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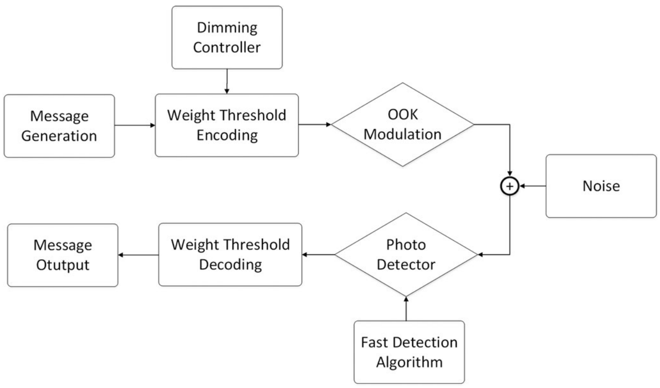

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Weight Threshold Check Coding for Dimmable Indoor Visible Light Communication Systems

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Abstract: To provide energy savings and ecological benefits, dimming control is a crucial factor in indoor visible light communication (VLC) system where desired brightness levels can be achieved. General dimming control methods have an adverse effect on communication, e.g., limiting the achievable data rate or degrading the error performance. In this paper, we propose a code-based method weight threshold check code (WTCC), which can achieve dimming control as well as improve spectral efficiency further. Moreover, the proposed WTCC has a low implementation complexity with a simple encoding/decoding structure. Finally, simulations have been carried out in terms of normalized power requirement, spectral efficiency, and error performance, which prove WTCC can provide a balance between the two basic functions of VLC: illumination and communication.

Index Terms: Visible light communication (VLC), dimming control, weight threshold check code (WTCC), encoding/decoding structure.

1. Introduction

As a new generation green lighting source, light emitting diode (LED) is rapidly replacing the conventional incandescent and fluorescent lighting due to the long lifetime and high efficiency [1], [2]. Meanwhile, taking advantages of superior modulation capability of LEDs, visible light communication (VLC) has attracted numerous attention to achieve communication and illumination simultaneously in recent years [3]–[5]. Some notable advantages of VLC over radio frequency (RF) include huge bandwidth, high rate transmission, licence-free operation, inherent security, and no electromagnetic interference with RF system. Since VLC system serves the dual functions of supporting wireless data transmission and green lighting, both communication performance and lighting quality should be considered when we design signals. Therefore, to provide moods, energy savings and ecological benefits, dimming control is particularly important for indoor applications where brightness can be adjusted at desired levels. However, general dimming control schemes have an adverse effect on communication. Therefore, proper dimming control methods must be developed to create a balance between illumination and communication. As a result, the current challenges in dimming control have attracted more attentions in recent years [6]–[18].

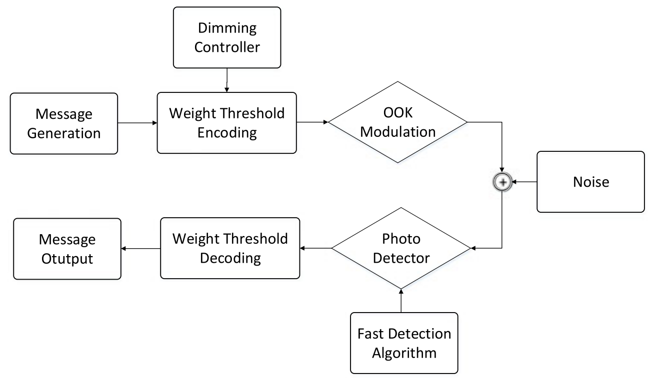

Fig. 1. Block diagram of the proposed scheme.

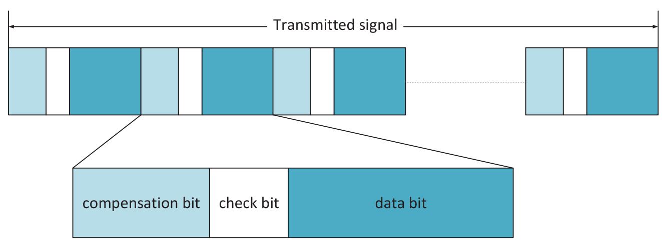

Fig. 2. The frame structure of transmitted signal.

