Location-based Equalization for OFDM Indoor Visible Light Communication Systems

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Abstract: In indoor visible light communication (VLC) systems based on orthogonal frequency division multiplexing (OFDM), we propose a novel location-based equalization (LBE) concept to counteract multi-path effects. Different implementation methods are also discussed. Results show that the LBE design, especially based on only a line-of-sight link, can effectively equalize OFDM multi-path signals and improve system bit error rate performance at different indoor locations.

OCIS codes: (060.4510) Optical communications; (060.2630) Frequency modulation; (120.7000) Transmission.

1. Introduction

Visible light communication (VLC) using light-emitting diodes (LEDs) has become a promising candidate for indoor mobile data access [1,2]. However, due to inherent multiple transmitters (Txs) and reflections from indoor environment such as walls, ceils, etc., optical signals will experience a dispersive multi-path channel. Consequently, severe inter-symbol interference (ISI) emerges and the system bit error rate (BER) performance will be degraded [2]. Orthogonal frequency division multiplexing (OFDM) has been widely adopted in indoor VLC [3]. The distortion caused by a linear multi-path dispersive channel can be corrected by simply using a “single-tap” equalizer in the frequency domain [4]. However, intermittent training sequences are required to estimate the real-time VLC channel, but at the cost of reduced efficiency and increased system work load. Recently, indoor positioning systems (IPSs) based on techniques such as cellular have become an intriguing alternative to the Global Positioning System (GPS) [5]. IPSs adopting LEDs have gained extensive attention due to its low cost and higher accuracy [6]. Therefore, it is easy for a mobile VLC receiver (Rx) terminal to get its real-time accurate indoor location. In this paper, we propose a novel equalization concept for OFDM VLC, called location-based equalization (LBE), to counteract OFDM multi-path effects in the frequency domain. The Rx location is utilized to estimate the VLC multi-path channel. Especially, the dominant line-of-sight (LOS) channel can be estimated. As a result, the single-tap equalizer parameters used for OFDM subcarrier channels can be calculated according to Rx coordinates. Different implementation schemes are compared. Results verify the effectiveness of the proposed LBE method under indoor multi-path channel conditions.

2. Proposed LBE for OFDM VLC

In VLC systems, optical OFDM signals propagate from LED Txs to the Rx via two main channels: the LOS and non-LOS channel (NLOS), respectively [1]. The total channel impulse response (CIR) can be simply written as:

$$h_{total}(t) = h_{LOS}(t) + h_{NLOS}(t) = \sum_{i=1}^{N_{LED}} \left[H_{i,LOS}(0)\,\delta\left(t-\tau_{i,LOS}\right) + \int_{wall} dH_{i,NLOS}(0)\,\delta\left(t - d\tau_{i,NLOS}\right) \right], \tag{1}$$

where N_{LED} is the total Tx number, $H_i(0)$ is the channel DC gain, and τ_i is the time delay of the optical signal from the ith Tx, respectively. Previous works have revealed that the NLOS components result from indoor reflections are so faint compared with the LOS components [2]. Considering the dominant LOS contributions only, the VLC total CIR can be simply modeled by Dirac pulses, whose frequency-domain transfer function (FDTF) is written as [1]:

$$\hat{H}_{total}(f) \approx H_{LOS}(f) = \sum_{i=1}^{N_{LED}} H_{i,LOS}(0)\exp\left(-j2\pi f \tau_{i,LOS}\right) = \sum_{i=1}^{N_{LED}} \frac{(m+1)a_R \cos^m(\phi_i) T_s(\theta_i) g(\theta_i)\cos(\theta_i)\,\mathrm{Rect}(\theta_i/\psi_c)}{2\pi D_i^2} \exp\left(\frac{-j2\pi f D_i}{c}\right), \tag{2}$$

