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An Improved Recursive Channel Model for Indoor Visible Light Communication Systems

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Abstract: An improved recursive channel model based on Barry's is proposed by introducing the wiring topology of light source for indoor visible light communication systems, including the path of communication access point to LED array access point and LED array access point to LED. Theoretical analysis and simulation results indicate that, the improved model presented in this paper can be used to better analyze the ISI phenomenon of an indoor visible light communication system. And mitigation strategies based on the formula of an improved channel model are proposed for ISI which provides a valuable reference for the actual application of a VLC system.

Key words: Visible light communication, channel model, wiring topology and inter-symbol interference

INTRODUCTION

Visible Light Communication (VLC) technology based on white LED has attracted much attention from the research community in the recent years because of its harmlessness to people, no application required for its frequency and its operability in unusual case (Lee *et al*., 2011; Sethakaset and Gulliver, 2006; Armstrong *et al*., 2012). In a VLC system, LED provides not only lighting but also communication. Because the illumination intensity of a single LED is small, a large LED array with more than 100 LED may be needed to achieve proper indoor lighting.

As the analysis of propagation channel characteristics is essential for all the telecommunication systems, much work has been done on channel characteristics for indoor infrared communication link (Gfeller and Bapst, 1979; Barry *et al*., 1993; Perez-Jimenez *et al*., 1997; Lopez-Hernandez *et al*., 1998a, b; Carruthers and Kahn, 1997, 2002; Hayasaka and Ito, 2007; Perez *et al*., 2002). For example, Gfeller and Bapst (1979) proposed the first propagation model which accounted for single reflections. Barry *et al*. (1993) proposed a recursive simulation model for multiple reflections and in 2011 extended the use of his 90's infrared channel model to indoor VLC systems (Lee *et al*., 2011), this model is still the only channel model for VLC so far.

Although, all these channel models mentioned above are not built using the same method, they are all used to analyze direct and reflection channels. The entire LED array light source is assumed to emit light simultaneously. Obviously, all LEDs may not emit light at the same time because of the difference of wiring topology and a LED may have more than one reflection channel. All those factors cause inter-symbol interference (ISI) and these should be taken into consideration while a channel model is built as a general form. As shown in Fig. 1, the signal travels from Communication Access Point (CAP) to LED via LED Array Access Point (LAAP) through wired connection. Paths CAP to LAAP and LAAP to LED are transmission lines, the distance from CAP to LAAP is fairly long and the number of LED used may exceed 100 which make the distance between LAAP and LED even longer, so the total distance is not negligible.

Therefore, an improved recursive channel model based on Barry's model is proposed by taken into consideration the wiring topology of CAP through LAAP to LED.

INDOOR VLC CHANNEL MODEL

The channel model proposed in this paper suits for an indoor VLC system with n LED, each LED has k path to a photodiode (PD) and each path needs to go through j reflection. This model includes three paths, firstly, CAP to LAAP, secondly, LAAP to LED and thirdly, LED emits light through direct and reflection paths to reach the PD.

Path CAP to LAAP: The signal travels from CAP to LAAP uses cable connection, if the length of CAP to the nth LAAP is $l_{c,n}$, then the time from CAP to nth LAAP $t_{c,n}$ can be expressed as:

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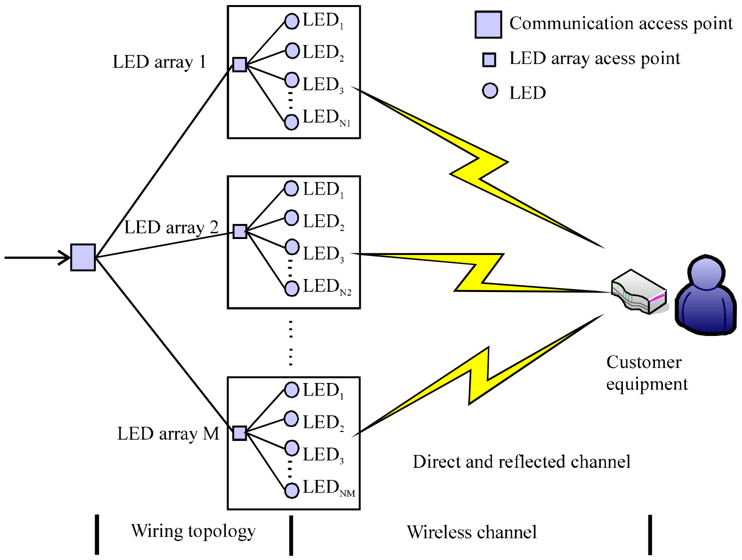