Generally, the existing OOK-based schemes can achieve dimming control via adding compensation symbols or alter the occurrence frequency of two levels (ON and OFF), which may limit the achievable data rate or degrade the error performance. Thus, both reliable data transmission and efficient data transmission require further research in dimmable VLC system. Variable on-off keying (VOOK) and variable pulse position modulation (VPPM) proposed by the IEEE 802.15.7 VLC Task Group in [7] are simple to implement, and they have better compatibility with channel coding to improve error performance. However, the two schemes can not offer high data rate support due to the bandwidth wastage by the compensation time intervals [9]. Based on binary entropy function, Kwon proposed inverse source coding (ISC) scheme to meet the theoretical maximum spectral efficiency under a given dimming target in [8]. Unfortunately, ISC has poor compatibility with channel coding, thus requiring an error-free condition. Multiple PPM (MPPM) aided dimming method proposed in [10] is capable of approaching the theoretic spectral efficiency limit as the codeword length increases. However, a long codeword increases the associated encoding/decoding complexity and imposes higher storage requirement. For sake of achieving joint dimming control and error correction, constant weight code (CWC) with large Hamming distance was proposed in [13], but it can not offer high data transmission rate. Afterwards, a modified scheme in [14] utilizing semi-CWC achieves significant enhancement in terms of spectral efficiency so far, but the codeword set needs further selection which should be constrained 2's power to exponentially map the massage which causes complex implementation. Thus, achieving reliable data transmission and efficient data transmission simultaneously is contradictory for a dimming scheme. Essentially, despite showing certain advantages, the existing dimming schemes are difficult to achieve a balance of overall performance.

Motivated by these challenges, in this paper, we propose a code-based scheme weight threshold check code (WTCC) to achieve dimming control as well as improve spectral efficiency further. Via setting a threshold on code weight, the construction of the proposed WTCC has a low implementation complexity, and the encoding/decoding algorithms are given accordingly. Meanwhile, the fast detection algorithm based on Maximum Likelihood (ML) detector is also provided for efficiency and effectiveness. Finally, simulation results show that WTCC provides a balance between illumination and communication, especially achieving significant enhancement in spectral efficiency.

The reminder of this paper is organized as follows: In Section 2, the system model of the general OOK-based dimming methods is provided. In Section 3, the implementation of WTCC is demonstrated and the construction of encoding/decoding algorithm is summarized accordingly. In Section 4, compared with the existing dimming control methods, WTCC behaves better performance in terms of the spectral efficiency and power requirement. In Section 5, simulation results of error performance are carried out. Finally we conclude our findings in Section 6.

2. System Model

In OOK-based VLC system with intensity modulation and direct detection, message is carried by the light intensity emitted from the LED, and the light intensity should be restricted to be nonnegative. On the receiver side, 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. Therefore, line of sight (LOS) path is assumed. The received signal can be modeled as

$$\mathbf{r} = h \cdot \mathbf{b} + \mathbf{n}, \tag{1}$$

where **b** denotes the transmitted signal and **n** denotes the additive white Gaussian noise (AWGN) with zero mean and variance σ^2 [19]. Without loss of generality, we assume the electro-optical-electro (EOE) channel gain $h = 1$ [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 [9]. Let P denote the peak intensity and $\bar{P}$ denote the average intensity of the received signal. Thus, the dimming factor can be defined as

$$\gamma = \frac{\bar{P}}{P}, \tag{2}$$

where $0 < \gamma < 1$.

Aiming at the different dimming schemes, the construction of the transmission signal **b** is different. Compensation time dimming methods (e.g. VOOK and VPPM) add all 1 s or 0 s compensation bit after data bit. MPPM-aid dimming scheme constructs the set of codewords by changing the occurrence frequency of 1 s and 0 s during the symbol time to match the dimming target. The codewords constructed by semi-CWC include original constant weight codes and additional codes with different code weight under the constraint that the average code weight remains constant. While WTCC selects the specific codeword set by setting the threshold value on code weight in the encoding structure, which will be detailedly demonstrated in next section.

3. The Proposed Weight Threshold Check Code

The whole process of WTCC is shown in Fig. 1 for reference. Dimming control can be operated by the "Dimming Controller" and the "Weight Threshold Encoding" part. Meanwhile, the fast detection algorithm based on ML detector is also provided accordingly for efficiency and effectiveness.

