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High-Bit-Rate Transmission in Visible Light Communication System Based on Adaptive Successive Interference Cancellation Technique

Brian Pamukti[1,2], Amirullah Wijayanto[2], Shien-Kuei Liaw[2*]

[1]*Department of Mechanical Engineering, Faculty of Engineering, Universitas Indonesia, Kampus UI Depok, 16424, Indonesia*
[2]*Laboratoire Energétique Mécanique Electromagnétisme, Université Paris Nanterre, Ville d'Avray, 92410, France*

Abstract. In this study, we proposed an adaptive successive interference cancellation (SIC) technique to enhance non-orthogonal multiple access visible light communication (NOMA-VLC) and demonstrate its effectiveness using extensive simulations. NOMA-VLC is a promising technology for high-speed wireless communication, but interference from multiple users can pose a significant challenge. SIC is a technique that can help mitigate this interference. We used non-return to zero (NRZ) modulation to achieve high bit rates up to 2 Gbps and evaluated the performance using bit error rate (BER) analysis. Our simulation showed that the static power allocation (SPA) performance on the NOMA-VLC system achieved a BER value of around 10^{-3} for both users, using power allocation α_1=0.7 and α_2=0.3. We also compared SPA against gain ratio power allocation (GRPA) and found that the performance of GRPA was not as good, with a BER value around 10^{-2}. Our results show the effectiveness of the proposed SIC technique in enhancing the performance of NOMA-VLC.

Keywords: Bit error rate; Optical power domain; Static power allocation; Successive interference cancellation; Visible light communication

1. Introduction

Visible light communication (VLC) is a type of optical wireless communication (OWC) that utilizes light-emitting diodes (LEDs) light to establish a communication link. VLC technology provides an affordable communication solution as users do not require access points, only a visible light source from LED lights. The wavelength range of VLC technology is from 380 nm to 750 nm, which is visible to the human eye. VLC communication systems are considered safe for the environment and are therefore suitable for use in the ocean environment (Ibrahimy *et al.*, 2022). In addition, due to the advantages of high switching speed, inexpensive, and low power consumption, LEDs are suitable for VLC technology (Nugroho, Wijayanto, and Hadiyoso, 2018).

Although non-orthogonal multiple access (NOMA) technology has the potential for significant benefits, it still faces several significant challenges. These include signal interference, power allocation, and channel fading. While many successive interference cancellation (SIC) methods have been proposed to mitigate these challenges, most are

*Corresponding author's email: skliaw@mail.ntust.edu.tw, Tel.: +886-2-27376384; Fax: +886-2-27376424
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designed for bipolar modulation and have not been fully explored for unipolar modulation, especially at high bit rates. VLC limits the practical applicability of NOMA in real-world scenarios. Furthermore, VLC has been identified as a promising innovation engine for information and communications technology (ICT), as highlighted by recent research (Suryanegara *et al*., 2019). VLC has several issues transmitting multi-users with security problems decoding their information (Garg, Sharma, and Gupta, 2021). Therefore, developing new and effective methods for NOMA-based VLC suitable for high bit rates is of great importance and has the potential to revolutionize the field of ICT.

Optical power domain non-orthogonal multiple access (OPD-NOMA) was proposed as a promising solution for high-speed, short-range wireless communications. This technology was studied by (Lin, Tang, and Ghassemlooy, 2019). OPD-NOMA reduces the nonlinear distortion of low-power signals. Experimental results show that OPD-NOMA is better utilized in the linear dynamic range of the LED's power-current response (Trisdianto *et al*., 2016); thus, improved transmission performance compared to traditional NOMA with the same driver circuit is provided. Researchers (Ding *et al*., 2014) have applied NOMA to the downlink VLC system and increased the desired data rate on VLC.

