the presence in real conditions of propagation of the effects of re-reflection, scattering, etc. in this case, the empirical models of Okumura-Hata and COST231- Hata cannot be applied.

Since data transmission between UAVs is carried out at an altitude, as a rule, exceeding the level of urban buildings and structures (up to 120 m), and the orientation of streets and radio wave reflections from the walls of buildings in this case are not so significant, it can be assumed that these conditions correspond to the case of the presence line of sight and you can use the modified formula (1) by analogy with the empirical formula COST231-Walfisch-Ikegami

$$L = (32{,}4 + \Delta_1) + 20\lg(f) + (20 + \Delta_2)\lg(R), \qquad (2)$$

where Δ_1 and $\Delta_2$are correction factors that take into account losses on the real path of radio signal propagation in urban conditions.

As a rule, the values of the coefficient $\Delta_1$are in the range from 0 to 10.2, the values of the coefficient Δ_2 are in the range from 0 to 6.

Due to the fact that the propagation conditions during data transmission between the UAVs and the GCS are the opposite of the traditional model of information exchange between the base station and mobile nodes (the flight height of the UAVs is an order of magnitude higher than the antenna height of the GCS, while in the classical model the antenna of the base station is an order of magnitude above the height of the antennas of mobile nodes), then in this case it is possible to apply the Xia-Bertoni model, adapted taking into account this feature by inverting a number of coefficients. Then, for the flight height of the UAVs above the average level of the roofs of buildings, the value of the average on the route will be determined as

$$L = -10\lg\left(\left(\frac{\lambda}{4\pi R}\right)^2\right) - 10\lg\left(\frac{\lambda}{2\pi^2 r}\left(\frac{1}{\theta} - \frac{1}{2\pi+\theta}\right)^2\right) - 10\lg\left(2{,}35^2\left(\frac{\Delta h_{\mathrm{UAV}}}{R}\sqrt{\frac{b}{\lambda}}\right)^{1.8}\right);(3)$$

where λ is the wavelength, R is expressed in meters, $\Delta h_{\mathrm{UAV}} = h_{UAV} - h_r$is the difference in flight heights of the UAV and the average roof level in meters, $\theta = arctg(\Delta h_{\mathrm{GCS}}/x)$is the angle of incidence of the refracted beam on the antenna of the GCS , $\Delta h_{\mathrm{GCS}} = h_r - h_{GCS}$ - the difference between the heights of the average level of the roofs and the antenna of the GCS in meters, x is the distance in meters horizontally between the GCS and the edge of the roof, on which the wave diffracts (usually $x = w/2$), w is the average width of streets (usually 15-30 meters), b - average interval between blocks (usually 40-80 meters), $r = \sqrt{\Delta h_{\mathrm{GCS}}{}^2 + x^2}$ - distance from the point of refraction of the beam to the GCS antenna in meters.

In the case when the flight height of the UAVs is commensurate with the level of the roofs, the loss of propagation of the radio signal is determined as

$$L = -10\lg\left(\left(\frac{\lambda}{2\sqrt{2}\pi R}\right)^2\right) - 10\lg\left(\frac{\lambda}{2\pi^2 r}\left(\frac{1}{\theta} - \frac{1}{2\pi+\theta}\right)^2\right) - 10\lg\left(\left(\frac{b}{R}\right)^2\right), \qquad (4)$$

aand in the case when the flight height of the UAVs is below the roof level – as

$$L = -10\lg\left(\left(\frac{\lambda}{2\sqrt{2}\pi R}\right)^2\right) - 10\lg\left(\frac{\lambda}{2\pi^2 r}\left(\frac{1}{\theta} - \frac{1}{2\pi+\theta}\right)^2\right)$$
$$-10\lg\left(\left(\frac{b}{2\pi(R-b)}\right)^2\frac{\lambda}{\sqrt{\Delta h_{\mathrm{UAV}}{}^2 + b^2}}\left(\frac{1}{\varphi} - \frac{1}{2\pi+\varphi}\right)^2\right), \qquad (5)$$

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

Initial data for estimating radio signal propagation losses during data transmission using unmanned aerial vehicles

As the initial data for assessing the characteristics of radio communication channels with UAVs [26-29], we will take the following parameters:

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

The selected frequencies comply with internationally accepted standards for frequency regulation for consumer use without special permits or licenses. They match the UHF range and provide a good compromise between range and radio bandwidth.

