Modulations for Visible Light Communications With Dimming Control

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***Abstract*—Visible light communication (VLC) uses solid-state lightings to transmit information; therefore, it is necessary that modulation schemes for VLC provide dimming control. In this letter, we propose a multiple pulse position modulation (MPPM) to offer both functions of modulating data-stream and controlling the brightness at the same time. According to the dimming level, we control the number of pulses of MPPM in one symbol duration. We analyze communication performance in terms of the normalized power requirement and spectral efficiency. From our studies, we show that MPPM is superior to variable on–off keying (VOOK) and variable pulse position modulation (VPPM) proposed in the IEEE 802.15 VLC task group.**

***Index Terms*—Light-emitting diode (LED)-lighting, optical wireless communications, spectral reflectance, visible light communications (VLCs).**

I. Introduction

VISIBLE light communication (VLC) is a short-range optical wireless communication system. The VLC uses white light-emitting diode (LED) lighting as a transmitter. Hence, we must take into account modulation schemes having functions such as nonflickering and dimming control [1]. Since most people cannot perceive the flickering at a frequency greater than 100 Hz, we do not thus discuss the flickering problem in detail.

We will examine a brightness control more closely. Dimming control is a mandatory for LED lighting. It has been used to provide moods, energy savings, and ecological benefits. LEDs are current-driven devices whose brightness is proportional to their forward current. Forward current can be controlled in two ways. The first method is to adjust the current continuously. 50% brightness is achieved by applying half of the maximum current to LEDs. Although it is simple and cost-effective system, changing the current will affect the emitted light wavelength so called chromaticity shift problem [2], and it is difficult to control the brightness of LEDs precisely. The second way of LED dimming is to use pulse width modulation (PWM). When the maximum current is applied to LEDs, we dim the light by reducing the pulse width or brighten the light by increasing the pulse width. When PWM dimming is used, the brightness of an LED lighting relates to the duty cycle, which can be expressed as $\delta = \tau/T$, where τ is the amount of time that the pulse is on, and T is the PWM symbol duration.

In this letter, we analyze the performance in terms of both normalized power requirement which is defined by required optical power to achieve a given bit error rate (BER), and spectral efficiency which is measured by the bit rate given a bandwidth. And we compare the modulation schemes with respect to the brightness control of the LED lighting. Also we assume perfect synchronization.

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II. Modulation Schemes With Dimming Control

Optical wireless communications, including the VLC, use intensity-modulation and direct-detection (IM/DD). Intensity-modulation is obtained by varying the bias current of LEDs. A photodetector in a DD receiver produces a photocurrent that is proportional to the optical power incident upon it. Let $x(t)$ and $y(t)$ denote the transmitted and received optical signals, respectively. When the channel has impulse response $h(t)$, the received signal is $y(t) = \int_{-\infty}^{\infty} x(\tau)h(t-\tau)d\tau + n(t)$, where $n(t)$ is an additive white Gaussian noise (AWGN) with a variance of N_0. Here we assume $h(t) = \delta(t)$. It should be that in VLC, $x(t)$ represents optical power from LED lightings, not amplitude, and thus it must satisfy [3]:

$$x(t) \geq 0 \ \text{and} \ \lim_{T\to\infty} \frac{1}{T}\int_0^T x(t)dt \leq \gamma P, \tag{1}$$

where P is an average power, and $0 \leq \gamma \leq 1$ is a dimming factor. The brightness depends on the LED lighting's dimming factor and the average optical power. For example, if an LED lighting is under full brightness ($\gamma = 1$) and 50% brightness ($\gamma = 0.5$), then the average power of $x(t)$ is P and $0.5P$, respectively.

A. Variable On–Off Keying (VOOK)

An on–off keying (OOK) transmitter emits a rectangular pulse of duration T and of intensity $2P$ to signify a one bit and no pulse to signify a zero bit. Under equiprobable input condition, the OOK can provide a full brightness without control of adjustment. The OOK signal is: $x(t) = 2Pd\,\mathrm{rect}\,(t/T)$, where $d \in \{0, 1\}$ is information bit, and $\mathrm{rect}(x)$ is defined as one for $0 < x \leq 1$ and zero for otherwise.

