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# Angular and Multipath Effects in Indoor Visible Light Communication Channels for Biomedical Monitoring Systems


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***Abstract*—The rapid advancement of medical technologies is driving the demand for reliable, energy-efficient, and secure systems capable of real-time health monitoring. The widespread deployment of light-emitting diode lighting systems opens up opportunities for the implementation of promising wireless optical communication technology - Visible Light Communication. This technology transmits data via visible light and offers several advantages over radio-frequency solutions. In the context of medical applications, this is high throughput, data privacy, and the absence of electromagnetic interference on the operation of sensitive medical equipment. However, its implementation is constrained by the requirement for a direct line-of-sight between the receiver and transmitter, and high sensitivity to external optical interference. The study presents models in line-of-sight and no-line-of-sight conditions indoors to assess data transmission parameters and identify factors affecting communication reliability. Using the OptiSystem simulation platform, the effect of emission and incidence angles, along with multipath signal propagation caused by surfaces reflections, we analyzed. The results allowed the determination of optimal emission and incidence angles ranges, and the assessment of the influence of the receiver field-of-view on system throughput.**

***Keywords*—visible light communications, optical wireless channel, health monitoring systems, multipath propagation, data transmission rate.***

## I. INTRODUCTION

The development of modern technologies in the field of medicine requires the creation of highly accurate, energy-efficient and affordable solutions for monitoring human health in real time. At the state level, support for the digitalization of healthcare is carried out through national programs and initiatives aimed at increasing the availability of medical care and improving the quality of services provided.

According to the legislation of the Republic of Kazakhstan [1], the priority of the healthcare system is to protect the health of the population and form an infrastructure that ensures accurate and timely collection of information about patients.

Wireless radio frequency technologies such as Wi-Fi, Bluetooth, ZigBee are widely used in medical practice [2-5]. Telemedicine systems provide data transmission to remote devices, allowing doctors to promptly monitor the condition of patients and promptly respond to changes. Wireless infrastructure can also be used for remote consultations, access to electronic patient records, and data exchange between medical institutions. This is especially important in conditions of limited access to medical care, for example, in remote regions or during self-isolation of patients. Modern technologies allow surgeons to perform operations remotely, controlling robots via a wireless connection. Radio frequency technologies facilitate the integration and interaction of various components of the information system, supporting the concept of the Internet of Things. This ensures centralized control and monitoring of equipment operation, reduces the likelihood of errors, and increases patient comfort.

Despite the active introduction of radio frequency technologies into medical systems, their use is associated with a number of limitations and potential risks. One of the significant disadvantages is the limited bandwidth of the radio frequency range, which prevents the simultaneous operation of a large number of devices in one network. In addition, these technologies are characterized by low noise immunity, sensitivity to the effects of other electronic devices, dependence on the density of repeater coverage and weather conditions. There is also a need to study the possible impact of electromagnetic radiation on human health, especially with long-term and intense exposure in clinical settings.

Of particular concern is the potential for electromagnetic interference with other critical equipment. If high-power transmitting devices are not used correctly, radio frequency interference may occur that could disrupt the functioning of medical equipment. This is especially true for life-sustaining equipment, such as ventilators. There is also a potential threat of disruption to the operation of implantable medical devices, such as pacemakers and neurostimulators, which are sensitive to radio frequency background.

In this regard, the wireless optical communication technology Visible Light Communication (VLC), which uses visible light to transmit data, is of interest. It has a number of key advantages over radio frequency solutions, especially in conditions where the use of RF radiation is limited or undesirable. The main advantages of VLC include high throughput, energy efficiency, wide range of available frequencies, the absence of electromagnetic interference, as well as the ability to accurately localize indoors and a high level of confidentiality of transmitted data. These characteristics make the technology relevant for use in health monitoring systems in hospitals, mobile medical centers and at home.

However, VLC technology has a number of limitations that hinder its implementation. These include the need for direct line of sight between the transmitter and receiver, sensitivity to interference from external light sources, limited transmission range, and the need for specialized infrastructure. To improve the efficiency and scale of application of such systems in healthcare, these technical barriers must be overcome, as well as solutions for integration with existing information and communication networks.

