Journal of Computer and Communications, 2022, 10, 66-85
https://www.scirp.org/journal/jcc
ISSN Online: 2327-5227
ISSN Print: 2327-5219

Optical Wireless Systems Channel Modelling

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How to cite this paper: Long, Z.C. (2022) Optical Wireless Systems Channel Modelling. *Journal of Computer and Communications*, **10**, 66-85.
https://doi.org/10.4236/jcc.2022.103005

Received: February 9, 2022
Accepted: March 14, 2022
Published: March 17, 2022

Abstract

With the development of society, the users of mobile devices and electronic devices increase exponentially. As a result, the demand of high-performance communication system becomes more and more significant. Optical wireless communication (OWC) is an effective method to address the increasing number of internet users, which is a promising field. It is significantly important to understand the parameters and characteristics of communication channel if researchers want to design, generate, accomplish, and operate the OWC systems. In this paper, the propagation model discussed in optical wireless communication can be divided into two types: directed Line of Sight (LOS) propagation model and non-Line of Sight propagation model. In case of directed LOS, multipath reflection does not need to be addressed, which is easier to calculate the LOS channel gain. In case of non-Line of Sight propagation, there are some reflections produced from room ceilings and walls, which can be divided mainly into two methods: first order reflection and second order reflection. Based on the conventional diffuse systems and optical wireless systems with angle diversity receivers, the impulse response, delay spread and signal to noise ratio (SNR) will be calculated. In order to optimize the optical wireless system access point and wavelength allocation to users so as to maximize the sum rate offered to all users, the mixed-integer linear programming (MILP) model was proposed and developed.

Keywords

VLC, OWC Systems, LOS, SNR, MILP

1. Introduction

Hundred's years ago, people started employing the visible light as a component of communication information [1]. Now, with the increasing of high data rates demand and number of internet users, the characteristic of current RF (ratio frequency) will no longer be able to satisfy these demands [2]. Therefore, a new wireless communication architecture called optical wireless channel communication was designed. Energy efficiency, flexibility and expandability are the three main advantages of optical wireless communication systems [3]. As a result, Elmirghani [4] has suggested that the OWC systems are able to replace the cables and optical fiber used in communication systems. In addition, there is a promising technology called optical spectrum that can provide some prominent indoor channel characteristics and sufficient bandwidth, which can lead to a low-cost component [4].

Osama [5] has argued that there is a lot of research devoted to optical wireless (OW), by contrast, about how the OW front end is connected to internet, the relative research is not extensive. According to much research, the video, picture, data and voice, in the indoor surroundings, can be spread at a high data rate (up to 25 Gbps) by OWC system [6]-[17]. Particularly, if the position of receiver and configuration of the room change, the characteristic of channel will change, for example, the delay will decrease and the signal to noise ratio will increase [10] [18]-[25]. So, in order to reduce the degradation of signal, effective resource allocation is significant. The role of MILP is to optimize the utilization of signals and resources.

Chapter 2 analyzes the VLC system, including the comparison of VLC system and radio frequency communication system. Moreover, the progress of basic OWC system is provided, and introductions about the components of the VLC system, angle diversity receiver are provided. Besides, chapter 3 is focusing on developing an optical wireless channel simulator by using MATLAB. Three propagations model is introduced. Two major receivers, called single wide field of view receiver and angle diversity receiver, are discussed. In addition, the impulse response is calculated. Moreover, impulse response is used to analyze the delay spread and signal to interference plus noise ratio (SINR). The performance of two receivers is compared in the end.

2. Literature Review of Visible Light Communication (VLC) Systems

1) VLC Systems and RFC Systems

Visible light communication (VLC), as one of the OWC system, can be employed for data center in order to ensure the high data rates [26]. The VLC system has more advantages than ratio frequency communication. Firstly, Because of the increasing requirement of high data rates for users, the market of radio frequency (RF) communication systems is experiencing a downward trend, in comparation, VLC systems, set in indoor situation, is able to reach an extremely high data rates, about 20 Gbps, which can also ensure a perfect security and low-cost [11]. Secondly, the physical size of VLC system receiver is very small, about 1 cm^2, so that the multipath fading will be decreased, while the multipath fading is a main problem for RFC system [27]. In addition, the signal of VLC system cannot propagate through the wall but glass, so the signal can stay in the original place, which provide a high security environment and scenario [28].

However, there are some disadvantages in VLC systems, for example [4], without line of sight (LOS), the performance of VLC systems will be affected significantly. Apart from this, the multipath propagation such as first order reflection and second order reflection will decrease the operation of VLC systems because of the production of distortion [29]. Besides, the penetrability of the VLC system signals is poor, so in order to connect the rooms and ensure the communication, people should install the transmitter in every room, which will cause a high installment cost [29] [30].

2) Indoor Visible Light Communication System

Intensity modulation with direct detection (IM/DD) is an effective technology to decreasing the cost and intricacy [31] [32] [33]. As show in **Figure 1** [3], an input signal through transmitter and LED/LD, generating an optical intensity modulated signal $x(t)$, the receiver should use a photodetector in order to transform the incident optical signal into photocurrent, which is an instantaneous optical power. In this process, the drive current I_{LED} is directly modulated by the modulating signal $(m)_t$. A photodetector, with a response, is installed in the receiver, which can generate photocurrent $y(t)$ through integrate tens of thousands of incidents optical signal. The current $y(t)$ proportional to the instantaneous optical power mentioned before. In terms of IM/DD-based OWC system, Carruthers [34] suggested that this system is able to hide the high-frequency characteristic of the optical carrier because of it has an equivalent baseband model.

