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BYTE-INVERT TRANSMISSION FOR FLICKER PREVENTION AND ILLUMINATION CONTROL FOR VISIBLE LIGHT COMMUNICATION

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ABSTRACT

In this paper, we introduce a new method, byte-invert transmission, for preventing LED flicker and controlling illumination in visible light communication (VLC). In byte-invert transmission, each data byte is sent in sequence with its inverted version. The inverted byte is an eight-bit data whose bits have been changed to the opposite state of their original value. In this configuration, the average power of the LED light is kept constant regardless of data change, keeping it flicker-free, and the illumination is controlled by changing the duty factor of the return-to-zero (RZ) data waveform. In experiments, the LED optical power was varied from 4.5% to 45% of its DC value by changing the duty factor from 10% to 100%.

Keywords: visible light communication, LED flickering, byte-invert transmission, flicker-free, sync pulse.

1. INTRODUCTION

Visible light communication (VLC) is a type of short-range wireless communication, in which illuminating light is utilized as the transmission carrier [1-3]. The visible light radiated from the source is modulated at a speed that human eyes do not perceive, and detected through free-space by a VLC receiver. Illumination and communication are carried out simultaneously. VLC has advantages in that it is free from electromagnetic interference because it does not interfere with conventional radio frequencies, and it is safe from outdoor eavesdropping because the signal light does not radiate through indoor walls.

Recently, high power light emitting diodes (LEDs) have been developed and widely used as light sources in various fields including indoor lighting, street lighting, automobile lighting, billboard lighting, etc. LEDs have high conversion efficiency, long lifetime, small size, and are robust against mechanical impact compared to conventional lighting lamps such as incandescent or fluorescent lamps. In addition, LED lighting can be easily controlled by controlling the injection current, and the response speed is much higher than conventional lighting lamps. Given these advantages, LEDs have also been used as the light sources in VLC, where illumination and wireless communications are carried out simultaneously.

In VLC systems, the lighting and communication should not affect each other during data transmission. If the average optical power of the LED changes during data transmission, flickering can arise that creates human discomfort. Therefore, the VLC system should be well designed so that the flicker does not occur during communication. In addition, it is desirable that the illumination in VLC systems be controlled easily by the user without affecting the communication [4, 5].

Subcarrier modulations such as amplitude-shift keying (ASK) or frequency-shift keying (FSK) are efficient ways of suppressing LED flicker because the average power remains constant during communication [6]. For illumination control in subcarrier modulations, an additional dimming control section may need to be inserted in the data stream in order to change the average power. In base-band VLC systems, Manchester coding or pulse position modulation (PPM) has been widely used to prevent LED flicker. Illumination control in these systems can be performed by changing the pulse width of the data bits.

In this paper, we introduce a new simple method, byte-invert transmission, for flicker prevention and illumination control of LED light. In the byte-invert transmission, byte-wise power control is performed to keep power constant instead of bitwise control. In each byte transmission, the original byte and its inverted version are sent in sequence. The inverted byte is an eight-bit signal in which each bit is changed to the opposite of its original value. This method keeps the average optical power of LED constant, and thus flicker-free, during data transmission. In the byte-invert transmission, the sync pulse period, which is the time required for sending one pair of original and inverted bytes, is set to be shorter than the maximum flickering time period (MFTP) of 5ms for flicker-free transmission [4]. The sync pulse is modulated with a subcarrier and transmitted in front of each original byte.

Illumination control in the byte-invert transmission is performed by changing the duty factor of the RZ data waveform. The byte-invert transmission method is very simple and easy to use because it does not require a bitwise accurate clock to recover the data bits in the receiver. This method is suitable for constructing flicker-free base-band VLC systems with illumination control capability.

2. SYSTEM MODEL AND METHODS

2.1 Byte-invert transmission

Byte-invert transmission is used to keep the average optical power of the LED light constant during data transmission, in order to prevent flickering of the LED light used as the light source in the visible light communication system. The waveform of the byte-invert transmission is schematically illustrated in Figure-1.

