Reliability and Availability Study of Modern Indoor VLC Systems with eSSK Modulation

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Abstract. Indoor visible light communication (VLC) systems that use Light Emitting Diode (LED) technology are used in various modern very high data rate communication applications due to the plenty of advantages they offer such as their very high bandwidth and their low operational and installation cost. Furthermore, due to the weakness of light to penetrate the walls, such systems have very low vulnerability to security attacks so they are suitable for indoor military communications. VLC systems can be easily deployed in navy ships or submarines where security and low power consumption are very important factors. In order to increase the performance of such systems, many modulation techniques can be used with the enhanced Space Shift Keying (eSSK) being an effective one. The drawback of such modulation technique is the decrease of the coverage area for a receiver that needs to communicate with all Light Emitting Diode (LED) transmitters. In this work, the coverage area and the performance of the system will be investigated for various patterns of LED transmitters. The performance metric that will be calculated is the bit error rate (BER), a very important metric that is associated with the reliability of the system and its value is strictly determined in modern communication standards. So by achieving lower BER using eSSK technique, the communication systems become more suitable for modern applications. Simulation results will be provided for the performance of the VLC system.

Keywords: Visible light communications, eSSK, Bit error rate, LED.
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I. INTRODUCTION

The last few years there is an increasing scientific research and commercial interest for Visible Light Communication (VLC) systems, since they offer many advantages and can successfully cover the requirements of modern communication systems, [1]. The most important of them are the high data rate they can achieve, along with the low installation and operational cost, [2], and that’s why they will be extensively used for 5th generation (5G) networks in order

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to solve many issues of modern networks, [1], [3]. Moreover, these systems operating in visible electromagnetic spectrum where no license is required, while at the same time these frequencies are environmentally friendly and completely safe for humans [1]. These advantages, have introduced Light Fidelity (LiFi) systems, which already being used commercially, [4], [5], for data transmission, while at the same time they offer room illumination. Furthermore, VLC systems, are suitable for fulfilling global communication and information projects such as smart home and smart cities applications, [1], [2], [6].

An effective modulation technique for the VLC systems is the space shift keying (SSK) which is a kind of spatial modulation technique where each transmitter is active in a specific time slot and transmits a unique symbol, [2], [7], [8]. In conventional SSK, the duration and the amplitude of the transmitted pulses are the same for every transmitter while in eSSK their width is different and unique for each transmitter, [2]. In this work the BER performance of the eSSK VLC system is estimated.

However, a performance mitigation factor of the VLC systems, as for every wireless communication system, is the incoming noise through the receiver's photodiode which deteriorates the signal to noise ratio (SNR) of the optical link, [1], [9], [10]. A very significant coefficient that increases the noise of such a system is the background optical noise, and the main source of this, is the sunlight radiation which is difficult to be avoided. In this work, in order to reduce the effect of background noise, we adopt the technique of , [1], with the application of an optical filter, [11], [12], at the receiver's photodiode. In this way, we can decrease the received wavelength range, that's not used for data transmission.

The remainder of this work is organized as follows: in section II we describe the system model, while in Section III we derive mathematical expression for the SNR after the application of an optical filter at the receiver, and we study the technique of the coverage area calculation. Next, in section IV we estimate the Bit Error Rate (BER) of the system, while in Section V we demonstrate the corresponding numerical results for the BER of the system. Finally, the conclusions are presented in Section VI.

II. SYSTEM MODEL

In this work we consider that 4 Red Green Blue (RGB) white LED lamps have been installed on the ceiling of a room, with height h, for illumination and data transmission. The length and the width of the room are L and W respectively. Here it should be mentioned that, for the data transmission we only use the red color. The exact positions of the LED lamps, which actually are our transmitters, on the ceiling are LED1(0,0,h), LED2(L,0,h), LED3(0,W,h), LED4(L,W,h), where the values are measured in meters.

