Alternative Line Coding Scheme with Fixed Dimming for Visible Light Communication

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Abstract. An alternative line coding scheme called fixed-dimming on/off keying (FD-OOK) is proposed for visible-light communication (VLC). FD-OOK reduces the flickering caused by a VLC transmitter and can maintain a 50% dimming level. Simple encoder and decoder are proposed which generates codes where the number of bits representing one is same as the number of bits representing zero. By keeping the number of ones and zeros equal the change in the brightness of lighting may be minimized and kept constant at 50%, thereby reducing the flickering in VLC. The performance of FD-OOK is analysed with two parameters: the spectral efficiency and power requirement.

1. Introduction
Light emitting diodes (LEDs) have been adopted for lighting mainly owing to their lower energy consumption and longer lifetime. They have provided a way to replace conventional illumination devices, e.g., incandescent, the gas discharged, etc. [1-3]. LED light sources offer a small size, a low forward voltage and drive current, excellent brightness in the visible spectrum, and the option of emission at a single wavelength or a range of wavelengths [4]. These properties of LEDs have enabled the possibility of wireless communication for data transfer. The use of light for transferring data is known as visual-light communication (VLC) and was drafted as the IEEE 802.15.7 standard [5].

In VLC systems, pulse width modulation (PWM) and pulse amplitude modulation (PAM) are usually used to achieve dimming support [6]; in contrast, on/off keying (OOK) and pulse position modulation (PPM) are usually used for data transmission. There are variants of the PPM available in the literature [7]: L-pulsed position modulation (LPPM), inverted PPM (I-PPM), and multipulse PPM (MPPM) [8]. Most of these modulation schemes were originally designed for free-space optical wireless communication (FSOWC) based on infrared (IR) transmission and not for VLC. The core component of VLC is the use of off-the-shelf LED lights. These LED lights exhibit nonlinear behavior when operated under normal circumstances. This nonlinearity is directly related to the...
dimming and flickering of the LED that is experienced in the VLC system. There are two ways to address the abovementioned issues: 1) to control the input current by introducing some bias and 2) to use the appropriate modulation scheme by fixing the current and voltage at the optimum values. Rather than the first method that requires a change in the circuit of the LED, the efficient way to address the issue is to use a modulation scheme along with line coding schemes that are easier to implement.

In order to resolve the abovementioned issues, an alternative line coding scheme called fixed-dimming OOK (FD-OOK) is proposed. The main objective of FD-OOK is to make the number of ones and zeros equal within each code word, which will make the dimming level equal to 50% and also reduce flickering. The performance of FD-OOK is evaluated in terms of both the normalized power requirement defined by the required optical power and the spectral efficiency measured by the bit rate given at a specific bandwidth.

The main contributions are as follows:
• The FD-OOK scheme is proposed so that a constant 50% dimming level is maintained at all times.
• A new encoder and decoder are proposed to implement the FD-OOK scheme.
• Flickering is controlled to keep the brightness level of the LEDs constant.

The rest of the paper is outlined as follows. Section 2 discusses the VLC system model, and Section 3 describes the proposed FD-OOK scheme in detail. In Section 4, the performance is evaluated through simulation, and Section 5 finally concludes the paper.

2. System Model
The VLC system model considered in this study is shown in Fig. 1. It is assumed that the receiver containing photodiodes (PDs) is located at the desktop surface height, and line-of-sight (LOS) is assumed for the communication scenario as well as illumination.

The flux produced by the LED lamp can be computed as:

\[ \phi_i = N \times \phi_{\text{max}} \]

where \( i \) is the \( i^{th} \) LED lamp, \( N \) is the dimming factor, and \( \phi_{\text{max}} \) is the maximum luminous flux for each LED lamp when the input waveform has a maximum-amplitude direct-current (DC) component. \( N \) is computed as

\[ N = \frac{a}{T} \]

where \( a \) denotes the number of high pulses in a particular code word waveform, and \( T \) is the time period of one code word waveform.

