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Demonstration of a Low-Complexity Indoor Visible Light Positioning System Using an Enhanced TDOA Scheme

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Abstract: In this paper, a low-complexity time-difference-of-arrival (TDOA) based indoor visible light positioning (VLP) system using an enhanced practical localization scheme based on cross correlation is proposed and experimentally demonstrated. The proposed TDOA scheme offers two advantages: 1) the use of virtual local oscillator to replace the real local oscillator for cross correlation at the receiver side so as to reduce the hardware complexity; 2) the application of cubic spline interpolation on the correlation function to reduce the rigorous requirement on the sampling rate and to enhance the time-resolution of cross correlation. In order to achieve the high positioning accuracy with minimum implementation complexity, parameter optimization is first performed in terms of sampling rate, interpolation factor, and data length for correlation. Using the obtained optimal parameters, we demonstrate a low-complexity indoor two-dimensional VLP system using the correlation-based TDOA scheme in a coverage area of 1.2 $\times$ 1.2 m^2 with a height of 2 m. The experimental results validate the feasibility of the proposed TDOA scheme, and an average positioning accuracy of 9.2 cm is achieved with a sampling rate of 500 MSa/s, an interpolation factor of 100 and a data length of 250 k samples.

Index Terms: Visible light communication (VLC), visible light positioning (VLP), time difference of arrival (TDOA), cross-correlation.

1. Introduction

In recent years, visible light positioning (VLP) becomes more and more promising in the scenario of indoor positioning services as the LED lighting infrastructure is blooming worldwide [1], [2]. Indoor VLP technique enjoys many advantages over other techniques such as Wi-Fi and UWB, including low cost of transmitter, less multipath effect due to the inherent characteristic of line-of-sight transmission, and great potential of higher bandwidth usage [2], [3]. Apart from that, VLP can be a reasonable alternative to those RF-based positioning systems in some RF prohibited areas such as hospitals, aircraft cabins and oil plants. Most of researchers resort to received-signal-strength (RSS) schemes [4], [5], angle-of-arrival (AOA) approaches or imaging sensor based methods

[6]–[8], and time-of-arrival (TOA) methods or time-difference-of-arrival (TDOA) approaches [9], [10]. Among those various means, RSS cannot achieve high accuracy without fitting or tedious offline preparation [4], [5], while the accuracy of VLP using AOA or imaging sensor highly relies on the complexity of the hardware [6], [8]. Therefore, TDOA based VLP is relatively more cost-effective, considering the ease of usage and the complexity of hardware.

In 2014, Do and Yoo proposed a fundamental VLP scheme using cross-correlation [10], which was an effective TDOA scheme compared with those involving phase calculation which is so called phase-of-arrival method [11]. However, it is challenging in terms of practical implementation, so the relevant experimental demonstration has never been reported since then. Considering the practical realization, there are two major drawbacks of the previous proposition. Firstly, it needs a synchronized real local oscillator (RLO) at the receiver side like the one deployed in GPS receivers to calculate the TDOA value which is complicated and expensive for indoor positioning applications [12]. What is worse, common approach for such a system is based on cross correlation which relies on an expensive high-speed analog-to-digital converter (ADC) [9], and hence it further hinders the implementation.

In this paper, we propose and demonstrate a practical VLP system using cross-correlation based TDOA scheme to address the drawbacks mentioned above. The proposed system adopts the TDOA measurement scheme by means of cross-correlation armed with the cubic spline interpolation [13]. Also, the local signal for cross-correlation is proposed to be digitally generated by a virtual local oscillator (VLO) inside software, hence achieving the modest requirement on ADC. To further save resources consumption as much as possible while maintaining the system performance, optimization on the relevant parameters such as the data length for correlation and the interpolation factor is conducted. The proposed system is realized and verified experimentally. To the best of our knowledge, this is the first experimental demonstration of the VLP system using cross-correlation based TDOA scheme. The average positioning accuracy of the VLP system utilizing the proposed scheme is less than 10 cm in a coverage area of 1.2×1.2 m^2 with the sampling rate of the digitizer no more than 500 MSa/s. Overall, the proposed system is proved to provide good positioning accuracy while offering the advantages of lower complexity and lower cost compared with the previous propositions, by getting rid of RLO components and reducing the requirement on the sampling rate of digitizer.