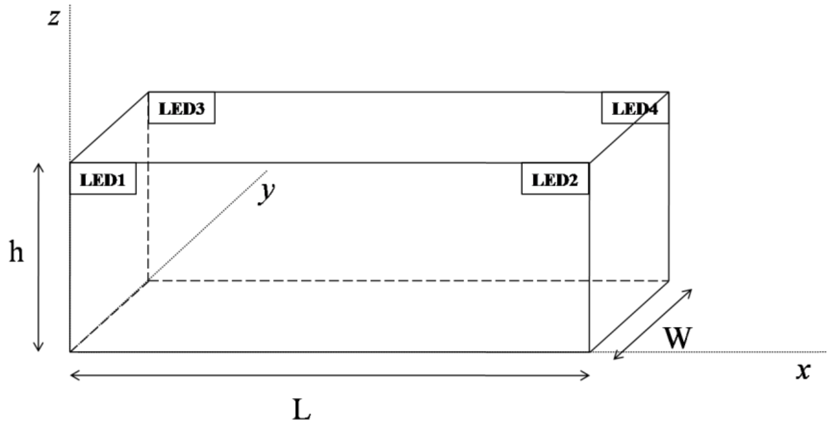

FIGURE 1: Room Dimensions and LED installation

The photodiode is supposed to be able for the reception of a wide range of wavelengths, [1], while the order of emission of each transmitter, is assumed to be Lambertian, m, and is determined as, [10], [13]:

$$m = -\frac{\ln 2}{\ln[\cos(\varphi_s)]} \tag{1}$$

where φ_s is the semi-angle at half power. Furthermore, in a direct optical link the DC gain of the channel is given as, [1], [10], [13]:

$$H_0 = A\frac{m+1}{2\pi d^2}\cos^m(\varphi)T_s(\psi)\cos(\psi)g(\psi) \text{ for } 0 \le \psi \le \psi_c \tag{2}$$

where A represents the physical area of the photodiode of the detector, d is the distance between transmitter and receiver, while φ and ψ are the angle of incidence and normalized irradiance respectively. Parameter $T_s(\psi)$ stands for the gain of an optical filter and ψ_c for the width of field of view (FOV) at the photodiode of the receiver. Finally, $g(\psi)$ is the gain of an optical concentrator which defined as, [2], [10], [13]:

$$g(\psi) = \frac{n^2}{\sin^2(\psi)} \text{ for } 0 \le \psi \le \psi_c \tag{3}$$

where n is the refractive index of the medium. In the case where $\psi \ge \psi_c$, both H_0 and $g(\psi)$ are zero. Considering P_t as the optical power of the transmitter, the power in the receiver side is given as, [10], [13], [14]:

$$P_r = P_t A\frac{m+1}{2\pi d^2}\cos^m(\varphi)T_s(\psi)\cos(\psi)g(\psi) \tag{4}$$

A typical emission pattern of a LED transmitter according to Lambertian model is shown in Fig. 2:

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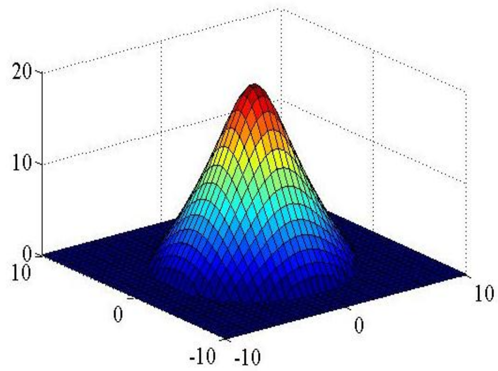

FIGURE 2: 3-D emission pattern

The modulation that will be used in this work is the eSSK technique that is very effective and widely used. Applying this modulation, each transmitter has a different and unique width of the emitted pulse, while the amplitude remains the same. Hence, the pulse width of the transmitted signal is the identity of each LED lamp, [2], [10]. At the same time the width of the transmitted pulse is different and unique for each transmitter and the pulse duration of the transmitted symbol is $\tau_i T$ where i indicates each different transmitter that symbol comes from and T is the duration T of the transmitted pulse and the received signal is expressed as:

$$r(t) = \gamma H(t) * x(\mathrm{t}) + \mathrm{n(t)} \tag{5}$$

where "*" represents the convolution between **H(t)** and **x(t)**, γ is the responsivity of the receiver, **H(t)** is the channel gain, **x(t)** is the matrix of transmitted signal and **n(t)** is the matrix of the Additive White Gaussian Noise (AWGN). The channel gain for a system with 4 transmitters and 1 receiver will be given as:

$$H(\mathrm{t}) = \begin{bmatrix} h_{11} & h_{21} & h_{31} & h_{41} \end{bmatrix} \tag{6}$$

So by using 4 transmitters, the following symbols may be generated as: LED1(00), LED2(01), LED3(10), LED4(11).

