Numerical and Analytical Modeling of Wireless UV Communication Channels for the Organization of Wireless Ad-Hoc Network

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Summary
Currently, the direction of development and application of wireless optical communication systems in the ultraviolet (UV) range of spectrum is of particular relevance. An important advantage of the UV channel is the ability to provide reliable communication, protected from intentional suppression and interception, in the absence of line of sight between the transmitter and receiver. To create effective means of wireless UV communication, it is necessary to develop and analyze mathematical models of the UV channel at the physical and channel levels of information transmission. Many well-known numerical and analytical models of the UV channels do not take into account the particular geometry of the channel, relevant to mobile ad-hoc network (MANET): changing azimuths of transmitters and receivers when communication nodes are turning, communication mode with a different number of transmitters and receivers, etc. In the article mathematical software and software for analytical and numerical simulation of wireless UV communication channels in different terrain conditions at the physical and channel levels, allowing to investigate and analyze communication systems with a different number of transmitters and receivers of UV radiation, as well as to vary their spatial and angular coordinates, has been developed. To improve the reliability of modeling UV channels, known mathematical model of the channel based on the Monte Carlo method complemented by a model of obstacle, models of the geometrical arrangement and directional diagrams of the transmitters and receivers of UV radiation were modified. We obtained a number of simulation results of the losses of light propagation for different UV channels depending on the communication distance and angular parameters of transmitters and receivers: elevation angles, widths and azimuths of the directional diagrams. To assess a reliability of new numerical-analytical approach using the Monte Carlo method, comparative modeling with known analytical models was used. The perspective directions of further modeling of wireless self-organizing networks functioning on the basis of wireless UV communication channels are designated.

Key words:
Wireless ultraviolet communication; Mobile Ad-Hoc Network, MANET; MIMO; Monte Carlo; modeling.

1. Introduction

Now the direction on development and application of optical communication systems on the basis of infrared communications (IrDA) and visible light communications (VLC) possessing a number of important advantages in comparison with communication systems of the radio-frequency range gets special urgency. The construction of high-quality communication systems in optical bands makes it possible to significantly improve the technical characteristics of the systems by using the physical characteristics of the communication channels in these ranges. A separate realm of research is wireless communication in the ultraviolet (UV) range of spectrum. Particularly promising is the "solar-blind" UV range from 200 to 280 nm (UV-C), not exposed to solar radiation, which is largely blocked by ozone layer of the atmosphere. The development and research of UV communication systems, especially the UV-C range, is highlighting in the significant number of scientific articles, for example, [Xu 2008, Wang 2011, Wang 2010, Luettgen 1991, 2008 Ding, Ding 2009, Li 2010, Li 2011]. Communication channel in this range differs substantially from the radio next to the key properties, in particular, the presence of scattering of photons and a significant influence of the intersymbol interference, quantum character of the noise, and others. Important advantage of the UV channel is the ability to ensure reliable communication in non-line-of-sight mode (NLOS) protected from intentional jamming and interception. Reliable NLOS mode is relevant in the presence of obstacles between the transmitter (light-emitting diode or laser) and the receiver (photodiode or photoelectron multiplier) and is not possible when using radio frequency or other optical ranges.
An important task in the creation of effective equipment for wireless UV communication is the development and analysis of mathematical models of the UV channel at the physical and channel levels of information transmission. It should be noted that modeling of UV channels meets many difficulties. This is the complex nature of the angular photon scattering function, the presence of multiple scattering [Ding 2009, Yin 2009], the complex influence of weather conditions on the noise level and other channel characteristics [Chen 2008], etc. These problems necessitate for an analysis of the UV channels, along with analytical models [Luettgen 1991, Xu 2008, 2010 Yin, Hou 2017], hybrid numerical-analytical approaches using

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the Monte-Carlo method of statistical simulation [Ding 2009, Drost 2011].

Numerical modeling is of particular importance for the analysis of the UV channel at the physical and channel levels with noncoplanar geometry, in which the central rays of the directional diagrams (DD) of the transmitter and receiver are not in the same plane. This phenomenon, which negatively affects the quality of communication, inevitably occurs when communication nodes are moving and turning, which is important, in particular, for mobile ad-hoc network (MANET) [Choudhury 2012].

