Method for forming a directional diagram of the receiving and transmitting module of a multi-channel mobile wireless ultraviolet communication system

G.S. Vasilyev [1], O.R. Kuzichkin [1], D.I. Surzhik [2], I.S. Konstantinov [1,3], S.A.Lazarev [1]

[1] Belgorod State University, Belgorod, 308015, Russia
[2] Vladimir State University, Vladimir, 600000, Russia
[3] Russian Timiryazev State Agrarian University, Moscow, 127550, Russia
Iran

Abstract:
To organize mobile ad-hoc networks (MANET) based on UV-C communication modules, it is necessary to provide communication with nodes in all possible directions, both at the availability of line-of-sight (LOS) and non-line-of-sight (NLOS) conditions. It is shown that the use of circular arrays of optical transmitters and receivers is promising for solving this problem. A two-tier configuration of the optical component arrays is proposed, in which the single lower tier with small elevation angles is used for communication in LOS mode, and the upper tier with large elevation angles is used to round high terrain obstacles in NLOS mode. The performance characteristics of this multiple input, multiple output (MIMO) UV communication systems with spatial channel multiplexing are calculated using the proposed configuration. The detection on the receiving side is based on one of three criteria: Maximum Likelihood (ML); Zero-Forcing Successive Interference Cancellation (ZF-SIC), and Minimum-Mean-Square-Error SIC (MMSE-SIC). It is shown that in real systems it seems appropriate to use the MMSE-SIC method, which provides a compromise between computational complexity and the number of bit errors. The results show that the application and optimization of circular arrays of optical transmitters and receivers are promising for building a MANET network with a UV channel.

Key words:
wireless ultraviolet communication; Mobile Ad-Hoc Network (MANET); MIMO.

1. INTRODUCTION

The use of UV communication systems makes it possible to ensure reliable communication in difficult conditions when traditional radio communication or optical communication in other spectral ranges (infrared and visible) is ineffective or impossible. In particular, such conditions are: a difficult terrain with high obstacles between the transmitter and the receiver, a strong influence of natural electromagnetic interference, and deliberate suppression by electronic warfare. These advantages are provided through the use of the UV-C range devices with a wavelength of 200-280 nm not exposed to solar radiation, which in this range is blocked by the ozone layer of the atmosphere. Strong scattering of UV-C radiation in the atmosphere makes it possible to organize communication not only in the line-of-sight (LOS), but also in the non-line-of-sight (NLOS) modes [1-3].

To organize a mobile ad hoc network (MANET) based on UV communication modules, it is necessary to provide communication with nodes in all possible directions. This problem can be solved by means of the physical layer of the communication network or by routing at the network level through communication through intermediate nodes [4, 5]. The disadvantage of the second approach is the lack of widely tested routing protocols specialized for use in UV networks [6]. It is also worth noting the non-standard problems associated with the detection of neighboring UV communication nodes [7–10], which are especially critical when the spatial distribution of the nodes is far from uniform. These aspects determine the relevance of omnidirectional UV communication by means of a physical layer.

Attenuation of UV radiation in the atmosphere in the NLOS mode is more than 100 dB at distances of more than 100 m [11, 12]. To ensure an acceptable signal level on the receiving side, it is necessary to use highly directional emitters (LEDs or lasers). The inevitable use of solar-blind filters as part of an optical receiver to suppress solar radiation leads to a narrowing of the field-of-view (FOV) parameter of the receiver to 30-40 degrees [13]. Sometimes FOV has to be additionally limited to increase the bit rate of data transmission due to the weakening of intersymbol interference caused by the narrowing of the pulse characteristics of the UV channel. When using a single directional transmitter and a single directional receiver, rotation of the nodes in the azimuth plane leads to a strong increase in losses in the UV channel (by 40 dB or more) [14-16]. Therefore, to ensure

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acceptable attenuation within the entire azimuth range from –180° to 180°, it is necessary to use arrays of differently directed emitters and receivers.

The aim of the work is to develop and simulate a method for forming the directional pattern of a receiving-transmitting module of a multichannel mobile wireless ultraviolet communication system for its use in MANET.

2. CONFIGURATIONS OF UV EMITTER AND RECEIVER ARRAYS

The configurations of the emitter and receiver arrays are specified by the following parameters: the number of components, their azimuths and elevation angles. Most of the solutions are aimed at using visible and, less often, infrared bands of optical systems in the LOS mode. An example is the US patent for an optical transceiver for a wireless data transmission system [17]. This transceiver has a dome-shaped housing, inside which there is a mounting plate and an optical transmitter containing an array of light-emitting diodes is on the plate. Under the mounting plate there is an optical receiver containing four photodiodes protected from electromagnetic fields by a Faraday cage and facing in different directions to receive light incident on the housing from all sides. The disadvantage of this device is the need to provide a large angle of view for four optical receivers; this angle significantly reduces the range of the communication system. Other disadvantages are the lack of communication out of line of sight between network subscribers and the need to protect optical receivers from electromagnetic fields in view of the selected wavelength range for information transmission.

