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A Model of a Free-Space Optical Communication Line with a Smart Reflector

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***Abstract*—The article considers a model of a free-space communication line between several closely located points on the terrain that are outside the line of sight. For the rapid deployment of communication lines with a range of up to hundreds of meters, any tall building visible to all callers can be a kind of optical signal repeater. Compared to radio communication channels, an optical communication line has a higher speed of information transmission, is insensitive to electromagnetic interference and is more protected from eavesdropping. To increase the range of the communication line and increase the signal to noise ratio, it is proposed to use a smart reflector based on the mirror of the two-axis scanner, the angular position of which is controlled by the microcontroller. The microcontroller receives information about the angle of incidence of the laser beam on the smart reflector in the form of photoelectric signals. These signals are formed by a position-sensitive photodetector and a lens in front of it. Depending on the angle of incidence of the laser beam, the position of the laser spot focused by the lens on the photodetector changes, and with it, both signals at its output. To facilitate the search of the smart reflector by transceivers, it is suggested to use an LED beacon in it.**

Key words — free-space optical communication; laser diode; pin-photodiode; diffuse reflector; smart reflector; position-sensitive photodetector; microcontroller; scanner; signal to noise ratio.

I. Introduction

Communication in the broadest sense of the word means interaction between objects. One form of optical communication is the transfer of energy from one object to another, for example, from the Sun to the Earth, or from a terrestrial laser to a drone [1]. Another form is the transmission of information by means of light, and such optical communication has a long history that began several millennia ago, when armies announced their victory or defeat with a relay of balefires on hills [2]. In ancient Rome, polished metal plates were used as mirrors to transmit signals by solar "bunnies". In the Middle Ages, the first optical lines of communication appeared, built on the spatial coding of symbols, for example, by torches located in certain windows of the tower, and later by semaphores (like a signalman on a fleet with flags in his hands) [3]. In 1880, the American inventor Alexander Bell developed his "photophone", which made it possible to transmit a telephone signal by solar radiation using the vibration of a mirror moving under the influence of the voice, and to receive a signal from a distance of several hundred meters with a selenium photocell. It was the first demonstration of the transmission of a human voice using light, 19 years before the advent of radio communication [4]. But the era of optical communication really began in the early 60s of the last century with the advent of LEDs and lasers.

In recent decades, the amount of information that needs to be transmitted over communication channels has increased significantly, which is associated with the development and needs of space technology, television, mobile communication and the Internet. As far back as 1956, a year before the launch of the first satellite, the American scientist and writer John Pierce, the inventor of some ultra-high-frequency tubes and the term "transistor", warned: "In addressing the future of communication problems, we must take into account some provisions... One of them is bandwidth...For many years now we have seen...a continuous increase in the need for ever wider bandwidths. We have come a long way from the telegraph, which is limited to a bandwidth of several tens of hertz, to voice transmission, which already requires a bandwidth of several thousand hertz, to television with a necessary bandwidth of several million hertz" [5].

In the 1970s and 1980s, various options for free-space laser communication were created and tested: between ground points, between a satellite or aircraft and a ground point, between an aircraft and a submarine, etc. For covert optical communication in

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the field, binoculars were developed, in which an optical transceiver was created on the basis of one half, and the other half was used to aim at the transceiver of the caller. With the power of an infrared LED of several milliwatts, the range of such a communication line reached 1 km [6, 7, 8].

In 1979 the first experiments were carried out using the reflected radiation of infrared LEDs for indoor multiple access communication [9].

In 2007 the German professor Harald Haas proposed an optical analogue of Wi-Fi – namely a Li-Fi technology. In the name of this type of communication, Wi (Wireless) was replaced by Li (Light). In 2011, at the "TED Global" conference, Haas demonstrated the transmission of a video signal using light coming from the LED [10].

The 90s were marked by the rapid development of fiber-optic communication. Optical losses in the fiber decreased to 0.1 dB/km, the WDM (Wavelength Division Multiplexing) technology appeared, and these achievements made it possible to transmit more than a hundred signals simultaneously over the optical fiber [11].

In 2005, the possibility of secure communication between a ground station and a satellite in low orbit was demonstrated [12]. The protected nature of information transmission was provided by quantum key distribution, a technology that allows information to be exchanged over open communication channels, having previously created a common key in the form of entangled states of photon polarization. The peculiarity of this technology is that an attempt to interfere with the communication channel destroys the common quantum state of the callers and becomes noticeable.

Quantum communication between two drones was demonstrated in 2021 [13]. One of the drones distributed entangled photons, and the other acted as an optical repeater. The use of the repeater made it possible to restore the shape of the wave front of the laser beam and increased the communication range. In the future, similar systems can be used to create mobile quantum networks.

This article considers the possibilities of rapid deployment of a laser communication network in the field with the use of reflectors of natural or artificial origin. The use of reflectors will allow to bypass the requirement of direct optical visibility between the source and receiver of the signal and expand the scope of application of terrestrial laser communication.

II. Advantages and Disadvantages of the Free-Space Communication

Optical communication has a number of advantages compared to radio communication:

- a hundred times higher speed of information transmission, which is due to the fact that the frequencies of optical radiation are much higher than the frequencies of the microwave range, on which mobile and satellite com munication devices work, and, accordingly, wider frequency bands are available for communication;
- LED lamps, which are increasingly used for indoor lighting, can be used to access the Internet;
- the possibility of using LED traffic lights and street lights to provide information to drivers of vehicles about traffic routes and the situation on the roads;
- the absence of electromagnetic radiation, similar to microwave radiation from mobile phones and Wi-Fi routers, which can interfere with the normal operation of sensitive medical equipment (tomographs, cardiographs, encephalographs, etc.) in hospitals and diagnostic centers;
- the possibility of communication under water using light;
- the insensitivity of the optical communication channel to electromagnetic interference, in particular to means of electronic warfare;
- the security of the communication channel against interception of information.

