Performance Analysis of Visible Light Communication Systems over Fading Channels

Haitham S. Khallaf[1,4], **Abdallah S. Ghazy**[2], **Hossam M. H. Shalaby**[3], **and Salah S. A. Obayya**[4]
[1]*Nuclear Research Center, Atomic Energy Authority of Egypt, Egypt*
[2]*Faculty of Engineering, Azher University, Cairo, Egypt*
[3]*Faculty of Engineering, Alexandria University, Alexandria 21544, Egypt*
[4]*Center for Photonics and Smart Materials, Zewail City of Science and Technology, Giza 12588, Egypt*
hsoliman@zewailcity.edu.eg, Abdallah.Ghazy@ejust.edu.eg, shalaby@ieee.org, sobayya@zewailcity.edu.eg

Abstract

The performance of visible light communication (VLC) systems, adopting hybrid modulation techniques, is investigated under dynamic fading channels. Hybrid M-ary quadrature amplitude modulation and multi-pulse pulse-position modulation (hybrid QAM-MPPM) scheme is considered because of its high-power efficiency under constrained spectral efficiency. Expressions for bit-error rate (BER) and outage probability are derived for VLC systems adopting hybrid QAM-MPPM scheme under dynamic channels modeled by Rayleigh distribution. The derived expressions are used to investigate the performance of proposed VLC and compare it to corresponding ordinary QAM and MPPM schemes. Our results reveal that the BER of the proposed hybrid scheme outperforms that of ordinary MPPM by more than 4 dB. In addition, the outage probability of VLC systems is improved when using the hybrid scheme compared to that of ordinary QAM scheme.

Keywords: Fading channels, hybrid modulation schemes, visible light communications.

1. Introduction

Visible light communication (VLC) systems, where light-emitting diodes (LEDs) are used for both communication and illumination, have many advantages compared to ordinary wireless systems (WiFi). These advantages include low cost, harmless to human, immunity to electromagnetic interference, and wide license-free band. Accordingly, researchers have been motivated to consider VLC for indoor communication for 5G mobile network, where it will cooperate with WiFi or replace it in cellular system offloading [1]. However, there are different impairments that affect the performance of VLC system, e.g., multi-path fading, path loss, blockage (shadowing), and background noises [2]. Lambertian distribution model is usually used to characterizes multi-path in case of static and quasi-static VLC channels [3]. In [4], Chvojka *et al.* have considered the effect of user mobility within an indoor environment, on shadowing, and blocking of dynamic VLC channels. They have shown that fluctuation in the envelope of the received signal is well described by Rayleigh distribution.

Hybrid QAM-MPPM modulation technique has been proposed in [5]. It has been shown that over turbulent channels in free-space optical communication systems, the BER performance of this technique outperforms that of ordinary MPPM and ordinary QAM techniques [6]. This motivates us to investigate performance of the hybrid QAM-MPPM scheme over dynamic VLC channels. In this paper, we derive exact expressions for both the BER and outage probability for VLC adopting hybrid QAM-MPPM, over dynamic channels.

2. VLC Channel Model

For static channels, the total received optical power at receiver is given as [3]:

$$p_r = \sum_{i=1}^{Z} p_t \times H_i = \sum_{i=1}^{Z} p_t \times \left[H_{d,i} + \int_{wall} H_{ref,i}\, dA_{wall} \right], \quad 0 \le H_i \le 1\,, \tag{1}$$

where p_t is the average transmitted optical power, H_i is the total channel gain seen by signal from i^{th} source, dA_{wall} is a small reflective area on the wall, and $H_{d,i}$ and $H_{ref,i}$ are the DC channels gain of direct path and reflected path, respectively, of signal from i^{th} source, $i \in \{1,\ldots,Z\}$. Based on Lambertain equations $H_{d,i}$ and $H_{ref,i}$ are given as follows [3]:

$$H_{d,i} = \frac{(m+1)}{(2\pi\, d_i^2)}\, A_{det}\, \cos^m(\theta_{ir,i})\, T_s(\theta_{in,i})\, g_s(\theta_{in,i})\, \cos(\theta_{in,i}), \quad \text{for} \quad 0 \le \theta_{in,i} \le \theta_{FoV}. \tag{2}$$

