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Multi-Channel Ultraviolet Communication System and Environmental Concerns

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Abstract

The problems of communication in the UV-C range with mobile nodes that require the use of a multi-channel UV-C communication system with optical channels oriented in different directions are considered. The review and analysis of the known methods of multichannel transmission of optical signals and their environmental impacts are carried out, their disadvantages are noted. In order to reduce the high hardware costs of the UV-C communication method based on a circular radiation pattern, a method for the multi-channel transceiver of optical signals of the UV-C range based on the formation of sector radiation patterns has been developed and investigated. The formation principle of sector radiation patterns in the UV-C range is considered. A block diagram of an angle-measuring tracking system based on the maximum useful signal for adjusting the position of the UV-C receiving and transmitting module in azimuth has been developed. A variant of the device implementing a new method is proposed, which is a design of a receiving and transmitting module in the form of a spherical sector. Based on the Monte Carlo method, the losses in the UV-C channel were simulated using three variants of two-row arrays of optical transmitters and receivers: flat, as well as sector ones with azimuthal width angles of 20 and 40 degrees. The efficiency and prospects of the proposed method when using UV-C

Introduction:

UV communication systems of the solar-blind UV-C range from 200 nm to 280 nm have a number of advantages over radio frequency and other optical systems (infrared and visible ranges). In particular, they allow organizing communication in the non-line-of-sight (NLOS) mode (Xu & Sadler, 2008; Shaw *et al.*, 2003; Siegel *et al.*, 2004). They are also insensitive to the effects of solar radiation, since its share in the used range is extremely small, and the rest of the radiation can be effectively blocked by a solar-blind filter on the receiver side (Lu *et al.*, 2020).

To create a wireless data transmission mobile ad-hoc network (MANET) in the UV-C range, it is necessary to establish a connection with nodes in various directions. To achieve a sufficient signal level in the optical receiver, narrowly directed emitters are needed (lasers or LEDs with a radiation focusing system based on lenses or mirrors). It is also necessary to note the limited angle of radiation reception by an optical filter (30-40 degrees) installed at the

input of an optical receiver (photoelectronic multiplier) (Hamamatsu Photomultiplier Tubes: basics and applications; Bicon Corp.: Ruggedized High-Temperature Detector Technology). If a single-channel UV communication system is used (one emitter and one receiver), the rotation of the nodes along the azimuth causes a strong decrease in the level of the received useful signal (by more than 45 dB) (Wang *et al.*, 2011; Xu & Sadler, 2008; Chen *et al.*, 2014). These aspects determine the relevance of the application of a multi-channel UV-C communication system with optical channels oriented in different directions. Creating a circular radiation pattern allows to provide an acceptable signal level for any azimuthal orientation of the nodes, but requires high hardware costs (Vasilyev *et al.*, 2010).

The aim of the work is to develop and simulate a method for the multichannel transceiver of optical signals of the UV-C range based on the formation of sector radiation patterns.

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Methods of multichannel transmission of optical signals:

There are various methods of multi-channel transmission of optical signals and devices based on them, which differ in a number of parameters (the number of receiving and transmitting channels, their azimuths and elevation angles). A method for organizing access to the data packet transmission network is known, based on the direct rearrangement of the radiation beam of a laser transmitting device in the direction of the corresponding receiving device. The disadvantage of the method is the complexity of the alignment and, accordingly, the possibility of losing part of the transmitted information by subscribers (receiving devices) due to the mismatch of the orientation of the receiving and transmitting optical antennas (especially in a mobile communication line) (Zhong *et al.*, 2021). There is also a known method for multi-channel transmission of optical signals using duplication of the main optical channel with additional optical channels (Netheti *et al.*, 2021). In this method, laser receiving devices are installed at a distance with an arrangement to the side relative to the considered axis of propagation of the radiation beam of the transmitting laser means. In this case, the receiving devices obtain the radiation scattered by the atmosphere of the transmitting laser device. To do this, the receiving antennas of the laser receiving devices are oriented in the direction of the beam axis of the transmitting laser device, and the information transmitted by the laser transmitting device is isolated by each of the laser receiving devices by changing the amplitude of the front and backside of the output impulse of the photodetector. The stability of information transmission to several subscribers is achieved by duplicating the main optical channel with additional channels that are less critical to the orientation of the radiation patterns of optical antennas. In this case, in the method of multi-channel transmission of optical signals based on targeting the radiation flux of the laser transmitting device in the direction of one of the N laser receiving devices, $N-1$ laser receiving devices are additionally installed at a distance with an arrangement to the side relative to the considered axis of propagation of the radiation beam of the transmitting laser means. At the same time, the radiation pattern of the receiving device is much wider than the duration of the transmitted impulse and the cross-section diameter of the laser beam, which allows them to receive the radiation scattered by the atmosphere of the transmitting laser device. The receiving antennas of the $N-1$ laser receiving devices are oriented in the direction of the beam axis of the transmitting laser device, and the information transmitted by the laser transmitting device is isolated by each of the $N-1$ laser receiving devices by changing the amplitude of the front and back sides of the output impulse of the photodetector.

