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A mixed-interval multi-pulse position modulation scheme for real-time visible light communication system

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ABSTRACT

In the paper, a mixed-interval multi-pulse position modulation (MI-MPPM) scheme for visible light communication (VLC) system is theoretical proposed and implemented on field programmable gate array (FPGA). It has better bandwidth efficiency than PPM and MPPM. And it has better anti-jamming than MPPM. A real-time VLC link based on phosphorescent white LED is also built to measure the performance of the proposed MI-MPPM scheme. The data rate of 104 Mbps in our VLC system under the distance of 60 cm could be achieved, and bit error rate is 3.81×10^{-5}. As far as we know, it is the highest data rate that can be achieved in continuous real-time VLC system with phosphorescent white LED based on PPM and its derivative modulation. The performance of VLC system under different distances, advantages and the possible application scenarios of MI-MPPM are also discussed.

1. Introduction

With the world's focus on energy-saving and emission-reduction, white light emitting diode (LED) is becoming more and more popular. Visible light communication (VLC) enables white LED to communicate while lighting, which further enhances resource utilization [1,2]. VLC has many advantages such as wide range of communication bandwidth, no need to apply for spectrum, strong confidentiality and high security. And it can be used in airplanes, military bases, indoor visible light positioning systems and so on [3–5].

Japanese visible light communication association issued the JEITA CP-1222 agreement that mentioned pulse position modulation (PPM) in 2007. Variable PPM is also introduced in IEEE 802.15.7 issued in 2011 [6]. So far, many scientific research institutions in the field of OOK-based real-time visible light communication have made significant progress [7,8]. In 2014, a real-time data rate of 550 Mbps was achieved at the distance of 60 cm with phosphorescent white LED [9]. In 2014, the data rate was improved to 662 Mbps at the distance of 15 cm with a single blue LED of RGB type white LED [10]. In 2016, the data rate was further increased to 750 Mbps with a monochromatic red LED [11].

The IEEE 802.15.7 VLC standard mentioned that the effects of light flicker on lighting should be considered [6]. OOK may have signals with a long time of 0 or 1, resulting in flicking, while PPM can be more beneficial for dimming. Compared with OOK, PPM has better resistance to interference and higher power utilization [12]. But real-time visible light communication researches based on PPM are still relatively scarce. There are many PPM derivative modulation methods such as overlapping pulse position modulation (OPPM), digital pulse interval modulation (DPIM), dual header pulse interval modulation (DH-PIM) and so on [13–15]. Because their numbers of slots are not fixed, they are difficult to be realized to achieve real-time communication. K. Lee et al. have proposed multi-pulse position modulation (MPPM) to improve the bandwidth efficiency [16]. It assumes that the number of pulses per frame is greater than one and equal in MPPM. But MPPM sacrifices a lot of anti-jamming.

In this paper, a mixed-interval multi-pulse position modulation (MI-MPPM) scheme which can further enhance the bandwidth efficiency is proposed. At the same time, it can enhance the anti-jamming on the basis of MPPM. MI-MPPM has a fixed number of time slots in each frame to ensure that continuous data transmission is easy to be realized. Real-time VLC system using phosphorescent white LED is built to measure the performance of PPM, MPPM and MI-MPPM schemes. The experiment based on field-programmable gate array (FPGA) shows that MI-MPPM has the highest bandwidth efficiency than PPM and MPPM. Our proposed VLC system can meet the data rate requirements of IEEE

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Table 1
Mapping between source data and transmitted symbols when m is equal to 3.

Data	PPM	MPPM	MI-MPPM
000	011_10000000	0111_11000	011_10000
001	011_01000000	0111_10100	011_01000
010	011_00100000	0111_10010	011_00100
011	011_00010000	0111_10001	011_00010
100	011_00001000	0111_01100	011_00001
101	011_00000100	0111_01010	011_10100
110	011_00000010	0111_01001	011_10010
111	011_00000001	0111_00110	011_10001

802.15.7 standard. The proposed MI-MPPM scheme can be applied into many VLC scenarios such as indoor visible light positioning system, VLC audio and video transmission system and so on which require a low complexity system with good stability.

The rest of this paper is organized as follows. Section 2 describes the frame format of the three modulation schemes and shows the theoretical analysis and simulation results. In Section 3, the real-time system is presented. Section 4 compares the performance of three modulation schemes by the experimental results. Finally, Section 5 concludes the paper.

2. Theoretical analysis and simulation results

PPM is a way of passing information through the position of the pulse. After the m-bit binary source data has been encoded, there are n_{PPM} time slots in one frame, and $n_{\mathrm{PPM}} = 2^m$. There is only one pulse in a frame, and each light pulse has a one-to-one correspondence between the position of each frame signal and the m-bit source data.

MPPM allows multiple pulses to appear in one frame, but the number of pulses per frame must be the same, which greatly improves bandwidth efficiency. Taking into account the optical power and other factors in VLC system, common MPPM mostly uses two pulses. The number of pulses per frame in the MI-MPPM can be different. At the same time, the multi-pulse connection in MI-MPPM is discarded. After the m-bit binary source data has been encoded, there are n_{MPPM} time slots in one frame. It satisfies the following equation.

$$2^{m+1} > C^2_{n_{\mathrm{MPPM}}} \geq 2^m. \tag{1}$$

n_{MPPM} takes the minimum value that satisfies the condition. We correspond to a frame with m-bit source data through the look-up table method. There are $n_{\mathrm{MPPM}} - 1$ cases that the two pulses are connected in MPPM. In MI-MPPM, the above $n_{\mathrm{MPPM}} - 1$ cases are discarded. And there are n_{MPPM} cases that there is only one pulse in a frame. In MI-MPPM, the above n cases are used. It ensures that the number of time slots required for MI-MPPM to transmit the same m-bit source data is no more than that required for MPPM while ensuring that there is no connected pulse in the MI-MPPM.