where m is the LED Lambertian coefficient, a_R is the photo-detector area, ϕ_i is the angle of irradiance, θ_i is the angle of incidence, T_s is the gain of an optical filter, g is the gain of an optical concentrator, ψ_c is the Rx filed-of-view, D_i is the distance between the Rx and the ith Tx, c is the velocity of light, respectively. From Eq. (2), as long as the indoor coordinates of the mobile Rx are obtained by means of IPS, the LOS channel can be theoretically fixed and approximately calculable. Due to the dominant role of the LOS components in the total collected light at the Rx, the estimated LOS channel can be seen as a close estimation of the total multi-path channel. These results can be further utilized to equalize the total VLC signals. Conventionally, in order to restore OFDM signal, zero-forcing schemes using a “single-tap” equalizer apply the inverse of the channel frequency response to the received signal [7]. Therefore, the equalizer FDTF can be theoretically designed as: $H_{EQ1}(f)=1/H_{LOS}(f)$. Assuming the coordinates of the ith Tx to be (x_{ti}, y_{ti}, z_{ti}), the relationship between the Rx coordinates (x_r, y_r, z_r) and $H_{LOS}(f)$ can be established via:

$$D_i = \sqrt{\left(x_r - x_{ti}\right)^2 + \left(y_r - y_{ti}\right)^2 + \left(z_r - z_{ti}\right)^2},\ \theta_i = \phi_i = arccos\left[\left(z_r - z_{ti}\right)/D_i\right]. \tag{3}$$

From the above, $H_{EQ1}(f)$ can be directly calculated according to the Rx coordinates, thus the *location-based equalization* concept as shown in Fig. 1, together with the indoor VLC system configuration.

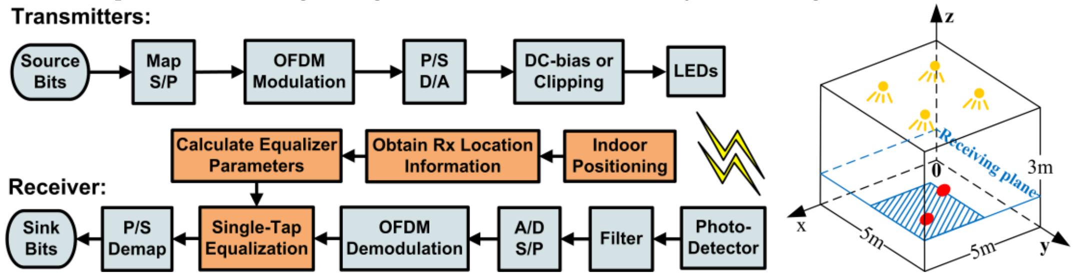

Fig. 1. Block diagram of the LBE scheme for OFDM VLC systems, together with the indoor VLC configuration.

Actually, $H_{EQ1}(f)$ depends on many factors, including the LED radiation pattern and the Rx configuration parameters. Among these factors, the distance D_i between the Tx and Rx plays the most significant role because it determines the attenuation and delay of the received signals from multi-paths. Specifically, $H_i(0)$ is inversely proportional to the power of D_i and τ_i can be denoted by D_i/c. Moreover, it may be difficult for the Rx to know all the system parameters. Therefore, from the point of view of system implementation, we propose to approximately calculate the LOS channel only based on D_i. Accordingly, the equalizer FDTF in terms of D_i can be designed as:

$$H_{EQ2}(f) = 1\Big/\left[\sum_{i=1}^{N_{LED}} \exp\left(-j2\pi fD_i/c\right)/D_i^2\right]. \tag{4}$$