Hence, (1) can be expressed by substituting (2) for \( N \) as

\[ \phi_i = \left(\frac{a}{T}\right) \times \phi_{\text{max}} \]
and we can see that the dimming range can go from 0% to 100% by changing the variables a and T.

The illuminance expresses the brightness of the illuminated surface. Let \( E_j \) denote the illuminance at some workplace \( j \) from all LED lamps, which is calculated as [9]

\[
E_j = \sum_{i=1}^{t} \frac{(m + 1)\phi_i}{2\pi r^2} \cos^m(\theta) \cos \Psi
\]

where \( m \) is the Lambertian order, \( r \) is the distance between the LED and the PD, and \( \theta \) and \( \Psi \) are the angles of irradiance and incidence, respectively. The recommended illuminance value for homes and offices set by the ISO is 400–800 lux.

The total energy irradiated by the LED lamp is indicated by the total transmitted optical power, which determines the signal strength of optical communication [10]. VLC uses intensity modulation and direct detection (IM/DD). IM is obtained by varying the bias current of the LED lamps. DD is achieved by capturing the photocurrent induced by the PD, which is proportional to the optical power incident on it. In VLC, \( x(t) \) represents the optical power from the LED lamps and not the amplitude; thus, it must satisfy

\[
x(t) \geq 0 \text{ and } \lim_{T \to \infty} \frac{1}{T} \int_0^T x(t) \, dt \leq NP
\]

here \( P \) is the average optical power, and \( 0 \leq N \leq 1 \) is the dimming factor [11]. The brightness depends on the LED lamp dimming factor and the average optical power. As an example, if an LED lamp is at full brightness \( (N = 1) \) or 50% brightness \( (N = 0.5) \), the average power of \( x(t) \) is \( P \) or \( 0.5P \), respectively.

3. Proposed FD-OOK Scheme

In this study, the above mentioned issues are solved by introducing an alternative encoding and decoding scheme for VLC, which is proposed in our patent [12]. The scheme has two major objectives. First, the proposed scheme maintains a 50% dimming level, and second, flickering can be avoided by maintaining equal numbers of ones and zeros. One additional benefit from this encoder is that it maintains a steady running length of not more than four ones or zeros at any time.

| Table 1. Code-word Comparison between different line coding scheme |
| --- |
| **Decimal** | **HEX** | **4-Bit Binary** | **Existing 4B/5B** | **Proposed Scheme** |
| 1 | 0 | 0000 | 11110 | 010011 |
| 2 | 1 | 0001 | 01001 | 110001 |
| 3 | 2 | 0010 | 10100 | 110100 |
| 4 | 3 | 0011 | 10101 | 100011 |
| 5 | 4 | 0100 | 01010 | 110100 |
| 6 | 5 | 0101 | 01011 | 100101 |
| 7 | 6 | 0110 | 01110 | 100110 |
| 8 | 7 | 0111 | 01111 | 010110 |
| 9 | 8 | 1000 | 10010 | 011001 |
| 10 | 9 | 1001 | 10011 | 101001 |
| 11 | A | 1010 | 10110 | 101010 |
| 12 | B | 1011 | 10111 | 001011 |

| Table 2. Simulation Parameters |
| --- |
| **Parameter** | **Value** |
| Room dimensions | \( 5 \times 5 \) [m] |
| Height of receiving plane | 0.8 [m] |
| Number of array of LEDs | 3600 |
| Center luminous intensity | 0.73 [cd] |
| Single LED bulb power | 20 [mW] |
| Semiangle at half power | 30 [°] |
| Photodiode | 0.4 |
3.1 Encoder and Decoder Design
The encoder is designed in such a manner that it will keep the number of ones and zeros equal. The first task of the encoder is to create a code word such that it has an even-numbered length. For this, the proposed encoder changes the 4-bit hex number into a 6-bit code word. The 6-bit code word will have the following properties:

- By making the code-word length even numbered, the numbers of one and zeros can be made equal.
- The proposed code word will have a code run equal to four bits.

