A UNIVERSITY TESTBED FOR DATA TRANSMISSIONS OVER VISIBLE LIGHT COMMUNICATION CHANNELS

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ABSTRACT This paper presents visible light communication (VLC) system architecture, theory of VLC channel model and university prototype test-bed of different transmission scenarios for full-duplex indoor VLC applications to show the capability of real-time text and image transmission over visible light channels. Experimental results shown that at the baud rate of 19.2 kbps and 28.8 kbps, data transmission can be achieved at the same delay of several tens milliseconds over the distances of 80 cm and 240 cm using single LED and three LEDs transmitter, respectively.

1. INTRODUCTION

White Light Emitting Diodes (LEDs) has recently been promising as a new growth technology which is expected to replace traditional illumination sources. White LEDs has more advantages compared to the existing incandescent in terms of long life expectancy, high tolerance to humidity, low power consumption, etc. Their applications include numeric displays, flash-lights, vehicle brake lights, traffic signals and the ubiquitous power-on indicator light [1-4].

Besides the above mentioned unique advantages of the while LED as an illumination light source, needs for indoor communication systems using white LEDs are increasingly growing because there are many devices using lightings in our offices, home, home appliances including TVs and so on. The typical LED has special characteristics to light on and off very fast at ultra-high speed. By using visible light for the data transmission, problems related to radio communications are almost resolved such as transmitting at ultra-high speed, harmless for human body [5-6]. The LED based visible light communication is interpreted as a convergence communication technology which is not only used as a lighting device, but also to be used as communication device [7]. It is a kind of indoor optical wireless communication (OWC) that uses 'visible light' rays as communication medium.

There are a number of VLC research projects have been carried out [8-11]. In [8], the VLC Consortium (VLCC) established in 2003 with major companies in Japan aiming to publicize and standardize the visible light communication technology, which has been discussed and evaluated in the various industry fields. This ubiquitous and human interface technology provides the communication capability through LED lightings in our offices and homes, LED commercial displays, LED traffic signals, LED small lamps on electronic home appliances, etc in our daily life. Then, the European OMEGA project [9], the Wireless World Research Forum (WWRF) [10] and a forthcoming IEEE standard for VLC [11] have dedicated to this research area. In addition, research works on high speed data transmission, channel characteristics and modulation schemes have been proposed for the possibility of designing a new model that could fit the present infrastructure for indoor applications [12-16]. In [12] Vucic *et. al.* reported a wireless visible-light link operating for the first time at 125 Mb/s over 5 m distance indoor by use of on-off-keying (OOK) at the bit-error-ratios (BER) below 2.10^{-3}. Hoa *et. al.* described in [13] a high-speed VLC link of 10 Mb/s data rate using a white-light LED and OOK nonreturn-to-zero (NRZ) modulation. In [14] authors reviewed the recent improvements on bandwidth extension and methods increasing transmission speed and discussed major application areas of the VLC. In [15] Mesleh *et. al.* proposed a power and bandwidth efficient pulsed modulation technique for OWC. Moreover, in [16] a data rate of 20 Mb/s achieved in a 1 m free space transmission by using the quaternary amplitude shift keying (4-ASK) modulation with digital filtering to enhance the direct modulation speed of white LED in VLC system.

In the most recently, there has been increasing research interest in VLC transceiver system design and demonstration depending on the indoor application scenarios [17-21]. In [17] and [18], authors investigated wireless optical transceiver especially focusing on the high speed and short range visible communication with expectation to be used as a peripheral interface of hand-held devices such as mobile phones, notebook computers, digital cameras. In [19] Png *et. al*. presented VLC audio transmitter and receiver circuit that can be integrated with LED reading lights above passengers' seats for the development of wireless airline entertainment systems. Png also described in [20] a circuit construction of VLC mass-storage prototypes that enable file transfers between the SD (Secure Digital) memory card and the PC via white-LED light. The entire system consists of a pair of identical white-LED transceivers: one is connected to the PC, whereas the other is connected to the SD-card sub-circuit. File transfer operates at 19200 bps. In [21] Rajbhandari *et. al.* presented divide constraints and design considerations of high-speed integrated VLC system to demonstrate a preliminary result of a MIMO system implementation operating at a data rate of 1 Gb/s. In addition, VLC transceiver designs were implemented on a field programmable gate array (FPGA) [22-24], in which the digital basebands for the transmitter and the receiver are implemented using two separate FPGAs. Thus far, the reported works mainly focused on basic functionality demonstration or signal processing algorithms and techniques to improve the data rate. However, the detail fundamental design consideration of uni-testbed VLC transmission including system model, channel model, circuit modules, testing scenarios of indoor full-duplex transceiver, text and image demonstration using the Graphic User Interface (GUI) testbed software have not been clarified.

