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Two-LED Indoor Visible Light Positioning Method Based on Channel Estimation with a Mirror

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Abstract: A simple two-LED VLP model with mirror is proposed. By observing channel characteristics, the distances from real and virtual LEDs to receiver are estimated respectively with TDM, thus facilitating indoor positioning with accuracy < 10cm.

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1. Introduction

Indoor visible light positioning (VLP) systems using LEDs have many advantages such as energy conservation, low implementation cost and high accuracy [1-3]. For conventional VLP, at least three LEDs with known locations are required for trilateration algorithms to locate the receivers [4]. However, it is not suitable for some scenarios with limited number of LED lamps, because more LED sources also mean higher cost for wiring and installation. Although multiple photo-detectors (PDs) and a single LED can be used for positioning, this will increase implementation complexity at terminals [5]. Also, in some indoor scenarios, there exist mirrors that could be utilized for positioning. Thus, in this work, we develop a new VLP model that replaces a wall by a mirror, which can reduce the number of required LEDs used for positioning. By observing the estimated channel frequency domain transfer function (FDTF) from LEDs and their mirror images to the receiver, respectively, the required information for indoor localization can be measured. Numerical results verify the feasibility of the proposed scheme.

2. Proposed Scheme

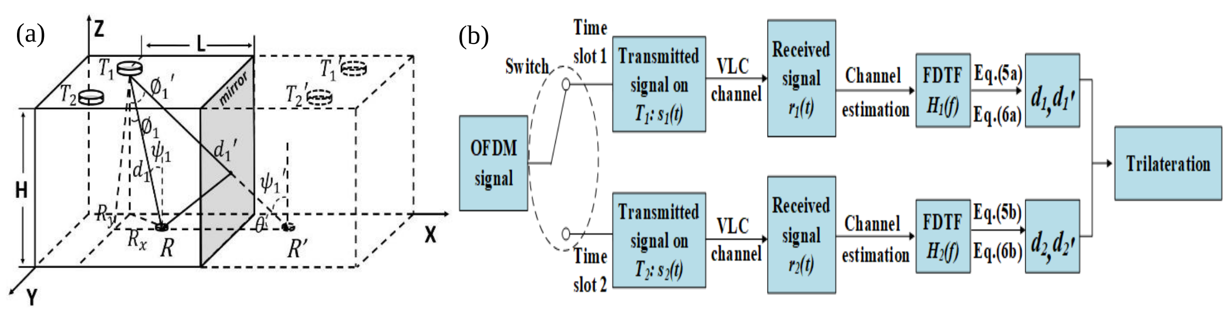

Fig.1. (a) Two-LED positioning model with mirror; and (b) block diagram of proposed positioning method.

As shown in Fig.1(a), in the proposed model, only two LEDs (T_i, i=1, 2) with a mirror are used for positioning. According to the principle of mirror imaging, T_1 and T_2 generate two virtual images (T_i', i=1, 2), respectively. T_1 and T_2 are turned on alternately based on time division multiplex (TDM). For example, when T_1 is modulated, the receiver (R) will receives multi-path signals coming from real and virtual image of T_1 simultaneously. According to optical wireless channel model [6], the received electrical signal is expressed as:

$$r(t) = \gamma s(t) \otimes h(t) + n(t), \quad (1)$$

where γ is the detector responsivity, $s(t)$ is transmitted OFDM signal, $h(t)$ is the channel impulse response (CIR), $n(t)$ is noise. If we assume perfect synchronization and ignore the noise, the CIR for T_1 and T_2 can be written as:

$$h_1(t) = H_{1\_real}(0)\delta(t) + H_{1\_image}(0)\delta(t - \Delta t_1), \quad (2a)$$

$$h_2(t) = H_{2\_real}(0)\delta(t) + H_{2\_image}(0)\delta(t - \Delta t_2), \quad (2b)$$

respectively, where $H_{i\_real}(0)$ and $H_{i\_image}(0)$ (i=1, 2) are channel DC gains for real and virtual transmitters, respectively. Here Δt_i (i=1, 2) is the optical time difference between T_i to R and T_i' to R, which is related to the optical path difference and can be represented as:

$$\Delta t_i = \frac{d_i' - d_i}{c} = \frac{\sqrt{R_y^2 + H^2 + (2L - R_x)^2} - \sqrt{R_y^2 + H^2 + R_x^2}}{c} (i = 1\ for\ LED1, i = 2\ for\ LED2). \quad (3)$$

