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Characteristics of an Ideal Location-based Zero-forcing Equalizer in Indoor Visible Light Communication Systems

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***Abstract*—In this paper, we propose to design an ideal location-based zero-forcing equalizer (LB-ZFE) to counteract the multi-path effects in indoor visible light communication systems. The proposed ZFE is assumed to match the line-of-sight signal components perfectly. The analytical signal-to-noise ratios (SNRs) of the output electrical signal with and without the LB-ZFE are derived, respectively. Results show an SNR improvement by adopting the LB-ZFE and also indicate a bandwidth limitation in the partial indoor area when the data rate reaches hundreds of Mbps.**

***Index Terms*—Visible light communication; visible light positioning; zero-forcing; location; equalization.**

I. Introduction

Visible light communication (VLC) using light emitting diodes (LEDs) is popular due to its dual function of illumination and communication [1−3]. Optical signals propagate from LED transmitters (Txs) to the receiver (Rx) via two main channels: the line-of-sight (LOS) channel and the diffuse channel, respectively [2]. The optical path differences from multiple LED lamps and indoor reflections from walls and other objects will cause a time dispersion of received signals. This means that, at the Rx the same transmitted data signals will be superimposed at different time delay and attenuation. This multi-path dispersion will result in severe inter-symbol interference (ISI) and consequently degrade the VLC system performance [3]. In conventional infrared (IR) wireless systems, the zero-forcing decision feedback equalizer was applied to mitigate the ISI effects with the knowledge of pre-measured IR channel at the Rx [4]. For indoor mobile VLC systems, very few papers have investigated the channel equalization schemes. In [5] an adaptive equalization method was adopted to track the time-varying VLC channel with intermittent training sequences and complicated adaptive algorithms. Orthogonal frequency division multiplexing (OFDM) can be also adopted for channel equalization, but at the cost of reduced efficiency due to its long guard interval [6].

Recently, for indoor environments, the Global Positioning System (GPS) is not applicable since a satellite signal suffers from severe attenuation when passing though solid walls [7]. Indoor positioning systems (IPSs) based on cellular, radio frequency identification (RFID), Bluetooth, etc., have been an intriguing alternative to the GPS and provide users with location-based services [8]. Specifically, the VLC-based IPS adopting LEDs has gained extensive attention due to its low cost and higher accuracy [9,10]. Several algorithms were proposed to calculate the Rx coordinates, where specialized data signals are carefully designed and transmitted to facilitate the Rx to distinguish individual signals coming from different LEDs so as to increase the positioning accuracy [11,12]. Therefore, it is easy for a mobile VLC Rx terminal to get its real-time indoor location. In this paper, according to the Rx coordinates obtained by means of IPS, we propose to design an ideal location-based zero-forcing equalizer (LB-ZFE) at the Rx. The LB-ZFE is basically assumed to counteract the multi-path effects of the LOS signal components from different LED lamps perfectly. The performance of the LB-ZFE in terms of signal-to-noise ratio (SNR) will also be evaluated.

II. Principle of the Proposed LB-ZFE

Considering the dominant LOS contributions only, the VLC channel response can be modeled by Dirac pulses [1]. Therefore, the frequency-domain transfer function (FDTF) of the LOS channel can be written as [1]:

$$H(f)=\sum_{i=1}^{N_{LED}}\frac{(m+1)a_R\cos^m(\phi_i)T_s(\theta_i)g(\theta_i)\cos(\theta_i)\mathrm{Rect}(\theta_i/\psi_c)}{2\pi D_i^2}\exp(\frac{-j2\pi f D_i}{c}), \quad (1)$$

where N_{LED} is the total Tx number, 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. Conventional zero-forcing equalization schemes apply the inverse of the channel frequency response to the received signal, in order to restore the signal after the channel [13]. Therefore, for the indoor VLC system, the FDTF of the ideal LB-ZFE should also be designed as:

$$H_{EQ}(f)=1/H(f). \quad (2)$$

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 $H_{EQ}(f)$ can be therefore established via:

TABLE I. SIMULATION PARAMETERS

Room size (length × width × height)	5 m × 5 m × 3 m
Locations of LED Txs	(1.5,1.5,3) (1.5,3.5,3) (3.5,1.5,3) (3.5,3.5,3)
Height of receiving plane	0.85 m
Transmit Power of Each Tx	5 W (20 W in Fig. 5(d))
Modulation index	0.1
Reflection coefficients of walls/ceiling/floor	0.83/0.4/0.63
Txs' semi-angle at half power	60 deg.
Physical area of photo-detector	10^{-4} m^2
Rx's field of view	85 deg.
Responsivity of photo-detector	0.54 A/W
Gain of optical concentrator	1
Refractive index of optical concentrator	1.5

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

From the above, the FDTF of the LB-ZFE in Eq. (2) can be directly calculated according to the Rx coordinates obtained by means of IPS, thus the *location-based zero-forcing* concept.