The rest of our paper is organized as follows. In Section 2, the proposed VLP system is presented and the adopted TDOA scheme based on cross-correlation is introduced. The proof-of-concept VLP system is realized and demonstrated in Section 3, where the system details are described. The optimal parameters for digitization and interpolation are experimentally determined. The localization performance is further demonstrated. Finally, Section 4 gives the summary.

2. Principle

2.1 System Overview

The proposed VLP system using the enhanced TDOA scheme is depicted in Fig. 1. For simplicity and without loss of generality, two-dimension (2D) positioning is specifically discussed herein. It is not substantially different from three-dimension (3D) VLP positioning, and the only difference is that one more LED with another carrier frequency is required. At the transmitter side, synchronized carrier waves in all channels are initially generated from a signal generator, e.g. an arbitrary waveform generator (AWG), and amplified by current boosters. Each individual LED is direct current (DC) biased and electrically driven by the corresponding amplified carrier. The receiver consists of an avalanche photodetector (APD) and a localization module. The APD receives the mixed signal of different radio frequencies (RFs) radiated by all LED transmitters through free space, which is then fed to the localization module. The window of the APD is covered by an optical blue filter to remove the slow florescent component from the modulated signal. As shown in Fig. 1, the localization module operates in three steps: 1) TDOA measurement using cross-correlation between the RF

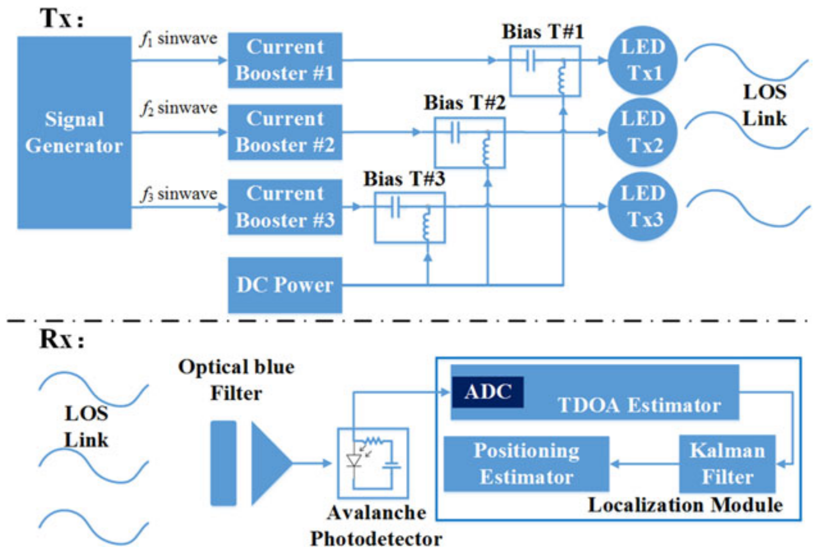

Fig. 1. Schematic of the VLP system using the enhanced TDOA scheme

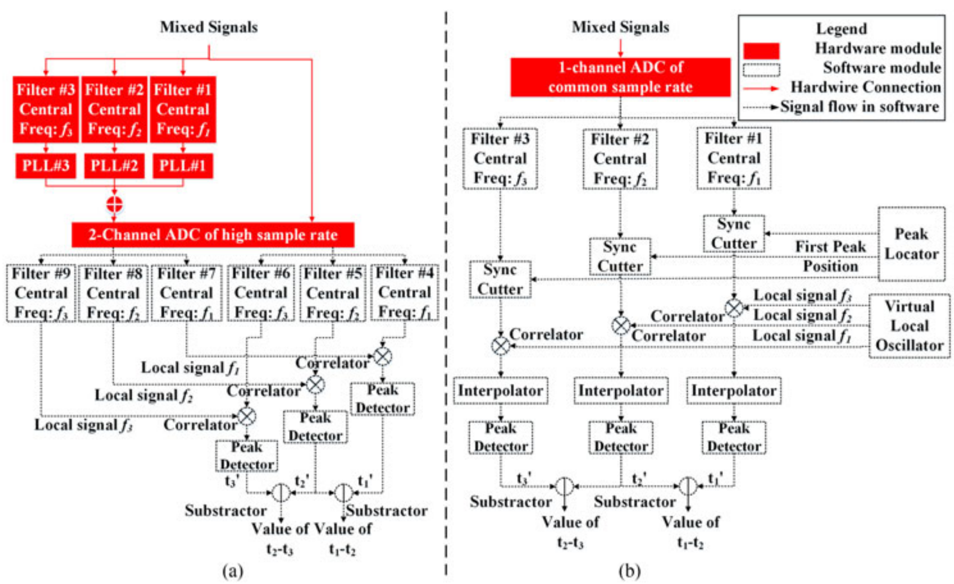

Fig. 2. Diagram of the proposed TDOA estimator in comparison with the conventional one.

carriers in the enhanced TDOA estimator, 2) error minimization based on Kalman filtering and 3) position estimation in the trilateration-based positioning estimator.

