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Analysis of Energy Characteristics of a Hybrid Communication System with a UAV based on a Radio Frequency and Ultraviolet Channel

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Abstract

Effective use of unmanned aerial vehicles (UAVs) in many cases requires to organize reliable communication channels between individual UAVs, as well as UAVs and ground control centers. Radio frequency communication systems, traditionally used for communications in UAV networks, show significant disadvantages in a number of conditions: the presence of high terrain obstacles or dense urban development, a strong external electromagnetic background, and the effect of electronic warfare. To overcome these disadvantages, it is proposed to use hybrid communication systems with UAVs based on radio frequency and ultraviolet channels. The energy characteristics of the proposed hybrid system are determined and the conditions for the best use of both RF and UV channels in a complex urban environment are determined.

Keywords: unmanned aerial vehicle, UAVs, flying ad-hoc network, FANET, physical level, UV communication, UV-C, NLOS.

INTRODUCTION

Telecommunications networks that use radio communication at the physical level are ineffective in a number of conditions (the presence of high obstacles in dense urban development or complex terrain, a high level of external electromagnetic background, the action of electronic warfare etc.). Optical communication systems of the infrared range (IrDA) [1] and visible range (VLC) [2,3] function only when there is a line of sight (LOS) between the transmitter and receiver. This requirement significantly limits the scope of communication systems with mobile objects–unmanned aerial vehicles (UAVs), especially in conditions of dense urban development and difficult terrain [4]. It should be noted that this problem is typical for communication between individual UAVs, and between the UAV and the ground control point. If there is no direct line of sight between the UAV network nodes (non-line-of-sight mode, NLOS), it is promising to use optical communication via UV-C radiation in the wavelength range from 200 nm to 280 nm. The disadvantages of this type of communication are a limited range (up to 4 km), as well as a low bitrate (tens to hundreds of kbit/s) [5-7]. To reduce the disadvantages of radio frequency (RF) and optical UV-C channels in communication networks with UAVs, it is promising to perform their aggregation.

Aggregation is a well-known approach to improving the performance of communication systems. In [8], it is proposed to use complexing of several communication channels operating in different frequency ranges to meet strict requirements for the range of operation, noise immunity and the probability of bit error in UAV communication systems. The use of multiple communication channels increases the reliability of the data transmission system and at the same time is redundant in terms of effective use of the RF spectrum. One of the ways to improve the efficiency of a complex communication system is its adaptive operation, which involves transmitting part of the payload data over command and telemetry channels, the volume of which varies depending on the current conditions for transmitting the radio signal.

At the same time, the integration of RF and optical UV-C channels in communication with UAVs was apparently not previously used. One of the obvious advantages of this approach compared to using multiple RF channels is to save the licensed radio resource, since the optical UV-C radiation does not contribute to the deterioration of the electromagnetic environment for other electronic means (except spurious radiation of cascades of optical transmitter and optical receiver, which can be reduced by shielding).

The purpose of this work is the study and justification of complex communication systems with UAVs based on radio frequency and optical UV-C channels.

UAV COMMUNICATION SYSTEM VIA NLOS UV CHANNEL

The general scheme of the communication channel with the UAV group is shown in Fig. 1. in this scheme, communication is provided both between individual UAVs and between the UAV and the ground station (UAV K acts as an intermediate node).