The frame structure of the transmitted signal mainly consists of three parts, i.e. N_d data bit, 1 check bit and N_c compensation bit (all 0 s or 1 s), as shown in Fig. 2. The length of data bit and compensation bit is variable, while the length of check bit is fixed as one. Thus, the whole length of the codeword is $N = N_d + 1 + N_c$. Comparatively speaking, the construction of WTCC has a structured design. For simplification, we discuss dimming factor $\gamma \in (0, 0.5)$ here, which is symmetrical to $\gamma \in (0.5, 1)$ part.

3.1 Dimming Encoder

For any binary data bit with length $N_d = 2K$, the bit string $\mathbf{b}_l = [b_{2K}, \ldots, b_2, b_1]$ is the input of the "Weight Threshold Encoding" part under the threshold value K. We increase 1 check bit and $N_c = \bar{K}$ compensation bit (all 0s) in front of $\mathbf{b}_l$. Thus, the encoding structure can be divided into two cases according to the code weight:

1) If code weight of the input bit string $\sum_{k=1}^{2K} b_k \leq K$, the output of the encoder is given by $\mathbf{b} = [0, \ldots, 0, 0, b_{2K}, \ldots, b_2, b_1]$.
2) If code weight of the input bit string $\sum_{k=1}^{2K} b_k \geq K+1$, the output of the encoder is given by $\mathbf{b} = [0, \ldots, 0, 1, \bar{b}_{2K}, \ldots, \bar{b}_2, \bar{b}_1]$, where $\bar{b}_k = 1 - b_k$.

Example 1: The construction of length $N = 5$ codeword with 4 data bit, 1 check bit and no compensation bit

i	Input 4-bit	Codeword	i	Input 4-bit	Codeword
1	0000	00000	9	0110	00110
2	0001	00001	10	1010	01010
3	0010	00010	11	1100	01100
4	0100	00100	12	0111	11000
5	1000	01000	13	1011	10100
6	0011	00011	14	1101	10010
7	0101	00101	15	1110	10001
8	1001	01001	16	1111	10000

From the above analysis, the achievable dimming levels of WTCC can be controlled by varying the number of input data bit and compensation bit. After encoding process, we note that the designed codeword has the following mathematical character. Given length $N = 2K + 1$ codeword ($2K$ data bit, 1 check bit and no compensation bit), the allowable codeword set can be marked as

$$\mathcal{B} = \left\{\mathbf{b} : b_k \in \{0, 1\}, k = 1, 2, \ldots, 2K+1, \sum_{k=1}^{2K+1} b_k \leq K\right\}, \tag{3}$$

where $\mathcal{B}$ denotes the set of all length $N = 2K + 1$ codeword with code weight $\sum_{k=1}^{2K+1} b_k \leq K$.

Thus, the cardinality of $\mathcal{B}$ is

$$|\mathcal{B}| = \sum_{\omega=0}^{K} \frac{(2K+1)!}{(2K+1-\omega)!\omega!} = 2^{2K}. \tag{4}$$

With the threshold value of code weight K fixed, the allowable codewords are equal to the forbidden codewords.

Essentially, the code weight of codeword can be regarded as the average light intensity during transmitted data frame. In fact, the usual coded data consist almost the same number of 1 s and 0 s, which means the occurrence of 1 s and 0 s equiprobable. Apparently, when not adding check bit and compensation bit, the dimming level of the input bit string is $\gamma = \frac{1}{2}$. When adding check bit and compensation bit $\bar{K} = 0$, the output of encoder $\mathbf{b}$ satisfies the property of the designed bit string $\mathcal{B}$. Accordingly, we can conclude the peak intensity of the transmitted data frame is $P = 2K + 1$. The average intensity is $\bar{P} = \frac{1}{2^{2K}} \sum_{\omega=0}^{K} \omega \frac{(2K+1)!}{(2K+1-\omega)!\omega!}$, which can be simplified as $\bar{P} = \frac{2K+1}{2^{2K}}(2^{2K-1} - \frac{(2K)!}{2(K!)^2})$.