In this paper, we therefore report a uni-testbed for real time data full-duplex transmission system system using LED based on USB port with 2 Mbps data rate for indoor visible light application scenarios. Self-written software is also developed to achieve the data transmission and real-time text/image transmissions between two PCs. Design and analysis of an integrated VLC receiver with an USB 2.0 interface for PC or Note Book has been introduced in [25] and [26]. USB interface is a universal standard of external bus to specify the connection and communication between PC and electronic devices. The data rate and transmission distance could be improved by increasing the number of LEDs at transmitter and PDs at the receiver.

The rest of the paper is organized as follows: section 2 introduces the VLC system description including system model, channel model. Section 3 gives VLC uni-testbed for real-time data transmission. Finally, the conclusions and future work are given in Section 4.

2. VLC SYSTEM DESCRIPTION

2.1 VLC System Model

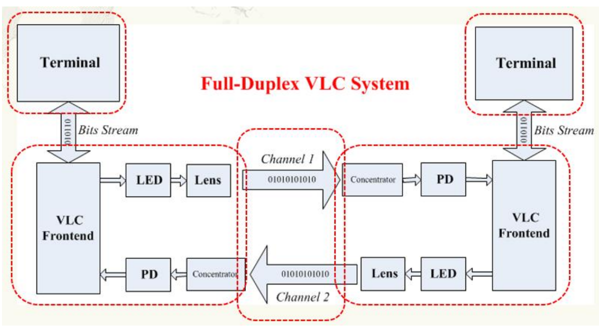

Fig. 1 VLC system model.

The designed VLC system architecture is shown in Figure 1. This system consists of VLC front ends which connected to communication terminals at one side and to LED and Photodiode at the other side. LED play role of a light source which emits light as well as data simultaneously. Data is sent between two or more terminals; in each front end there is a receiver and an emitter. The emitter transmits data into free space, to be received by a receiver from a different terminal.

Communication terminal permits users to transmit or receive data in type of text or images. Terminals could be a Laptop/PC, embedded computer or even a smart phone/tablet. Necessary software will be installed in these terminals. Software is used to generate a bit stream pushing to physical layer of the VLC transmitter in transmitting direction and to receive the bit stream from physical layer of VLC receiver in the reverse direction. Other software also is used to measure the communication delay or throughput over VLC channels. VLC Front – End is a hardware part which designed to convert data in term of bit streams at the input to suitable signal for controlling light intensity of light source by turn on and off the LED. The third part at transmitting side is LED and Lens to generate and direct the light source for high luminous flux efficiency. At the receiving side, a PhotoDiode (PD) is used convert optical signal into electrical signal. Concentrators could be also used to reduce interference from other light sources or to limit the light received outside of field of view of the Photodiode.

2.2 VLC Channel Model

Indoor VLC channels are classified into two main types of Line-of Sight (LOS) and Non-Line-Of-Sight (NLOS) as shown in figure 2. However, for indoor VLC links in a typical room with dimension of (5m×5m×3m), the light in the NLOS paths are much weaker than that in the LOS paths. The intensity of an LOS path is about 10 times higher than that of the first reflective path as shown in [19, 20].

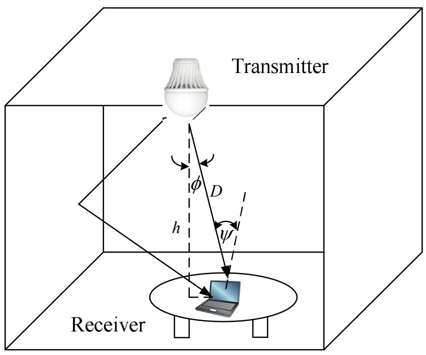

Fig. 2 VLC channel model.

In next part, the theory of LOS channel model will be introduced. Path loss and received optical power will be deduced basing on the photometric parameters. The simulation results of luminous flux distribution based on the theory analysis will provide guidance to the selection of the appropriate LEDs used in our VLC testbed.