In this and similar solutions, the optical components are oriented in the horizontal plane (with zero elevation angles), which is also characteristic of the channel level of ad-hoc networks with directional emitters (directional MAC, DMAC) [18, 19]. The disadvantage of such solutions for the UV range is the lack of communication in NLOS mode.

Fig. 1 shows an example of a configuration of a UV communication module with 4 (left) and 6 (right) directional emitters on its side faces and one wide directional receiver on its top face [20].

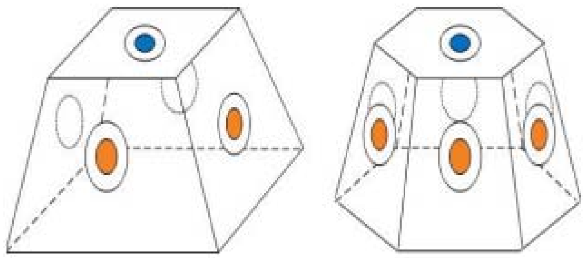

Fig. 1. An example of a configuration for a UV communication module with 4 (left) and 6 (right) narrow directional emitters on the side faces and one wide directional receiver on the top face [20].

The upward directivity of the receiver determines the disadvantages of such a solution: a low level of received UV radiation, a decrease in the bit rate of data transmission due to the use of a wide directional receiver, the need to use more complex multichannel access algorithms at the medium access control (MAC) level of the network (in comparison with the option of using several narrowly targeted receivers).

The proposed method intended for the formation of a transceiver module radiation pattern for a multichannel mobile system of wireless UV communication for omnidirectional light ray transmission and reception in the conditions of presence and absence of direct visibility between the transmitter and the receiver consists in using almost half-spherical shape of the transceiver module which is a multi-tiered truncated pyramid in its cross section and features by:

- The use of several lower tiers in its structure located at small and large elevation angles and having several edges at its base for placing optical transmitters there, providing a circular radiation pattern for the propagation of transmitted light rays;

- The use of several upper tiers in its structure, also located at small and large elevation angles and having several edges at its base for placing optical receivers there, providing a circular radiation pattern for omnidirectional reception of transmitted light rays.

The availability of several channels for transmitting and receiving ultraviolet radiation with a circular arrangement of optical transmitters and receivers allows for reliable communication in the absence of line of sight between network subscribers when moving and turning mobile communication nodes, as well as increase its range and sensitivity of receiving channels by narrowing the optical radiation angles of transmitters and angles of view of optical receivers. The technical result of the proposed method is to increase the reliability and range of communication in the mode of lack of direct visibility between network subscribers when moving and turning mobile communication nodes.

An experimental sample of the configuration of the transmitter and receiver arrays practically implemented by the authors is shown in Figure 2.

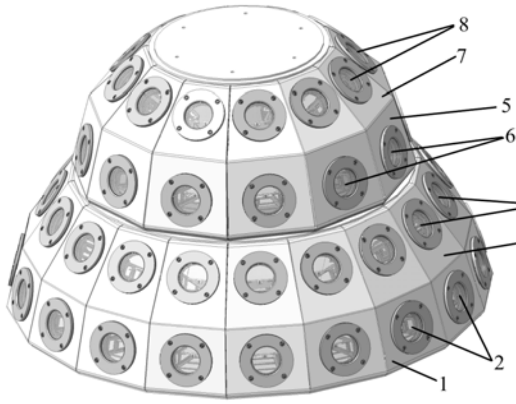

Figure 2. Experimental configuration of transmitter and receiver arrays

A feature of this configuration is the availability of several UV radiation transmission and reception channels arranged in a circle. This allows for reliable communication in NLOS mode when moving and turning mobile communication nodes. In addition, due to the narrowing of the radiation angles of optical transmitters and the angles of view of optical receivers, the sensitivity of the receiving channels and, consequently, the communication range increases.

The two lower tiers of the structure (1 and 3) each have 18 edges at the base located at different angles to the horizontal. Each cell of the lower tiers (2 and 4) contains an optical transmitter; their combination provides a circular radiation pattern of emitted photons. The first row of optical transmitters with a low elevation angle is used to create a communication channel with minimal radiation propagation losses in LOS mode. The second row with a high elevation angle provides a communication channel with high losses in NLOS mode due to difficult terrain conditions (presence of obstacles).

The two upper tiers of the structure (5 and 7) each have 12 edges at the base. The faces of the upper tiers are also located at different angles to the horizontal and contain cells (6 and 8) for placement of 12 optical receivers in them, providing reliable omnidirectional reception of emitted photons in LOS and NLOS modes.

3. THE MODELLING OF THE PROPOSED UV TRANSMITTER AND RECEIVER ARRAY CONFIGURATIONS

The modelling of performance characteristics of a multiple input, multiple output (MIMO) communication system with spatial channel multiplexing using the proposed configuration was carried out. Detection on the receiving side is carried out based on one of three criteria [21]:

1) Maximum-Likelihood (ML);

2) Zero-Forcing Successive Interference Cancellation (ZF-SIC);

3) Minimum-Mean-Square-Error SIC (MMSE-SIC).