LOS links and non-LOS links, especially for indoor links and channels, will be affected by multipath propagation, and these effects are more obvious and serious than RF communication system [3]. As show in **Figure 2**, the OWC system is modelled by three parts, transmitter part includes light source (LED/LD) and drive circuit, propagation part is a channel in space, and the receiver part includes photodetector, which can be a positive intrinsic negative (PIN) or avalanche photodiode (APD). Due to the cheap LEDs/LDs are available, several studies [35] [36] show that the band wavelengths between 780 nm and 950 nm is employed as a better opportunity for indoor VLC systems.

Figure 2 shows the basic process of OWC system [3]. The input signal is modulated by drive circuit, through light source (LED/LD), then these signals will be transmitted in the form of optical power signals and be received by photodetector. In order to generate and change the current of LED or LD, the intensity modulation (IM) will be installed in the visible light system. It is worth mentioning that the surface area of the detector used by the OWC receiver is usually several orders of magnitude larger than the transmission wavelength. In addition, the total optical current generated is proportional to the integral of the optical power on the entire photodetector surface which can provide an inherent spatial diversity, this is impossible in RF-based systems.

3) Components of VLC system

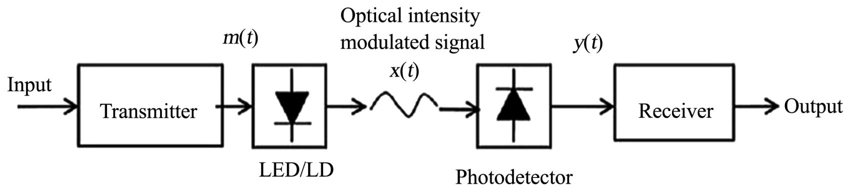

Figure 1. Block of an IM/DD OWC system.

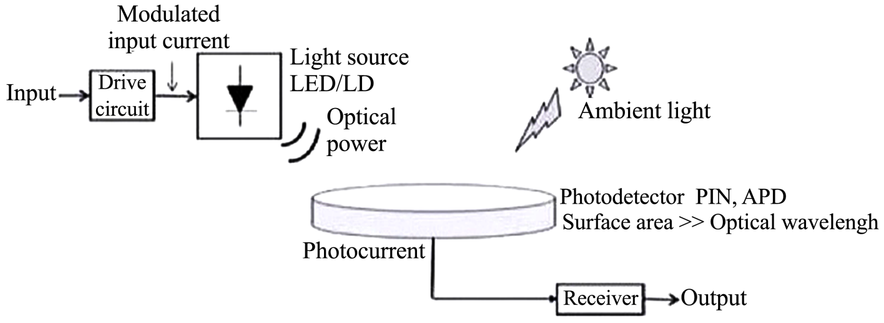

Figure 2. Block diagram of OWC system.

a) Transmitter part

LEDs and LDs are most commonly used in VLC system. In this study, the transmitter for communication is RYGB LDs light. The semi angle set 60π degree. Compared with LEDs, firstly, the cost of LDs is higher than LEDs because LDs need a comprehensive drive circuit to operate the input. Secondly, the optical power of LDs is much higher than that of LEDs. Thirdly, the electro-optic power conversion efficient, as a critical factor, LDs show a better performance, the value of efficient is about 30% - 70% while that of LEDs is 10% - 20%. As a result, compared to LEDs, LDs are more suitable for use in VLC systems. However, LDs suffer from some disadvantages, in term of the safety of eyes, LEDs are more suitable than LDs, and the cost of LEDs is significantly lower than that of LDs [1].

b) The design of indoor VLC transmission link

The indoor VLC system may not affect by fog, cloud, wind and mist, which is an advantage of indoor VLC system. The indoor VLC system, however, will lost power when transmit the optical signal because the multipath signal propagation and signal loss at the receiver side. In addition, in terms of the line-of-sight system, the power loss can reach 20 dB, and the non-line of the sight system, the power loss can reach 40 dB [35].

Moreover, the VLC transmission link can be designed based on two principles, one is the direct and indirect propagation path from transmitter to receiver, another one is the position and direction of transmitter and receiver.

There are some specific designs and configurations fit for indoor VLC system such as line-of-sight propagation and non-line-of-sight system [13] [26] [28] [31]. Compared with LOS system, non-LOS system will cause more dispersion so that the power efficient will be declined. However, non-LOS system prevents shadows and strong links by using reflected signals from reflective elements such as walls and ceilings, but it is affected by multipath dispersion, which leads to inter symbol interference and pulse spread [31].