NOMA uses two methods for multiplexing: power domain (PD) NOMA and code domain (CD) NOMA. Both of these methods employ superposition coding, which allows for greater spectral efficiency than orthogonal multiple access (OMA) (Pamukti *et al.,* 2020). PD-NOMA has proven to be very suitable for VLC communication with a high Signal Noise to Ratio (SNR) ratio, short distance specifications, and a small number of users in each cell—several power allocation techniques in NOMA, such as static power allocation (SPA), gain ratio power allocation (GRPA), and Joint Detection. In (Yang *et al*., 2021), GRPA for VLC systems is studied. The study aims to maximize the total downlinks under the constraints of quality of service (QoS), power consumption and LED operating area (LOR). With variable transformations, auxiliary functions, and the Taylor series, the numerical results show that the proposed scheme can have a higher total rate than the modified GRPA algorithm (Pratama, Adriansyah, and Pamukti, 2021).

Paper (Astharini, Asvial, and Gunawan, 2022a) proposed using Kalman filter (KF) estimation for VLC channel gain based on angular parameters according to the Lambertian model. The proposed angular model is based on two state variables directly determining factors in channel condition changes, and it is developed with the channel model in mind. Three schemes of KF were explored, with the proposed extended KF (EKF) with the angular parameter of Lambertian VLC succeeding in reducing the processing time by 80% from the previous model with Cartesian coordinates. Linear KF showed good performance with a standard deviation estimation error of 0.0219. Researchers (Astharini, Asvial, Gunawan, 2022b) evaluate the performance of a trellis-coded modulation (TCM) technique for NOMA VLC systems with two different convolutional encoders and decoders: four-state and eight-state. Using a four-state trellis-coded, the system is compared to an on-off keying (OOK) system with maximum likelihood signal detection (MLSD). The authors observe the bit error rate (BER) values over a range of signal-to-noise ratios (SNR) for the three users in each system. The results show that with careful power allocation, all three TCM systems users can receive good quality signals on SNRs of 30 and above. The performance of TCM 4 and TCM 8 is satisfactorily comparable to that of OOK NOMA VLC.

The main contribution of this study lies in developing an adaptive SIC technique that is particularly well-suited for unipolar modulation at high bit rates. We specifically focused on using SPA for VLC-NOMA, a power allocation technique that allocates power to each receiver based on its channel gain and the time bit. By applying SPA to VLC-NOMA with a high bit rate of 2 Gbps, we aimed to enhance the system's performance, which was evaluated using the BER. To validate our approach, we implemented our proposed technique in a VLC-NOMA system with a Line-of-Sight (LOS) channel within a closed room. Overall, this study provides novel insights into the use of adaptive SIC and SPA for improving the performance of VLC-NOMA systems, which could have significant practical implications for indoor wireless communication.

The paper is organized into three main sections. In Section II, the model of the SPA NOMA-VLC system is presented. Section III provides an analysis of the simulation results, which show the SNR and BER performance of the system. Finally, the conclusion of the simulation results is summarized in Section IV. This section briefly overviews the study's findings and highlights the research's main contributions.

2. Methods

This research used the system model and parameters to evaluate SPA on VLC communication with LOS channel in applying multiple access techniques, namely NOMA. The outline of the VLC system is divided into three parts: the transmitter, the transmission channel, and the receiver. In the NOMA VLC scheme, superposition coding (SPC) is applied on the transmitter side, and SIC is implemented at the receiver.

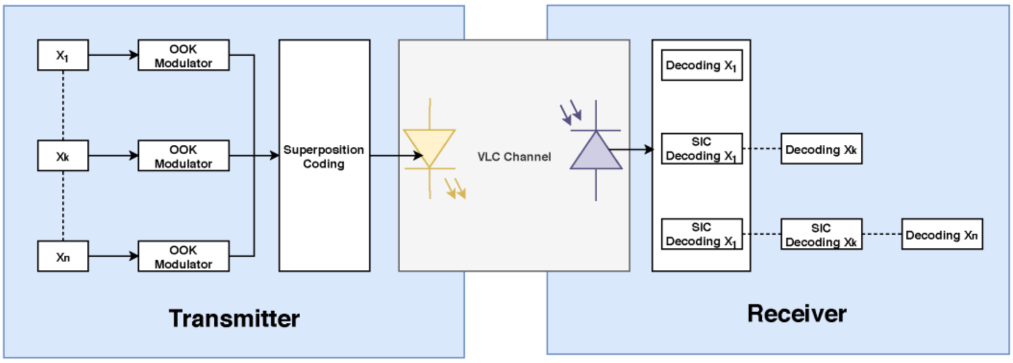


Figure 1 Block Diagram for adaptive successive interference cancellation of visible light communication.