Note that both the Tx irradiance angle and Rx incidence angle in $H_i(0)$ are also related to the coordinates. More priori knowledge of the VLC system parameters can surely derive a more accurate LOS channel. However, by simply adopting Eq. (4) as a close estimation of the real channel, the equalizer is assumed to roughly match with the VLC multi-path channel. Then we can utilize it to equalize the total received signals, including the weak NLOS components. In practical application, we can also adopt a fast equalization process based on look-up table. The equalizer parameters used at different indoor locations can be calculated in advance and stored in the look-up table together with corresponding Rx coordinates. In this way there is no need to calculate the equalizer parameters in real time, which reduces the work load of the mobile Rx terminal. By establishing the look-up table, the precision of VLC channel estimation can be further improved if the equalizer FDTF is designed and pre-stored according to: $H_{EQ3}(f)=1/H_{total}(f)$. By conducting time-frequency transform, $H_{total}(f)$ can be calculated from Eq. (1), meanwhile by using the deterministic algorithm in [8]. Considering more times of reflections will surely result in a more accurate $H_{EQ3}(f)$ for channel equalization, but at the cost of extra complexity in advance of actual data transmission. Here we only consider the 1st reflection to pre-calculate $H_{EQ3}(f)$, with the trade-off to be discussed in the future work.

3. Simulation results and discussions

The proposed LBE schemes based on $H_{EQ1}(f)$, $H_{EQ2}(f)$, and $H_{EQ3}(f)$ are evaluated and compared, respectively. Due to the symmetrical properties, we only consider one quarter of the receiving plane, as shown in Fig. 1, where the Rx is assumed to locate at different locations of (4,4,0.85) (corner) and (2.5,3,0.85) (near centre), respectively. Due to its significance, the 1st indoor reflections are currently considered in the VLC multi-path channel as a proof-of-concept. Without loss of generality, DCO-OFDM with 64-point IFFT is adopted. QPSK symbols are employed in all data subcarrier channels and the total bit rate is ~194 Mbps. Table 1 provides some primary simulation parameters.

TABLE I. SIMULATION PARAMETERS

Locations of LED Txs	(1,1,3) (1,4,3) (4,1,3) (4,4,3)	Reflection coefficients of walls/ceiling/floor	0.83/0.4/0.63
Modulation index	0.1	Physical area of photo-detector	10^{-4} m^2
Tx's Lambertian emission order	1	Room size (length × width × height)	5 m × 5 m × 3 m
Rx's field of view	170 deg.	Responsivity of photo-detector	0.54 A/W

All LED Txs transmit the same OFDM signal simuteneously and we assume the Rx is synchronized with the first arrived LOS path. As shown in Figs. 2 and 3, the normalized amplitude and the phase of the estimated channel FDTF in $H_{EQ1}(f)$ match well with that of the real channel (assumed as $H_{EQ3}(f)$), respectively, at both corner and near centre locations. Specifically, $H_{EQ1}(f)$ in the near centre is much closer to $H_{EQ3}(f)$ than that in the corner. This is because the NLOS components due to indoor reflections are much weaker at the centre location, thus having less impact on calculating $H_{EQ1}(f)$ for channel estimation. Therefore, simple taking the LOS link as a close estimation of the real multi-path channel is reasonable. For $H_{EQ2}(f)$, we can also observe it matches well with $H_{EQ3}(f)$ in the near centre, like $H_{EQ1}(f)$. However, in the corner the estimation accuracy will be affected. The estimation error mainly comes from the Tx irradiance angle and Rx incidence angle, because we did not consider them in $H_{EQ2}(f)$ at all.

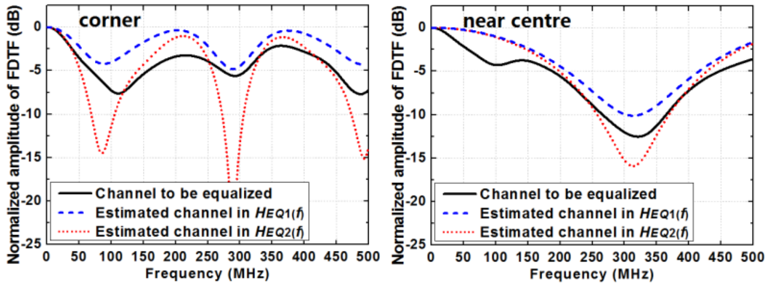

Fig. 2. Comparison for the amplitude of the estimated VLC channel FDTF at locations of: (4,4,0.85) (left) and (2.5,3,0.85) (right), respectively.

