Flicker-Optimized Visible Light Communication: A Modulation-Dependent Trade-Off Between Data Rate, Ber, And Human-Centric Performance

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Using Light Emitting Diodes (LEDs), Visible Light Communication (VLC) has two uses: lighting and sending data. However, fast on–off switching for data modulation causes flickering that can negatively impact human health even at imperceptible frequencies. Current flickering reduction strategies do not provide accurate measurement of flickering generated by modulation schemes such as PPM and DPPM. Worse channel conditions decrease data rates, thereby increasing flicker duration; nonetheless, earlier research disregards the trade-offs between flickering and communication performance. This study introduces a new flicker estimation technique for PPM and DPPM, examining how empty slots affect flicker. We investigate the balance among flickering rate, data rate, and BER to optimize VLC systems for both data transmission and human health**.** Using a threshold-based method derived from biological research, we simulate flickering. Theoretical analysis looks at the OFF cycles in PPM/DPPM symbols, and simulations compare the flickering rate, data rate, and BER for different modulation orders (4PPM to 8PPM) under different slot lengths. The findings reveal that shorter symbol durations ($T_s = 2\ ms$), which correspond to higher data rates, generate insignificant LED flashing, whereas longer symbol durations ($T_s = 10\ ms$), which correspond to lower data rates, increase flickering. But longer symbol durations provide better BER performance than shorter ones. DPPM also lowers the flickering rate by about 50% compared to PPM by removing unnecessary empty slots while still providing almost twice the data rate of PPM. Higher-order modulation (8PPM) lowers flickering but degrades BER (10^{-1} *to* $10^{-1.3}$), while lower-order modulation (4PPM) enhances BER (10^{-3} *to* $10^{-2.8}$) at the cost of more flickering. Moreover, to statistically validate the simulation results, each experiment was repeated 30 independent times using different random binary sequences. The mean and standard deviation of the flickering rate and BER were computed. This study offers a quantitative framework to create flicker-aware VLC systems, emphasizing DPPM for settings prone to flicker and directing modulation choice for applications where performance is critical.

Keywords: Flicker Mitigation Technique, IEEE Standard 1789 Analysis, Optical Wireless Communication, Photobiological Safety Metrics, Pulse Interval Modulation.

Introduction:

VLC has been a prevalent research area lately. LEDs have now been extensively used in our daily lives, such as general lighting, billboards, traffic light, etc. These LEDs can be deployed as transmitters for VLC. Many studies of the VLC systems use different schemes to solve the illumination, flickering and communication problems and produce high-performance systems [1][2][3][4][5][6].

The flickering light emission can cause numerous side effects, including retinal stress, increased fatigue, headaches, and reduced visual comfort in prolonged exposure scenarios. Thus, studies on the impact of the flickering light on vision have appealed to increasing attention. It has been exhibited that experimental animals' sustained exposure to conventional covered lighting has been linked with reproductive deviations and augmented vulnerability to cancer [7]. Studies in individuals also show increased exhaustion, lessened performance, reduced immunologic reflexes, reduced basic fitness and compromised fertility under bright, fluorescent or cool white light [8]. The flickering light increases retinal vessel diameters in humans. The effects of flickering light on retinal vessels in diabetic patients are investigated in [9], however, flicker stimulation increased retinal blood flow by +59±20%. A non-flickering 0.10 km far across RGB VLC communication based on a complementary metal oxide semiconductor (CMOS) camera is explored in [10]. A code is designed in [11] which uses finite-state machines and provide concurrently a coding gain and mitigates the flickering. The codes have the supplementary benefit of being optimally soft-decision decodable using the Viterbi algorithm. An efficient and flicker-free Forward Error Correction (FEC) coding scheme based on Polar Codes (PC) is proposed in [12], to improve the transmission efficiency of dimmable VLC systems. A novel VLC data encoding algorithm is proposed in [13] which uses the bit shuffling to mitigate the flickering, improve transmission efficiency, and reduce hardware overheads. The bit reordering with an Omega network can produce code words vigorously, which assures short runs of sequential 0's or 1's, prevention of worst-case bit strings, and a quite short code length. A simple encoding structure is proposed in [14] which provides flicker-free and enhances the transmission effectiveness compared to PC with and without run-length-limited coding and improves the significant BER performance. A VLC neural network (VLCnet) deep learning-based method is proposed in [15], the flickering is reduced, and sustaining a certain illumination level is achieved. However, the Flicker-Reducing Activation Units (FRAU) are proposed which is the key part of VLCnet. These trials are insufficient in our analysis as they depict the flicker of lighting of deterministic optical waves and do not compute the effect of the parameters of transmission systems.

