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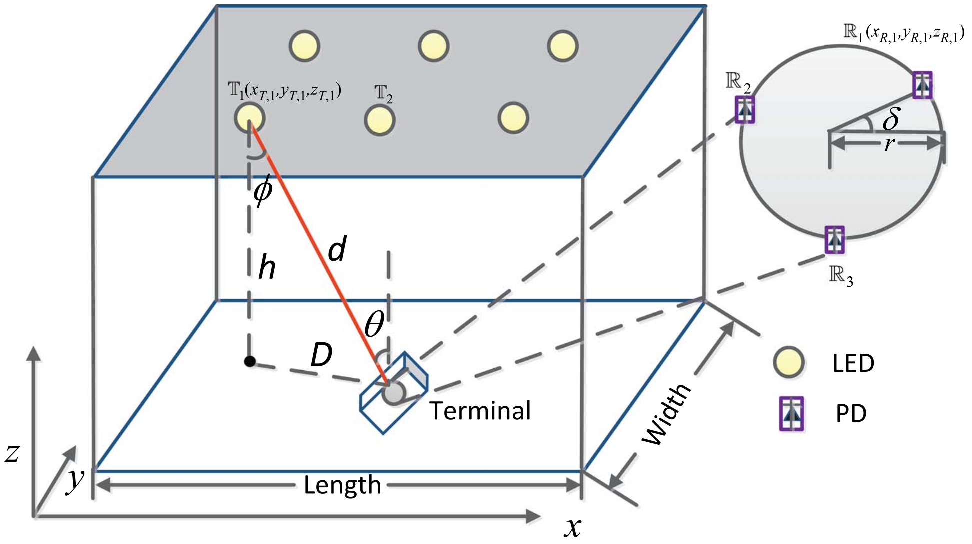

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Indoor Positioning for Multiphotodiode Device Using Visible-Light Communications

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Abstract: With the widespread use of light-emitting diodes (LEDs) for lighting, their ability to support communications through visible light has become promising for various wireless applications. In particular, visible-light communication (VLC) assisted indoor positioning enjoys its unique advantage of electromagnetic interference immunity and high accuracy. Instead of directly extending conventional wireless positioning using radio-frequency equipment, we consider the indoor positioning specified for a popular VLC scenario where the target device has multiple photodiodes (PDs) while having no help from other fixed receiving nodes with known coordinates. A general framework is presented for multi-PD device positioning by exploiting relative positions, as well as the received signal strength indications, of the multiple PDs. Moreover, the feasible condition for realizing effective positioning is also presented. Finally, we validate the accuracy of the proposed method via numerical tests.

Index Terms: Indoor positioning, visible light communications (VLC), light-emitting diode (LED).

1. Introduction

The light-emitting diode (LED) has been a popular lighting device with widespread deployment due to many characteristics, including long life expectancy, low power consumption, high tolerance to humidity, and minimal heat generation lighting. Besides its illumination function, LEDs also modulate electric signals to lighting wave signals at a high rate without introducing electromagnetic interference that enables the LED to be not only a lighting device but a communication device for visible light communications (VLC) as well [1]–[3]. Recently, many promising applications based on VLC have been developed and, in particular, location-based services via indoor positioning via VLC have been recognized as extremely attractive applications [4]. Traditional indoor positioning techniques rely on radio frequencies like WiFi [5], infrared [6], lasers [7], etc. Compared to these techniques, LED supported indoor localization has the advantages of high accuracy, no extra equipment for deployment, high security, and short response time [8].

Extensive studies have been reported on various indoor positioning approaches by exploiting radio frequency or light signals. Particularly for VLC, there are generally two ways of indoor location estimation based on geometric properties, namely, trilateration and angulation [9]–[12]. The trilateration approach estimates the target location by measuring distances from multiple reference points with known coordinates. The distances can be estimated via different measurements, like received signal strength (RSS) [9] and received signal strength ratio (RSSR) [10]. Alternatively, following a similar trilateration philosophy of the distance-based positioning, time difference of arrival (TDOA) can also be utilized to locate the target position in some applications [11]. On the other hand, the angulation approach estimates the target location by measuring angles from multiple reference nodes [12].

Generally, the existing studies on LED based indoor positioning as mentioned above are direct extensions of wireless positioning approaches in radio frequency communications to the VLC field. The most popular way of location estimate in VLC is to use RSS. However, it requires help from other receiving nodes with fixed and known coordinates, which is in general hard to achieve in many practical VLC applications. In some VLC applications [13], [14], it becomes common that there exists a terminal with multiple receivers, i.e., PDs, to be located while no other fixed receiving nodes exist with known coordinates. Under this case without known coordinates of receiving nodes, few related research has been conducted with well defined solutions.