The disadvantages of optical communication when compared with radio communication are:

- the need for direct visibility between the source and receiver of the optical signal;
- the possibility of a significant weakening of the optical signal in the atmosphere under adverse weather conditions.

One of the main elements of the free-space optical communication line, which determine the quality of the communication, is the medium in which the radiation propagates. If in space and the upper layers of the atmosphere, the influence of the environment on the propagation of radiation can be neglected, then near the surface of the Earth, the atmosphere is a determining factor when choosing a source of radiation. When using visible radiation, poor visibility means poor communication. Visibility is affected by clouds, precipitation, fog, smoke, and dust,

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particles of which attenuate radiation due to Rayleigh scattering by nanoparticles and Mie scattering by microparticles. Scattering is the result of the secondary radiation of electrons present in the material particles and rocked by the electric field of the light wave. Another reason for the attenuation of radiation is absorption (mainly by water molecules). The energy absorbed by the molecule is transformed either into heat or back into radiation energy, but already scattered [14].

The propagation of optical radiation in the atmosphere is accompanied by losses, the magnitude of which strongly depends on the radiation spectrum.

The spread of laser radiation in the lower layers of the atmosphere is influenced by several factors [15]:

- turbulence, which causes local changes in the refractive index of air, especially noticeable at heights below 20 m; these changes lead to the expansion of the beam, the wandering of its optical axis and the appearance of scintillation, and also cause a decrease in the radiation coherence radius;
- scattering by aerosols (dust particles, smoke, water vapor), which decreases with increasing radiation wavelength;
- absorption in aerosols, which is an order of magnitude greater than scattering;
- molecular absorption, which strongly depends on the wavelength of radiation; molecular absorption has narrow spectral lines that should not overlap with laser emission lines.

Atmosphere is much less selective to radio wavelengths than to optical wavelengths. Only medium and long waves ($\lambda > 100$ m) do not penetrate through the Earth's ionosphere, which is rich in charged particles. These waves are not blocked by houses and hills and are able to follow the curvature of the Earth, which was used by the first broadcasting stations at the beginning of the last century.

The main window of atmospheric transparency is observed at a wavelengths near 10 microns, and it is in this infrared range that a powerful CO_2 laser generates radiation. Some of the first atmospheric communication lines were built on this laser [8].

A solid-state Nd:YAG laser whose second harmonic with a wavelength $\lambda = 532$ nm (blue light) was weakly absorbed by water turned out to be suitable for communication between an aircraft or a satellite and a submarine. Highly efficient small-sized semiconductor lasers based on GaAs and GaAlAs, emitting at wavelengths of 800–900 nm in the near-infrared range, were more suitable for communication between satellites [6].

In 1977, the European Space Agency began research aimed at developing an optical communication link between satellites. The first space-based optical communication system appeared in 2001. Communication was established between the ARTEMIS and SPOT-4 satellites, which were located, respectively, at an altitude of 31,000 and 728 km above the Earth. The image of the Earth's surface obtained by the digital camera of the SPOT-4 satellite was transmitted by the radiation of a GaAlAs laser to the ARTEMIS satellite, from which it was sent to the ground station by radio waves in the Ka range (26.5–40 GHz). The laser beacon of the ARTEMIS satellite and the laser transmitter of the SPOT-4 satellite operated in the wavelength range of 800–850 nm with an average radiation power of 100 mW. Later, the semiconductor laser was replaced by an Nd:YAG laser with a wavelength of 1064 nm and a power of 10 W. The laser was pumped by a line of GaAs laser diodes [16, 17].

Similar studies also took place in the USA after the announcement of the Strategic Defense Initiative program in 1983. In the early 1990s, as part of this program, three laser beams were directed at a satellite located at an altitude of 350 km and returned to Earth by the satellite's retroreflector [18].

Similar studies were conducted in Japan. In 2005 a laser communication session was conducted between the European ARTEMIS satellite and the Japanese “Kirari” satellite [19].

The latest generation of Starlink satellites is equipped with laser transceivers, which allow the satellites to exchange information much faster than it was possible to use microwave devices [20].

One of the first applications of LEDs for optical communication was optocouplers, galvanic isolation devices that enabled voltage, current, and resistance matching within an electronic device or between devices. Another application involved short fiber optic communication lines on multimode fibers. The fundamental difference of the optical communication line, which is based on the incoherent radiation of an LED, is the possibility of using the modulation of radiation only by intensity in the transmitter, and the direct method of photoreception (not heterodyne) in the receiver. At the same time, radiowaves and laser radiation allow both amplitude and phase modulation [21].

One of the advantages of Li-Fi over Wi-Fi is the combination of lighting and information transmission functions with LEDs. Light does not penetrate

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through walls or partitions, which provides Li-Fi greater security of the communication channel.

The concept of cellular radio communication, which began to be successfully implemented in the 70s of the last century and led to the spread of mobile phones from the 80s, turned out to be applicable to optical communication as well. The radius of action of a cell (macrocell) is usually within 1–30 km. It was observed that reducing the distance between the base stations increases the spectral efficiency of the cellular network, that is, the number of successfully transmitted bits per 1 s, which corresponds to 1 Hz of the frequency band of the communication line. Cells with a small coverage radius came to be called micro-, pico-, and femtocells. The femtocell network is designed for indoor deployment and has a fairly cheap and low-power base station that is directly connected indoors to an outlet. The main disadvantage of the femtocellular network is that it operates on the same frequencies as the macrocellular network, which causes interference (parasitic modulation) of indoor signals [22].