There has been arising apprehension about the health effects of lighting because of "invisible" flicker [16]. Most individuals are incapable of observing flicker in light beyond 0.06 kHz, but there remain significant genetic consequences. Electro radiogram reactions denote that invisible flicker is conveyed over the retina, even up to 0.2 kHz [17][18]. Some visual anxiety scientists have advised that this flicker may lead to headaches and eye strain for an extensive reference list on the health effects of flicker [19]. Other magnetic ballast luminous is known to have flicker at two times the AC Mains line frequency (0.1 kHz/0.12 kHz). This is likewise the case with latest LED illumination technologies. IEEE Standards P1789 group on LED flicker is investigating these concerns and presenting recommended practices to the public. The flickering mitigation schemes are addressed in [11][12][13], however, in this paper the novel scheme is used to measure the flickering rate, and it is resolved via different modulation schemes by using different order of modulation. The trade-off between order of PPM, DPPM, data rate and bit error rate (BER) and flickering rate are investigated. The objective of this research resolves the flicking problem in long term health. The health problem due to various flickering technical is addressed in [16][17][18][19], which make the significance of importance contribution of this research in the field of VLC. The authors in

[20] investigated the therapeutic potential of 0.04 kHz light stimulation for chronic pain management. Their results connected analgesic actions to the retina-central amygdala pathway, where increased extracellular adenosine inhibited nociceptive signaling and pain memory development. Study [21] presented a hybrid burst and frequency mode control for single-stage LED drivers that lowers flicker while retaining high efficiency, a power factor of 0.97, and adherence to IEEE 1789-2015. Study [22] showed that heterochromatic 0.04 kHz amber red flicker elicited more robust visual evoked responses with less discomfort for Alzheimer's therapy compared to standard white stimulation. According to a VLC survey for Extended Reality applications, micro-LEDs, hybrid VLC RF architectures, and new methods with high bandwidth and low latency were highlighted [23]. Although low frame rates constrained sophisticated MIMO capabilities, a low-cost VLC platform using cheap gear attained consistent short-range communication [24].

Recent research has looked at flicker monitoring, adaptive visual stimulation, display optimization, lighting safety, and VLC receiver technologies. While tailored checkerboard flicker patterns boosted BCI signal reliability [25], low-cost optical sensors with Raspberry Pi have made practical flickr measurement possible according to IEEE 1789 2015 [26]. Studies of OLED displays found flickering and stroboscopic effects, especially at low brightness levels [27]. Studies of LED, fluorescent, and halogen lighting associated too much temporal light modulation with possible cognitive and biological problems [28]. VLC receiver research has concentrated on sensitivity, scalability, security, ambient light interference, modulation, architecture, and detector materials [29]. The study improves the Perceptual Modulation flicker metric by reducing spectral leakage through windowing techniques and correction factors [30].

Taken together, these studies show that flickers are a major issue for lights, displays, and VLC systems, emphasizing the need to find a balance between communication effectiveness and human-centered lighting safety. However, current studies mainly focus on flicker reduction, receiver design, and communication performance separately, with limited analysis of the link between flickering rate, data rate, and BER under various channel conditions. This gap drives the development of a framework that concurrently assesses communication efficiency, channel degradation, symbol duration, BER, and flicker perception in next-generation VLC systems.

Current flicker definitions do not properly separate flicker frequencies or consider communication situations. Increased distance, obstructions, and channel degradation in VLC can lower the data rate and lengthen the symbol period, therefore perhaps raising visible flickering. Therefore, performance of communication should be taken into account together with flicker.

VLC systems have to find a compromise between data rate, BER, SNR, and flicker-free lighting. Affected by modulation order and symbol duration, PPM and DPPM could create flickers by means of repeated off slots or vacant slots. This research creates a quantitative framework for assessing flickering in PPM and DPPM based VLC systems and looks at its link to modulation order, flickering rate, data rate, and BER. The framework uses flicker thresholds to help in modulating reliable and human-centric VLC. The paper covers **research objectives**, system model, system model, theoretical analysis, simulation results, and important ramifications for VLC flickering.

Research Objectives:

The main goal is to create and verify an analytical framework for measuring flicker in VLC systems by using PPM and DPPM. This research particularly seeks to:

Create a mathematical model to estimate the flicker rate in VLC systems that use PPM and DPPM.

Look at how well you can talk to each other and how much the light flickers under different channel conditions.

Considering the effects of channel degradation on symbol duration, reliability, and flicker exposure, examine the balance among flicker rate, BER, and data rate.

Validate the proposed analytical model through comprehensive simulation-based performance evaluation and demonstrate its effectiveness as a quantitative framework for assessing flicker in conventional VLC systems.

