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Abstract. Communication systems of the solar-blind ultraviolet range UV-C from 200 to 280 nm provide the possibility of communication in the absence of line of sight due to the strong scattering of UV radiation in the atmosphere. For the effective use of UV-C communication systems, an adequate assessment of the energy budget of the UV channel is necessary. Analytical expressions are obtained that characterize the energy reserve of the UV-C system in relation to the specified characteristics of the optical receiver, transmitter, and UV channel. Based on the analytical and numerical model of losses in the UV channel, the energy reserve of the UV-C communication system is modeled on the distance between the transmitter and receiver, the elevation angles and the azimuthal deviation of the transmitter and receiver. The results obtained can be used to calculate and optimize ad-hoc communication networks with UV-C channel, characterized by changes in the spatial location of network nodes during operation.

1. Introduction

Effective use of mobile ad-hoc networks (MANET) is impossible without competent construction of the physical layer. One of the problems that arise when modeling and designing the physical layer of ad-hoc networks is the assessment of the energy reserve of communication systems between individual network nodes. The problem is relevant due to changes in the spatial location of network nodes during operation (their movements and turns), which is characteristic, in particular, for the subclass of MANET networks – flying ad-hoc networks (FANET) between unmanned aerial vehicles (UAVs) and ground control stations.

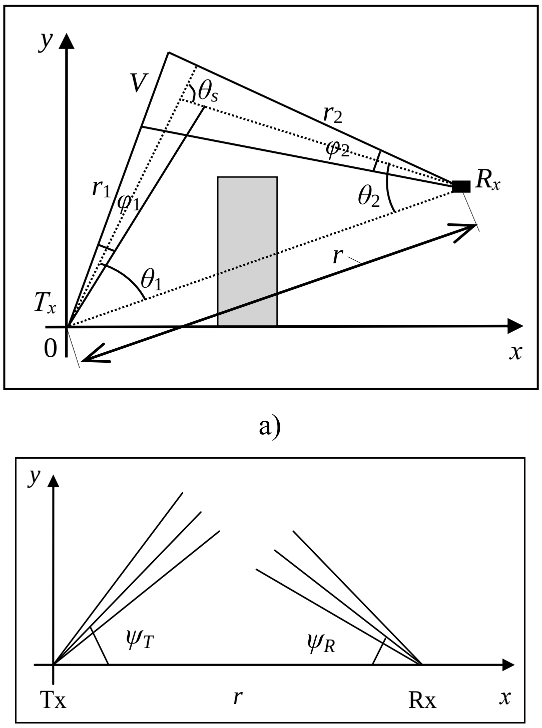
The use of traditional solutions at the physical level of MANET in general and FANET in particular in a number of conditions is impractical. Thus, the use of radio communication is problematic in the presence of obstacles between the transmitter and receiver, a high level of electromagnetic background, the creation of deliberate interference by means of electronic warfare, etc. Optical systems of the infrared [1], [2] and visible [3]-[5] ranges are resistant to electromagnetic interference, but they function only in line-of-sight conditions (infrared communication due to radiation reflections from walls is real only in indoor conditions at extremely short distances of no more than 20 m). Communication systems of the solar-blind ultraviolet range UV-C from 200 to 280 nm provide the possibility of communication in the absence of direct visibility (non line-of-sight, NLOS) due to strong scattering of UV radiation in the atmosphere, the communication range is up to 4 km or more [6], [7]. Thus, only this method of communication is effective in the difficult conditions noted above.

The estimation of the energy reserve is widely used in the theory and practice of radio communication [8], [9]. At the same time, examples of the analysis of the energy reserve of UV-C communication systems are quite rare in the literature. Modeling of such systems, as a rule, is limited to the calculation of the channel characteristics (loss and sometimes impulse response) [10]-[12] and the throughput of the system as a whole [13], [14].

The aim of the work is to develop and justify a methodology for estimating the energy reserve of a mobile ad-hoc communication network with a UV-C channel based on modeling a system with different characteristics of an optical receiver, transmitter, and UV channel.