Above all, the TDOA values are measured by means of cross-correlation between the received RF carriers. It is realized by the TDOA estimator which is the core of the system. The principle of TDOA estimator is described herein by introducing the conventional TDOA estimator. As in Fig. 2(a), the conventional TDOA estimator borrows the design of GPS receiver, consisting of phase locking loop (PLL) circuits, filters, ADCs, correlators, peak detectors and subtractors [12], [14]. Traditionally, PLL circuits track the received RF carriers and generate phase-locked local carriers as reference signals for the following cross-correlation. Then, the mixed received signals and reference signals are digitized by the ADC and split by the corresponding narrow bandpass filters (see Filters #4–#9 in Fig. 2(a)) into individual RF carrier signals, respectively. Denote the RF carrier from the i-th LED as the discrete sequence $R_i(m)$, and the corresponding local RF carrier as the another discrete sequence $L_i(m)$. The cross-correlation between those two sequences is subsequently performed, and the correlation result is given by

$$Rlr_i(n) = \sum_{m=-\infty}^{\infty} L_i(m) \cdot R_i(m+n), \tag{1}$$

where n is the displacement of $L_i(m)$ relative to $R_i(m)$. With the help of peak detectors, the location of the peak of the cross-correlation function $Rlr_i(n)$ is determined. It is equal to the relative time difference between the i-th RF carrier from the i-th LED and the local signal, denoted as t_i' given by

$$t_i' = (1/\text{Sp}) \cdot \underset{n}{\text{argmax}}\,(Rlr_i(n)), \tag{2}$$

where Sp is the sampling rate of those discrete sequences. Theoretically, t_i' can also be written as

$$t_i' = t_i + t_{PR}, \tag{3}$$

where t_i is referred to as the time-of-flight (TOF) from the i-th LED to the receiver, t_{PR} represents the unknown initial phase difference between the received RF carrier and the local RF carrier, which is similar to the ideal pseudo-range (PR) in the GPS system. If the RF carriers irradiated from all LEDs are both synchronized to each other and synchronized to the local RF carriers, t_{PR} is expected to be the same for all the outputs of peak detectors. Hence, t_{PR} can be cancelled mutually through calculating the time difference [12]. Consequently, combining (2) and (3), the estimated $TDOA_i$, i.e., the difference of TOF from the (i+1)-th LED and the i-th LED to the receiver, can be obtained by subtracting t_{i+1} from t_i as in

$$\begin{aligned} \text{TDOA}_i &= t_{i+1} - t_i \\ &= (t_{i+1} + t_{PR}) - (t_i + t_{PR}) \\ &= (1/\text{Sp}) \cdot (\underset{n}{\text{argmax}}\,(Rlr_{i+1}(n)) - \underset{n}{\text{argmax}}\,(Rlr_i(n))). \end{aligned} \tag{4}$$

The second stage is to minimize the fluctuation of the estimated TDOA values. Herein, we apply a same design of extended Kalman filter as in [15] on the raw results of TDOAs to obtain more stable values.

With regards to localization estimation, a common method of trilateration is deployed. Let (x_i, y_i, z_i) be the coordinates of the i-th LED and (X_r, Y_r, Z_r) be the coordinates of the receiver. We have

$$\frac{\sqrt{(x_i - X_r)^2 + (y_i - Y_r)^2 + (z_i - Z_r)^2}}{c} - \frac{\sqrt{(x_{i+1} - X_r)^2 + (y_{i+1} - Y_r)^2 + (z_{i+1} - Z_r)^2}}{c} = t_i - t_{i+1}. \tag{5}$$

Therefore, the position estimation can be solved according to the set of TDOA obtained in the second stage. In (5), $i = 1, 2$ with Z_r known if the VLP scheme is targeted to 2D positioning, while $i = 1, 2, 3$ if it is targeted to 3D positioning.