In [4], the brightness is controlled by varying the data duty cycle, δ_d, of OOK where $\delta_d = \tau_d/T$, where τ_d is the amount of time that the data pulse is on. The inactive portions of duty cycle are filled with the filler bits with either ones or zeros according to the dimming factor. In Table I, VOOK codewords are shown

TABLE I
VOOK AND VPPM CODEWORDS

γ	δ	VOOK		VPPM	
		δ_d	codeword	codeword (Bit 0)	codeword (Bit 1)
1.0	1.0	0.0	1111111111	1111111111	1111111111
0.9	0.9	0.2	dd11111111	1111111110	0111111111
0.8	0.8	0.4	$dddd$111111	1111111100	0011111111
0.7	0.7	0.6	$dddddd$1111	1111111000	0001111111
0.6	0.6	0.8	$dddddddd$11	1111110000	0000111111
0.5	0.5	1.0	$dddddddddd$	1111100000	0000011111
0.4	0.4	0.8	$dddddddd$00	1111000000	0000001111
0.3	0.3	0.6	$dddddd$0000	1110000000	0000000111
0.2	0.2	0.4	$dddd$000000	1100000000	0000000011
0.1	0.1	0.2	dd00000000	1000000000	0000000001
0.0	0.0	0.0	0000000000	0000000000	0000000000

where 0 or 1 is a filler bit. The VOOK provides a brightness with $\Pr\{d=0\} = \Pr\{d=1\} = 1/2$:

$$\gamma_{\text{vook}} = \begin{cases} \frac{1}{2}\delta_d & 0 < \gamma \le 0.5 \\ 1 - \frac{1}{2}\delta_d & 0.5 \le \gamma < 1. \end{cases} \tag{2}$$

When $\delta = 0$ or 1, information cannot be transmitted by VOOK.

B. Variable Pulse Position Modulation (VPPM)

In L-PPM [3], each symbol duration T is partitioned into L subintervals, and the transmitter sends only one optical pulse during $T/L = \log_2 L/LR_b$, where R_b is a bit rate. Thus, the information is sent in the position of the pulse within the symbol interval. The transmitted L-PPM signal $x(t)$ is given as $x(t) = LP\sum_{i=0}^{L-1} c_i \text{ rect}((L/T)t - i)$, where $\mathbf{c} = [c_0, c_1, \ldots, c_{L-1}]$ is an L-PPM codeword. The average optical power of L-PPM is P, under full brightness. PPM is not suitable for the VLC, because it is difficult to control the brightness of LED lighting as OOK.

Variable PPM (VPPM) [5] is a combination of PWM and 2-PPM ($L = 2$) and it provides a brightness control:

$$\gamma_{\text{vppm}} = \delta. \tag{3}$$

In Table I, VPPM codewords are presented. Note that for VPPM, the data duty cycle is equal to the duty cycle, $\delta = \delta_d$ unlike for VOOK. Since VPPM is a variant of 2-PPM, only one bit of information is carrying during one symbol duration. Moreover, VPPM signals cannot transmit information when the lighting is under full brightness as VOOK.

C. Multiple PPM (MPPM)

In MPPM [6], each symbol duration T is partitioned into n chips. The transmitter sends $w(1 \le w \le w_{\max} = n)$ optical pulses during one symbol duration. For dimming control, we fix n, and vary the number of optical pulses w, according to the dimming level. When $w = w_{\max}$, the system is said to be under full brightness. And thus we define the dimming factor as

$$\gamma_{\text{mppm}} = \frac{w}{w_{\max}}. \tag{4}$$

The possible dimming levels are, $1, (w_{\max}-1)/w_{\max}, \ldots, 1/w_{\max}$, and the total number of the dimming levels is $w_{\max}$. Note that this definition is different from that of conventional MPPM. The transmitted MPPM signal $x(t)$ is given by $x(t) = (nP/w_{\max})\sum_{i=0}^{n-1} c_i \text{ rect}((n/T)t - i)$. $\mathbf{c} = [c_0, c_1, \ldots, c_{n-1}]$ is a binary n-tuple vector of weight w codeword.

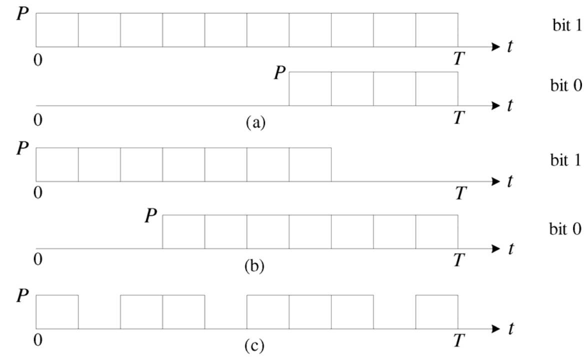

Fig. 1. Comparison of symbol structures with $\gamma = 0.7$ for several modulation schemes (a) VOOK, (b) VPPM, and (c) MPPM.