Thus, the dimming factor can be calculated as

$$\gamma = \frac{\bar{P}}{P} = \frac{1}{2} - \frac{(2K)!}{2^{2K+1}(K!)^2}. \tag{5}$$

TABLE 1
Dimming Range Under WTCC

compensation bit \ data bit	$N_d=2$	$N_d=4$	$N_d=6$	$N_d=8$	$\cdots$	$N_d=2K$
no check bit, $N_c=0$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\cdots$	$\frac{1}{2}$
1 check bit, $N_c=0$	$\frac{1}{4}$	$\frac{5}{16}$	$\frac{11}{32}$	$\frac{93}{256}$	$\cdots$	$\frac{1}{2}-\frac{(2K)!}{2^{2K+1}(K!)^2}$
1 check bit, $N_c=1$	$\frac{3}{16}$	$\frac{25}{96}$	$\frac{77}{256}$	$\frac{837}{2560}$	$\cdots$	$\frac{2K+1}{2K+2}[\frac{1}{2}-\frac{(2K)!}{2^{2K+1}(K!)^2}]$
1 check bit, $N_c=2$	$\frac{3}{20}$	$\frac{25}{112}$	$\frac{77}{288}$	$\frac{837}{2816}$	$\cdots$	$\frac{2K+1}{2K+3}[\frac{1}{2}-\frac{(2K)!}{2^{2K+1}(K!)^2}]$
1 check bit, $N_c=3$	$\frac{1}{8}$	$\frac{25}{128}$	$\frac{77}{320}$	$\frac{279}{1024}$	$\cdots$	$\frac{2K+1}{2K+4}[\frac{1}{2}-\frac{(2K)!}{2^{2K+1}(K!)^2}]$
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\cdots$	$\vdots$
1 check bit, $N_c=\bar{K}$	$\frac{3}{4(3+\bar{K})}$	$\frac{25}{16(5+\bar{K})}$	$\frac{77}{32(7+\bar{K})}$	$\frac{837}{256(9+\bar{K})}$	$\cdots$	$\frac{2K+1}{2K+1+\bar{K}}[\frac{1}{2}-\frac{(2K)!}{2^{2K+1}(K!)^2}]$

Algorithm 1: Weight Threshold Encoding.

Input: dimming factor γ and the input data bit $\mathbf{b}_I$
then get K and $\bar{K}$ via Look-Up Table
Output: transmitted signal $\mathbf{b}$
if $\sum_{k=1}^{2K} b_k \leq K$
$\mathbf{b} = [0, \cdots, 0, 0, b_{2K}, \cdots, b_2, b_1]$
else $\sum_{k=1}^{2K} b_k \geq K+1$
$\mathbf{b} = [0, \cdots, 0, 1, \bar{b}_{2K}, \cdots, \bar{b}_2, \bar{b}_1]$, where $\bar{b}_k = 1 - b_k$

When compensation bit $\bar{K} \geq 1$, accordingly, the dimming factor is

$$\gamma = \frac{2K+1}{2K+1+\bar{K}}\left[\frac{1}{2} - \frac{(2K)!}{2^{2K+1}(K!)^2}\right]. \tag{6}$$

Analysis indicates that smaller and precise dimming levels can be obtained with the increase of compensation bit. However, overmuch compensation bit can degrade the performance of spectral efficiency. Table 1 is shown to demonstrate the dimming range with the proposed WTCC. Therefore, the whole above-mentioned encoding process can be summarized as Algorithm 1.

3.2 Dimming Decoder

With the system model (1), the probability density function of the received signal $\mathbf{r}$ conditioned on $\mathbf{b}$ can be given by

$$p(\mathbf{r}|\mathbf{b}) = \frac{1}{(\sqrt{2\pi\sigma^2})^N}\exp\left(-\frac{\|\mathbf{r}-\mathbf{b}\|_2^2}{2\sigma^2}\right) \tag{7}$$

The output of the ML detector, equivalent to minimum Euclidean distance detector, is given by

$$\hat{\mathbf{b}} = \arg\min \|\mathbf{r}-\mathbf{b}\|_2^2. \tag{8}$$

A simple method to estimate the transmitted signal $\mathbf{b}$ is exhaustive search to the Euclidean distance of the received signal and transmitted signal. The overall complexity is $O(2^N)$. Our principal is to develop a detection algorithm efficiently and effectively estimating the transmitted signal $\mathbf{b}$ from the given received signal $\mathbf{r}$.