In this study, we consider a positioning framework for a multi-PD terminal device using VLC. Our paper focuses on the scenario specified for VLC applications where a single target terminal is located with the help of multiple PDs on it given their relative positions known. Note that for the VLC applications, we assume that there exists no other fixed receiving node with known coordinate for the positioning. To the best of our knowledge, positioning in this general case for VLC applications has not been studied. Though RSS is considered for positioning like in studies [10] and [15], different from our scenario, both studies considered the LED ceiling lamps environment where a single-PD receiver is to be located with the help of multiple LED transmitters. In particular, the contributions of our study are summarized as follows.

- We consider a different scenario as existing studies on indoor position using visible light communications (VLC), though most of existing studies directly considered positioning approaches developed in radio frequency communications for VLC applications. More specifically, these positioning approaches mostly need absolute coordinates of multiple receive references or the positioning algorithm requires iterations to achieve reasonable accuracy. In our work, we focus on the scenario where a single target terminal with multiple PDs given their relative positions known is to be located. An obvious and major difference is that there is no other fixed receiving node with known coordinate for the positioning. Under this setup, the existing positioning approaches do not apply and, to our best knowledge, iterative mechanism is required for effective positioning even for a specific three-PD device following this setup and positioning accuracy is not guaranteed.
- Considering the multi-PD device positioning, a general framework is presented by exploiting relative, instead of absolute, positions of receiving PDs. We formulation the problem into a linear matrix equation in terms of the relative positions, as well as the RSS indications, of the multiple PDs. In this way, the problem of positioning consequently allows a standard least squared solution as expected. Moreover, given the problem formulation, we also present the feasible conditions for realizing effective positioning under the multi-PD scenario. If the condition can not be satisfied, effective positioning becomes unavailable even for the ideal case without noise and measurement mismatch.
- The proposed positioning is evaluated under both ideal line-of-sight (LoS) VLC channels and real channel measurements from our prototype. It is shown that the positioning accuracy can be achieved on the order of millimeter under the LoS channels. While for real VLC applications, the positioning accuracy of the proposed scheme slightly increases to the order of centimeter in real VLC applications due to the effects of channel dispersion and model mismatch.

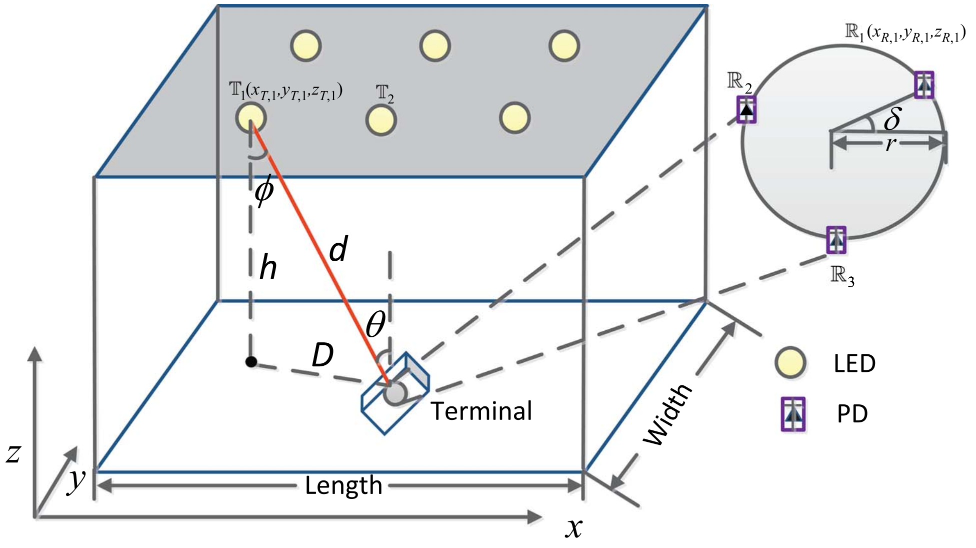

Fig. 1. Indoor positioning in the VLC system.