There are some configurations of the system used in OWC system such as conventional diffuse system (CDS), line strip multi-spot diffusing system and optical wireless system. Among these three configurations, conventional diffuse system is the mostly employed in OWC system because it employed single wide FOV receiver, which could transmit the signals from transmitters to receiver by various reflections. However, it will cause a high multipath dispersion and generate inter symbol interference so that the received power and communication quality will be declined [31].

c) Receiver part

The receiver is consisted of concentrator, optical filter, photodetector and preamplifier. The concentrator is at the top, and the purpose is to strengthen the signal. Below the concentrator is an optical filter to reduce ambient light noise. The bottom is the photodetector, which is also the most important part, to convert the light signal into an electrical signal. Behind the photodetector is the preamplifier.

i) Concentrator

Barry has argued [31] that the purpose of using the concentrator is to enhance the signal power and increase the effective receiving area, so some low photosensitivity and low capacitance photodetectors can be used. The function of the concentrator is to convert a large area of incident light into a very narrow light, so it can reduce the transmission power and improve optical safety and power consumption.

Imaging and non-imaging concentrators are often used in OWC systems, and non-imaging concentrators are used more frequently. OWC systems with a wide FOV at the receiver use hemispherical lens concentrator, which is a non-imaging concentrator with a function of supporting indirection links. As shown in **Figure 3**, when the filter is between the photodetector and hemisphere, the high-pass filter is used. As shown in **Figure 4**, when the filter is outside the hemispherical concentrator, a band-pass filter is used [37] [38]. **Figure 3** and **Figure 4** are collected from [39].

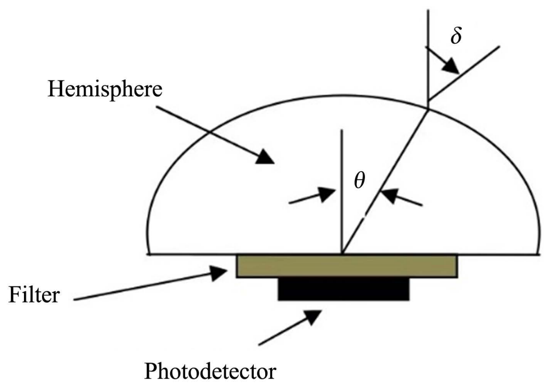

Figure 3. Hemispherical lens concentrator (1).

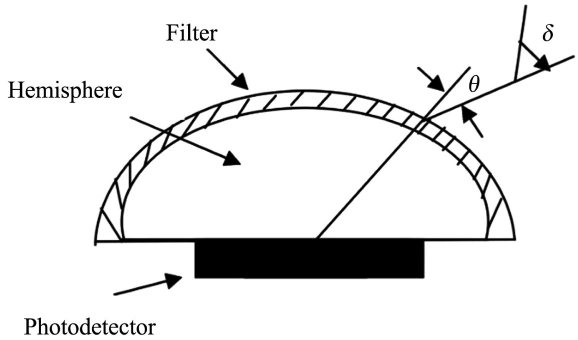

Figure 4. Hemispherical lens concentrator (2).

ii) Optical filter

Since the receiver of the OWC system is easily affected by undesirable light noises, it is necessary to use an optical filter. The high-pass filter and the band-pass filter mentioned earlier are two kinds of optical filters employed to reduce the influence of undesirable light noises. Band-pass filters are composed of narrow and dielectric layers, which can effectively filter out ambient light to obtain the optical signal required by the photodetector. The other is high-pass filters, the principle is to reduce the influence of undesirable light noises by cutting off all wavelengths other than the desired wavelength [31].

iii) Photodetector

The photodetector is the most important part of the receiver, providing the function of converting optical signals into electrical signals. silicon positive-intrinsic negative (PIN) photodiodes and avalanche photodiodes (APDs) are employed in OWC system [31].

These two kinds of detectors can increase the optical power because they have a larger detection area. They are generally used in the case of direct detection of the receiver, because the preamplifier noise is the main noise source, and the amount of environmental noise is very small. APDs can improve the SNR of the receiver by dealing with the effects of front-end noise. However, when the environment is noisy, PIN photodiodes are a better choice.

iv) Preamplifier

Three types of preamplifiers are called low impedance, high impedance and trans-impedance preamplifiers will be introduced below.

4) Angle Diversity Receiver

Recently, some studies [40]-[43] indicate that in the OWC systems, the role of angle diversity receiver (ADR) can reduce the multipath dispersion in indirect link transmission. Each angle diversity receiver, in indoor environment, employ multiple photodetectors with a field of view (FOV), which are pointed to a particular direction. Each photodetector faces a different direction to receiver the signals from the transmitters in the ceiling through using Azimuth (*Az*) and Elevation (*El*) angles [8]. Apart from this, for decreasing the influence of surrounding noise sources, angle diversity receiver can be employed through choosing an appropriate photodetector, which only receive the desired signal with minimal noise.

Two technologies called selection combining (SC) and maximum ratio combining (MRC) are mentioned in [43].

In terms of the SC technology, the branch with maximum SNR will be selected by receiver based on the test result from received signal component in every branch. In addition, SC when directional narrow FOV receivers are employed, the SC can decrease the pulse spread. Compared with other technology, by using the SC, however, cannot generate the desired SNR compared with other technology. In terms of MRC technology, the adder circuit, where every output is proportional to its SNR, can combine all output signals from receiver branches. This method is mainly maximizing the SNR by modulating its SNR independently, which can decrease the significant influence of background noise through distributing the lower SNR to the branch affected by the background noise most, so that the performance and characteristics of OWC system will be increased.

