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The Concept of Location-based Equalization for Indoor Visible Light Communications

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Abstract—**In this paper, we propose a novel concept of the location-based equalization scheme for indoor visible light communication (VLC) systems. For the first time, indoor VLC can become an indoor visible light positioning based service. Numerical results prove that the proposed scheme is a simple and effective solution to counteract the inter-symbol interference induced by the indoor VLC dispersive channel. For example, for a 100 Mbps transmission link, the proportion of the indoor area with a bit error rate of less than 10^{-6} can be increased from around 70.4% to 92.3% by adopting the proposed scheme.**

Index Terms—**Visible light communication; visible light positioning; equalization.**

I. Introduction

The indoor visible light communication (VLC) system based on white light emitting diode (LED) technique has become a promising candidate for indoor mobile data access due to its advantages such as unregulated huge bandwidth, high energy efficiency and electromagnetic immunity [1−3]. However, due to inherent multiple transmitters (Txs) and reflections from indoor environment such as walls, ceils, etc., the optical signals will experience a dispersive multi-path channel. This will cause severe inter-symbol interference (ISI) among data symbols [3]. It was shown that the bit error rate (BER) performance of the indoor VLC system will be degraded significantly by the effects of ISI. Conventionally, intermittent training sequences with adaptive equalization algorithms and orthogonal frequency division multiplexing (OFDM) with a long guard interval (GI) can be adopted to counteract ISI deterioration, but at the cost of reduced transmission efficiency and extra complexity [4−6].

Recently, with the development of wireless technologies including wireless local area network (WLAN), Zigbee, Bluetooth, etc., the indoor positioning systems have become popular [7]. Specifically, the indoor visible light positioning (VLP) system adopting LEDs has gained extensive attention due to its low cost, simple implementation and high accuracy [8,9]. Therefore, it is easy for a mobile VLC receiver (Rx) terminal to get its real-time accurate indoor location. Furthermore, this can provide users with location-based services in the fields such as indoor navigation, asset tracking and intelligent mobile robot [10]. However, indoor mobile data transmission has never been a value-added service based on such indoor VLP systems. In this paper, in order to eliminate the ISI induced by indoor VLC multi-path channel, we first propose a novel concept of the location-based equalization (LBE) scheme for indoor VLC systems. VLC features intensity modulation and direct detection. The received signals consists of both the line-of-sight (LOS) and non-LOS (NLOS) components. As long as the Rx coordinates are obtained by means of techniques like VLP, the LOS channel impulse response (CIR) can be theoretically fixed and approximately calculable. Besides, the NLOS components result from indoor reflections are so faint compared with the LOS components [2,3]. Therefore, due to the dominant role of the LOS components in the total collected light at the Rx, the estimated LOS CIR can be considered as a close estimation of the total CIR. These estimated results will be further utilized to equalize the total VLC dispersive multi-path channel. Simulation results show that the proposed LBE scheme can effectively improve system performance and extend the range for reliable data transmission in indoor VLC systems.

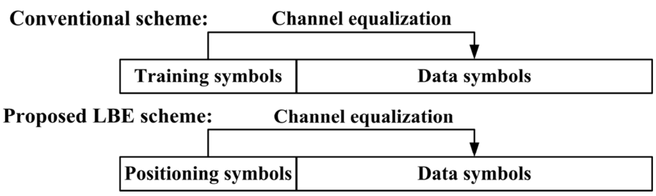


Figure 1. Comparison for the general concept of VLC channel equalization.

II. Principle of the Proposed Concept

Fig. 1 compares the general concept between the conventional VLC channel equalization scheme and the proposed LBE scheme. For the conventional system, training symbols are required to estimate the VLC dispersive channel in order to equalize the subsequent data symbols. However, there is no connection with VLP at all. VLC and VLP should be implemented using two independent systems due to the limited time or spectral resources. However, for the proposed LBE system, positioning symbols are transmitted for VLP at first. Then the location information obtained by these positioning symbols are further utilized for the channel equalization of subsequent data symbols. This means that, the positioning symbols can serve a dual-function: positioning and equalization. In this way, VLC and VLP can be successfully compromised within a single system. Therefore, we do not need training symbols for channel estimation and equalization any more, which can effectively reduce extra system payload.