Previously, the authors conducted studies on the use of VLC technology for transmitting data of various formats. In [6], a system was presented and experimentally tested, including electronic circuits of a transmitter and receiver, designed to transmit audio signals using a white light-emitting diode (LED) in conditions of limited natural light. In [7], the transmission of symbolic data between two personal computers was implemented using a similar source and physical encoding methods. In [8], an experimental system for transmitting current room temperature values using LED lighting is presented. The system provided bidirectional communication for transmitting data and control signals to maintain a given temperature. The transmission error was hundredths of a fraction. The experimental results confirmed stable operation system while maintaining the level of illumination and visual comfort.

This study is a logical continuation of previous scientific works and is focused on the creation of simulation models of a wireless optical communication channel using visible light in order to evaluate data transmission parameters and analyze the applicability of the technology in human health monitoring systems.

Thus, the implementation of the set goal will allow us to substantiate the main parameters of the optical communication channel to ensure reliable transmission of information, determine the influence of external factors on the characteristics of the signal, and also formulate recommendations for the use of VLC technology in medical practice, including mobile and stationary monitoring systems.

## II. Analysis of the Application of VLC Technology in Medical Monitoring Systems

To assess the potential of VLC technology in medical applications, it is necessary to analyze system architectures, data transmission models, and identify existing limitations and promising development directions.

The article [9] proposes a system for transmitting patient biomedical data using white LED illumination via a downlink. The system provides transmission of two types of data: text information about the patient and analog signals of physiological parameters in real time. The HL7 protocol is used for transmission. This standard is accredited by the American National Standards Institute for the confidentiality of medical data. The On-Off Keying (OOK) method is selected as a modulation. A data transmission rate of 56 kbit/s and a bit error rate of $1x10^{-6}$ at a distance of 0.5 meters without the use of collimating optics are achieved. Also, experiments have shown the possibility of data transmission with a decrease in the illumination level to 90% of the nominal optical power of the light source.

The article [10] describes a static patient monitoring system using an uplink data transmission channel in the visible range. Studies related to external interference from ceiling and natural lighting were conducted. Photodetectors in the system are placed in such a way as to minimize the impact of ceiling lamps on signal reception. The experimental setup was pre-loaded with data on human physiological parameters, including electrocardiogram (ECG), body temperature and heart rate. The data were transmitted using OOK modulation. The emitter LED was located at a distance of 130 cm in direct visibility from the receivers installed at an interval of 20 cm. The low transmission rate of 10 bit/s is explained by the use of a low-power LED. According to the authors, this value is sufficient for data transmission in the specified mode.

The correctness of VLC systems in medical applications was considered in [11]. Wireless data transmission via Wi-Fi and via a visible light channel was compared. An experimental setup for patient ECG monitoring showed an error in data transmission via VLC within 3%. The signal was received with minor distortions associated with the experimental conditions. The possibility of stable data transmission at a distance of up to 2 meters between the receiving and transmitting devices was recorded.

The use of RGB LEDs in such systems allows for increased reliability and accuracy due to three-channel communication [12]. However, it should be noted that such systems are much more difficult to implement. In [13], an RGB LED and a color sensor were used to simplify the system design, allowing signals to be separated into color channels on the receiving side. An active low-pass filter was used to suppress background light, after which the signal was demodulated using a microcontroller and stored on a database server in real time. The wavelength division multiplexing principle allowed three different signals (ECG, photoplethysmogram, body temperature) to be transmitted simultaneously over a distance of 11 meters with a PER of $5x10^{-6}$.

The existing limitations of VLC systems necessitate their integration with radio frequency (RF) technologies. In [14], hybrid optical-RF architecture is proposed as a means to overcome the constraints of VLC and improve overall performance. Hybrid networks provide better coverage and communication reliability by utilizing VLC in line-of-sight areas and RF to support communication in blind zones.