2. Positioning for Multi-Photodiode Device

The indoor positioning system has a basic schematic as exemplified in Fig. 1. There are M LEDs and a target device with N PDs. Assume that the position coordinates of M LEDs, denoted as $\mathbb{T}_i(x_{T,i}, y_{T,i})$ $(i = 1, \ldots, M)$,[1] are known. The target terminal device has N PDs whose coordinates labeled by $\mathbb{R}_j(x_{R,j}, y_{R,j})$ $(j = 1, \ldots, N)$ are unknown while their relative positions are known to the target device itself. Our objective is to locate the target device with the knowledge of their relative positions of multiple PDs as well as the coordinates of $\mathbb{T}_i$'s.

Generally, the optical channels are well modeled as LoS links and the illuminance of LED follows the Lambertian radiation pattern [10], [12]. Let $m = -\ln 2/\ln(\cos\phi_{1/2})$ be the mode number of the radiation lobe where $\phi_{1/2}$ denotes the semi-angles at half power and denote FOV as the LED field of view at 70 degrees. The channel direct current gain $H(0)$ can be calculated as [16]

$$H(0) = \frac{m+1}{2\pi d^2} A\cos^m(\phi)\cos(\theta)\mathrm{rect}\left(\frac{\theta}{\mathrm{FOV}}\right) \tag{1}$$

where d is the distance between the LED transmitter and the PD, A is the photo-detector area, ϕ is the light angle of incidence, θ is the angle of reception of the light at the photodiode, and $\mathrm{rect}(\cdot)$ is the rectangular function defined by $\mathrm{rect}(x) = 1$ for $|x| \leq 1$, and otherwise, $\mathrm{rect}(x) = 0$. Without loss of generality, assume both the photodiode axis and the transmitter axis to be perpendicular to the ceiling, which gives

$$\cos(\phi) = \cos(\theta) = h/d \tag{2}$$

where h is the height from the LED to the receiver plane.

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[1] The coordinates of LEDs are more rigorously $(x_{T,i}, y_{T,i}, h)$ $(i = 1, \ldots, M)$, and the coordinates of target device can thus be $(x, y, 0)$. For notational simplicity and without causing ambiguity, the z coordinates of LEDs and the target device can be omit without loss of generality. In this paper, the coordinate of LED is denoted as $\mathbb{T}_i(x_{T,i}, y_{T,i})$ $(i = 1, \ldots, M)$, and the coordinate of the target device is denoted as (x, y).

Given the PD's FOV is large enough so that $0 \leq \theta \leq \mathrm{FOV}$ always holds and based on (1), the receiver power at the photodiode equals

$$P_r = H(0)P_t = \frac{m+1}{2\pi d^{m+3}} A h^{m+1} P_t \tag{3}$$

where P_t is the transmit power of the LED. Accordingly, the distance d between the LED and the receiving PD can be expressed as follows:

$$d = \sqrt[(m+3)]{\frac{m+1}{2\pi} A h^{m+1} \frac{P_t}{P_r}}. \tag{4}$$

Accordingly, given the received power P_r detected by the PDs, each $\mathbb{R}_j$ can calculate its distances $d_{i,j}$ to all $\mathbb{T}_i$ for $i = 1, \ldots, M$. For positioning in the VLC system, we therefore need to solve the target position that is the center of the target device, denoted by $\mathbb{C}(x, y)$, based on the knowledge of obtained $\{d_{i,j}\}'s$ and the relative positions of all PDs.

In order to construct a relationship between (x, y) and the available knowledge as mentioned above, the target device first calculates the horizontal distance $D = \sqrt{d^2 - h^2}$ as exemplified in Fig. 1. In particular, the distance between the ith LED and the jth PD can be estimated by

$$\hat{D}_{i,j} = \sqrt{d_{i,j}^2 - h^2}. \tag{5}$$

Recall that only the relative positions between multiple PDs are known. We assume that all PDs locate as an equilateral polygon in shape and our target location can be the center of the equilateral polygon. Let the target $\mathbb{C}(x, y)$ be the center coordinate of the polygon. Then, the coordinate of $\mathbb{R}_j$ equals

$$\begin{cases} x_{R,j} = x + r\cos\left(\frac{2\pi(j-1)}{N} + \delta\right) \\ y_{R,j} = y + r\sin\left(\frac{2\pi(j-1)}{N} + \delta\right) \end{cases}, \quad j = 1, 2, \ldots, N \tag{6}$$

where r is the radius of the equilateral polygon, and δ is the rotation angle of the device that can be determined, e.g., by a gyroscope in smart devices. Now, we are ready to construct the following equations by subtracting $\hat{D}_{1,1}$ from $\hat{D}_{i,j}$ for all $i, j \neq 1$. It gives

