International Journal of Engineering Research and Technology. ISSN 0974-3154, Volume 13, Number 12 (2020), pp. 4653-4657

Modeling the Dynamic Properties of Communication Channels in UAV-based Networks based on Spectral Piecewise Linear Approximation Method

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Abstract

This work is devoted to the application of methods for approximating signals and characteristics based on continuous piecewise linear functions (CPLF) for modeling wireless radio communication channels using unmanned aerial vehicles (UAVs). The relevance and prospects of using this class of aircraft as part of flying ad-hoc networks (FANET) for transmitting high-speed information in "smart cities" are shown. The problem of these networks is also noted, due to uncertain reliability and quality of wireless communication, associated with multipath propagation of signals and a number of other factors. It is shown that the development of mathematical modeling methods for analyzing signals at the inputs of UAV radio receivers for evaluating their amplitude-phase transformations by a communication channel is particularly relevant. It is established that the relationship between the signals on the transmitting and receiving sides of an arbitrary wireless radio channel, assuming its linearity, can be uniquely determined by a complex transfer function in the frequency domain, which in practice is very complex and difficult to describe analytically. In this regard, an approach to its approximation by an equivalent model described by fractional-rational functions of a complex variable that are physically realized by connection of various linear inertial and non-inertial links is proposed, and for modeling dynamic characteristics, a method of numerical and analytical modeling based on the spectral method and piecewise linear approximation is proposed.

Keywords: unmanned aerial vehicles, "smart cities", ad-hoc networks, communication channel, approximation, continuous piecewise linear functions, fuzzy logic, neural networks.

I. INTRODUCTION

Currently, unmanned aerial vehicles (UAVs) [1] are actively used to solve a wide range of tasks for various purposes [2-5]. At the same time, in recent years, their use in rapidly developing "smart cities" [6-11] as part of flying ad-hoc networks (FANET) has become particularly popular [12-15]. These networks are characterized by scalability, rapid recovery, and optimal coverage of the served territory. They consist of two segments: ground-based, represented by one or more ground-based control complexes (GCCs), and air-based segment, represented by network nodes based on small-sized UAVs.

One of the technical problems of ad-hoc UAV-based networks in "smart cities" is to ensure acceptable reliability and quality of wireless communication [16-18]. This problem is caused by the dense development of "smart cities", as well as the presence of buildings of various geometries and storeys, which affect the nature of radio signal propagation through communication channels both between individual UAVs and between UAVs and GCC.

Complex properties of wireless communication channels in terms of "smart cities" implies following aspects. Radio propagation via such channels is largely determined by the lack of simple analytical models to describe them, as well as multi-path signal propagation, a variety of real propagation conditions, different ranges, mobility of mobile nodes and signal-interference situation at the receiving end that determines the relevance of the present study.

I.I Features of wireless radio communication channels for UAVs in "smart cities"

A wireless radio communication channel [19-27] is a physical medium that is used for transmitting signals from radio transmitters to radio receivers, which in this case can be carried by both UAVs and GCC. An ideal option for communication between individual UAVs, as well as between UAVs and GCC, is to transmit data in free space. In this case, it is usually assumed that the propagation medium is uniform and the signal energy depends only on the distance between the transmitter and receiver.

However, in the reality of "smart cities", data transmission in free space is difficult to achieve and in practice is traditionally described by a multipath model of radio wave propagation, taking into account the phenomena of re-reflection, scattering and diffraction. According to this model, the signal on the receiving side is the sum of individual signals reflected from a large number of scatterers that are randomly arranged and have a random effective scattering surface. In addition, another feature of real wireless radio communication channels for UAVs in "smart cities" is a significant level of electromagnetic interference.

The consequence of this set of factors is the presence of a number of effects relevant for the FANET in "smart cities": signal propagation losses, fading of their amplitudes and fluctuations in the time of arrival at receiving antennas.