In Fig. 1, symbol structures for VOOK, VOOM, and MPPM are given when $\gamma = 0.7$.

D. Normalized Power Requirement and Spectral Efficiency

First, the power requirement is a measure that how much power is needed to achieve a given BER, at a given bit rate. To simplify analysis, we make the high signal-to-noise ratio (SNR) assumption that the BER is dominated by the nearest two signals. Accordingly, the equivalent BER is well approximated as $Q(d_{\min}/2\sigma)$ [7], where $d_{\min}$ is the minimum Euclidean distance between any pair of valid signals. We use OOK as a benchmark to compare power requirements of various modulation schemes. The power required by a modulation scheme to achieve the same BER is approximately $P \approx (d_{\text{ook}}/d_{\min})P_{\text{ook}}$, where $P_{\text{ook}} = Q^{-1}(\text{BER})\sqrt{N_0 R_b}$.

The Euclidean distance of VOOK is:

$$d_{\text{vook}} = \begin{cases} P\sqrt{\frac{2\gamma}{R_b}} & 0 < \gamma \le 0.5 \\ P\sqrt{\frac{2(1-\gamma)}{R_b}} & 0.5 \le \gamma < 1. \end{cases} \tag{5}$$

The ratio of d_{ook} to d_{vook} gives the power requirement with respect to the required power of OOK,

$$\bar{P}_{\text{vook}} \equiv \frac{P_{\text{vook}}}{P_{\text{ook}}} = \begin{cases} \sqrt{\frac{2}{\gamma}} & 0 < \gamma \le 0.5 \\ \sqrt{\frac{2}{1-\gamma}} & 0.5 \le \gamma < 1. \end{cases} \tag{6}$$

From (6), we find that there is increase in power with respect to OOK due to the filler.

The Euclidean distance of VPPM is

$$d_{\text{vppm}} = \begin{cases} P\sqrt{\frac{2\gamma}{R_b}} & 0 < \gamma \le 0.5 \\ P\sqrt{\frac{2(1-\gamma)}{R_b}} & 0.5 \le \gamma < 1. \end{cases} \tag{7}$$

Since the Euclidean distance of VPPM is equal to that of VOOK, they have the same required power.

For MPPM [6], the minimum distance is given as $d_{\text{mppm}} = (P/w_{\max})\sqrt{2n\log_2\binom{n}{w}/R_b}$. The normalized power requirement for MPPM is given in Table II. According to the dimming factor $\gamma = w/w_{\max}$, the required power is also varied.

TABLE II
NORMALIZED POWER REQUIREMENT AND SPECTRAL EFFICIENCY OF MODULATION SCHEMES

	Required power $\overline{P}$	Spectral efficiency ν
OOK	1	1
L-PPM	$\sqrt{\frac{2}{L\log_2 L}}$	$\frac{\log_2 L}{L}$
VOOK	$\begin{cases}\sqrt{\frac{2}{\gamma}} & 0<\gamma\le 0.5\\ \sqrt{\frac{2}{1-\gamma}} & 0.5\le\gamma<1\end{cases}$	$\begin{cases}2\gamma & 0<\gamma\le 0.5\\ 2(1-\gamma) & 0.5\le\gamma<1\end{cases}$
VPPM	$\begin{cases}\sqrt{\frac{2}{\gamma}} & 0<\gamma\le 0.5\\ \sqrt{\frac{2}{1-\gamma}} & 0.5\le\gamma<1\end{cases}$	$\begin{cases}\gamma & 0<\gamma\le 0.5\\ 1-\gamma & 0.5\le\gamma<1\end{cases}$
MPPM	$w_{\max}\sqrt{\frac{2}{n\log_2\binom{n}{w}}}$	$\frac{\log_2\binom{n}{w}}{n}$

Second, the spectral efficiency, ν, is a measure that how efficiently a limited spectrum is utilized by a given modulation scheme. It can be defined as the ratio of the bit rate R_b to the required bandwidth B [7]: R_b/B [bits/sec $\cdot$ Hz].

