A real-time VLC to UART protocol conversion system*

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A real-time visible light communication (VLC) to universal asynchronous receiver/transmitter (UART) conversion system is made up of a transmitter with a light emitting diode (LED) and a receiver with a photodiode (PD), by which a VLC system is connected to traditional communication modes, and the data are transferred by wireless visible light. UART packets are converted to light packets by the modulation of a 10 kHz on-off-keying (OOK) light signal, and the data losses in the transportation are avoided by the protection of a data buffer mechanism. The experimental results reveal that the real-time VLC to UART conversion system can provide a real-time VLC transmission way for two UART devices in not less than 10 m at a baud rate not less than 19 200 Bd with stable ambient lighting at the same time.

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Visible light communication (VLC) system can provide a license-free, secure and no electromagnetic interference (EMI) communication link by using high-speed flash visible light. In VLC system, the communication range can cover the lamplight, so personal computer (PC) or other micro controller unit (MCU) and mobile phone can connect to the wireless network when they are in the light[1-4]. As a new wireless communication method, VLC needs an interface to connect to the traditional method, so that it can be used to accomplish transparent transmission in traditional devices.

Universal asynchronous receiver/transmitter (UART) is a common device to translate data between parallel and serial forms. UART is used in conjunction with communication standards, such as RS232, RS485 and USB. It provides a common interface in PC, embedded device and wireless module. But it does not directly transmit or receive the external signals between two devices. The logic level signals of UART are used to be converted to other signal by external interface devices[5-7].

In order to make a VLC system compatible with traditional device, a protocol conversion method between VLC and UART is presented in this paper.

The VLC to UART protocol conversion system is used to connect two devices with UART by VLC link. Fig.1 depicts the schematic diagram of the established protocol conversion system, including a transmitter (TX) and receiver (RX). The transmitter is combined with downlink interface, TX-MCU, driver and light emitting diode (LED), while the receiver is combined with uplink interface, RX-MCU, decision and photodiode (PD).

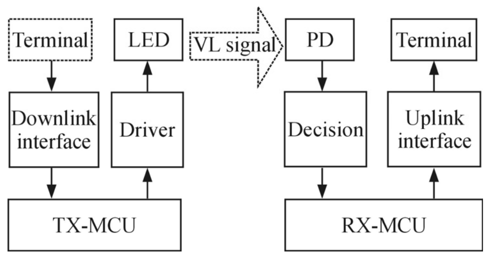

Fig.1 Schematic diagram of the protocol conversion system

Downlink interface is used to receive the UART data frame from TX upper terminal. TX-MCU is used for unpacking, coding and modulating the UART data to light data. Driver is used to drive the LED flash according to the light data. PD and decision circuit are used to receive the modulated visible light signal and then convert the analog signal to digital signal. RX-MCU is used for demodulating, decoding and repacking the light data to UART data frame. Uplink interface is used to send UART data to the RX upper terminal.

On the TX side, TX upper terminal outputs the UART data to the TX-MCU firstly. The TX-MCU extracts the data part from the UART data frame, and then converts

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the data part into a light frame. Thirdly, the driver drives the LED flash according to the light frame.

On the RX side, PD receives the light flash signal and converts it to analog signal. Decision circuit converts the analog signal output from PD to digital signal. RX-MCU decodes and repacks the digital signal into UART data frame, and then uploads it to RX upper terminal.

In VLC system, LED is employed as the antenna of transmitter with good light modulation performance. The response time of LED can reach nanosecond magnitude theoretically. PD is a semiconductor device for converting light into electric current in high speed. A PD with response time in nanosecond even picosecond magnitude can provide an available bandwidth for signal modulation and data transmission when it is used in a VLC system[8-10].

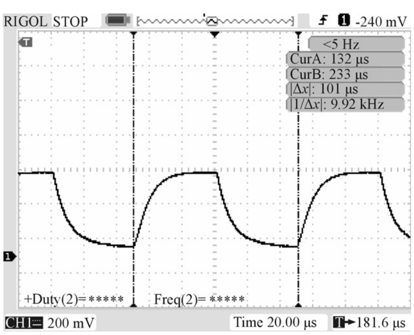
A 1 W white LED and a PD BPW21 are used as light signal emitter and receiver in this design, respectively. A function generator is connected to the 1 W white LED for providing a square wave with frequency of 1 MHz and amplitude of 3 V. The LED's response time is about 440 ns. The rising edge is about 40 ns, while the falling edge is about 400 ns[11,12].