The VLC channel model can be expressed as [3]:

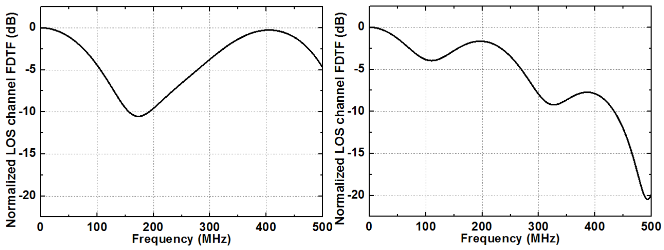
$$y(t) = r(t) + n(t) = \gamma x(t) \otimes h(t) + n(t), \quad (4)$$

where $y(t)$ is the total received current, $r(t)$ is the received signal current, γ is the responsivity of the photo-detector, $x(t)$ is the transmitted optical pulse, $h(t)$ is the VLC multi-path channel impulse response (CIR), $n(t)$ is the additive white Gaussian noise with the variance of σ^2, respectively. Note that the additive noise here mainly consists of the shot noise and thermal noise. In order to evaluate the system performance, we derive the analytical SNR of the output electrical signal at the Rx. For each transmitted symbol, we assume that all signals arriving at the Rx within the symbol period contribute to the signal components. We also assume that all signals arriving at the Rx residing outside the symbol period contribute to the noise components. Therefore, the analytical expression of the SNR without the LB-ZFE is derived, which can be written as:

$$SNR_{w/o} = \frac{\left[\frac{1}{T_b}\int_0^{T_b} r(t)\otimes f(t)dt\right]^2}{\sigma^2 + 0.5\left\{\frac{1}{T_b}\left[\int_{-\infty}^{0} r(t)\otimes f(t)dt + \int_{T_b}^{+\infty} r(t)\otimes f(t)dt\right]\right\}^2}. \quad (5)$$

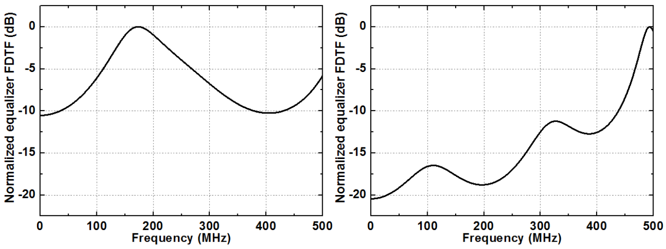
Here we adopt on-off-keying (OOK) signals of equal probability with rectangular transmitted pulses of a duration equal to the bit period T_b. This also explains the coefficient of 0.5 in the denominator. Besides, a receiver filter $f(t)$ with a rectangle spectrum is used to simulate the system bandwidth limitation and also equalize the received signal pulse. Next, by adopting the proposed LB-ZFE, the total received current will be equalized. Consequently, the analytical expression of the SNR with the LB-ZFE is derived, which can be written as:

$$SNR_{w/} = \frac{\left[\frac{1}{T_b}\int_0^{T_b} r(t)\otimes f(t)\otimes h_{EQ}(t)dt\right]^2}{\sigma^2\int_{-\infty}^{+\infty} h_{EQ}^2(t)dt + 0.5\left\{\frac{1}{T_b}\left[\int_{-\infty}^{0} r(t)\otimes f(t)\otimes h_{EQ}(t)dt + \int_{T_b}^{+\infty} r(t)\otimes f(t)\otimes h_{EQ}(t)dt\right]\right\}^2}, \quad (6)$$



(a) (b)

Figure 1. Normalized FDTF for the LOS channel at locations of: (a) (4.9,2.9,0.85) and (b) (3.5,3.5,0.85), respectively.



(a) (b)

Figure 2. Normalized FDTF for the proposed LB-ZFE at locations of: (a) (4.9,2.9,0.85) and (b) (3.5,3.5,0.85), respectively.

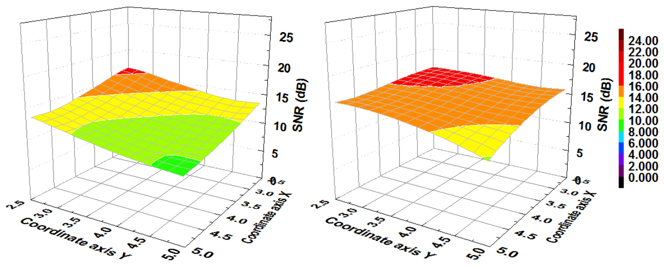
where $h_{EQ}(t)$ is the CIR of the proposed LB-ZFE. By conducting time-frequency transform, $h_{EQ}(t)$ can be simply derived from Eq. (2).