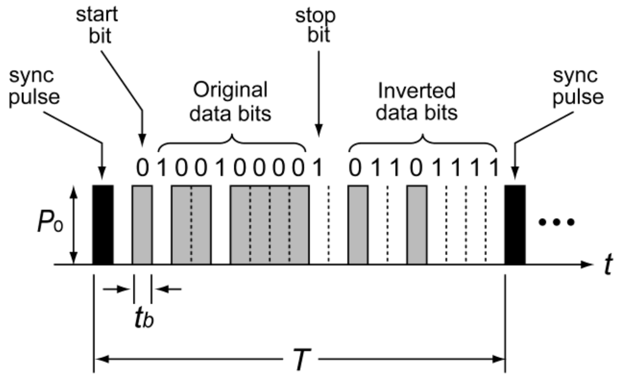

Figure-1. Waveform of byte-invert transmission.

In one sync pulse period T, a start bit, an original data byte, a stop bit, and an inverted data byte are sequentially transmitted. The original byte is an eight-bit data to be sent from the transmitter to the receiver. The inverted byte is an added eight-bit signal, in which each bit is changed to the opposite state of the original in order to keep the average optical power constant, to prevent LED flicker. The original and the inverted byte signals are coded in base-band non-return-to-zero (NRZ) waveforms and the sync pulse is modulated with a subcarrier frequency. The optical energy contained in one start bit, one original byte and one stop bit can be expressed as

$$W_{org} = P_0 \times t_b \left(1 + \sum_{i=0}^{7} b_i\right) \tag{1}$$

where P_0 is the amplitude of optical power, t_b is one bit time, and b_i is the state of the ith bit in the original byte. The original byte is transmitted just before the inverted byte, in which each bit is changed to the opposite state, i.e. a 1 bit changed to 0 and a 0 bit to 1. The optical energy in the inverted byte is

$$W_{inv} = P_0 \times t_b \sum_{i=0}^{7} \bar{b}_i \tag{2}$$

where $\bar{b}_i$ is the inverted state of the ith bit. The sync pulse is modulated with a subcarrier whose frequency is much higher than the data rate. In experiments we used a data rate of 9.6 kbps for the original and the inverted bytes, a 100 kHz square wave for the sync pulse subcarrier. If the width of the sync pulse is set to be equal to one bit time, the optical energy of the sync pulse is

$$W_{sync} = P_0 \times t_b / 2 \tag{3}$$

The average optical power of the LED can be expressed as follows:

$$\begin{aligned} P_{avg} &= \frac{1}{T}\left\{W_{org} + W_{inv} + W_{sync}\right\} \\ &= \frac{P_0 t_b}{T}\left\{0.5 + 1 + \sum_{i=0}^{7}(b_i + \bar{b}_i)\right\} \end{aligned} \tag{4}$$

The sum of ith bit and its inverted version is always 1, that is

$$b_i + \bar{b}_i = 1 \tag{5}$$

Therefore, the average optical power of the LED is expressed as

$$P_{avg} = \frac{P_0 t_b}{T}(1.5 + 8) = 9.5\, P_0 \left(\frac{t_b}{T}\right) \tag{6}$$

The average optical power is independent of the data bit state b_i, thus the LED light becomes flicker-free. If the data bit in a “high” state is changed to the return-to-zero (RZ) waveform with a duty factor of D, the bit time t_b in (6) is replaced with ($D \times t_b$) and the average optical power becomes

$$P_{avg} = 9.5\, P_0 \left(\frac{D \times t_b}{T}\right) \tag{7}$$

If the interval between the sync pulse and the original byte is set to be equal to one bit time t_b, and the interval between the original and the inverted bytes is also t_b, then the period becomes T=21t_b. In this case the average optical power is

$$P_{avg} = P_0 \times D\left(\frac{9.5}{21}\right) \cong 0.45\, D\, P_0 \tag{8}$$

` As shown in equation (8), the average optical power of the LED is independent of the data bit state and proportional to the duty factor D. Therefore, if the duty factor is fixed, the average optical power is kept constant in an observing time larger than period T. As noted, in experiments we used a data rate of 9.6 kbps, and one bit time was $t_b \approx 104$ us. The period was $T \approx 2.2$ms, shorter than the maximum flickering time period (MFTP) of 5ms which is generally considered to be safe [4]. As a result, the LED showed flicker-free illumination.