III. SNR AND COVERAGE AREA

A. Coverage Area

There is a threshold value for the optical power that can be detected in every photodiode. Hence, if the received optical power of each LED lamp is above this threshold, the system will be efficient. Otherwise, if the received optical power of each LED lamp is below this threshold, the user will not be able receive certain symbols and as a result the performance and the efficiency of the system will be significantly deteriorated, [2]. As long as, eSSK modulation technique is used, the receiver must be able to communicate with all 4 receivers. Thus, the calculation of the area where the receiver is able to detect all the symbols is very important. The coverage area of the system is the overlapping area of all threshold circles from all LED lamps, as shown in Fig.3:

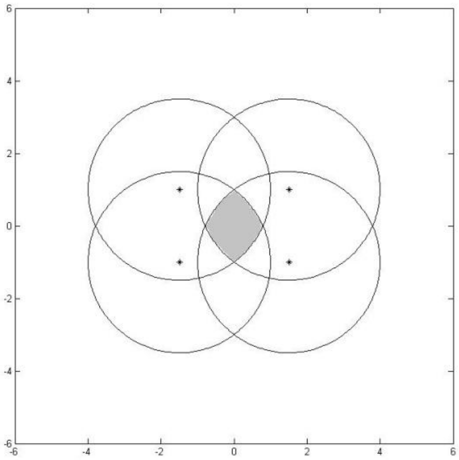

FIGURE 3: Overlapping Area of 4 LED lamps

In order to deploy an effective VLC system with eSSK, the parameters and the installing pattern of the LED transmitter must be carefully selected depending on the standard requirements of the link.

B.SNR after the application of an optical filter

In the case of eSSK modulation the SNR is given as, [7], [15]:

$$SNR = \frac{(\gamma P_t)^2}{N\sigma_{total}^2}\sum_{i=1}^{N}\tau_i \tag{7}$$

where γ represents the responsivity of the photodiode, P_t stands for the transmitted power, τ_i is the duty cycle parameter and σ_{total}^2 is the total noise variance that is given by, [1], [9], [10]:

$$\sigma_{total}^2 = \sigma_{thermal}^2 + \sigma_{shot}^2 \tag{8}$$

where $\sigma_{thermal}^2$ represents the variance of the thermal noise, which is the electronic noise generated from thermal agitation of charge carriers inside a conductor and given as [1], [9], [10]:

$$\sigma_{thermal}^2 = 8\pi nkT_k AB^2\left[\frac{I_2}{G} + \frac{2\pi\Gamma nAI_3B}{g_m}\right] \tag{9}$$

with k being Boltzmann's constant, G is the open loop voltage gain, T_k is the absolute temperature, A is the physical receiver area, I_2 and I_3 are noise bandwidth factors, n is the capacitance of photo detector per unit area, g_m is the transconductance and B is the noise's bandwidth. Additionally, σ_{shot}^2 represents the variance of the shot noise, which is the noise induced by ambient light and its variance is given as, [1], [9], [10]:

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$$\sigma_{shot}^2 = 2q\gamma P_r B + 2q\gamma P_{bg} I_2 B \quad (10)$$

with q being the electronic charge and P_{bg} is the background noise power. Assuming that the value of P_{bg} depends on the received sunlight noise, the mathematical expression is given as, [16]:

$$P_{bg} = r_{coe} E_{\det} T_0 A v^2 \quad (11)$$

where r_{coe} is the reflection coefficient, and T_0 is the peak filter transmission coefficient. For downlink communication, the receiving side, which is equipped on the exterior, is under direct exposure to sunlight and thus r_{coe} becomes equal to one. For uplink communication, the light bulbs that face toward the ground are affected by backscattering sunlight reflected from the floor's surface and thus r_{coe} = 0.1. Additionally, $E_{\det}$, which is the irradiance within the spectral range of the receiver in W/m^2, can be calculated as, [1],[16]:

$$E_{\det} = \int_{\lambda_1}^{\lambda_2} \frac{S_{peak} W(\lambda, T_B)}{\max[W(\lambda, T_B)} d\lambda \quad (12)$$

In expression (10) λ_1 and λ_2 are the lower and upper spectral limits of the wavelength of the sunlight noise, while $W(\lambda, T_B)$ stands for the spectral irradiance of a blackbody radiation model, [1], [16]:

$$W(\lambda, T_B) = \frac{2\pi h_p c^2}{\lambda^5}\left(\frac{1}{e^{h_p c/\lambda k T_B} - 1}\right) \quad (13)$$

where h_p stands for the Planck's constant, c is the speed of light in vacuum and T_B is the average surface temperature of the Sun in Kelvin degrees. The Sun's spectral irradiance measure outside the earth's atmosphere closely resembles a blackbody of 6000°K, [1],[5]. Here, it should be mentioned that, for the calculation of the integral of expression (10), the Monte Carlo method is deployed using 1×10^6 random samples Furthermore the peak spectral irradiance in $W/m^2/\mu m$ is given as, [17]:

$$S_{peak} = 10^{-4} E_{global}^2 + 1.5768 E_{global} \quad (14)$$

with E_{global} being the global solar irradiance. The band-pass filter can be used for the reduction of the received background noise from higher and lower wavelengths, as the information of our system is transmitted by using the red light of the RGB led lamp. Such optical filters can be easily constructed using various materials, [1].

IV. BER ESTIMATION

In this section, we study the performance of our system in terms of Bit Error Rate (BER). BER is one of the most well-known and crucial metrics for the performance estimation of every communication system, [18], as it is associated with the reliability of the system and its value is strictly determined in modern communication standards. The BER expression for the eSSK modulation scheme, based on, [15], can be written as:

$$BER \le \frac{4}{N\log_2(N)(N-1)} \sum_{j=1}^{N-1} \sum_{i=j+1}^{N} Q\left(\sqrt{\left(\frac{TN}{4S} SNR\left(\| \tau_i h_i - \tau_j h_j \|_F\right)^2\right)}\right) \tag{15}$$

where $S = \sum_{i=1}^{N} \tau_i$, $h_{ij}(t)$ is the channel gain between the *i-th* transmitter and the receiver, i = 1,2,3 and 4, T is the duration of the transmitted pulses which is the same for every transmitter, N is the number of transmitters, and $\|.\|_F$ is Frobenius norm about matrices.

V. NUMERICAL RESULTS

In this section the numerical results of the indoor VLC system described above will be presented. The VLC systems is modulated with eSSK technique using 4 LED transmitters that are installed at the corners of a room with dimensions 5m x 5m x 3m. The transmitted power of each LED is 1 Watt and the semi-angle φ=85°. The receiver is placed 1.5m above the floor and has the technical characteristics presented in table (2):

Technical Characteristics of Receiver Photodiode	
Detectors Surface (A)	*$8\cdot10^{-4}m^2$*
Field of view (FOV)	*60^o*
SNR threshold	*5dB*

TABLE 1: Technical characteristics of receiver Photodiode

According to these characteristics, the overlapping area in the room can be precisely calculated with Monte Carlo simulation using 10^6 random samples.

