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Implementation and evaluation of a comprehensive Li-Fi system using Matlab/Simulink

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ABSTRACT

Li-Fi technology is a type of visible light communication that uses LEDs as a data transmission source. Li-Fi is expected to occupy an important place in wireless network technology by providing high-speed internet access and having high bandwidth. It may be a common technology to provide internet access instead of Wi-Fi in places where radio waves are inconvenient, such as hospitals and airplanes. In this paper, a comprehensive Li-Fi system model implemented using Simulink® is proposed and evaluated. The model is equipped with a mirror and a thin convex lens to increase the efficiency of the Li-Fi system by reflecting and focusing the light beam emitted from the LEDs. The result obtained from the evaluation test shows that the output signal from the model of the proposed Li-Fi system is much higher than that of the basic Li-Fi system. Thus, using the proposed comprehensive model, more efficient Li-Fi systems can be realized.

1. Introduction

With the development of technology, the internet has become a part of daily life. Internet use has turned out to be more common as computers, phones, televisions, and many devices have Wi-Fi receivers. Wi-Fi uses radio waves to transmit data. Radio waves correspond to the frequency range of 3 Hz to 300 GHz in the electromagnetic spectrum. With the increasing use of radio waves, when this bandwidth starts to fill up, the data transfer rate of Wi-Fi devices slows down [1]. There are also places where radio waves are not suitable. Wi-Fi use is not appropriate for hospitals as the health of people exposed to radio waves is negatively affected (tumor, cancer, etc.). At the same time, radio waves can interfere with the equipment used in hospitals. Radio waves are not suitable for use not only on hospital equipment but also on airplanes due to safety concerns and device interference [2-3].

As a solution to these limitations, Li-Fi (Light Fidelity) technology is recommended. Li-Fi technology, proposed by the German physicist Harald Haas, sends data via a light-emitting diode (LED) bulb that flashes too fast for the human eye [4]. Using the visible light spectrum to transmit data, Li-Fi technology corresponds to a frequency range of 430 THz to 790 THz. This means that the size of the infrared and visible light spectrum together is approximately 2600 times the size of the entire radio frequency spectrum of 300 GHz [5]. Consequently, this wide bandwidth range is considered an alternative to the limited bandwidth of radio waves [6]. Li-Fi is also advantageous in terms of internet speed. Researchers at the University of Oxford have achieved bidirectional speeds of 224 Gbps. In the study, LEDs and receivers working with different fields of view are used and internet connection speeds of 224 Gbps and 112 Gbps are achieved for 60° and 36° wide viewing areas at a distance of 3 meters. These speeds are well above those offered by modern Wi-Fi technology (approximately 600 Mbps) [1]. Thanks to the Li-Fi system's use of visible light, it does not cause interference to devices. In addition, since no light can pass through the walls in a closed environment, internet access cannot be provided to other areas. Although this may seem like a negative effect, it is important from a safety point of view. Li-Fi's usage areas are very advantageous compared to Wi-Fi in terms of high bandwidth, harmless to human health and speed [7]. All in all, Li-Fi is an advantageous alternative to Wi-Fi.

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The basic principle of data transmission is to turn the light on and off. In other words, digital '1' information is transmitted when the light is turned on and digital '0' when the light is turned off. The intensity of the LED is modulated so fast that the human eye cannot perceive it and therefore the light appears constant [8-9].

In recent researches several models to describe and simulate the Li-Fi systems are developed. In [10], a Li-Fi model including a standard transceiver circuit is developed using MATLAB®. Through simulations, Wi-Fi and Li-Fi technology are compared in terms of data transfer rate, packet loss, delay data and it is seen that Li-Fi technology is superior. In [11], Li-Fi is introduced as a communication system with its modulation techniques, and analysis of the system modelled with the Simulink® block diagrams is performed. In [12], Li-Fi system with ambient noise is modelled in Optisystem 15. The ambient light effects on the Li-Fi communication link and the performance of the receiver under ambient noise power due to different sources is evaluated through simulations. In [13], a prototype model for a Li-Fi health monitoring system is created to transmit data from a patient-held FBG sensor to an optical receiver installed in the patient's ceiling room via different propagation links. In [14], a model of a Li-Fi system for transmitting audio signals is considered and designed with a minimum number of electrical elements.