In order to solve the problem, we note that the objective function in (8) can be expressed as

$$\|\mathbf{r}-\mathbf{b}\|_2^2 = \|\mathbf{r}\|_2^2 + \|\mathbf{b}\|_2^2 - 2\mathbf{r}^T\mathbf{b}, \tag{9}$$

Algorithm 2: Weight Threshold Decoding.

Input: received signal $\mathbf{r}$
Output: the estimation bit $\hat{\mathbf{b}}$ and decoding bit $\mathbf{b}_D$
for $0 \le C \le K$
  $R[C] = C - 2\sum_{i=1}^{C} r_k^{(i)}$
then $\hat{C} = \arg\min_{0\le C\le K} R[C]$
  if $\hat{C} = 0$
    $\hat{\mathbf{b}} = \mathbf{0}_{1\times(2K+1+\bar{K})}$
  else
    for $1 \le i \le \hat{C}$
      $\hat{b}_k = \hat{b}_k^{(i)} = 1$
    for $\hat{C}+1 \le i \le 2K+1+\bar{K}$
      $\hat{b}_k = \hat{b}_k^{(i)} = 0$
if $\hat{b}_{2K+1} = 0$
  $\mathbf{b}_D = [\hat{b}_{2K}, \ldots, \hat{b}_2, \hat{b}_1]$
else $\hat{b}_{2K+1} = 1$
  $\mathbf{b}_D = [1-\hat{b}_{2K}, \ldots, 1-\hat{b}_2, 1-\hat{b}_1]$

where $\|\mathbf{b}\|_2^2 = \sum_{k=1}^{2K+1+\bar{K}} b_k$ since $b_k^2 = b_k$ holds for any $b_k \in \{0, 1\}$ and $\|\mathbf{r}\|_2^2 = \sum_{k=1}^{2K+1+\bar{K}} r_k$ is a constant. Therefore, the objective function of the ML detector is equivalent to

$$\hat{\mathbf{b}} = \arg\min \sum_{k=1}^{2K+1+\bar{K}} b_k - 2\mathbf{r}^T\mathbf{b}. \tag{10}$$

To make our presentation as understandable as possible, we define the following three notations:

1) We first define the code weight of the codeword as

$$C = \sum_{k=1}^{2K+1+\bar{K}} b_k = \sum_{k=1}^{2K+1} b_k. \tag{11}$$

In fact, C denotes the summation number of $b_k = 1$ in OOK modulation. Therefore, the number of bit 1 is fixed. Besides, to avoid the occurrence of forbidden codewords, the value range of the defined code weight C is $0 \le C \le K$.

2) Rearrange the first $2K+1$ terms of $\mathbf{r}$ with the decreasing order as $r_k^{(1)} \ge r_k^{(2)} \ge \cdots \ge r_k^{(i)} \ge \cdots \ge r_k^{(2K+1)}$, where index k is the original index of r_k in $\mathbf{r}$ and index i is the ordering number after arrangement. For example, if $\mathbf{r} = (r_5, r_4, r_3, r_2, r_1)^T = (0.1, 1.1, 1.2, 0.3, 0.2)^T$, then $r_3^{(1)} = 1.2$, $r_4^{(2)} = 1.1$, $r_2^{(3)} = 0.3$, $r_1^{(4)} = 0.2$, $r_5^{(5)} = 0.1$ after arrangement.

3) Let $b_k^{(i)}$ be the corresponding symbol of $r_k^{(i)}$, and we define

$$R = C - 2\mathbf{r}^T\mathbf{b} = C - 2\sum_{k=1}^{2K+1} r_k^{(i)} b_k^{(i)} = C - 2\sum_{i=1}^{C} r_k^{(i)}. \tag{12}$$

The decoder can be regarded as the inverse process of encoder. Based on the fast detection algorithm, it is essential to the make a judgement for the value of $\hat{b}_{2K+1}$ with the estimation of transmitted signal $\hat{\mathbf{b}}$. Therefore, all the above discussions can be summarized in Algorithm 2 with the following successive steps.