2.2 Enhanced TDOA Estimator

Differing from the conventional TDOA estimator, the proposed TDOA estimator adopts the VLO technique and the cubic spline interpolation technique for cross-correlation. The schematic diagram of the enhanced TDOA estimator is shown in Fig. 2(b) in comparison with the conventional one [12], [14]. In the proposed estimator, almost all the signal processing is performed digitally inside the software. As shown in Fig. 2(b), the proposed TDOA estimator has only one hardware component (i.e., a single-channel ADC) and no longer needs the PLL circuits to act as RLOs. Moreover, an ADC of a much reduced sampling rate can be applied due to the cubic spline interpolation technique, while the added software components mostly consist of logical components and adders, indicating negligible additional complexity.

The principle of the VLO technique is discussed below. As depicted by Fig. 2(b), the VLO technique is realized by a sync cutter, a peak locator and a VLO. VLO acts as a local signal source which generates the virtual local signal with frequency predetermined, while the combination of the sync cutter and the peak locator is to synchronize the received signal with the virtual local signal. As discussed in section 2.1, t_{PR} is same only if the RF carriers irradiated from all LEDs are both synchronized to each other and synchronized to the local RF carriers. Equivalently, regarding the estimator armed with VLO, t_{PR} is the same value for all the outputs of peak detector only at that instant when the time interval between data acquisitions in each measurement is the integer multiples of the common period shared by all the signals. Therefore, we can ensure that the data sent to the correlator is synchronized to the local signal, if the initial phase of the local signal is fixed at zero and the received data sent for correlation always starts at the maximum peak in each correlation. Specifically, in the presented system herein using RF carrier, the sync cutter and the peak locator are combined to find the right time i.e., the common period, to cancel t_{PR}. Finally, the output of each subtractor becomes the TDOA that is exactly desired to obtain.

Combining the principle stated above, the process of the VLO technique is described below. As in Fig. 2(b), after the mixed signal output from the ADC is split by the corresponding narrow bandpass filters (see Filter #1–#3 in Fig. 2(b)) into the various RF carrier signals, the RF carrier signals are sent to the sync cutters and a peak locator simultaneously. The peak locator outputs the location of the first peak of the mixed waveform in the unit of sample points, whereas it firstly accumulates the RF carrier signals into a mixed sinewave, and then localizes the maximum absolute value within the first period. The sync cutter behind the filters on each RF carrier channel collects the original data samples, and then cuts and abandons a certain amount of sample points according to the information provided by the peak locator. Once the truncation task by sync cutter is finished, the result is handed over to the correlator which correlates it with the virtual local signal. The remaining procedures are exactly same as the conventional TDOA estimators. Likewise, the output of the TDOA estimator is obtained by subtracting t_{i+1} from t_i that is output by the corresponding peak detector.

Additionally, the accumulation technique is exploited to enhance the precision of peak search in the peak locator. This is a common approach to increase signal-to-noise ratio (SNR) [16]. In the peak locator, first several periods of data samples are accumulated to form high SNR received signal. It is noteworthy that the peak locator only needs few memory resources to perform the task, because only partial data samples are involved.

The interpolator based on the cubic spline interpolation technique is introduced in this part. As in Fig. 2(b), after the correlation function is obtained from the correlator, it is interpolated by an interpolator with a predetermined interpolator factor ranging from 2 to 100. Inspired by TDOA optimization research in the microwave field, here we adopt similar interpolators to enhance the time resolution of correlation and to reduce the requirement on sampling rate of ADC [13], [17]. The principle of the interpolator is to enhance the time resolution by means of applying all kinds of interpolations on the correlation function. As the signal is only sinusoid carrier herein, the interpolation on the correlation function can be easily performed using cubic spline interpolation.

Note that there is no substantial difference if the estimator is used for 3D positioning, where one more signal stream corresponding to the additional frequency is just added. Besides, it should be emphasized that the proposed scheme is not strictly subjected to the type of the transmitted signal. In this paper, the RF carrier wave or the frequency division multiplexing is used only in the convenience of explanation, the scheme is also applicable to the various code division multiplexing systems only if the VLO is set to generate the predetermined codes for local signals and the suitable interpolation is chosen for the corresponding correlation function.

