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조광제어를 고려한 MIMO-VLC 시스템의 전력 효율 분석

Power-efficiency Analysis of the MIMO-VLC System considering Dimming Control

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요 약 백색 발광다이오드(LEDs)는 형광등보다 경제적이며 높은 밝기, 수명, 내구성을 제공한다. 이러한 LED는 사람들의 일상생활과 밀접하게 연결되어 있기 때문에 LED의 조광제어는 에너지 절약과 삶의 질 향상에 중요한 요소이다. 이 LED를 사용하는 가시광통신시스템에서는 안테나 수에 비례해 채널 용량을 확보할 수 있다는 점에서 복수의 MIMO(입력 다중 출력) 기술이 많은 관심을 끌었다. 본 논문은 가시광통신(VLC) 시스템에서 적용된 공간-시간 블록 코드(STBC) 기법의 세 가지 변조의 전력 성능을 분석한다. 변조 방식은 RZ-OOK(Return-to-On-Ok), 가변 펄스 위치 변조(VPPM), 중첩 펄스 위치 변조(OPPM) 및 조광 제어를 적용하였다. 전력 요구사항과 전력 소비는 세 가지 종류의 변조 하에서 2×2 STBC-VLC 환경에서 전력 효율을 비교하는 지표로 사용되었다. 조광 제어가 각 변조 체계의 통신 성능에 영향을 미치는지 확인하였다. 확인 결과 VPPM은 세 가지 변조 중 소비량이 더 많았으며 OPPM은 VPPM에 비해 에너지 절감 효과를 보였다.

Abstract White light-emitting diodes (LEDs) are more economical than fluorescent lights, and provide high brightness, a high lifetime expectancy, and greater durability. As LEDs are closely connected with people's daily lives, dimming control of LED is an important component in providing energy savings and improving quality of life. In visible light communications systems using these LEDs, multiple input multiple output (MIMO) technology has attracted a lot of attention, in that it can attain the channel capacity in proportion to the number of antennas. This paper analyzes the power performance of three kinds of modulation in visible light communications (VLC) systems applied space-time block code (STBC) techniques. The modulation schemes are return-to-zero on-off keying (RZ-OOK), variable pulse position modulation (VPPM), and overlapping pulse position modulation (OPPM), and dimming control was applied. The power requirements and power consumption were used as metrics to compare the power efficiency in 2x2 STBC-VLC environments under the three kinds of modulation. We confirm that dimming control affects the communications performance of each modulation scheme. VPPM showed greater consumption among the three modulations, and OPPM showed energy savings comparable to VPPM.

Key Words : Dimming control, MIMO, Modulation, Power consumption, Power efficiency, Space-time block codes, Visible light communications

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Ⅰ. Introduction

Over the last few years, light-emitting diode (LED) lighting technology has developed rapidly. White LEDs consume approximately 20 times less power than conventional light sources and five times less power than fluorescent bulbs[1]-[4]. In addition LEDs offer high brightness, a long lifetime expectancy and greater durability. For this reason, white LEDs will soon replace fluorescent and incandescent lighting over the next couple of years. Visible light communications (VLC) technology using these LEDs has attracted considerable attention in wireless communications[5]-[7]. VLC has a basic on/off principle, with LEDs switching to light from electricity in a very short time. Because LEDs can switch faster than the human eye can perceive, they offer communications capabilities in addition to illumination. Currently, the replacement of LEDs is accelerating due to the government's policy of exclusion of incandescent lamps and the policy to promote LED lighting products. Because of this policy, it is not necessary to re-install the LED only for visible light communication, and the installation cost for the communication is reduced because communication is possible with the LED already installed for the illumination. In addition, since it is possible to communicate anywhere LED lighting is installed, it can be used in hospitals, aircrafts, and the like, which are not available in existing communication. Unlike the existing wireless communication, it has security function because it can communicate only in the lighting area. Many LEDs used for necessary lighting intensity offer the opportunity to transmit different data on each emitter. Multiple-input multiple-output (MIMO) is a method for multiplying the capacity of a radio link using multiple transmit and receive antennas to exploit multipath propagation[8]. An important component for effective use of MIMO-VLC systems and energy savings is dimming control. To achieve dimming control, one of the widely adopted solutions is pulse width modulation (PWM). When using a PWM scheme, the brightness of the LED lighting is related to the duty cycle, which is the amount of time the pulse is on[13]-[15]. Dimming schemes in VLC systems have been studied using on-off keying (OOK) and pulse-position modulation (PPM) over Poisson and Gaussian channels. According to the IEEE 802.15.7 VLC standard[11], OOK and variable pulse position modulation (VPPM) are supported for seamless compatibility with a constant current LED driver. Overlapping pulse position modulation (OPPM) is a promising modulation scheme that allows more than one pulse per pulse width. The scheme has some useful properties, such as equal energy signals and a low duty cycle. The OPPM method can achieve a higher channel capacity and communications rate[12].