Many well-known models of UV channels [for example, Ding 2009], take into account different angles of location (slopes) of transmitters and receivers, but do not take into account their azimuths (rotations). In addition, the models are focused on the analysis of communication system with one transmitter and one receiver (SISO mode – single input, single output), and do not allow to choose combinations with different numbers of transmitters and receivers (MIMO mode – multiple input, multiple output), as well as to vary their spatial and angular coordinates.

The aim of the work is to develop mathematical base and software for analytical and numerical simulation of wireless UV communication channels at the physical and channel levels, allowing to investigate and analyze communication systems with a different number of transmitters and receivers of UV radiation, as well as the variation of their spatial and angular coordinates.

2. Model of UV Radiation Scattering

Parameters of the UV communication channel are determined by the properties of UV radiation scattering. Probability of photon scattering in a given direction is determined by the phase (angular) scattering function. The phase function is a weighted sum of the phase functions of Rayleigh molecular scattering and Mie aerosol scattering [Xu 2008, Bohren 1983]:

$$P(\mu) = \frac{k_s^{Ray}}{k_s} p^{Ray}(\mu) + \frac{k_s^{Mie}}{k_s} p^{Mie}(\mu) , \quad (1)$$

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. Two phase functions correspond to the generalized Rayleigh model and the generalized Henyey-Greenstein function, respectively,

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

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

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

Scattering coefficients k_s^{Ray}, k_s^{Mie} and absorption coefficient ka for the different wavelengths are determined in accordance with table 1 [Xu 2007, Chen 2008]. In the table ka= k_a^{Ray}, k_a^{Mie} =0.

Table 1: Scattering and absorption coefficients for different wavelengths of radiation

Wavelength λ, nm	k_s (km–1)	k_s (km–1)	ka (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 (1-3), and coefficient values from table 1, characterizes the UV channel in clear weather conditions. Calculation of coefficients for intermediate wavelength values can be performed by spline interpolation of the table values.

3. Obstacle Model in the UV Channel

An important advantage of the UV channel is an ability to provide reliable communication in NLOS mode, protected from intentional suppression and interception. Reliable NLOS mode is relevant in the presence of obstacles between the transmitter (light-emitting diode or laser) and the receiver (photodiode or photoelectron multiplier) and is not possible when using radio frequency or other optical ranges. At the same time, communication conditions deteriorate significantly when, due to the suboptimal choice of elevation angles or azimuths of transmitters and receivers, part of the paths of photon propagation is blocked by an obstacle. Modeling of this situation is relevant, in particular, for the MANET network. Because of the movement of nodes of such a network, the optimal guidance of the directional diagrams taking into account the terrain relief is problematic.

Models of the channel with an obstacle in the known works on UV communication are considered extremely rarely (for example, [Zhang 2011]). The model of the UV channel with an obstacle, considered in this paper, is shown in figure 1.

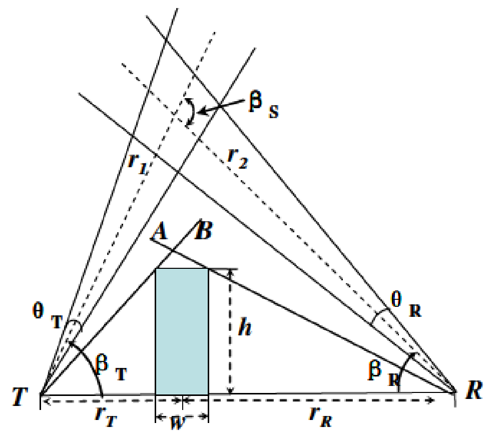


Fig. 1 UV channel model with an obstacle of width w and a height h between the transmitter T and receiver R

Creation of realistic models of obstacles (mountains, buildings, etc.) is difficult, and inevitably causes a significant increase in computational costs, since to establish the fact of crossing the photon trajectory the obstacle has to check compliance with a complex set of conditions. The proposed rectangular obstacle model is easy to implement and it slightly increases the computational complexity of the UV channel model.
The angles of view of a rectangular obstacle by transmitter TX and receiver Rx are determined by the expressions

$$\theta_T^* = arctg\frac{h \cdot \cos(\psi_T)}{r_T},$$
$$\theta_R^* = arctg\frac{h \cdot \cos(\psi_R)}{r_R}, \qquad (4)$$