The light signal emitted from LED is received by PD BPW21. BPW21 is a planar silicon PN photodiode with the best detection wavelength range from 350 nm to 820 nm. The response time can reach 6.1 μs. The maximum open circuit voltage is 500 mV.

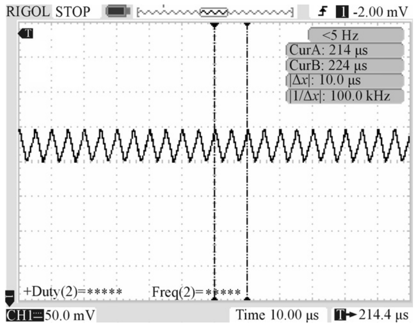
The received waveforms of BPW21 are shown in Fig.2 when two 5 V square waves with frequencies of 10 kHz and 200 kHz are loaded on the 1 W LED. The distance between LED and PD is 3 cm. When a 5 V square wave with frequency of 10 kHz is loaded on the LED, the peak to peak voltage (V_{pp}) is about 500 mV, the rising time is about 35 μs, and the falling time is about 40 μs. When a 5 V square wave with frequency of 200 kHz is loaded on the LED, the V_{pp} is about 50 mV, and the response time is about 2.5 μs.

In order to learn the relationships of V_{pp}, the signal strength and the distance between PD and LED, an experiment is finished in a room with 50 Hz light. And the ambient light illumination of receiving point is about 50—200 lux.

5 V square waves with duty cycle of 50% and different frequencies are output from the function generator loaded between the LEDs.



(a)

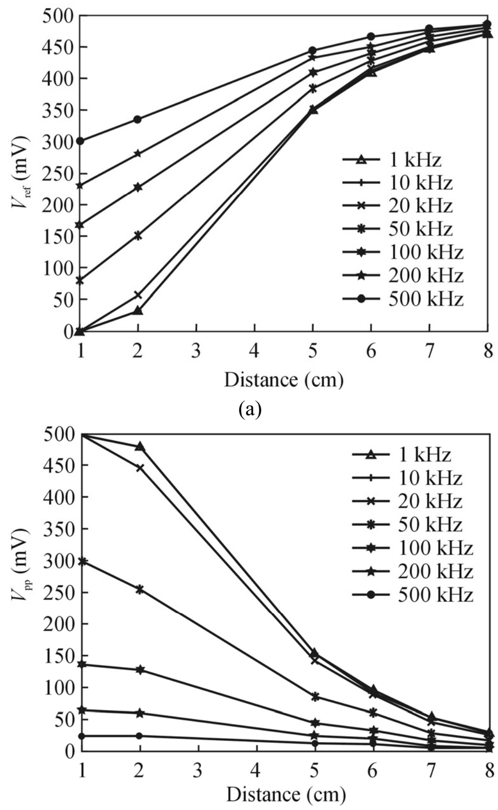


(b)

Fig.2 Received waveforms of BPW21 when loading two 5 V square waves with frequencies of (a) 10 kHz and (b) 200 kHz on the 1 W LED

It can be known from Fig.3 that the higher frequency the LED flashes, the higher reference voltage (V_{ref}) of PD is measured with the same distance between LED and PD. On the other side, the lower frequency the LED being load, the higher V_{pp} of PD is measured. And the resolution of signal is higher because the resolution mainly depends on V_{pp}.

Because the signal can be easily detected with a high resolution, 10 kHz square wave is changed to be the carrier so that the PD can detect an ideal signal reliably.



(b)

Fig.3 The relationship between (a) V_{ref} or (b) V_{pp} and distance of square waves with different frequencies

Serial communication is used for long distance communication where the cost and synchronization difficulties make parallel communication impractical. One bit is sent at a time in serial communication. As a popular standard for serial communication, the typical UART serial frame uses eight data bits, no parity and one stop bit.

In order to provide a stable and reliable communication, the serial rate is inversely proportional to the distance. A high rate is always used in short distance communication.