Signal propagation losses can be caused by a decrease in the power of the useful signal, an increase in the power of noise, or the power of signals that interfere with the useful signal. The following effects reduce the quality of the useful signal–losses caused by limiting the bandwidth of the communication channel, the effect of intersymbol interference, inter-modulation distortion, polarization losses, spatial losses, interference of the neighboring channel, modulation losses, receiver's own noise, losses in the antenna-feeder path, and a number of others. Atmospheric and galactic noise, and, most importantly, industrial noise, can be noted as sources of increased noise power.

Among the important characteristics of the signal propagation between the mobile communication devices are two types of fading amplitudes of signals: large-scale and small-scale. The first of them occur due to the presence of large ground objects between the radio transmitter and the radio receiver (for example, buildings, industrial structures, hills, etc.). The duration of these fades depends on the speed of mobile communication nodes and, as a rule, is seconds, which can lead to the loss of large amounts of information. The second ones represent significant variations in the amplitudes and phases of the transmitted signals on scales of the order of the wavelength.

Changes in the arrival time of transmitted radio signals to the receiving antennas of UAVs and GCC may be associated with the movement of mobile communication nodes in space, as well as with the presence of different signal propagation paths due to the phenomenon of multipath.

There are many mathematical models [24, 26, 27] that describe both mobile radio channels and signals recorded by antenna modules of radio receivers.

Traditionally, there are general and particular models of radio channels with multipath propagation. At the same time, there are four variants of their fading models: frequency-selective fading (intersymbol interference), slow fading (Gaussian interference distribution), fast fading and flat fading (Rayleigh distribution law, Rice distribution law), and the multipath model with slow fading satisfactorily describes most communication channels in different frequency ranges. In addition, regular studies are conducted under the auspices of NASA to refine these models for cases of radio wave propagation in different areas.

I.II Characteristics of wireless radio communication channels for UAVs

The relationship between the signals at the transmitting and receiving sides of an arbitrary wireless radio communication channel, assuming its linearity, can be uniquely determined by the pulse response in the time domain and the complex transfer function in the frequency domain [24, 27], which can be written on the basis of the "classical" input-output model when representing a given communication channel in the form of a two-pole

$$H(p) = \frac{Y(p)}{X(p)}, \tag{1}$$

or in an exponential form as

$$H(p) = A(p)e^{j\varphi(p)}, \tag{2}$$

where $X(p)$ is a signal on the transmitting side of the communication channel in the operator form, $Y(p)$ is a signal on the receiving side of the communication channel in the operator form, $A(p) = |H(p)| = \sqrt{\mathrm{Re}^2[H(p)] + \mathrm{Im}^2[H(p)]}$ is frequency response of the communication channel, Re - real part of the complex transfer function, Im - imaginary part of the complex transfer function $\varphi(p) = \arg[H(p)] = arctg\left[\frac{\mathrm{Im}[H(p)]}{\mathrm{Re}[H(p)]}\right]$ is phase response of the communication channel.

In accordance with (2), the frequency response of a communication channel describes signal propagation losses and amplitude distortions due to the fading effect, and the frequency response describes signal propagation delay and phase distortions due to different arrival times of signals to receiving antennas due to the multipath effect and mobility of communication nodes. Examples of frequency response and frequency response of various wireless radio channels are presented, for example, in [24].

The complex transfer function (1) of a real wireless communication channel, taking into account the amplitude-phase distortions due to signal losses on the track and the results of the multipath effect, is very complex and difficult to describe analytically. In this regard, it is relevant to approximate it by an equivalent model described by fractional-rational functions of a complex variable $p = j\omega$, physically realized by mixed connections of various linear inertial and non-inertial links. This approach makes it possible to represent an arbitrary radio communication channel as an equivalent functional scheme that connects input and output values by a linear differential equation of finite order. A similar solution was proposed, for example, in [24] and used by the authors to describe the transfer function of a geoelectric section.