In VLC, the fixed -dimming index is equal to \( \frac{r}{n} \), where a time slot is \( n \) bits, and \( r \) bits amongst these \( n \) bits are used to represent meaningful data. Because the proposed scheme uses \( n = 6 \) and \( r = 3 \), the fixed -dimming index becomes 0.5 or 50%. This means that the dimming level is maintained as a constant at 50%, regardless of the data sent. In other words, the ratio of ones to zeros in a code word is always 1:1. A time slot of \( n = 6 \) bits results in a total of 64 code words to choose from. Among these 64 code words, there are 20 code words in which the number of ones and zeros are equal. 16 code words out of the 20 are used by the data, the remaining four code words can be used for other tasks such as synchronizing and ideal patterns. This can be understood from the truth table and comparing it with the existing 4B/5B line coding pattern in Table 1.

3.2 Algorithm for the Encoder and Decoder
The encoder is designed in consideration of the number of ones in the code word. This scheme generates a 6-bit code word that has equal numbers of ones and zeros. To ensure that there are equal numbers of ones and zeros, a counting method is applied. This method counts the number of ones in the 4-bit input and generates a 6-bit output that has equal numbers of ones and zeros.

In Table 1, the sum of the ones in a 4-bit binary pattern has five cases: zero, one, two, three, and four. The encoder handles each case individually and encodes the 4-bit pattern in the unique 6-bit pattern with equal numbers of ones and zeros. The method of encoding is described in Algorithm 1 while the decoding algorithm is described in Algorithm 2.

4. Performance Evaluation
To evaluate the performance of the proposed encoding and decoding scheme, a simulation was performed. The indoor environment in Fig. 1 was considered. Four LED lamps were installed at a height of 3 m above the floor with 60 × 60 LEDs in each lamp [13]. The simulation parameters are given in Table 2.

| Algorithm 1 Proposed FD-OOK encoder | Algorithm 2 Proposed FD-OOK decoder |
The simulation was conducted to check the performance of the scheme on two main parameters: the normalized power requirement and the spectral efficiencies. The proposed FD-OOK scheme is compared with existing modulation schemes such as variable on-off keying (VOOK) and variable pulse position modulation (VPPM), which focus on dimming control. Fig. 2 shows the normalized required power with respect to the dimming factor $N$ for each modulation scheme. FD-OOK exhibits better performance than VPPM and VOOK. VPPM and VOOK have almost the same performance for the same system model. For the region enclosed within the concerned window, it can be seen that FD-OOK can only work for $N = 0.5$ or a 50% dimming index. As compared to other schemes, FD-OOK requires the lowest optical power to operate with $N = 0.5$. In addition, the graph is symmetric along the $N = 0.5$ dimming index. From the simulation, it is seen that the optimal required power is achieved when the ratio of ones and zeros is 1:1 at the dimming index of 0.5. Fig. 3 shows the spectral efficiencies of the modulation schemes. Considering the concerned window again because FD-OOK has a 50% fixed - dimming index, a spike appears at $N = 0.5$. The VPPM scheme has poor spectral efficiency compared to VOOK and FD-OOK. The performance of VOOK is better, as it is spread over a large dimming-index range from 0.2 to 0.8. Because we are only concerned with the value of $N = 0.5$, FD-OOK outperforms VOOK and VPPM.
5. Conclusion
In this paper, a new scheme FD-OOK was proposed to address the problems of dimming and flickering present in VLC, and its encoder and decoder designs were proposed. To overcome the problem of dimming, the FD-OOK encoder scheme maintains a constant 50% dimming level. This, in turn, also reduces flickering by keeping the number of ones and zeros equal within a code word. The performance was evaluated for the normalized power requirement and spectral efficiency. The FD-OOK scheme was compared with other well-known schemes and its performance was better. In future work, the proposed scheme will be implemented as a real-time system, and the results for the data rate will be investigated.

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