Asychronous visible light positioning system using FDMA and ID techniques

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Abstract—**In this paper, an indoor localization system making use of LEDs, is proposed and demonstrated in the space of 100 cm × 118.5 cm × 128.7 cm. Different LED lamps transmitted signals with different central frequencies and the identities (IDs) of the transmitters are encoded on the envelopes of the transmitted signals. At the receiver side, the finite impulse response (FIR) filters are applied to discriminate the signals from different lamps. The IDs could be successfully decoded and the received signal strength (RSS) from each transmitter could be achieved. The experimental results show that the average positioning errors of x-scale and y-scale are 1.76 cm and 2.20 cm, respectively.**

Keywords-visible light positioning; hamming filter; frequency division multiple access; identity technique; received signal strength

I. INTRODUCTION

The light emitted diodes (LEDs) are revolutionizing the indoor illustration for its long lifespan, high tolerance to humidity and energy efficiency. Besides illumination, the LEDs are also available for data communication and localization service.

For the large indoor positioning environments such as super markets, hospitals and kindergartens, multiple LED lamps are employed for both illumination and positioning. In order to distinguish the signals from different lamps, various multiple access technologies have been proposed for the visible light positioning (VLP) system. Although time division multiple access (TDMA) [1] and dual tone multi-frequency (DTMF) [2] can achieve high accuracy positioning in practical experiment environments, both systems require strict synchronization between LEDs. Thus, it is necessary to build a backbone network. An asynchronous VLP system based on radio frequency (RF) carrier allocation technique is proposed in [3]. At the transmitter side, the ID information from three LEDs is modulated on different carrier frequencies while at the receiver side, a solar cell panel performs as a detector. However, the experimental results show that in the triangle with side length of 80 cm, more than 85% measurement results can only achieve 10 cm positioning accuracy. Maybe it is enough for guiding people. However, the positioning accuracy is not enough for guiding automatic robots. In our previous work [4], a positioning system based on visible light communication

using frequency division multiple access (FDMA) are proposed. However, it didn't use ID technique. Thus, if extending this method to larger planes, more frequencies are required to distinguish different transmitters, which wastes frequency sources and becomes difficult to design high-order filters at receiver side. In this article, an asynchronous indoor positioning system (IPS) with high accuracy, based on FDMA and ID techniques is proposed and demonstrated on the test-bed.

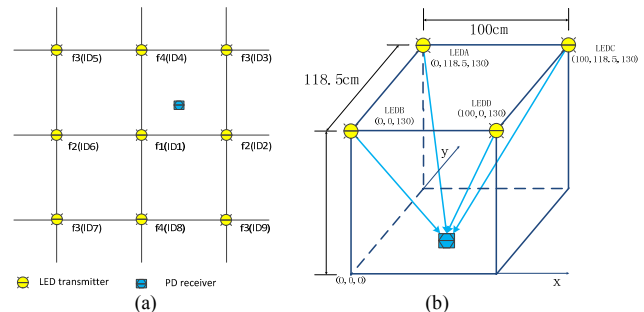## II. SYSTEM CONFIGURATION

Figure 1. Architecture of the proposed VLP system (a) center frequencies and IDs assignment (b) experimental set-up.

In Fig. 1, the proposed architecture of VLP system is depicted. In order to realize illumination as well as positioning in large indoor areas, multiple LEDs are involved. The whole positioning area could be divided into small unit cells. In each cell, four light sources with different carrier frequencies (f_1, f_2, f_3 and f_4) are included. Each LED will convey its ID information by modulating the IDs on the envelope of the transmitted signals. The distribution of carriers and ID arrangement is demonstrated in Fig. 1(a). The accurate positioning could be realized in two steps. Firstly, as the detector will receive the signals from nearest four LED transmitters simultaneously in any small unit cell, the detector could recognize in which unit cell it locates based on the demodulated ID signals. If the receiver moves to another unit cell, the detected IDs will be updated and thus the determined unit cell could be renewed accordingly. This step can help roughly determine the target's position. Secondly, after applying four finite impulse response (FIR) filters to the

received signal, the signal strength from different transmitters could be known. According to the power-distance relationship, the received signal strength (RSS) can be changed to the distance between the detector and LEDs. Then, trilateration method could be applied to compute the accurate location of the target.

Fig. 1(b) shows the experimental set-up to simulate conditions in a typical indoor positioning system. LED lamps (LEDA, LEDB, LEDC and LEDD) are mounted on the ceiling. The receiver (OSD-15E) is manufactured by Centronic, which is a photodiode (PD) with a wide field of view (FOV). To distinguish the signal from different lamps, we modulate four different carrier frequencies on the four LED transmitters. The experiments are carried out in a space within 118.5 cm × 100 cm × 130 cm. Signals from the four LED transmitters are collected by the receiver when it is moving on the test-bed. Then the four FIR filters are applied to the received signal to get the signal strengths from each lamp, which can be used to determine the distance between corresponding transmitter and the receiver. Then the location of the receiver can be calculated with the help of trilateration.

