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Abstract. It is predicted that the number of internet-of-things (IoT) devices will be >28 billion in 2020. Due to the shortage of the conventional radio-frequency spectrum, using visible light communication (VLC) for IoT can be promising. IoT networks may only require very low-data rate communication for transmitting sensing or identity information. The implementation of a VLC link on existing computer communication standards and interfaces is important. Among the standards, universal asynchronous receiver/transmitter (UART) is very popular. We propose and demonstrate a VLC-over-UART system. Bit error rate analysis is performed. Different components and modules used in the proposed VLC-over-UART system are discussed. Then, we also demonstrate a real-time simultaneous temperature, humidity, and illuminance monitoring using the proposed VLC link. [DOI: 10.1117/1.OE.55.6.060501]

Keywords: optical communications; visible light communication; optical wireless communication; sensing.

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1 Introduction

Visible light communication (VLC) can be a promising technique for the future 5G wireless network,[1] since it can use the visible light spectrum for communication instead of the congested conventional radio-frequency (RF) spectrum. It is predicted that the number of internet-of-things (IoT) devices will be >28 billion in 2020.[2] Due to the shortage of conventional RF spectrum, using VLC for IoT can be promising.[3] VLC uses the visible spectrum for communication, which is license free. This can decrease the deployment cost of IoT. In addition, VLC uses simple modulation and demodulation without complicated signal processing; hence, it is suitable for IoT devices with limited processing capability. High-data rate (>Gbit/s) VLC transmissions have also been demonstrated.[4–10]

IoT networks may only require very low-data rate communication for transmitting sensing or identity information. The implementation of a VLC link on existing computer communication standards and interfaces is important. Among the standards, universal asynchronous receiver/transmitter (UART) is very popular for connecting a microcontroller unit (MCU)-to-MCU; and sensor-to-MCU. UART is simple, full-duplex, and asynchronous. The UART device has low power consumption, low electromagnetic interference (EMI), and good modularity in large systems, such as IoT networks. Recently, Chanthosot et al.[11] have demonstrated a VLC-over-UART transmission; however, only word characters are transmitted and there is no signal analysis, such as bit error rate (BER).

In this work, we propose and demonstrate a VLC-over-UART system. BER analysis is performed. Different components and modules used in the proposed VLC-over-UART system are discussed. In the BER analysis, experimental results show that there is no error count at the transmission distance of <100 cm (corresponding to an illuminance of 80 lux). At a transmission distance of 110 cm, the measured BERs are 4×10^{-6} and 7×10^{-5}, respectively, at payload lengths of 32 and 64 bits. These correspond to data rates of 22 and 44 kbit/s. Then, we also demonstrate a real-time simultaneous temperature, humidity, and illuminance monitoring using the proposed VLC link.

2 Architecture and Experiment

Figure 1 shows the IoT architecture of using VLC for connecting different devices. Portable devices equipped with LED and photodiode (PD) or camera can be used to transmit and receive VLC signals. For example, as shown in Fig. 1, a sensor node can transmit environment data to a user via VLC, allowing a real-time and continuous monitoring. Since the data rate of IoT communication is low, using PD, smartphone camera with the rolling-shutter algorithm[12] or solar cell panel[12] can be used as VLC receivers (Rxs).

In order to evaluate the transmission performance of the VLC-over-UART system, a proof-of-concept demonstration as shown in Fig. 2(a) has been performed. In the transmitter (Tx) side, a commercially available Universal Serial Bus (USB)-to-UART/RS-232 cable is used to convert the USB data sending from a computer terminal into UART/RS-232 signal. Then, a UART Tx (SIPEX 3232EC) is used to drive a single white-light phosphor-LED (Edison, EDEW 3LS5). Figure 2(b) shows the photograph of the UART transceiver (including the UART Tx and Rx). This transceiver meets the RS-232 standard and can be implemented in battery-powered, portable, and hand-held applications. This transceiver can operate at a data rate of 120 kbit/s fully loaded with 3 kΩ in parallel with 1000 pF, ensuring compatibility with computer-to-computer communication.

The UART Tx sends data bits in a serial manner via the VLC link. After different distances of free space transmissions, the VLC signals are received by a silicon-based PD (Thorlabs FDS-100). Its spectral response is from 350 to 1100 nm with active area of 13 mm^2. Its rise and fall times are about 10 ns; and dark current of 20 nA when biased at 20 V. As a single LED Tx is used in this proof-of-concept demonstration, the received VLC signal is weak, resulting in

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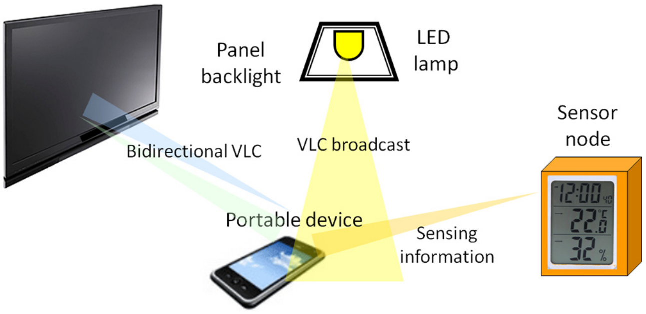

Fig. 1 IoT architecture of using VLC as a method of optical wireless communication.

