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Method of semi-natural scale modeling of a wireless ultraviolet communication system

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Abstract

The use of deep ultraviolet communications (UV-C from 200 to 280 nm) is appropriate in a number of conditions when traditional radio means are ineffective (strong influence of the electromagnetic background, the creation of deliberate interference by electronic warfare, difficult terrain, etc.). In order to create effective UV-C communications, reliable mathematical modeling and subsequent field testing are required. To simplify the implementation of full-scale UV system, semi-natural modeling approach is proposed and justified, which is designed to predict system performance in new conditions based on the results of experimental testing for initial conditions. Based on the analytical model of the UV channel and the UV communication system, the signal-to-noise ratio (SNR) conversion coefficient in the optical receiver was introduced under new conditions in comparison with the initial conditions of the experiment. Based on the obtained expressions, a simulation of the UV communication system was performed, which showed a change in the receiver's SNR with varying light levels and a model of a sun-blind filter. The developed approach makes it possible to predict the expected communication range under new conditions based on experimental results for the initial conditions and the SNR conversion coefficient in the optical receiver.

Keywords: UV-C communication, non-line-of-sight, NLOS, signal-to-noise ratio, semi-natural modeling, scale modeling

INTRODUCTION

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 electronic warfare, etc. The use of optical communication systems is advisable under the influence of strong electromagnetic interference. However, infrared communication (IrDA) [1,2] and visible light communication (VLC) [3-5] function only in line-of-sight mode. The possibility of infrared communication due to reflection from walls is only real in indoor environments at extremely short distances of no more than 20 m [2]. Solar-blind UV-C communication systems from 200 to 280 nm enable communication in non-line-of-sight (NLOS) mode due to the strong scattering of UV radiation in the atmosphere, the communication range is up to 2-5 km [6,7]. Thus, only this method of communication is effective in the above-mentioned complex conditions.

One of the problems of UV communication systems is the strong influence of radiation scattering parameters determined by the state of the atmosphere on the characteristics of such systems. To create effective UV communication tools, a detailed model representation of the transmission channel, optical transmitter, and optical receiver is required. A large number of well-known mathematical models consider in detail variants of NLOS UV channels with different geometries (different elevation angles and widths of the transmitter's and receiver's directional diagrams), different weather conditions, turbulence, radiation polarization, etc. [8-13]. However, the use of such models is focused on the mathematical description of the UV communication system, and not on processing the results of experimental testing of a full-scale model of such a system. At the same time, creating a full-scale model of a UV communication system at the initial stage of technical implementation can be extremely difficult due to the high requirements imposed on the components of the optical receiver and transmitter. In particular, to ensure the above-mentioned communication range of the order of kilometers, a solar-blind absorption-type filter with a wide field-of-view of more than 40^0 and suppression of the visible range of more than 12 orders of magnitude is required for effective suppression of solar radiation (for example, a filter made by Ofil Systems) [14]. Therefore, at the beginning of development and debugging of UV communication system, it is advisable to limit yourself to more accessible components. An urgent task in this approach is to evaluate the system’s performance under new conditions with new components based on experimental results obtained for the initial conditions with the original components. This approach involves modification of mathematical models of the UV channel and implements the idea of scale semi-natural modeling, widely used for experimental testing of a wide class of electromagnetic models and devices, such as antennas in various material media [15], sensing systems for various geoelectric sections [16,17], etc. [18].

The aim of this work is to substantiate the method of semi-natural modeling of a wireless ultraviolet communication system for predicting the system characteristics under new conditions based on the results of experimental testing for current conditions.