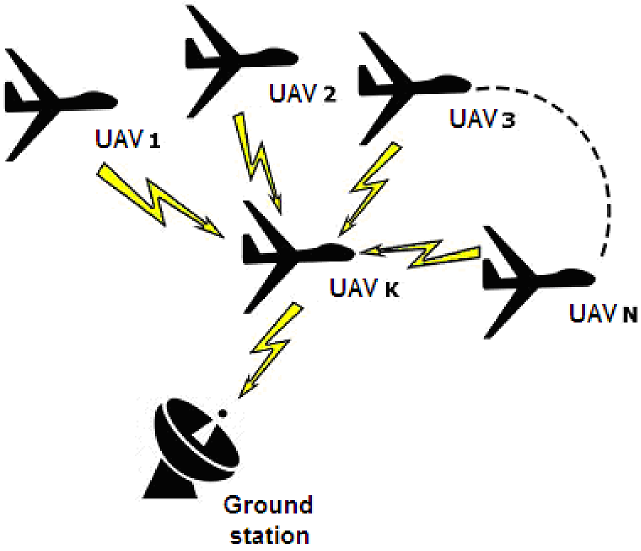
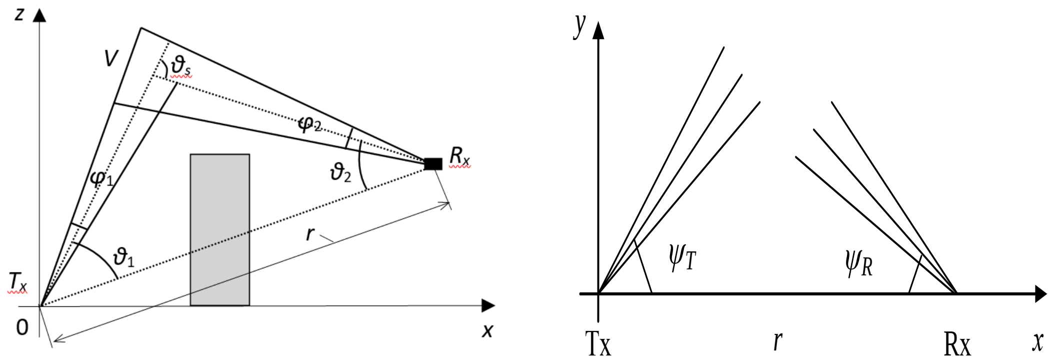


Figure 1. Diagram of the communication channel

The geometry of the communication channel in NLOS mode due to radiation scattering in the atmosphere is shown in Fig. 2. Fig. 2A shows the vertical projection of the channel and indicates: Tx–ground station's transmitter, Rx–UAV's receiver, *r*–the distance between Tx and Rx, $\theta_{1,2}$ and $\varphi_{1,2}$–the position angle and width of the directional diagram, index 1 refers to the transmitter, index 2 to the receiver, θ_s–the scattering angle, *V*–the total volume of the directional diagrams of Tx and Rx, the gray rectangle indicates an obstacle. Fig. 1B shows the possible orientation of the Tx and Rx directional diagrams, taking into account the azimuths of the transmitter and receiver $\psi_{T,R}$.



a) b)

Figure 2. Vertical (a) and horizontal (b) projection of the NLOS UV channel

The general scheme of the UV communication system is shown in Fig. 3.