The aim of this paper is implementation and evaluation of a more advanced and efficient model for Li-Fi system. To increase efficiency over previous Li-Fi models [10-11], various components such as mirrors and lenses are added to the Simulink® model of the Li-Fi system. As the light emitted from the LED using a mirror and/or lens is focused on the photodiode, an increase in the magnitude of the output signal is expected [10, 15].

The paper is organized as follows: In Section 2 basic concepts about the Li-Fi architecture and how light interacts with mirrors and lenses are briefly presented. In Section 3 Simulink® models developed for Li-Fi system are given, with details. Performance verification of the implemented models through simulations are evaluated in Section 4. Finally, in Section 5, conclusions are drawn.

2. Basic Concepts

2.1 Li-Fi Architecture

Li-Fi can be thought of as light-based Wi-Fi. In short, Li-Fi uses light with the help of high-speed switchable LEDs instead of radio waves to transmit data [16].

A basic Li-Fi system consists of two main parts. The first part, called the transmitter circuit, includes the converter that converts the incoming signal into binary information in the form of 1s and 0s, the driver circuit used to switch the LED, and the LEDs used to transmit information. The second part, called the receiver circuit, includes a photodiode used to detect information coming from the LED, an amplifier circuit used to amplify the detected signal, and a converter circuit that converts the obtained information to its original state. The receiver and transmitter circuits are physically separate and distant from each other. However, an empty optical communication channel (Li-Fi channel) connects these two main parts [17-19]. The block diagram of the basic Li-Fi system is shown in Figure 1.

As visible light passes through the communication channel, its intensity decreases inversely with the square of the distance, causing the signal to the receiver to be very low. As a photodiode moves away from the light source (LED), the light falling on the photodiode per unit time decreases. The inverse square law formula is applied as shown below,

$$\frac{I_1}{I_2} = \frac{d_2^2}{d_1^2} \quad (1)$$

where I_1 and I_2 are the light intensities of LED at distances d_1 and d_2 from the photodiode, respectively.

The communication channel can contain multiple sources of optical noise. During the daytime, the most important source of noise is the sun. Other noise sources are represented by transmitters in visible light communication or any light source with or without data transmission capabilities. In outdoor visible light communication applications, the unpredictability is even greater due to weather. The water particle caused by rain, snow, or heavy fog can cause the light containing the data to scatter, affecting the visible light communication link [20].

2.2 Interaction of Light with Mirror and Lens

Mirrors and glossy surfaces reflect most of the light falling on them according to the laws of reflection. The reflection event is illustrated in Figure 2.

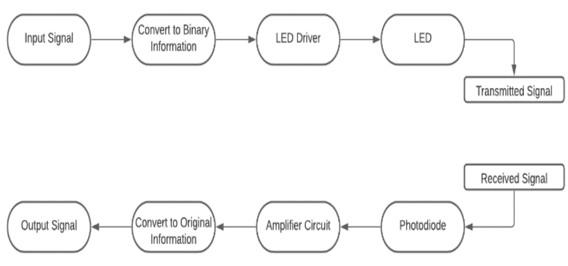

Figure 1. Block diagram of the basic Li-Fi system

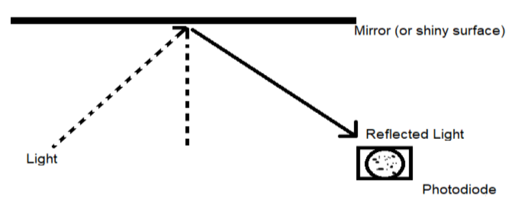

Figure 2. Illustration of specular reflection

In a Li-Fi system with mirror, incoming light is reflected from the surface and directed to the photodiode. Snell's law describes the reflection and refraction phenomena of light. According to Snell's law, the ratio of the sines of the angles of incidence and refraction is equivalent to the ratio of phase velocities in the two media, or equivalent to the reciprocal of the ratio of the indices of refraction:

$$\frac{sin\theta_1}{sin\theta_2} = \frac{v_1}{v_2} = \frac{n_2}{n_1} \quad (2)$$

where θ_1 is the angle of incidence and θ_2 is the angle of refraction, both measured from the normal of the boundary, v_1 and v_2 are the velocities of incoming and outgoing lights, n_1 and n_2 are the refractive indices of the respective mediums [21].