Analysis indicates that the main complexity of fast detection algorithm comes from sorting the received signal $\mathbf{r}$, and the complexity is $O(N\log_2 N)$, thus appearing an efficient performance. However, the check bit error will bring the entire $2K$ input bit errors, so the value of parameter K

TABLE 2
Normalized Power Requirement and Spectral Efficiency of Different Schemes

	Normalized Power Requirement	Spectral Efficiency
OOK	1	1
VOOK	$\begin{cases} \sqrt{\frac{2}{\gamma}}, & 0 < \gamma < 0.5 \\ \sqrt{\frac{2}{1-\gamma}}, & 0.5 \le \gamma < 1 \end{cases}$	$\begin{cases} 2\gamma, & 0 < \gamma < 0.5 \\ 2(1-\gamma), & 0.5 \le \gamma < 1 \end{cases}$
VPPM	$\begin{cases} \sqrt{\frac{2}{\gamma}}, & 0 < \gamma < 0.5 \\ \sqrt{\frac{2}{1-\gamma}}, & 0.5 \le \gamma < 1 \end{cases}$	$\begin{cases} \gamma, & 0 < \gamma < 0.5 \\ 1-\gamma, & 0.5 \le \gamma < 1 \end{cases}$
MPPM[1]	$\sqrt{\frac{2n}{\lfloor \log_2 \binom{n}{\omega} \rfloor}}$	$\frac{\lfloor \log_2 \binom{n}{\omega} \rfloor}{n}$
semi-CWC[2]	$2\sqrt{\frac{n}{k}}$	$\frac{k}{n}$
WTCC	$\sqrt{\frac{2(2K+1+\bar{K})}{K}}$	$\frac{2K}{2K+1+\bar{K}}$

[1] n denotes the length of codeword and ω denotes fixed code weight.
[2] n denotes the length of codeword and k denotes the number of bits formed by codewords.

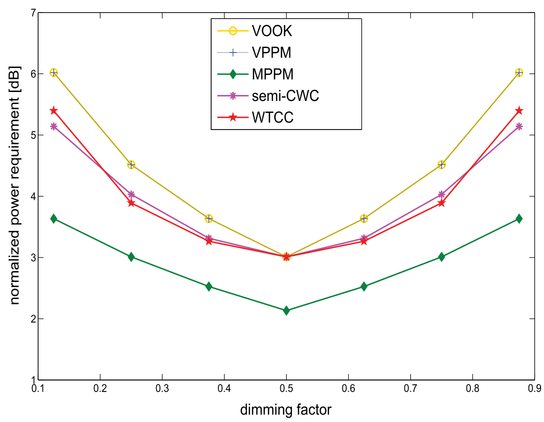

Fig. 3. Normalized power requirement of different schemes.

should keep small in general. In conclusion, with the aid of encoding/decoding structure, we can achieve data transmission and dimming control simultaneously.

4. Performance Analysis

Efficient dimming schemes need to create a balance between illumination and communication, where spectral efficiency and power requirement are the common evaluation indicators. This section gives the performance comparison of several dimming schemes.

For power limited applications, lower power requirement is preferable. Accordingly, the conception of normalized power requirement is first defined in [20], which is a measure that how much power is needed to achieve a given bit-error-rate (BER) and bit rate. When comparing the power requirement of different schemes, OOK is regarded as a benchmark. Thus, the power requirement of WTCC can be approximately as

$$P_{WTCC} \approx \frac{d_{OOK}}{d_{WTCC}} P_{OOK}. \tag{13}$$

where $d_{OOK} = \frac{2P}{\sqrt{R_b}}$.

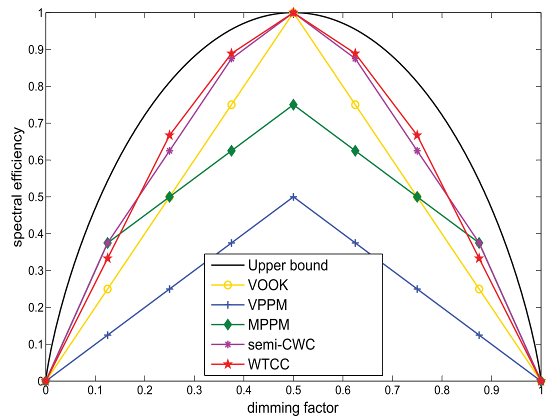

Fig. 4. Spectral efficiency of different schemes.