$$\begin{aligned} \hat{D}_{i,j}^2 - \hat{D}_{1,1}^2 &= x_{R,j}^2 - x_{R,1}^2 - 2x_{R,j}x_{T,i} + 2x_{R,1}x_{T,1} + x_{T,i}^2 - x_{T,1}^2 + y_{R,j}^2 - y_{R,1}^2 \\ &\quad - 2y_{R,j}y_{T,i} + 2y_{R,1}y_{T,1} + y_{T,i}^2 - y_{T,1}^2 && (7) \\ &= 2xr\cos\left(\frac{2\pi(j-1)}{N} + \delta\right) - 2xx_{T,i} - 2xr\cos\delta + 2xx_{T,1} + 2yr\sin\left(\frac{2\pi(j-1)}{N} + \delta\right) \\ &\quad - 2yy_{T,i} - 2yr\sin\delta + 2yy_{T,1} - 2rx_{T,i}\cos\left(\frac{2\pi(j-1)}{N} + \delta\right) - 2ry_{T,i}\sin\left(\frac{2\pi(j-1)}{N} + \delta\right) \\ &\quad + 2ry_{T,1}\sin\delta + 2rx_{T,1}\cos\delta + x_{T,i}^2 + y_{T,i}^2 - x_{T,1}^2 - y_{T,1}^2 && (8) \\ &\triangleq [\alpha_{i,j} \quad \beta_{i,j}] \begin{bmatrix} x \\ y \end{bmatrix} + \gamma_{i,j} && (9) \end{aligned}$$

where equality (7) follows from the fact that

$$\hat{D}_{i,j}^2 = (x_{R,j} - x_{T,i})^2 + (y_{R,j} - y_{T,i})^2. \tag{10}$$

Equation (8) is obtained by substituting (6) into (7). In the last equality of (9), we define

$$\begin{aligned}
\alpha_{i,j} &= 2\left[x_{T,1} - x_{T,i} + r\left(\cos\left(\frac{2\pi(j-1)}{N} + \delta\right) - \cos\delta\right)\right] \\
\beta_{i,j} &= 2\left[y_{T,1} - y_{T,i} + r\left(\sin\left(\frac{2\pi(j-1)}{N} + \delta\right) - \sin\delta\right)\right] \\
\gamma_{i,j} &= 2r\left[x_{T,1}\cos\delta - x_{T,i}\cos\left(\frac{2\pi(j-1)}{N} + \delta\right)\right] + 2r\left[y_{T,1}\sin\delta - y_{T,i}\sin\left(\frac{2\pi(j-1)}{N} + \delta\right)\right] \\
&\quad - \left(x_{T,1}^2 - x_{T,i}^2\right) - \left(y_{T,1}^2 - y_{T,i}^2\right).
\end{aligned} \tag{11}$$

Note that there are overall $(MN-1)$ equations represented in (9) for all $i = 2, \ldots, M$ and $j = 2, \ldots, N$. For notational brevity, let us define

$$\mathbf{A} = \begin{bmatrix} \alpha_{1,2} & \beta_{1,2} \\ \vdots & \vdots \\ \alpha_{M,N} & \beta_{M,N} \end{bmatrix}_{(MN-1)\times 2}, \qquad \mathbf{x} = \begin{bmatrix} x \\ y \end{bmatrix} \tag{12}$$

$$\mathbf{b} = \begin{bmatrix} \hat{D}_{1,2}^2 - \hat{D}_{1,1}^2 - \gamma_{1,2} \\ \vdots \\ \hat{D}_{M,N}^2 - \hat{D}_{1,1}^2 - \gamma_{M,N} \end{bmatrix}_{(MN-1)\times 1}. \tag{13}$$

Then after some basic manipulations, the $(MN-1)$ equations in (9) can be stacked in the following form:

$$\mathbf{A}\mathbf{x} = \mathbf{b} \tag{14}$$

which obviously admits a standard least squares (LS) estimator given by

$$\hat{\mathbf{x}} = \left(\mathbf{A}^T\mathbf{A}\right)^{-1}\mathbf{A}^T\mathbf{b} \tag{15}$$

where $\mathbf{A}^T$ is the transpose of $\mathbf{A}$.