The frequency range near the 433 MHz carrier frequency has good power consumption, providing reliable communication in urban conditions with small antenna sizes and a minimum transmitter power (no more than 10 mW). Among the disadvantages of this range, it should be noted the problem of ensuring electromagnetic compatibility due to the many different electronic devices operating in this range, which leads to false alarms and unstable operation of the transceiving equipment.

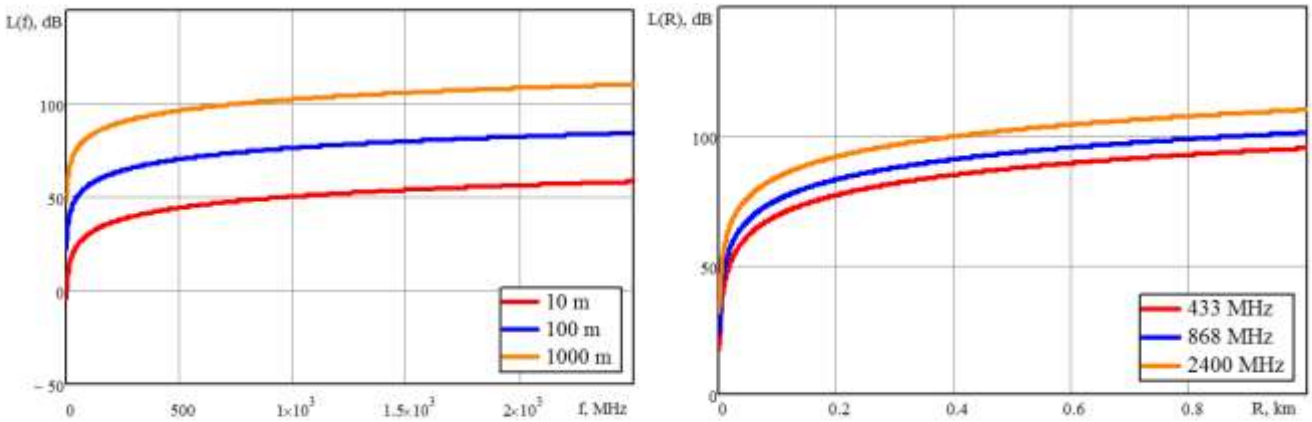
One of the solutions to this problem is the transition for transceiving to another frequency range, for example, to the frequency range within the carrier frequency of 868 MHz, which is characterized by a greater penetrating ability of electromagnetic waves and their protection from the effects of interference of natural and artificial origin.

The use of a higher carrier frequency (2400 MHz) makes it possible to reduce the size of the antenna and increase the radiation efficiency. The transition to shorter wavelengths also reduces the impact on communication quality of interference from industrial installations (transformers, trolleybus and tram lines, industrial generators) and other sources that create a citywide noise background of electromagnetic radiation. However, in this case, shorter waves lose their ability to bend around obstacles, and therefore they are less effective in urban environments with dense buildings and stationary installations. At the moment, such popular standards as Bluetooth, Wi-Fi and ZigBee operate in the 2400 MHz range.

The selected heights of the antennas of the GCS are typical for communication systems using UAVs in urban conditions, and the flight heights of the UAVs are also characteristic of the values regulated when using UAVs in the city.

Results of modeling radio signal propagation losses during data transmission using unmanned aerial vehicles