In Figure 1, on the receiving side, there are several input signals from the first initialized input signal x_1 to $x_{n,}$, which is initialized as the last signal. The transmitter block is part of the VLC system that functions as a source of sending information signals through the transmission channel. The system model design in this study uses an LED lamp with a power of 5 watts placed in the middle of the room with a total bandwidth of 20 MHz (Zeng *et al*., 2018). From the input signal, it continues to the modulator side to carry out laying the information to the carrier signal.

This study's modulation process is on-off keying non-return to zero (OOK-NRZ). OOK is a form of amplitude shift keying (ASK) modulation representing digital data as a carrier wave's presence or absence. OOK is a simple and widely used modulation technique, but it can suffer from low spectral efficiency and high error rates, especially in noise and interference. The use of NRZ coding in this study helps to increase the bit rate up to 2 Gbps, which is twice the bit rate compared to the previous research (Putri, Hambali, and Pamukti 2019).

The receiver block is part of the VLC system, which can decode the information signal received through the transmission channel. The system model is designed with a receiver that has a 1 cm^2 area, a 70° field of view (FOV), and a responsivity of 0.55 A/W, as previously studied (Tabassum and Hossain, 2018). A photodetector converts optical power signals to electrical signals not separated from the information signal. After the photodetector, the signal passes through the SIC side (Dixit and Kumar, 2021).

2.1. Transmission Channel Model

This study examines a LOS channel, which is a type of transmission where the signal path between the transmitter and the receiver is unobstructed. One of the parameters that affects the LOS channel is the Lambertian order, which is given by (1) and related to the full-width half maximum (FWHM) angle as shown below:

$$m = -\frac{\ln(2)}{\ln(\cos\theta)}, \tag{1}$$

where the value θ is for the transmitted angle of FWHM. For the LOS channel for each user, the equation is

$$h_i = \frac{m+1}{2\pi d_i^2} A_{det} \cos^m(\psi). \tag{2}$$

The area of the photodetector on the receiver side, A_{det}, and the distance from the transmitter to the receiver, d_i, are factors that determine the channel gain in (2). In addition to the distance, other factors such as ambient light, shadows, and atmospheric turbulence can also affect the channel gain, even at trim levels (Darusalam, Priambodo, and Rahardjo, 2015).

2.2. Power Allocation

SPA is a technique that involves pre-determining the power allocation factor (α) for the optical signal. The power allocation is determined based on the channel gain of each receiver that receives the signal (Nabavi and Yuksel, 2020). The amount of power allocation is allocated according to the channel gain, where receivers with weaker channel gain will receive a higher power allocation and vice versa. This technique is often used as a simple and practical method for power allocation in VLC systems, especially when channel conditions are not highly variable.

The GRPA algorithm uses the channel state information (CSI) to calculate the channel gain of each user and estimate the optimal power allocation value, as shown by (3). The total power allocated to all users must be equal to 1, as expressed by (4). GRPA is also a power-allocating technique involving channel gain values from other users against n^{th} users. Another researcher (Zhao *et al.*, 2020) proposed a scheme that discriminates between an original receiving plane and an inclined to receive plane. The proposed scheme does not change the core idea of the GRPA strategy but only adjusts the method of acquiring channel gains. It can be expanded and applied to other improved GRPA schemes besides the traditional GRPA scheme. Systematically, the calculation of GRPA values can be expressed in the equation as follows (Tao *et al.*, 2018):

$$\alpha_i = \frac{\frac{h_1}{h_i}}{1 + \frac{h_1}{h_i} + \cdots \frac{h_1}{h_N}}, \tag{3}$$

where h_N is the last N^{th} user. The power allocation factor has to be equal to the one as follows.

$$\sum_{i=1}^{N} \alpha_i = 1, \tag{4}$$

where range α is from zero to one ($0 < \alpha < 1$).