III. OPERATION PRINCIPLE OF POSITIONING

A. Design of the FIR Filters

In our experimental set-up, four carrier frequencies (12.5 kHz, 25 kHz, 50 kHz, and 100 kHz) are allocated to four LED lamps. Thus, four FIR filters are required to separate signals coming from different transmitters. Following is the steps to design the FIR filters.

- For the stopband attenuation (-50 dB) and transitional bandwidth (5 kHz) requirements are not very high, hamming filter can achieve such performance. Based on the stopband attenuation and transitional bandwidth, the filter order (N) can be calculated.

- The impulse response for hamming filter is $h(n) = h_d(n)w(n), n = 0, 1, 2, \cdots, N-1$, where,

$$h_d(n) = \frac{\sin\left((n-N)\times\omega_2\right) - \sin\left((n-N)\times\omega_1\right)}{(n-N)\pi}$$

and $w(n) = 0.54 - 0.46\cos(2n\pi)/(N-1)$. Here, ω_1 and ω_2 are corresponding to the upper and lower cut-off angular frequency, respectively.

- The signal through hamming filter can be represented as $y(n) = \sum_{k=0}^{N-1} h(k)x(n-k)$, where $x(n)$ is the input signal while $y(n)$ is the output signal.

B. Power-Distance Relationship

Assuming P_t as the power difference when transmitting logical 0s and 1s, the relationship between the power strength received by the PD and the transmitted light intensity could be

$$P_r^i = \frac{C}{d^2}\cos(\phi)\cos(\psi)^n P_t, i = 1, 2, 3, 4, \qquad (1)$$

where $n = 1.4738$ [4,5], ϕ is the angle of irradiance, ψ is the angle of incidence, C is a constant value, and d is the distance from the LEDs to the PD. Substitute the geometrical relationship $\cos(\phi) = \cos(\psi) = h/d$ into (1), and $P_r^i = \frac{Ch^{n+1}}{d^{n+3}}P_t$ is derived, where h is the vertical distance between the LED lamps to the receiver plane. Assume P_0^i is reference received power which is collected at the point just below each lamp with perpendicular distance of h . The relationship of normalized detected optical power versus distance can be represented as

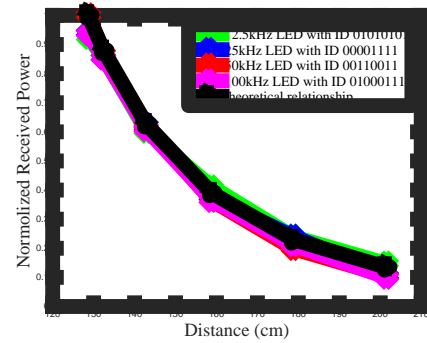$$P_r^i / P_0^i = \left(\frac{h}{d}\right)^{n+3}. \qquad (2)$$

Figure 2. The normalized power versus distance.

As shown in Fig. 2, the above mathematical model matches well with the experimental measurement results. Thus, if the received signal power from each transmitters can be known at receiver side, the distance from the lamp to the PD detector can be calculated. However, with the increase of the distance, the misalignment between the experimental results and the theoretical relationship becomes more obvious, as reflected in Fig. 2.

C. Trilateration

Once the distance between the receiver and each transmitter is measured, the target position can be further estimated. In order to reduce the computing complexity, we choose three in four distances to localization. As indicated in Fig. 2, for the LED has a relatively large distance to the receiving end, the distance estimation could become inaccurate. Therefore, the three LED signals with relatively large received power will be used for positioning as follows:

$$\begin{cases} (x_e - x_1)^2 + (y_e - y_1)^2 + (z_e - z_1)^2 = l_1^2 \\ (x_e - x_2)^2 + (y_e - y_2)^2 + (z_e - z_2)^2 = l_2^2 \\ (x_e - x_3)^2 + (y_e - y_3)^2 + (z_e - z_3)^2 = l_3^2 \end{cases} \qquad (3)$$

where x_i , y_i , and z_i ($i=1,2,3$) are the coordinates of three transmitters with larger RSS and shorter distance. l_1, l_2 and l_3 are the line of sight (LOS) distances from the lamps to the PD. In this work, we will discuss two-dimensional (2-D)

positioning only. Thus, z_e is set as 0 for convenience. Besides, $z_1 = z_2 = z_3 = h$, for the height of each light is assumed the same. In this case, the least square solution provides a standard approach to approximate solution of the VLP system. By subtracting the second and third equations from the first in (3), the estimated position (x_e, y_e) can be calculated. If the equation is rewritten into a matrix $AX = B$, A, X, and B can be illustrated as

$$A = \begin{bmatrix} x_2 - x_1 & y_2 - y_1 \\ x_3 - x_1 & y_3 - y_1 \end{bmatrix} \tag{4}$$

$$X = \begin{bmatrix} x_e \\ y_e \end{bmatrix} \tag{5}$$

and

$$B = \frac{1}{2} \begin{bmatrix} l_1^2 - l_2^2 + x_2^2 + y_2^2 - x_1^2 - y_1^2 \\ l_1^2 - l_3^2 + x_3^2 + y_3^2 - x_1^2 - y_1^2 \end{bmatrix}. \tag{6}$$