Energy characteristics of on-of keying modulation without return to zero (NRZ-OOK) are determined in accordance with the expression [22]:

$$BER_{NRZ-OOK}(SNR) = \frac{1}{2}\operatorname{erfc}\left(\frac{1}{2\sqrt{2}}\sqrt{SNR}\right).$$

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

$$SNR = N_d / N_n,$$

Where $N_d = \eta_f \eta_r N_r = \frac{\eta_f \eta_r N_r}{Loss} = \frac{\eta_f \eta_r P_t \lambda}{hcR \cdot Loss}$. P_t is the transmitter radiation power, η_f is the transmission coefficient of the sun-blind filter, η_r is the quantum efficiency of the detector (receiver), η_r is the number of received photons, λ is the radiation wavelength, *Loss* is the channel loss obtained by statistical modelling using the Monte Carlo method based on the algorithm developed by the authors [23,24], R is the bitrate, h = $6.626 \cdot 10^{-34}$ J · s is the Planck constant, s = $3 \cdot 10^{8}$ m / s is the speed of light in vacuum. The detection frequency of noise photons is assumed to be 15000 Hz according to the experimental results on a clear day when using an absorption solar-blind filter with suppression of more than 12 orders of magnitude and a photomultiplier with an aperture of 1.92 cm^2) [25].

The calculated performance characteristics of the MIMO UV communication system are shown in Fig. 3, 4. The communication range is taken equal to r = 100 m, the width of the radiation patterns of the transmitters and receivers φ1 = 10° and φ2 = 30°, the radiation wavelength λ = 260 nm, the scattering and absorption coefficients for clear weather, the receiver aperture area A_r = 1, 92 cm^2). Also the values of P_T = 50 mW, *SNR* = 10 dB are accepted.

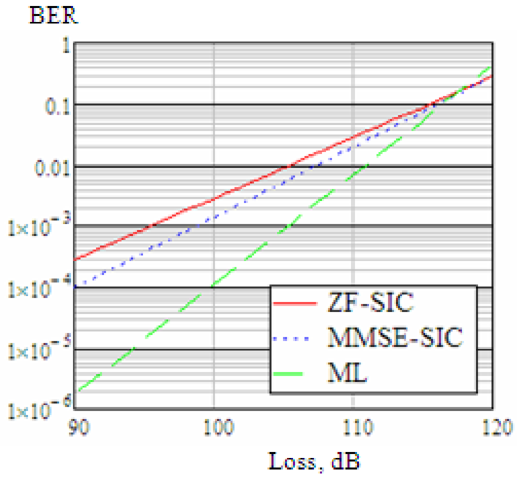

Fig. 3. Dependencies of BER versus losses for different types of spatial multiplexing

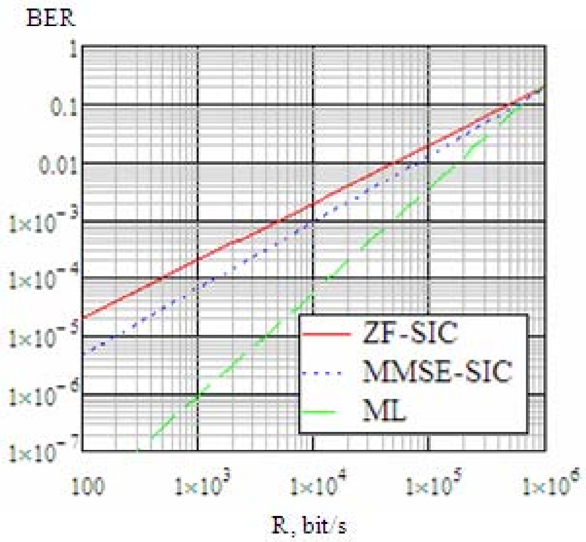

Fig. 4. Dependencies of BER on bit rate for three types of spatial multiplexing

Fig. 3 and 4 show that the multiplexing method based on the criterion of maximum likelihood (ML) provides the lowest bit error rate (BER), all other things being equal; the MMSE-SIC method has slightly better characteristics compared to ZF-SIC. However, the disadvantage of the ML method is the high computational cost, so in real systems it seems appropriate to use the MMSE-SIC method, which provides a compromise between computational complexity and the number of bit errors. The results show that the application and optimization of circular arrays of optical transmitters and receivers are promising for building a MANET network with a UV channel.

4. CONCLUSION

A method of forming the directional diagram for a transceiver module of a multichannel mobile wireless UV communication system designed for use in MANET networks is proposed. To implement the method, a two-tier configuration of optical component arrays is considered, in which a single lower tier with small elevation angles is used for communication in the LOS mode, and the upper tier with large elevation angles is used to avoid high terrain obstacles in the NLOS mode. The modelling of the MIMO UV communication system performance with the use of three spatial multiplexing methods and the proposed configuration is carried out. The modelling has shown that in real systems it seems appropriate to use the MMSE-SIC method, which provides a compromise between the computational complexity and the number of bit errors. The results show the promise of using and optimizing circular arrays made of optical transmitters and receivers for building a MANET network with a UV channel.

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