$$H_{ref,i} = \frac{(m+1)\, A_{det}\, \rho}{(2\pi^2\, d_{1,i}^2\, d_{2,i}^2)}\, \cos^m(\theta_{ir,i})\, \cos(\beta_i)\, \cos(\alpha_i)\, T_s(\theta_{in,i})\, g_s(\theta_{in,i})\, \cos(\theta_{in,i}), \quad \text{for} \quad 0 \le \theta_{in,i} \le \theta_{FoV}, \tag{3}$$

where m is the order of the Lambertian radiant, d_i is the distance between transmitter and receiver, A_{det} is the area of the detector, $\theta_{ir,i}$ is the angle irradiance of i^{th} light source, $\theta_{in,i}$ is the angle of incidence, $T_s(\theta_{in,i})$ is the optical filter gain, $g_s(\theta_{in,i})$ is the optical concentrator gain, θ_{FoV} is the FOV of the receiver, $d_{1,i}$ is the distance between i^{th} transmitter and reflective point, $d_{2,i}$ is the distance between reflected point and the receiver, ρ is the reflectance coefficient of the wall, α_i is the angle of incidence from the i^{th} transmitter, and β_i is the angle of irradiance from a reflected point.

In case of considering people movement between transmitter and receiver, the fluctuation in channel gain H can be well described by Rayleigh distribution. Hence, the distribution of the electrical signal-to-noise ratio (SNR) γ at receiver can be written as follows [4]:

$$P(\gamma) = \frac{1}{2(\frac{N}{w})^2\overline{\gamma}\sigma_f^2} \exp\left[\frac{-\gamma}{2(\frac{N}{w})^2\overline{\gamma}\sigma_f^2}\right], \tag{4}$$

where σ_f is scale parameter based on people density in the room, $\gamma = \overline{\gamma} H^2 \left(\frac{N}{w}\right)^2$ is the instantaneous electrical SNR, $\overline{\gamma} = \left(\frac{\Re p_t}{\sigma_n}\right)^2$ is the average electrical SNR, $\Re$ is PD representativity, and σ_n^2 is the variance of Gaussian noise. Also, N and w are the number of time slots and signal slots of MPPM modulation, respectively, as will be shown in next section.

3. BER and Outage Probability Performance Analysis

In the hybrid QAM-MPPM scheme, symbol duration T is divided into N time slots and optical power transmitted during $w \in \{1,2,...,N/2\}$ signal slots. Each of the signal slots is modulated by M-ary QAM symbol. The output optical power from LED transmitter is given as [6]:

$$p_t(t) = \frac{N\, p_t}{w} \sum_{i=0}^{N-1} \left[\Big(1 + M\, D_i(t)\Big)\, B_i(t)\, \text{rect}\left(t - \frac{T}{N}\, i\right)\right] \tag{5}$$

where

$$B_i(t) = \begin{cases} 1; & \text{signal slot,} \\ 0; & \text{non-signal slot.} \end{cases} \quad D_i(t) = \begin{cases} S_{mqam}(t); & M\text{-QAM signal,} \\ 0; & M\text{-QAM non-signal.} \end{cases} \quad \text{rect}(t) = \begin{cases} 1; & 0 \le t \le T/N, \\ 0; & \text{else.} \end{cases} \tag{6}$$

Hybrid QAM-MPPM technique is based on two independent ordinary techniques, QAM and MPPM. So the BER of the hybrid scheme is the average of them and is given as follows [5]:

$$BER = \frac{\log_2\binom{N}{w}}{\log_2\binom{N}{w} + w\log_2 M_q} BER_{MPPM} + \frac{w\log_2 M_q}{\log_2\binom{N}{w} + w\log_2 M_q}\left[\Big(1 - SER_{MPPM}\Big) BER_{QAM} + \frac{SER_{MPPM}}{2}\right], \tag{7}$$

where BER_{QAM} is the bit-error rate of ordinary QAM and SER_{MPPM} is the symbol-error rate of the ordinary MPPM, given as follows:

$$SER_{MPPM}(\gamma) \le \frac{\binom{N}{w} - 1}{2}\, \text{erfc}\left(\sqrt{\frac{\gamma \log_2\binom{N}{w}}{4N}}\right). \tag{8}$$