2. Model of the NLOS UV channel and UV communication system

The geometry of the NLOS UV communication channel is shown in Fig. 1. Figure 1a shows the vertical projection of the channel and indicates: Tx-the ground station transmitter, Rx-the UAV receiver, r – the distance between Tx and Rx, $\theta_{1,2}$ and $\varphi_{1,2}$ – the angle of location and the width of the radiation pattern, index 1 refers to the transmitter, index 2 – to the receiver, θ_s – the scattering angle, V – the total volume of the radiation patterns Tx and Rx, $r_{1,2}$ – the distance from Tx and Rx to the center of the area V, the gray rectangle indicates an obstacle. To analyze the performance of a network with different spatial orientations of nodes, it is also necessary to take into account the azimuths of the transmitter and receiver $\psi_{T,R}$, as shown in Figure 1b.



a)

b)

Figure 1. Vertical (a) and horizontal (b) projection of the UV channel in NLOS mode

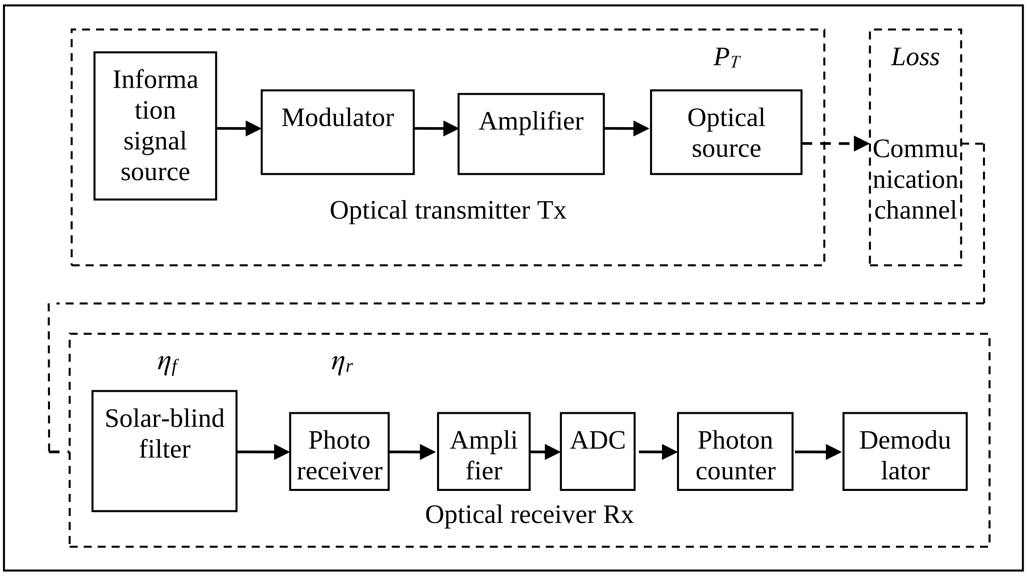


Figure 2. General diagram of the UV-C communication system

The general scheme of a single-channel UV-C communication system is shown in Fig. 2. As an optical emitter with a power of RT, a laser, a single light-emitting diode (LED) or an array of LEDs can be used. The figure also shows: *Loss* – losses in the channel, η_f – the transmission coefficient of the solar-blind filter in the UV-C band, η_r – the quantum efficiency of the photodetector.

The threshold sensitivity of the photodetector is defined as the minimum level of radiation power, taking into account the duration of the information pulse, detected by the receiver:

$$P_{r\min} = n_{\min} hc/\lambda t_{pulse}, \tag{1}$$

where $n_{\min}$ is the minimum number of detected signal photons within the duration of the information pulse received at the input of the optical receiver amplifier (hereinafter referred to as $n_{\min} = 7$), hc/λ – the energy of a photon with a wavelength λ, h=6.626 × 10^{-34} J · s – Planck's constant, c=3 × 10^8 m/s – the speed of light in a vacuum, t_{pulse} – the duration of the information pulse (for four-position pulse-phase modulation 4-PPM, $t_{\text{pulse}} = 1/(4R)$, where R is the bitrate of transmission data. The ratio (1) is valid for a small noise effect, which is typical when using a high-quality solar-blind filter of the absorption type with visible range suppression of more than 12 orders of magnitude (for example, Ofil Systems [15]).

In accordance with the scheme of Fig. 2, the energy reserve of the UV-C coupling system in decibels is defined as the excess of the received power over the minimum level determined by the expression (1):

$$M_{dB} = (P_T)_{dBm} - Loss_{dB} - (P_{r\min})_{dBm} + (\eta_f \eta_r)_{dB}. \tag{2}$$