IV. EXPERIMENTS RESULTS AND DISCUSSION

The Cartesian coordinate system is set up in Fig. 1(b) to quantitatively investigate the positioning performance of the system. The LED lamps' coordinates, carrier frequency and ID assignments are listed in Table1. The length of the test-bed is 100 cm while the width is 118.5 cm.

TABLE I. LEDS ASSIGNMENTS

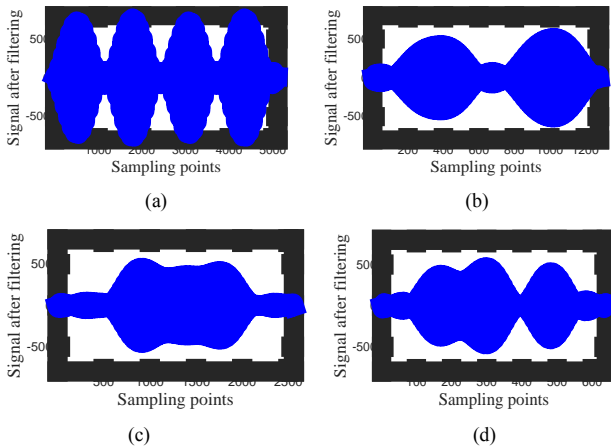| LED Name	Carrier Frequencies	IDs	Coordinate
LEDA	100 kHz	01000111	(100,0,130)
LEDB	12.5 kHz	01010101	(0,118.5,130)
LEDC	25 kHz	00001111	(100,118.5,130)
LEDD	50 kHz	00110011	(0,0,130)

Figure 3. The received signals after FIR filters at (40,71.1). Recoginized signal from (a) LEDA (b) LEDB (c) LEDC (d) LEDD.

First step is to obtain the ID of each transmitter. The experimental results show that the IDs of four LED lamps could recognize their IDs correctly at the receiving end. An example is given in Fig. 3. From the envelope of the filtered signals, the IDs of the transmitters can be determined accordingly, which matches with the IDs assigned to each lamp. Then, in second step, the receiver is moving around on the test-bed. After applying trilateration method, the accurate estimated position coordinates could be achieved. Comparing the calculated position with its real coordinate, the x-direction and y-direction positioning error is shown in Fig. 4(a) and Fig.4 (b), respectively. Compared with the dot chain lines, which represents the real coordinates, the maximum positioning errors of coordinate x and y are 4.00 cm and 6.36 cm and the corresponding average localization error are 1.76 cm and 2.20 cm, respectively. The disagreements between the estimated points and the accurate locations are shown in Fig. 5. Compared with the results in [4], the positioning error becomes a little larger. Because with IDs added, it is more difficult to measure the amplitude of the transmitted signal accurately. However, the results are acceptable since the average positioning error is still around 3 cm, which is tolerable for most of the indoor positioning applications.
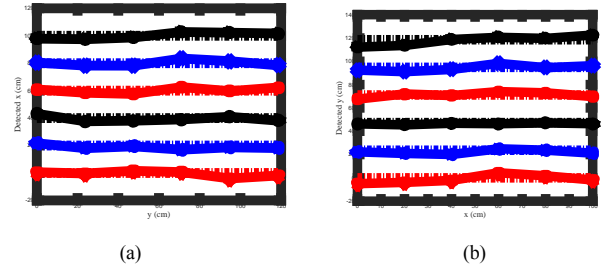

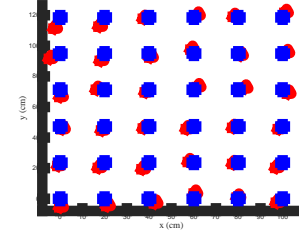Figure 4. Experimental results of estimated distance error of (a) coordinate x (b) coordinate y.

Figure 5. The estimated positions are represented by red triangles while the real positions are represented by blue crosses.

V. CONCLUSION

An indoor positioning system making use of the visible light is proposed in this paper. At the transmitter side, we modulated the identities of LEDs on the envelope of the transmitted signals and each LED lamp is assigned a carrier frequency. At the receiver side, Hamming filters are applied to the received signal. The ID of each lamp can be successfully decoded. The received signal strength could be transferred to the distance based on the power-distance relationship, and then used for trilateration method. Thus, the accurate location

information of the detector could be achieved. The average positioning error is around 3 cm. The proposed localization strategy is promising to be used in large indoor positioning environments.

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