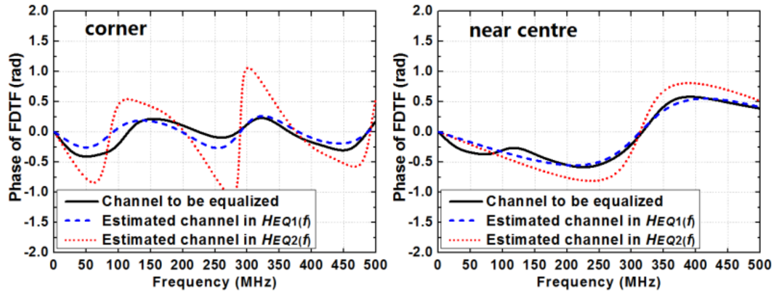

Fig. 3. Comparison for the phase of the estimated VLC channel FDTF at locations of: (4,4,0.85) (left) and (2.5,3,0.85) (right), respectively.

Via Monte-Carlo simulations, Fig. 4 compares the BER performance with and without adopting the LBE schemes, respectively. In the corner, the BER performance without equalization is better than that in the near centre, because the LOS multi-path interference to the first arrived OFDM LOS signal path is relatively smaller. All types of location-based equalizer show similar performance. E.g., compared with the scenario without equalization, adopting $H_{EQ1}(f)$, $H_{EQ2}(f)$, and $H_{EQ3}(f)$ can result in a signal-noise ratio (SNR) improvement of ~2.0 dB, 1.4 dB and 2.6 dB, respectively, at a BER of 10^{-3}. Due to lower complexity, $H_{EQ1}(f)$ and $H_{EQ2}(f)$, where only the LOS link is involved, are preferred. In the near centre, the LOS multi-path interference gets stronger because D_i from multiple Txs are closer. Adopting $H_{EQ1}(f)$, $H_{EQ2}(f)$, and $H_{EQ3}(f)$ results in a SNR improvement of ~8.8 dB, 5.0 dB and 8.9 dB, respectively, at a BER of 10^{-3}. The performance based on $H_{EQ1}(f)$ and $H_{EQ3}(f)$ are very similar, because the NLOS components are so weak here that we can simply ignore them when designing the equalizer. Therefore, adopting $H_{EQ1}(f)$ can effectively achieve a significant improvement while maintaining an acceptable system complexity.

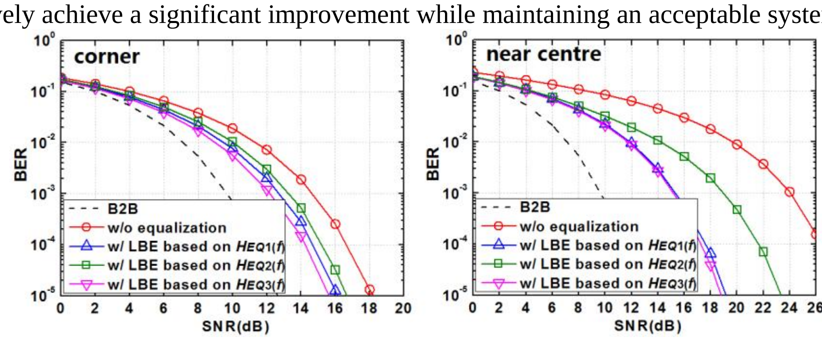

Fig. 4. BER performance comparison w/ and w/o LBE at locations of: (4,4,0.85) (left) and (2.5,3,0.85) (right), respectively.

4. Conclusion

In indoor OFDM VLC, we have proposed a novel LBE scheme by utilizing the Rx indoor coordinates for equalization. The LBE design, especially based on only a LOS link, can effectively alleviate OFDM multi-path effects with a SNR improvement to be ~2.0 dB and 8.8 dB in the corner and near centre locations, respectively, for a BER of 10^{-3}. Results also reveal that futuristic VLC systems can benefit from cooperation with IPSs.

5. References

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