$$BER_{QAM}(\gamma) = \begin{cases} \frac{2}{\log_2 M_q}\left(1 - \frac{1}{\sqrt{M_q}}\right)\sum_{i=1}^{\sqrt{M_q}/2} \text{erfc}\left((2i-1)\sqrt{\frac{3M^2\gamma}{4(M_q-1)}}\right) & \text{if } m \text{ is even,} \\ \frac{2}{\log_2 M_q}\, \text{erfc}\left(\sqrt{\frac{3M^2\gamma}{4(M_q-1)}}\right) & \text{if } m \text{ is odd,} \end{cases} \tag{9}$$

where $m = \log_2 M_q$, M_q is the number of QAM modulation levels, and M is the modulation index. In order to get the average of the net BER over fading channel, we need to get the average of each of the ordinary schemes then substitute in (7). After rigorous mathematical analysis, the average SER of MPPM and BER of QAM are calculated over fading channel as given in (10) and (11), respectively:

$$SER_{MPPM} \leq \frac{N\left[\binom{N}{w}-1\right]}{\sqrt{\pi}\bar{\gamma}\left(\frac{N}{w}\right)^2\sigma_f^2\log_2\binom{N}{w}} G_{2,2}^{1,2}\left(\frac{2N}{\bar{\gamma}\left(\frac{N}{w}\right)^2\sigma_f^2\log_2\binom{N}{w}}\middle|_{0,-1}^{0,-0.5}\right) \tag{10}$$

$$BER_{QAM} = \begin{cases} \dfrac{4\left[1-1/\sqrt{M_q}\right](M_q-1)}{3\sqrt{\pi}\log_2(M_q)M^2\bar{\gamma}(N/w)^2\sigma_f^2}\sum_{i=1}^{\sqrt{(M_q)}/2}\frac{1}{(2i-1)^2}G_{2,2}^{1,2}\left(\dfrac{2(M_q-1)}{3(2i-1)^2M^2\bar{\gamma}(N/w)^2\sigma_f^2}\middle|_{0,-1}^{0,-0.5}\right) & \text{if } m \text{ is even,} \\ \dfrac{4(M_q-1)}{3\sqrt{\pi}\log_2(M_q)M^2\bar{\gamma}(N/w)^2\sigma_f^2}G_{2,2}^{1,2}\left(\dfrac{2(M_q-1)}{3M^2\bar{\gamma}(N/w)^2\sigma_f^2}\middle|_{0,-1}^{0,-0.5}\right) & \text{if } m \text{ is odd.} \end{cases} \tag{11}$$

Another metric for quantifying the performance of VLC communication systems over dynamic channels is the outage probability P_{out}^{Net}. It is the probability that the bit error rate of the system is higher than a threshold error rate BER_{th} or the SNR is lower than threshold value γ_{th}. The upper bound for the outage probability of VLC systems adopting hybrid QAM-MPPM scheme, P_{out}^{Net}, is given as follows [6]:

$$P_{out}^{Net} \leq 1-\left(1-P_{out}^{MPPM}\right)\left(1-P_{out}^{QAM}\right), \tag{12}$$

where P_{out}^{MPPM} and P_{out}^{QAM} are outage probabilities of ordinary MPPM and ordinary QAM, respectively. The outage probability for a given γ_{th} can be written as follows:

$$P_{out}(\gamma_{th}) = \int_0^{\gamma_{th}} \frac{1}{2(\frac{N}{w})^2\bar{\gamma}\sigma_f^2}\exp\left[\frac{-\gamma}{2(\frac{N}{w})^2\bar{\gamma}\sigma_f^2}\right]d\gamma = 1-\exp\left[\frac{-\gamma_{th}}{2(\frac{N}{w})^2\bar{\gamma}\sigma_f^2}\right] \tag{13}$$

Threshold SNR γ_{th} for both MPPM and QAM are related to threshold of BER (BER_{th}) as shown in (14) and (15), respectively:

$$\gamma_{th}^{MPPM} = \frac{4w^2}{N\log_2\binom{N}{w}}\left(\operatorname{erfc}^{-1}\left[\frac{\left(2^{\log_2\binom{N}{w}}-1\right)BER_{th}}{2^{\log_2\binom{N}{w}-2}\left(\binom{N}{w}-1\right)}\right]\right)^2 \tag{14}$$