Any incident ray traveling parallel to the principal axis of a converging lens is refracted through the lens and passes through the focal point F' on the opposite side of the lens. The diagram in Figure 3 shows the behavior of two incident rays approaching parallel to the principal axis. In this case, the point where the two rays converge is known as the focal point F' of the lens. In a Li-Fi system, the photodiode has a specific viewing angle. It cannot see light rays that are out of this field of view. If the photodiode is placed at the F' point, the light intensity falling on the photodiode increases [21].

Lenses consist of two curvilinear refractive surfaces. The refractive power P or the reciprocal of the focal length f (distance between lens and focal point) of a lens in air is given by the lensmaker's general equation:

$$P = \frac{1}{f} = (n-1)\left[\frac{1}{R_1} - \frac{1}{R_2} + \frac{(n-1)d}{nR_1R_2}\right] \quad (3)$$

where n is the index of refraction of the lens material, d is the distance along the optical axis between the two surfaces of the lens, known as the thickness of the lens, and R_1 and R_2 are the radii of curvature of the two surfaces.

3. Implementation of a Comprehensive Li-Fi System Using Simulink®

3.1 Simulink® Model of the Basic Li-Fi System

Simulink® model for the basic Li-Fi system illustrated in Figure 1 is shown in Figure 4.

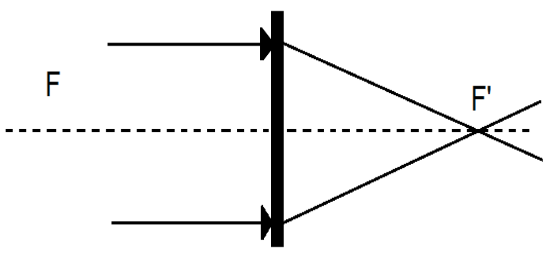

Figure 3. Movement of light through a converging lens [19]

The model consists of a transmitter part involving a square wave generator used to represent the conversion of the input signal to binary information, a switching circuitry used to drive the LED, and the LED transmitting the information through light. Following the transmitter an optical channel serving as the medium through which the light propagates, and used to transmit the information to the receiver's side, is added. Next, a receiver part involving a photodiode that converts optical power to electrical signal and an amplifier circuit used to amplify the converted electrical signal is placed [10-11].

3.2 Simulink® Model of the Li-Fi System with Mirror

Simulink® model for the Li-Fi system with mirror is shown in Figure 5. The model includes the model developed for the basic Li-Fi system in the previous section, and a mirror model represented by a Matlab® function arranged according to Equation (2), which directs light from the LED to the photodiode. While modeling the mirror in Simulink®, the refractive index of the air medium, the refractive index of the mirror used to reflect the light, and the angle of the mirror are selected as 1, 1.75 and 30°, respectively. The values used for the simulation are based on the 300-1500 lx value range that the research in [22] provides for adequately illuminating an office with LEDs and the angles of the mirrors used to increase the performance of the system. Values may vary in the model, depending on the need and application.

3.3 Simulink® Model of the Li-Fi System with Convex Lens

While the light produced by the LED spreads to all parts of the environment (room, office, airplane cabin, etc.), it does not spread evenly at every point, and the photodiode can detect the incoming data at a certain viewing angle. Although not all of the emitted light can be collected on the photodiode using a thin convex lens, light outside the field of view can be focused onto the photodiode. Simulink® model for the Li-Fi system with thin convex lens is shown in Figure 6. The model includes the model developed for the basic Li-Fi system, and a thin lens model represented by a Matlab® function arranged according to Equation (3), which focuses the scattered light on the photodiode. Values may vary in the model, depending on the need and application.

3.3 Simulink® Model of the Comprehensive Li-Fi System

When the thin convex lens and mirror are used simultaneously, the scattered lights are diverted and more light is focused on the photodiode. Because in this case, the light reflected from the mirror and the thin convex lens falls directly on the photodiode. Thus, the signal to be obtained at the output of the system is expected to increase even more. Simulink® model incorporating both a thin convex lens and a mirror, for the comprehensive Li-Fi system, is shown in Figure 7.