The analysis shows that most VLC systems aimed at medical applications use OOK modulation. In addition, such systems usually require direct visibility between the transmitter and receiver. The signal quality is significantly affected by external optical interference from both natural light and neighboring lighting fixtures. These features emphasize the importance of the optical channel design stage, the choice of adequate modulation methods, and create prerequisites for the development of hybrid solutions using radio frequency technologies.

The efficiency of indoor optical wireless communication depends on the lighting system parameters and the characteristics of optical signal propagation. The geometry of the transmitter and receiver arrangement as well as the angles of emission and reception, significantly affects the channel characteristics due to the inverse square law of distance and Law of Lambert of diffusion.

In this regard, this study focuses on the analysis of the influence of geometric parameters on the characteristics of the optical channel. Understanding these aspects allows us to more accurately model the behavior of VLC systems and optimize the placement of transmitting and receiving devices to ensure reliable transmission of biomedical data.

## III. Modeling of Indoor Wireless Optical Communication Channels

In the process of taking biomedical parameters, there may be situations in which the LED transmitting the data and the photodetector are not located strictly on the same optical axis, i.e. the angle of deviation from the line of sight differs from zero. To assess the signal quality, we will consider the effect of the emission and incidence angles in the indoor line-of-sight (LOS) propagation model.

The geometric model of optical signal propagation under LOS conditions is illustrated in Fig. 1. In this model, d is the distance between the LED and the photodetector, φ is the LED emission angle relative to its axis, $\Phi_{1/2}$ is the LED half-power emission angle, FOV is the field-of-view photodetector, ψ is the photodetector incidence angle. A two-dimensional room model with a height of 3m and a length of 5m is considered. An LED serves as the transmitter, while photodiode functions as the receiver. The field of view of the photodetector and the half-power emission angle of the model are set to 70°.

Fig. 2 shows a simulation model developed in the OptiSystem software environment for studying the properties of a transmitted signal in an optical wireless system under line-of-sight conditions. The presented model is not connected to real data, so a bit sequence generator is used. The generated data are converted into an electrical signal of the non-return-to-zero (NRZ) format, displayed on an oscilloscope for monitoring. The LED modulates the signal into an optical one and transmits it through a diffuse channel to a photodetector.

The received light signal is converted back into an electrical signal, after which it passes through a low-pass Bessel filter to suppress high-frequency noise. At this stage, a check is performed using a second oscilloscope. Then, the regenerator performs signal reshaping, retiming, and amplification to compensate for distortions. At the final stage, the error analyzer compares the restored signal with the original bit sequence, assessing the transmission accuracy.

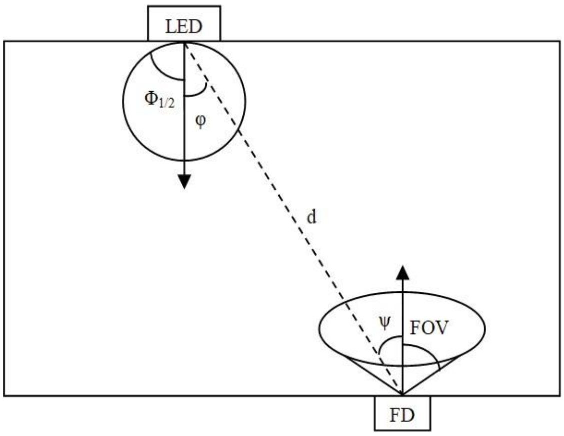


Fig. 1. Geometric model of optical signal propagation in LOS chanel

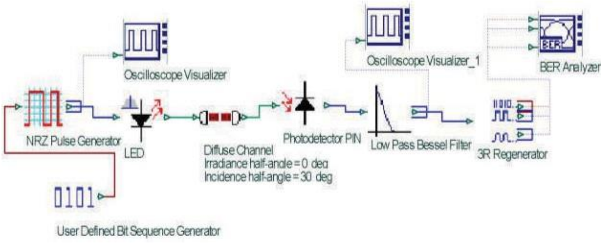


Fig. 2. Simulation model LOS chanel

The study analyzed the influence of the angles of emission and incidence in the LOS propagation model. At the first stage of modeling, the angle of incidence was fixed at 30°, and the angle of emission varied from 0 to 50°. Then, conversely, the angle of emission was set at a constant value of 30°, and the angle of incidence varied from 0 to 50°. Fig. 3 shows the results for all modeling options.