The relationship between receive power and transmit power for LOS channel is expressed as

$$P_r = P_t L_L \tag{1}$$

where L_L is path loss of the communication channel, which can be given as

$$L_L = \frac{(m+1)A_r}{2\pi D^2}\cos\psi\cos^m\phi \tag{2}$$

$m = -\ln 2/\ln(\cos\phi_{1/2})$, A_r is physical area of detector in photo detector, D is distance between transmitter and receiver, ϕ is the angle of irradiance at transmitter, ψ is the angle of incidence at receiver, m is the order of Lumberton emission, $\phi_{1/2}$ is the transmitter semi-angle defined at half power, and it physically determines the illuminating beam width of the a single LED.

In case of multiple LOS channels, the receive power is summed up of all receive power for each LOS that is given as

$$P_r = \sum_i^n P_{ri} \tag{3}$$

The electrical power distribution at receiver depends on the illuminance distribution of light source. The illuminance expresses the brightness of an illuminated surface. The luminous intensity in angle ϕ is given by (4) based on Lambert's Cosine Law

$$I(\phi) = I(0)\cos^m(\phi) \tag{4}$$

Almost every commercial LED is produced following Lambert's Cosine Law. The luminous intensity reduces when the angle ϕ increases. In Eq. (4), $I(0)$ is the LED's centre luminous intensity, ϕ is the angle of irradiance and m is the order of Lumberton emission. The horizontal illuminance, E_{hor}, at the point (x, y) is defined as

$$E_{\text{hor}} = \frac{I(0)\cos^m(\phi)\cos(\psi)}{D^2}, \tag{5}$$

where ψ is the angle of incidence and D is the distance between LED and detector's surface.

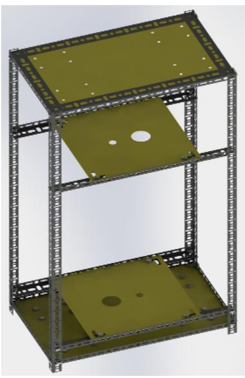

Fig. 3 VLC testbed frame.

The illuminance intensity distribution is investigated through simulation in Matlab™ software. A LED Lambert Luxeon 1W is used to illuminate light source in the space with dimension of 0.5×0.5×0.7 m. This is corresponding to the dimension of VLC testbed frame shown in figure 3. A light source (transmitter) is located at position (x=0.25, y=0.25, z=0.7). The Photodiode (receiver) is place on different position on the plane of z = 0.

The relative position of transmitter and receiver in simulation scenario is illustrated in figure 1. In the case of $\phi = \psi$, then $\cos(\phi)$ and D can be, respectively, calculated as

$$\cos\phi = \cos\psi = \frac{h}{\sqrt{h^2 + (x-0.25)^2 + (y-0.25)^2}}, \tag{6}$$

$$D = \sqrt{h^2 + (x-0.25^2 + (y-0.25)^2}, \tag{7}$$

where h is the vertical distance between transmitter and receiver. Replace Eqs. (6), (7) into Eq. (5), the horizontal illuminance is given as

$$E_{\text{hor}}(x,y,0) = \frac{358h^{m+1}}{\left[h^2 + (x-0.25)^2 + (y-0.25)^2\right]^{\frac{m+3}{2}}} \tag{8}$$

Base on the theory analysis above, the simulation of Illuminance intensity distribution was carried out with the result shown in figure 4. The illuminance concentrated with luminous intensity at the center of the frame and reduces gradually to the edge. The luminous intensity varies a small amount when receiver located nearby center of the ground plane.

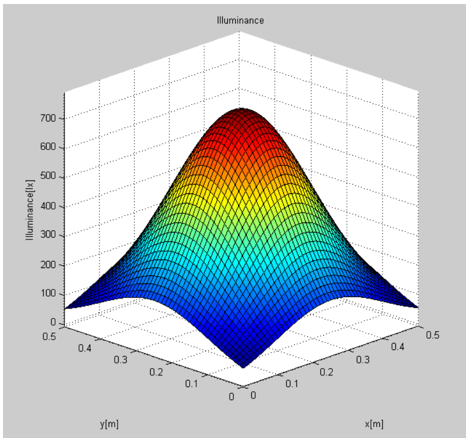

Fig. 4 Illuminance intensity distribution.

The luminous flux at center of 700 lx is suitable for both lighting and data communications for the small space of the target VLC testbed frame. In case of normal room, the power or number of LED needs to be increased.

3. VLC UNI-TESTBED FOR REAL-TIME DATA TRANSMISSION

3.1 VLC Testbed Scenarios

For practical experiment testbed, the system architecture consists of all elements of VLC overall system architecture as shown in Fig. 5, including the communications realized by Laptops, Smartphone and Embedded Computers. In the testbed presented in Fig. 5, LED and PD are placed in the vertical direction. In this model, the interference from other light sources of environment is limited because LED and PD are place in vertical axis. In addition, PD is located in the bottom of a PVC pipe with the length of 8cm. In this testbed, the experiments can be done at any time without effecting by surrounded light sources. Practical experiments have shown that this feature leads to many advantages compared to our previous testbed model.