3. Experimental Demonstration

3.1 Experimental Setup

The proof-of-concept VLP system is implemented and demonstrated in Section 3. The signal flow and the experimental setup are illustrated in Fig. 3(a) and (b), respectively. Three LED (Lumileds Rebel white LED) transmitters are mounted on a horizontal panel with a height of 2.2 m. The RF carrier frequencies allocated to LED#1, LED#2 and LED#3 are 4, 4.2 and 4.4 MHz, respectively. The

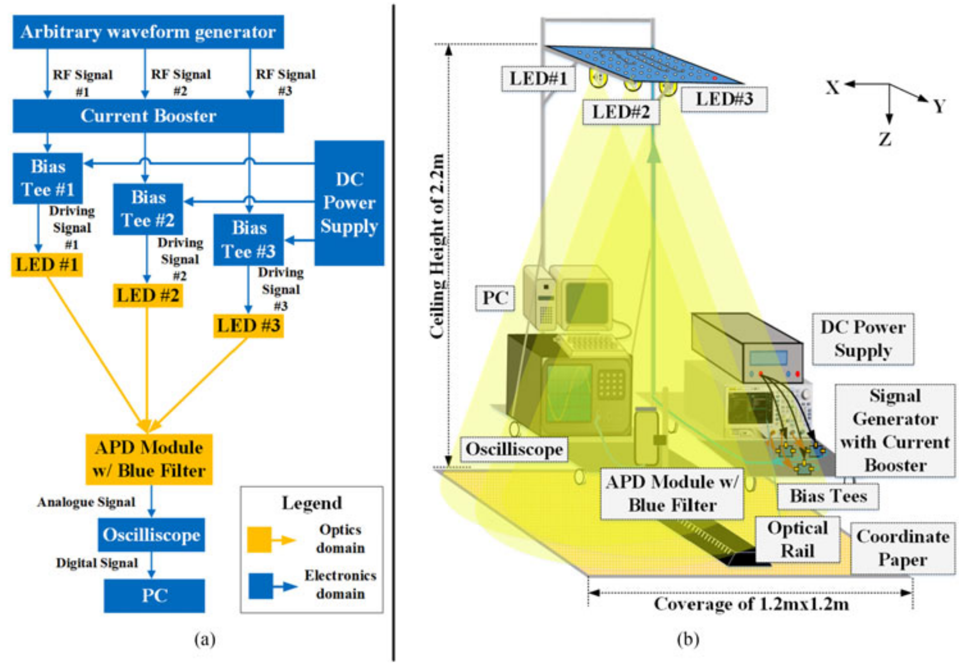

Fig. 3. (a) Signal flow and (b) experimental setup of the VLP system.

RF carriers are generated from an AWG (Tabor WW2074) and amplified by the current boosters (Analog Devices Inc. AD811 and Burr-Brown BUF634) before they are used to drive the LEDs. The receiver is composed of an APD module (Hamamatsu C12907) attached with a blue filter, an oscilloscope (Tektronix MSO3102) and a personal computer (PC).

Before signal measurements, the LEDs positions are first determined. As shown in Fig. 3(b), the origin is the drilling hole at the edge of the horizontal panel and the coordinate system is arranged as per the left-thumb rule. With regard to the LED arrangement, three LEDs form an isosceles triangle. The coordinates for LED#1, #2 and #3 are (0.675, 0.125, 0), (0.225, 0.125, 0), and (0.425, 0.475, 0), respectively, and the units are all meters.

3.2 Parameter Optimization

In this section, we utilize the proof-of-concept VLP system to determine the optimal parameters including the original sampling rate, the data length for correlation and the interpolation factor, which can help to further reduce the ADCs sampling rate and the memory size required for correlation while maintaining a reasonable localization performance. In the optimization experiment, we choose six positions for data collection. The positions have the spacing of 20 cm in both X and Y directions, forming an area of 20×40 cm^2 at the central region of the receiver plane (i.e. X-Y plane at Z = 2.06 m). For each chosen position, the data is collected at different sampling rates of 500 MSa/s, 1 GSa/s and 2.5 GSa/s. The original data has 1 M points, and we also truncate the data length for correlation to see the acceptable minimum data length for TDOA estimation.