where h is an obstacle height, ψT and ψR - azimuths of the Tx and Rx DD, rT and $r_R = r - r_T$ are the distances from the obstacle to the transmitter and receiver, respectively; r is the distance between the transmitter and receiver (communication range), w – an obstacle width.
Elevation angles of the photon scattering point with coordinates (x,y,z) relative to Tx and Rx, respectively:

$$\theta_1^* = arctg\frac{z - z_T}{\sqrt{(x - x_T)^2 + (y - y_T)^2}},$$
$$\theta_2^* = arctg\frac{z - z_R}{\sqrt{(x - x_R)^2 + (y - y_R)^2}}, \qquad (5)$$

where xT, yT, zT are the transmitter coordinates; xR, yR, zR are the receiver coordinates.
A photon can reach a point (x,y,z) from Tx in a straight line by bypassing an obstacle if the condition is satisfied:

$$\theta_1^* > \theta_T^*. \qquad (6)$$

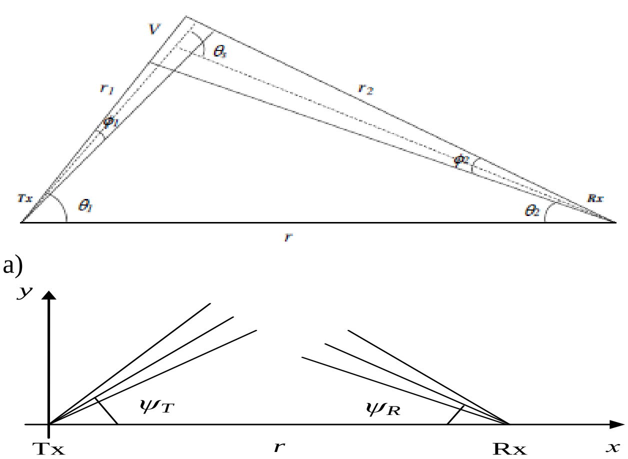
A photon can get from a point (x,y,z) to Rx in a straight line if the condition is satisfied:

$$\theta_2^* > \theta_R^*. \qquad (7)$$

Effect of obstacle is accounted in the UV channel model using the Monte-Carlo method in the calculation of the arrival probability of photons to the receiver, which is discussed later in this article.

4. Geometric Arrangement Models of Transmitters and Receivers of UV Radiation

Standard geometry of the NLOS UV channel with one transmitter and one receiver, used in a large number of works [Luettgen 1991, 2008 Xu, Hou 2017 and many others], is shown in figure 2a.



b)
Figure 2. Vertical (a) and horizontal (b) projection of the NLOS UV channel with one transmitter and one receiver
Figure 2a shows vertical projection of the channel and includes following designations: Tx – transmitter, Rx – receiver, r is a distance between Tx and Rx, θ1,2 and φ1,2 – elevation angle and DD width, index 1 refers to the transmitter, index 2 – to the receiver, θs is a scattering

angle, V is a total volume of the Tx and Rx radiation patterns, r1,2 – distance from Tx and Rx to the center of V region.

Displacement and rotations of the MANET nodes require you to specify in the model the relevant spatial and angular parameters, adequate to the real nodes. As before, the article uses symbols xT, yT, zT – transmitter coordinates; xR, yR, zR – receiver coordinates (in the case of a single transmitter and a single receiver, SISO mode). In general, for an array of many transmitters and many receivers (MIMO mode), the corresponding coordinates are vector quantities. To provide communication with nodes in different directions, it is necessary to vary the Tx and Rx azimuths. To increase an information capacity of the channels, it is advisable to use an additional degree of freedom of spatial separation – the difference between elevation angles between individual Tx and individual Rx.

The spatial orientation of arrays (lattices) of transmitters Tx and receivers Rx is given by the following angular parameters: elevation angle θ and azimuth ψ of the lattice center, the scope of DD in elevation and in azimuth, shift in azimuth between two sets of transmitters (receivers). Zero azimuth values correspond to the communication mode, when the central beams of the receiver and transmitter are in the same plane. Positive azimuth values correspond to the rays deviation in the positive half-plane of the horizontal projection of the UV channel. Different values of the Tx and Rx angular parameters allow you to simulate the arrays of transmitters and receivers of different shapes: flat, sector, circular.