In equation (8) the average optical power is linearly proportional to the duty factor, thus the illumination of the LED can be controlled by changing the duty factor. We measured the optical power as the duty factor was changed. For the measurements, a 2×3 LED array was used as the light source, made of six identical 1 W white LEDs. The LED light was modulated by the byte-invert transmission waveform as shown in Figure-1. An optical multi-meter OMM-6810B was installed at a distance of about 1 meter from the LED array to detect the optical power density as the duty factor was changed. Figure-2 shows the optical power of the LED array versus duty factor.

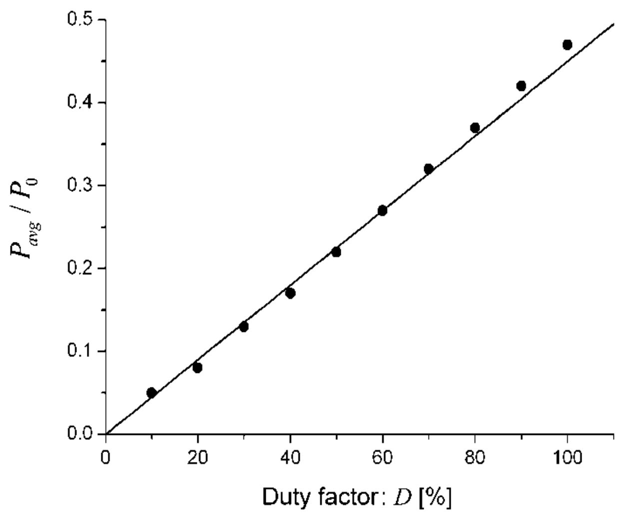

Figure-2. Average optical power versus duty factor.

In Figure-2, the solid line is the calculation using (8) and the symbols (•) are the measured results. The LED optical power increased almost linearly with the duty factor. Through this measurement, we observed that the LED illumination could be controlled by changing the duty factor in the byte-invert transmission.

2.2 VLC transmitter

The VLC transmitter used in the proposed byte-invert transmission is schematically shown in Figure-3.

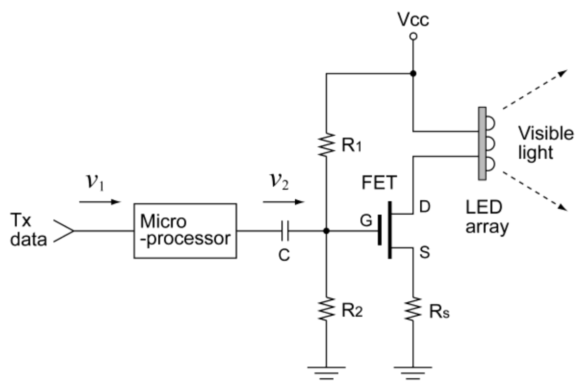

Figure-3. VLC transmitter circuit.

When the input data (v_1) in non-return-to-zero (NRZ) format is applied to the input port, the microprocessor generates a byte-invert signal (v_2) which is composed of the sync pulse, the original and the inverted bytes. The sync pulse is on-off keying (OOK) modulated with a subcarrier of 100 kHz square wave and the original and the inverted data bytes are 9.6 kbps base-band signals in NRZ format.

The output voltage of the microprocessor is applied to the gate of a field effect transistor (FET).The FET is used as the current source for the LED array, is biased to operate in a linear region using the two resistances R_1 and R_2. The drain current of the FET is proportional to the gate voltage and flows through the LED array. In the VLC transmitter, we used an Atmega8 microprocessor, an IRF540 FET, and the LED array was made of six identical LEDs in the form of a 2×3 planar array. Each LED was 1 W white LED.

To see the operation of the VLC transmitter, a character string "\tByte-invert\r\n" in the universal asynchronous receiver-transmitter (UART) format was transmitted repeatedly and we observed the voltage waveforms in the VLC transmitter. Figure-4 shows the voltage waveforms observed with an oscilloscope.