System Model:

The model for indoor wireless VLC environment the communication links employs intensity modulation and direct detection (IM/DD). The suitable channel model links the intensity-modulation constraint of the photon-counting channel with the multipath distortion and AWGN of standard radio channels. Let's x(t) the instant optical power of the transmitter. The constraints on.

$$\boldsymbol{x(t)} = lim_{T\to\infty} \frac{1}{2T}\int_{-T}^{T} P_t(t)dt.$$

$$y(t) = Rh(t)x(t) + n(t) \ (1)$$

Where *h(t)* is the complex channel gain and R represent the responsively of the photo detector (in A/W), y(t) is received signal, however, the model *n(t)* as white, Gaussian, and independent of signal *x(t)* as given in Eq. (1). The *h(t)* is the channel impulse response, which is fixed for a allocated configuration of transmitter and receiver. The received average optical power is:

$$P_r = P_t\, H(0) \ (2)$$

where the channel DC gain given in [14] is LOS (line of site) and non-LOS is *h(t)* = *hLOS(t)* + *hNLOS(t)*:

$$H(0) = \int_{-\infty}^{\infty} h(t)dt \ (3)$$

$$H(0)_{LOS+NLOS} = \begin{Bmatrix} \frac{(l+1)N_r A_r \gamma cos^l(\varphi) g(\psi) T(\psi)_{cof}\, cos(\psi)}{2\pi d^2}, \\ 0 \le \psi \le \psi_c. \\ 0, else \end{Bmatrix} \ (4)$$

$$g(\psi) = \begin{cases} \frac{p^2}{sin^2\psi_c}, & 0 \le \psi \le \psi_c \\ 0, & 0 \ge \psi_c \end{cases} \ (5)$$

The *g(ψ)* is the gain of the optical concentrator which is expressed in Eq. (5). The line of sight (LOS) or direct signal is considered though; signals power from non-LOS (NLOS) are insignificant. The transmitter and receiver distance are d, *APD* is the reception area, p is the refractive index, *ψ* is the incidence angle, *φ* is the irradiance angle, γ is the reflectance factor, l is the order of Lambertian emission, *ψc* is the Field of View (FOV), $T(\psi)cof$ is the signal spread coefficient of an optical filter. *Aeff* is affecting the area of photodiode, the *Ar* is the surface area of the photodiode, which can be written mathematically in Eq. (6).

$$A_{eff}(\psi) = \begin{cases} N_r A_r cos\psi T_s(\psi) g(\psi), & 0 \le \psi \le \psi_c \\ 0, & \psi > \psi_c \end{cases} \ (6)$$

The transmitted P_t and received P_r power can be expressed as $P_r = P_t$ *H(0)LOS+HNLOS*. The P_r is LOS+NLOS therefore, is the photodetector $P_r = \frac{I(\emptyset)}{d^2} A_{eff}(\psi), P_t$ responsive.

$$P_r = \frac{I(\emptyset)}{d^2} A_{eff}(\psi) \ (7)$$

The PPM is an orthogonal modulation scheme and M-PPM length has $log_2 M$ input bits mapped to distinct waveforms. However, a pulse *p(t)* is broadcast during the "on" slot. In the

case of DPPM, a symbol is obtained from the corresponding PPM by eliminating empty slots at left side of symbols. The M-DPPM symbol set $s_n(t)$, $0 \leq n \leq M-1$, using rectangular pulses, $s_n(t) = 0 (t < nt_s)$ and $s_n(t) = P_s, nt_s \leq t \leq (n+1)t_s$. The P_s is peak power and t_s is slot duration. Figure. 1. shows that the empty slots of OOK, PPM and DPPM. The empty slots of off cycles depend upon the bit stream, modulation schemes and slot time or symbol time of the signal as shown in Figure. 1. The high order modulation in PPM and DPPM is a key factor to improving data rate and effect the flickering rate. Figure. 1. shows the off cycle of given bit stream varies as per data bit stream. The symbol time duration is considered as T_s and slot time duration is t_s. In the OOK scheme the symbol time is equal to slot time $T_s = t_s$, however, in case of PPM and DPPM $t_s = T_s / M$, where M is maximum number of slots in a symbol T_s.

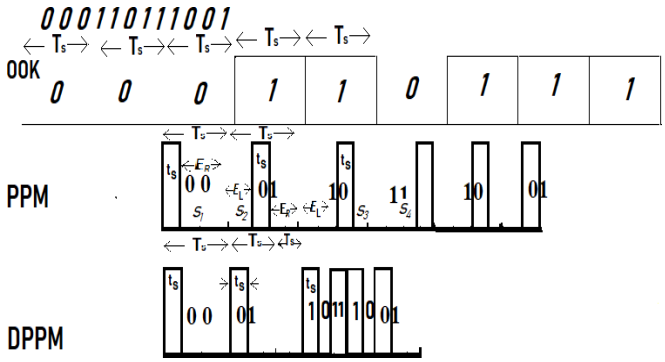


Figure 1. The empty slots of OOK, 4PPM, and 4DPPM.