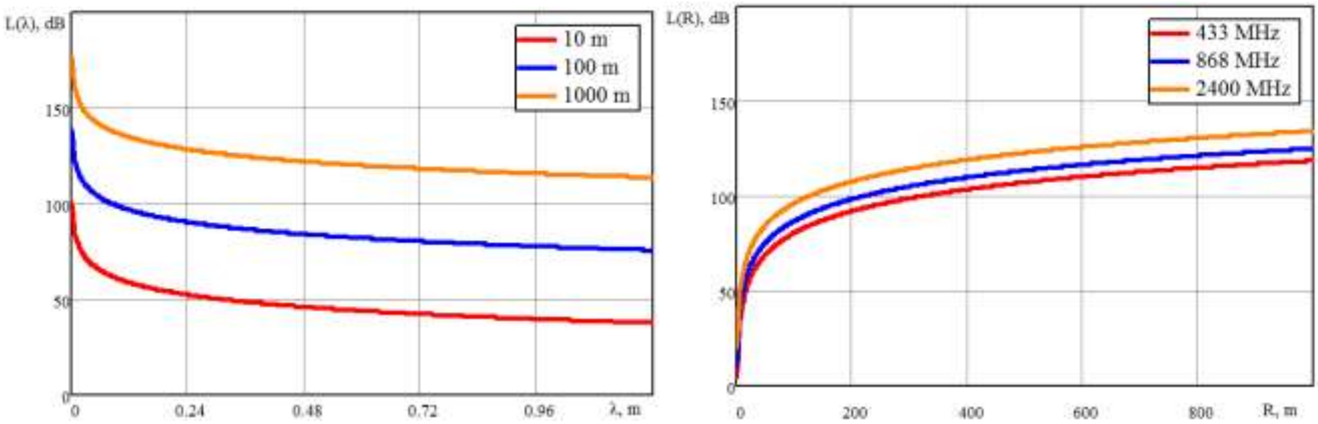
Figure 4 shows the results of modeling the propagation loss of radio signals during data transmission between UAVs, depending on the carrier frequency of the transmitted radio signal, as well as on the distance between the transmitting and receiving network nodes.



a) b)

Figure 4 - Dependences of radio signal propagation losses during data transmission between UAVs depending on the carrier frequency of the transmitted radio signal (a) and the distance between the transmitting and receiving network nodes (b)

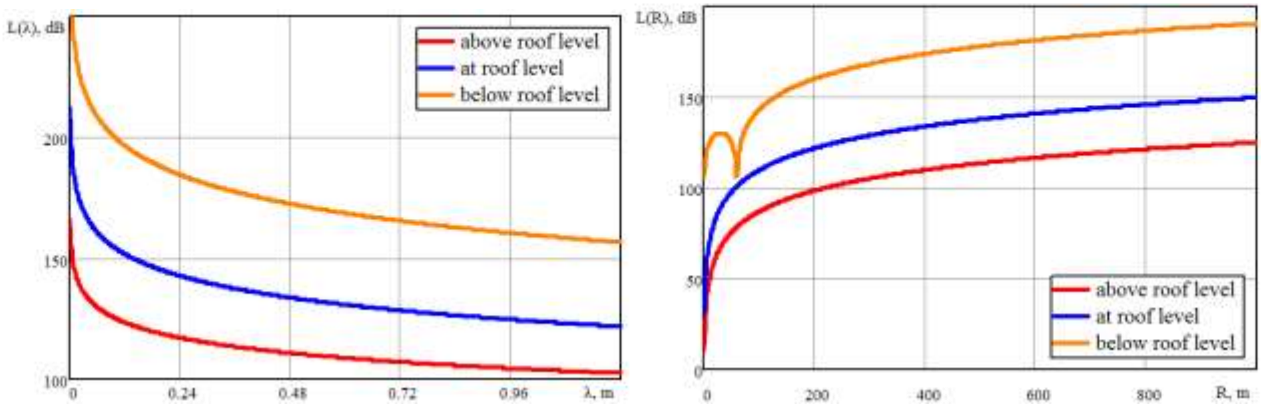
Figure 5 shows, as an example, the results of modeling radio signal propagation losses during data transmission between UAVs and GCS depending on the wavelength of the transmitted radio signal (in meters), as well as on the distance between the transmitting and receiving network nodes (in meters) for the most common in practice case described by model (3). In this case, the following values were used as simulation parameters: h_{GCS} = 10 m, Δh_{UAV}= 60 m, h_r = 15 m, w = 22.5 m, b = 60 m.



a) b)

Figure 5 - Dependences of radio signal propagation losses during data transmission between UAVs and GCS depending on the wavelength of the transmitted radio signal (a) and the distance between the transmitting and receiving network nodes (b)

The results of comparing the values of the propagation loss of radio signals during data transmission between the UAVs and the GCS in real conditions for different flight altitudes of the UAVs are shown in Figure 6.



a) b)

Figure 6 - Dependences of radio signal propagation losses on wavelength (a) and communication range (b) during data transmission between UAVs and GCS in real conditions for different flight altitudes