2.3. Superposition Code

Superposition coding is a technique that allows a single source to transmit information to multiple receivers simultaneously, as expressed by (5). In other words, it allows the transmitter to transmit multiple user information simultaneously. In order for the superposition code to function correctly on the receiver side, the transmitter must encode the relevant information for each piece of information (Chen and Ma, 2018). The transmitted information signal s is a linear superimposition to all users, as follows.

$$x = \sum_{i=1}^{n} \sqrt{\alpha_i}\, s_i t_b. \tag{5}$$

The information signal from the i^{th} user, s_i, the signal from the last user, s_n, and the bit duration, t_b, as given by (6) are parameters that define the superposition coding technique. The formula for t_b as shown below:

$$t_b = \frac{1}{B_r}\,, \tag{6}$$

where B_r is the bit rate.

2.4. Adaptive Successive Interference Cancellation

The received signal after SPC for each user is shown by (7), which contains interference information from other users. To decode its own information, the receiver must apply SIC to the received signal. SIC can be imagined by utilizing specifications on the difference in the strength of the transmitted signal between the desired signals. The basic idea of SIC is that the user signals are decoded sequentially. After one user signal is decoded, it must be subtracted from the combined signal before the next one is decoded. SIC in unipolar is less complex than bipolar decode due to the multiplication among CSI, power allocation, and time bit necessary for decoding threshold. The SIC method plays a crucial role in decoding information at the receiver, which can be expressed.

$$y_i = xh_i + N, \tag{7}$$

where N is initialized as the amount of Gaussian noise (Islam *et al.,* 2016). The SIC process starts by decoding the user with the highest received power using a hard decoding threshold, which is given by (8). The hard decoding threshold can be expressed as follows:

$$\overline{s_i} = \begin{cases} 1 & : y_i \geq \gamma_i \\ 0 & : y_i < \gamma_i \end{cases}, \tag{8}$$

where $\gamma_i = h_i \alpha_i t_b$ is the threshold for hard decision decoding, y_i is the received signal of the i^{th} user, and h_i and α_i are the channel gain from CSI and power allocation coefficients for the i^{th} user, respectively. After the first signal is decoded, the next user subtracts the decoded signal of the first user from its received signal as a cancellation formula, which can be expressed as follows.

$$\overline{y_{i+1}} = y_{i+1} - \left(\sqrt{\alpha_i} s_i h_{i+1} t_b\right). \tag{9}$$

After the cancellation is accomplished at the next user signal, the following user decodes immediately using its threshold hard decoding to obtain owned original information as written in (9). This study considered some critical parameters affecting each research scenario, as shown in Table 1.

Table 1 Research Parameter

	Parameter	Value
Room	Size	9 x 9 x 3 m
Transmitter	Type	LED
	Number of LED Bulb	1
	Transmitted Power	5 Watt
	Channel Model	LOS
	Bandwidth	20 MHz
Receiver	Detector Area	1 cm^2
	Field of View	70°
	Responsivity	0.55 A/W