3. Channel Modelling of Indoor VLC System

In order to model the channel in VLC system, several factors have to be considered such as optical wireless link which connect the transmitter and receiver, multipath propagation, impulse response, background noise, delay spread and SNR. In the end, is the simulation analysis. These factors can optimize the performance of VLC system, similarly, can degrade the VLC system because of the distortion and noise distribution in the receiver. The simulations and calculations will be done by using the MATLAB.

1) Indoor visible light communication channel

Because of intensity modulation with direct detection (IM/DD) can reduce the intricacy and cost of the VLC system, it usually considered as an efficient technology to solve the problem about the indoor OWC system [1]. Just like **Figure 1**, the input includes some signal, and the transmitter modulates them into instantaneous optical power through varying the intensity of the optical source. Furthermore, at the receiver side, the receiver can generate a photocurrent $y(t)$, which is proportional to the incident instantaneous optical power. The detector can prevent fading and permit spatial diversity due to its area includes numerous short wavelengths of received signal. The indoor VLC system employ IM/DD can be modelled by impulse response $h(t)$, the formulation can be expressed as [24]:

$$y(t, Az, El) = \sum_{k=1}^{K} Rx(t) \otimes h_k(t, Az, El) + R\sum_{k=1}^{K} N_k(t, Az, El) \tag{3.1.1}$$

In this formula, $y(t, Az, El)$ is the received photocurrent, t is the absolute time, R is the photodetector responsivity, Az is direction of arrival at azimuth angle, El is the direction of arrival at elevation angle. $x(t)$ is transmitted instantaneous optical power, K is the number of reflective elements while h is the channel, $\otimes$ is a symbol of convolution, N_k is background light noise. In addition, the input signal is non-negative due to the $x(t)$ is power not amplitude.

In case of directed LOS model, the transmitter and receiver are connected directed. The propagation path loss is mainly from transmitter beam divergence, size of receiver and separation distance between the transmitter and receiver [3]. In terms of the size of receiver, the suitable detector should be with a large area for collecting more power, but this technology will cause a high manufacturing cost, increased junction capacitance, as a result, the receiver bandwidth will decrease, and the receiver noise will increase. Hence, ghassemlooy [3] proposed that for improving the overall efficient collection area, employ an optical concentrator is a low-cost method. The optical gain of an ideal non-imaging concentrator with an internal refractive index n_i is:

$$g(\delta) = \begin{cases} \dfrac{n_i^2}{\sin^2 \psi_c} & 0 \le \delta \le \psi_c \\ 0 & \delta \ge \psi_c \end{cases} \tag{3.1.2}$$

Because of Field of View (FOV), the $\psi_c \le \frac{\pi}{2}$.

As **Figure 5** shown below, the transmitter is installed in the ceiling and sends a signal downward. So, the angle is −90˚. And the receiver is installed on the ground floor, sending a signal upward and the angle is 90˚. The distance of transmitter and receiver is R_d and the angle with respect to the transmitter is α, the received angle is δ, the semi-angle at half power is ψ_c, the receiver with an optical band-pass filter of a transmission $T_s(\psi)$, so the DC gain for a receiver is:

$$P_{LOS} = \begin{cases} \dfrac{n+1}{2\pi R_d^2} \times A \times P_s \times \cos(\delta) \times \cos^n(\alpha) \times A & 0 \le \delta \le \psi_c \\ 0 & \delta \ge \psi_c \end{cases} \tag{3.1.3}$$

2) Non-LOS Propagation Model

Non-directed LOS is known as diffuse channel. This propagation model is difficult to compute due to the reflection elements such as furniture in the room, room dimensions, walls and so on. The total receiver optical power in non-LOS propagation, including first order reflection and second order reflection, so the total receiver optical power can be generally defined as:

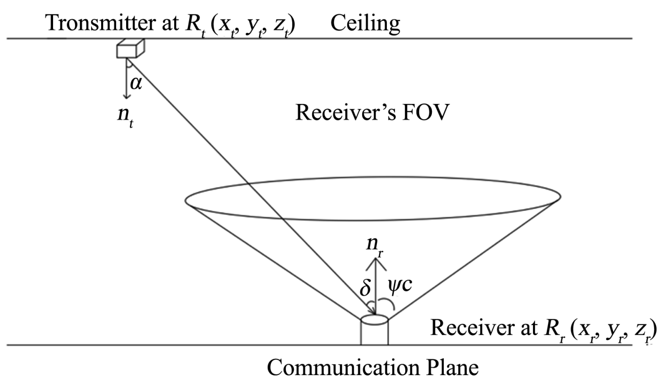

Figure 5. Propagation path beam of LOS.

$$P_r = \sum_{i=1}^{K} P_{Fir} + \sum_{i=1}^{S} P_{Sec} \tag{3.2.1}$$

The K is that the light has undergone exactly K first order reflections and the S is that the light has undergone exactly S first order reflections.