The analytical model of losses in the UV-C channel [12] is described by the expression

$$Loss(\mathbf{\Lambda}) = \frac{96 r \sin\theta_1 \sin^2\theta_2 \left(1 - \cos\frac{\varphi_1}{2}\right) \exp\left[\frac{k_e r(\sin\theta_1 + \sin\theta_2)}{\sin\theta_s}\right]}{k_s P(\mu) A_r \varphi_1^2 \varphi_2 \sin\theta_s (12\sin^2\theta_2 + \varphi_2^2 \sin^2\theta_1)}, \tag{3}$$

where $\mathbf{\Lambda}=(r, \theta_1, \theta_2, \varphi_1, \varphi_2, k_s, k_e, A_r)^T$ is the vector of the channel parameters,

r is the communication range,

θ_1 and θ_2 are the elevation angles of the transmitter and receiver,

φ_1 and φ_2 are widths of the directional diagram of the transmitter and receiver,

$P(\mu)$ is the scattering phase function (μ is the cosine of the scattering angle),

k_s and k_e are the scattering and extinction coefficients),

A_r is receiver aperture,

$\theta_s = \theta_1 + \theta_2$ is the angle of the scattered photon with respect to the original direction.

The parameters of the UV communication channel are determined by the properties of UV radiation scattering. The probability of a photon scattering in a given direction is determined by the phase (angular) scattering function. The phase function is the weighted sum of the phase functions of the Rayleigh molecular scattering (Rayleigh) and the Mie aerosol scattering (Mie) [12,16]:

$$P(\mu) = \frac{k_s^{Ray}}{k_s} p^{Ray}(\mu) + \frac{k_s^{Mie}}{k_s} p^{Mie}(\mu). \quad (4)$$

where $k_s = k_s^{Ray} + k_s^{Mie}$ is the total scattering coefficient.

The two phase functions correspond to the generalized Rayleigh model and the generalized Henyey-Greenstein function, respectively,

$$p^{Ray}(\mu) = \frac{3\left[1 + 3\gamma + (1-\gamma)\mu^2\right]}{16\pi(1+2\gamma)}, \quad (5)$$

$$p^{Mie}(\mu) = \frac{1-g^2}{4\pi}\left[\frac{1}{\left(1+g^2-2g\mu\right)^{3/2}} + f\,\frac{0.5\left(3\mu^2-1\right)}{\left(1+g^2\right)^{3/2}}\right], \quad (6)$$

where γ, g, f are the parameters of the scattering model.

The model defined by expressions (4-6) characterizes the UV channel in clear weather conditions. The comparative results of Monte Carlo simulation obtained by the authors [17-19] indicate an acceptable error of the analytical model of no more than 5 dB with a loss value of 80 ... 140 dB in a wide range of distances r (1m...3 km), elevation angles θ_1 and θ_2 (100...90^0) and the angles φ_1 and φ_2 (10...90^0).

The disadvantage of the analytical model (3) is that it is impossible to take into account the azimuthal angles ψ of the transmitter and receiver (Fig. 1b). Based on the analysis of the Monte Carlo simulation results, it was found that the dependence of losses on the azimuthal deviation Tx and Rx $\delta\psi$ (in degrees) with good accuracy for practice (error less than 3 dB) is described by the following expression

$$Loss(\Delta\psi) = L_0 + K \cdot \Delta\psi^2 \text{ dB}, \quad (7)$$

model parameters: L_0 – constant term (the amount of losses in the channel in the absence of azimuthal deviation); K-scale factor. The model is valid in the range of absolute values $\Delta\psi$ from 0 to 35-40^0.

3. Modeling of the energy reserve of the UV communication system

The dependences of the losses in the UV-C channel on the communication range r for different elevation angles of the transmitter and receiver (θ1, θ2), obtained through the expression (3), are shown in Fig. 3. In the simulation, the following values of the UV channel parameters were taken: the communication range, the widths of the radiation patterns of the transmitter and receiver φ_1 =10^0 and φ_2 =30^0, the radiation wavelength λ=260 nm, the Rayleigh and Mie scattering coefficients k_{sRay} =0.266 km^{-1} and k_{sMie} = 0.284 km^{-1}, the absorption coefficient k_a =0.802 km^{-1}, the receiver aperture area A_r=1.77 cm^2. A strong dependence of the loss on the range and elevation angles is obvious (the range of the loss value changes from 80 dB to 160 dB when the range changes from 10 m to 2 km and the elevation angles from 10 to 70 degrees). Based on the analysis of the results of the simulations using

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the Monte-Carlo, parameters of the model (7) correspond to the communication range *r* =100 m, the elevation angles of the transmitter and receiver θ_1 =30^0 and θ_2 =30^0 (other parameters unchanged), L_0=102 dB; *K*=0.022.