The spectral efficiencies of VOOK and VPPM are given, respectively,

$$\nu_{\text{vook}} = \begin{cases} 2\gamma & \text{for } 0<\gamma\le 0.5\\ 2(1-\gamma) & \text{for } 0.5\le\gamma<1,\end{cases} \tag{8}$$

$$\nu_{\text{vppm}} = \begin{cases} \gamma & \text{for } 0<\gamma\le 0.5\\ 1-\gamma & \text{for } 0.5\le\gamma<1.\end{cases} \tag{9}$$

From (8) and (9), we can see that VOOK has better spectral efficiency than VPPM. Spectral efficiencies for MPPM is also listed in Table II [3].

In MPPM, if we increase n, we can control the brightness level of the lighting precisely. We use Stirling's approximation [8]: $\binom{n}{w} \to 2^{nh(w/n)}$ as $n\to\infty$, where $h(x) = -x\log_2 x - (1-x)\log_2(1-x)$ is the binary entropy function. An MPPM bound on the required power and spectral efficiency of MPPM as $n\to\infty$ is, respectively

$$\bar{P}_{\text{mppm}} \to \sqrt{\frac{2}{h(\gamma)}}, \tag{10}$$

$$\nu_{\text{mppm}} \to h(\gamma). \tag{11}$$

Note that if $n\to\infty$, and $\gamma\to 1/2$ then $\bar{P}_{\text{mppm}}\to\sqrt{2}$ (1.5 dB), and $\nu_{\text{mppm}}\to 1$. In other words, under 50% brightness certain MPPM codeword with infinite codeword length, at least theoretically can achieve the spectral efficiency of 1 [[bits/sec $\cdot$ Hz] but require 1.5 dB more power than OOK. However, as $\gamma\to 0$ or 1, $\bar{P}_{\text{mppm}}\to\infty$, and $\nu_{\text{mppm}}\to 0$.

III. SIMULATION RESULTS

Figs. 2 and 3 demonstrate the required power and spectral efficiency with respect to the dimming factor for each modulation scheme. We can see that VOOK has the same required power as VPPM, but it has better spectral efficiency. MPPM shows better performance than VOOK and VPPM in terms of required power over all dimming factors. As for spectral efficiency, MPPM with $n = 20$ shows better spectral efficiency than VOOK except $0.45 \le \gamma \le 0.55$. But as the codeword length $n\to\infty$, the performance of MPPM shows the best performance over all modulation schemes.

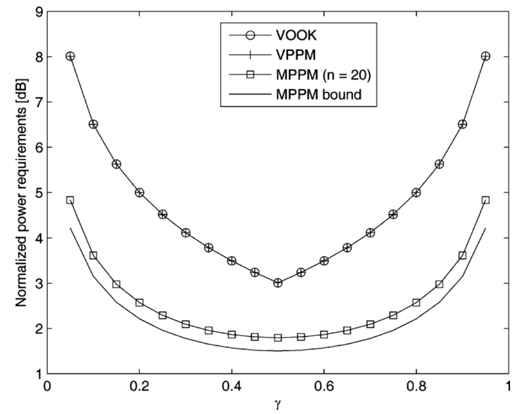

Fig. 2. Normalized power requirements of several modulation schemes.

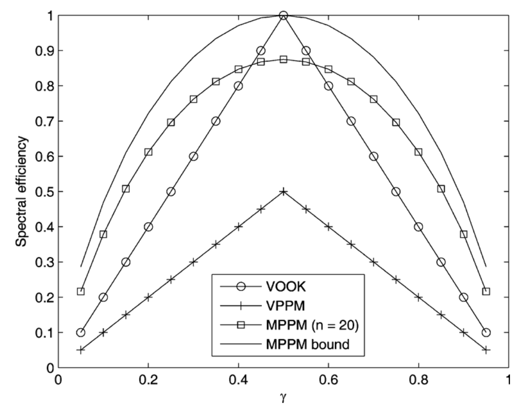

Fig. 3. Spectral efficiencies of several modulation schemes.

IV. CONCLUSION

A VLC modulation scheme requires compatibility with the dimming system of the LED lighting. We propose an MPPM based dimming system by changing the number of optical pulses within one symbol duration, as the dimming factor can be expressed by MPPM parameters: n and w. We have calculated the required power and spectral efficiency according to the dimming factor. MPPM is more attractive than VOOK and VPPM, because it can achieve a higher spectral efficiency with less optical power as the codeword length n increases. Although we assume perfect synchronization, chip and symbol synchronization schemes are required.

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