This paper proposes an STBC-VLC system to increase the capacity and efficiency of a wireless. Among the MIMO schemes, space-time block code (STBC) technique is code that correlates signals transmitted from various antennas in time and space in order to improve performance security and reliability of transmission data. It supports a full coding rate for multiple transmissions with more than two transmit antennas. This scheme increases link reliability and system performance. In addition, it can be used to increase the capacity of coherent optical wireless communications, and to decrease the required optical power at the transmitter[9],[10].

We analyze the performance of modulation schemes in terms of power efficiency in STBC-VLC systems. For the performance comparison, three modulation schemes (return-to-zero on - off-keying (RZ-OOK), VPPM, and OPPM) were used. The remainder of this paper is organized as follows. Section 2 describes the system model, including the STBC transmitter, the channel model, and the receiver. Performance from the three kinds of modulation is compared in terms of power requirements and power consumption. The simulation results are presented in Section 3, and the paper is concluded in Section 4.

II. System Model

This study considered a $N_t \times N_r$ STBC-VLC system with intensity modulation and direct detection (IM/DD), where N_t is the number of transmitting antennas and N_r is the number of receiving antennas. Then the received signal vector is

$$r = RHx + n = RH(Fs + p) + n \quad (1)$$

where H denotes the $N_r \times N_t$ optical wireless MIMO channel matrix and n is the additive white Gaussian noise with zero mean where R is the photodiode responsivity. Before the data vector is sent through the optical channels, it will be firstly precoded by a precoding matrix F. We have. $x = Fs$, $x = [x_1, \cdots x_{N_t}]^T$ is the transmitted signal, $x_i = w_i s = \sum_{j=1}^{K} w_{ij} + p_i$, where w_i is the i^{th} row of F and w_{ij} is the element in the i^{th} column and j^{th} row of F, p_i is the DC offset vector. $s = [s_1, \cdots, s_K]^T$ denote the real source data vector, and n_j is the additive white Gaussian noise; h_{ij} is an element of the i^{th} row and the j^{th} column in channel matrix H and can be estimated by summing the power of all the i^{th} transmitter to reach the j^{th} receiver. The line-of-sight (LOS) channel $h_{ij} \in H$ can be written as

$$h_{ij} = \begin{cases} \frac{A_{rx}}{r_{ij}^2} R_0(\phi_{ij}) \cos(\psi_{ij})\, T_f(\psi_{ij})\, v(\psi_{ij}), & 0 \le \psi_{ij} \le \Psi_c \\ 0, & \psi_{ij} > \Psi_c \end{cases} \quad (2)$$

where A_{rx} is the detector area, r is the distance between the transmitter and receiver, ϕ_{ij} is the emission angle, $R_0(\phi_{ij})$ is the Lambertian radiant intensity, ψ_{ij} is the angle of incidence, and Ψ_c is the field of view (FOV) of the photodiode. $T_f(\psi_{ij})$ is the gain of an optical filter and $v(\psi_{ij})$ is the gain of an optical concentrator[19]-[21]. As show in Fig. 1, a 5m× 5m×3m room, two transmitters, and two receivers were assumed. As the STBC transmission scheme, a modulated pulse via RZ-OOK, VPPM, or OPPM at the transmitter is transmitted to the detector.

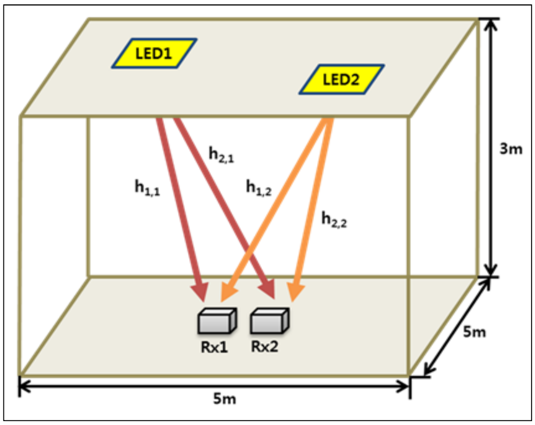

Fig. 1. Model of the 2×2 STBC-VLC system
그림 1. 2×2 STBC-VLC 시스템

III. Analysis of Power Efficiency in STBC-VLC Systems

1. Modulation Scheme for Dimming Control

To achieve dimming control, one of the widely adopted solutions is PWM. When using a PWM scheme, the brightness of LED lighting relates to the duty cycle, which is the amount of time the pulse is on[16]. We can dim the light by reducing the pulse width or brighten the light by increasing the pulse width. Dimming control methods of RZ-OOK and VPPM change the pulse width according to the duty cycle (D_c) [17]. The dimming ranges (d_c) for RZ-OOK and VPPM, respectively, are