Figure 4(a) shows the measured positioning error at 90% confidence versus the interpolation factor. It can be evidently found that the positioning error decreases with the multiplication of the original sampling rate and the interpolation factor. In other words, the positioning accuracies under significantly different original sampling rate can still be close to each other only if the multiplication of the original sampling rate and the interpolation factor are same. When the multiplication value of the original sampling rate and the interpolation factor becomes more than 50 GSa/s, the decreasing trend of the positioning error becomes flat, implying that the enhancement from interpolation has an upper limit. This is due to that the interpolation can enhance the time resolution to identify

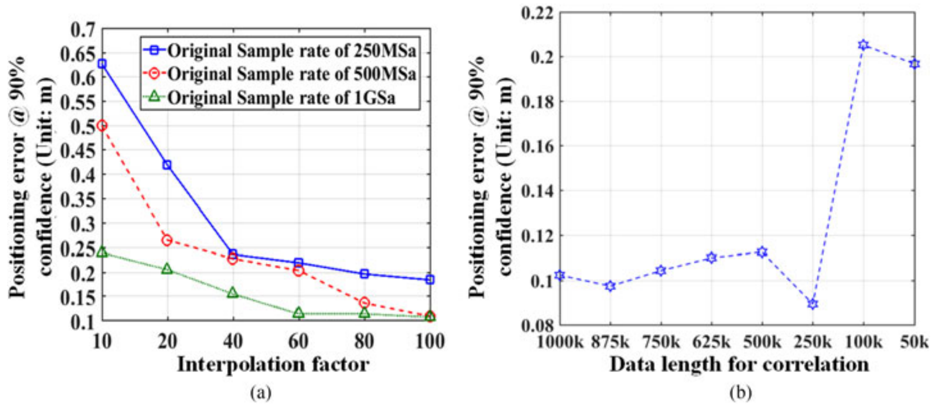

Fig. 4. Positioning error at 90% confidence vs. (a) the interpolation factor under different original sampling rates and (b) the data length for correlation under 500 MSa/s and an interpolation factor of 100.

the TOF value but cannot effectively compensate the measured TOF value itself which inherently contains the digitization error and fluctuation caused by all kinds of noise from practical hardware settings. Therefore, it is appropriate to set the multiplication of the original sampling rate and the interpolation factor as 50 GSa/s. Furthermore, in order to reduce the original sampling rate, the optimal combination of the original sampling rate and the interpolation factor should be 500 MSa/s and 100 for the VLP system.

As shown in Fig. 4(b), we consider the positioning error at 90% confidence versus the data length for correlation under 500 MSa/s and an interpolation factor of 100, from which the acceptable minimum data length for correlation can be decided. Consistent with the analysis from TDOA research in the microwave field, the positioning error increases with the data length decrease, and there exists a critical value below which the corresponding error is dramatically increased. This is because the capability of suppressing the zero-mean noise in the cross-correlation function is dependent on the data length [18]. When the data length falls below a certain value, the rising noise in the correlation function will distort the peak of the correlation function hence affecting the judgement of TOF. In our case, dramatic increase of positioning error occurs near 250 k samples when the data length reduced from 1000 k samples to 50 k samples. In one word, the acceptable minimum data length can be as low as 250 k sample points. All these optimal parameters will be directly employed in the following experimental demonstration. It is noteworthy that the robustness of the optimization results can be ensured only if the span of SNR in the optimization experiment can represent the span of SNR in actual usage. In accordance with this rule, the test points in the optimization experiment have to be adjusted depending on different coverage areas. For example, if the coverage is an expanded version from the following experiment in the actual usage, the distance between the test points have to be increased and the number of test points are necessarily increased to ensure the reliability of the optimization, which is worthy of being discussed in the future work.

3.3 Experimental Results

A 2D VLP experiment with a coverage area of 1.2×1.2 m^2 is demonstrated below. The feasibility of our proposed system will be verified by the evaluation of the positioning accuracy. Also, the impact of the VLO and cubic spline interpolation techniques are studied in comparison with the existing conventional systems. Based on the obtained optimization results, here we set the sampling rate as 500 MSa/s, the interpolation factor as 100 and the data length for correlation as 250 k. Fig. 5 depicts the measured TDOA values in one of the positions to be localized. The measurement variation is 0.0096 ns, and the estimation error is less than 0.030 ns. Fig. 6(a) shows the position estimation results. Each position is estimated 25 times in order to ensure the reliability of the measurements. As we can see, the estimations are consistent and close to the true position. Due to the geometric