Now, the remaining task is to show that the target device is able to achieve full knowledge of both $\mathbf{A}$ and $\mathbf{b}$. By checking all elements in $\mathbf{A}$ and $\mathbf{b}$, it can be observed that all involved parameters including r, δ, and all coordinates of $\mathbb{T}_i(x_{T,i}, y_{T,i})$ are known, and $\hat{D}_{i,j}$ is estimated from (5) by all PDs. Generally in positioning systems, it is a prerequisite for the positioning that signals from multiple LEDs need to be distinguished and this is achieved by letting each LED send its own beacon signal to the device via a dedicated, or in some sense orthogonal, channels [11], [17], [18]. For instance, multiple LEDs can broadcast their individual beacon signals within the dedicated times-slot assigned to each LED. The beacon signal contains the information of the LED index so that the device PD can distinguish the LED by detecting the beacon signal from each specific time-slot without mutual interference from others. Note that the time slot can be reused for LEDs far from each other so that the interference from these LEDs sharing the same time-slot for beacon transmission is minimized to approaching zero. In VLC, the mutual interference is therefore effectively minimized due to the non-dispersive nature of the light channel and the finite field-of-view of PDs. In location systems using radio frequency, similar techniques have been utilized for distinguishing different transmitter references while interference leakage is however inevitable due to reflections and scattering, even though dedicated or orthogonal source is allocated for transmitting different reference signals. Alternatively, LED beacon signals can also be well distinguished in other ways, like different carriers [11]. Thus far, we are able to estimate the location of $\mathbb{C}(x, y)$ by using (15) with only relative positions of multiple PDs. It is important to stress that our proposed method applies for various scenarios with arbitrary relative PD positions although for neat representation a symmetric equilateral polygon is assumed in shape in (6). For an arbitrary relative PD position, one only needs to reformulate the relationship in (6) and make corresponding changes in the following equations. Specifically, for $N = 2$, that is popular in many smart devices, the assumption of equilateral polygon always applies.

The above-presented is a general solution to the positioning problem in VLC with only relative multi-PD positions. From the following Lemma 1, we are able to check the feasibility of the problem of position estimation in (15).

Lemma 1

For the indoor positioning in VLC, there are M LEDs and one target terminal device with N PDs. The target can be effectively positioned if and only if $M + N \geq 4$.

Proof

This condition can be readily obtained by checking the feasibility of the solution in (15) to the positioning problem. From (15), the estimate $\hat{\mathbf{x}}$ exists if and only if $\mathbf{A}^T\mathbf{A}$ is nonsingular. Hence the rank of matrix $\mathbf{A}$ is required to be no smaller than two. Concerning $\mathbf{A}$ is an $(MN - 1) \times 2$ matrix, we get

$$MN \geq 3. \tag{16}$$

Since M and N are integers for "antenna" numbers, it is easy to equivalently transform the condition in (16) as follows:

$$M + N \geq 4, \qquad M, N > 0 \tag{17}$$

which implies that the total number of both available LED transmitter(s) and PD(s) must be at least four in order to make the positioning. ■

From Lemma 1, it implies that position is effective in the system if $M + N \geq 4$. Considering an ideal case with noiseless channel, perfect position can be achieved via the proposed scheme if the condition in (17) is satisfied. Otherwise, if the condition does not hold, an accurate position can never be achieved, even in the ideal case without any noise or interference. Therefore, according to Lemma 1, the setup of at least $M + N = 4$ is suggested in the presence of noise and interference in practical applications.

3. Simulation and Experimental Tests

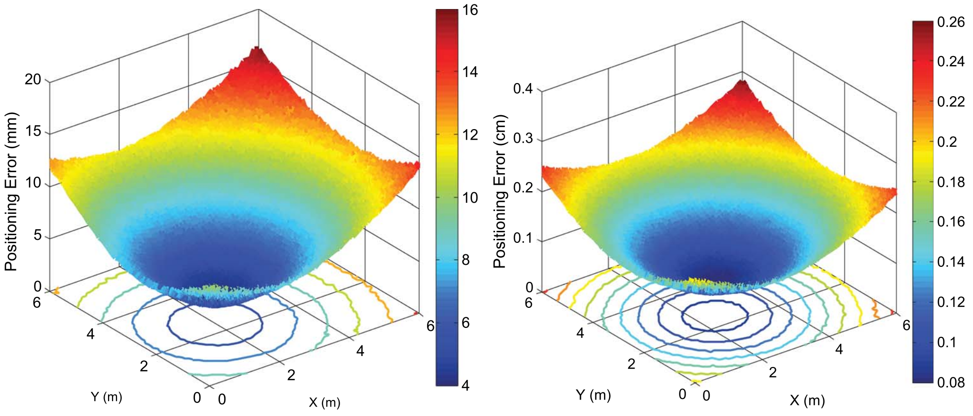
We tested the proposed VLC positioning approach by simulations. The simulation parameters are summarized in Table 1. We set the LED transmitters according to Table 1 and the coordinates of LEDs are set by order as specified in Table 1. Fig. 2 describes the averaged positioning error of different device locations within the tested room at SNR = 5 dB, under $M = 2$, $N = 2$ and $M = 4$, $N = 2$ respectively. From the results, it is observed that the positioning accuracy degrades as the device moves from center to corner. This is because the device becomes far from some LEDs and therefore the positioning accuracy degrades. Notice that we also exemplify in Fig. 4 the illumination level of the considered room under a typical test setup with four LEDs since the LEDs are deployed for illumination. The coordinations of the LEDs are specified in Table 1. From Fig. 4, it shows that the illumination level ranges approximately from 400–1000 Lux at different locations in the room, which satisfies the illumination requirement specified by ISO as 200 up to 1500 Lux [1], [19].