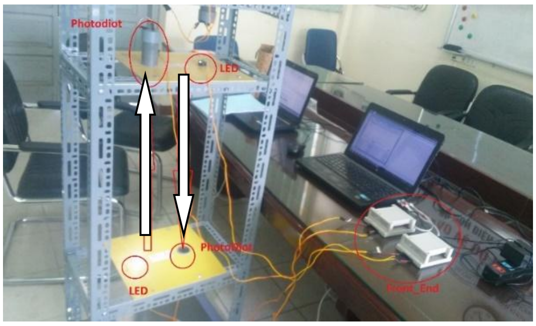

Fig. 5 VLC testbed system: topology of 1LED×1PD and transmission distance of 0.8 m.

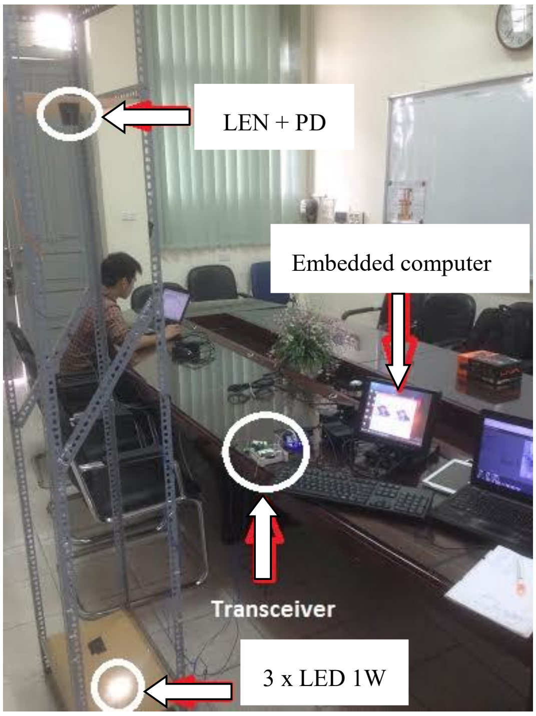

Fig. 6 VLC testbed system: topology of 3LED×1PD and transmission distance of 2.4 m.

Another model is to increase transmission distance by using more LEDs at the transmitter and focus lens at the receiver. Figure 6 presents the topology of the VLC testbed system using three parallel LEDs 1W at transmitter and one focusing Len equipped before PD at the receiver. The focus converged on the surface of the PD to obtain the highest intensity. The VLC testbed topologies are established in Figs. 5 and Figs. 6. The data in type of text and image is transferred in real-time between two transceivers connected to the same Laptop with a self-written GUI software installed.

3.2 VLC Testbed Experiments

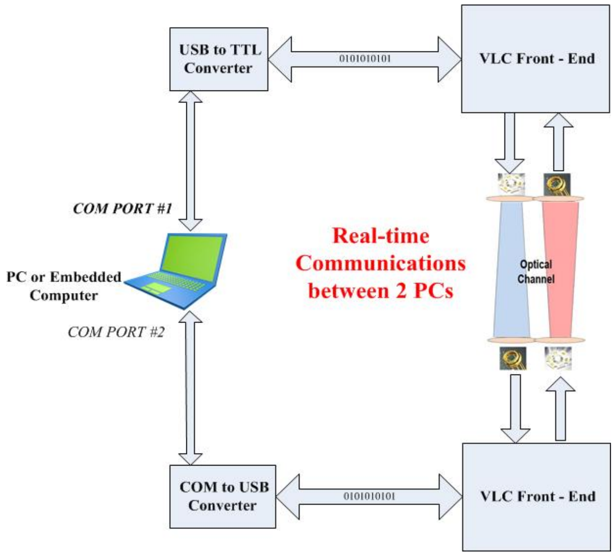

Fig. 7 PC to PC testbed over VLC channels.

The experimental topology (Fig. 7) helps us measuring exactly value of communication transmission delay due to elimination of clock offset in case of using two Laptops or two different physical devices. The software is developed for experiments with VLC testbed (see Figs. 8 and Figs.9), which is designed for experiments of real-time data communications with following main functions: (1) measure transmission delay using customized "Ping" command, wherein the timestamp of short "Ping" packets at moment of sending at transmitter and receiving moment at receiver are recorded. The delay value the is calculated based these timestamp and save to the log files; (2) transfer text in both way with different bit rates, measure transmission delay and save into log files; (3) transfer images in both forward and backward links, with different format, resolution and bit rates, display received images, measure transmission delay and save into log files.