Conclusion

From the obtained graphical dependencies, describing the influence of the main operating factors on the loss of propagation of radio signals during data transmission using UAVs, it was found that:

- due to the smaller number of radio waves re-reflections during data transmission between UAVs, this type of communication is characterized by 10-15 dB less loss of propagation of radio signals and, therefore, higher quality and reliability than the communication channel between the UAVs and the GCS (moreover, the lower the flight altitude UAVs and the higher the level of urban development, the worse the quality of such a communication channel);

- for both considered scenarios of information exchange using UAVs, an increase in the carrier frequency of data transmission and communication range is accompanied by an increase in radio signal propagation losses, and the dependence on the carrier frequency is more pronounced.

The models of radio signal propagation losses proposed in the work are based on the well-proven COST231-Walfisch-Ikegami and Xia-Bertoni models, which have proven themselves in practice, taking into account the peculiarities of data transmission both between individual UAVs in line-of-sight conditions, and between UAVs and GCS. They allow one to take into account the main factors that determine the amount of attenuation of radio signals along the route: the carrier frequency of the transmitted signal, the communication range between the transmitter and the receiver, the height of the antenna mast of the GCS, the flight heights of the UAVs, the average roof level of specific urban areas, as well as such effects of multipath propagation as diffraction and reflection. Their use will make it possible to model and evaluate the quality and reliability of communication with a sufficient degree of accuracy, depending on various parameters and conditions of operation of wireless communication channels.

Further development of the proposed models is seen in the correction and creation, on the basis of real experimental data, of a statistical base of correction factors, which make it possible to refine the model data depending on the specific conditions of data transmission.

Acknowledgments

The work was supported by the RFBR grant 19-29-06030-mk "Research and development of a wireless ad-hoc network technology between UAVs and smart city control centers based on the adaptation of transmission mode parameters at various levels of network interaction". The theory was prepared within the framework of the state task of the Russian Federation FZWG-2020-0029 "Development of theoretical foundations for building information and analytical support for telecommunications systems for geoecological monitoring of natural resources in agriculture".

Reference

1. Chertova O.G., Chirov D.S. Building a core communication network which is based on small size unmanned aircraft vehicle without ground infrasrtuvture / H&ES Research. -2019. -Vol. 11. -No. 3. -Pp. 60–71.
2. A.N. Bondarev, R.V. Kirichek. Overview of unmanned aerial vehicles for general use and air traffic control UAVs in different countries / Information technology and telecommunications. - 2016, Volume 4, No. 4. - Pp. 13-23.
3. A.D. Vyrelkin, A.E. Curly. The use of unmanned aerial vehicles for solving the problems of the "smart city" / Information technology and telecommunications. -2017, Vol. 5, No. 1. - Pp. 105-113.
4. D. Votzel, E. Kuznetsova. Smart City Technologies: What Affects Citizens' Choices? - McKinsey center for government. - 2018.- 66 p.
5. D. McLaren, J. Agyeman. Sharing Cities. A Case for Truly Smart and Sustainable Cities/ The MIT Press. - Cambridge, Massachusetts. – 2015. - 461p.
6. M. Ablameiko, S. Ablameiko. "Smart city": from theory to practice / Science and innovation. –2018. - No. 6 (184). -Pp. 28-34.
7. V.N. Knyaginin. Priority areas for the implementation of smart city technologies in Russian cities / Expert and analytical report. – Moscow. - 2018. - 178 p.
8. KheirAl-Kodmany. SentientCity: UbiquitousComputing, Architecture, andtheFutureofUrbanSpace / JournalofUrbanTechnology. - 2012. - Pp. 137-140.
9. Kurcheeva G.I., Klochkov G.A. Development of a process model "smart city" / Internet journal "Science". – 2017. - Volume 9. - No. 5. - Pp. 1-8.
10. A.V. Leonov V.A. Chaplyshkin. FANET networks / Omsk Scientific Bulletin. - 2015, No. 3 (143). - Pp. 297-301.
11. I. Bekmezci, O. K. Sahingoz, S. Temel., Flying Ad-Hoc Networks (FANETs): A Survey, Ad Hoc Networks. – 2013. - Vol. 11. - № 3. -Pp. 1254–1270.
12. Ananiev A.V., Stafeev M.A., Makeev E.V. Development of a method for organizing communication using short-range unmanned aerial vehicles / Proceedings of the MAI. - Issue No. 105. - 2019. - Pp. 1-18.