According to ghassemlooy [3], the reflection coefficient of various element surfaces in a room is different, which is depended on its materials, roughness of the surfaces, transmission wavelength and angle of incidence. In term of the materials of element surfaces, Gfeller [44] has suggested that the reflection coefficients of normal materials ranged from 0.4 to 0.9. In the MATLAB code, the reflection coefficient was set to 3.

a) First order reflection

First order reflection means the beam has only reflected once from the transmitter to the receiver, and the position of reflection is called reflective element 1. Figure 6 shows below. In the Lambertian model, $n_e = 1$ [45], the receiver optical power in first order reflection can be defined as:

$$P_{Fir} = \begin{cases} \dfrac{(n+1)(n_e+1)}{4\pi^2 R_1^2 R_2^2} \times P_s \times \rho_1 \times \mathrm{d}A_1 \times \cos(\beta) \times \cos(\delta) \times \cos^n(\alpha) & \\ \times \cos^m(\gamma) \times A & 0 \le \delta \le \psi_c \\ 0 & \delta > \psi_c \end{cases} \tag{3.2.2}$$

The transmitter is installed in ceiling and the receiver is installed in ground floor, α is the angle between the irradiance beam and the normal of transmitter, R_1 is the distance from transmitter and reflective element 1, R_2 is the distance from receiver element 1 to receiver, $\mathrm{d}A_1$ is the area of reflecting elements, ρ_1 is the reflection coefficient of ceiling, n_t, n and n_r are the normal of the transmitter, reflective elements and receiver respectively. α is the angle between R_1 and n_t, β is the angle between n_1 and R_1, γ is the angle between n_1 and R_2, δ is the angle between n_r and R_2.

b) Second order reflection

The second order reflection can be divided into three parts, first part is the optical power between transmitter and reflective element 1, second part is the optical power from reflective element 1 to reflective element 2, last part is the optical power between reflective element 2 and receiver. Figure 7 shows the propagation of second order reflection.

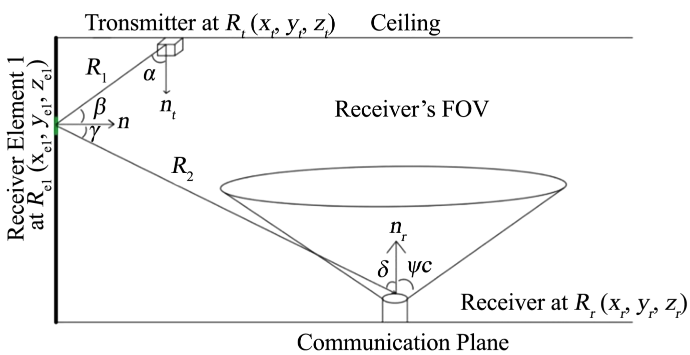

Figure 6. Propagation path beam of first order reflection.

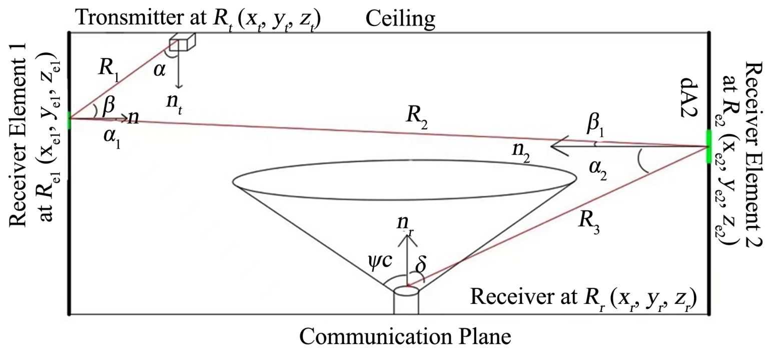

Figure 7. Propagation path beam of second order reflection.

$$P_{Sec} = \begin{cases} \dfrac{(n+1)(n_e+1)^2}{8\pi^3 R_1^2 R_2^2 R_3^2} \times P_s \times \rho_1 \times \rho_2 \times \mathrm{d}A_1 \times \mathrm{d}A_2 \times \cos(\beta) \times \cos(\beta_1) & \\ \times \cos(\delta) \times \cos^n(\alpha) \times \cos^m(\alpha_2) \times \cos^m(\gamma) \times A & 0 \le \delta \le \psi_c \\ 0 & \delta > \psi_c \end{cases} \quad (3.2.3)$$

As for the parameters, n_t, n, n_2 and n_r are the normal of the transmitter, reflective element 1, reflective element 2 and receiver respectively. The R_1 is the distance between transmitter and receiver element 1, where the first order reflection occurred. The R_2 is the distance between receiver element 2 and receiver element 1, where the second order reflection occurred. The R_3 is the distance between receiver element 2 and receiver. ρ_1 and ρ_2 is the reflection coefficient of ceiling, reflective elements and receiver respectively. α is the angle between R_1 and n_t, β is the angle between n and R_1, α_1 is the angle between R_2 and n, β_1 is the angle between n_2 and R_2, α_2 is the angle between n_r and R_3. $\mathrm{d}A_1$ and $\mathrm{d}A_2$ are the aera of the reflective element.