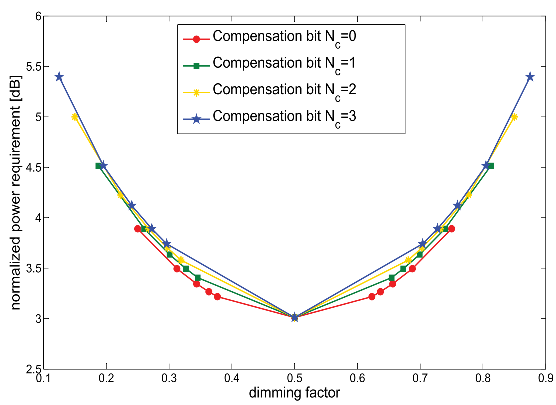

Fig. 5. Normalized power requirement of WTCC with different compensation bit.

For fair comparison, the peak power constraint of transmitted signal is set as P based on [10]. The minimum Euclidean distance between the two signals of WTCC is

$$d_{WTCC} = P\sqrt{\frac{2(2K+1+\bar{K})}{KR_b}}. \tag{14}$$

Therefore, the normalized power requirement of the proposed WTCC is

$$\bar{P}_{WTCC} = \frac{P_{WTCC}}{P_{OOK}} = \sqrt{\frac{2(2K+1+\bar{K})}{K}}. \tag{15}$$

In addition, the spectral efficiency ν, defined as the ratio of bit rate to the required bandwidth, is also an important factor. For bandwidth limited applications, better spectral efficiency and transmission rate are needed. Accordingly, [8] gives the theoretical maximum spectral efficiency under a given dimming target. So the spectral efficiency of WTCC is

$$\nu = \frac{2K}{2K+1+\bar{K}}. \tag{16}$$

With normalized power requirement and spectral efficiency of VOOK, VPPM, MPPM obtained in [10], semi-CWC in [14] and the proposed WTCC, the performance comparison of the dimming schemes is listed in Table 2. In terms of power requirement, VOOK and VPPM have the same required power due to the same Euclidean distance, while MPPM-aided dimming scheme performs

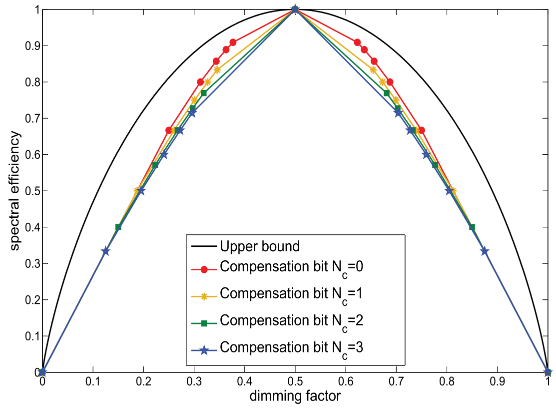

Fig. 6. Spectral efficiency of WTCC with different compensation bit.

better [10]. The performance of semi-CWC and the proposed WTCC fall in between VOOK and MPPM. As for spectral efficiency, VOOK and VPPM can not offer high data rate support due to the bandwidth wastage by the compensation time intervals, while MPPM, semi-CWC and WTCC can achieve higher spectral efficiency.

Moreover, computational complexity is also an essential factor to check the feasibility of different dimming schemes. As far as our concerned, the main implementation complexity comes from the construction of transmitted codeword, which has been analysed qualitatively in [9]. VOOK and VPPM are simple to implement where PWM signal is utilized by filling the inactive portion of the duty cycle with either ones or zeros based on the dimming target. However, in MPPM-aided dimming scheme, a long code length of MPPM symbol increases the associated encoding/decoding complexity and imposes higher storage requirement. Meanwhile, the codeword set needs further selection which should be constrained 2's power to exponentially map the massage, thus increasing complex implementation further. In the proposed scheme, the codeword of WTCC has a structured design. For any input binary data string, the transmitted codeword can be generated via the proposed encoding algorithm. Thus, the main complexity comes from the comparison of code weight for every input codeword with threshold value and the binary operation for the transmitted codewords.

5. Simulation Results

For comparing the performance among the above-mentioned schemes, simulations have been carried out under different dimming levels.

As shown in Figs. 3 and 4, the performance of different dimming schemes with $\gamma \in (0, 0.5)$ is symmetrical to $\gamma \in (0.5, 1)$ part, and better performance can be obtained when the dimming factor is close to 0.5. In terms of normalized power requirement, WTCC performs better then VOOK and VPPM in the whole dimming range and performs better then semi-CWC in [14] at $0.2 \leq \gamma \leq 0.8$. Moreover, based on the upper bound of spectral efficiency which is determined by the entropy [8], the performance comparison of spectral efficiency under several schemes are also shown in Fig. 4. We can see that the proposed WTCC achieves significant enhancement compared with the existing dimming schemes.