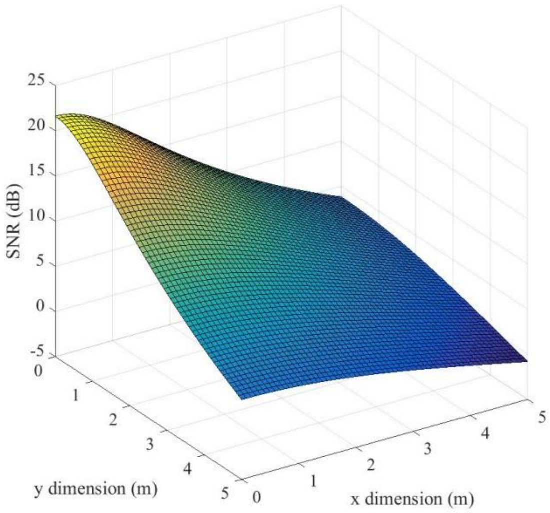

FIGURE 4: SNR of each LED in case no optical filter is applied

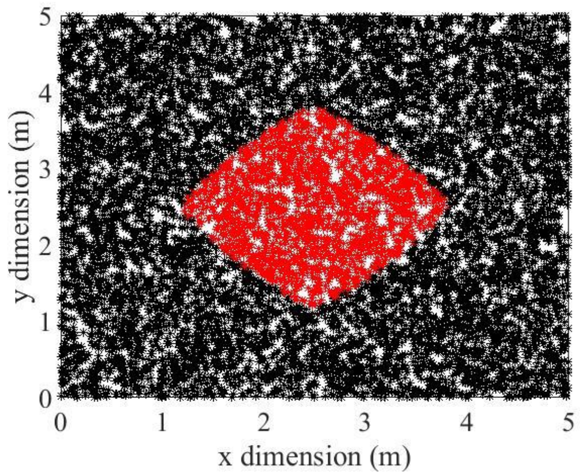

FIGURE 5: Overlapping area of VLC system in case no optical filter is applied

In figure (4) the SNR of each LED is presented. This SNR corresponds to the total SNR the at the receiver as in eSSK modulation only one LED transmits every time slot. In figure (5) the overlapping area is presented. In this area, the receiver is able to receive all 4 symbols. The maximum SNR equals 21dB while the surface of the overlapping area is A_e=4m^2.