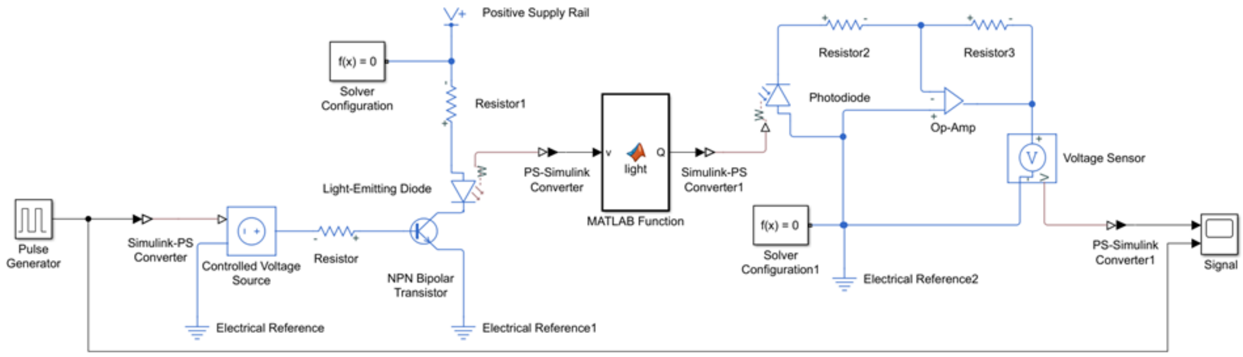

Figure 4. Simulink® model of the basic Li-Fi system

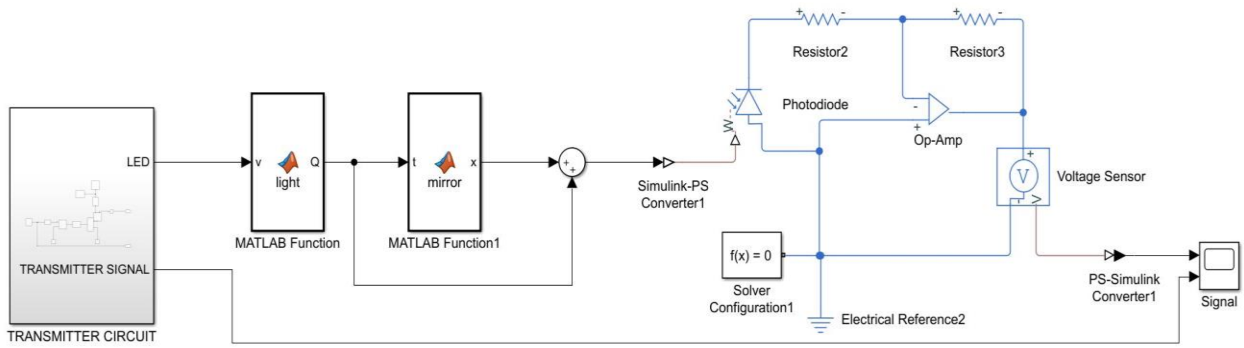

Figure 5. Simulink® model of the Li-Fi system with mirror

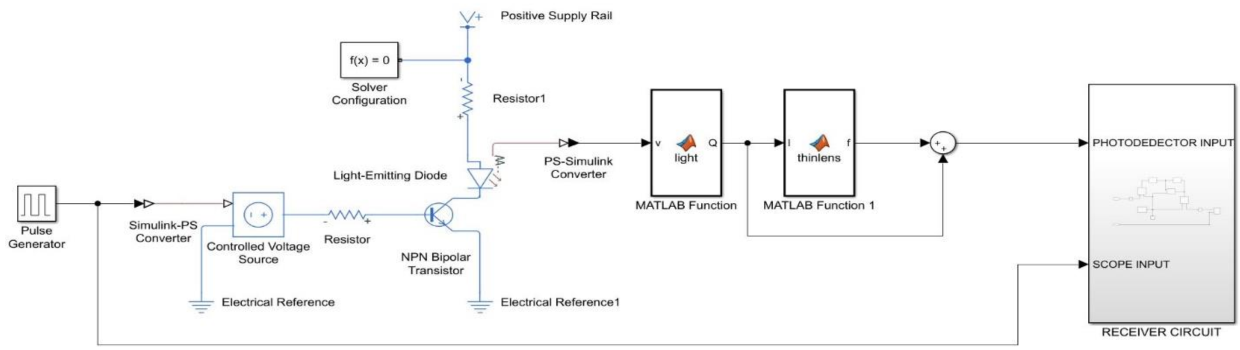

Figure 6. Simulink® model of the Li-Fi system with thin convex lens

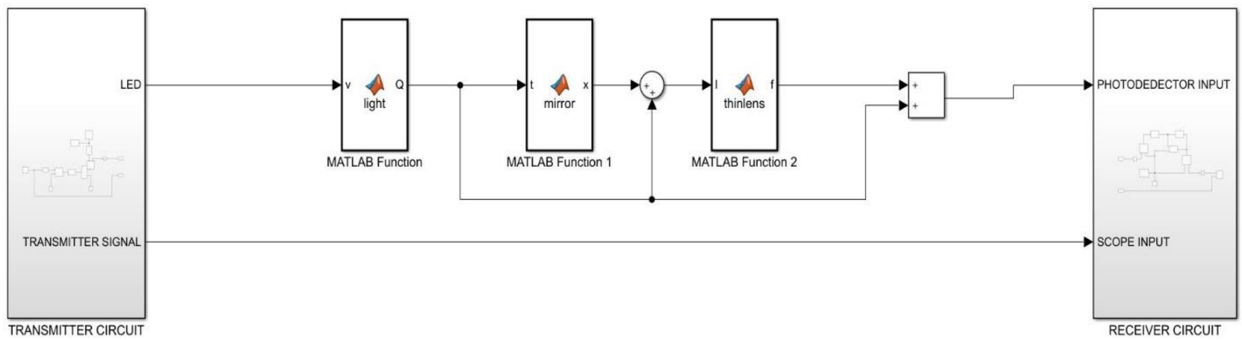

Figure 7. Simulink® model of the proposed comprehensive Li-Fi system

4. Performance Verification

The implemented models are evaluated through simulations. The performance of the models is examined by applying an input signal with amplitude of 3.3 V and obtaining the output signal. Figure 8 shows the waveforms of the transmitter and receiver (input and output signals of the system) signals for Simulink® model of the basic Li-Fi system.

As seen in Figure 8, the 3.3 V signal sent from the transmitter circuit is received as 1.213 V in the receiver circuit.

Figure 9 shows the waveforms of the transmitter and receiver (input and output signals of the system) signals for Simulink® model of the Li-Fi system with mirror.

As seen in Figure 9, the 3.3 V signal sent from the transmitter circuit is received as 1.396 V in the receiver circuit. The signal obtained at the receiver is increased by the effect of the mirror.

Figure 10 shows the waveforms of the transmitter and receiver (input and output signals of the system) signals for Simulink® model of the Li-Fi system with thin convex lens.

As seen in Figure 10, the 3.3 V signal sent from the transmitter circuit is received as 1.549 V in the receiver circuit. With the focusing effect created by the thin convex lens, the signal obtained at the receiver is increased.

Figure 11 shows the waveforms of the transmitter and receiver (input and output signals of the system) signals for Simulink® model of the proposed comprehensive Li-Fi system.

As seen in Figure 11, the 3.3 V signal sent from the transmitter circuit is received as 2.687 V in the receiver circuit. By using both the mirror and the thin convex lens in the model at the same time, the signal obtained at the receiver's output is significantly increased.

Comparison of the implemented Li-Fi system Simulink® models in terms of output signal is given in Table 1.

As a result, when the proposed models are compared, the output signal increases by about 15% in the Li-Fi system with mirror, about 28% in the Li-Fi system with thin convex lens, and about 122% in the comprehensive Li-Fi system, compared to the basic Li-Fi system. In addition, the comprehensive Li-Fi system outperforms the Li-Fi system with mirror and the Li-Fi system with thin convex lens by 93% and 74%, respectively. Although a unity gain amplifier is used in the mirror and convex lens model, a higher amplitude signal is obtained compared to the study in [11] that uses an amplifier with gain.