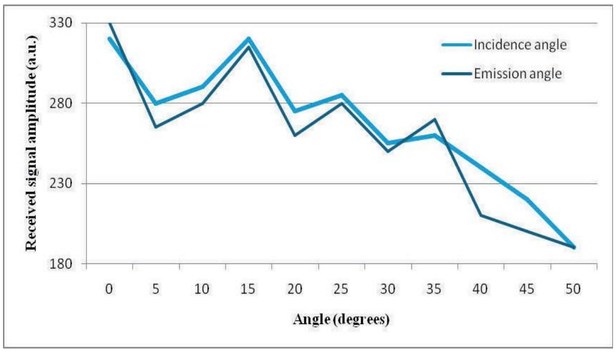


Fig. 3. The influence of the angle on the amplitude of the received signal

The graph demonstrates the dependence of the received signal amplitude on the deviation angles of the source and receiver. In the range up to 15°, amplitude fluctuations are observed, probably due to the peculiarities of the optical flow distribution and the sensitivity of the receiving surface. The maximum amplitude is achieved at minimum angles, after which a gradual and then more pronounced signal decrease are observed. In the range from 30° to 50°, the signal amplitude steadily decreases, regardless of whether the emission angle or the incidence angle changes, which indicates signal degradation when deviating from the optical axis. Both curves almost coincide, which may indicate a symmetrical effect of deviation angles on the resulting signal power.

This confirms that the VLC system is most resistant to distortions at small angles up to 20° and loses efficiency at values above 30°, which is important to consider when designing and positioning system components. The results confirm that, to ensure reliable data transmission in VLC systems, it is necessary to account for the spatial arrangement of the transmitter and receiver and to minimize angular deviation from the LOS direction.

The situation when the LED and photodiode are located strictly on the same line is relatively rare due to the limitations and features of the interior architecture of the premises. However, even with direct visibility between the source and receiver, in most scenarios the internal optical communication line is characterized by multipath propagation. This is due to the fact that part of the emission from the LED is reflected from the walls, ceiling and other surfaces, forming additional components of the signal.

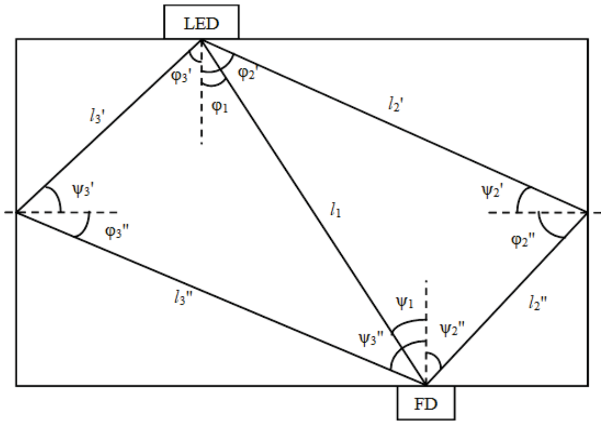


Fig. 4. The influence of the angle on the amplitude of the received signal

Therefore, for visible optical communication systems, a scenario is of particular interest when the signal reaches the receiving device both along a direct path and due to reflections from related surfaces.

The geometric model considering multipath propagation is shown in Fig. 4. In this configuration, the LED emits the primary signal propagating directly to the photodetector (ray $l_1$), as well as two reflected signals (rays $l_2$ and $l_3$) formed as a result of walls reflections. Each path is characterized by its own pair of emission angles $\varphi_i$ and incidence $\psi_i$, and by its path length $l_i$, which affects signal attenuation.