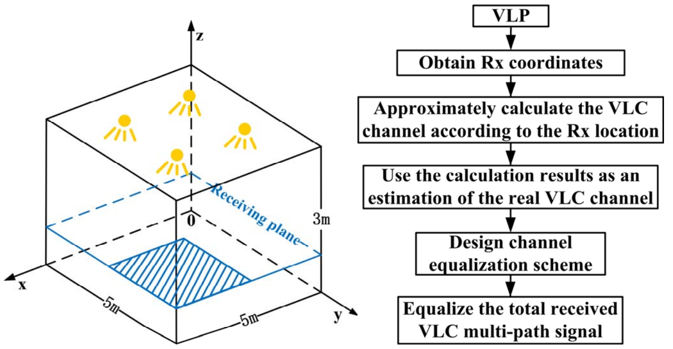


Figure 2. Indoor VLC system configuration for the proposed LBE concept.

In the indoor VLC system, the LOS CIR can be simply given as [2]:

$$h_{LOS}(t)=\sum_{i=1}^{N_{LED}} H_i(0)\delta(t-\tau_i)\,, \tag{1}$$

where N_{LED} is the total Tx number (at least three for implementing VLP), $H_i(0)$ is the channel DC gain, and τ_i is the time delay of the LOS signal from the ith Tx, respectively. The detail of $H_i(0)$ can be also found in [3]. The channel DC gain depends on many factors, including the LED radiation pattern and the Rx configuration parameters. However, among these factors, the distance between the Tx and Rx plays the most significant role because it determines the attenuation and delay of the received signals from multi-paths. Assuming the coordinates of the ith Tx and Rx to be (x_{ti},y_{ti},z_{ti}) and (x_r,y_r,z_r) respectively, the distances between them can be represented as:

$$D_i=\sqrt{(x_r-x_{ti})^2+(y_r-y_{ti})^2+(z_r-z_{ti})^2}\,. \tag{2}$$

Therefore, $H_i(0)$ and τ_i can be simply calculated based on the Tx and Rx coordinates as well as other Tx and Rx parameters. Specifically, $H_i(0)$ is inversely proportional to the power of D_i and τ_i can be denoted by D_i/c, where c is the velocity of light. Note that both the Tx irradiance angle and Rx incidence angle in $H_i(0)$ are also related to these coordinates. Since the locations of LED sources are fixed, the calculation of $h_{LOS}(t)$ is then highly dependent on Rx locations, which can be obtained by means of VLP with acceptable high accuracy. Therefore, $h_{LOS}(t)$ can be theoretically calculated based on Rx locations and all other system parameters. However, it may be difficult for the Rx to know all the system parameters. Therefore, from the point of view of system implementation and simplicity, we can propose to approximately calculate the LOS CIR only according to D_i, which can be represented as:

$$\hat{h}_{LOS}(t)\propto\sum_{i=1}^{N_{LED}} \delta(t-D_i/c)\big/(D_i^2)\,. \tag{3}$$

Note that more priori knowledge of the VLC system parameters can surely derive a more accurate LOS CIR. However, by simply adopting Eq. (3) as a close estimation of the real VLC channel, we can already design an equalization scheme which is assumed to be matched well with the estimated VLC LOS channel, and then utilize it to equalize the total received VLC multi-path signal, including the weak NLOS components.

The indoor VLC system configuration for the proposed scheme is shown in Fig. 2, with the block diagram of the procedures for the proposed LBE concept. VLP is realized at first to give assistance to subsequent VLC equalization. All these procedures will be carried out by digital signal processing at the Rx.