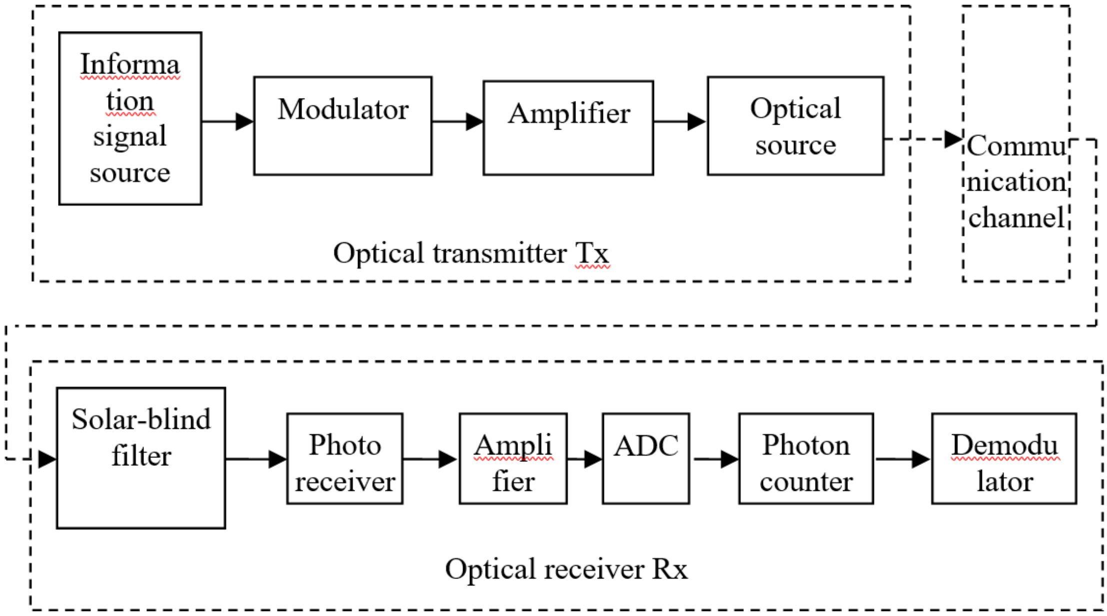


Figure 3. General scheme of the UV-C communication system

UV lasers [5], single LEDs or arrays of LEDs are used as optical emitters in UV communication systems [9]. As a photodetector, it is advisable to use a photoelectronic multiplier tube (PMT) with better sensitivity compared to single photodiodes or photodiode matrices, which is critical for receiving a weak scattered signal in the NLOS mode [10]. Due to the influence of vibration on board the UAV, it is advisable to use ruggedized PMT [11,12]. An absorbtion-type solar-blind filter with suppression of the visible range radiation of more than 12 orders of magnitude [13] is required at the output of the PMT. A transimpedance amplifier [14] is used as a photodetector current amplifier. To register individual photons, an analog-to-digital converter (ADC) and a photon counter are used.

Analytical models of the NLOS UV channel, as well as modeling based on the Monte Carlo method [15,16], are used to evaluate achievable characteristics of NLOS UV communication systems. Based on the loss L in the channel, signal-to noise ratio (SNR) at the receiver input is defined as the ratio of the useful received (detected) power P_d to the noise power N_{UV}:

$$SNR = P_d / N_{UV} , \tag{1}$$

where $P_d = \eta_f \eta_r P_T / L$. Here following designations are obtained: P_T–the radiation power of the transmitter, η_f–the transmission coefficient of the solar-blind filter, η_r–the quantum efficiency of the detector (receiver). The results of measurements showed that the typical detection frequencies of noise photons with an aperture of 1.92 cm^2 are from 150 Hz to 15 kHz [17], which corresponds to the noise power from 10^{-16} W to 10^{-14} W.

Accordingly, if the *SNR*=10 dB is acceptable for UV-C communication, the useful power detected should be at least 10^{-15} W to 10^{-13} W, depending on the noise level. In known experiments, UV-C communication at low speeds (several kbit/s) is implemented at channel losses up to *L*=160 dB, which corresponds to ranges up to 4 km at elevation angles up to 45^0 [5].

CHARACTERISTICS OF RF COMMUNICATION SYSTEMS WITH UAVS IN THE URBAN ENVIRONMENT

The empirical models of losses Okumura-Hata and COST231–Hata are not applicable for the analysis of communication systems with UAVs in the urban environment, since they do not take into account the effects of re-reflection and scattering. To account for these effects, we have developed a modified Xia-Bertoni model. Based on a modified model for UAVs above the average roof level of buildings losses are defined as

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

where λ is the wavelength, $\Delta h_{\mathrm{UAV}} = h_{UAV} - h_r$ is difference of heights between the UAV and mid-level roofs, $\theta = arctg(2\Delta h_{\mathrm{GS}}/w)$ is the angle of incidence of the refracted beam to the antenna of the ground station, $\Delta h_{\mathrm{GS}} = h_r - h_{GS}$ is height difference in the average level of rooftops and antennas of ground station, *w* is the average width of the streets, *b* is average interval between blocks (typically about 50 m), $r = \sqrt{\Delta h_{\mathrm{GS}}{}^2 + x^2}$ is 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

$$L = -10\lg\left(\left(\frac{\lambda}{2\sqrt{2}\pi R}\right)^2\right) - 10\lg\left(\frac{\lambda}{2\pi^2 r}\left(\frac{1}{\theta} - \frac{1}{2\pi+\theta}\right)^2\right) - 10\lg\left(\left(\frac{b}{R}\right)^2\right), \quad (3)$$

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

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

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

Based on the losses *L* in the channel the maximum *SNR* at the receiver input when exposed to thermal noise *N* is defined as

$$SNR = PT/LN,$$

where $N = kTB$ [18], k=1.38 • 10^{-23} J/K is the Boltzmann's constant, *T* is the absolute temperature in Kelvin, B is bandwidth in Hz. With the maximum possible bandwidth B = 22 MHz for the 2.4 GHz band [19] and a temperature T = 320 K, the thermal noise power at the receiver input will be N = –100 dBm. At frequencies above 300 MHz, the cosmic noise level is so low that the effective noise temperature of the receiver will only be determined by thermal noise. The sensitivity level required for receiving an RF signal at 1.2 kbit/s (CC11L and CC110x standards) is –112 dBm or $6.3 \cdot 10^{-15}$ W, i.e. higher than for UV-C communication (at the end of the previous section).