3) Data Centre configuration

In this report, the data center dimension is 5 m × 5 m × 3 m, which is similar to [4] [7]. The communication plane is 0.25 m above the ground. The conventional diffuse systems (CDS) and optical wireless systems with Angle diversity receivers are considered in order to evaluate SINR and delay spread. The configuration of CDS and optical wireless systems with Angle diversity receivers will be discussed below.

There are two rows of racks considered in this data center [46] [47] [48] [49]. Each row of rack has 5 racks. There is a top of rack (ToR) switch set at the top of the rack and each of them plays the role of a communication coordinator between servers [4]. On the top of the racks, there are two types of optical receivers called single wide FOV receiver and angle diversity receiver (ADR), which is used to receive signals from transmitter and decrease interference [4]. The receiver is set at (1.6 m, 2.5 m, 2 m), (3.4 m, 2.5 m, 2 m). The LDs lights, in VLC system, are employed as transmitter for communication. Each one of these light units consists of 9 wide-semi angle RYGB LDs. The transmitted optical power by individual LD is 1.9 W. Three lights are used, and the position of these light units are (1.6 m, 1.25 m, 3 m), (1.6 m, 2.5 m, 3 m), (1.6 m, 3.75 m, 3 m), (3.4 m, 1.25 m, 3 m), (3.4 m, 2.5 m, 3 m), (3.4 m, 3.75 m, 3 m). In addition, according to Gfeller [44], the reflection elements such as plaster walls can be considered in a Lambertian pattern. As a result, the reflection coefficient of ceiling and walls, as Lambertian reflectors, is 0.8, and the reflection coefficient of floor is 0.3 [44].

a) Conventional diffuse systems

Several recent studies [50] [51] have suggested that conventional diffuse systems with a single wide FOV receiver is an efficient technology of OWC system. This receiver has a detector with a FOV equal to 90˚. The walls have many small areas play a role of transmitters. According to the research [52], the smaller these areas, the longer the simulation time and the resolution will be higher. Therefore, this paper selects the 5 cm × 5 cm as the first order reflection position and the 20 cm × 20 cm as the second order reflection position.

b) Optical wireless systems with Angle diversity receiver

This system uses the ADR as receiver. This receiver has three branches, branches on both side is 2 and 3, branch in the middle is 1. Each branch has detector and each of them faces a different direction to receiver the signals from the transmitters in the ceiling through using Azimuth (*Az*) and Elevation (*El*) angles [5]. The calculation of reception angle δ shows below. Three points *P*, *R*, *E* are used, and Azimuth (*Az*) and Elevation (*El*) angles need to be taken into account. Point *p* is 1 m above the detector. Point *E* is a reflective element. As show in **Figure 8**, The formulation of reception angle δ can be obtained from [34].

$$\cos\delta = \frac{|PR|^2 + |ER|^2 - |EP|^2}{2 \times |PR| \times |ER|} \tag{3.3.1}$$

PR: The distance between receiver and point.

ER: The distance between reflection element and point.

EP: The distance between reflection element and receiver.

The *El* angles of the detectors are set as follows: two detectors have an angle equal to 40˚, while the branch that faces upwards is set to 90˚. The *Az* angles of the branches are 90˚, 0˚ and 270˚. In terms of the FOV of each detector, the detector facing upwards, and the others are set at 20˚. All of these settings are based on the studies [14] [53] in order to getting a best SNR.

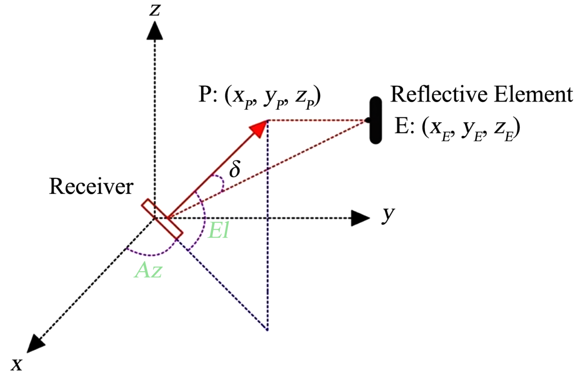

Figure 8. Angle diversity receiver.

4) Impulse response

The channel impulse response of the receiver is continuous. According to [50] [54], the time bin can be expressed as $\frac{\sqrt{\mathrm{d}A}}{c}$, in this formulation, d$A$ is the reflection element area, c is the speed of light. Every time bin is the time required for light propagates between adjacent elements [45].

Mathematically, in the multipath propagation, the power of all reflective elements at receiver will affect the value of impulse response [55]. In this report, impulse response can determine the value of delay spread and SNR. There are three kinds of visible light propagation: line of sight propagation model and non-line of sight propagation. Three receiver positions and transmitter positions are compared, which are show below.

Here is the impulse response of CDS, **Figure 9** shows when receiver position is (1.6 m, 2.5 m, 2 m) and (3.4 m, 2.5 m, 2 m).

In terms of Optical wireless systems with Angle diversity receiver, when the El angle is 90˚, Az angle is 0˚ and FOV is 20˚, the impulse response shows in **Figure 10**.