Here, d_i and d_i' are the distances from real and virtual LEDs to receiver, R_x and R_y are the X- and Y- coordinates of receiver, H is the height of room, and L is the horizontal distance between LEDs and the mirror, respectively. After Fourier Transform, Eqs. 2 (a) and (b) are written as:

$$|H_1(f)| = \left|H_{1\_real}(0) + H_{1\_image}(0)e^{-j2\pi f\Delta t_1}\right|, \quad (4a)$$

$$|H_2(f)| = \left|H_{2\_real}(0) + H_{2\_image}(0)e^{-j2\pi f\Delta t_2}\right|. \quad (4b)$$

When $2\pi f\Delta t = k\pi$ (k is integer), $|H_i(f)|$ (i=1, 2) can reach its maximum or minimum value. Thus, we can obtain corresponding channel DC gains from LEDs or their mirror images to the receiver, respectively, according to:

$$H_{1\_real}(0) = \frac{|H_1(f)|_{max} + |H_1(f)|_{min}}{2}, H_{1\_image}(0) = \frac{|H_1(f)|_{max} - |H_1(f)|_{min}}{2}, \quad (5a)$$

$$H_{2\_real}(0) = \frac{|H_2(f)|_{max} + |H_2(f)|_{min}}{2}, H_{2\_image}(0) = \frac{|H_2(f)|_{max} - |H_2(f)|_{min}}{2}, \quad (5b)$$

where $|H_i(f)|_{max}$ and $|H_i(f)|_{min}$ are the maximum and minimum value of $|H_i(f)|$ (i=1, 2).

With calculated channel DC gains, the distance from each LED and its virtual image to receiver is given as [7]:

$$d_i = \sqrt{\frac{(m+1)A_r cos^m(\phi)T_s(\psi)g(\psi)\cos(\psi)}{2\pi H_{i\_real}(0)}}, i = 1, 2. \quad (6a)$$

$$d_i' = \sqrt{\frac{(m+1)A_r cos^m(\phi')T_s(\psi')g(\psi')\cos(\psi')}{2\pi H_{i\_image}(0)}}, i = 1, 2. \quad (6b)$$

respectively, where m is the order of Lambertian emission, A_r is the physical area of PD, ϕ is the angle of irradiance, ψ is the angle of incidence, $T_s(\psi)$ is the gain of an optical filter, $g(\psi)$ is the gain of an optical concentrator, respectively. Here Eq. 6(b) is for the case of mirror image.

Since the coordinates of LEDs and their mirror images are known, based on above d_i and d_i', the position of the receiver can be estimated by using trilateration algorithm. The block diagram of the proposed method is shown in Fig. 1(b). T_1 and T_2 alternately transmit OFDM training signals $s_1(t)$ and $s_2(t)$ via TDM. After passing through independent VLC channels, the receiver can obtain two signals $r_1(t)$ and $r_2(t)$, respectively. Then, by utilizing channel estimation, we can get FDTFs of both $H_1(f)$ and $H_2(f)$. Finally, at least three distances for trilateration algorithm can be measured to facilitate indoor VLP, with only two LED transmitters.

3. Results and Discussions

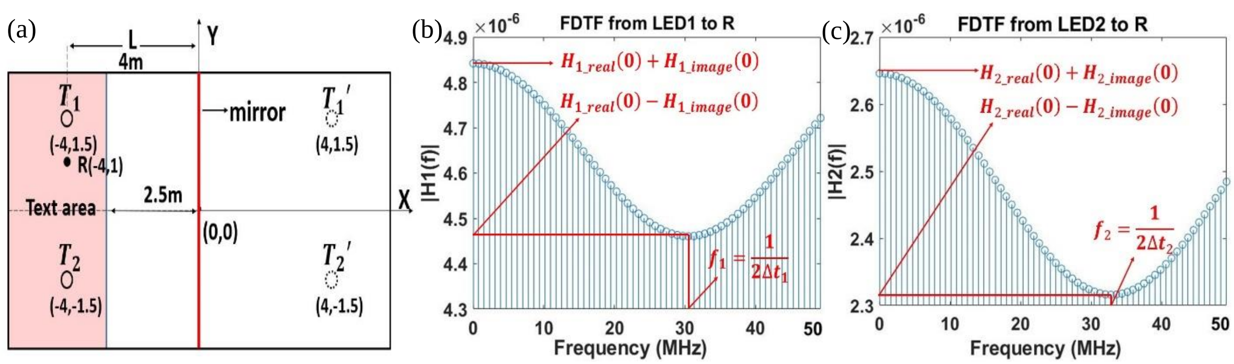

Fig. 2. (a) Bird view of positioning model; and FDTF from (b) T1 and (c) T2 to R (-4, 1, 0), respectively.