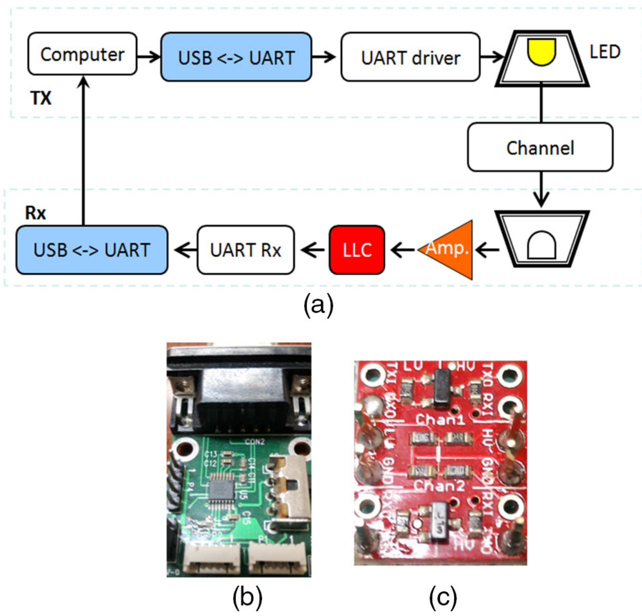

Fig. 2 (a) Proof-of-concept demonstration of VLC over UART. USB, Universal Serial Bus; UART, universal asynchronous receiver/transmitter; LLC, logic level converter; Tx, transmitter; Rx, receiver. Photographs of (b) URTA/RS-232 transceiver and (c) logic level converter (LLC).

low signal-to-noise ratio (SNR). A junction gate field-effect transistor (JFET) operational amplifier (LF356) is used to amplify the signal after the PD. As the free space transmission distance can vary from very short (<10 cm) to relatively long (>100 cm), the received signal level can vary a lot. Hence, at the Rx side, a logic level converter (LLC) (BOB-11978) as shown in Fig. 2(c) could be added to stabilize the output signal levels. Then, the UART Rx inside the SIPEX 3232EC reassembles the bits. During the synchronization, the self-timed process in the UART Rx will be alerted by the start bit at the beginning of each received packet, making the clock in the Rx to synchronize with the clock in the Tx. Finally, as shown in Fig. 2(a), the UART/RS-232-to-USB cable at the UART Rx output port converts the data to USB format, which will be sent to the computer for signal analysis.

3 Results and Discussion

We first measure the illuminance of the single white-light LED Tx at different distances using a lux-meter. Figure 3(a) shows the measured illuminance against different free space transmission distances. For a typical illuminance in an indoor environment of 500 lux, the free space distance is about 40 cm. When the transmission distance increases to 100 cm, the illuminance is only 80 lux. Then, we evaluate the BER performance of the VLC-over-UART system with different payload lengths. As shown in Fig. 3(b), there is no error count at the transmission distance of <100 cm. When the VLC transmission distance increases to 110 cm, the measured BERs are 4×10^{-6} and 7×10^{-5} at payload lengths of 32 and 64 bits, respectively. These correspond to data rates of 22 and 44 kbit/s. When the transmission distance is further increased, the BER increases rapidly due to the reduction of SNR. At transmission distance of 120 cm (56 lux), the 32-bit VLC-over-UART payload data can still achieve 7% forward error correction (FEC) (BER of 3.8×10^{-3}) requirement. The 32-bit payload performs better because the data rate is lower than the 64-bit payload. The VLC performance is determined by the PD received optical power, which in-turn affects the SNR. When there is a PD offset with respect to the LED, if the illuminance can still >80 lux, FEC transmission requirement can still be satisfied.