Fig. 1: Improved channel model for indoor VLC systems

$$t_{c,n} = \frac{l_{c,n}}{v_1} \tag{1}$$

where, v_1 is the speed of an electromagnetic wave on the cable and v_1 can be expressed as (Eric, 2010):

$$v_1 = \frac{12}{\sqrt{\varepsilon_{r1}}}\frac{in}{ns} \tag{2}$$

where, ε_{r1} is the relative dielectric constant of materials used on path CAP to LAAP.

Path LAAP to LED: The signal travels from LAAP to LED uses cable or Printed Circuit Board (PCB) connection, if the length of path LAAP to the nth LED is $l_{s,n}$, then the time from LAAP to nth LED $t_{s,n}$ can be expressed as:

$$t_{s,n} = \frac{l_{s,n}}{v_2} \tag{3}$$

where, v_2 is the speed of an electromagnetic wave on the cable or PCB used on path LAAP to LED and v_2 can be expressed as:

$$v_2 = \frac{12}{\sqrt{\varepsilon_{r2}}}\frac{in}{ns} \tag{4}$$

where, ε_{r2} is the relative dielectric constant of materials used on cable or PCB along LAAP to LED.

Direct and reflection channels: As shown in Fig. 2, the signal coming from the nth LED through direct and reflection channels can be captured by PD, when (n,k,j) means path j for reflection channel k at nth LED, $k \geq 0$ and $j \geq 0$ and (n, 0, 0) is a direct channel. If the length of channel (n, k, j) is $l_{n,k,j}$, then the time from reflection channel (n, k, j) can be expressed as:

$$t_{n,k,j} = \frac{l_{n,k,j}}{c} \tag{5}$$

where, c is the speed of light. Then the waveform through path (n, k, j) arrives PD can be expressed as:

$$y_{n,k,j}(t) = \gamma_{n,k,j} \cdot x\left(t - \frac{l_{c,n}}{v_1} - \frac{l_{s,n}}{v_2} - \frac{l_{n,k,j}}{c}\right) \tag{6}$$

where, $\gamma_{n,k,j}$ is the channel attenuation coefficient of path (n, k, j) and $\gamma_{n,k,j}$ can be expressed as:

$$\gamma_{n,k,j} = \int_s \left[L_{n,k,1} L_{n,k,2} \cdots L_{n,k,j+1} \Gamma_{n,k}^{(j)} \mathrm{rect}\left(\frac{\theta_{n,k+1}}{FOV}\right)\right] d\mathcal{A}_{ref} \tag{7}$$

Where:

$$L_{n,k,1} = \frac{A_{n,k}(m_{n,k}+1)\cos^{m_{n,k}}\phi_{n,k,1}\cos\theta_{n,k,1}}{2\pi d_{n,k,1}^2}$$

$$L_{n,k,2} = \frac{A_{n,k}\cos\phi_{n,k,2}\cos\theta_{n,k,2}}{\pi d_{n,k,2}^2}$$

$$L_{n,k,j+1} = \frac{A_{PD}\cos\phi_{n,k,j+1}\cos\theta_{n,k,j+1}}{\pi d_{n,k,j+1}^2}$$