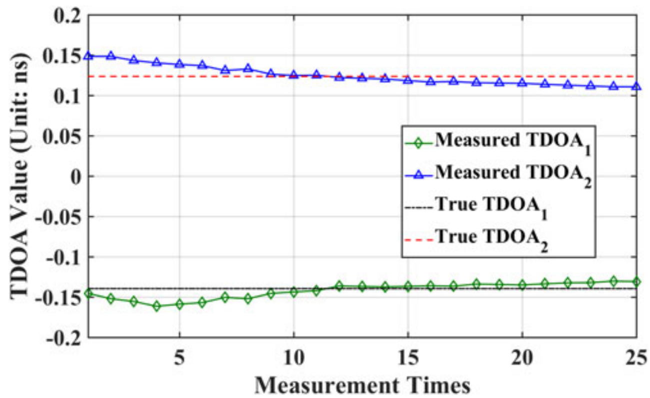

Fig. 5. TDOA estimation at the position (0.2560, −0.0034, 2.0600).

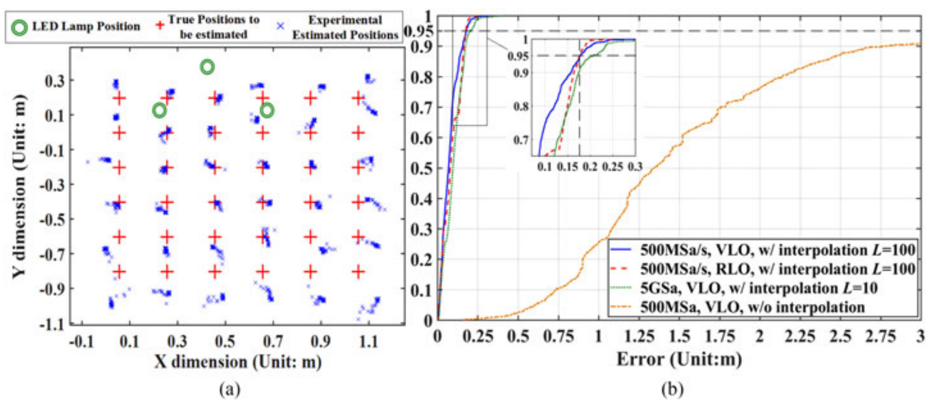

Fig. 6. (a) Positioning estimation results from experiment. (b) CDF plot of the positioning error. VLO: virtual local oscillator, RLO: real local oscillator, L: interpolation factor.

layout of the LEDs which are placed at the edge of the coverage shown in Fig. 6(a), we can expect a similar localization performance at the opposite area, i.e. 0 to 1.2 m in the X direction and 0.3 to 1.5 m in the Y direction. Therefore, a much larger coverage can be achieved in practice in the demonstrated VLP system, which is at least 2×1.2 m^2. Generally, it is possible to further expand the coverage of the prototype by increasing the SNR of the received signal at the edge of coverage. There are many ways to achieve this goal, such as to increase the modulation index and the optical power of the modulated signal and to use a photodetector with a higher responsivity or a larger active area. Since the modulation index currently set is 0.5 and the optical power of the modulated signal is no more than 1 W, the prototype system has large potential for an expanded coverage. Apart from that, we can also duplicate the prototype unit to form a cellular network with multiple units to cover a much larger coverage in actual usage which can be investigated in future.

It should be noted that the positioning error is small in the central area while there exist relatively large positioning shifting errors at the edge of the coverage. This is due to two factors: 1) the bias error of TDOA measurement introduced by the practical implementation of the hardware and 2) the calibration process on the initial TDOA at all LED transmitters. The bias error of TDOA measurement is common in a practical system which is particularly caused by the accuracy and the instability of the measurement equipment [19]. Worse still, the calibration process before the launch of the system operation in principle will amplify the bias error of TDOA measurement at the edge of the coverage. In the calibration process, the initial TDOA caused by the hardware is obtained by subtracting the true TDOA from the measured TDOA at a reference position right below the transmitter whose true position coordinates is already known. During the operation of the VLP