For the analysis, the numerical values of angles and distances parameters given in Table 1 are used.

TABLE I. MODEL PARAMETERS

| Path length | Emission angle | Incidence angle |
|---|---|---|
| $l_1$ = 3,3 m | $\varphi_1 = 26^\circ$ | $\psi_1 = 26^\circ$ |
| $l_2'$ = 3,5 m | $\varphi'_2 = 65^\circ$ | $\psi'_2 = 22^\circ$ |
| $l_2''$ = 3,6 m | $\varphi'_2{}' = 38^\circ$ | $\psi'_2{}' = 51^\circ$ |
| $l_3'$ = 2,8 m | $\varphi_3' = 55^\circ$ | $\psi_3' = 35^\circ$ |
| $l_3''$ = 3,1 m | $\varphi_3' = 32^\circ$ | $\psi_3' = 55^\circ$ |

The simulation model of a wireless optical communication channel under conditions of multipath propagation of light is developed based on the previous model. The difference lies in the addition of reflection simulation (Fig. 5).

For this purpose, an Optical Attenuator block with 5 dB attenuation at the reflection point is used. A Power Splitter block is used to split the input optical signal into several output ports with specified power division factors. Before sending the signal to the photodetector, it is necessary to use the Power Combiner block to combine the optical signals into one output. To clean the signal from extraneous noise, in our case additional noise from reflection, we use a low-pass filter.

The model provides the ability to obtain waveforms signals: the generated input signal supplied to the LED; the signal recorded by the PIN diode; the signal after passing through the low-pass Bessel filter.

The input signal (Fig. 6a) demonstrates an ideal digital pulse shape. Its amplitude is stable, the fronts are sharp, and the noise level is minimal. This confirms the correct operation of the bit sequence generator and NRZ pulse modulation.

The received signal (Fig. 6b) is heavily distorted compared to the original. Amplitude fluctuations, overlaps, spikes, and a characteristic pulse broadening effect typical of multipath propagation are observed. The causes of the distortions are reflections from the walls, which occur due to the fact that each channel in the model has different emission and incidence angles, and varying transmission distances. Notably, emission/incidence angles greater 30 degrees in channels contribute to energy dispersion and increase the delays between reflected signal components. This, in turn, intensifies interference and leads to significant distortion of the received signal.

The filtered signal (Fig. 6c) exhibits an improved waveform compared to the unprocessed signal, with partial restoration of the rectangular pulse structure. Although high-frequency noise is partially mitigated, residual distortions persist, indicating incomplete suppression of multipath effects and the limited effectiveness of the applied filtering. Potential improvements to the model may include implementing an equalizer after the low-pass filter, as well as employing adaptive digital filters capable of dynamically adjusting to the multipath propagation conditions in real time. The simulation results show that the angular parameters of the channel significantly affect the shape of the output signal, which is especially important for VLC systems under multipath propagation conditions.