13. A.V. Polynkin, H.T. Le. Investigation of the characteristics of the radio communication channel with unmanned aerial vehicles / Izvestiya TulGU. Technical science. – 2013. - Iss. 7., Ch. 2. - Pp. 98-107.
14. Fokin G.A. Review of models of radio communication channel with unmanned aerial vehicles / Proceedings of educational institutions of communication. - 2018. - Vol. - 4.No. 4. -Pp. 85–101.
15. Kulikov G.V., Tambovskiy S.S. Assessment of the quality of communication with UAVs in urban development / Bulletin of MSTU MIREA. – 2015. - No. 1(6). - Pp. 205-217.
16. Golikov A.M. Modulation, coding and modeling in telecommunication systems. Theory and practice: textbook. allowance. - SPb.: Lan. -2018 .-452p.
17. Kirillov V.I. Multichannel data transmission systems: Textbook / V.I. Kirillov. - M .: New knowledge. - 2002. - 751 p.
18. Irwin J., Harl D. Data transmission in networks: an engineering approach: Per. from English - SPb.: BHV-Petersburg. - 2003.- 448 p.
19. Babkov V.Yu., Voznyuk M.A., Nikitin A.N., Sivers M.A. Communication systems with code division channels / SPbGUT. SPb. - 1999.- 120 p.
20. Shvartsman V.O., Emelyanov G.A. Theory of Discrete Information Transmission: A Textbook for Communication Universities. - M.: Communication. - 1979.- 424 p.
21. V.V. Krukhmalev. Fundamentals of building telecommunication systems and networks: Textbook for universities / V.V. Krukhmalev, V.N. Gordienko, A.D. Mochenov et al. Ed. V.N. Gordienko and V.V. Krukhmaleva. - M.: Hot line – Telecom. - 2004.- 510 p.
22. Ipatov V.P. Mobile communication systems: Textbook for universities / V.P. Ipatov, V.K. Orlov, I.M. Samoilov, V.N. Smirnov; ed. V.P. Ipatov. - M.: Hot line – Telecom. - 2003.- 272 p.
23. Sklyar B. Digital communication. Theoretical foundations and practical application. Ed. 2nd, rev .: Per. from English - M.: Publishing house "Williams". - 2003. - 1104 p.
24. Vasin V.A. Radio systems for transmitting information: a textbook for universities / V.A. Vasin, V.V. Kalmykov, Yu.N. Sebekin, A.I. Senin, I.B. Fedotov; ed. I.B. Fedotov and V.V. Kalmykov. - M .: Hotline – Telecom. - 2005. –472 p.
25. V.A. Utz. Investigation of losses in the propagation of cellular radio signal on the basis of statistical models / Bulletin of the Baltic State University. I. Kant. - 2011. - Issue. 5. -Pp. 44-49.
26. Kuzichkin OR, Vasilyev GS, Surzhik DI. Design an algorithm for analyzing the stability of information exchange between UAVS in the high-order agent formation / INGENIERIA UC. - Volume 27, Issue: 2, Pp. 224-232. – 2020
27. Vasilyev GS, Kuzichkin OR, Kurilov IA, Surzhik DI. Method for analyzing the stability of information transfer between unmanned aerial vehicles in the formation / REVISTA DE LA UNIVERSIDAD DEL ZULIA. - Volume 11, Issue: 30, Pp. 125-136. – 2020
28. Surzhik D.I., Vasilyev G.S., Kuzichkin O.R. Modeling the dynamic properties of communication channels in UAV-based networks based on spectral piecewise linear approximation method / International Journal of Engineering Research and Technology. - Volume 13, Issue 12. – 2021. – Pp. 4653-4657
29. Vasilyev G.S., Surzhik D.I., Kuzichkin O.R. Integration of radio frequency and optical channels in communication networks with unmanned aerial vehicles / International Multidisciplinary Scientific GeoConference Surveying Geology and Mining Ecology Management, SGEM. - Volume 2020-August, Issue 2.1. – 2020. – Pp. 177-184