We have demonstrated that various dimming levels can be achieved via adding proper length of input data bit and compensation bit. As shown in Figs. 5 and 6, the performance of WTCC with different compensation bit N_c is compared. On one hand, fewer compensation bit have better performance in terms of the normalized power requirement and spectral efficiency. However, longer length of compensation bit can achieve a wider dimming range, as shown in Table 2. On the other hand, longer length of input data bit is capable of approaching the theoretical upper bound of spectral efficiency as we move near to dimming level $\gamma = 0.5$ especially, but increase the implementation

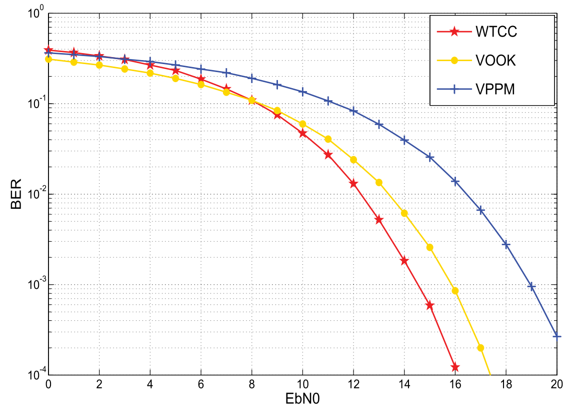

Fig. 7. Error performance of several schemes when $\gamma = \frac{5}{16}$.

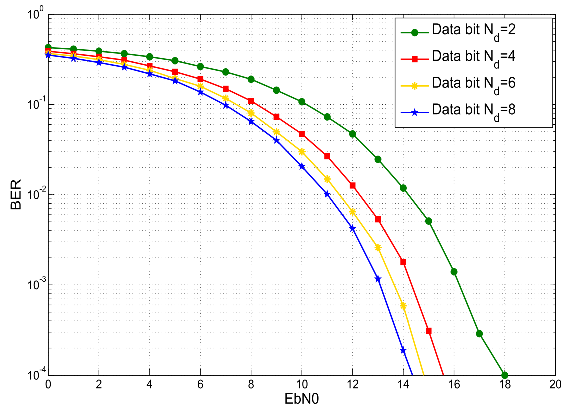

Fig. 8. Error performance of WTCC with different data bit with compensation bit $N_c = 0$.

complexity accordingly. In addition to show the performance difference, the dimming range with different length of compensation bit can be also shown accordingly.

The error performance of WTCC has been evaluated compared with two reference schemes, i.e. VOOK and VPPM. For MPPM-aided dimming scheme lacks efficient encoding and decoding structure, so we do not take it into comparison. According to [18], with the peak power constraint, the signal to noise ratio (SNR) is expressed as $SNR = P^2/\sigma^2$. For fair comparison, energy per bit to noise power spectral E_b/N_0 should be utilized to compare error performance for different dimming levels which is determined by the code rate R_c, expressed as $E_b/N_0 = SNR/R_c$. As shown in Fig. 7, given dimming factor $\gamma = \frac{5}{16}$, it can be seen that WTCC achieves 1.4 dB and 4.6 dB E_b/N_0 gains compared with VOOK and VPPM respectively when $BER = 10^{-3}$. However, WTCC behaves poor error performance at low SNR because the check bit error will bring the entire $2K$ input bit errors. Thus, high SNR is required to mention a reliable data transmission. The error performance of the proposed WTCC with different dimming levels is shown in Fig. 8, where different curves represent the different data bit N_d under compensation bit $N_c = 0$ and 1 check bit. We can see that as we move near to 50% dimming level, better error performance appears.

6. Conclusion

In this paper, the proposed WTCC can achieve data transmission as well as dimming control function. A wide range of dimming levels can be achieved via adding proper length of data bit and compensation bit. The structured design of WTCC can lower implementation complexity, and the encoding/decoding algorithms are given accordingly. Simulation results show that WTCC creates a balance between illumination and communication where better performance of spectral efficiency can be achieved especially. Therefore, the proposed WTCC can be regarded as an attractive alternative to achieve dimming control.

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