$$0 < d_{c_{RZ-OOK}} = \frac{D_c}{2} \le \frac{1}{2} \quad (3)$$

$$0 < d_{c_{VPPM}} = D_c \le 1 \quad (4)$$

For OPPM, the ratio of the number of pulses and the number of chips is D_c [14]. The dimming ranges for OPPM, respectively, are

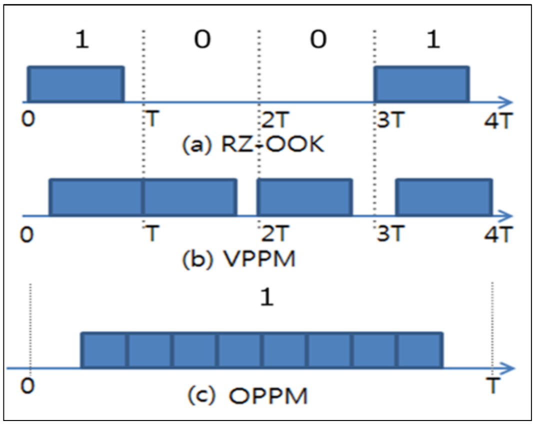

Fig. 2. Example of symbol structures with D_c = 0.8 of modulation schemes
그림 2. 변조 방식들의 D_c = 0.8 일 때 구조 예시

$$\frac{1}{n} \leq d_{cOPPM} = \frac{w}{n} \leq \frac{n-1}{n} \tag{5}$$

Fig. 2 is an example of when the duty cycle is 0.8. It shows the differences in the modulation schemes as well as a method of dimming control.

2. Analysis of Power Requirements

Mathematically, the dimming control of VLC requires [18]

$$E[y_i] = \sum_{k=1}^{N_t} w_{i,k} E[s_k] + p_i = P_T \tag{6}$$

where E[·] denotes the statistical expectation, $\boldsymbol{P_T} = [P_{T,1}, \cdots, P_{T,Nt}]^T$ is the average drive current of the LEDs required for the target dimming level. $w_{i,k}$ denotes the element in the i^{th} row and the j^{th} column of the precoder matrix F. Due to the nonlinear LED transfer characteristic, the transmitted signal is constrained to a limited linear dynamic range, i.e., we have $P_{L,i} \leq x_i \leq P_{H,i}$ where $P_{L,i}$ and $P_{H,i}$ denote the minimum and maximum drive current permitted by the i^{th} LED, respectively [9]. The dimming level of the i^{th} LED is defined as $\varsigma = (P_{T,i} - P_{L,i})/(P_{H,i} - P_{L,i})$. From (6), we can observe that both w_i and p_i have to be adjusted simultaneously to achieve the target dimming level. Thus, dimming/brightness control can be well supported in the proposed STBC-VLC system.

The receiver was assumed to perfectly know the effective channel H and the maximum likelihood (ML) detection was used. ML detection was used to find the lowest value from the entire transmitted signal vector in channel H. Therefore, it was optimal in the sense of minimizing the error probability [22]. This can be written as

$$\hat{x}_{ML} = \underset{x \in A^M}{\arg min} \parallel y - Hx \parallel^2 \tag{7}$$

Pairwise error probability (PEP) of ML detection is the probability that the receiver mistakes transmitted signal vector $x^{(k)}$ for another vector $x^{(v)}$, given the information about channel matrix H [23]. Conditioned on channel H, the PEP of ML detection can be calculated as follows:

$$P_{PEP}(x^{(k)} \to x^{(v)} | H) = Q\left(\sqrt{\frac{SNR}{2N_t} \parallel H(x^{(k)} \to x^{(v)}) \parallel_F^2}\right) \tag{8}$$

where $Q(x) = \int_x^{\infty} dt \frac{1}{\sqrt{2\pi}} exp(-\frac{t^2}{2})$ is the Q-function, signal-to-noise ratio (SNR) is . And denotes the matrix Frobenius norm, $\parallel H(x^{(k)} \to x^{(v)}) \parallel_F^2$ is the pairwise Euclidean distance at the receiver[24]. BER applying the PEP can be determined from