The room size is 5m × 5m × 4m (length × width × height) and L is set at 4m. The coordinates of LEDs and their mirror images are (-4, 1.5, 4), (4, 1.5, 4), (-4, -1.5, 4), and (4, -1.5, 4), respectively, shown in Fig. 2(a). We assume the receiver is on the floor and facing upward. The receiver is located at (-4, 1, 0) and we test the FDTF from T_1 and

T_2 to R without noise. As observed in Fig. 2(b) and 2(c), we can calculate the required channel DC gains for localization by testing the maximum and minimum value of FDTF as in Eqs. 5(a) and (b). It worth to mention when we measure the minimum value of FDTF using OFDM training symbols, there is a maximum quantization error related to subcarrier interval. This will somewhat lead to small positioning error. However, this problem could be alleviated by increasing the subcarrier number of each OFDM symbol or add a correction to tested results. In addition, from Fig. 2(b) and 2(c), to ensure that the minimum FDTF value is located within the observed spectrum, a large optical time difference $\Delta t_{\rm i}$ (i=1, 2) should be guaranteed. Thus, for proof-of-concept the boundary of the tested area is about 2.5m away from the mirror in our current setup.

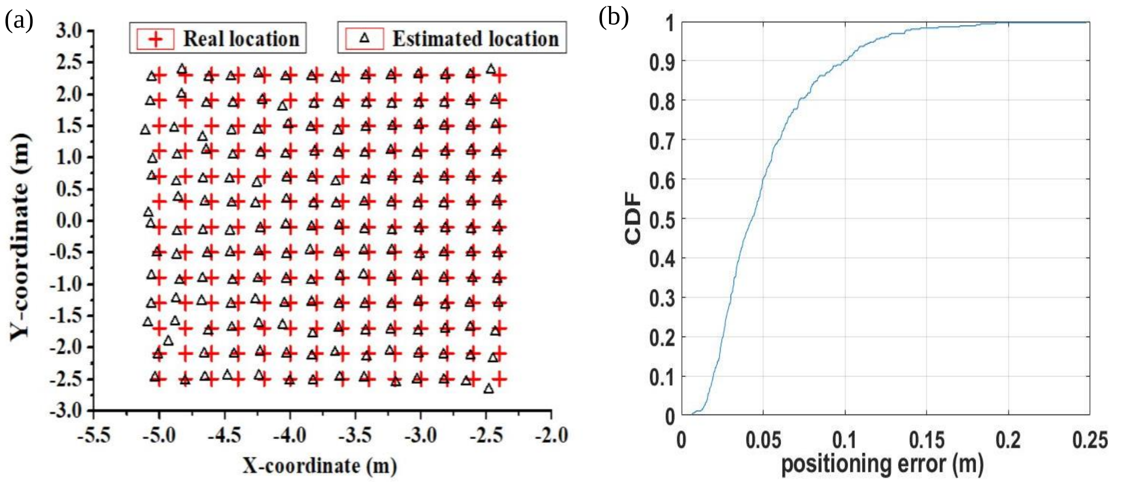

Fig. 3. (a) Indoor positioning results within tested area; and (b) The CDF of positioning error

As shown in Fig. 3(a), the positioning error decreases when the receiver is close to mirror. This is because that higher power of reflecting light can lead to better signal-to-noise ratio (SNR) in the area close to mirror. Thus, the estimation accuracy for $H_{1\_image}(0)$ and $H_{2\_image}(0)$ will improve. Also, if we increase LED power, the positioning accuracy for regions far from the mirror can be improved. In addition, most tested results are located at the left side of the real receiver location. This is due to the quantization error as discussed above. According to Fig. 3(b), the cumulative distribution function (CDF) for positioning error less than 10cm is about 90%, which proves the feasibility of the proposed method in scenarios with limited LED number or with a mirror.

4. Conclusions

We propose a novel two-LED positioning method with mirror, which can overcome the limitation of using at least three LEDs for conventional trilateration algorithms. The method can achieve reliable indoor VLP with location error < 10cm within 90% of the tested area.

5. Acknowledgment

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