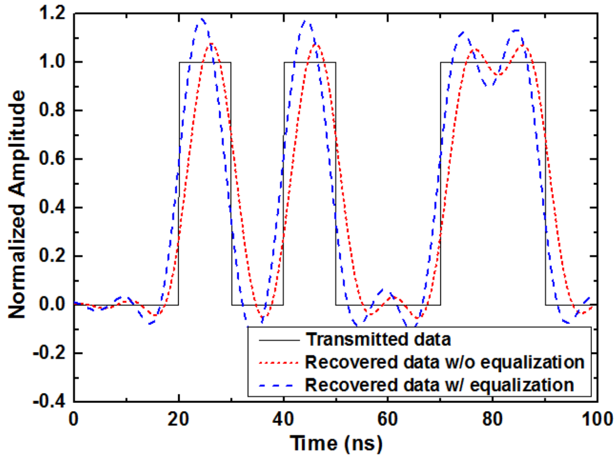


Figure 3. Waveform comparison at 100 Mbps considering only a LOS channel. Here the transmitted data sequence is assumed to be “0010100110”.

III. Simulation and Discussions

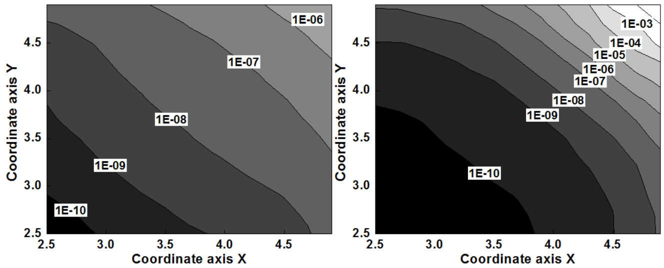
In this section, assuming the Rx locations are known by the mobile Rx terminal via VLP, numerical simulation is conducted to evaluate the performance of the proposed LBE. The room size is 5m*5m*3m (length*width*height). The model in Fig. 2 is adopted with four LED lamps at the locations of (1.5,1.5,3), (1.5,3.5,3) , (3.5,1.5,3) and (3.5,3.5,3) respectively. The single LED lamp power is 5 Watt and the modulation index is 0.1. The height of the receiving plane is 0.85m. A low-pass filter is adopted to simulate the bandwidth limitation of the VLC system. The equalization scheme at the Rx is designed in order to match the estimated LOS CIR according to Eq. (3). Due to the indoor symmetrical properties, we only consider one quarter of the receiving plane, as shadowed in Fig. 2.

Considering only a LOS channel, Fig. 3 compares the waveforms of the transmitted, received and equalized signals for on-off keying (OOK) signals at 100 Mbps at the location of (3.5,3.5,0.85). It can be seen that the proposed LBE concept can effectively equalize the multi-path dispersive LOS channel and thus improve the received signal quality.

Next, we will evaluate the system BER performance under the scenarios of both LOS and LOS+NLOS channels. The bipolar OOK data signal is adopted with the theoretical BER performance given by [11]:

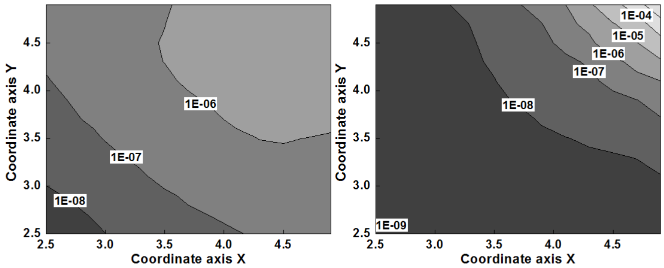
$$BER=Q(\sqrt{2r_s})\;, \tag{4}$$

where $Q(\cdot)$ is the Q-function and r_s is the signal-to-noise ratio of the electrical signal. Figs. 4 show a BER performance comparison at the data rate of 100 Mbps considering only a LOS channel. We can see that the proposed LBE scheme can effectively improve the BER performance for the LOS VLC channel in most indoor area. Specifically, around the centre of the room, the theoritical BER can be improved by nearly an order of magnitude when adopting LBE. However, in the corner of the room we can observe BER performance



(a) (b)

Figure 4. BER performance comparison at 100 Mbps considering only a LOS channel: (a) w/o LBE; (b) w/ LBE.