Wi-Fi operates in the 2.4–5 GHz frequency range (λ = 6–12.5 cm), while visible light is in the 430–750 THz range (λ = 400–700 nm). The huge amount of information transmitted by radio waves has led to dense filling of the radio frequency range with information channels. The optical range is about 10,000 times wider than the radio range, which opens new perspectives for mobile communication, especially in the case of combining Wi-Fi and Li-Fi capabilities [22].

An attocell network is an optical analogue of a femtocell network. Such a network can simultaneously perform lighting functions and look like several LED lamps located, for example, at a distance of 3 m. An optical network consumes more power than a radio frequency network, but it additionally performs lighting functions, can have 2-3 orders of magnitude higher spectral efficiency, and does not require licensing.

A usual white LED provides a data transfer rate of more than 1 Gbit/s. The speed of information transfer using Li-Fi can reach 5 Gbit/s, especially for RGB-LEDs, while this value is 2 orders of magnitude lower for Wi-Fi [23].

The range of Li-Fi within direct line of sight reaches 10 m, while Wi-Fi can work even through walls and has a range of up to 32 m. The operation of Li-Fi can be affected by solar radiation falling on the photodetector [21].

III. Structure of a Free-Space Optical Communication Line with Multiple Access

The scheme of a free-space optical communication line with multiple access differs from a typical optical communication scheme by the presence of a reflector, which provides limited or unlimited access, depending on the design and properties of this reflector. Any surface with diffuse reflection can serve as a reflector, but the efficiency of such a passive reflector will be low, because a very small part of the energy of the signal source will reach the photodetector. In this case, a sufficiently powerful signal source and a high-sensitivity photodetector will be required for communication. Much higher reflector efficiency can be achieved by using an active reflector, namely a flat mirror oriented perpendicular to the bisector of the angle between the optical axes of the coupled transceivers. The way to implement such a smart reflector is described below.

One of the problems associated with a reflector is its visibility to transceivers. To maintain communication between transceivers, their optical axes must be directed to the reflector. The solution to this problem depends on the specific conditions of the deployment of the communication line. In any case, the reflector must signal about its location. This can be done by flashing a laser spot on a diffuse surface, specially prepared or selected on the terrain as a passive reflector. An active reflector can include an LED beacon.

Let's consider the structural model of a laser communication line with multiple access through a diffuse reflector and describe the interaction algorithm of its elements. The structural diagram of the proposed free-space line of laser communication is shown in Fig. 1. The diagram shows a connection option between three points, each of which has the same transceivers installed. The structure of the transceiver is shown to transmit voice information in the form of an analog signal, but it can be transformed to transmit a digital signal by using analog-to-digital converters.

The transceiver consists of a transmitter, a receiver and a reflector targeting system. In the transmitter, the electrical signal of the microphone, amplified by the low-frequency amplifier LFA2, is fed to the driver of the laser diode. The driver controls the current of the laser diode and converts the electrical signal into an optical one. The lens collimates the radiation of the laser diode and directs it towards the reflector. The receiver of the transceiver, with the help of an objective and a light-splitting prism, receives the optical signal sent to the reflector by another transceiver and directs it to the photodiode (PD). The photoelectric signal of the PD is amplified by the LFA1 and sent to the telephone.

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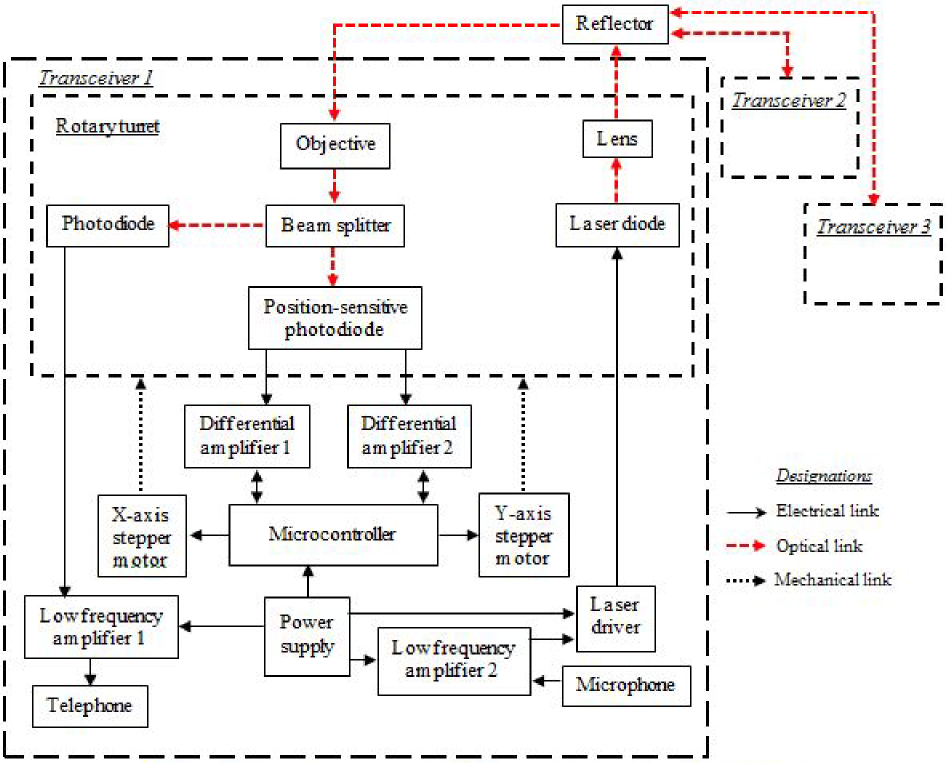

Fig. 1 Structural diagram of a free-space optical communication line with multiple access