PHYSICAL IMPLEMENTATION OF THE UV COMMUNICATION SYSTEM

The general scheme of the UV communication system includes an optical transmitter Tx, a wireless communication channel, and an optical receiver Rx. Optical transmitter consists the following blocks connected in series: information signal source, modulator, amplifier and optical emitter. Optical receiver Rx consists of a solar-blind filter, a photodetector, an amplifier, an analog-to-digital converter (ADC), a photon counter, and a demodulator connected in series. UV lasers, single LEDs, or arrays of LEDs are used as optical emitters in UV communication systems. As a photodetector, it is advisable to use a photoelectronic multiplier tube (PMT), which has a higher sensitivity compared to photodiodes; in mobile communications, ruggedized PMTs are advisable [19,20]. A solar-blind absorption filter with a wide angle of view of more than 40^0 and visible range suppression of more than 12 orders of magnitude is required for effective suppression of solar radiation [14]. A transimpedance amplifier is used to amplify the current of the photodetector [21]. An automatic gain control system with a large adjustment depth (up to 100 dB or more) in the receiver's amplifier is necessary for receiving signals with different levels, since the attenuation in the NLOS UV channel varies from 60 dB to 160 dB or more, depending on the communication range from 1 m to 4 km and other conditions [7]. The UV NLOS communication system must register single photons, so the PMT's analog mode is not applicable, and it is necessary to use an ADC and a photon counter.

MODEL OF NLOS UV CHANNEL AND UV COMMUNICATION SYSTEM

The geometry of the NLOS UV channel model is shown in Fig. 1. The figure shows the channel's vertical projection and contains following designations: Tx–transmitter, Rx–receiver, r is the distance between Tx and Rx, $\theta_{1,2}$ and $\varphi_{1,2}$ are the elevation angle and width of a direction pattern, index 1 refers to the transmitter, index 2–to the receiver, θ_s is the scattering angle, V is the total volume of the radiation patterns of the Tx and Rx, $r_{1,2}$–distance from Tx and Rx to the center of region V. In the horizontal plane, the central rays of the Tx's and Rx's radiation patterns are directed at each other.

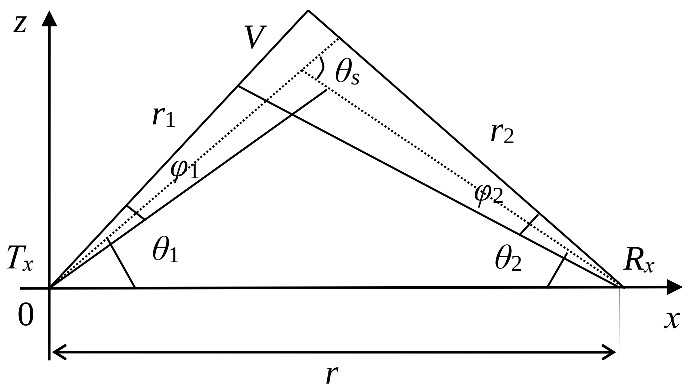


Fig. 1: Vertical projection of the NLOS UV channel

Numerical methods based on Monte Carlo statistical methods [8,9,13] and analytical models [22,23] were tested for modeling UV channels. To predict the characteristics of UV communication systems under new conditions, it is difficult to use numerical models, since such models are focused on calculating characteristics only for specific parameters and do not allow direct generalization to the case of variable parameters. Therefore, for the problem of semi-natural modeling, it is advisable to consider analytical methods.

In analytical modeling of a UV channel, all stages of UV radiation propagation are described by analytical expressions (photon emission by the transmitter according to its radiation pattern, signal attenuation with distance, single photon scattering, arrival of photons to the receiver according to its field of view and aperture area). The loss model in the channel is described by the expression [22]

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

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 elevation angles of the transmitter and receiver, φ_1 and φ_2 are widths of the transmitter's and receiver's radiation patterns, $P(\mu)$ is the scattering phase function, k_s and k_e are the scattering and extinction coefficients, A_r is the receiver aperture, $\theta_s = \theta_1 + \theta_2$ is the angle of the scattered photon relative to the initial direction.