$L_{n,k,j}$ represents path-loss for path (n, k, j). $\mathcal{A}_{ref}$ is the area of reflecting element. $m_{n,k}$ is the mode number of the kth reflection path of nth LED radiation lobe and $m_{n,k}$ can be expressed as:

$$m_{n,k} = \frac{-1}{\log_2\left(\cos\phi_{n,k,1/2}\right)} \tag{8}$$

where, $\phi_{n,k,1/2}$ is the viewing angle of the nth LED, kth reflection path. $\phi_{n,k}$ and $\theta_{n,k}$ represent the angles of irradiance and incidence of the nth LED, $d_{n,kj}$ is the distance between the source and the destination as shown in Fig. 2. The photodiode detects the angle of incidence of light is less than the Field Of View (FOV). The constant term of c is the speed of light and rect(x) is the rectangular function and can be expressed as:

$$\mathrm{rect}(x) = \begin{cases} 1 & -1 < x < 1, \\ 0 & \text{otherwise.} \end{cases} \tag{9}$$

$\Gamma^{(j)}_{n,k}$ is the power of reflected ray after j-bounces of the kth reflection path from the nth LED. And the reflected power can be expressed as:

$$\Gamma^{(j)}_{n,k} = \int_{\lambda} \Phi_{n,k}(\lambda)\rho_{k,1}(\lambda)\rho_{k,2}(\lambda)\cdots\rho_{k,j}(\lambda)d\lambda \tag{10}$$

$\rho_{k,j}$ (λ) is the reflectivity varying its value as a function of wavelength λ of the jth path in the kth reflection channel. So the waveforms from nth LED through direct and reflection channels to reach PD can be expressed as:

$$y_n(t) = \sum_{k=0}^{K_n}\sum_{j=0}^{J_1}\gamma_{n,k,j}\cdot x\left(t - \frac{l_{c,n}}{v_1} - \frac{l_{s,n}}{v_2} - \frac{l_{n,k,j}}{c}\right) \tag{11}$$

then all the signals that PD receives from all the LED arrays can be expressed as:

$$y(t) = \sum_{n=1}^{N} y_n(t) = \sum_{n=1}^{N}\sum_{k=0}^{K_n}\sum_{j=0}^{J_1}\gamma_{n,k,j}\cdot x\left(t - \frac{l_{c,n}}{v_1} - \frac{l_{s,n}}{v_2} - \frac{l_{n,k,j}}{c}\right) \tag{12}$$

where N is the number of LED in the VLC system and the impulse response h(t) of the VLC system can be expressed as:

$$h(t) = \sum_{n=1}^{N}\sum_{k=0}^{K_n}\sum_{j=0}^{J_1}\gamma_{n,k,j}\cdot \delta\left(t - \frac{l_{c,n}}{v_1} - \frac{l_{s,n}}{v_2} - \frac{l_{n,k,j}}{c}\right) \tag{13}$$

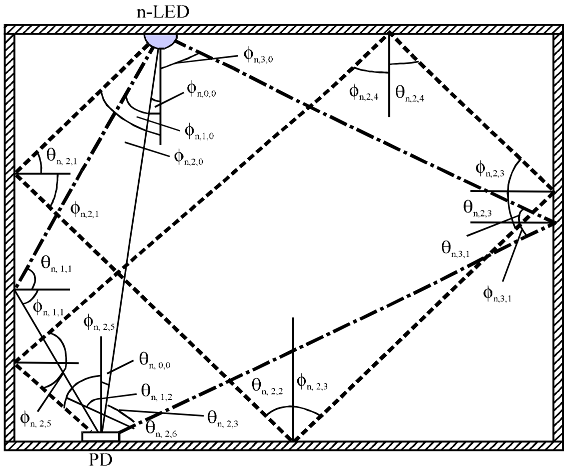

Fig. 2: Direct and reflection channels for an indoor VLC system

RESULTS AND DISCUSSION

In order to see the effectiveness of the improved model, we consider in the following simulation parameters result in an empty room, as shown in Table 1.