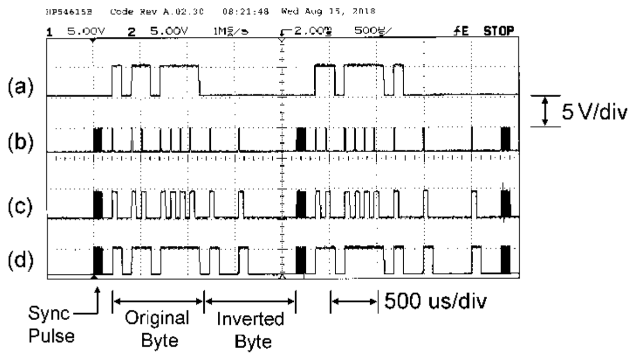

Figure-4. Waveforms in the VLC transmitter. (a) NRZ input data v_1, (b) byte-invert waveforms v_2 with a duty factor of 10%, (c) 50%, and (d) 100%, respectively.

Figure-4(a) shows the NRZ waveforms (v_1) of the first two characters "'\tB" among the transmitted character string. The American Standard Code for Information Interchange (ASCII) for the first character "\t" (tab) is "00001001". In the UART, the data bits are sent in the order of least significant bit first, thus the bit sequence becomes "10010000". A start bit "0" and a stop bit "1" are added to the bit sequence and the total bits for the character "\t" becomes a ten-bit signal of "0100100001". In the UART transmission, a high voltage (H) is assigned to a bit "0" and a low voltage (L) to a bit "1". Accordingly, the voltage waveform of the character "\t" becomes "HLHHLHHHHL" as shown in Figure-4(a).

Figure-4(b), (c) and (d) show the byte-invert transmission waveforms (v_2) with duty factors of 10%, 50% and 100%, respectively, which were applied to the gate of the FET. In each waveform, the first bit in black is the sync pulse which was modulated with a 100 kHz rectangular subcarrier. The ten bits just after the sync pulse correspond to one start bit, eight data bits (original byte), and one stop bit. The eight-bit data after them is the inverted byte, where each bit has the opposite value of the original. In Figure-4(a), the second character was a "B" and the byte-invert waveforms were generated and transmitted in the same manner as the first character "\t".

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2.3 VLC receiver

The VLC receiver detects the visible light signal from the transmitter and recovers the original data. The VLC receiver is configured as shown in Figure-5.

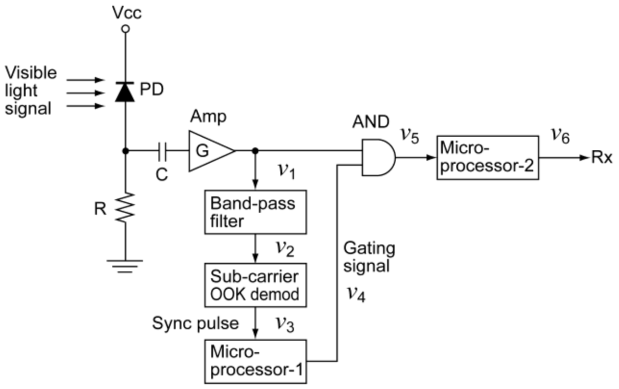

Figure-5. Configuration of the VLC receiver.

The photodiode (PD) detects the visible light and generates photocurrent, which flows through the load resistance *R*. The AC voltage is amplified through a capacitor *C*. The amplified output voltage (v_1) includes the sync pulse, the original and the inverted byte signals. The sync pulse, which is OOK modulated with a 100 kHz subcarrier, passes through a band-pass filter (v_2), is demodulated to a base-band pulse (v_3) and applied to the interrupt port of microprocessor-1. At the falling edge of the sync pulse, microprocessor-1 generates a gating signal (v_4). The gating pulse is used to pass only the original byte while cutting off the inverted byte at an AND gate. The inverted byte is only used to prevent the LED flickering, and is cut off at the VLC receiver.