The number of empty slots is reduced in DPPM as compared to PPM. The length of DPPM symbol is also not fixed and can be calculated on an average basis. The $M_{avg} = (M+1)/2$ is number of slots in DPPM symbols varies depending upon data stream input.

The flow chart of the complete system model, which includes all steps and processes, is presented in Figure 2. The flow chart presents the complete proposed VLC framework, beginning with random binary data generation and selection of PPM/DPPM and modulation order. The signal is transmitted through the indoor VLC channel using IM/DD and photodiode detection, after which the received symbol stream is analyzed by the proposed flicker-estimation module. This module identifies consecutive OFF cycles, measures their duration, compares them with the selected flicker threshold (*4 or 5 ms*), and counts events exceeding the threshold to calculate the flickering rate. Finally, the system evaluates data rate, BER, and bandwidth, performs the flicker–BER–data-rate trade-off analysis, compares PPM and DPPM, and selects the most suitable modulation scheme. This workflow directly supports the paper's stated objective of jointly evaluating flickering and communication performance.

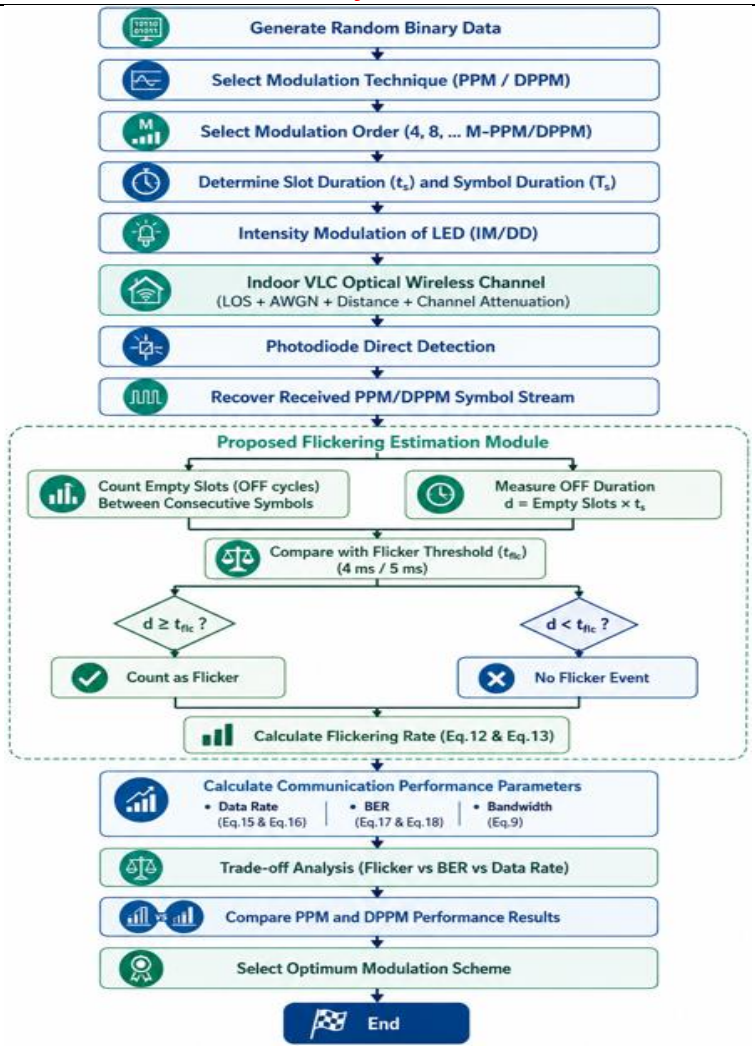


Figure 2. Proposed Flicker flow chart for VLC System

Table 1. Flickering rate vs modulation scheme

t_{flc} = 5ms	T_s=10ms ,t_b=2.5ms		T_s=5ms ,t_b=1.25ms	
Modulation Scheme	Flicker	Flickers/bits	Flicker	Flickers /bits
OOK (no t_s in this case)	12	1	6	0.5
4PPM	9	0.75	3	0.25
4DPPM	3	0.25	0	0
T_s=4ms ,t_s=1ms	t_{flc} = 5ms		t_{flc} = 4ms	
Modulation Scheme	Flicker	Flickers/bits	Flicker	Flickers /bits
OOK (no t_s in this case)	3	0.25	6	0.5
4PPM	1	0.083	2	0.166
4DPPM	0	0	1	0.083
T_s=2ms ,t_s=0.5ms	t_{flc} = 5ms		t_{flc} = 4ms	
OOK (no t_s in this case)	0	0	0	0
4PPM	0	0	0	0
4DPPM	0	0	0	0

The slot duration t_S is the same in PPM and DPPM, therefore, the bandwidth of PPM and DPPM is fixed. However, the symbol time duration Ts and data rate vary. The empty slots can be seen in Figure 1, with the maximum number in OOK and the minimum

in DPPM. The slot size reduces, and bandwidth requirements increase as the order of modulation increases.