MODELING OF UAV COMMUNICATION SYSTEM BASED ON UV AND RF CHANNELS

As a result of the Monte Carlo simulation, the path loss dependences on various channel parameters (range and receiver azimuth ψ_2) for a wavelength of 260 nm are obtained. The following values of the UV channel parameters were accepted: the communication range r =100 m, the elevation angles of the transmitter and receiver θ_1 =30^0 and θ_2 =50^0, the widths of the transmitter's and receiver's directional diagrams φ_1 =17^0 and φ_2 =30^0, the radiation wavelength λ=260 nm, the Rayleigh scattering coefficient ks_{Ray} =0.266 km^{-1}, the Mie scattering coefficient ks_{Mie} =0.284 km^{-1}, the absorption coefficient k_a =0.802 km^{-1}, the aperture area of the receiver A_r=1.92 cm^2.

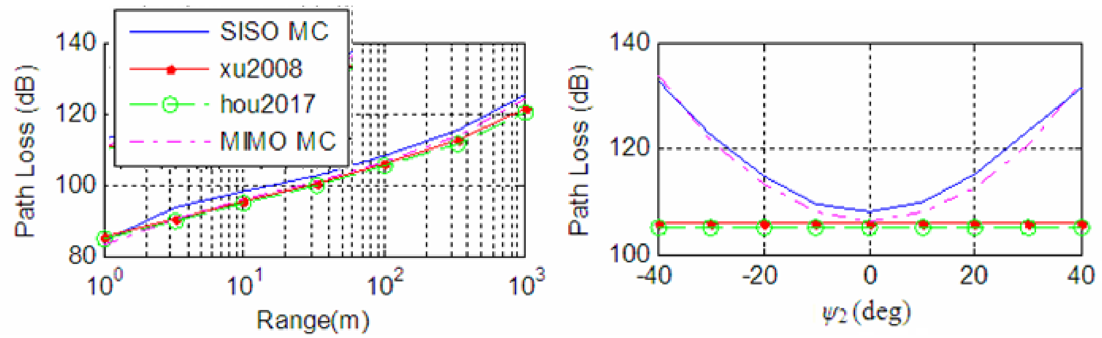


Figure 4. UV-C radiation losses at 260 nm in the NLOS channel for various range distances and azimuthal deviations ψ_2

In Fig. 4 shows the dependences xu2008 and hou2017 calculated on the basis of known analytical models [20] and [21] respectively, and also based on the Monte Carlo (MC) method [15,16]. A small difference between curves SISO (single-channel mode–single input, single output) and MIMO (multiple-channel mode–multiple input, multiple output) is explained by the fact that for the MIMO model a set of unidirectional transmitters Tx and receivers Rx was applied, so that the characteristics of the channels between the separate Tx and separate Rx are identical to each other and the characteristics of the SISO channel. Analytical models (xu2008 and hou2017) do not take into account the difference in azimuths, so the dependences on ψ_2 for these models are straight lines. It should be noted that the obtained dependences characterize the loss of UV-C radiation in free space (absence of re-reflections). The presence of re-

reflections leads to an increase in the received useful signal by an order of magnitude or more, which is typical for the urban environment.

Analysis of RF channel losses (Fig. 5-7) shows that in difficult conditions (when the UAV's flight altitude is below the average roof level, especially for the frequency of 2400 MHz, Fig. 7), the RF channel losses are higher than in the NLOS UV-C channel. Thus, at a comparable level of RF and UV sensitivity, which is true for low transmission speeds (several kbit/s), the use of UV-C communication with UAVs in a number of conditions is more promising than radio communications of comparable power. At the same time, in other conditions RF communication is more promising (when the flight height of the UAV is higher or at the average roof level, Fig. 5 and 6).