A rotary turret controlled by a microcontroller is used to automatically direct the optical axis of the transceiver (axis of the laser diode beam) to the reflector. On the turret there is a lens and an objective, the axes of which are parallel, a light-splitting prism, LD, FD and a two-coordinate position-sensitive photodetector (PCFD). Pairs of the PCHFD photodiodes are connected to differential amplifiers 1 and 2. The process of setting up the communication line consists of two stages – searching for the LED beacon of the reflector and directing the axis of the transceiver to the reflector. At the first stage, according to the commands of the microcontroller, the stepper motors of the X and Y axes are turned on alternately. As soon as the LED beacon enters the field of view of the transceiver objective and a light spot appears on the PSPD, the microcontroller switches to the mode of precise adjustment of the axis of the transceiver to the reflector. If the light spot on the PSPD is located asymmetrically with respect to the photodiodes of the pair, their output signals differ. Differences in signals at the inputs of differential amplifiers form unbalance signals at their outputs. The microcontroller controls the operation of stepper motors based on these signals. As soon as the light spot appears in the center of the PSPD, the unbalance signals of both pairs of photodiodes disappear and the stepper motors stop. The optical axis of the transceiver turns out to be directed at the reflector and the signal of the photo diode of the receiver becomes maximum.

IV. Calculation of the Laser Communication Range with the Diffuse Reflector

Consider the mathematical model of a laser communication line through a diffuse reflector. The model will make it possible to predict what results should be expected during field experiments, namely to find the communication range according to the given system parameters and vice versa – to formulate the requirements for the laser, detector and reflector to ensure the desired quality of communication.

Let's calculate what part of the energy of the optical signal transmitted by one transceiver will be received by the second transceiver if a reflector is used. Let the laser radiation with a wavelength λ and a power P_{las} be directed to a diffuse reflector with a reflection coefficient R. To calculate the maximum achievable signal value at the input of the photodetector, we will assume that our diffuse reflector distributes reflected radiation in accordance with Lambert's law. Such properties are possessed, for example, by the white matte surface of the ceiling in a room or a sheet of printer paper. For simplicity, we will assume that the reflector is equidistant from the signal source and receiver. If the diameter of the laser spot on the reflector is significantly smaller than the distance L to the photodiode, then the reflector can be considered as a secondary point source of radiation with power $2RP_{las}$, which emits half of its power into the hemisphere, and distributes it in space in

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accordance with Lambert's law, that is, in proportion to the cosine of the angle of reflection of the radiation. Thus, the radiation power incident on the photodiode turns out to be proportional to the ratio of the area of the receiver objective with diameter D_{ob} to the area of a hemisphere with radius L, multiplied by the cosine of the angle of reflection of the radiation from the diffuse reflector:

$$P_{pd} = \frac{K\left(\pi D_{ob}^2/4\right)\cos\theta}{2\pi L^2} P_{las} = \frac{K D_{ob}^2 \cos\theta}{8L^2} P_{las}, \quad (1)$$

where K is an attenuation coefficient.

Attenuation of radiation will occur due to losses on the reflector, in the atmosphere and in the objective. In this case, the attenuation coefficient can be represented as

$$K = RT_{ob}\exp(-\alpha L), \quad (2)$$

where T_{ob} is the objective transmittance, and α is the atmospheric absorption coefficient.

To receive weak radiation beams, PIN-photo diodes, avalanche photodiodes (APD) and photoelectronic multipliers (PEM) are used. If we briefly characterize these photodetectors, PIN-photodiodes and FEP have the smallest dark current, and the FEP has a gain of up to 10^7, which is 4 orders of magnitude greater than that of LFD. The choice of a PIN-photodiode for such communication systems is due to simpler manufacturing technology and, accordingly, lower cost, much lower supply voltage and higher reliability.

To amplify the photoelectric signal of the PIN-photodiode, an amplifier with a silicon field-effect transistor is used in the input stage, if the data transfer rate is less than 50 Mbit/s, and a silicon bipolar transistor at higher speeds [24].

The noise of the photo-receiving device, composed of a silicon PIN-photodiode and an amplifier with a field-effect transistor at the input, has 3 components: 1) shot noise; 2) thermal noise and 3) FET noise.

If the photodiode has spectral sensitivity S_λ at the wavelength λ, then the current of the photodiode I_{pd} will consist of the photocurrent I_{ph} and the dark current I_d:

$$_{pd} = I_{ph} + I_d = S_\lambda P_{pd} + I_d. \quad (3)$$

For calculations, we will adopt the values of the dark current I_d = 10 pA and the photocurrent I_{ph} = 320 pA (or the 30 dB value of the "signal/noise" ratio, which sufficient for satisfactory receiving an analog signal).

The magnitude of the shot noise of the photodiode can be found using the formula [2]

$$I_{sh} = \left(2eI_{pd}\Delta f\right)^{1/2}, \quad (4)$$

where e is the charge of the electron, Δf is the amplified frequency band. This formula reflects the discrete nature of both electric current and optical radiation. We can estimate the magnitude of this noise in the case of transmission of an analog signal (for example, conversation) in the frequency band Δf = 3 kHz: shot noise equals 5 pA.

Thermal noise at temperature T is determined by the resistance of the equivalent resistor formed by the internal resistance of the photodiode and the input impedance of the amplifier:

$$I_{th} = \left(4kT/R_{eq}\right)^{1/2}, \quad (5)$$

where k is the Boltzmann constant, R_{eq} is the equivalent resistance of the photodiode and the input stage of the amplifier. Taking R_{eq} = 1 MΩ and T = 293 K, we find that I_{th} = 0.1 pA.