(a) (b)

Figure 5. BER performance comparison at 100 Mbps considering both the LOS signal and the 1st indoor reflections: (a) w/o LBE; (b) w/ LBE.

degradation resulted from the LBE scheme. The reason is that the estimated LOS CIR in Eq. (3) cannot approximate the real LOS CIR in the corner locations. The estimation error mainly comes from the Tx irradiance angle and Rx incidence angle, because we did not consider them in Eq. (3) at all.

In Figs. 5, at 100 Mbps, we take the first indoor reflections into consideration. Although the received NLOS components will result in an overall BER performance degradation compared with Figs. 4, the proposed LBE can still achieve a significant performance improvement in most indoor area as in Fig. 4. Due to imperfect channel knowledge, a BER performance degradation can be also observed in the corner locations. However, the range of improved BER performance is also extended. For example, the proportion of the indoor area with a BER of less than 10^{-6} can be increased from around 70.4% to 92.3% by adopting LBE. These results indicate a promising future of the proposed LBE concept in indoor mobile VLC systems.

IV. Conclusion

In indoor VLC systems, we have first proposed a LBE concept. This concept is attractive because, for the first time, the Rx locations obtained by means of VLP can be efficiently utilized to equalize the indoor VLC multi-path dispersive channel. Compared with conventional equalization schemes, the proposed scheme is effective, simple to implement, and it also avoids extra overhead such as training sequences or OFDM GI. Since the results in this paper are mainly based on the estimated LOS CIR in Eq. (3), the imperfect channel knowledge will limit the performance improvement from LBE. In the future work, we will investigate other kinds of more accurate designs for the VLC equalization schemes based on the Rx locations.

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References

[1] H. Elgala, R. Mesleh, and H. Haas, "Indoor optical wireless communication: potential and state-of-the-art", *IEEE Commun. Mag. Electron.*, vol. 49, no. 9, pp. 56–62, 2011.

[2] Z. Ghassemlooy, W. Popoola, and S. Rajbhandari, "*Optical wireless communications: system and channel modelling with Matlab*", Boca Raton, USA, CRC Press, 2012.

[3] T. Komine and M. Nakagawa, "Fundamental analysis for visible-light communication system using LED lights", *IEEE Trans. Consum. Electron.*, vol. 50, no. 1, pp. 100−107, 2004.

[4] T. Komine, J. H. Lee, S. Haruyama and M. Nakagawa, "Adaptive equalization system for visible light wireless communication utilizing multiple white LED lighting equipment", *IEEE Trans. Wireless Commun.*, vol. 8, no. 6, pp. 2892−2990, 2009.

[5] J. Armstrong, "OFDM for optical communications", *IEEE J. Lightw. Technol.*, vol. 27, no. 3, pp. 189–204, 2009.

[6] H. Elgala, R. Mesleh, and H. Haas, "Indoor broadcasting via white LEDs and OFDM", *IEEE Trans. Consum. Electron.*, vol. 55, no. 3, pp. 1127–1134, 2009.

[7] H. Liu, H. Darabi, P. Banerjee, and J. Liu, " Survey of wireless indoor positioning techniques and systems", *IEEE Trans. Syst., Man, Cybern. C, Appl. Rev.*, vol. 37, no. 6, pp. 1067−1080, 2007.

[8] N. U. Hassan, A. Naeem, M. A. Pasha, T. Jadoon, and C. Yuen, "Indoor positioning using visible LED lights: a survey", *ACM Computing Surveys*, vol. 48, no. 2, pp. 1–32, 2015.

[9] D. R. Kim, H. S. Kim, S. K. Han, S. H. Yang, and Y. H. Son, " An indoor visible light communication positioning system using a RF carrier allocation technique", *IEEE J. Lightw. Technol.*, vol. 31, no. 1, pp. 134–144, 2013.

[10] J. Armstrong, Y. Sekercioglu, and A. Neild, "Visible light positioning: a road map for international standardization", *IEEE Commun. Mag.*, vol. 51, no. 12, pp. 68−73, 2013.

[11] J. G. Proakis and M. Salehi, "*Contemporary communication systems using MATLAB*", PWS Publishing Company, 1998.