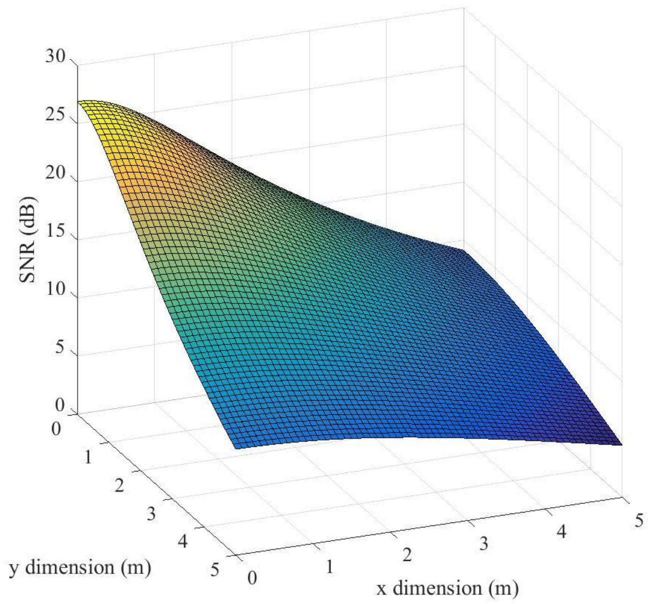

FIGURE 6: SNR of each LED using optical filter

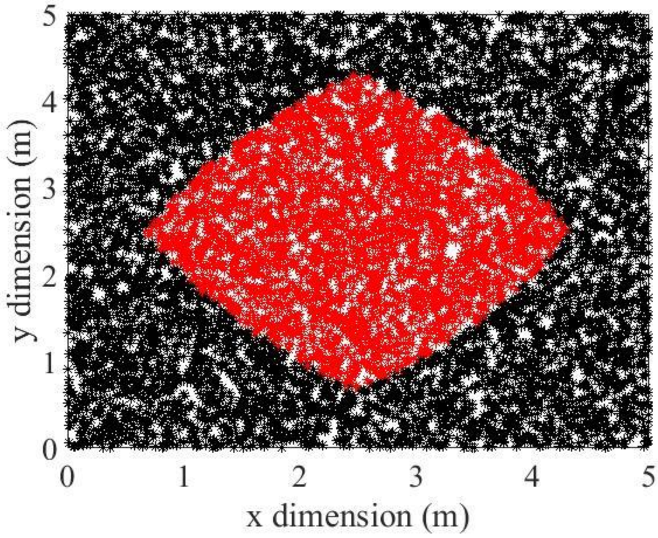

FIGURE 7: Overlapping Area using optical filter

In figures (6) and (7), an optical filter with frequencies cutoff at 600nm and 800nm, so that only red light that carries the information can pass to the receiver, is applied to the system and the corresponding results are presented. According to the results the performance of the system clearly increases as the maximum SNR is 27 dB. At the same time the availability of the system improves as the overlapping area expands by 100% with the total surface area increasing to 8m^2.

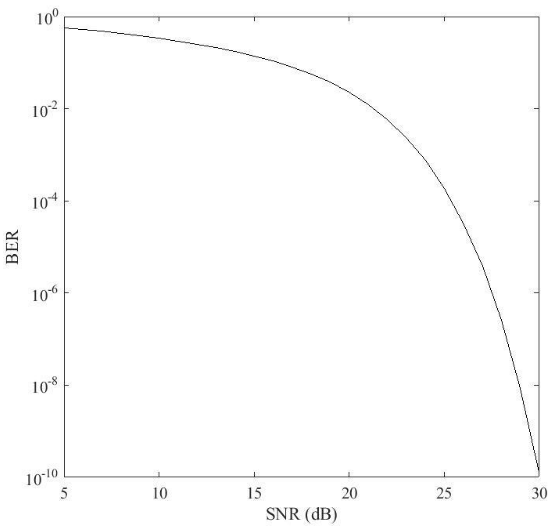

FIGURE 8: BER for the eSSK

Furthermore, the BER of the eSSK VLC link is presented in figure (8). These results corresponds to a specific point in the room where the channel gain is h=[1, 0.8, 0.6, 0.4]. It is clear that as the SNR increases, the performance of the systems increases as the BER becomes lower. More specifically, for an SNR value greater than 25 dB the system's performance becomes very reliable. So the use of the optical filter that increases the SNR, makes the system even more robust for networks that require high reliability and security. More specifically, for the values of

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SNR that were calculated in cases with and without filter, the BER decreases more than 4 orders of magnitude.

VI. CONCLUSIONS

In this work, the SNR performance of a VLC system using an optical bandpass filter for the deterioration of the sunlight background noise has been estimated, and the coverage area of such a system using various patterns of LED transmitters has been investigated. Additionally, the reliability of the VLC system using eSSK modulation scheme has been studied in terms of BER and the relevant closed form mathematical expression has been derived. The corresponding numerical results demonstrated that the use of an optical filter can greatly improve the performance and the availability of the VLC system, as the overlapping area expands and the BER decreases many orders of magnitude.

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REFERENCES

1. D. K. Manousou, A. N. Stassinakis, E. Syskakis, H. E. Nistazakis, G. S. Tombras, Ch. K. Volos, and A.D. Tsigopoulos, "Estimation of the influence of Vanadium Dioxide Optical Filters at the Performance of Visible Light Communication Systems," *2018 7th Int. Conf. Mod. Circuits Syst. Technol.*, pp. 1–4, 2018.
2. S. Menounou, A. N. Stassinakis, H. E. Nistazakis, G. S. Tombras, and H. G. Sandalidis, "Coverage Area Estimation for High Performance eSSK Visible Light Communication Systems," *2017 Panhellenic Conf. Electron. Telecommun.*, pp. 1–4, 2017.
3. S. Jayasudha, N. Bakkiyalakshmi, M. Manju, R. Sivabarani, and M. Subasridevi, "Visible Light Communications For 5g Wireless Networking Technology," vol. 10, no. 4, pp. 390–395, 2016.
4. D. Tsonev, S. Videv, and H. Haas, "Light Fidelity (Li-Fi): Towards All-Optical Networking," *Proc. SPIE, Vol. 9007, Broadband Access Commun. Technol. VIII; 900702, doi 10.1117/12.2044649*, no. 0, 2014.
5. H. Chun, C. J. Chiang, A. Monkman, and D. Obrien, "A study of illumination and communication using organic light emitting diodes," *J. Light. Technol.*, vol. 31, no. 22, pp. 3511–3517, 2013.
6. D. Karunatilaka, F. Zafar, V. Kalavally, and R. Parthiban, "LED based indoor visible light communications: State of the art," *IEEE Commun. Surv. Tutorials*, vol. 17, no. 3, pp. 1649–1678, 2015.
7. W. O. Popoola, S. Sinanovic, and H. E. Nistazakis, "Enhancing the error performance of optical SSK under correlated channel condition," *2016 IEEE Int. Conf. Commun. Work. ICC 2016*, pp. 7–11, 2016.