Provided that $S_\lambda P_{pd} >> I_d$ the signal-to-noise ratio (SNR) at the photodiode output can be found using the formula

$$SNR = \frac{I_{pd}^2}{I_n^2} = \frac{\left(S_\lambda P_{pd}\right)^2}{I_n^2}. \quad (6)$$

In this formula I_n is the noise of the photodiode at frequencies $f \geq 1\,kHz$ where the $1/f$-noise disappears:

$$I_n = I_d + I_{sh} + I_{th}. \quad (7)$$

Note that the formulas (1) and (2) can also be used to find the distance at which a given SNR is obtained:

$$L = \left(\frac{K S_\lambda D_{ob}^2 P_{las}\cos\theta}{8 I_d}\right)^{\frac{1}{2}} SNR^{-\frac{1}{4}}. \quad (8)$$

Formulas (1) – (8) are a mathematical model of a laser communication line with a diffuse reflector as a means of overcoming the requirement of a direct line of sight between the source and receiver of an optical signal.

Let's use the following parameters of the circuit elements to calculate L according to the formula (8):

- reflection coefficient of the reflector R = 0.7;
- angle of reflection θ = 60°;
- diameter of the objective entrance aperture D_{ob} = 50 mm;
- objective transmittance T_{ob} = 0.9;
- spectral sensitivity of the photodiode S_λ = 0.3 A/W;
- photodiode dark current I_d = 10 pA;

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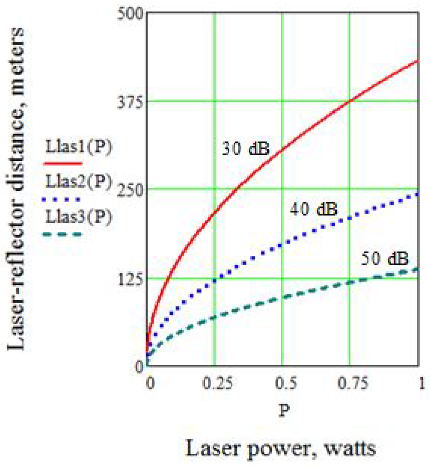

Fig. 2 Dependence on the range of the laser line of communication with the reflector from the power of the laser

- signal-to-noise ratio SNR = 10^3, 10^4 and 10^5 (30, 40 and 50 dB, respectively).

The dependence of the range of the laser communication line with diffuse reflector on the laser power for the specified "signal/noise" ratios is shown in Fig. 2. At a radiation power of 50 mW, the typical power of laser diodes in DVD drives, the range of the communication line will be 97 m (30 dB), 54 m (40 dB), and 31 m (50 dB). According to the last formula, the range of the communication line does not change if the ratio P_{las}/I_d is kept constant. Atmospheric absorption of radiation and additional noise associated with phase fluctuations and laser beam jitter in a turbulent atmosphere will reduce the range of the communication line compared to the calculated one [24].

V. PASSIVE AND ACTIVE REFLECTORS FOR THE FREE-SPACE OPTICAL COMMUNICATION

In 1979, the possibility of using diffuse infrared radiation with a wavelength of 950 nm was considered for the first time for multiple access to the signal source within the room. The walls or ceiling of the room served as diffuse reflectors [9]. In 2019, the first experiments were carried out with the Li-Fi line of indirect visibility, in which the radiation of one white and four infrared LEDs was reflected from the ceiling and walls of a room measuring 5.7×4.5××3 m, and then already fell on the photodetectors [25]. To the LEDs was applied a sinusoidal electric signal with a power of 1 mW and a frequency change in the range of 0.2–200 MHz. In one of the experiments, 4 infrared LEDs SFH 4715AS (860 nm, 780 mW) connected to the driver in parallel and 5 pin photodiodes Hamamatsu S6968 with amplifiers whose output signals were combined were used [26]. In this configuration, the optical power increased 20 times, and the photoelectric signal increased by 26 dB compared to the scheme with one LED and one photodetector. Experiments showed that in the case of directing the axes of LEDs and photodiodes to the ceiling, losses at a distance of 3 m at low frequencies were 25 dB, and at 200 MHz they increased to 37 dB. The authors note that infrared LEDs provide a wider bandwidth and more low-frequency gain than white LEDs. The infrared LEDs are better used in mobile devices, and white LEDs are suitable for signal transmitters in indoor lighting systems when there is no power constraint.

The ceiling, which usually has a reflection coefficient R = 0.7, can be used as a diffuse reflector in the room. If such a communication line is deployed in an open area, a wall of a house, a pole of a power line, a tower, etc., can serve as a reflector, that is, any surface with a diffuse scattering of reflected radiation and a reflection coefficient in the range of 0.3–0.7.

A diffuse reflector is a passive element that loses most of the optical signal energy. It is possible to significantly increase the signal strength at the input of the photodetector by using active (smart) mirror reflectors, which direct the reflected radiation in the direction of the receivers and act as switches.

The idea of an active reflector was first implemented in Bell's photophone in the form of a voice-activated mirror. With the advent of radars came the need for the transmitter to receive power from the receiver. In 1948, the Swedish-born American inventor and scientist Harry Stockman published an article entitled «Communication by means of reflected power», in which he described a new principle of information transfer, which he defined as communication «with the carrier power generated at the receiving end and the transmitter replaced by the modulated reflector» [27]. Stockman proposed using a corner reflector for this purpose, in which one mirror facet oscillates under the influence of voice. Stockman's research formed the basis of the radio frequency identification (RFID) method, so he is credited with inventing this technology, which was embodied in 1966 in the form of the RFID tags that protect goods in stores from theft [28].