III. SIMULATION AND DISCUSSIONS

Table 1 provides the primary simulation parameters adopted in this paper. Due to its significance in the total received diffuse components, the 1st indoor reflections are considered as a proof of concept so as to evaluate the performance of the LB-ZFE. The scenario of multi-reflections will be investigated in the future work. Due to the indoor symmetrical properties, we only consider one quarter of the receiving plane. Figs. 1 and 2 show the normalized FDTF for the LOS channel and the ideal LB-ZFE at different locations of (4.9,2.9,0.85) and (3.5,3.5,0.85), respectively. It can be seen that the proposed equalizer completely applies the inverse of the channel FDTF, which is assumed to perfectly match the VLC LOS channel. However, this potentially induces the singularities of $H_{EQ}(f)$ during the demodulation process, which will amplify the term of the additive noise according to Eq. (6).

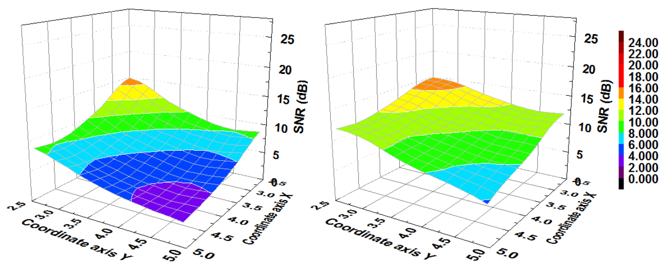
Figs. 3 and 4 show the comparison of the analytical SNRs at 100 and 200 Mbps, with and without the LB-ZFE, respectively. A significant SNR improvement can be achieved by adopting the LB-ZFE. Compared with the 100 Mbps case, reduced SNR performance can be also observed for 200 Mbps due to the reduced signal power and increased noise power.

Figs. 5 illustrate the difference values of the analytical SNRs with and without the LB-ZFE, respectively, at different data rates. For 200 Mbps, a SNR improvement can be observed at all locations, regardless of the existence of indoor reflections. Therefore, in this case, adopting an ideal LB-ZFE proves to be an effective solution to counteract multi-path induced ISI. However, the proposed ZFE will start to induce singularities of $H_{EQ}(f)$ at 400 Mbps. These singularities will



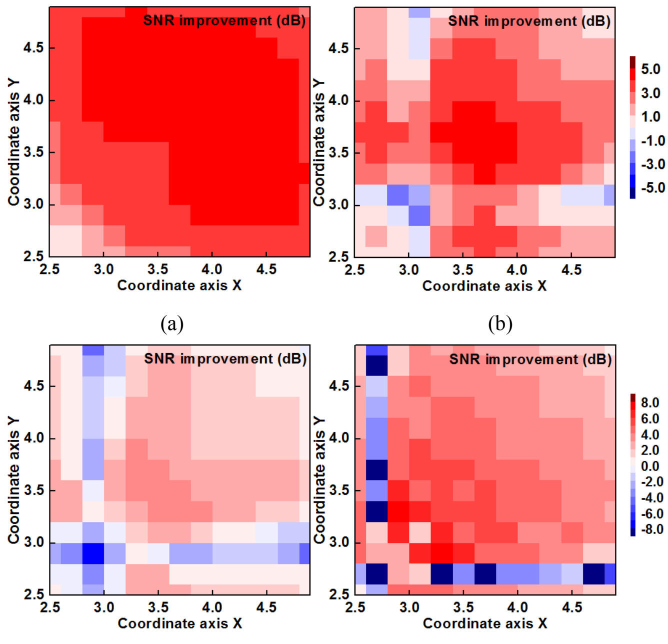
(a) (b)

Figure 3. Comparison of analytical SNRs at 100 Mbps: (a) w/o ZFE; (b) w/ ZFE. Only one quarter of the receiving plane is considered.



(a) (b)

Figure 4. Comparison of analytical SNRs at 200 Mbps: (a) w/o ZFE; (b) w/ ZFE. Only one quarter of the receiving plane is considered.



(a) (b) (c) (d)

Figure 5. Improvement of analytical SNRs at (a) 200 Mbps; (b) 400 Mbps; (c) 500 Mbps; and (d) 1 Gbps, respectively.

result in an enhancement of the additive noise in a VLC Rx, thus slightly reduce the SNR in the partial indoor area, as illustrated in blue. Despite this, a SNR improvement can be still achieved in most indoor area. For higher system data rates, the impact of singularities becomes more severe. For example, for a link at 1 Gbps, around 12.4% of the indoor area will experience a SNR degradation after adopting the proposed ZFE. This indicates a bandwidth limitation of the ideal LB-ZFE in the partial indoor area for the mobile VLC system.

IV. Conclusion

In indoor VLC systems, we have designed an ideal LB-ZFE to counteract the ISI caused by multi-path effects. The proposed ZFE is assumed to perfectly match the LOS signal components. Results showed a significant SNR improvement at different data rates. In the future work, we will investigate the methods to overcome the bandwidth limitation of the LB-ZFE in the partial indoor area for the mobile VLC system.

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