Fig. 3(a) and (b) compare the positioning performance of different LED and PD setups. In Fig. 3(a), we compare the performance under fixed $M = 1$ and $M = 2$ with varying numbers of PDs at the target device. While in Fig. 3(b), we test the cases under fixed $N = 1$ and $N = 2$ with varying numbers of LED transmitters for positioning. From Fig. 3(b), the increase in N plays

TABLE 1

Parameters

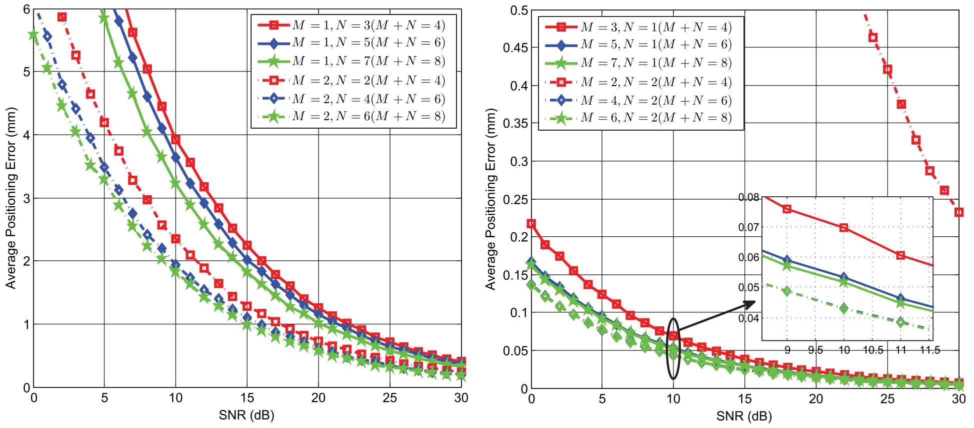
	Parameter	Value
	Room size	$6 \times 6 \times 3\ m^3$
	h (m)	2
PD module	PD model	Si APD S5343
	PD responsivity	1 A/W
	Area of PD (A)	1.0 mm^2
	Receiver FOV	70 deg
	polygon radius (γ)	0.02m
	rotation angle (δ)	45 deg
LED module	LED model	LZ4-00MA00
	LED power	1 W
	Semi-angles ($\phi_{1/2}$)	60 deg
	LED numbers (M)	LED coordinates
	1, 3, 5, 7	(3, 3, 2), (2, 2, 2), (4, 2, 2), (4, 4, 2), (2, 4, 2), (3, 2, 2), (3, 4, 2)
	2, 4, 6	(2, 2, 2), (4, 2, 2), (4, 4, 2), (2, 4, 2), (3, 2, 2), (3, 4, 2)



(a) (b)

Fig. 2. Spatial distribution at SNR = 5 dB. (a) $M = 2$ and $N = 2$. (b) $M = 4$ and $N = 2$.