5. Models of the Directional Diagrams of the Transmitters and Recivers

Characteristics of UV communication channels depend significantly on the directional properties of transmitters and receivers. At the same time, depending on the specific requirements for the communication system, the optimal forms of DD can vary significantly. So, to ensure the lowest propagation losses (the highest signal level on the receiving side, the greatest communication range), it is advisable to choose an omnidirectional receiver (Rx DD width φR=1800). However, the bitrate is minimal due to the maximum duration of the pulse characteristic of the channel. To achieve the maximum bit rate, it is necessary to use narrowly directed transmitters and receivers (φT of the order of angular minutes for the UV laser and about 100 for the light-emitting diode, φR=10…300), since in this case the pulse characteristic duration is minimal due to the small difference in the time of flight of individual photons.

UV channel modeling requires to take into account both the width and shape of the DD. Unfortunately, most of the analytical and numerical models of the UV channel contain an idealized rectangular DD of the transmitter (laser or light-emitting diode) and the receiver (photodiode or photoelectron multiplier):

$$f_{T,R}^{(\text{rect})}(U)=\begin{cases}1, & U\subset[0,\dfrac{\varphi_{T,R}}{2}],\\ 0, & U\not\subset[0,\dfrac{\varphi_{T,R}}{2}]\end{cases}, \qquad (8)$$

where U is an angular deviation from the DD central beam. For a laser model with a narrow beam, the DD shape is not so important, but for other types of transmitters and receivers, the use of ideal DD models can lead to a significant increase in the simulation error.

Analysis of technical documentation (data sheets) for many LEDs and photodiodes [LEUVA66G00HV00, LEUVA66H70HF00, LEUVA66X00V00, LEUVS33G10TZ00] allows us to conclude that a function (9) can serve as a good approximation for the DD of the real components:

$$f_{T,R}^{(\cos)}(U)=\begin{cases}\dfrac{\pi}{2}\cos\left(\dfrac{\pi}{\varphi_{T,R}}U\right), & U\subset[0,\dfrac{\varphi_{T,R}}{2}],\\ 0, & U\not\subset[0,\dfrac{\varphi_{T,R}}{2}]\end{cases}, \qquad (9)$$

Unlike antennas, side lobes effect of LEDs and photodiodes is insignificant and is assumed to be 0. The normalizing factor π/2 is equal to the ratio of the areas of rectangular and cosine DD.

In the Monte Carlo simulation method [Ding 2009; Drost 2011] the probability of the initial trajectory of the photon, which has left the transmitter, is determined by its DD. For a rectangular DD, the probability of deflection of the trajectory from the central beam is characterized by a uniform distribution

$$U_{ini}^{(\text{rect})}=\frac{\varphi_T}{2}\text{rand}(1), \qquad (10)$$

where rand(1) is a random variable, uniformly distributed between 0 and 1.

For cosine DD probability U is determined on the basis of (9) according to the inverse function:

$$U_{ini}^{(\cos)}=\frac{\varphi_T}{\pi}\arcsin\left[\text{rand}(1)\right] \qquad (11)$$

Comparative modeling of losses in the UV channel with the use of models of rectangular and cosine DD of LEDs and photodiodes have shown the discrepancy between the calculated values of loss 3-4 dB on both in one and in the other direction for various channel parameters. Thus, the error of DD idealization is significant, and the use of cosine DD models is promising.

6. Numerical-Analytical Models of UV Channels Based on Monte Carlo Method

It should be noted that the modeling of UV channels encounters numerous difficulties: the complex nature of the angular photon scattering function, the presence of multiple scattering [Ding 2009, Yin 2009], the complex nature of the influence of weather conditions on the noise level and other channel characteristics [Chen 2008], etc. These problems determine the need for the analysis of UV channels, along with analytical models [Xu 2008, Hou 2017], hybrid numerical and analytical approaches using the Monte Carlo statistical modeling method [Ding 2009, Drost 2011].

In numerical and analytical modeling of the UV channel, the probability of scattered photons arriving at the receiver with a given field-of-view (FOV) and aperture is still calculated analytically. Numerical simulation of this stage would require a tremendous increase in computational costs, because at a typical value of losses in the NLOS UV channel of 100 dB for the successful arrival of a single photon would have to perform radiation simulation on average 1010 photons. The hybrid approach reduces the required number of photons to acceptable values of 106-107 [Ding 2009, Drost 2011]. The remaining stages of the spread of UV radiation are well described by the numerical model according to the Monte Carlo statistical testing method: the emission of photons by the transmitter according to its DD, the attenuation of signal with distance, multiple scattering of photons.

