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A spectral-efficient dimming control scheme with multi-level incremental constant weight codes in visible light communication systems[☆]

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ABSTRACT

As an essential requirement for visible light communication (VLC) system, dimming control has attracted increasing attentions where arbitrary brightness levels can be achieved. Conventional dimming schemes based on binary modulation are spectral inefficient. In this paper, we propose multi-level incremental constant weight codes (ML-ICWC) scheme to achieve dimming control via controlling the number of LEDs on per lighting source simultaneously. Meanwhile, the construction algorithm of the codeword set is developed accordingly to guarantee reliable data transmission. Finally, simulation results show that the proposed scheme achieves significant improvement in terms of spectral efficiency compared with existing dimming schemes under various dimming levels.

1. Introduction

Light-emitted diode (LED) based lighting is expected to replace the conventional incandescent and fluorescent lighting due to the low consumption, high efficiency and long lifetime [1,2]. Meanwhile, with the increasing demand for high speed indoor wireless communication, visible light communication (VLC) has become a promising option utilizing the superior modulation capability of LEDs [3–5]. Capable of providing communication and illumination simultaneously, VLC has notable advantages over radio frequency such as huge bandwidth, high rate transmission, licence-free operation and no health concerns. Thus, plenty of researches have been carried out, and the standardization for VLC has been proposed by the IEEE 802.15.7 VLC Task Group [6].

Since VLC system facilitates the dual functions of supporting wireless data transmission and green lighting, both communication performance and lighting quality should be considered when we design signals. As an important indoor applications, dimming control technique is proposed to enhance commercial implementation and ecological benefits where arbitrary brightness levels can be achieved. Realizing dimming function may degrade communication performance, where conventional dimming schemes based on binary modulation are spectral inefficient because only one LED lighting is utilized. Therefore, proper dimming schemes must be developed to create a balance between illumination and communication. The current challenges in dimming control have attracted more attentions in recent years [7–15]. âĂÍâĂÍ

Essentially, dimming requirement can be achieved via controlling the average light intensity. Few attempts have been made via designing modulation and coding schemes to simultaneously provide data transmission and dimming control. Based on binary modulation, variable on–off keying (VOOK) modulation, variable pulse position modulation (VPPM) and multiple pulse position modulation (MPPM) are proposed in [10–12] respectively, where the ratio of "ON" time to "OFF" time of the signal is adjusted to meet the dimming requirement. Among them, VOOK and VPPM are simple to implement, but they cannot offer high data rate support due to the bandwidth wastage by the compensation time intervals [8]. MPPM, also regarded as constant weight code (CWC) from the perspective of coding, is capable of approaching the theoretic spectral efficiency limit as the codeword length increases in terms of binary scheme. Furthermore, a possible solution to solve the problem of low spectral efficiency is the multi-level scheme which can provide improved spectral efficiency. In [13], multi-level pulse amplitude modulation (ML-PAM) is proposed via concatenating different PAM symbols with the average amplitude matching the required dimming levels. However, this approach constructs multi-level pulses via adjusting the DC bias of the signal which may cause chromaticity shifts. Multi-level MPPM (ML-MPPM) proposed in [14] controls the number of LEDs on per lighting source to achieve high-order modulation of MPPM, which can improve the spectral efficiency further. Therefore, many researches have been carried out in terms of efficient data transmission as well as achieving dimming control function.

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Table 1
Maximum number of symbols in $R_{n,\omega}$ with $l_{max} = 3$.

n \ ω	0	1	2	3	4	5	6	7	8	9	10	11	12
0	1												
1	1	1	1										
2	1	2	3	2	1								
3	1	3	6	7	6	3	1						
4	1	4	10	16	19	16	10	4	1				
5	1	5	15	30	45	51	45	30	15	5	1		
6	1	6	21	50	90	126	141	126	90	50	21	6	1

Motivated by the work [14], we propose multi-level incremental constant weight codes (ML-ICWC) scheme to achieve dimming control and higher spectral efficiency. Via adding more allowable codewords into the original code set under the constraint that the average code weight remains constant, the proposed dimming scheme achieves better performance in terms of spectral efficiency.

The reminder of this paper is organized as follows: The system model is provided in Section 2. In Section 3, the construction of ML-ICWC is demonstrated and the algorithm is summarized accordingly. In Section 4, simulation results have been carried out to compare the different dimming schemes. Finally we conclude our findings in Section 5.