Finally, we demonstrate a real-time practical application of the proposed VLC-over-UART system. This demonstration is to simultaneously transmit temperature, humidity, and illuminance sensor data from a sensor node to a computer via the proposed VLC link, as shown in Fig. 4(a). The experimental setup is similar to that shown in Fig. 2(a), but the Tx is now a sensor node (the photography of the sensor is shown in inset of Fig. 4). Then, we use a computer program as shown in Fig. 4(b) to obtain the sensing information,

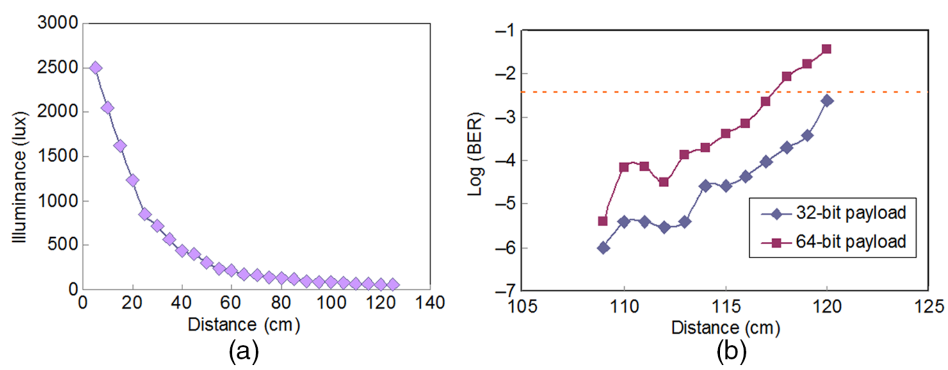

Fig. 3 (a) Measured illuminance against different free space distances and (b) measured BER of the VLC over UART with different payload lengths against different transmission distances.

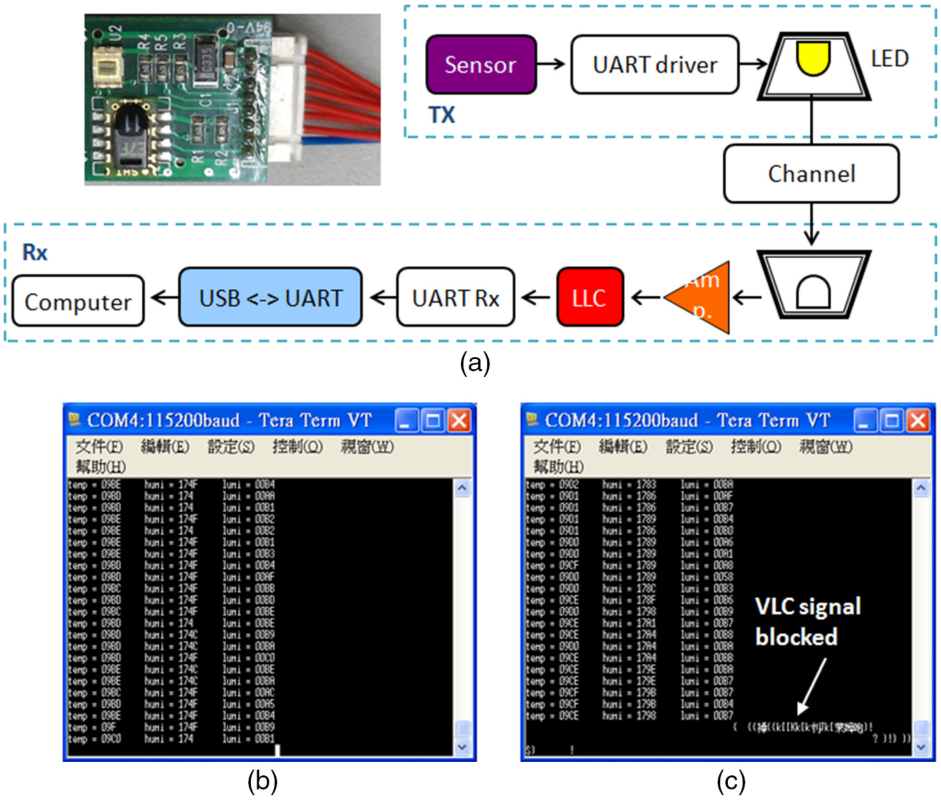

Fig. 4 (a) Setup of the simultaneously transmission of temperature, humidity, and illuminance data from a sensor node to a computer via the proposed VLC link. (b) and (c) Sensing information obtained in the computer.

including the temperature (temp), humidity (humi), and luminance (lumi) through a free space transmission distance of 100 cm. The data shown in Figs. 4(b) and 4(c) are in hexadecimal format and refreshed every 2 s. If the VLC signal is blocked by hand, some strange characters will be displayed as shown in Fig. 4(c) owing to the sudden increase in error counts. The refresh of sensing information stops until the obstacle in the VLC link is removed. When the VLC link is restored, the sensing information will be displayed in the program window again immediately.

4 Conclusion

In this work, we proposed and demonstrated a VLC-over-UART system. Different components and modules used in the proposed VLC-over-UART system were discussed. In the BER analysis, experimental results showed that there was no error count at the transmission distance of <100 cm (80 lux). At a transmission distance of 110 cm, the measured BERs were 4×10^{-6} and 7×10^{-5} at payload lengths of 32 and 64 bits, respectively. Finally, we also successfully demonstrated a real-time simultaneous temperature, humidity, and illuminance monitoring using the proposed VLC-over-UART system.

Acknowledgments

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