Three typical wiring topologies styles and there are non-delay style, "E" style and "S" style, are used in this study for simulation (Fig. 3a-c). Non-delay style means the length of path CAP to LAAP or LAAP to LED is equal and can not cause any delay, this style is also the style Barry's model is based on. "E" style refers to the layout arrangement in the form of letter "E", as shown in Fig. 3b.

Table 1: System simulation parameters

Room size (m)	5×5×3
No. of LED array	4
Coordinates of each LED array	(1.5, 1.5, 3.0); (1.5, 3.5, 3.0); (3.5, 1.5, 3.0); (3.5, 3.5, 3.0).
Number of LED in a LED array	25(5×5)
Coordinates of user equipment	(0.5, 1.0, 0.0)
Distance between two adjacent LED	1cm
Reflection coefficient	0.8
Power of a single LED	1 mW
Viewing angle of LED, $2Ö_{1/2}$	120

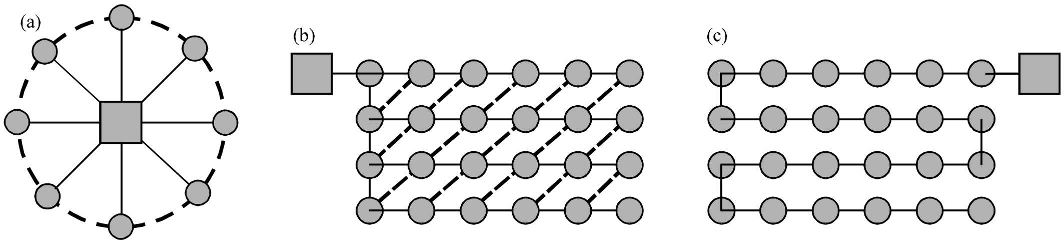

Fig. 3(a-c): Topologies used for simulation (a) Non-delay style, (b) "E" style and (c) "S" style

If the distance between adjacent LEDs in a LED array is equal, then there will be some LED light earlier and some light later. "S" style refers to the layout arrangement in the form of the letter "S", as shown in Fig. 3c, the LED gradually turn on in a "S" style and may cause a maximum delay. There are different combinations of wiring style for different unusual cases, as shown in Table 2.

According to Fig. 4-7, theoretical analysis and simulation results indicate that, a different wiring topology may cause a different received waveform and how to choose a wiring topology to make the received waveform better is a question must be considered, especially in a high-speed data transmission system. The performance of an indoor VLC system can be improved through the following strategies.

Table 2: Unusual cases used for simulation

Simulation case	CAP to LAAP	LAAP to LED
Case 1	Non-delay style	Non-delay style
Case 2	Non-delay style	"E" style
Case 3	Non-delay style	"S" style
Case 4	"S" style	"S" style

Optimization of wiring topology: According to Eq. 13, the difference in length from path CAP to LAAP and LAAP to LED can aggravate the effect of ISI phenomena on receiving waveform. So an effective solution is to optimize the wiring topology and make the length from path CAP to LAAP and LAAP to LED as equal as possible.

Minimization of the number of LED array and the number of LEDs in an array: One reason which causes ISI is that the time of LED luminous is different, so minimize the number of LED array and the number of LED in an array is an effective method to reduce the ISI phenomena of an indoor VLC system. On the other hand, the number of LED arrays and the number of LED in an