I.III Approximation of the response spectrum of the UAV communication channel

Using the proposed approach to the representation of transfer functions of wireless communication channels (and with a priori known transmitted signals), it is possible to simulate signals at the inputs of UAV radio receivers to evaluate their amplitude-phase transformations by the communication channel. In this case, based on integral transformations, for example, the Laplace operator method, analytical relations can be obtained for signals on the receiving sides of communication channels. However, this approach is convenient and only applicable for transfer functions that are equivalent to differential equations of the 4th order at most. The traditional solution to this problem can be the numerical methods for solving differential equations, which, in turn, do not allow obtaining analytical solutions that are valid for the model parameters being changed and require significant computational costs.

To overcome these disadvantages of numerical methods, a method of numerical-analytical modeling based on the spectral method can be applied, which allows performing a piecewise linear approximation of the transmitted signals [28-31], the transfer function of the communication channel and the spectrum of the received signal, and then obtaining the desired expressions of dynamic characteristics by performing the inverse Fourier transform from the signal spectrum at the input of the UAV radio receiver. This approximation is easy to record and allows to obtain analytical solutions in a generalized form for describing various models of the "radio transmitter–wireless communication channel–radio receiver" system.

Let's look at this method in more detail.

Since the communication channel can be considered a linear system, the signal transformation in it can be described by the expression

$$Y(j\omega) = X(j\omega)\cdot H(j\omega), \tag{3}$$

where $X(j\omega)$ and $Y(j\omega)$ are spectra of transmitted and received signals in the communication channel, $H(j\omega)$ is the complex transfer function (1) of the communication channel.

If the transmitted signal has a complex shape, it is difficult or impossible to obtain an analytical expression of its spectrum $H(j\omega)$. In this case, we approximate it by switching continuous piecewise linear functions (PCLF) of the form

$$q_i(t) = \frac{A_i}{2\Delta_i}\left(\left|t - t_i\right| - \left|t - t_i + \Delta_i\right| + \Delta_i\right), \tag{4}$$

which allows to obtain a compact generalized expression of the spectrum of the transmitted signal using the direct Fourier transform

$$X(j\omega) = \sum_{i=0}^{N-1} \frac{A_i}{\Delta_i \omega^2}\left[e^{-j\omega(t_i+\Delta_i)} - e^{-j\omega t_i}\right], \tag{5}$$

where i is the number of the current approximation node, t_i is the time at the current node, Δ_i is the approximation step, and $A_i = x(t_i + \Delta_i) - x(t_i)$ is the difference between the values of the approximated signal at the time $t_i + \Delta_i$ and t_i.

It is known that the spectral density of the received signal $Y(j\omega)$ can be represented as the sum of the real and imaginary parts, and to find the original $y(t) \leftarrow Y(j\omega)$, it is enough to use only one of them. In this case, for cases of a complex transfer function of the communication channel or a complex form of the transmitted signal, it is convenient to use an approximation using N-nodes switching CPLF for the real and imaginary spectrum of the received signal

$$y_R(t) = x(t)\cdot H(j\omega_k) + \frac{2}{\pi}\sum_{i=0}^{N-1} a_{0i}^{*}\omega_i \frac{\sin\omega_i^{*}t}{\omega_i^{*}t}\frac{\sin\Delta_i^{*}t}{\Delta_i^{*}t} \tag{6}$$

$$y_I(t) = x(t)\cdot H(j\omega_k) + \frac{2}{\pi}\sum_{i=0}^{N-1} b_{0i}^{*}\omega_i \frac{\cos\omega_i^{*}}{\omega_i^{*}}\frac{\sin\Delta_i^{*}t}{\Delta_i^{*}t}, \tag{7}$$

where $a_{0i}^{*} = Y_R^{*}(\omega_i) - Y_R^{*}(\omega_{i+1})$ and $b_{0i}^{*} = Y_I^{*}(\omega_i) - Y_I^{*}(\omega_{i+1})$ are coefficients of the i-th switching CPLF, $\Delta_i^{*} = \Delta_i/2$, and $\omega_i^{*} = \omega_i + \Delta_i/2$ is the central frequency of the inclined side of the i-th switching CPLF.