8. W. O. Popoola, E. Poves, and H. Haas, “Error Performance of Generalised Space Shift Keying for Indoor Visible Light Communications,” *IEEE Trans. Commun.*, vol. 61, no. 5, pp. 1968–1976, May 2013.
9. M. S. Ab-Rahman, N. I. Shuhaimi, L. A. H. Azizan, and M. R. Hassan, “Analytical study of signal-to-noise ratio for visible light communication by using single source,” *J. Comput. Sci.*, vol. 8, no. 1, pp. 141–144, 2012.
10. T. Komine and M. Nakagawa, “Fundamental analysis for visible-light communication system using LED lights,” *IEEE Trans. Consum. Electron.*, vol. 50, no. 1, pp. 100–107, 2004.
11. W. Lu, G. Zhao, B. Song, J. Li, X. Zhang, and G. Han, “Preparation and thermochromic properties of sol-gel-derived Zr-doped VO2films,” *Surf. Coatings Technol.*, vol. 320, pp. 311–314, 2017.
12. J. Du, Y. Gao, H. Luo, Z. Zhang, L. Kang, and Z. Chen, “Formation and metal-to-insulator transition properties of VO2ZrV2O7composite films by polymer-assisted deposition,” *Sol. Energy Mater. Sol. Cells*, vol. 95, no. 7, pp. 1604–1609, 2011.
13. Z. Ghassemlooy, D. Wu, M. A. Khalighi, and X. Tang, “Indoor Non-directed Optical Wireless Communications - Optimization of the Lambertian Order,” *J. Electr. Comput. Eng. Innov.*, vol. 1, no. 1, pp. 1–9, 2013.
14. S. Menounou, A. N. Stassinakis, H. E. Nistazakis, A. Tzanakaki, H. G. Sandalidis, and G. S. Tombras, “Study and simulation on performance of a VLC communication system.” 7th IC-EPSMSO, 2017.
15. K. N. Manganaris, H. E. Nistazakis, A. N. Stassinakis, A. Tzanakaki, G. Mkrttchian, and G. S. Tombras, “eight transmitter-short range indoor vlc systems using spatial modulation technique of enhanced ssk with variable pulse width and correlated channel conditions.” 7th International Conference on “Experiments/Process/System Modeling/Simulation/Optimization” 7th IC-EPSMSO Athens, 2017.
16. H. C. Kim, B. W. Kim, and S. Y. Jung, “Performance of a wavelength hopping MC-VPPM scheme for vehicle-to-infrastructure(V2I) VLC,” *Photonic Netw. Commun.*, vol. 33, no. 1, pp. 1–9, 2016.
17. D. G. Kaskaoutis, H. D. Kambezidis, S. Kumar Kharol, and K. V. S. Badarinath, “The diffuse-to-global spectral irradiance ratio as a cloud-screening technique for radiometric data,” *J. Atmos. Solar-Terrestrial Phys.*, vol. 70, no. 13, pp. 1597–1606, 2008.
18. G. K. Varotsos, H. E. Nistazakis, and G. S. Tombras, “OFDM RoFSO Links with Relays Over Turbulence Channels and Nonzero Boresight Pointing Errors,” vol. 12, no. 12, 2017.

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