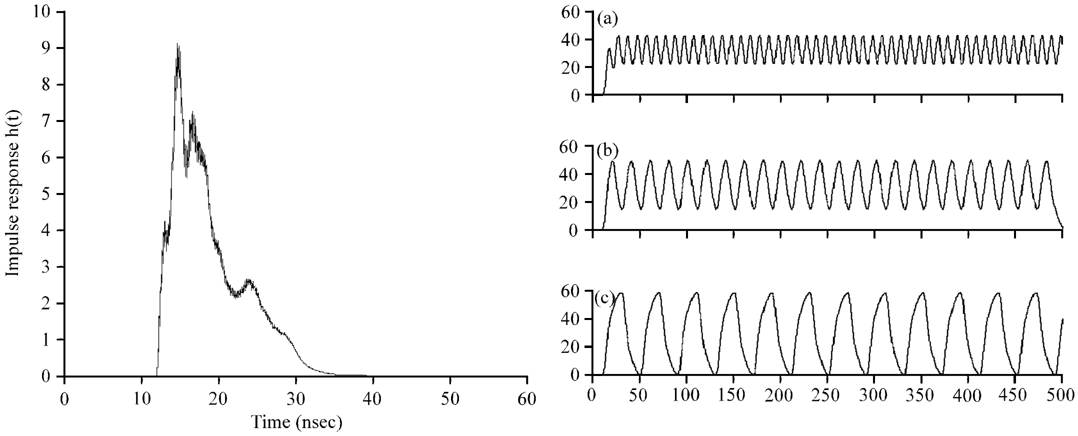

Fig. 4(a-c): Impulse response vs. time for simulation case 1 (a) 100 MHZ, (b) 50 MHZ and (c) 25 MHZ

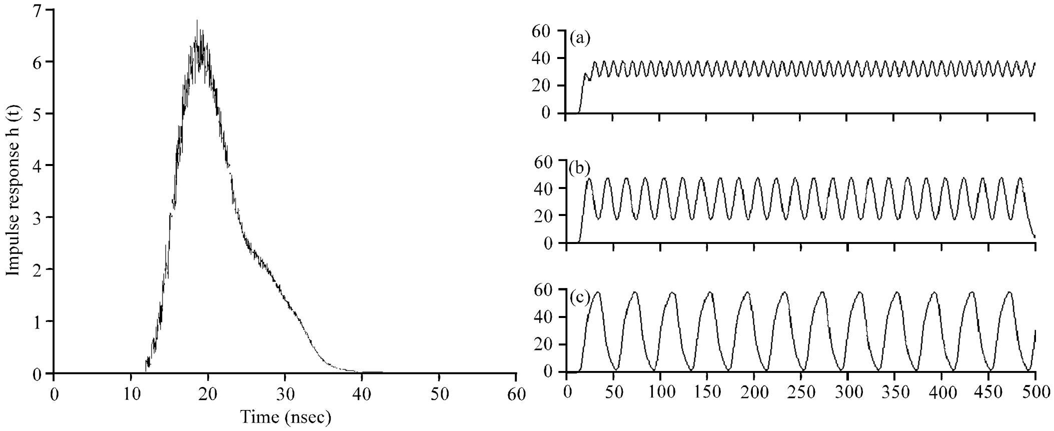

Fig. 5(a-c): Impulse response vs. time for simulation case 2 (a) 100 MHZ, (b) 50 MHZ and (c) 25 MHZ

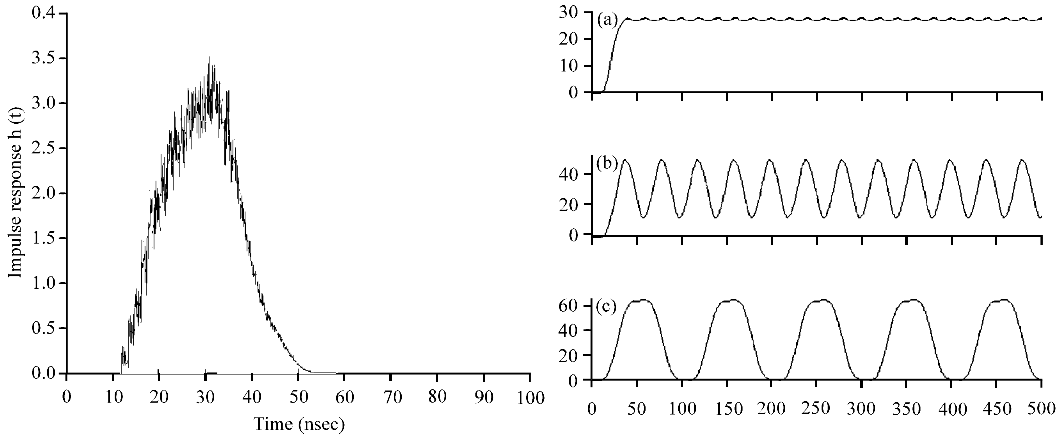

Fig. 6(a-c): Impulse response vs. time for simulation case 3 (a) 50 MHZ, (b) 25 MHZ and (c) 10 MHZ