In this paper, the baud rate is set as 14 400 Bd and 19 200 Bd, which are the typical rates of audio signal transmission with phone line.

Every light packet can pack up a couple of UART data frames, so that it can transmit efficiency.

Visible light signal is sent as a light packet, which is composed of head segment, index segment, length segment, check segment and data segment. The head segment is a special combination of high level and low level, and it is used to indicate the beginning of packet. And head segment is a unique group of bits that can synchronize signal between transmitter and receiver. The index segment with size of 9 bit indicates the number of UART data, in which the maximum number is equal to the buffer size. Length segment with size of 1 bit means the length of each UART data, where "0" implies 6 bit, and "1" implies 7 bit. Check segment with size of 1 bit indicates that the number of bits in the data segment is even or odd. Data segment with size of 1—400 byte is the UART data which need to be transmitted.

On the TX side, data in UART packet is picked up and linked up in order. Then repack it into a light packet according to the light packet pattern. The link-up order of light packet is shown in Fig.4.

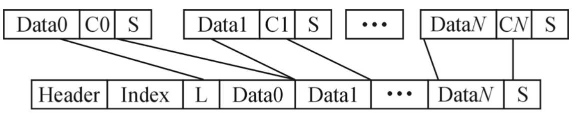


Fig.4 The structure of light packet

IEEE 802.15.7 provides dimming adaptable mechanisms for flicker-free high-data-rate VLC.

On-off-keying (OOK) is the simplest modulation scheme for VLC, where LEDs are turned on or off depending on the data bits of "1" or "0". The "off" level in OOK does not mean to completely turn off the light. The intensity of the light may be simply reduced as long as one can distinguish clearly the "on" and "off" levels[13-15].

The protocol conversion system is composed of a TX and an RX. On the TX side, data rebuild up a light packet from UART packet to complete the downlink from TX upper terminal to TX-MCU. Then the light packet is modulated, encoded and transmitted by driving the LED flash. On the RX side, visible light signal is detected. And data is extracted, decoded and demodulated from a modulated visible light signal. The UART packet is repacked by the data and uploaded to the RX upper terminal. The process flow charts in TX and RX are shown in Fig.5.

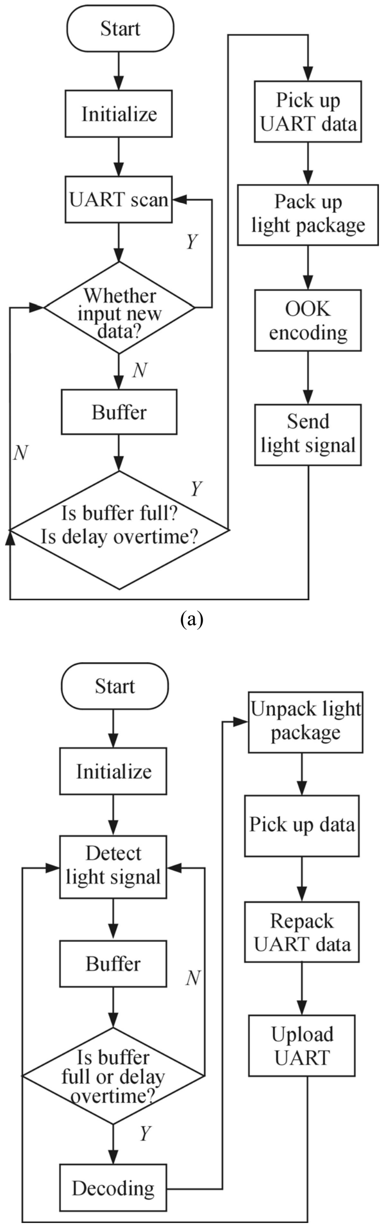
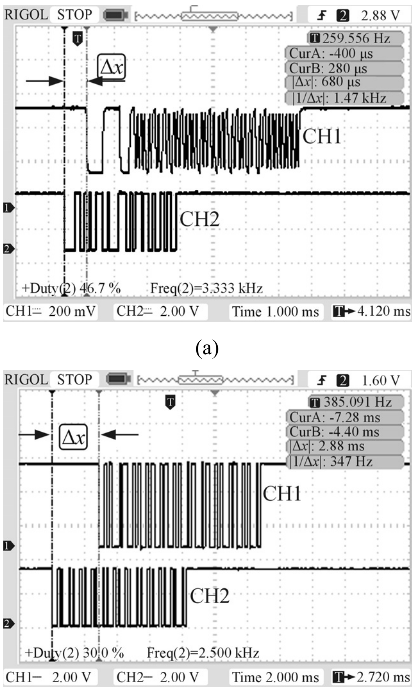