similar impacts on reducing the positioning error under different setups with M. Moreover, by comparing the results in both figures, it can be observed that, given the same total number of $M + N$, using more LED transmitters for positioning achieves significantly better performance than using more PDs at the target device. Notice that our observation is, as intuitively expected, due to the high correlation between the PDs on the device and relatively much less correlation between individual LEDs. Moreover from the results, we can see that the average position error always approaches to zero as the SNR grows large with $M + N \geq 4$, which verifies the correctness of Lemma 1 for effective positioning under the ideal case. While as the receiving SNR becomes worse, the position accuracy becomes high even though the condition in Lemma 1 is satisfied. This is intuitively reasonable since additional noise and interference always degrade the effective SNR and, thus, deteriorate position performance. For instance, if there exists some interference due to the non-orthogonal LED setup, the interference can equivalently be treated as additional noise imposed on the received signal by PD. In this case, the effective SNR of the positioning system decreases as the interference grows. As illustrated in Fig. 3, the average positioning error doubles from 1 mm to 2 mm under the setup with two LEDs and 2-PD receiver, while the error degradation becomes relatively much insignificant as 0.025 mm under



(a) (b)

Fig. 3. Performance comparison with multiple LEDs and multiple PDs. (a) One LED and two LEDs. (b) Single-PD device and two-PD device.

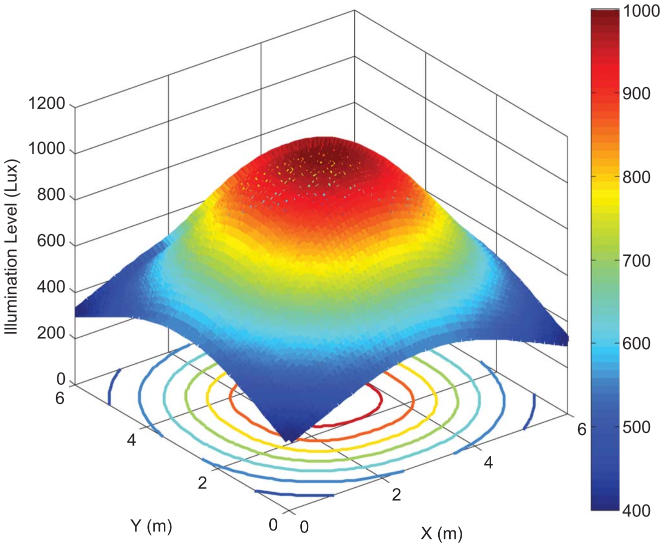


Fig. 4. Illumination level distribution in the room with four LEDs.

the setup with four LEDs and the 2-PD receiver. It indicates that more LEDs are helpful in enhancing the position accuracy, as well as maintaining robust against this kind of additional interference.

Moreover, we further verify the proposed positioning scheme under the real visible light channel measured by our VLC prototype as illustrated in Fig. 5. The experiments were conducted by using the prototype comprised of three components including the LED transmitter, the receiver with PDs and complementary computers for data generation and collection. Pseudo-noise sequences were generated as sources for transmission, and the received data are collected by the computers; therefore, the visible light channels were measured by data detection and minimum mean square error (MMSE) channel estimation is exploited. Note that the parameters of the LED and PD modules have been detailed in Table 1. In particular, we use the LED with module LZ4-00MA00, and the LED power is set to 1 W. The PD module referred to the Si APD S5343 with PD area as 1.0 mm^2 and responsivity 1 A/W. The FOV of the PD module is 70 degrees.

Fig. 5. VLC prototype for channel measurements.

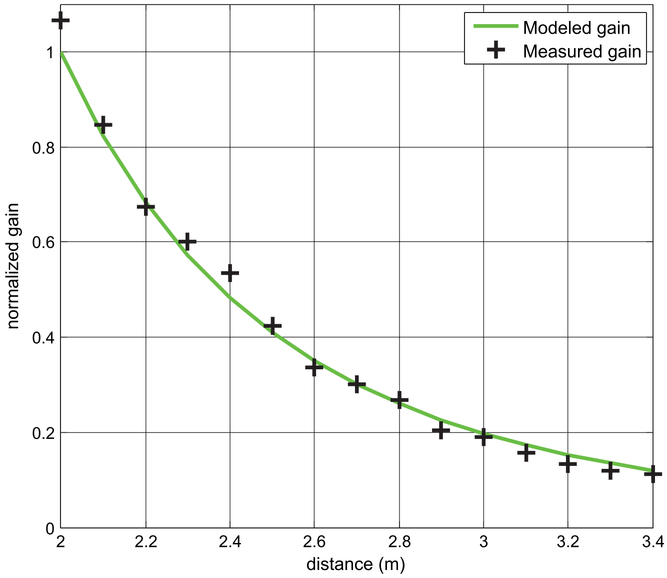


Fig. 6. VLC prototype and channel gain comparison.