$$\begin{aligned} BER_{SISO} &= Q\left(\frac{d_{\min}}{2\sqrt{N_0}}\right) = Q\left(\frac{E_s}{N_0}\right) \\ \to BER_{MIMO} &= Q\left(\frac{d_{\min}}{2N_t\sqrt{N_o}} \parallel H\left(x^{(k)} \to x^{(v)}\right) \parallel_F^2\right) \end{aligned} \tag{9}$$

where $\parallel H(x^{(k)} \to x^{(v)}) \parallel_F^2 = \left(\sqrt{\sum_{n_r=1}^{N_r} \sum_{n_t=1}^{N_t} |h_{r,n_t}|^2}\right)^2$, $d_{\min}$ is the minimum Euclidean distance and N0 is the white Gaussian noise power spectral density. To obtain the power requirement of each modulation, first, the minimum Euclidean distances of the modulations [14],[17] are determined as follows:

$$d_{RZ-OOK} = 2P_T\sqrt{\frac{2d_c}{R_b}} \quad 0 < d_c \leq 0.5 \tag{10}$$

$$d_{VPPM} = \begin{cases} P_T\sqrt{\frac{2d_c}{R_b}} & 0 < d_c < 0.5 \\ P_T\sqrt{\frac{2(1-d_c)}{R_b}} & 0.5 < d_c < 1 \end{cases} \tag{11}$$

$$d_{OPPM} = P_T\sqrt{\frac{2(n/w)\log_2(n-w+1)}{wR_b}} \quad \frac{1}{n} \leq d_c \leq \frac{n-1}{n} \tag{12}$$

where R_b is the bit rate, d_c is the dimming of RZ-OOK and VPPM, and w/n is the dimming in OPPM. OPPM modulation is divided into n chips for the symbol period, and w light pulses are transmitted in a row. Dimming control in OPPM was obtained by varying w in the range $1 \leq w \leq n-1$ and was fixed to n. The BER for each of the modulations was obtained as follows using (10), (11), and (12) as applied to (9).

$$BER_{RZ-OOK} = Q\left(\sqrt{\frac{2d_c}{N_0R_bN_t^2}}\left(\sqrt{\sum_{n_r=1}^{N_r}\sum_{n_t=1}^{N_t}|h_{n_rn_t}|^2}\right)^2\right) \tag{13}$$

$$0 < d_c \leq 0.5$$

$$BER_{VPPM} \begin{cases} Q\left(P_T\sqrt{\frac{d_c}{2N_0R_bN_t^2}}\left(\sqrt{\sum_{n_r=1}^{N_r}\sum_{n_t=1}^{N_t}|h_{n_rn_t}|^2}\right)^2\right) \\ \qquad 0 < d_c \leq 0.5 \\ Q\left(P_T\sqrt{\frac{1-d_c}{2N_0R_bN_t^2}}\left(\sqrt{\sum_{n_r=1}^{N_r}\sum_{n_t=1}^{N_t}|h_{n_rn_t}|^2}\right)^2\right) \\ \qquad 0.5 \leq d_c < 1 \end{cases} \tag{14}$$

$$BER_{OPPM} = Q\left(P_T\sqrt{\frac{(n/w)\log_2(n-w+1)}{2wN_0R_bN_t^2}}\left(\sqrt{\sum_{n_r=1}^{N_r}\sum_{n_t=1}^{N_t}|h_{n_rn_t}|^2}\right)^2\right) \tag{15}$$

$$\frac{1}{n} < d_c \leq \frac{n-1}{n}$$

Table 1. Power requirement of each modulation scheme
표 1. 각 변조 방식의 전력 요구량

Modulation	Power requirement
RZ-OOK	$\sqrt{\frac{N_0R_bN_t^2}{2dc\left(\sqrt{\sum_{n_r=1}^{N_r}\sum_{n_t=1}^{N_t}\|h_{n_rn_t}\|^2}\right)^2}}\, Q^{-1}(BER)$ $0 < d_c \leq 0.5$
VPPM	$\begin{cases} \sqrt{\frac{2N_0R_bN_t^2}{dc\left(\sqrt{\sum_{n_r=1}^{N_r}\sum_{n_t=1}^{N_t}\|h_{n_rn_t}\|^2}\right)^2}}\, Q^{-1}(BER) \\ \quad 0 < d_c \leq 0.5 \\ \sqrt{\frac{2N_0R_bN_t^2}{(1-dc)\left(\sqrt{\sum_{n_r=1}^{N_r}\sum_{n_t=1}^{N_t}\|h_{n_rn_t}\|^2}\right)^2}}\, Q^{-1}(BER) \\ \quad 0.5 \leq d_c < 1 \end{cases}$
OPPM	$\sqrt{\frac{2wN_0R_bN_t^2}{\frac{nlog_2M}{w}\left(\sqrt{\sum_{n_r=1}^{N_r}\sum_{n_t=1}^{N_t}\|h_{n_rn_t}\|^2}\right)^2}}\, Q^{-1}(BER)$ $\frac{1}{n} < d_c \leq \frac{n-1}{n}$