Fig.5 The process flow charts in (a) TX and (b) RX

Fig.6 shows the waveforms of the system without buffer mechanism obtained by oscilloscope. Channel-2 (CH2) is the waveform of the input UART in TX side, while Channel-1 (CH1) in Fig.6(a) is the LED flash output waveform after UART data conversion, and CH1 in Fig.6(b) is waveform of the UART output in the RX side. It can be known from Fig.6 that the conversion in the TX side leads to a 660—700 μs processing delay, and the conversion in both TX and RX sides leads to a processing delay about 2.88 μs.

The data will be lost due to the processing delay when a large number of data need to be transmitted in a short time. For example, three characters are lost while four characters are transmitted without buffer.



(a)

(b)

Fig.6 The waveforms of (a) TX processing delay and (b) the system processing delay

Setting up a buffer data is the key to preventing the data losses in this design. By using the buffer, it can make the speed match between the transmitted light signal and the upper terminal downlink or uplink UART packet in both the TX and RX sides.

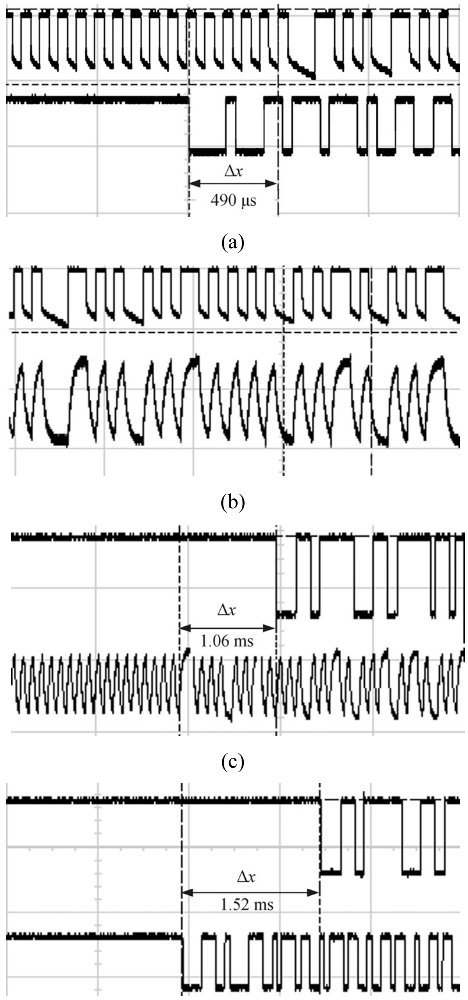
The buffer is used for preventing the data loss that TX-MCU can't convert UART in time on the TX side, and RX-MCU can't process the light packet in time on the RX side.

On the TX side, TX-MCU put the UART packet in the buffer firstly when it receives the UART packet from upper terminal. When the buffer is full or delay is overtime, the UART packet is converted to a light packet.

Because the signal is modulated in the lamplight, LED will flash obviously just like noise when TX transmits burst data. It makes eye uncomfortable. Illumination equalization scheme provides a stable illumination while the data is transmitted. So a pulse-width modulated (PWM) signal with duty cycle of 50% is used as a carrier instead of steady light.

The experiments are mainly conducted indoors where ambient illumination is about 20—2 000 lux with 50 Hz lamplight.

Fig.7 shows the results of the protocol conversion system with data buffer mechanism and illumination equalization. It can be known that there is a 490 μs processing delay in TX side as shown in Fig.7(a), while there is a 1.06 ms processing delay in RX side as shown in Fig.7(c). The system can transport the UART packet with a 1.52 ms delay as shown in Fig.7(d). And Fig.7(b) is the received signal waveforms before and after the decision when the illumination equalization scheme is added to the system.