The flicker can be calculated if the OFF cycles are greater than the t_{flc} threshold. The t_{flc} is the threshold to define the flickering theoretically. If an empty slot or consecutive empty slots in a symbol or between two symbols of PPM or DPPM symbol is equal to or greater than t_{flc} is called a flicker. Table. 1. defines the theoretical flicker at t_{flc} = 4 and 5ms.

Moreover, Table. 1. shows the flicker and flickering rate for bit stream given in Figure. 1. The threshold reference frequency is 0.20 kHz and 0.25 kHz which is taken from [17][18] and [19]. The cycles corresponding to the low frequencies of 0.10 kHz, 0.20 kHz, 0.25 kHz, and 0.50 kHz are 10ms, 5ms, 4ms and 2ms respectively. As described in previous literature, these frequencies are harmful for human eyes.

Therefore, duration of the empty slots of PPM and DPPM greater than that threshold in investigated and presented in Table. Table. 1. evaluated the flickering problem in OOK, PPM and DPPM for 0.1 kHz, 0.2 kHz, 0.25 kHz and 0.5 kHz. Similarly, in higher order, the slot t_S decrease with and the flickering rate also affected. Figure. 1. and Table. 1. show the sample data for 2bits per symbol for PPM and DPPM. However, the symbol duration and threshold limit vary as per hardware availability and the optimum requirement of flickering in the room.

Analysis:

OOK, PPM, and DPPM are suitable for low and medium-data rate applications. However, DPPM is a modified modulation scheme of PPM. The left or right empty slots of PPM are removed in DPPM to improve the data rate. The major contribution of this paper is to minimize the flickering at the optimum data rate and maintain the adequate brightness in the room. The illumination or dimming control in the room during OFF slots of PPM and DPPM can be handled by DC biasing and other techniques [20][21]. However, the flickering problem is investigated in this paper.

The data rate, BER, SNR, flickering rate, and bandwidth depend on the modulation scheme and order of the modulation scheme. However, the flickering rate is one of the most significant parameters of a VLC system. In general, it refers to it refers to the deviation in the illumination of the light perceived by the human eye. This occurs because of the deviation in the illumination of light due to repeated ON/OFF switching of the light source due to communication. The illuminance of incandescent and fluorescent lamps utilizes 220v and 0.05 kHz frequency to glow light in the room. In 0.05 kHz the AC signal operates *10ms* ON cycle and 10ms OFF cycle. The flickering occurs due to off cycle of any light source. However, the bottom line of flickering at which we didn't notice any flicker is at 10ms OFF cycle but in literature some research suggests that 0. 2 kHz or some higher frequency could be harmful for human health [17][18]. The slot time t_s of PPM and DPPM is directly proportional to flicker rate, and it increases with higher order PPM and DPPM. Flickering rate is inversely proportional to data rate, and bandwidth.

In every PPM symbol, only one slot is high or peak while rest of slots are empty. The bandwidth can be measured from the slot duration of PPM and DPPM symbols. One PPM symbol contains M number of slots; therefore, the symbol duration can be expressed as:

$$T_s = M * t_s \quad (8)$$

where t_s is slot duration, M is number of slots and T_s is symbol duration however, the Bandwidth is the inverse of slot duration t_s.

$$B.W = 1/\ t_s = M\ /\ T_s \quad (9)$$

where s_1, s_2, s_3,…., s_N define the consecutive number of symbols transmitted to receivers, and Eq. (10) shows the OFF slots of right-side E_R of current symbol and E_L is left side empty slots of next symbol.

$$E_R = \sum_{m=P+1}^{K} t_{s_m}$$

$$E_L = \sum_{m=1}^{P} t_{s_m}$$

$$t_{flc} \geq \sum_{n=1}^{N} E_R + E_L \quad (10)$$

The OFF cycle can be measured as the total OFF slot on the right side of current symbol and OFF slots of next symbol in the left-hand side which is defined in Eq. (10) and shown in Figure.1. However, the Eq. (10) is only for PPM, but in case of DPPM $t_{flc} \geq \sum N E_R$ because the left-side empty slots are removed. The empty cycles of PPM and DPPM shown in Figure. 1 and A Flicker can be defined as the total duration of empty slots of current symbol and next symbol should be greater than or equal to predefine threshold t_{flc}. In [17] the threshold is t_{flc} *c= 1/0.2 kHz*, the flickers can be defined as $d > t_{flc}$, d has different thresholds which are defined in Table. 1.