Assuming that the three modulations have the same BER, it is possible to compare the power requirement of each modulation to achieve a given BER. At this time, P_T becomes P_{req} in (13)-(15). Table 1 summarizes the equations of the power requirements.

3. Analysis of Power Consumption

Power consumption can be determined in a STBC-VLC environment. The power consumption differs according to the modulation for each different transmission power. The following equations can be used to determine the power consumption.

$$P_T \times R = \overline{E}_bR_b \times \frac{2\pi d^2}{(m+1)Acos^m(\phi)\,T_s(\psi)\,g(\psi)\cos(\psi)} \tag{16}$$

$$P_c = N_{\leq D} \times P_T \tag{17}$$

where N_{LED} is the number of rows in an LED panel. First, the required energy per bit $\overline{E_b}$ was determined in order to obtain the transmission power. In (13)-(15), regarding BER, energy per bit E_b represents $E_b = P_r/R_b$, where P_r is the received power. The energy per bit of RZ-OOK is expressed as follows:

$$E_{b,RZ-OOK} = \frac{4d_c P_T^2}{R_b N_t^2}\left(\sqrt{\sum_{n_r=1}^{N_r}\sum_{n_t=1}^{N_t}|h_{r,n_t}|^2}\right)^2 \quad 0 < d_c \le 0.5 \tag{18}$$

Equation (13) applying (18) can be re-written as follows $BER_{RZ-OOK} = Q(\sqrt{\frac{E_{b,RZ-OOK}}{2N_0}})$. The required energy per bit is

$$\overline{E}_{b,RZ-OOK} = 2N_0(Q^{-1}(BER))^2 \tag{19}$$

Like the RZ-OOK scheme, VPPM and OPPM can obtain the required energy per bit and the energy per bit using (14) and (15). The energy per bit for VPPM is expressed as follows:

$$E_{b,VPPM} = \begin{cases} \frac{2d_c P_T^2}{R_b N_t^2}\left(\sqrt{\sum_{n_r=1}^{N_r}\sum_{n_t=1}^{N_t}|h_{n_r n_t}|^2}\right)^2 & 0 < d_c \le 0.5 \\ \frac{2(1-d_c)P_T^2}{R_b N_t^2}\left(\sqrt{\sum_{n_r=1}^{N_r}\sum_{n_t=1}^{N_t}|h_{n_r n_t}|^2}\right)^2 & 0.5 \le d_c < 1 \end{cases} \tag{20}$$

Applying (17) to (11), the required energy per bit under VPPM can be expressed as

$$\overline{E}_{b,VPPM} = \begin{cases} 4N_0(Q^{-1}(BER))^2 & 0 < d_c \le 0.5 \\ 4N_0(Q^{-1}(BER))^2 & 0.5 \le d_c < 1 \end{cases} \tag{21}$$

The required energy per bit for OPPM can be obtained using the same method:

$$E_{b,OPPM} = \frac{(n/w)\log_2(n-w+1)P_T^2}{2wR_b N_t^2}\left(\sqrt{\sum_{n_r=1}^{N_r}\sum_{n_t=1}^{N_t}|h_{n_r n_t}|^2}\right)^2 \quad \frac{1}{n} < d_c \le \frac{n-1}{n} \tag{22}$$

$$\overline{E}_{b,OPPM} = N_0(Q^{-1}(BER))^2 \tag{23}$$

Using (19), (21), and (23) obtained from above, the transmitted power of (16) can be obtained as follows:

$$P_{T,RZ-OOK} = \frac{1}{R}\sqrt{\frac{2N_0(Q^{-1}(BER))^2 R_b}{4d_c}\frac{N_t^2}{\left(\sqrt{\sum_{n_r=1}^{N_r}\sum_{n_t=1}^{N_t}|h_{n_r n_t}|^2}\right)^2}} \quad 0 < d_c \le 0.5 \tag{24}$$