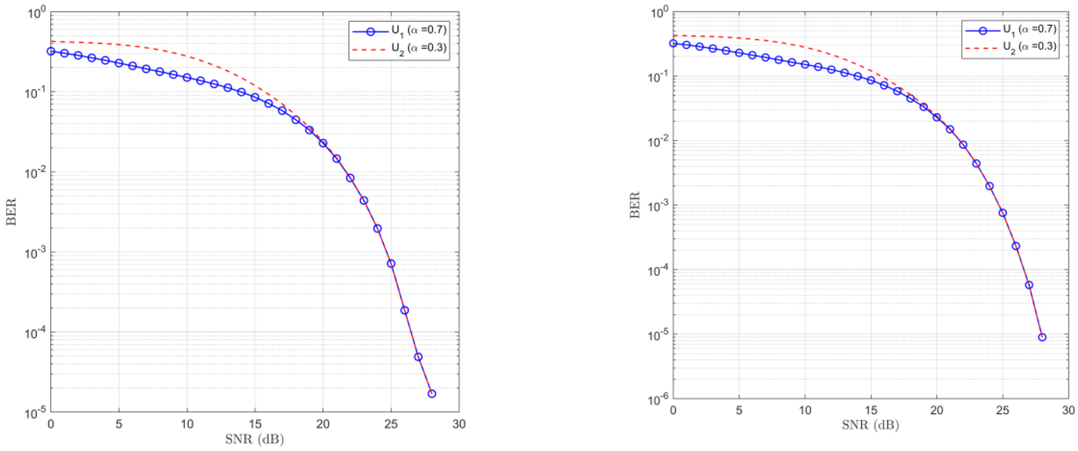
3. Results and Discussion

This section presents and analyzes the results obtained from tests conducted using predefined scenarios and parameters. The main objective of this research is to evaluate the performance of the adaptive SIC scheme and compare it with two other power allocation techniques, namely SPA and GRPA. Our statistical analysis highlights the importance of evaluating the performance of power allocation schemes using various statistical techniques to ensure the accuracy and reliability of the results.

3.1. SPA Performance

The simulation setup shown in Figure 2(a) involves the 1st user being far away at 7 m, while the 2nd user is closer to the lamp at a distance of 5 m. The power allocation is set to 70% for the 1st user and 30% for the 2nd user. At SNR of 20 dB, we observed a significant difference in the BER values, exceeding 10^{-3}. After the SNR surpasses 20 dB, the SPA performs similarly for both users. Further analysis revealed that the difference in transmission distance of 2 m did not affect the SPA's performance. Additionally, our proposed method achieved a higher bit rate and supported two users with almost the same level of performance compared to the research (Zhang *et al*., 2021). After extensive simulations of both users, we operated the research by moving the second user just under the lights; thus, the distance for the 2nd user is 3 meters.

We obtained the result that the SNR needed to be lower to achieve equality of performance. The SNR value of 17 dB becomes the point of performance similarity between the 1st and 2nd users and continues to experience decreased errors, as shown in Figure 2(b). We found that the longer the distance between users, the smaller the interference value, which made the SIC process more perfect. Compared to the first experiment, we learned that the 2nd user affects the performance value of both users because it has the closest transmission distance, just below the lights. At the same time, the 1st user who carried out the first decoding process did not experience any challenges.

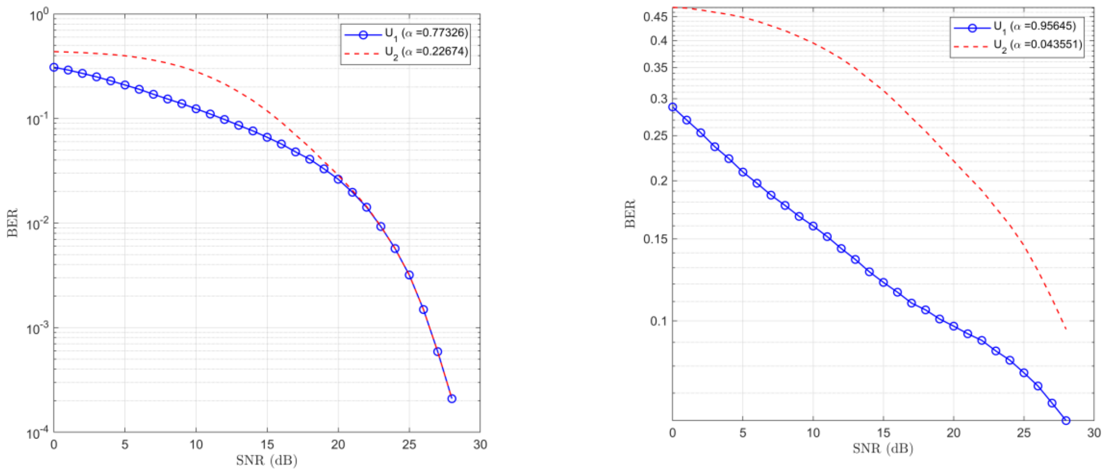


(a) (b)

Figure 2 Performance SPA for (a) distances 7 m and 5 m; (b) distances 7 m and 3 m, respectively

3.2. GRPA Performance

The results showed that the estimated power allocation values obtained by GRPA were not significantly different from those obtained by SPA, as seen in Figure 3(a). We observed that the power allocation values were highly sensitive to the VLC NOMA performance, which indicates the need for careful consideration when selecting a power allocation scheme.