In case of 4PPM the possible symbols are s_1, s_2, s_3, s_4 as shown in Figure. 1. The transmitted symbols are transmitted randomly and possible combinations of transmitted symbols are given in Eq (11):

$$(s_1,s_1), (s_1,s_2), (s_1,s_3), (s_1,s_4), (s_2,s_1), (s_2,s_2), \ldots, (s_4,s_4) \quad (11)$$

As shown in Eq. (7) and total combinations are 24. The maximum OFF cycle or empty slots is observed when (s_1, s_4) is transmitted. The six empty slots occurred between s_1 and s_4. Similarly, the different symbol combinations as shown in Eq. (11) have different numbers of empty slots or different duration of OFF cycles. The transmitted symbols are s_1, s_2, s_3, s_4, the sequence of transmission is random. For example, if s_1, is first symbol to transmit then next symbol could be s_2 or s_3 or s_4. Another scenario is if s_2, is first symbol to transmit then next symbol could be s_1 or s_3 or s_4. Therefore, the total possible combinations are 16. The probability of each combination of 4PPM are equal 1⁄16. Every consecutive symbol has different empty slots, and flicker is defined as $d > t_{flc}$ in Eq(12). The minimum empty slot is zero, which may occur between s_4 and s_1. The Eq (12) shows the N equal to 16 in case of 4PPM and the general equation for flickering rate can be defined as:

$$Flickering\ rate = \sum_{s_0}^{s_N} \frac{F(d > t_{flc})}{N} \quad (12)$$

where N is total number of symbols and $F(d>t_{flc})$ is OFF cycle between two peak symbols or consider as empty slots between two symbols having time duration greater than t_{flc}. The Eq. (12) measured the total flickering rate on random data stream for high order and low order modulation schemes (all value of M). The higher order PPM can be represented by M-PPM and combination of all possible symbols can be represented as 2M.

Similarly, the maximum and minimum empty slots are in between (s_0,s_M) and (s_M, s_0) respectively. The maximum empty slots can be formulated as $2(M-1)$ and minimum empty slots of (s_M,s_0) symbol is zero. The probability of empty slots greater than given threshold of each combination of symbol is shown in Eq. (13).

$$P(C_{s_n,s_{n+1}}) = \frac{1}{2^M} \sum_{c=0}^{2(M-1)} F\left(d > t_{flc}\right) \quad (13)$$

All combinations of symbols have same probability $1/2^M$ but the flickers or number of empty slots rate varying. However, the flickers also depend upon slot duration t_s. The Eq. (13) shows the calculated flickering rate for higher and lower order of modulation. The analytical flickering rate is the number of all possible combinations of symbols empty slots per total number of bits.

The bandwidth is $B = 1/t_s$ in terms of slots duration and the symbol time can be

defined as:

$$T_s = M\, t_s \quad (14)$$

The data rate of MPPM can be defined as log2(M/Ts) from Eq. (14).

$$\text{Data rate} = M / 2M\ ts \quad (15)$$

Similarly, the data rate of DPPM with variable symbol length can be defined as in Eq. (16)

$$Data\ Rate\ = \frac{2M}{(1+2^M)t_s} \quad (16)$$

The Eq. (15) and Eq. (16) show the inverse relation of data rate with ts duration. However, flickering rates have direct relation with the order of modulation. With the difference between Eq. (15) and Eq. (16), the DPPM data rate is almost double the PPM. Therefore, the flickering rate of DPPM is about half of PPM. The flickering varies with slot time duration as giving in Table. 1. In Table. 1 the threshold of flickering is 5ms and 4ms at different values of ts. The data rate deteriorates in wireless data transmission due to worse channel conditions, distance and obstacles between transmitter and receiver, the received signal strength decreases, potentially leading to lower data rates. Lowering the data rate increases the symbol time and increases the flickering rate. Therefore, in this paper the data rate of PPM and DPPM modulation schemes is analysed and the trade-off between data rate and flickering rate is obtained.

The error probability P_e of performance is deteriorated in high order modulation (HOM). The error performance improves at low data rate; therefore, the error probability has inverse relation with flickering rate. As slot size t_s increases, the error performance for PPM and DPPM improves and data rate decreases. The PPM error performance can be derived as in Eq. (17).

$$P_{e(PPM)} = \frac{M-1}{2M} erfc\left\{\sqrt{\frac{M(log_2 M)E_b}{2\sigma}}\right\} \quad (17)$$

Similarly, in case of DPPM, the left slots of symbol are removed, and average symbol time is reduced. The error performance in case of DPPM is given as in Eq. (18).

$$P_{e(DPPM)} = \frac{M_{avg}-1}{M_{avg}} erfc\left\{\sqrt{\frac{(log_2 M)M_{avg}E_b}{2\sigma}}\right\} \quad (18)$$

where $P_{e(DPPM)}$, $P_{e(PPM)}$ is error probability of PPM and DPPM in Eq(17) and Eq(18), σ is AWGN, and M_{avg} is average number of slots.