TABLE 1
Comparison of Our Proposed System With Other Works

Ref No.	Lin et al. [5]	Zhang et al. [7]	Yasir et al. [6]	Our proposition
Average accuracy (m)	0.017	0.07	0.25	0.092
Positioning principle	RSS +Trilateration	Pin-hole Camera Model	RSS +Trilateration	TDOA +Hyperbolic trilateration
Receiver type	Photodetector	Camera sensor	Photodetector +Gyroscope	Photodetector
Coverage Area (m^2)	0.2×0.2	1×1	2×1.4	1.2×1.2
Verified in a condition of actual usage	No	Yes	Yes	Yes
Hardware Complexity	Low	High	High	Low
Sensitive to incident angle of light	Yes	No	No	No
Offline Preparation	Tedious	Minor	Minor	Moderate

system, all the TDOA measurement will be calibrated by removing the calculated initial TDOA. Hence, the bias error of TDOA measurement will be accumulated for those positions to be localized away from the reference point in the center. Consequently, the positioning shifting error is relatively larger at the edge of the coverage.

Fig. 6(b) depicts the cumulative distribution function (CDF) curves of the estimation results shown in Fig. 6(a). It can be found that the positioning error of the proposed system is less than 18 cm at the confidence of 95% and that the average positioning accuracy is 9.2 cm. As can be seen from Fig. 6(b), the proposed system using VLO has slightly higher positioning accuracy than that using RLO. This is due to that the additional instability is introduced where the RLO is mimicked in the demonstration by means of transmitting a real local signal via a cable from the AWG to the oscilloscope. The impedance of the cable carrying the real local signal slightly changes with the bending and rotation of the cable, hence causing slightly different initial TDOA at different positions which are generally assumed to be constant. Consequently, it can be concluded that the proposed system applying the VLO technique can successfully reduce the hardware components such as RLOs and still maintain equivalent or even higher positioning accuracy.

Fig. 6(b) further demonstrates the positive impacts from cubic spline interpolation applied to the cross-correlation based TDOA measurement. We compare the estimation results under three configuration settings: 1) a sampling rate of 500 MSa/s and an interpolation factor of 100; 2) a sampling rate of 5 GSa/s and an interpolation factor of 10; 3) a sampling rate of 500 MSa/s without interpolation. It can be found that the positioning error is as high as 3 m at 90% confidence when using a sampling rate of 500 MSa/s without interpolation. However, when interpolation with a factor of 100 is adopted, the positioning error can be significantly reduced, verifying the feasibility of applying interpolation to enhance the positioning accuracy of TDOA-based VLP systems. In turn, it can be concluded that the applied interpolation technique helps to significantly reduce the system requirement on the sampling rate of ADC by increasing the time-resolution of cross-correlation in software. Moreover, compared with the data set sampled at 5 GSa/s with interpolation factor of 10 for cross-correlation and the one sampled at 500 MSa/s with interpolation factor of 100 for cross-correlation, it can be observed that the data with both a lower sampling rate and a higher interpolation factor reveals slightly better localization performance if the two data sets have the same value of the multiplication of the original sampling rate and the interpolation factor. This is mainly caused by the relationship between the performance of the digital filter and the sampling rate. The frequency resolution of the digital bandpass filter is higher if the sampling rate is lower, which implies that the filtered data used for TDOA estimation has much less noise remained. Therefore, the TDOA calculation is more accurate when the sampling rate is relatively lower.

To give a better view on our proposed system to readers, we summarize the accuracy, methodology, advantages and disadvantages in comparison with the previous existing VLP works in Table 1. As we can see from Table 1, among the works verified in conditions close to the actual usage, our proposed system achieves high accuracy while retaining the feature of low hardware complexity and ease of usage.

4. Summary

In this paper, a low-complexity TDOA-based VLP system using a novel and practical localization scheme based on cross-correlation has been proposed and experimentally demonstrated for the first time. The proposed VLP system has mainly two advantages compared with the other existing ones: 1) a reduced hardware complexity due to the design of VLO to replace RLO for cross-correlation at the receiver side; 2) a reduced requirement on the sampling rate due to the enhancement of time-resolution of cross-correlation by applying the cubic spline interpolation. Furthermore, system parameter optimization has also been performed to achieve optimal performance, in terms of the sampling rate, the interpolation factor and the data length for correlation. The experimental results regarding a 2D VLP system with a coverage of 1.2×1.2 m^2 show that the average positioning accuracy is 9.2 cm with a sampling rate of 500 MSa/s.

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