Numerical modeling is of particular importance for the analysis of the UV channel with noncoplanar geometry, in which the central rays of the transmitter and receiver radiation patterns are not in the same plane. This phenomenon inevitably occurs during the movement and (or) turns of communication nodes, which is important, in particular, for MANET. Many well-known models of UV channels [for example, Ding 2009], take into account the different elevation angles (slopes) of transmitters and receivers, but do not take into account their azimuths (turns). The analytical approach used by [Elshimy 2015] takes into account the azimuth change, however, uses the single scattering model and has an unacceptable simulation error when the contribution of multiple scattering is significant [Yin 2009]. In addition, the known models are focused on the analysis of the communication system with one transmitter and one receiver (SISO mode), and do not allow to choose combinations with different numbers of transmitters and receivers (MIMO mode), as well as to vary their spatial and angular coordinates.

The proposed modeling algorithm of the channel losses based on the work [Ding 2009]. The following parameters of radiation propagation are simulated:

- average distance between the scattering points of the photons (mean free path of photons);
- new coordinates of the scattering points;
- new direction of flight of the photons after scattering;
- photon energy loss with distance;
- photons survival probability taking into account energy losses;
- the average value of survival probabilities of all model photons equal to the sought value of losses in the channel.

Photon emission by the transmitter is modeled by random numbers with probability distribution determined by the DD shape of the emitting element in accordance with the proposed cosine shape (9). The principal difference of the developed algorithm is that in the presence of more than one transmitter (MIMO mode or MISO – multiple input, single output), an additional discrete random variable with a uniform distribution sets the number of the transmitter that emits each specific photon. To simulate the initial trajectories of photons emitted by transmitters with different angles θT and azimuths ψT, coordinate transformation described by the product of two rotation matrices in three-dimensional space is performed:

$$M = M_y\left(\frac{\pi}{2} - \theta_T\right) \cdot M_z(\psi_T) \quad , \qquad (12)$$

where y and z rotation matrices

$$M_y(\alpha) = \begin{pmatrix} \cos\alpha & 0 & \sin\alpha \\ 0 & 1 & 0 \\ -\sin\alpha & 0 & \cos\alpha \end{pmatrix} ,$$

$$M_z(\alpha) = \begin{pmatrix} \cos\alpha & -\sin\alpha & 0 \\ \sin\alpha & \cos\alpha & 0 \\ 0 & 0 & 1 \end{pmatrix} . \qquad (13)$$

Coordinate transformation for receivers with different elevation angles θR and azimuths ψR is described by similar expressions and is performed by the M-function for calculating the receiver field-of-view FOV.m. When there are many receivers (MIMO or SIMO – single input, multiple output), the resulting field of view is calculated by summing the values of the functions FOV.m calculated for individual receivers.

In contrast to the algorithm [Ding 2009], when calculating the arrival probability of photons into the receiver, taking into account its field-of-view and aperture, an influence of obstacle is additionally taken into account.

7. Simulation Results of Losses in the UV Channel

As a result of modeling, dependences of losses on various channel parameters for a wavelength of 260 nm are obtained (figure 3).