(a)

(b)

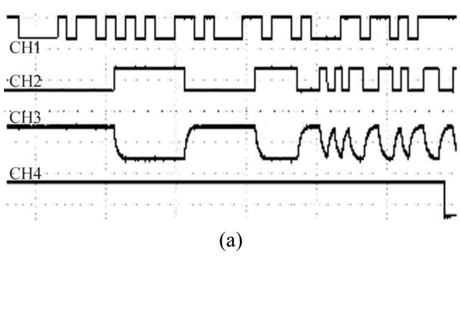
(c)

(d)

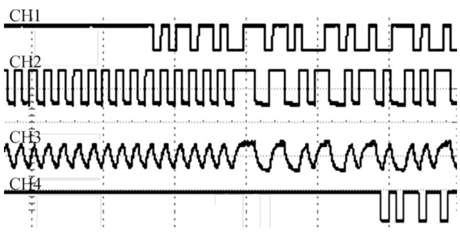
Fig.7 The waveforms of the system with data buffer mechanism and illumination equalization

A four-channel oscilloscope is used to detect the transmitted and received signals. The performances of transmitted and received signals are compared as shown in Fig.8. CH1 is the downlink waveform of UART from TX upper terminal. CH2 is the transmitted waveform of light signal. CH3 is the received waveform detected by PD. CH4 is the uplink waveform of UART to RX upper terminal.

The UART packet can be successfully transported with a short delay of 1.52 ms in this paper.



(a)



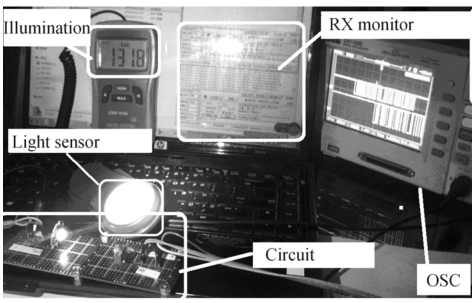
(b)

Fig.8 The waveforms of the system (a) without and (b) with data buffer mechanism

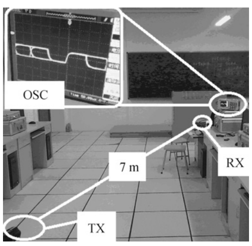
The experiment described above is mainly tested in a short distance about 20 cm. It is shown that the strength of received signal mainly depends on the distance when the illumination and carrier frequencies of LEDs are the same. And the resolution also depends on the frequency of carrier signal. In order to prove the design, two more experiments are conducted.

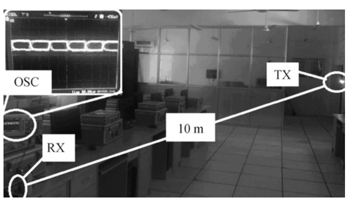
Firstly, an extra high light interference source is added in the experiment, and it can be seen from the RX monitor and oscilloscope shown in Fig.9(a) that the system can still work successfully.

Secondly, a 45° reflective cup is used to focus the light, and a 3 W LED is used to replace the 1 W LED. The illumination can be increased by about 30 times at the same distance from the TX. For example, the illumination at 2 cm in front of the LED is increased from 800 lux to 30 000 lux. When the distance is 5 m, the received performance is the same as that with the distance of about 6 cm before improving illumination. And the illumination



(a)





(b) (c)

Fig.9 (a) System test photos in light interference and with the distances between TX and RX of (b) 7 m and (c) 10 m

can be about 90 lux, V_{pp} is about 10—20 mV, and V_{ref} is 210 mV. According to the eye diagrams shown in the insets of Fig.9(b) and (c), we find that the performance of this protocol conversion system is excellent. And the distance of effective communication can reach 10 m at least.

The system accomplishes a stable wireless VLC between two devices with a UART interface. It particularly suits for indoor wireless communication. In this design, 10 kHz OOK modulation is mainly used to accomplish a UART transmissions in which the baud rate can reach at least 19 200 Bd. It can provide a real-time UART communication in not less than 10 m in the visible light channel. It can be known from the experimental results that the performance of this protocol conversion system can be enhanced by improving driver or using optical reflective tools.

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