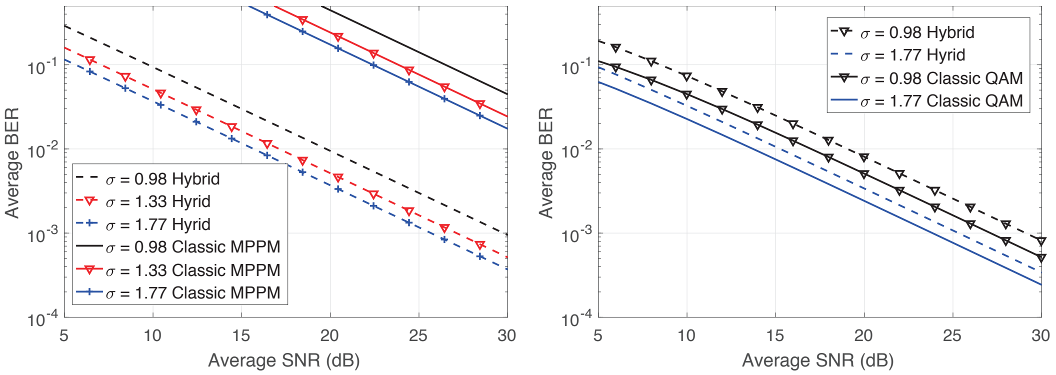
$$\gamma_{th}^{QAM} = \frac{4(M_q-1)}{3M^2}\left(\operatorname{erfc}^{-1}\left[\frac{BER_{th}\log_2(M_q)}{2}\right]\right)^2 \tag{15}$$

4. Simulation and Numerical Results

In this section, the derived expressions for the BER and outage probability are used to investigate the performance of VLC adopting hybrid scheme under different people density per m^2. In addition, the performance of hybrid scheme is compared to ordinary QAM and MPPM schemes under the conditions of comparable data rates, same bandwidth, and same energy per bit. In our simulation, we consider the same values of σ_f as obtained experimentally in [4].

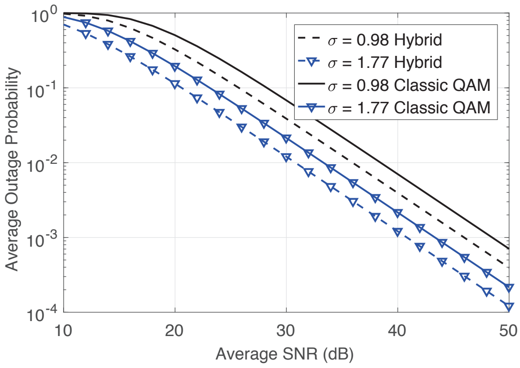
Figure 1a shows the average BER versus average electrical SNR for both of hybrid scheme and ordinary MPPM. It is clear that the hybrid scheme outperforms ordinary one by more than 4 dB. The main reason for that improvement is high energy concentration in case of hybrid scheme since the number of the signal slots for hybrid is less than half of it for ordinary MPPM.

Figures 1b and 1c show BER and outage probability versus average SNR, respectively, for both hybrid scheme and ordinary QAM. Although, the average BER of the ordinary QAM outperforms hybrid scheme by 2 dB at BER 10^{-3} , but regarding the outage probability, with BER threshold 10^{-3}, hybrid scheme outperforms ordinary QAM by 3 dB. This improvement in outage probability in case of hybrid scheme can be understood if we consider the non-signal slots as guard time where noise, multi-paths, and blocking of signals have no effect on the QAM portion of hybrid scheme. On the other hand, ordinary QAM sends symbols without that guard time so it will suffer from different degradation sources all the time.



(a) Average bit-error rates for both hybrid QAM-MPPM (with $N = 12$, $w = 2$, and $M_q = 4$) and ordinary MPPM (with $N = 12$ and $w = 5$) versus average electrical SNR (in dB).

(b) Average bit-error rates for both hybrid QAM-MPPM (with $N = 4$, $w = 2$, and $M_q = 8$) and ordinary QAM (with $M_q = 4$) versus average electrical SNR (in dB).



(c) Average outage probability for both hybrid QAM-MPPM (with $N = 4$, $w = 2$, and $M_q = 8$) and ordinary QAM (with $M_q = 4$) versus average electrical SNR (in dB).

Fig. 1. Average bit-error rates for hybrid QAM-MPPM and ordinary MPPM and QAM techniques.

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