$$P_{T,VPPM} = \begin{cases} \frac{1}{R}\sqrt{\frac{4N_0(Q^{-1}(BER))^2 R_b}{2d_c}\frac{N_t^2}{\left(\sqrt{\sum_{n_r=1}^{N_r}\sum_{n_t=1}^{N_t}|h_{n_r n_t}|^2}\right)^2}} \\ \frac{1}{R}\sqrt{\frac{4N_0(Q^{-1}(BER))^2 R_b}{2(1-d_c)}\frac{N_t^2}{\left(\sqrt{\sum_{n_r=1}^{N_r}\sum_{n_t=1}^{N_t}|h_{n_r n_t}|^2}\right)^2}} \end{cases} \quad 0.5 \le d_c < 1 \tag{25}$$

$$P_{T,OPPM} = \frac{1}{R}\sqrt{\frac{N_0(Q^{-1}(BER))^2 2wR_b}{(n/w)\log_2(n-w+1)}\frac{N_t^2}{\left(\sqrt{\sum_{n_r=1}^{N_r}\sum_{n_t=1}^{N_t}|h_{n_r n_t}|^2}\right)^2}} \quad \frac{1}{n} \le d_c \le \frac{n-1}{n} \tag{26}$$

By placing (24)-(26) as calculated into (17), the power consumption can be represented as listed in Table 2. In a STBC-VLC environment, SNR is the received signal-to-noise ratio, defined as

$$SNR = \frac{E_s}{N_0} = \frac{r^2 P_r^2}{N_0 R_b} = \frac{r^2 P_T^2}{N_0 R_b N_r^2}\left(\sum_{i=1}^{N_r}\sum_{j=1}^{N_t} h_{ij}\right)^2 \tag{27}$$

where $P_r = \frac{1}{N_r}\sum_{i=1}^{N_r}\sum_{j=1}^{N_t} h_{ij}P_T$ is the average received power. In the next section, the relationship among power requirement and power consumption due to dimming and between power consumption and SNR was simulated in three modulation schemes (RZ-OOK, VPPM, and OPPM). This was based on the environment shown in Fig. 1 and Table 3 using STBC.

Ⅳ. Simulation Results and Analysis

Fig. 1 shows a general office space with two LED lighting units on the ceiling. Suppose that the communications terminal is placed on the floor of the room, the receiver is facing up, the transmitter is facing down, and a channel exists between the lights and the terminal. The channel consists of a number of line-of-sight paths from the units to the terminal. Table 3 lists the parameters used in the simulation based on the parameters from other studies[25]-[27]. Fig. 3 shows the results of applying the LOS channels in a 2x2 STBC-VLC system. This figure shows that the maximum SNR is 36.21dB and the minimum SNR is 22.95dB.

Table 2. Power consumption of each modulation scheme
표 2. 각 변조 방식의 전력 소비량

Modulation	Power consumption
RZ-OOK	$\frac{N_t}{R}\sqrt{\frac{2N_0R_bN_t^2(Q^{-1}(BER))^2}{4d_c\left(\sqrt{\sum_{n_r=1}^{N_r}\sum_{n_t=1}^{N_t}\lvert h_{n_rn_t}\rvert^2}\right)^2}} \quad 0<d_c\leq 0.5$
VPPM	$\begin{cases}\frac{N_t}{R}\sqrt{\frac{4N_0R_bN_t^2(Q^{-1}(BER))^2}{2dc\left(\sqrt{\sum_{n_r=1}^{N_r}\sum_{n_t=1}^{N_t}\lvert h_{n_rn_t}\rvert^2}\right)^2}} & 0<d_c\leq 0.5\\ \frac{N_t}{R}\sqrt{\frac{4N_0R_bN_t^2(Q^{-1}(BER))^2}{2(1-dc)\left(\sqrt{\sum_{n_r=1}^{N_r}\sum_{n_t=1}^{N_t}\lvert h_{n_rn_t}\rvert^2}\right)^2}} & 0.5\leq d_c<1\end{cases}$
OPPM	$\frac{N_t}{R}\sqrt{\frac{2wN_0R_bN_t^2(Q^{-1}(BER))^2}{\frac{nlog_2M}{w}\left(\sqrt{\sum_{n_r=1}^{N_r}\sum_{n_t=1}^{N_t}\lvert h_{n_rn_t}\rvert^2}\right)^2}} \quad \frac{1}{n}\leq d_c\leq\frac{n-1}{n}$