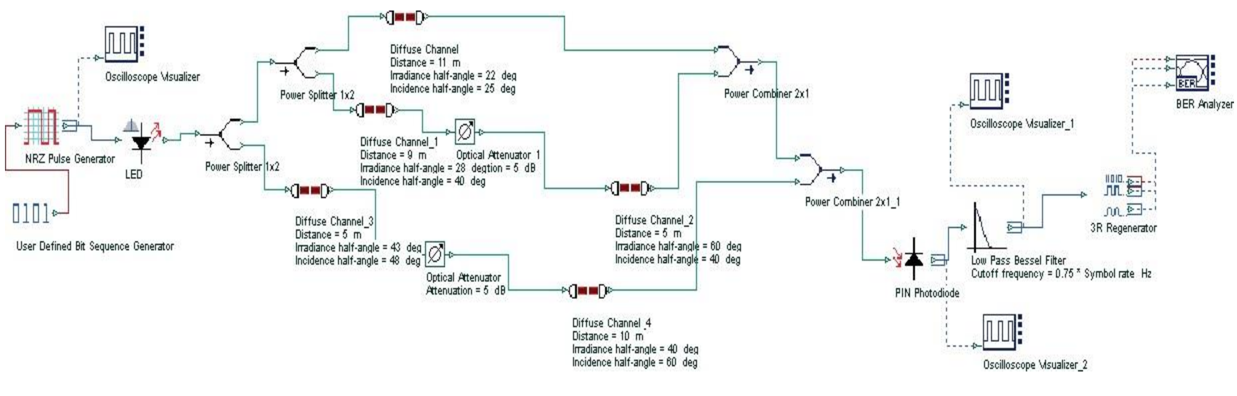


Fig. 5. Simulation model NLOS channel with multipath propagation

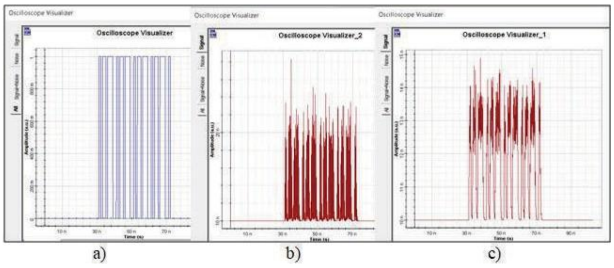


Fig. 6. Signal waveforms: generated input signal (a); signal received by the photodetector (b); filtered signal (c).

At the next stage, an analysis of the dependence of the data rate on the FOV angle of the photodetector was performed to estimate the channel capacity under multipath propagation conditions. Based on the data in Table 1 and the parameters of the room model, the transmission rate was calculated for different FOV values using an approximate relationship between the transmission rate and the root-mean-square (RMS) delay spread, which characterizes the level of intersymbol interference [15].

Analysis of the obtained results (Fig. 7) shows that increasing FOV of the receiver leads to a higher bit rate: from 5.12x$10^7$ bit/s at FOV=30° to 7.48x$10^7$ bit/s at the set maximum FOV=90°. This can be explained by the fact that a wider field of view allows the receiver captures more reflected signal components, thereby increasing the total received power and, consequently, improving data transmission performance.

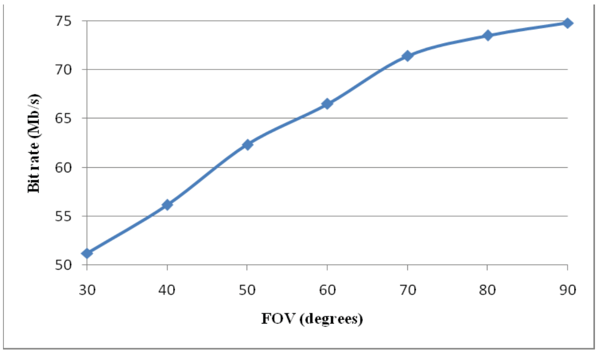


Fig. 7. The influence FOV of the receiver on the data transmission rate

The obtained date rate values are sufficient for most standard applications in household and industrial environments, such as text transmission, equipment control, sensor networks and IoT applications.

## IV. Conclusion

The modeling of optical wireless communication using a LED source was carried out. The models of optical signal propagation under the LOS and NLOS conditions indoor environment with given geometric dimensions and angular parameters of the transmitting and receiving devices were considered. In the LOS model, it was found that the optimal operating ranges of radiation and reception angles are 20°-35°, at which the signal amplitude remains stable. In the NLOS model, taking into account multipath propagation, significant signal distortions and a high noise level are observed. After applying filtering, the signal shape was partially restored. In addition, the effect of the FOV on the data transfer rate was studied. With a viewing angle of 30°, the calculated data transfer rate was 51 Mb/s, which is sufficient for transmitting biomedical data.

The results obtained confirm the promise of VLC technology for medical applications, and taking into account multipath signal reflections and the introduction of adaptive receiver orientation mechanisms can increase the reliability and stability of transmission in real operating conditions. It should be noted that this study did not consider the influence of interference from external light sources and adjacent transmission channels, which is an area for further research.

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