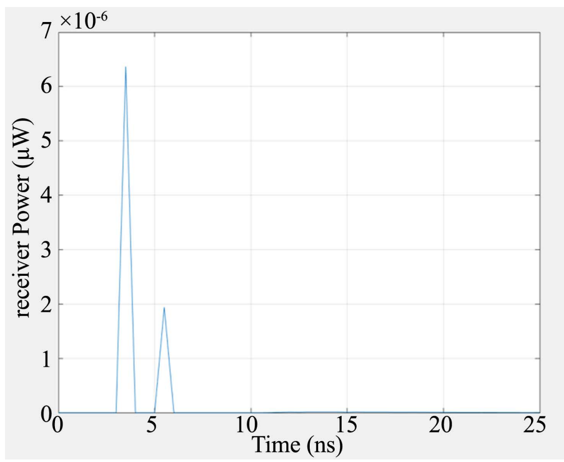

Figure 9. Received power at receiver 1 and 2 of CDS.

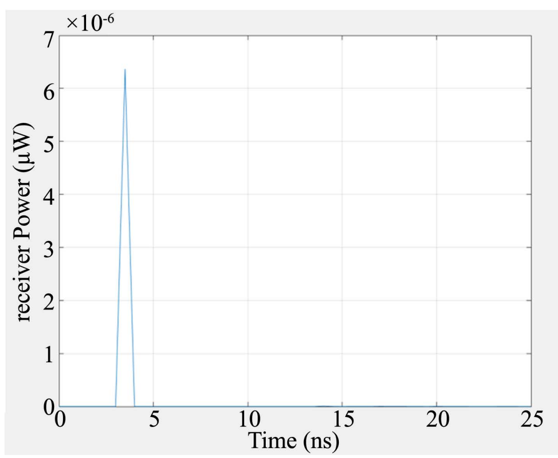

Figure 10. Received power at receiver 1 and 2 of ADR.

These figures illustrate that when the ADR is used, the angle set follow *El* angle is 90˚, *Az* angle is 0˚ and FOV is 20˚ will get a better result.

5) Delay spread

The impulse response is used to calculate the delay spread. In order to quantify the time dispersive properties of multipath channels, the root mean square (rms) delay spread D_{rms} is employed [35] [56]. The delay spread of the impulse response can be expressed as:

$$D_{rms} = \sqrt{\frac{\sum (t-\mu)^2 h^2(t)\mathrm{d}t}{\sum h^2(t)\mathrm{d}t}} \tag{3.5.1}$$

In this formulation, $h(t)dt$ is the impulse response $h(t)$ within time bin interval, in the MATLAB, it can be expressed as h_vector (ii, index), μ is mean delay, which can be expressed as:

$$\mu = \frac{\sum t h^2(t)\mathrm{d}t}{\sum h^2(t)\mathrm{d}t} \tag{3.5.2}$$

Figure 11 shows the Delay spread when the receiver is (1.6 m, 2.5 m, 2 m) and (3.4 m, 2.5 m, 2 m), the access point is (1.6 m, 2.5 m, 3 m) and (3.4 m, 2.5 m, 3 m) respectively.

Figure 11 shows the branch when *El* angle is 90˚, *Az* angle is 0˚ and FOV is 20˚. The receiver is (1.6 m, 2.5 m, 2 m) and (3.4 m, 2.5 m, 2 m), the access point is (1.6 m, 2.5 m, 3 m) and (3.4 m, 2.5 m, 3 m) respectively.

As the graphs show, the ADR provide a better result than FOV receiver. Because the wide FOV receiver in CDS collects more reflection than ADR. In terms of ADR, when the access point is directly above the receiver, better results will be obtained because less noise signal and delay spread will be generated.

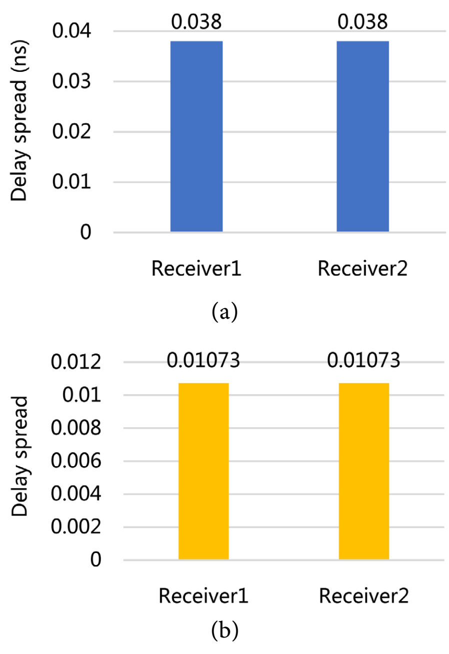

Figure 11. (a) the delay spread of CDS; (b) the delay spread of ADR.