The AND gate has two inputs, one is the amplified photodiode signal (v_1) and the other is the gating signal (v_4) from microprocessor-1. The output voltage (v_5) of the AND gate is the RZ original byte with a given duty factor, and it is applied to the input port of microprocessor-2. At each rising edge of the RZ signal, microprocessor-2 generates a 104μs pulse, which corresponds to the bit time of the 9.6 kbps data rate at which the input data was sent from the VLC transmitter. Through this process, the input NRZ data applied to the VLC transmitter is recovered in the VLC receiver.

In the VLC receiver we used a S6968 PIN photodiode for the photo-detector, an OPA228 op-amp for the amplifier, two Atmega8 microprocessors for gating signal generation and NRZ signal recovery. The AND gate was a 74LS11 and the BPF was a 5th order Chebyshev filter whose central frequency was 100 kHz. Figure-6 shows the sync pulse waveforms observed with an oscilloscope in the VLC receiver.

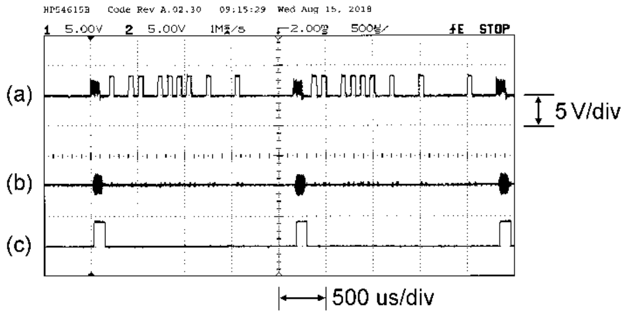

Figure-6. Sync pulse waveforms in the VLC receiver. (a) PD voltage v_1, (b) the OOK modulated sync pulse v_2, (c) demodulated sync pulse v_3.

Figure-6(a) is the amplified photodiode voltage, which is denoted as v_1 in Figure-5. This waveform contains the OOK modulated sync pulses, and the original and the inverted byte signals from the VLC transmitter. The original and the inverted byte signals are RZ waveforms with a duty factor of 50%. Figure-6(b) is the band-pass filter output voltage (v_2), the OOK modulated sync pulse with a 100 kHz subcarrier. Figure-6(c) shows the demodulated sync pulse waveform (v_3), which was applied to the input of the microprocessor-1. At the falling edge of the sync pulse, microprocessor-1 generated and sent gating pulses whose width is the same as the length of the original byte signal.
Figure-7 is the data waveforms observed with an oscilloscope in the VLC receiver.

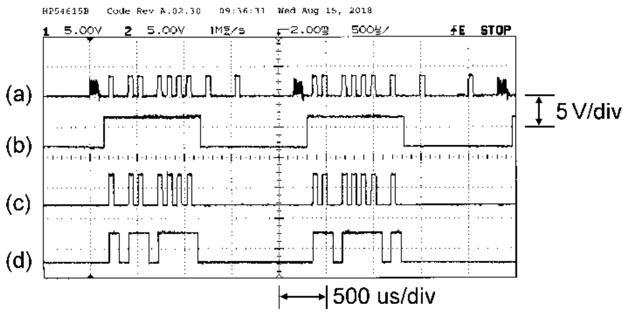

Figure-7. Data waveforms in the VLC receiver. (a) PD voltage, (b) gating signal, (c) RZ original byte signal with a duty factor of 50%, (d) recovered NRZ original byte signal.

Figure-7(a) is the amplified photodiode voltage (v_1) which is the same as in Figure-6(a). Figure -7(b) is the gating pulse (v_4) from microprocessor-1. The gating pulse width was set to be 1.04ms, which corresponds to the length of the ten-bit original byte, including the start and the stop bits. The waveforms in Figure-7(a) and (b) were applied to the two input ports of an AND gate. Figure-7(c) is the output of the AND gate (v_5), which is the RZ original byte signal with a duty factor of 50%. The RZ waveforms with 10% and 100% in Figure-4(b) and (d) were recovered through the same process. At each rising edge of this RZ signal, microprocessor-2 generated 104 μs

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pulse which corresponds to one bit time of the 9.6 kbps data rate. Figure-7(d) is the output voltage of microprocessor-2; (v_6) is the recovered NRZ original data at the VLC receiver, which is the same shape as the input signal in the VLC transmitter shown in Figure-4(a).