In the variant of the active reflector in the form of a corner reflector, the latter performs the functions of a transmitter. Another version of the active reflector is possible when the reflector acts as a switch that connects different transceivers. This requires a mirror-type reflector with a controlled tilt of the mirror.

In the work [29] proposed the use of DMD for laser beam scanning in lidars. DMD mirrors have only two stationary angular positions, the transition between which is carried out in 2 µs. By illuminating the DMD during this period with laser pulses of 8 ns duration, the authors obtained 5 discrete angular positions of

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the laser beam. An Arduino UNO microcontroller was used to synchronize the laser pulses with the rotation of the micromirrors, which allowed for the required pulse generation delay with an accuracy of 0.25 ns.

Reflectors similar, for example, to DMD (digital mirror device) chips used in DLP4710 laser projectors from the American company Texas Instruments can also be used for the laser communication line. The device contains more than 2 million micromirrors with a size of 10×10 µm, which can oscillate at a frequency of 4 kHz [30].

In general, scanning of a laser beam can be carried out by electromechanical, electro-optical, acousto-optical and piezoelectric methods. The largest beam deflection angles are provided by the electromechanical method, which is based on the rotation or rotation of a mirror or prism. The rotation of the mirror can be carried out under the action of electric forces, as in DMD, and magnetic forces, as in galvanometric scanners. For example, 2-coordinate galvanometric scanners of the German company Scanlab provide a rotation angle within ±20° with an accuracy of 0.3° [31]. The scanners of the American corporation Newport have greater speed and accuracy of mirror rotation. Thus, the FSM-300-NM scanner provides a mirror rotation within ±1.5° with an accuracy of 0.015° in less than 0.01 s [32]. If previously such scanners were used for targeting and communication between spacecraft, now they have found applications in laser processing of materials, 3D printing, confocal microscopy, and also in free-space laser communication. Their main disadvantage is their high cost: ten times higher than DMD.

2-axis scanners with electromechanical rotation of a flat micromirror, the deflection angles of which are increased due to resonance, can also be used for the laser communication line. Thus, work [33] demonstrated a microscanner with an increase in the angle of rotation of a mirror with a diameter of 1.2 mm at a frequency of 21 kHz for horizontal scanning and 60 Hz for vertical scanning. The microscanner was manufactured using MEMS technology, which made it possible to reduce its size, weight and cost. Such microscanners are expected to find applications in laser pico projectors, lidars, and optical coherence tomography.

In order for the reflector in the scheme of Fig. 1 became a smart reflector, it is necessary that it had information about the location of all transceivers. A possible version of such a reflector is shown in Fig. 3. Its main elements are a rotary mirror of the 2-axis scanner, a microcontroller with the power supply, a LED beacon, and a position-sensitive photodetector. Interaction of transceivers with the smart reflector takes place according to the following scenario. First, the transceiver looks for a reflector. For this,

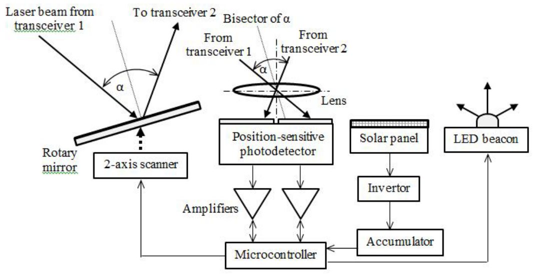

Fig. 3 Structure of the proposed smartreflector

the stepper motors of the X and Y axes are alternately turned on at the command of the microcontroller. The optical axis of the transceiver scans the sector where the LED beacon of the reflector can be found. If it falls into the field of view of the lens, a light spot appears on the position-sensitive photodetector, and on its outputs, potential differences, which go to differential amplifiers 1 and 2, and then to the microcontroller. The microcontroller sends control pulses to the stepper motors until the potential differences at the outputs of the differential amplifiers become zero. At this moment, the optical axis of the transceiver turns out to be directed at the LED reflector, and the maximum power optical signal from the laser diode of the transceiver hits the reflector. Similarly, other transceivers search for a reflector.

After that, the microcontroller of the smart reflector remembers the angular position of all transceivers that turned their optical axes towards the LED beacon. The microcontroller receives information about the angular position of the transceivers relative to the reflector based on the position of the laser spots on the position-sensitive photodetector and the corresponding photoelectric signals. Based on this information, the microcontroller determines the angular position of the bisector of the angle a between the directions of the communicating transceivers and commands the scanner to orient the mirror perpendicular to the bisector.

Depending on the algorithm embedded in the microcontroller program, the smart reflector can provide duplex communication between two transceivers or between several, if packet transmission of information is used.

Thus, the use of a smart reflector instead of a diffuse reflector will enhance the received optical signal and increase the communication range.

CONCLUSIONS

The main requirement for atmospheric lines of optical communication is the absence of obstacles in the path of light from the signal transmitter to the receiver. This requirement limits the possibilities of deploying optical communication lines in open

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terrain. This problem can be partially circumvented by the use of a reflector that is within the direct line of sight of the optical signal transmitter and its receiver. Such reflectors (of natural or artificial origin) allow quick deploying laser communication lines with multiple access on the ground. The disadvantage of such a reflector is the very low efficiency of using the energy of the optical signal sent by the transmitter.

The structural model of the laser communication line through the reflector is considered and the interaction algorithm of its elements is described.

To evaluate the possibilities of using diffuse reflectors in terrestrial laser communication lines, a mathematical model of such a communication line was built in this article. Calculations performed on the basis of this model showed that the range of such communication lines with a laser power of 1 W does not exceed 1 km.