I.IV Modeling of dynamic properties of wireless communication channels with UAVs

Using the proposed approach, the simulation of signals at the input of UAV radio receivers with a typical impact on the communication channel in the form of a single Heavyside function is carried out. Fig. 1 shows the received normed frequency response of the communication channel as an example, and Fig. 2 shows the normed transients at the input of UAV radio receivers. In this case, we assumed an ideal case of signal propagation in free space based on a single-beam model, and the communication channel itself was simulated by 1st, 2nd and 3rd-order aperiodic links with transmission coefficients of 10^{-4} (which corresponds to the simulation of signal attenuation on the route of 80 dB) and the same time constant equal to 10^{-5} s.

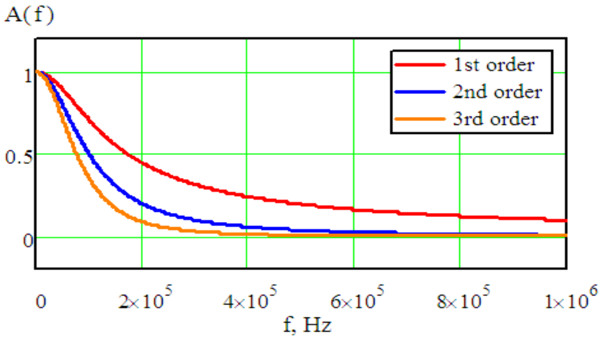

Fig. 1. A modeling example of the normed frequency response of a wireless communication channel under the assumption of a single-beam model of signal propagation

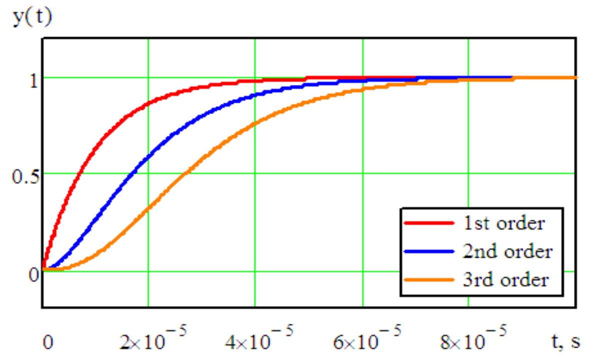

Fig. 2. Normed transients at the input of UAV radio receivers

II. CONCLUSION

The results of the simulation are in good agreement with the data of real experimental studies of wireless radio communication channels and can be easily extended to more complex cases of signal propagation. Thus, they can be used to model the characteristics of wireless radio channels of communication with UAVs, as well as to estimate the amplitude-phase distortions introduced into the transmitted signals when they propagate through these channels. The results obtained in this way can be effectively used later, for example, to adapt the physical transmission layer of the open systems interconnection (OSI) network model based on the neuro-fuzzy approach in order to improve the reliability and quality of information transmission. Such solutions include, in particular, the use of multiple input, multiple output (MIMO) technologies, adaptive coding and modulation methods. For example, the use of antenna arrays at both ends of the communication line can reduce the probability of bit errors, and the use of adaptive spatial encoding and fuzzy selection of modulation methods can significantly increase the data transfer rate.

ACKNOWLEDGEMENTS

The work was supported by RFBR grant 19-29-06030-MK "Research and development of wireless ad-hoc network technology between UAVs and control centers of "smart city" on the basis of adaptation of transmission mode parameters at different levels of network interaction". The theory was prepared in the framework of the state task FZWG-2020-0029 "Development of theoretical foundations for building information and analytical support for telecommunication systems for geo-ecological monitoring of natural resources in agriculture".

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