The voltage waveform in Figure-7(d) was applied to the serial port of a computer and displayed on a monitor. Figure-8 shows the characters observed on the monitor.

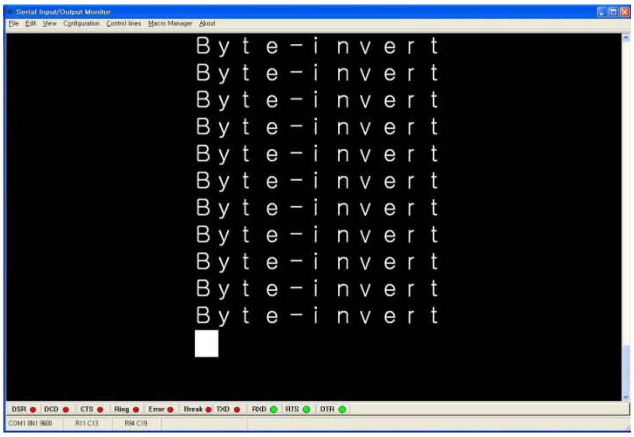

Figure-8. Characters displayed on a monitor.

The input characters which were supplied to the VLC transmitter were "\tByte-invert\r\n". Three of the characters, "\t" (tab), "\r" (return) and "\n" (line feed), were special characters used for position control and they do not appear on the monitor. The other eleven characters "Byte-invert" are shown in Figure-8.

So far, we have experimentally confirmed that the byte-invert transmission is effective at preventing flicker and in controlling the illumination of the LED light. The illumination control was performed from 4.5% to 45% of DC optical power by changing the duty factor from 10% to 100% of the RZ waveform. Figure-9 shows the circuit boards used in the experiments.

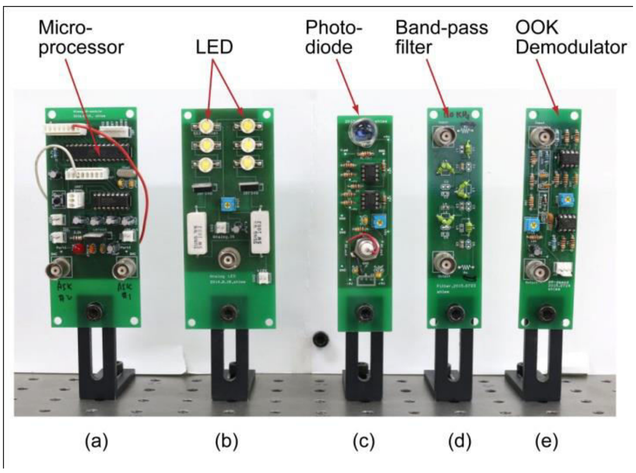

Figure-9. Circuits used in experiments.

Figure-9(a) is the Atmega8 microprocessor circuits used in the VLC transmitter and the receiver. Figure-9(b) shows the 2×3 LED array with its current driving circuit used in the VLC transmitter. Figure-9(c) shows the PIN photodiode S6968 and amplifier circuits. Figure-9(d) and (e) are the band-pass filter and the demodulator circuit, respectively, for detecting and regenerating the sync pulse which was OOK modulated with a 100 kHz subcarrier.

3. RESULTS AND DISCUSSIONS

We developed a new byte-invert transmission method for flicker-prevention and illumination control of the LED light in VLC systems. The original byte and the inverted byte signals were transmitted in sequence in a period which was shorter than the maximum flickering time period (MFTP) of 5ms (200 Hz), which is generally considered to be safe. Through a simple calculation and measurements, we have shown that the average optical power of the LED is independent of changing data, and is thus flicker-free, and the average optical power can be controlled by changing the duty cycle of the RZ signal in the byte-invert transmission.

In the experiments, we observed the waveforms in the VLC transmitter and the receiver, and illumination control was performed from 4.5% to 45% of the DC optical power of the LED by changing the duty factor from 10% to 100% of the RZ waveform. This transmission method is simple and easy to realize, can be utilized widely for constructing flicker-free VLC systems with illumination control capability.

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