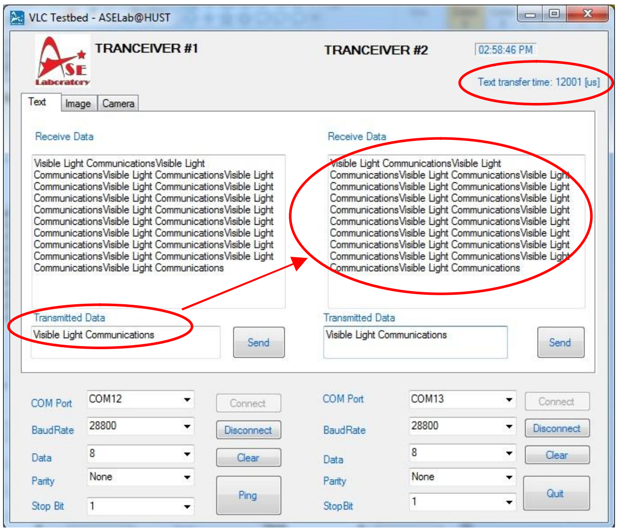

Fig. 8 GUI testbed software: Text-transfer mode with transmission distance of 2.4 m, baudrate of 28.8 kbps.

Fig. 9 GUI of VLC-testbed: transmission distance of 2.4m, file size of 17.133 kB, baudrate of 28.8 kbps.

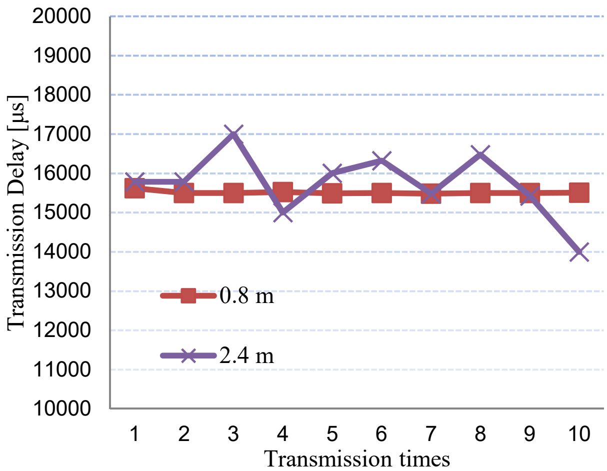

Fig. 10 Comparison of text transmission delay between *D*=0.8 m and 2.4 m, baudrate of 28.8 kbps.

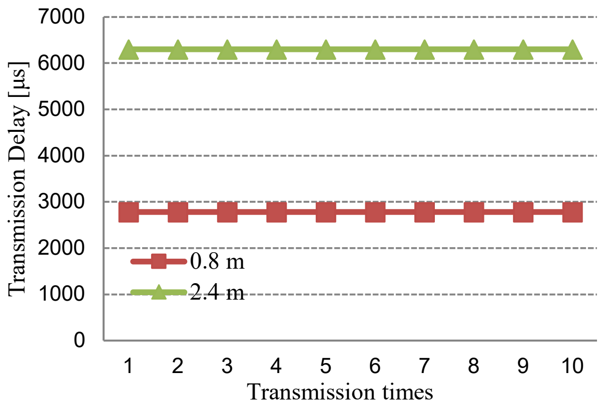

Fig. 11 Comparison of image transmission delay between *D*=0.8 m and 2.4 m, and baudrate of 28.8 kbps.

Fig. 10 shows the text transmission delays of visible light channel characteristics with the transmission distance of *D*=0.8 m and 2.4 m and the baudrate of 28.8 kbps. We used 10 transmission times for each distance *D*. It is shown that the transmission delays for both distances were around 15 ms. Similarly, Fig. 11 illustrates the image transmission delay snapped shot in 10 transmission times. It can be seen that the constant values of 2780 µs and 6300 µs are achieved at the distances of 0.8 m and 2.4 m, respectively.

CONCLUSION

This paper presented the university tested VLC real-time data transmission for research and development activities in the areas of optical wireless communications at Department of Aerospace Electronics, School of Electronics and Telecommunications, HUST. It could be confirmed that depend on the transmission distance and data rate, there are various testbed scenarios for evaluating channel characteristics such as transmission delay of packets.

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