Simulation Result and Discussion:

All simulations are based on slot size of PPM and DPPM. Figure. 3, Figure. 4. and Figure. 5. shows the trade-off between flickering rate, BER, and data rate respectively. The bandwidth, data rate, flickering rate and BER depend on slot duration. The order of PPM and DPPM also vary with slot size.

Figure 3 compares the flickering rates of PPM and DPPM, showing good agreement between the simulation results and the analytical results obtained from Eq. (12). Among the investigated schemes, 8DPPM exhibits the highest flickering rate, whereas 4DPPM shows the lowest flickering rate. The 4PPM scheme also produces a lower flickering rate than 8PPM due to differences in the number and arrangement of empty slots. Overall, the flickering rate is strongly influenced by the slot duration and symbol duration, because longer OFF periods are more likely to exceed the defined flicker threshold.

Figure. 4 compares the data rates of PPM and DPPM for different modulation orders. The highest data rate is achieved by 4DPPM because DPPM removes unnecessary empty slots, resulting in a shorter average symbol duration. In contrast, 8PPM shows the lowest data rate over the considered range of slot durations because each symbol contains eight slots, which

results in a longer symbol duration.

Figure. 5 shows the BER performance of PPM and DPPM for different slot durations. In general, increasing the slot duration increases the symbol duration and reduces the data rate, but improves BER performance. Conversely, shorter slot durations provide higher data rates but result in comparatively higher BER.

The results in Figures 3, 4, and 5 demonstrate a clear trade-off among flickering rate, data rate, and BER. Higher data rates generally correspond to shorter symbol durations and lower flickering rates, but with degraded BER performance. In contrast, lower data rates generally result in longer symbol durations, increased flickering, and improved BER performance. The effect of modulation order is also dependent on the modulation scheme and slot duration; therefore, higher-order modulation does not necessarily produce a uniformly higher or lower flickering rate. DPPM reduces the number of empty slots compared with PPM and can therefore provide a favorable trade-off between flickering and data-rate performance. To statistically validate the simulation results, each experiment was repeated 30 independent times using different random binary sequences. The mean and standard deviation of the flickering rate and BER were calculated to evaluate the consistency and variability of the simulation results.

Table 2. Statistical analysis of modulation scheme

Comparison	Mean Difference	p-value	Significant
4PPM vs 4DPPM Flicker	0.82	<0.001	Yes
8PPM vs 8DPPM Flicker	1.35	<0.001	Yes
4PPM vs 4DPPM BER	0.0014	0.003	Yes
8PPM vs 8DPPM BER	0.0062	<0.001	Yes

Statistical analysis in Table 2 confirms that the reduction in flickering achieved by DPPM compared with PPM is statistically significant ($p < 0.05$) for all investigated modulation orders. Likewise, the BER differences between low-order and high-order modulation schemes are statistically significant, confirming that the observed trade-off is not caused by simulation randomness. Statistical significance testing further confirmed that the observed improvements in flickering reduction and BER among the investigated modulation schemes are significant ($p < 0.05$), supporting the reliability of the proposed analytical framework.