Table 1. Comparison of the implemented Li-Fi system Simulink® models

Model	Transmitted Signal(V)	Received Signal(V)
Basic	3.3	1.213
Mirror	3.3	1.396
Convex Lens	3.3	1.549
Comprehensive	3.3	2.687

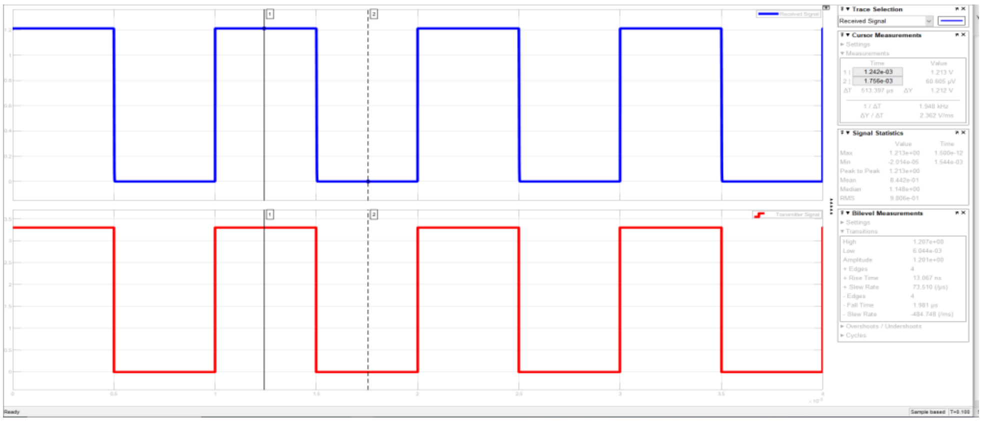

Figure 8. Transmitted and received signals for Simulink® model of the basic Li-Fi system

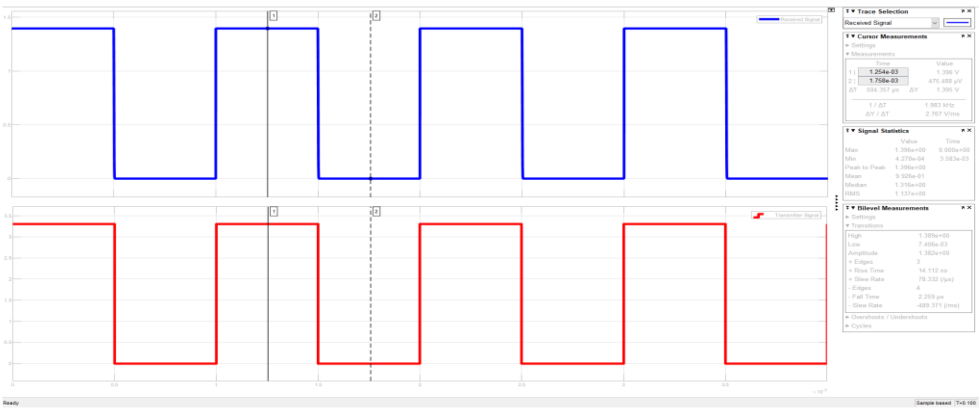

Figure 9. Transmitted and received signals for Simulink® model of the Li-Fi system with mirror