Fig. 4 shows the power requirement for each modulation scheme according to dimming. First, in case of RZ-OOK with dimming condition from 10% to 50%, the amount of power required decreases as the dimming value increases, and the minimum amount of power is required when dimming is 50% in the entire dimming range. The maximum power requirement is when the dimming is 10% and the minimum power requirement is when the dimming is 50%. The difference between the two is about twice. Second, as the dimming value increases from 10% to 50%, the power requirement of the VPPM decreases. And, the power requirement of VPPM increase as the dimming value increases from 50% to 90%. The minimum power is required when dimming is 50% in the entire dimming range, and the difference between the maximum power requirement and the minimum power requirement is approximately 2 times. Finally, as dimming increases, the OPPM draws a large rising curve because it sends successive pulses. As the dimming value increases over the entire dimming range, the power requirement of the OPPM increases and the difference between the minimum power requirement and the maximum power requirement is about 10. Comparing the three modulations, the power demand at 40% or less is OPPM < RZ-OOK < VPPM, and RZ-OOK < OPPM < VPPM at 50%. At more than 50%, OPPM requires less power than VPPM. In the full range of dimming, VPPM requires the greatest power, and OPPM requires the least power.

Fig. 5 shows the power consumption of the three modulations for SNR when dimming is 30% and 50%. The range of SNR is derived from fig. 3. The power consumption increases with increasing SNR. First, when the dimming is 30%, the power consumption is in the order of OPPM < RZ-OOK < VPPM. The difference between the VPPM with the largest power consumption and the OPPM with the lowest power consumption is about three times.

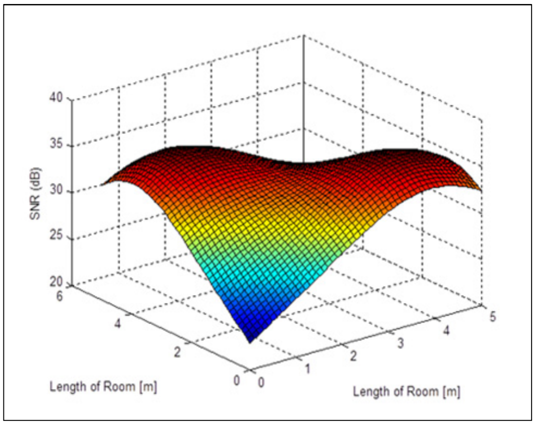

Fig. 3. SNR performance of a 22 STBC-VLC system
그림 3. 22 STBC-VLC 시스템의 SNR 성능

Next, when dimming is 50%, power consumption is in the order of RZ-OOK < OPPM < VPPM, unlike in the case of 30%, and the VPPM with the highest power consumption and the RZ-OOK with the lowest power consumption differ about 1.8 times. Compared with the modulation, VPPM consumes a large amount of power when the dimming is 30%, which is about 1.3 times greater than when the dimming is 50%. In the case of RZ-OOK, too, the power consumption is about 1.4 times larger when the dimming is 30% than when the dimming is 50%. On the other hand, in the case of OPPM, when the dimming is 50%, the power consumption is larger than the case where the dimming is 30%, which is about twice the difference. On the whole, VPPM has a large power consumption value and OPPM has a low power consumption value.

Table 4 lists the power consumption of each modulation scheme in accordance with dimming. In the case of RZ-OOK, the power consumption decreases as the dimming increases from 10% to 50%. In this case, the difference in power consumption between 10% dimming with the highest power consumption and 50% dimming with the lowest power consumption is about twice.

Table 3. The STBC-VLC environment of simulation
표 3. STBC-VLC 시뮬레이션 환경

Parameter	Value
Room size	5m x 5m x 3m
LED1 array location	[0.4m 4.6m 3m]
LED2 array location	[4.6m 0.4m 3m]
Distance of each receiver	50cm
FOV at the receiver	90 deg.
Photodiode responsibility	0.4(A/W)
Gain of optical filter	1
Optical concentrator	5
Amplifier bandwidth (Ba)	50MHz
Noise bandwidth factor (I2)	0.562
Data rate (Rb)	100Mbps

For VPPM, as the dimming increases from 10% to 50%, the power consumption decreases, and as the dimming increases from 50% to 90%, the power consumption increases. The difference between the largest power consumption and the lowest power consumption is about two times. For OPPM, the power consumption increases as the dimming increases from 10% to 90%. The difference between the maximum power consumption of 90% dimming and the minimum power consumption of 10% dimming is about 15 times. Among the three modulations, VPPM has high power consumption at 23.13W when dimming is 10% and 90%. When dimming is less than 40%, RZ-OOK has higher power consumption than OPPM. On the other hand, the power consumption of OPPM is higher than RZ-OOK when dimming is more than 40%. For RZ-OOK, the dimming condition is limited to 50%. In this dimming range, RZ-OOK appears to have approximately 50% lower power consumption than VPPM. A comparison of power efficiency performance under the same conditions, when BER is 10^{-6}, showed that RZ-OOK saves approximately 50% compared to VPPM. Inaddition, based on VPPM, OPPM shows energy savings of approximately 94.5%, 84.12%, 30.44%, and 9.99% at 10%, 20%, 50%, and 90% dimming, respectively.