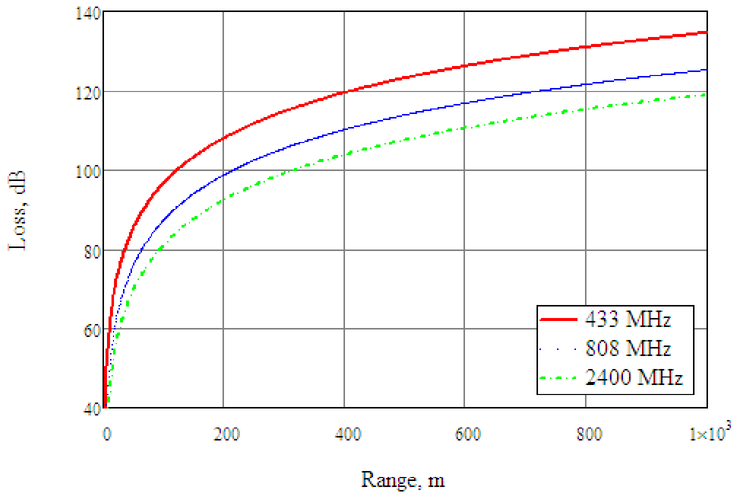


Figure 5. Average losses in the RF channel when the flight altitude of the UAV is higher than the average roof level.

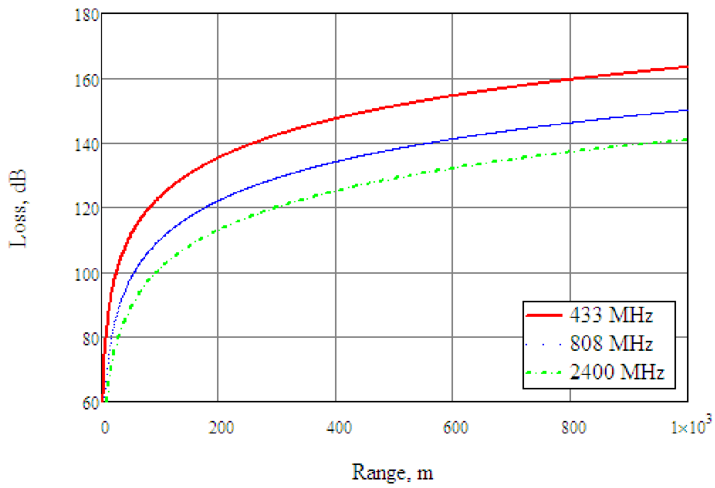


Figure 6. Average losses in the RF channel when the flight altitude of the UAV is at the level of the average roof level

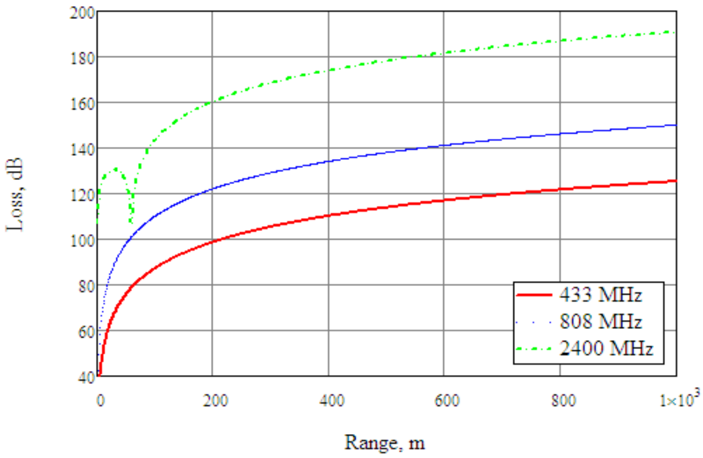


Figure 7. Average losses in the RF channel when the flight altitude of the UAV is below the average roof level.

CONCLUSION

It is shown that to improve the quality indicators of communication systems with UAVs, it is promising to use the combination of UV-C and RF means. To analyze the achievable characteristics of the NLOS UV-C channel, analytical modeling and Monte Carlo simulation were applied, and the Xia-Bertoni model was modified to analyze the RF channel in complex urban development conditions. Based on the simulation, it was found that in difficult conditions (when the UAV's flight altitude is lower than the average roof level, especially when using the 2400 MHz frequency), losses in the RF channel are higher than in the NLOS UV-C channel. Thus, at a comparable level of RF and UV sensitivity, which is true for low transmission speeds (several kbit/s), the use of UV-C communication with UAVs in a number of conditions is more promising than radio communications of comparable power. At the same time, in other conditions (when the flight height of the UAV is higher or at the average roof level), RF communication is more promising.