In order to correctly recognize the beginning and end of each frame at the time of demodulation, a frame header is added for each frame. Assuming that there are at most x consecutive pulses per frame, the first slot of the header is low and the next $x + 1$ time slots are high. Since there is no continuous pulse in MI-MPPM, only three bits in a frame are required as a synchronization sequence. And MPPM requires four bits as a synchronization sequence.

Table 1 describes the correspondence between the source data and the transmit symbols when m is equal to 3. The symbol includes a frame header for synchronization and a data portion carrying the original information. Taking MPPM as an example, there are at most two consecutive pulses in MPPM. So the frame header consists of a low level and three consecutive pulses. The next five bits are used to transfer source data. The two pulses correspond to different three-bit source data at different locations. MI-MPPM removes the cases that the pulses are connected in MPPM and increases the cases that a frame has only one pulse (see Fig. 1).

Table 2
Mapping between source data and transmitted symbols when m is equal to 4.

Data	PPM	MPPM	MI-MPPM
0000	011_1000000000000000	0111_1100000	011_1000000
0001	011_0100000000000000	0111_1010000	011_0100000
0010	011_0010000000000000	0111_1001000	011_0010000
0011	011_0001000000000000	0111_1000100	011_0001000
0100	011_0000100000000000	0111_1000010	011_0000100
0101	011_0000010000000000	0111_1000001	011_0000010
0110	011_0000001000000000	0111_0110000	011_0000001
0111	011_0000000100000000	0111_0101000	011_1010000
1000	011_0000000010000000	0111_0100100	011_1001000
1001	011_0000000001000000	0111_0100010	011_1000100
1010	011_0000000000100000	0111_0100001	011_1000010
1011	011_0000000000010000	0111_0011000	011_1000001
1100	011_0000000000001000	0111_0010100	011_0101000
1101	011_0000000000000100	0111_0010010	011_0100100
1110	011_0000000000000010	0111_0010001	011_0100010
1111	011_0000000000000001	0111_0001100	011_0100001

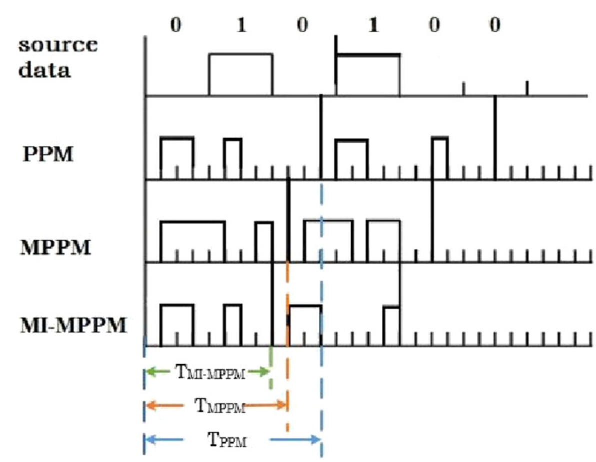

Fig. 1. The symbol structures of each modulation scheme when m is equal to 3.

Similar to the three original data, the correspondence between 4-bit source data and transmitted symbols is shown in Table 2.

When a frame transmits m-bit source data, the three modulations are compared. The average amount of source data that can be transmitted per time slot is regarded as the rate of information transmission. The number of transmission slots required for PPM to transmit m-bit source data is $2^m + 3$, and its information transmission rate can be simplified as

$$\gamma_{\mathrm{PPM}} = \frac{m}{2^m + 3}. \tag{2}$$

Eq. (1) describes the number of time slots for source data transmission from MPPM and MI-MPPM. After solving the Eq. (1), the following equation can be got.

$$n_{\mathrm{MI\text{-}MPPM}} = n_{\mathrm{MPPM}} < \sqrt{2^{m+2} + \frac{1}{4}} + \frac{1}{2} < 2^m - 1. \tag{3}$$

The frame header requires four time slots to synchronize in MPPM. The information transmission rate of MPPM can be simplified as

$$\gamma_{\mathrm{MPPM}} = \frac{m}{n_{\mathrm{MPPM}} + 4} > \frac{m}{2^m + 3} = \gamma_{\mathrm{PPM}}. \tag{4}$$

The frame header requires three time slots to synchronize in MI-MPPM. The information transmission rate of MI-MPPM can be simplified as

$$\gamma_{\mathrm{MI\text{-}MPPM}} = \frac{m}{n_{\mathrm{MI\text{-}MPPM}} + 3} > \frac{m}{n_{\mathrm{MPPM}} + 4} = \gamma_{\mathrm{MPPM}}. \tag{5}$$

Through the above derivation, it can be seen that the information transmission rate of MI-MPPM is highest and the information transmission rate of PPM is lowest in the case of the same bandwidth. Therefore, MI-MPPM has the highest bandwidth efficiency.