The parameters of the UV communication channel are determined by the properties of UV radiation scattering. The probability of scattering a photon in a given direction is determined by the phase (angular) scattering function. The phase function is the weighted sum of the phase functions of Rayleigh molecular scattering and Mie aerosol scattering [22,24]:

$$P(\mu) = \frac{k_s^{Ray}}{k_s} p^{Ray}(\mu) + \frac{k_s^{Mie}}{k_s} p^{Mie}(\mu), \tag{2}$$

where $\mu = \cos\theta_s$ is the cosine of the scattering angle, $k_s = k_s^{Ray} + k_s^{Mie}$ is the total scattering coefficient. The two phase functions correspond to the generalized Rayleigh model and the generalized Henyey-Greenstein function, respectively,

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

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

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

The scattering coefficients k_s^{Ray} and k_s^{Mie} as well as the absorption coefficient k_a for different wavelengths are determined in accordance with Table 1 [8]. In the table, $k_a = k_a^{Ray}$, $k_a^{Mie} = 0$.

Table 1: Scattering and absorption coefficients for different radiation wavelengths [8]

Wavelength λ, nm	k_s^{Ray} (km^{-1})	k_s^{Mie} (km^{-1})	k_a (km^{-1})
230	0.493	0.623	2.581
240	0.406	0.531	1.731
250	0.338	0.421	1.202
260	0.266	0.284	0.802
270	0.241	0.277	0.621
280	0.194	0.272	0.322
290	0.177	0.266	0.046
300	0.145	0.261	0.039
310	0.132	0.234	0.005

The model defined by expressions (2-4) and coefficient values from Table 1 characterizes the UV channel in clear weather conditions. Coefficients for intermediate wavelength values are calculated by spline interpolation of table values. The authors' comparative results of Monte Carlo modeling [11-13] indicate an acceptable error of the analytical model (1) of no more than 5 dB with a loss value of 80...140 dB over a wide range of distances r (1m...1 km), elevation angles θ_1 and θ_2 ($10^0...90^0$), and angles φ_1 and φ_2 ($10^0...90^0$).

The signal-to-noise ratio (SNR) of a UV channel is defined as the ratio of the number of detected signal photons N_d to the number of noise photons N_n:

$$SNR(\Lambda) = N_d(\Lambda)/N_n, \tag{5}$$

where $N_d(\Lambda) = \frac{\eta_f \eta_r N_r}{L(\Lambda)} = \frac{\eta_f \eta_r P_T}{L(\Lambda)R}\frac{\lambda}{hc}$. Here we denote P_T –the transmitter's radiation power, η_f –transmission coefficient of the solar-blind filter in the UV-C band, η_r –quantum efficiency of the detector (receiver), η_r –the number of photons received, λ–wavelength of radiation, L–losses in the channel, R–bitrate, $h = 6{,}626 \times 10^{-34}$ j · s–Planck's constant, $c = 3 \cdot 10^8$ m/s–the speed of light in a vacuum. The measurement results showed that the frequency of detection of noise photons is from 150 Hz to 14500 Hz (when using an absorption solar-blind filter and a photoelectronic multiplier with an aperture of 1.92 cm^2) [25]. The dependence of this parameter on the illumination level K_{light} and the transmission coefficient of the solar-blind filter in the suppression band K_f is linear.

Based on these considerations, we enter the SNR conversion coefficient in the receiver as:

$$K_{SNR}(\mathbf{\Lambda^0}, \mathbf{\Lambda^*}) = \frac{L(\mathbf{\Lambda^0})}{L(\mathbf{\Lambda^*})} \cdot \frac{K_{light}^0}{K_{light}^*} \cdot \frac{K_f^0}{K_f^*}. \tag{6}$$

This coefficient shows how many times the SNR will increase under the new conditions $\mathbf{\Lambda^*}$ compared to the initial conditions of the experiment $\mathbf{\Lambda^0}$.