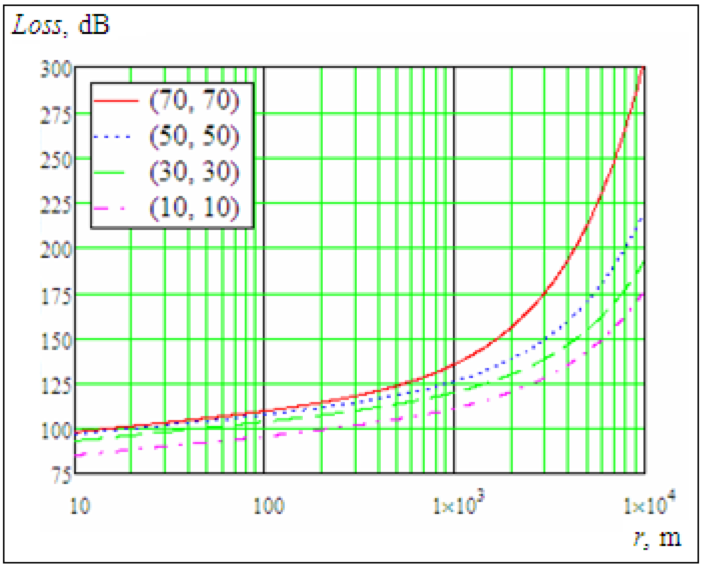
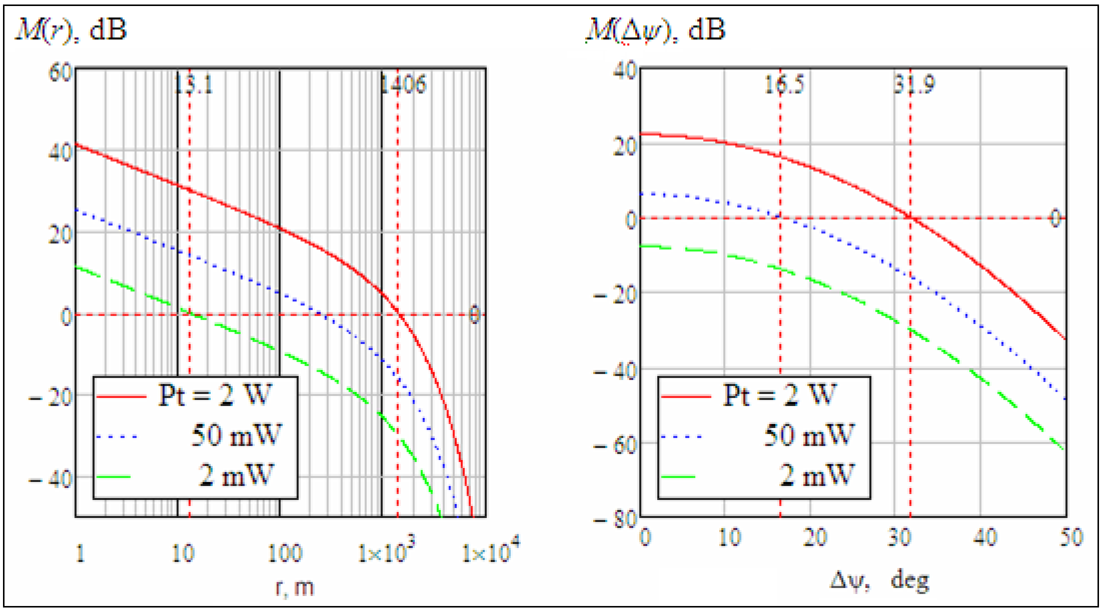


Figure 3. Dependence of the losses in the UV-C channel on the communication range r for different elevation angles of the transmitter and receiver (θ_1, θ_2)