Figure- 1: A variant of the device for multichannel transmission of optical signals of the UV-C range (Vasilyev *et al.*, 2020; Igor *et al.*, 2019)

This device for generating a radiation pattern is characterized by the use of several lower tiers of the structure, located at small and large elevation angles to the horizontal and having several facets at the base for optical transmitters, providing a circular radiation pattern for the propagation of transmitted light rays; as well as the use of several upper tiers of the structure, which are also located at small and large elevation angles to the horizontal and have several facets at the base to accommodate optical receivers in them, providing a circular radiation pattern for omnidirectional reception of transmitted light rays.

The disadvantage of this method and the device that implements it is the large hardware costs associated with the need to create a circle directional diagram of transmitters and a circle diagram of receivers. This disadvantage is especially critical for UV-C optical communication devices that require the use of rare and expensive optical components.

Multichannel transceiver of optical signals of the UV-C range based on sector radiation patterns:

The proposed method for multichannel UV-C signal transceiver allows decreasing hardware costs by reducing the number of channels for transmitting and receiving optical signals while maintaining the reliability and range of communication in NLOS mode when moving and turning mobile communication nodes.

In the proposed method, a sector pattern of the receiving and transmitting module of a multi-channel mobile wireless optical communication system is formed at mobile and stationary subscriber points of the network. The presence of several optical transmission and reception channels with a sector arrangement of optical transmitters and receivers allows to provide reliable communication in NLOS mode between network subscribers during movements and turns of mobile communication nodes, as

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well as to increase its range and sensitivity of receiving channels by narrowing the radiation angles of optical transmitters and the viewing angles of optical receivers (Fig.-2). Adjustment of the position of the receiving and transmitting module by azimuth is carried out using an angle-measuring tracking system to the maximum of the useful signal (Fig.-3).

Figure- 2: The principle of formation of sector radiation patterns in the UV-C range

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In Fig.-2 shows the vertical xOx and horizontal xxz projections of the channel in the NLOS mode with a sector arrangement of optical transmitters and receivers. The figure shows: T_x - the transmitting module, R_x - the receiving module, r - the distance between the transmitting and receiving modules, $\theta_{T,R}$, $\varphi_{T,R}$, $\chi_{T,R}$ - the elevation angle, the width of the radiation pattern and azimuth, the index T refers to the transmitter, the index R refers to the receiver, σ - the scattering angle, V - the total volume of the radiation patterns of the transmitter and receiver, $\theta_{T,R}$ - the distance from the transmitter and receiver to the center of the area V , $r_{T,R}$ - the distance from the obstacle to the transmitter and receiver. The individual optical transmitters of the transmitting module $S_1 \dots S_{NT}$ and the individual optical receivers of the receiving module $R_1 \dots R_{NR}$ are located in the horizontal projection of the channel along the circle sector and are shown by dots (not in scale, the distances between any individual transmitters and any individual receivers are much less than r). To ensure reliable communication between network subscribers during movements and turns of mobile communication nodes, the required number of N_T transmitters and the required number of N_R receivers is determined from the conditions for full coverage of the sector with the required azimuth width $\Delta\theta_{T,R}$: $N_{T,R} = \Delta\theta_{T,R} / \varphi_{T,R}$ (1)

A variant of the device implementing this method is a design of a receiving and transmitting module in the form of a spherical sector.

This device for generating a radiation pattern is characterized by the use of at least one tier of optical transmitters and at least one tier of optical receivers that provide a sector radiation pattern for receiving transmitted light rays in the required range of azimuth angles, as well as an angle-measuring tracking system to the maximum of the useful signal for adjusting the position of the receiving and transmitting module in azimuth.

A photo of the design of one of the variants of the receiving and transmitting module for multi-channel mobile systems of wireless ultraviolet communication, implementing the proposed method, is shown in Fig.-4

Figure-4: An example of a device for forming sector radiation patterns in the UV-C range

The lower tier of the structure 1 has M facets at the base, located at different angles to the vertical with an angular pitch $\Delta\theta_{T,R}/N_{T,R}$ and containing cells 2 for placing M optical transmitters in them, providing a sector radiation pattern for the propagation of transmitted light rays in the azimuth range $\Delta\theta_{T,R} = N_{T,R} \varphi_{T,R}$ in accordance with the formula (1). The second tier of the structure 3 has N facets at the base, also located at different angles to the horizontal and containing cells 4 for placing N optical receivers in them, providing reliable reception of transmitted light rays in the required range of azimuth angles, both in the presence and absence of a line of sight between the transmitter and the receiver.