The energy of the optical signal sent by the transceiver can be used more efficiently with the help of a smart mirror reflector. It is proposed to use a controlled mirror as a smart reflector, which, based on information about the spatial position of the transceivers, and set the mirror at such an angle that the laser beam with information transmitted by one transceiver is reflected towards another transceiver. The microcontroller obtains information about the spatial position of the transceivers from the position sensitive detector, which receives the optical signals from the transceivers. In this way, an indirect free-space optical communication channel can be built, in which the line-of-sight requirement between the transceivers is replaced by the line-of-sight requirement between the transceivers and the reflector, which is easier to satisfy in most cases.

REFERENCES

[1] M. N. Boukoberine, Z. Zhou and M. Benbouzid, "Power Supply Architectures for Drones - A Review," *IECON 2019 - 45th Annual Conference of the IEEE Industrial Electronics Society*, Lisbon, Portugal, pp. 5826-5831, 2019. **DOI**: 10.1109/IECON.2019.8927702

[2] A. Cozannet, H. Maitre, J. Fleuret and M. Rousseau, *Optique et telecommunication : transmission et traitement optiques de l'information* / Paris : Eyrolles, 1981

[3] J. Gowar, *Optical Communication Systems* / London, New Delhi, Tokyo, Toronto, Wellington : Prentice Hall, 1984. **ISBN**: 978-0136380566

[4] D. L. HUTT, K. J. SNELL and P. A. BÉLANGER, "Alexander Graham Bell's PHOTOPHONE", *Optics and Photonics News*, vol. 4, issue 6, pp. 20–25, 1993. **DOI:** 10.1364/OPN.4.6.000020

[5] J. R. Pierce, Electrons, Waves and Messages, New York : Hanover House, 1956

[6] M. Ross, "The History of Space Laser Communications", *Proc. SPIE 0885, Free-Space Laser Communication Technologies*, 2 May 1988. **DOI**: 10.1117/12.976542

[7] Y. Wang, H. Wang and X. Jiang, "Performance of Reconfigurable-Intelligent-Surface-Assisted Satellite Quasi-Stationary Aircraft–Terrestrial Laser Communication System", *Drones*, vol. 6, no. 12, pp. 405–410, 2022. **DOI**: 10.3390/drones6120405

[8] G. J. Olson, H. W. Mocker, N. A. Demma and J. B. Ross, "Coherent CO2 laser communication system with modulable retroreflectors," *Appl. Opt.*, vol. 34, issue 12, pp. 2033–2044, 1995. **URL:** https://opg.optica.org/ao/abstract.cfm?uri=ao-34-12-2033

[9] F. R. Gfeller, U. Bapst , "Wireless in-house data communication via diffuse infrared radiation", *Proc. of the IEEE*, vol. 67, issue 11, pp. 1474–1486, 1979. **DOI**: 10.1109/PROC.1979.11508

[10] H. Haas, "On wireless data from every light bulb," [Online]. Available: https://www.ted.com/talks/harald_haas_wireless_data_from_every_light_bulb?language=en [Accessed 19.08.2023].

[11] G. E. Keiser, "A Review of WDM Technology and Applications", *Optical Fiber Technology*, vol. 5, issue 1, pp.3–39, 1999. **DOI**: 10.1006/ofte.1998.0275

[12] M. Pfennigbauer et al., "Satellite-based quantum communication terminal employing state-of-the-art technology", *Journal of Optical Networking*, vol. 4, issue 9, pp. 549-560, 2005. **DOI**: 10.1364/JON.4.000549

[13] H.-Y. Liu, "Optical-Relayed Entanglement Distribution Using Drones as Mobile Nodes", *Phys. Rev. Lett.*, vol. 126, issue 2, pp. 020503–02959, 2021. **DOI:** 10.1103/PhysRevLett.126.020503

[14] C. F. Bohren and D. R. Huffman, Absorption and Scattering of Light by Small Particles, New York: Wiley-Interscience, 2010. **ISBN** 978-3-527-40664-7

[15] *Near-Earth Laser Communications*, edited by Hamid Hemmati, Boca Raton, London, New York : CRC Press, 2009. **ISBN** 978-0-8247-5381-8

[16] Z. Sodnik , H. Lutz, B. Furch and R. Meyer, "Optical satellite communications in Europe", *Proc. of SPIE, Free-Space Laser Communication Technologies* XXII, 758705, 26 February 2010. **DOI**: 10.1117/12.847075

[17] J. Conner, T. Fletcher, "Laser Communication Uplinks and Downlinks", *Proc. SPIE 0996, High Data Rate Atmospheric and Space Communications*, 29 November 1988. **DOI**: 10.1117/12.960167

[18] S. A. Ahmed , M. Mohsin and S. M. Z. Ali, "Survey and technological analysis of laser and its defense applications", *Defense Technology*, vol. 17, pp. 583–592, 2021. **DOI:** 10.1016/j.dt.2020.02.012

[19] M. Toyoshima et al., "Overview of the Laser Communication System for the NICT Optical Ground Station and Laser Communication Experiments on Ground-to-Satellite Links", *Journal of the National Institute of Information and Communications Technology*, Vol. 59 No. 1/2, 2012, pp. 53-75. [Online]. Available: https://www.nict.go.jp/publication/shuppan/kihou-journal/journalvol59-1_2/journal-vol59no1_2-0402.pdf. [Accessed 21.08.2023]

[20] A. U. Chaudhry and H. Yanikomeroglu, "Laser Intersatellite Links in a Starlink Constellation: A Classification and Analysis," *IEEE Vehicular Technology Magazine*, vol. 16, no. 2, pp. 48-56, June 2021. **DOI**: 10.1109/MVT.2021.3063706

[21] C. W. D. Lumoindong, A. Muslim, B. M. Nasreddin and M. Galina, "Performance and Environmental Impacts Review of Li-Fi and Wi-Fi Technologies", *Journal of Env. Engineering & Waste Management*, vol. 3, no. 2, pp. 68-75, October 2018. **DOI:** 10.33021/jenv.v3i2.442