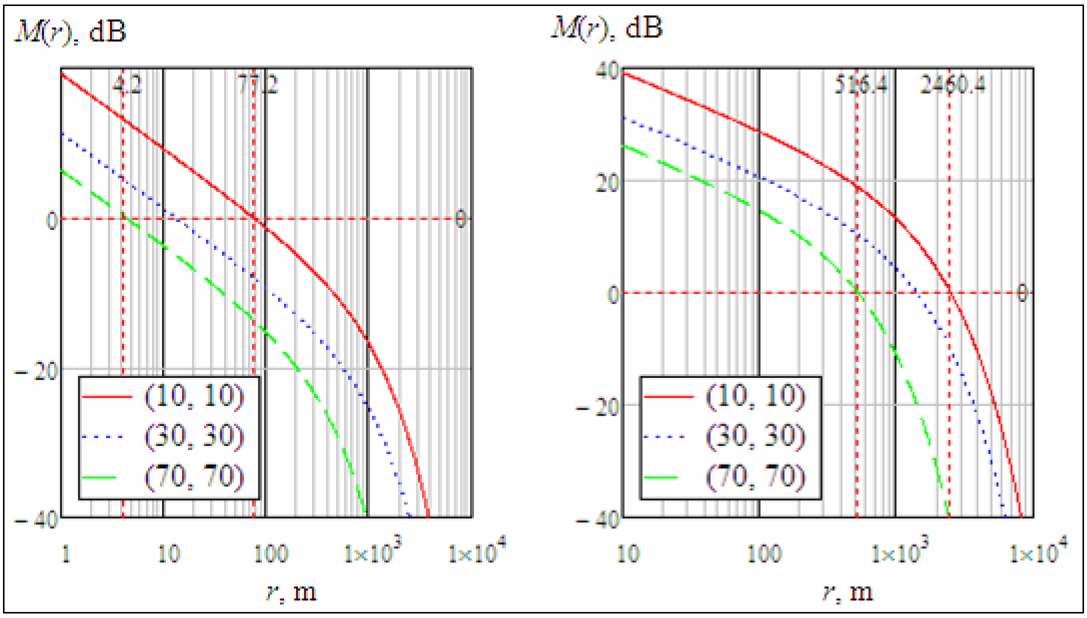
Figure 4 shows the energy reserve of the UV-C communication system for different power of the optical transmitter P_T equal to 2 mW, 50 mW, and 2 W. The bitrate of data transmission was assumed to be *R* =1 kbit/s, the modulation type is 4-PPM. the transmission coefficient of the solar-blind filter in the UV-C band is η_f =0.1, the quantum efficiency of the photodetector is η_r = 0.2. Low power 2 mW is typical for low-power UV-C LEDs, average power 50 mW – for high-power UV-C LEDs (for example, (SMD 6060 UVC LED High-Power), high power 2 W – for UV-C lasers or LED arrays (for example, (FLS 6060 UVC SMD LED 5x5 Array). The dependence of the margin on the range (Fig. 4a) shows that the maximum range at low power is 13.1 m; at medium power, 225 m; at high power, 1406 m (which corresponds to the margin value of 0 dB). The dependence of the energy reserve on the azimuthal deviation $\Delta\psi$ at a range of 100 m (Fig. 4b) shows that at this range, communication with a low-power 2 mW LED is not possible (the margin is less than 0 dB). At medium and high power, the limit value of $\Delta\psi$ is 16.5^0 and 31.9^0, respectively.



a) b)

Figure 4. Energy reserve of the UV-C communication system for different power of the optical transmitter P_T: a) from the range *r*; b) from the azimuthal deviation $\Delta\psi = |\psi_1| + |\psi_2|$

Figure 5 shows the energy reserve of the UV-C communication system for different elevation angles of the transmitter and receiver (θ_1, θ_2)=(10^0, 10^0); (30^0,30^0); (70^0, 70^0). The dependencies in Figure 5a correspond to a low level of optical power of the transmitter of 2 mW, in Figure 5b – to a high level of power of 2 W. As Figure 5a shows, the maximum range is from 4.2 m at low optical power to 77.3 m at high power; and according to Fig. 5b – from 516.4 m to 2460 m.



a) b)

Figure 5. Energy reserve of UV-C system from the distance *r* for different elevation angles of the transmitter and receiver (θ_1, θ_2) = (10^0, 10^0); (30^0,30^0); (70^0, 70^0):

a) when the transmitter power is P_T = 2 mW; b) when the transmitter power is P_T = 2 W

4. Conclusion

The analysis of known works on UV communication systems has shown that the modeling of such systems is usually limited to the calculation of the channel characteristics (loss and sometimes pulse response) and the throughput of the system as a whole. At the same time, examples of the analysis of the energy reserve of UV-C communication systems are quite rare. The problem of estimating the energy reserve is relevant due to changes in the spatial location of transmitters and receivers, which is important for ad-hoc networks with a UV channel. Analytical expressions are obtained that determine the energy reserve of the UV-C communication system with the specified characteristics of the optical receiver, transmitter, and UV channel. The energy reserve of the UV-C communication system is modeled for the bitrate of 1 kbit/s and the optical power of the transmitter from 2 mW to 2 W, the elevation angles from 10 to 70 degrees and the azimuthal deviation of the transmitter and receiver from 0 to 50 degrees. The simulation allowed us to determine the maximum communication range in various conditions from 4.2 m to 2460 m. In the future, it is planned to test the developed methodology on the basis of experimental testing of UV communication facilities.

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