The diagram of the angle-measuring tracking system for the maximum of the useful signal for adjusting the position of the receiving and transmitting module in azimuth is shown in Fig.-3. It consists of: a direction-finding (tracking) device, a low-pass filter (LPF) and an executive element (EE).

The input radiation passes through a sun-blind filter that blocks secondary solar radiation and passes a useful signal. The signal from the output of the solar-blind filter is fed to the input of an optical receiver (OPR) (a photodiode, an array of photodiodes or a photoelectronic multiplier). The OPR signal is amplified by the amplifier Amp. The direction-finding device generates a signal that characterizes the deviation of the signal source from the equal-signal direction (ESD), then this signal is filtered in the LPF and fed to the EE which turns the receiving and transmitting module in azimuth by an angle equal to the azimuthal deviation of the source from the ESD in the opposite direction, to compensate for this deviation.

Thus, the proposed method can lower the hardware

costs of a multi-channel optical communication system by reducing the number of channels for transmitting and receiving optical signals while maintaining the reliability and range of communication in the NLOS mode when moving and turning mobile communication nodes. The reduction of the cost and weight and size indicators of the optical communication system expands the possibilities of its application on stationary and, mainly, mobile objects (Vavoulas *et al.*, 2011).

Modeling of the UV-C communication system based on a sector radiation pattern:

As a result of Monte Carlo simulation (Drost *et al.*, 2011; Konstantinov *et al.*, 2018; Igor *et al.*, 2019; Konstantinov, *et al.*, 2018), the dependences of losses on the parameters of the channel geometry are obtained. The distance between the arrays of transmitters and receivers was assumed to be $r = 100$ m, the elevation angle of the center of the transmitter array $\theta_1 = 300$, same for the receiver array $\theta_2 = 500$, the width of the transmitter radiation pattern $\phi_1 = 170$, the receiver field of view $\phi_2 = 300$, the radiation wavelength $\lambda = 260$ nm, the aperture area of the receiver $A_r = 1.77$ cm². In each example, both optical transmitters and receivers are arranged in two rows, the number of transmitters and receivers in each row is $N_T = 3$ and $N_R = 3$.

As a result of the simulation, the dependences of the path loss in decibels on the azimuths of the transmitter $x_1 = x$ and the receiver $x_2 = x$ are indicated in Figures 5, 7, 9 as ψ_{11} and ψ_{12} .

When using flat arrays of transmitters and receivers (Fig. 4, 5), the attenuation from x_1 varies from 112 dB at $x_1 = 00$ to 160 dB at $x_1 = 300$. With the variation x_2 , the losses range from 117 to 165 dB.

The use of sector arrays of transmitters and receivers with azimuth width and elevation angles of 20 degrees (Fig.-6, 7) and 40 degrees (Fig.-8, 9) generally smoothes the dependence of losses on azimuths, although, with a certain arrangement of nodes, losses increase.

Conclusion:

A method for transmitting optical signals of the UV-C range based on a sector radiation pattern is proposed, which reduces hardware costs compared to the circular radiation

Figure-4: Azimuthal projection of transmitters and receivers (flat arrays)

Figure-5: Channel losses when using flat arrays of transmitters and receivers

Figure-6: Azimuthal projection of transmitters and receivers (sector arrays with azimuth width and elevation angles of 20°)

Figure-7: Channel losses when using sector arrays of transmitters and receivers (azimuth width and elevation angles of 20°)

Figure-8: Azimuthal projection of transmitters and receivers (sector arrays with azimuth width and elevation angles of 40°)

Figure-9: Losses in the channel when using sector arrays of transmitters and receivers (azimuth width 400, elevation angle 200)

pattern method. To implement the new method, a block diagram of an angle-measuring tracking system is developed. The system tracks the maximum of the useful signal for adjusting the position of the UV-C receiving and transmitting module in azimuth. An example of a device for forming sector radiation patterns in the UV-C range is also shown. The modelling of the UV-C communication system based on a sector radiation pattern with three variants of the arrays of transmitters and receivers (flat, sector with an azimuth width of 20 degrees and sector with an azimuth width of 40 degrees) was performed. The simulation has shown that the use of sector arrays of transmitters and receivers generally smooths the dependence of losses on azimuths, although losses increase with a certain arrangement of nodes. The results show the prospects of sector arrays of optical transmitters and receivers to build a data transmission network with a UV channel. The proposed method and device relate to the field of optoelectronic systems and can be used in laser (optical) UV-C communication systems with a dynamic structure, including scenarios with UV-C communication channels in networks with mobile subscriber stations.

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