6) SINR analysis

The performance of OWC system can be evaluated by calculating the signal to noise ratio, because it involved the factors such as noise and signal spread. The bit error rate (BER) can be reduced due to the high SNR, when using the on off keying (OOK), the BER can be expressed as [4]:

$$P_e = Q(SINR) \tag{3.6.1}$$

The $Q()$ function is the Gaussian function:

$$Q(x) = \frac{1}{2} erfc\left(\frac{x}{\sqrt{2}}\right) = \frac{1}{\sqrt{2\pi}} \times \frac{e^{-\frac{x^2}{\sqrt{2}}}}{x} \tag{3.6.2}$$

The $SINR$ can be expressed according to P_r, σ and interference. The SINR can be got from [57] [58].

$$SINR = \frac{(RP_r)^2}{\sigma^2 + (R \times interfencen)^2} \tag{3.6.3}$$

In this formulation, the value of R is photodetector responsivity 0.4 A/W, which is determined by the used wavelength.

$$\sigma = \sqrt{\sigma_{pr}^2 + \sigma_{bn}^2 + \sigma_{sig}^2} \tag{3.6.4}$$

σ are the shot noises associated with the signal can be expressed as formula (3.6.4). In this formula, the σ_{pr} is preamplifier noise, σ_{bn} is background shot noise, and the σ_{sig} is the shot noises associated with the P_r. Moreira [59] has argued that the shot noise σ_{sig} can be ignored because of the received signal is significantly weak.

The σ_{bn} can be computed as the following equation:

$$\sigma_{bn} = \sqrt{2RqP_{bn}BW} \tag{3.6.5}$$

In this formula, the R is detector responsivity, q is the electron charge, BW is the receiver bandwidth 5 GHz, P_{bn} is the received background noise.

According to Osama and Elmirghani [4], the type of this preamplifier is 5 GHz PIN-BJT, the spectral density of this receiver is 4.47 $\frac{\text{pA}}{\sqrt{\text{Hz}}}$. As a result, the noise of preamplifier is:

$$\sigma_{pr} = 4.47 \times 10^{-12} \times \sqrt{5 \times 10^9} = 31.607\ \mu\text{A} \tag{3.6.7}$$

There are two methods mentioned before, called selection combining and maximum ratio combining. After selecting the highest impulse response, the best $SINR$ can be calculated:

$$SINR_{sc} = \max_k \frac{(RP_r)^2}{\sigma^2 + (R \times interfencen)^2}_k ,$$

while $1 \le k \le J$, J is the sum of the number of angle diversity receivers.

The maximum ratio combining is employing an adder circuit to combine the outputs from detectors. The weight of detector is:

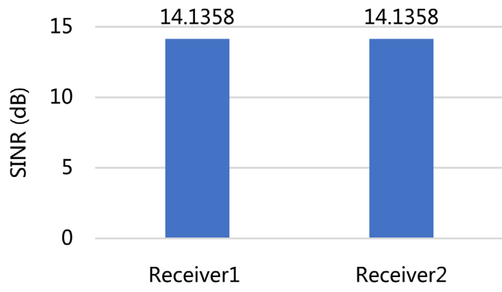

Figure 12. SINR of CDS.

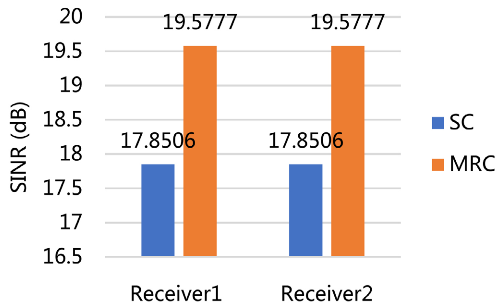

Figure 13. SINR of ADR.

$$W_k = \frac{R\left(P_{s1k} + P_{s0k}\right)}{\left(\sigma_{0k} + \sigma_{1k}\right)^2},$$

while $1 \le k \le J$, this value can determine the max output *SINR*.

The *SINR* is:

$$SINR_{MRC} = \sum_{k=1}^{J} \frac{\left(RP_r\right)^2}{\sigma^2 + \left(R \times interfencen\right)^2},$$

while $1 \le k \le J$.

When use the SC method, the highest *SINR* is chosen. Figure 12 is the *SINR* of CDS and Figure 13 is when *El* angle is 90˚, *Az* angle is 0˚ and FOV is 20˚. When use the SC method, the highest *SINR* is chosen. When use the MRC method, SINR of three branches are added up together. So, the MRC is better than SC. Because the CDS has a wide FOV receiver which will collect more reflection but the ADR has a narrow angle, so the interference is less than CDS, therefore, the SINR of ADR is larger than that of CDS.

4. Conclusions

The characteristics of an indoor VLC link can be designed and analyzed by modelling VLC channel. Background noise, interference, multipath dispersion and impulse response can be the criterion of the performance of OW systems. Compared with wide FOV receiver, it can be found that no matter delay spread, impulse response and SINR, ADR shows a better performance. Apart from this, it is worth mentioning that a FOV with a very small reflective area conducts to performance degradation, as a result, an optimum FOV can be utilized. In addition, the MRC shows a better result than SC. The simulation and calculation in this report are performed by MATLAB, the result match great with other research's result.

In addition, the simulator developed in this report is used to evaluate the new VLC system. Researched the performance evaluation of VLC system with various FOV (90˚ and 20˚), elevation angle (90˚ and 40˚) and azimuth angle (0˚, 90˚ and 270˚) receivers. It shows the ADR can increase the performance of system (reduce delay spread and improve SNR).

In the future, the structure of receiver should be improved, which can reduce the interference and background noise. Furthermore, improving the data rate ($\log_2(1+SINR)$) is necessary, some new technology should be researched to increase the SINR.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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