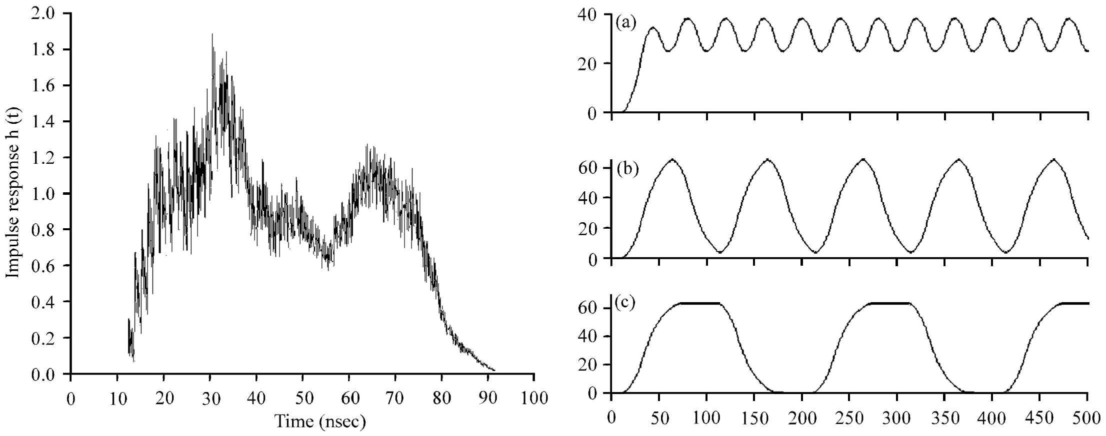

Fig. 7(a-c): Impulse response vs. time for simulation case 4 (a) 25 MHZ, (b) 10 MHZ and (c) 5 MHZ

array is not only defined by the communication function but also defined by the illumination required for the user firstly, so it is necessary to compromise to consider illumination and communication performance.

Reduction of reflection coefficient: Due to the existence of reflection path, multipath causes ISI, reduction of reflection coefficient is an effective method.

Reduction of viewing angle of receiver: The reduction of viewing angle of a receiver aims at the reduction of the intensity of reflected light entering the surface of a photosensitive device, so as the impact of the multipath problem can be alleviated, however, the reduction of viewing angle of receiver can also lead to decrease in direct light entering the reception area.

Use of modulation methods resistant to ISI: An indoor VLC system may use baseband modulation methods such as OOK (On-Off keying) or PPM (Pulse position Modulation). The resistance of OOK or PPM to ISI is limited, if the maximum data rate is R_b bit/sec and the receiver has an accurate synchronization, the ideal resistance of OOK to ISI is $1/2R_b$ second only and received waveform will aliase when ISI is bigger than $1/2R_b$. A possible strategy is to use a modulation, for example, m-ray digital pulse cycle modulation (MDPCM), with resistance to ISI. MDPCM is only sensitive to the rising edge of a waveform, as long as ISI is less than ½Rb, the receiver can demodulate the original information correctly.

CONCLUSION

An improved iterative channel model based on Barry's is proposed in the paper for an indoor VLC system by introducing the path of CAP to LAAP and LAAP to LED into the channel model and taking into consideration the influence of waveform on the receiver. Simulation results indicate that different wiring topology can cause different ISI phenomena and then limit the bandwidth of a VLC system finally. Five mitigation strategies are proposed to optimization the ISI performance of a VLC system and mitigate the interference of wiring topology. Theoretical analysis and simulation results indicate that, the improved channel model proposed in this paper is a candidate channel model and provided a valuable reference for the actual application of a VLC system.

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