MODELING OF THE UV COMMUNICATION SYSTEM

Based on the obtained expressions, the coefficient (6) is modeled for the following parameters:

initial communication range of the experiment $r^0 = 10$ m;

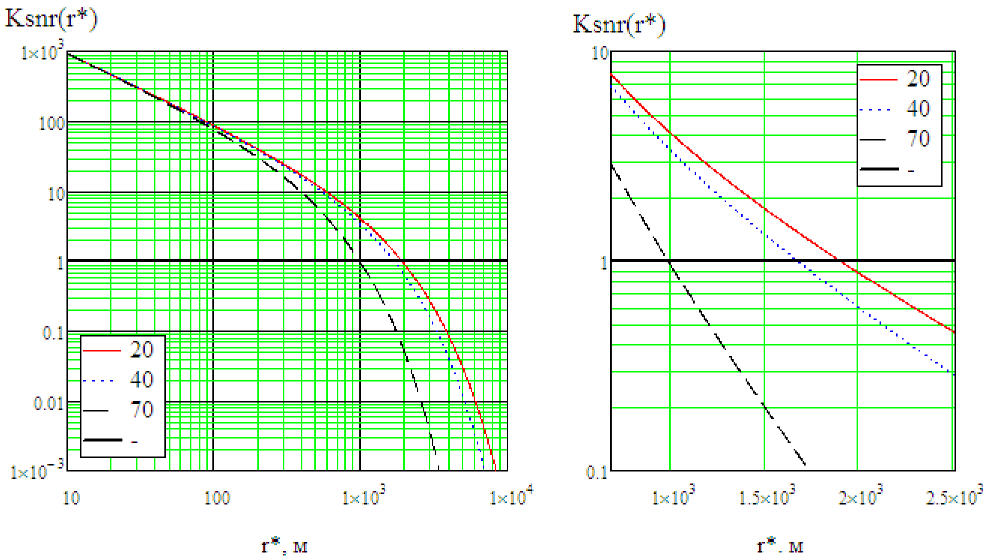
the original and new width of the receiver's angle of view is $\varphi_2^0 = 7^0$ and $\varphi_2^* = 60^0$, the original and new filter's coefficient is $K_f^0 = 10^{-7}$ and $K_f^* = 10^{-12}$ (these parameters correspond to the interference filter Semrock FF01-260-10-25 which is relatively affordable at the initial stage of the experiment, and at a new stage–an Ofil Systems' absorption type filter with a wide angle of view and visible range suppression of more than 12 orders of magnitude);

the original and new illumination levels are K_{light}^0 = 100 Lux (very cloudy) and K_{light}^* = 100,000 Lux (clear).

The parameters listed below are the same for the initial and new conditions: transmitter's elevation angle $\theta_1 = 40^0$, receiver's elevation angle $\theta_2 = 40^0$, transmitter's width of radiation pattern $\varphi_1 = 20^0$, radiation wavelength λ = 260 nm, Rayleigh and Mi scattering coefficients k_{sRay}=0,266 km^{-1} and k_{sMie} = 0,284 km^{-1}, absorption coefficient k_a=0,802 km^{-1}, receiver aperture area A_r = 1.92 cm^2.

The calculated SNR conversion coefficient in the receiver from the communication range in the new conditions r^* is shown in Fig. 2. Three curves in the graphs correspond to different elevation angles of the transmitter and receiver $\theta = \theta_1 = \theta_2 = 20^0$; 40^0; 70^0. When K_{SNR} = 1, the SNR values in the original and new conditions are equal. When using the same modulation type, this ensures the same performance of the communication system at a given bit error rate (if influence of intersymbol interference is negligible). Thus, the same SNR and, accordingly, the same bitrate is provided at the original range of 10 m and the new range:

- 1900 m (for elevation angles $\theta = \theta_1 = \theta_2 = 20^0$);
- 1700 m (for elevation angles 40^0);
- 1000 m (for elevation angles 70^0).



(a) (b)

Fig. 2: Dependence of the SNR conversion coefficient in the receiver on the communication range under new conditions r* for different elevation angles $\theta = \theta_1 = \theta_2 = 20^0$: a) the full graph; b) a fragment of the graph

CONCLUSION

The semi-natural scale modeling method of the UV communication system was developed. It is based on experimental results obtained for the initial parameters of the UV channel and components of the communication system and allows us to evaluate the characteristics of the communication system with new parameters. New approach also makes it possible to simplify the physical implementation of the full-scale model and predict the expected communication range under new conditions based on experimental results for the initial conditions and the SNR conversion coefficient in the optical receiver.

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