(a) (b)

Figure 3 Performance GRPA for (a) distances 7 m and 5 m; (b) distances 7 m and 3 m, respectively

After proving that the SPA performs better after the 2nd user is placed right under the lights, we tested on GRPA. In GRPA, adaptive SIC is also used to test the performance of various power allocations. From the results of GRPA, the power allocation for the 1st user is 0.95645, and for the 2nd user is 0.043551, with the comparison of channel values. We analyzed that the power comparison between the 1st and 2nd users significantly affects adaptive-SIC performance. Due to distances between users being farther than before, the delta of power allocation for each user is greater. The first user has dominated superposition coding too much, making detection harder for the cancellation interferences process. Although GRPA is adaptive power allocation due to propagation distances, we also found that it cannot ensure the performance is fulfilled enough. Therefore, for GRPA, no user meets the BER target of less than 10^{-3} as in Figure 3(b). In addition, we proved that adaptive SIC is more suitable for use in SPA and that studying enhanced GRPA (EGRPA) has the possibility to improve performance.

3.3. Comparison of SPA and GRPA Performance

We compared the simulation results and theoretical values to evaluate the proposed power allocation scheme further. Figure 4 demonstrates that the simulation results have a gap match of around 10 dB with the theoretical values, which shows the effectiveness of the proposed power allocation scheme in improving the system performance. It should be noted that the theoretical values were obtained for a single user and not for NOMA with interference in the first user. The simulation results also indicate that the proposed adaptive SIC scheme outperforms both SPA and GRPA regarding user and system data rates. These results demonstrated that the proposed scheme could efficiently mitigate inter-user interference and enhance system performance. Therefore, the proposed method can be considered a potential solution to address the issues of inter-user interference and power allocation in NOMA systems.

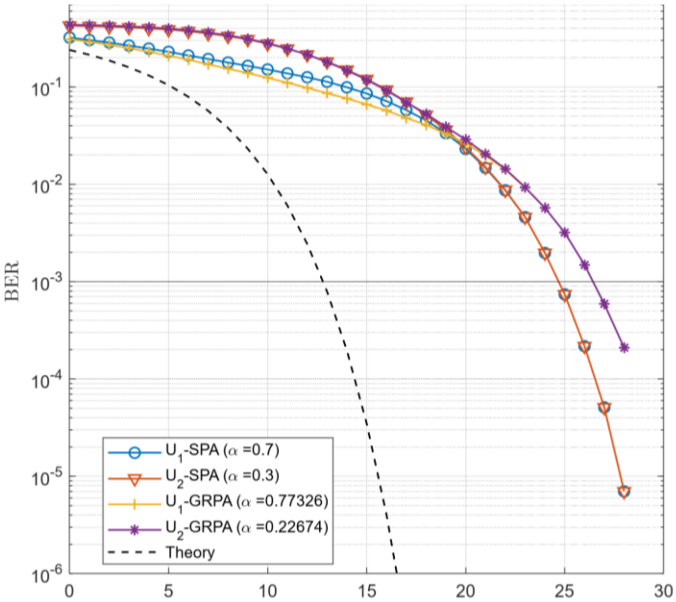


Figure 4 Performance GRPA and SPA for distances 7 m and 5 m

4. Conclusions

This study proposed adaptive SIC to decode high bit rates of up to 2 Gbps by sending one million bits. Simulations have been conducted in closed room conditions with 9 x 9 x 3 meters using one LED light as VLC. We conducted an adaptive-SIC test on two allocation powers, SPA and GRPA. In SPA, SNR is needed for identical performance on users about 20 dB, at the furthest user distance of 7 m and the nearest user 5 m. GRPA takes about 21 dB to produce BER performance below 10^{-3} at the same farthest and closest user position. After that, the user's position is changed from the nearest of 3 m, while the furthest remains 7 m to examine the relationship between the change in position and performance. Our simulations showed that when the nearest user position is changed, the (SPA) scheme is more stable compared to the (GRPA) scheme. The SNR value required by SPA is only 17 dB, while in GRPA, the value of SNR up to 25 dB is still not received. Finally, this research has the potential to be analyzed by different types of power allocation on PD NOMA. In addition, further studies on NOMA coded domain (CD) to compare performance against power domains can be done with different modulation types.

Acknowledgments

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