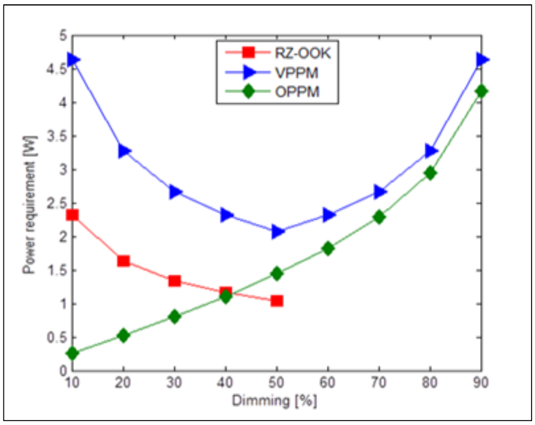

Fig. 4. Power requirement of each modulation scheme in a 2x2 STBC-VLC system
그림 4. 2x2 STBC-VLC 시스템 내 변조 방식별 전력 요구량

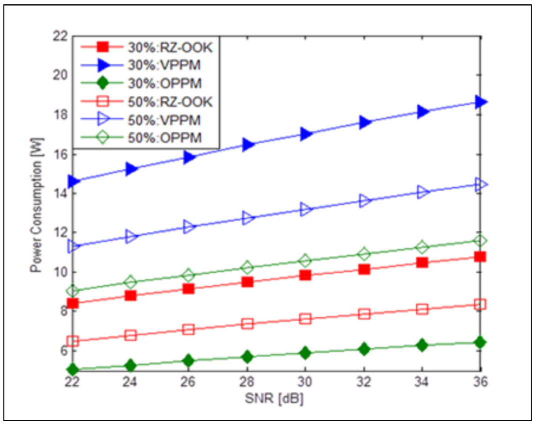

Fig. 5. Power consumption vs. SNR when dimming is 30% and 50%
그림 5. 조광이 30%, 50%일 때 전력 소비량 대 SNR

V. Conclusion

This paper analyzed an STBC system by simulating the power requirement and the power consumption of modulation methods under dimming control. In terms of power requirement results, as dimming increases, OPPM sends consecutive pulses, draws a large ascending curve, but requires less power than the other modulations.

Table 4. Power consumption of each modulation scheme in accordance with dimming
표 4. 조광에 따른 각 변조 방식의 전력 소비량

Dimming	RZ-OOK	VPPM	OPPM
10%	11.57	23.13	1.269
20%	8.178	16.36	2.598
30%	6.677	13.35	4.006
40%	5.783	11.57	5.522
50%	5.172	10.34	7.193
60%	.	11.57	9.108
70%	.	13.35	11.45
80%	.	16.36	14.7
90%	.	23.13	20.82

VPPM requires double the highest power of the other modulations. Comparing the three modulations, the power demand at 40% or less is OPPM < RZ-OOK < VPPM, and RZ-OOK < OPPM < VPPM at 50%. In the full range of dimming, VPPM requires the greatest power, and OPPM requires the least power.

In a comparison of power consumption and SNR when dimming is 30% and 50%, power consumption increases with an increasing SNR. When the dimming is 30%, the power consumption is in the order of OPPM < RZ-OOK < VPPM. When dimming is 50%, power consumption is in the order of RZ-OOK < OPPM < VPPM, unlike in the case of 30%. When dimming is 30% and 50%, the power consumption by VPPM is the highest. OPPM at 30% dimming and RZ-OOK at 50% dimming consume the lowest power. On the whole, VPPM has a large power consumption value and OPPM has a low power consumption value.

Among the three modulations, VPPM has high power consumption at 23.13W when dimming is 10% and 90%. When dimming is less than 40%, RZ-OOK has higher power consumption than OPPM. On the other hand, the power consumption of OPPM is higher than RZ-OOK when dimming is more than 40%. For RZ-OOK, the dimming condition is limited to 50%. A comparison of power efficiency performance under the same conditions, where BER is 10^{-6}, showed that RZ-OOK saves approximately 50%, compared to VPPM. In addition, based on VPPM, OPPM shows an energy saving of approximately 9.99% and up to 94.5%, depending on the dimming conditions. Through this result, we confirmed that dimming control affects the communications performance of each modulation scheme. And among the three modulations, OPPM modulation has good power efficiency better than RZ-OOK and VPPM.

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