2. System model

In VLC links, the input signal modulates the optical intensity of the light emitted from the LEDs, and the optical power is proportional to the input current. At the receiver, we assume perfect symbol synchronization. Typically, photodetector (PD) remains still and the direct light holds a dominant position compared with the reflected light in indoor VLC system. Thus, the received electrical signal detected by the PD can be modeled as

$$Y = hX + N, \tag{1}$$

where X denotes the driven electrical signal from LED, N includes both thermal and ambient-light noise, and h represents the electro-optical-electro (EOE) channel coefficient [1,16]. For practical consideration, the transmitted signals should be restricted to be nonnegative, i.e., $X > 0$. N is considered to be the additive white Gaussian noise (AWGN) with zero mean and variance σ^2, which is independent to X. Without loss of generality, we assume the EOE channel coefficient $h = 1$.

In general, the human eyes normally perceive the average illuminance instead of the instantaneous illuminance if the light intensity changes faster than 150–200 Hz [8]. In dimmable VLC system, the average light intensity shall remain constant. This implies the following constraint

$$E[X] = \gamma P, \tag{2}$$

where $E[\cdot]$ denotes expectation, P is the nominal optical intensity of LED devices and $\gamma \in (0, 1)$ is the dimming factor.

3. The proposed coding scheme

In this section, we review the original construction based on ML-MPPM proposed in [14], and introduce the proposed ML-ICWC scheme which can achieve higher spectral efficiency, and the construction algorithm is provided accordingly. In general, the commercial LED lights use more than one LED per light source, so the possibility of individual current control of these LEDs can help to achieve high order modulation, which can be applied in our proposed scheme.

3.1. The construction of ML-MPPM

In ML-MPPM, the symbol time is divided into n equal time slots, and l_i denotes the number of levels in the i_{th} slot where $l_i \in \{0, 1, 2, \ldots, l_{max} - 1\}$ and l_{max} is the number of levels permitted in each slot. Meanwhile, ω denotes the code weight in the codeword which is defined as $\omega = \sum_{i=1}^{n} l_i$ with $0 \le \omega \le n(l_{max} - 1)$. When the parameters n and l_{max} are given, various dimming levels can be obtained via adjusting the parameter ω, so the dimming factor can be expressed as

$$\gamma = \frac{\omega}{n(l_{max} - 1)}. \tag{3}$$

Thus, precise dimming levels can be obtained via changing the parameters n and l_{max}. When $l_{max} = 2$, the ML-MPPM reduces to binary MPPM.

Here, R_n denotes the set of all length-n non-binary codeword set, and the cardinality of R_n is $|R_n| = (l_{max})^n$. Accordingly, $R_{n,\omega}$ denotes the set of all length-n non-binary codewords with code weight ω, and the cardinality of $R_{n,\omega}$ is [14]

$$|R_{n,\omega}| = \begin{cases} 0, & n = 0 \\ 1, & n = 0, \omega = 0 \\ \displaystyle\sum_{i=0}^{l_{max}-1} |R_{n-1,\omega-i}|, & otherwise \end{cases} \tag{4}$$

Based on Eq. (4), we have constructed Table 1 with $l_{max} = 3$ for reference, where each value represents the maximum number of symbols that can be encoded for the given n and ω. Thus, the bits formed by the specific codewords are $k = \lfloor \log_2 |R_{n,\omega}| \rfloor$ where $\lfloor t \rfloor$ denotes the largest integer not greater than t. So the spectral efficiency can be regarded as

$$v = \frac{R_b}{B} = \frac{k}{n}. \tag{5}$$

where R_b is the transmission data rate and B is the bandwidth requirement.

3.2. The construction of ML-ICWC

Motivated by the work [14], we propose multi-level incremental constant weight codes (ML-ICWC) scheme to achieve dimming control and higher spectral efficiency. Essentially, to improve the achievable spectral efficiency further, incremental length-n non-binary codewords with different code weight can be added into the original dimming code set under the constraint that the average code weight remains constant. Therefore, the required dimming target can be maintained as well as increase achievable spectral efficiency, which is significant for bandwidth limited applications. To make our presentation as understandable as possible, we define the following notations:

1. Based on the codeword set of ML-MPPM $R_{n,\omega}$, we denote the codeword set of ML-ICWC as $\tilde{R}_{n,\omega}$, which represents incremental length-n non-binary codewords.
2. For the given n and ω, we denote the codeword set $\overleftarrow{R} = \bigcup_{i=0}^{\omega-1} R_{n,i}$ which includes all the codewords with code weight $i = 1, 2, \ldots, \omega - 1$. Accordingly, $\overrightarrow{R} = \bigcup_{i=\omega+1}^{n(l_{max}-1)} R_{n,i}$ is defined as the codeword set with code weight $i = \omega + 1, \omega + 2, \ldots, n(l_{max} - 1)$. $|\overleftarrow{R}|$ and $|\overrightarrow{R}|$ denote the cardinality of $\overleftarrow{R}$ and $\overrightarrow{R}$ respectively.