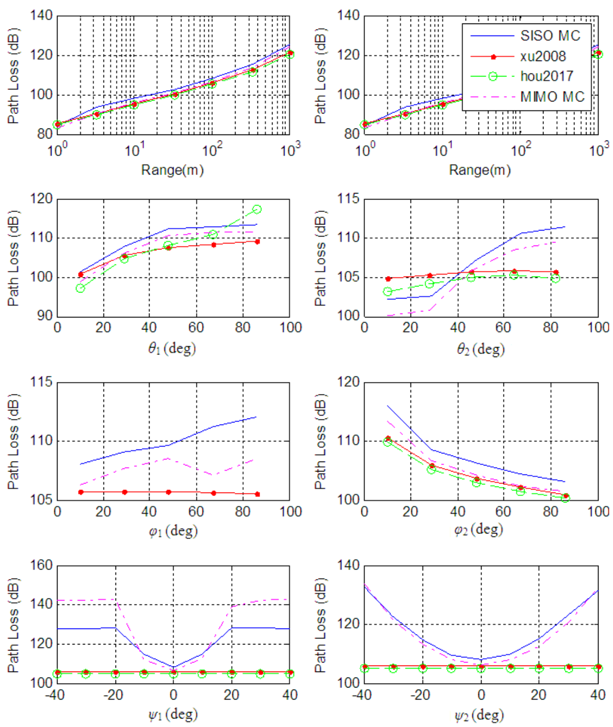


Fig. 3 Radiation losses with a wavelength of 260 nm

Curves SISO MC and MIMO MC are obtained on the basis of the developed approach using the Monte Carlo method (MC) for the corresponding mode (SISO or MIMO). To check the correctness of the proposed approach, the dependences of Xu2008 and Hou2017 calculated on the basis of known analytical models are given.

The simulation time of the figure was approximately 40-90 sec depending on the performance of the computer used (computers based on Intel processors Core 2 Duo E7500, Core 2 Duo E8400, Intel Core i3-3220 and the RAM from 2 GB to 4 GB were used, MatLAB version R2009), when the number of photons M=100000. A further increase in the number of photons does not lead to an increase in accuracy. Analysis of the time resource of the developed program using the built-in tool for profiling MatLAB environment showed that more than half of the modeling time is occupied by the calculation of hou2017.m functions. This is due to the poor convergence of integrals in the function, it was not possible to solve this problem by choosing the integration convergence parameter.

Small difference between the dependences of SISO and MIMO in figure 3 is explained by the fact that the model of flat lattices of unidirectional transmitters Tx and receivers Rx was used for MIMO, so that the characteristics of the channels between individual Tx and individual Rx are identical to each other and the characteristics of the SISO channel. Inverse dependence of the channel losses on the wavelength of the transmitter radiation is significant only at large communication distances (range more than 500 m) and is explained by the increase in radiation absorption in the atmosphere with a decrease in wavelength, at distances less than 500 m the dependence of losses on wavelength is absent. Some difference of graphs (especially at large azimuths Tx ψ1 and Rx ψ2) is caused by calculation errors. The analytical models used (xu2008 and hou2017) do not take into account the difference between the azimuths Tx and Rx, so the dependences on ψ1 and ψ2 for these models are straight lines.

The channel losses for an obstacle with a small width and different height (width<0,1·heightmin) are simulated. The simulation showed that at low height the losses grow insignificantly (less than 1 dB) until the obstacle with increasing height begins to overlap the total volume of the transmitter beam and the receiver field-of-view. With a further increase in height, the increase in losses is approximately proportional to the ratio of the cross-sectional area of the total volume of the obstacle plane to the area not affected by the influence of the obstacle. If the total volume of Tx and Rx DD is completely covered by an obstacle, once scattered photons do not reach the receiver; communication occurs only due to multiple scattering, with losses increasing by 20-40 dB or more.

8. Conclusion

The main result of the work is the developed mathematical base and software for analytical and numerical simulation of wireless ultraviolet communication channels in different terrain relief conditions, allowing you to choose combinations with different numbers of transmitters and receivers of UV radiation, as well as to vary their spatial and angular coordinates and characteristics of radiation patterns. The obtained result increases the modeling reliability of mobile ad-hoc network (MANET) with UV channel, characterized by spatial movements of communication nodes.

A number of simulation results of radiation propagation losses for different variants of UV channels are obtained. To assess the reliability of the new numerical-analytical approach using the Monte Carlo method, comparative modeling with known analytical models was used.

The developed mathematical base and software allows to perform simulation of UV channels for MIMO mode with a variety of options for the spatial location of transmitters and receivers. A promising direction is to study different applications of MIMO ultraviolet communication systems (space-time coding, spatial multiplexing, introduction of feedback, the joint use of MIMO and OFDM – orthogonal frequency multiplexing, etc.).

The use of the method taking into account inhomogeneities required a significant complication of the algorithm, which requires checking the conditions of intersection of individual layers by photons; calculating the probability of refraction, reflection or absorption of photons at the boundaries between layers. For the simulation of the UV channels in the conditions of atmospheric inhomogeneities, this approach has not previously been used.

Acknowledgments

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