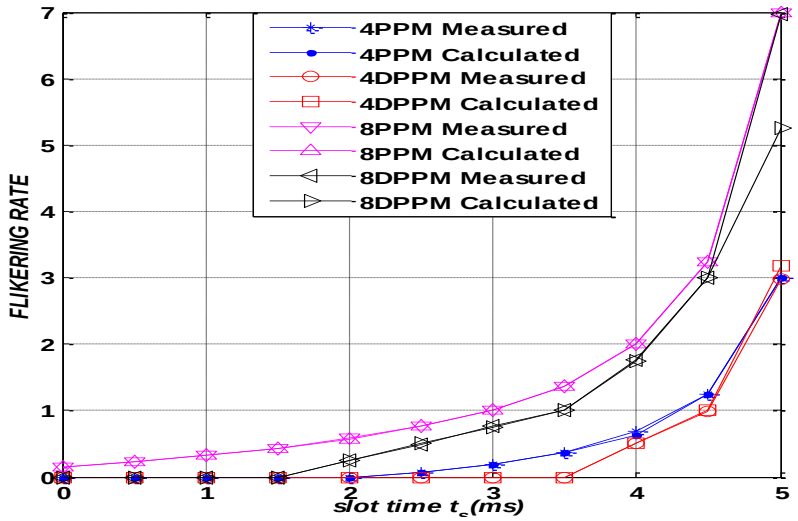


Figure 3. Flickering rate comparison of high and low order PPM and DPPM

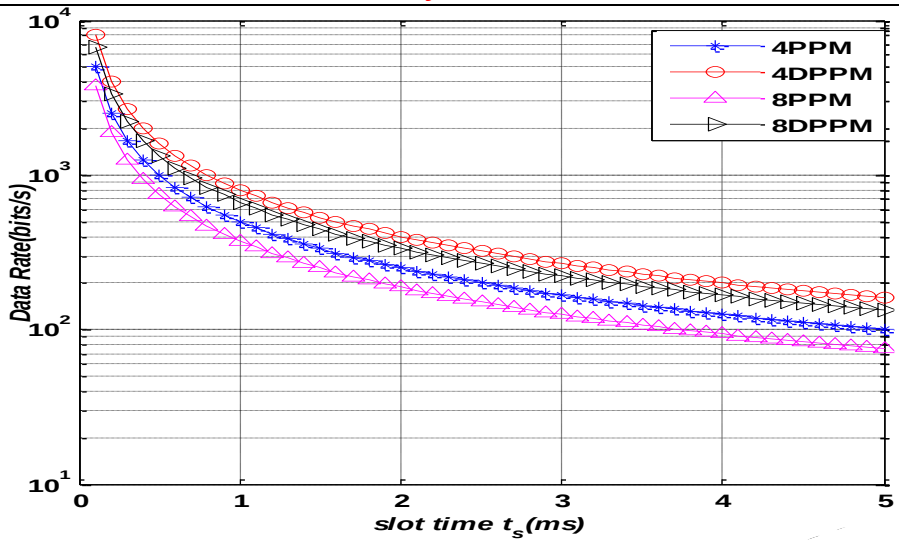


Figure 4. Data rate comparison of PPM & DPPM

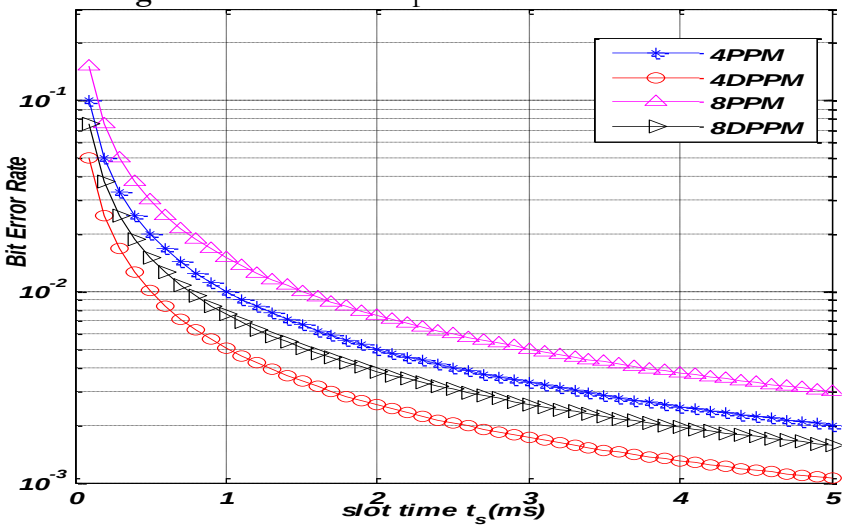


Figure 5. BER performance of PPM and DPPM at different slot duration

Recommendations and Future Research:

Future research should empirically verify the suggested framework using FPGA, SDR, and practical VLC testbeds. While machine learning-based adaptive modulation may **reduce** flickering and improve BER and data rate under varying channel conditions, the paradigm may be expanded to OFDM, PWM, DAPPM, PCM, and CAP. Future research should look into multi-user VLC as well as its integration with smart structures, homes, and cities that are IoT enabled.

Practical Implications:

The suggested framework aids in the choice of modulation for VLC applications in Industry 4.0, smart houses, classrooms, offices, hospitals, and smart lighting. It aids in balancing communication dependability, data rate, lighting quality, and user comfort by means of flicker estimation. The framework can allow dependable and human-centric VLC while preserving illumination quality and communication efficiency in flicker sensitive applications.

Conclusion:

This research addresses the communication and illumination performance of the VLC system in the room. The flickering problem is investigated via novel techniques, which examine the flickering rate of PPM and DPPM precisely. The threshold of flickering is adopted from previous research articles. The measured and calculated results show that the flickering

rate has an inverse relationship with data rate and a direct relationship with BER. However, in higher order modulation increases the flickering rate. The modulation schemes are subject to achieve the high-performance parameter in terms of communication and illumination in the room. However, the worse channel conditions, obstacles between the transmitter and receiver, and due to distance, received signal strength decreases, potentially leading to lower data rates. The flickering problem dominated at lower data rates and due to modulation scheme. In this paper the PPM and DPPM schemes are investigated and the trade-off between date rate, BER and flickering rate is examined. The results show that the flickering problem dominates low data rates and high order modulation schemes of PPM and DPPM. The novel flickering schemes can be applied at other modulation schemes (PWM, differential amplitude PPM DAPPM, PCM) to measure the precise results of flickering rate and other communication parameters.

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