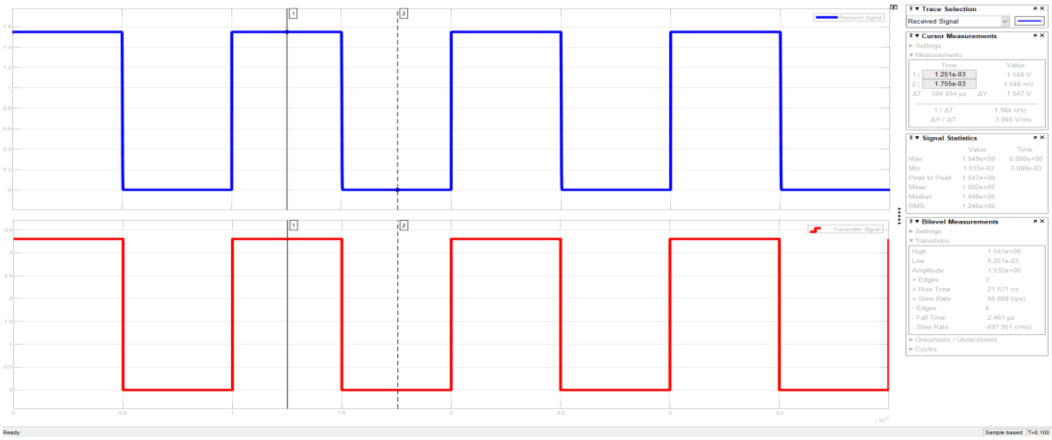

Figure 10. Transmitted and received signals for Simulink® model of the Li-Fi system with thin convex lens

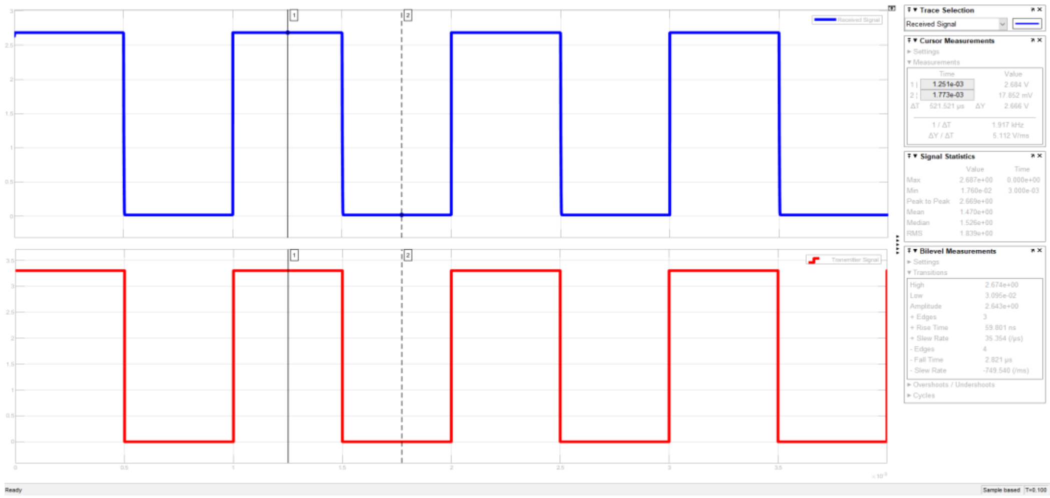

Figure 11. Transmitted and received signals for Simulink® model of the comprehensive Li-Fi system

5. Conclusions

In this paper, a comprehensive Li-Fi system model is developed. Prior to the proposed comprehensive model, two Simulink® models with mirror and thin convex lens, respectively, are implemented for the Li-Fi system. The performance of the models is compared with the model of the basic Li-Fi system existing in the literature, in terms of output signal. The proposed comprehensive model shows a very high performance. An increase of 122% is observed in the output signal compared to the basic model. In addition, the output signal obtained in mirror-only and thin convex lens-only models shows an increase of 15% and 28%, respectively, compared to the basic model. The proposed model lays the groundwork for further improving the efficiency of existing Li-Fi systems and offers a new approach for highly efficient applications in Li-Fi technology.

Declaration

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article. The authors also declared that this article is original, was prepared in accordance with international publication and research ethics, and ethical committee permission or any special permission is not required.

Author Contributions

I. Myderrizi, A. F. Yilmaz and B. D. Kalfa proposed and developed the models. A. F. Yilmaz performed the simulations. I. Myderrizi and A. F. Yilmaz wrote the manuscript. I. Myderrizi supervised and improved the study.

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Nomenclature

Li-Fi : Light Fidelity
Wi-Fi : Wireless Fidelity
LED : Light Emitting Diode
FBG : Fiber Bragg Grating
I : Light intensity
d : Distance

θ : Angle of incidence
v : Velocity
n : Refractive index
P : Refractive power
f : Focal length
R : Radii of curvature
V : Volt

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