The PD module contains multiple PDs, and these PDs locate as an equilateral polygon in shape. As for the distance between the LED and PD module, our experiments were conducted for a variety of LED-PD distance setups from 2 up to 3.4 m. The collected data reveals the relationship between the channel gain and distance is as depicted in Fig. 6, where we present the comparison between the measured channel gains and the theoretical channel models in the electrical domain by using PDs.

Under the real VLC channel, we evaluate the proposed positioning scheme by letting the target device at a fixed coordinate at (3,3). We chose two typical cases with $M = 1$, $N = 3$ and $M = 2$, $N = 2$. Figs. 7 and 8 show the positioning error under the signal-to-noise ratio SNR = 10 dB. From the results, the mean positioning error is observed at the mean of 6 cm with its maximum error around 14 cm under $M = 1$, $N = 3$. While under $M = 2$, $N = 2$, the mean positioning error is 4 cm with the maximum error is 13 cm. Unlike the ideal LoS channels, both figure results are tested under real visible light channels which is definitely dispersive and contains interference from other illumination sources. By comparing the results with Fig. 3, it is observed that the positioning error increases from the order of millimeter to centimeter. Thus, we can conclude that the effect of non-linear interference, e.g., channel model mismatch and measurement errors, appears as the major limiting factor to positioning scheme and the effect due to additive interference, e.g., from non-orthogonal LEDs as discussed above, is much less significant.

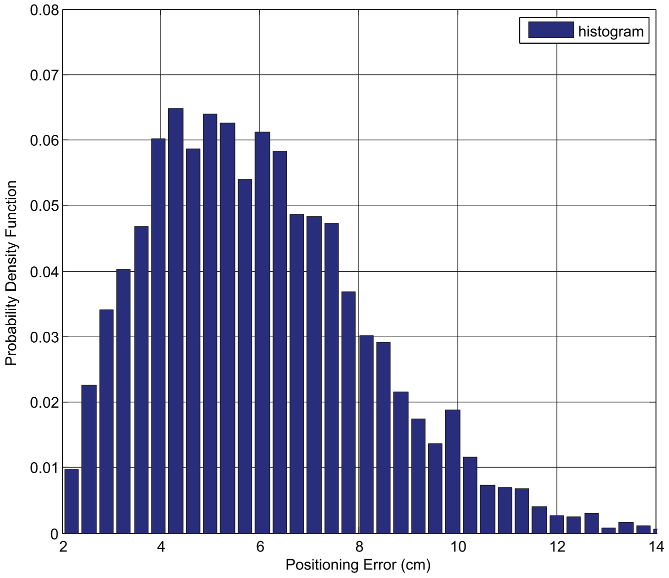


Fig. 7. Histogram of positioning error at SNR $= 10$ dB when $M = 1$ and $N = 3$.

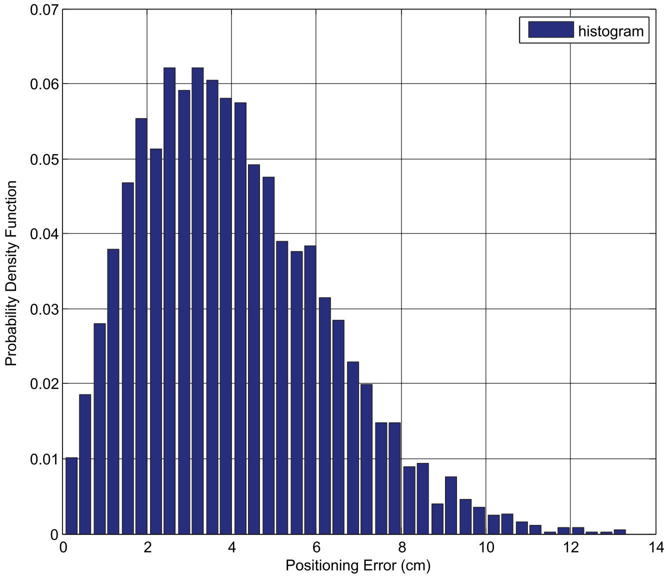


Fig. 8. Histogram of positioning error at SNR $= 10$ dB when $M = 2$ and $N = 2$.

4. Conclusion

An indoor positioning is presented for the VLC system with a multi-PD target device. The target device can be effectively positioned with multiple PDs if the total number of LEDs and PDs is no smaller than four. Moreover, given the same total number of $(M + N)$, it is observed that significantly better positioning accuracy can be achieved by using more LEDs than using more PDs at the target device. Location accuracy in the order of centimeters can be achieved according to realistic tested results.

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