[22] D. Tsonev, S. Videv and H. Haas, "Light Fidelity (Li-Fi): Towards All-Optical Networking", *Proc. SPIE*, vol. 9007, pp. 1–10, 2014. **DOI:** 10.1117/12.2044649

DOI: 10.20535/2523-4455.mea.286163

[23] A. Chakraborty, T. Dutta, S. Mondal and A. Nath, “Latest Advancement in Light Fidelity (Li-Fi) Technology”, *International Journal of Advance Research in Computer Science and Management Studies*, vol. 5, no. 12, December 2017, pp. 47-53. [Online]. Available: http://ijarcsms.com/docs/paper/volume5/issue12/V5I12-0017.pdf. [Accessed 21.08.2023]

[24] H. Henniger and O. Wilfert, “An Introduction to Free-space Optical Communications”, Radioengineering, vol. 19, no. 2, June 2010. pp. 203-212. [Online]. Available: https://www.radioeng.cz/fulltexts/2010/10_02_203_212.pdf. [Accessed 21.08.2023]

[25] S. M. Mana, P. Hellwig, J. Hilt, P. W. Berenguer, and V. Jungnickel, “Experiments in Non-Line-of-Sight Li-Fi Channels”, in 2019 Global LIFI Congress (GLC), Paris, France, 2019, pp. 1–6. **DOI:** 10.1109/GLC.2019.8864131 [Accessed 19.08.2023]

[26] Optical sensors. [Online]. Available: https://www.hamamatsu.com/eu/en.html. [Accessed 19.08.2023]

[27] H. Stockman, “Communication by Means of Reflected Power”, Proc. IRE, vol. 36, October, pp.1196–1204, 1948

[28] R. Rice, “From radar to RFID: how did we get here?” [Online]. Available: https://www.controldesign.com/sensing/rfid/article/11298327/from-radar-to-rfid-how-did-we-get-here [Accessed 19.08.2023]

[29] B. Smith et al., “Single chip lidar with discrete beam steering digital micromirror device”, *Optics Express*, vol. 25, no. 13, pp. 14732–14745, 2017. **DOI**: 10.1364/OE.25.014732

[30] Digital micromirror array DLP4710. [Online]. Available: https://www.ti.com/lit/ds/symlink/dlp4710.pdf. [Accessed 19.08.2023]

[31] Scan Components. [Online]. Available: https://www.scanlab.de/en/products/scan-components. [Accessed 19.08.2023]

[32] Fast Steering System. [Online]. Available: https://www.newport.com/p/FSM-300-NM. [Accessed 19.08.2023]

[33] A. R. Cho et al. “Electromagnetic biaxial microscanner with mechanical amplification at resonance””, *Optics Express*, vol. 23, no. 13, pp. 16792–16802, 2015. **DOI**: 10.1364/OE.23.016792

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Модель лінії вільно-просторового оптичного зв'язку зі смарт-рефлектором

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Анотація — У статті розглянуто модель лінії вільно-просторового оптичного зв'язку між декількома близько розташованими точками на місцевості, які знаходяться поза зоною прямої видимості. Для швидкого розгортання ліній зв'язку з радіусом дії до сотень метрів будь-яка висока будівля, видима всім абонентам, може бути своєрідним ретранслятором оптичного сигналу. Порівняно з радіоканалами зв'язку оптична лінія зв'язку має вищу швидкість передачі інформації, нечутлива до електромагнітних перешкод і більш захищена від прослуховування.

Основною вимогою до атмосферних ліній оптичного зв'язку є відсутність перешкод на шляху світла від передавача сигналу до приймача. Ця вимога обмежує можливості розміщення оптичних ліній зв'язку на відкритій місцевості. Цю проблему можна частково обійти, використовуючи відбивач, який знаходиться в межах прямої видимості передавача оптичного сигналу та його приймача. У статті розглянуто можливості використання дифузних відбивачів у наземних лазерних лініях зв'язку. Такі відбивачі (природного або штучного походження) дозволяють швидко розгортати на місцевості лазерні лінії зв'язку з множинним доступом. Недоліком таких відбивачів є дуже низька ефективність використання енергії оптичного сигналу, що надсилається передавачем.

Енергію оптичного сигналу, надісланого трансивером, можна ефективніше використовувати за допомогою смарт-рефлектора. Смарт-рефлектор запропоновано зробити у вигляді керованого дзеркала, яке на основі інформації про просторове положення трансиверів автоматично встановлюється під таким кутом, щоб лазерний промінь одного трансивера відбивався в бік іншого трансивера. Кутове положення трансиверів відносно дзеркала визначається за допомогою двокоординатного позиційно-чутливого фотоприймача та лінзи перед ним. В залежності від кута падіння лазерного променя на лінзу змінюється положення сфокусованої лазерної плями на фотоприймачі, а з ним і відповідні фотоелектричні сигнали. Ці сигнали використовуються мікроконтролером для керування нахилом дзеркала за допомогою двоосьового сканера.

Таким чином можна створити непряму оптичну лінію зв'язку на місцевості, в якій вимога прямої видимості між трансиверами замінюється вимогою прямої видимості між трансиверами та відбивачем, яку легше задовольнити у більшості випадків. Використання смарт-рефлектора дозволить збільшити дальність дії такої лінії зв'язку.

Ключові слова — вільно-просторовий оптичний зв'язок; лазерний діод; pin-фотодіод; дифузний відбивач; смарт-рефлектор; позиційно-чутливий фотоприймач; мікроконтролер; сканер; співвідношення «сигнал/шум».