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REFERENCES

[1] Al-Nassar S., Hatem H., Shehab J. (2018). Design and Implementation of Infrared (IR) Communication System. 29-33. 10.26367/DJES/VOL.11/NO.3/5.

[2] Ndjiongue A.R., Ferreira H.N., Telex. (2015). Visible Light Communications (VLC) Technology. Wiley Encyclopedia of Electrical and Electronics Engineering. 1-15. 10.1002/047134608X.W8267.

[3] Giustiniano D., Tippenhauer N. O., Mangold S. (2012). "Low-complexity Visible Light Networking with LED-to-LED communication". 2012 IFIP Wireless Days. pp. 1–8. doi:10.1109/WD.2012.6402861. ISBN 978-1-4673-4404-3.

[4] Austin R. Unmanned aircraft systems: UAVs Design, Development and Deployment / John Wiley & Sons, Ltd., 2010.

[5] Chen G., Liao L., Li Z., et al. Experimental and simulated evaluation of long distance NLOS UV communication[C]//Communication Systems, Networks & Digital Signal Processing (CSND-SP), 2014 9th International Symposium on. IEEE, 2014: 904-909.

[6] Han D, Liu Y, Zhang K. Theoretical and experimental research on diversity reception technology in NLOS UV communication system[J]. Optics express, 2012, 20(14): 15833-15842.

[7] Shaw G., Nischan M., Iyengar M., Kaushik S. and Griffin M. NLOS UV communication for distributed sensor systems Proc. SPIE412683–96, 2000.

[8] Boev N.M. Analysis of radio lines of communication with unmanned aerial vehicles / Institute of engineering physics and Radioelectronics of the Siberian Federal University, Krasnoyarsk, 2017.

[9] Chen G, Abou-Galala F, Xu Z. Experimental evaluation of LED-based solar blind NLOS communication links[J]. Optics Express, 2008, 16(19): 15059-15068

[10] Raptis N., Pikasis E., Syvridis D. (2016). Performance evaluation of non-line-of-sight optical communication system operating in the solar-blind ultraviolet spectrum. 999107. 10.1117/12.2241424.

[11] Hamamatsu Photomultiplier Tubes: basics and applications.–4th edition, - P. 258.

[12] Bicron Corp.: Ruggedized High-Temperature Detector Technology.

[13] Ofil's Solar blind UV filters: http://www.sbuv.com/filters/sb268.html.

[14] Eduard S. Analysis and Design of Transimpedance Amplifiers for Optical Receivers, 2007, 592 p, ISBN: 978-1-119-26441-5.

[15] Konstantinov I.S., Vasyliev G.S., Kuzichkin O.R., Surzhik D.I., Kurilov I.A., Lazarev S.A. Development Of UV Communication Channels Characteristics Modeling Algorithm In A Mobile Ad-Hoc Network / Journal of Advanced Research in Dynamical and Control Systems (JARDCS) / ISSN: 1943-023X / Volume 11 | 08-Special Issue, 2019. Pages: 1920-1928.

[16] Konstantinov I.S., Vasyliev G.S., Kuzichkin O.R., Surzhik D.I., Kurilov I.A., Lazarev S.A. AUV Link Mobile Ad-Hoc Network Examination, International Journal of Engineering and Advanced Technology (IJEAT) ISSN: 2249–8958, Volume-8, Issue-5S July 2019, DOI:10.35940/ijeat.E1063.0785S319.

[17] Chen G, Abou-Galala F, Xu Z. Experimental evaluation of LED-based solar blind NLOS communication links[J]. Optics Express, 2008, 16(19): 15059-15068

[18] Sklyar B. Digital communication. Theoretical foundations and practical application / M.: Williams, 2003.

[19] Decision of the State radio frequency Commission under the Ministry of information technology and communications of the Russian Federation No. 04-03-04-003 of December 6, 2004 On the use of the 2400-2483.5 MHz radio frequency band for intra-office data transmission systems.

[20] Xu Z., Ding H., Sadler B.M., Chen G.“Analytical performance study of solar blind non-line-of-sight ultraviolet short-range communication links,”Optics Letters, vol. 33, no. 16, pp. 1860-1862, Aug. 2008.

[21] Hou W., Liu C., Lu F., Kang J., Mao Z., Li B. Non-line-of-sight ultraviolet single-scatter path loss model.–Phonon Network Communications, Oct 05, 2017. - DOI 10.1007/s11107-017-0737-5.