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TDOA-based indoor positioning using visible light

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Abstract In this paper, we propose an indoor positioning system in which the visible light radiated from LEDs is used to locate the position of receiver. Compared to current indoor positioning systems using LED light, our system has the advantages of simple implementation, low cost, and high accuracy. In our system, a single photo diode receives pilot signals from LED panels on the ceiling. Then, the time differences of arrival of these pilot signals are used to estimate the position of the receiver. The system can be employed easily because it does not require embedding any ID to the pilot signal. In the paper, the estimation accuracy of the proposed system is analyzed through the simulation. The causes of estimation error are analyzed, and the estimation accuracy of the system in various conditions is shown by simulations.

Keywords Light-emitting diodes · Photo diodes · Indoor positioning · TDOA

1 Introduction

Indoor positioning has been studied widely in the recent years. A lot of positioning techniques using GPS, IR, RFID, Ultrasound, Bluetooth, Wi-Fi [1–3] have been researched but there is no standard method for indoor positioning like using GPS in outdoor positioning systems. Beside the expensive cost, the RF-based systems also have the disadvantages of security and safety problem since the RF signal can go beyond the room. RF signals are also unsuitable for using in hospitals, airplanes, or some hazardous environment. Infrared is more suitable for indoor positioning, but they require additional cost to implement the network infrastructure of location sensor. The approach of using visible light for indoor positioning has been studied recently to overcome these limitations.

Beside the main function which is positioning, the visible light indoor positioning system undertakes the function of illuminating. With the rapid development of LED technology, illuminating systems using LED will be deployed in any building and they can be utilized to build indoor positioning systems with just a little extra cost. There have been studies using visible light for indoor positioning [4–10], but neither of them achieve high accuracy nor have a simple implementation.

Many positioning techniques using received signal strength (RSS), time of arrival (TOA), time difference of arrival (TDOA) and angle of arrival (AOA) can be used to locate the position of mobile node.

The technique of AOA can achieve very good accuracy estimation, but require deploying an array of image sensors, which is expensive, at the receiver side. Because of the complicated effect of reflections, the technique of RSS is hard to acquire an accurate positioning, especially at the region near the walls. In indoor positioning, the traveling time of signal is so short due to the short distance between transmitters and receiver. This makes the ToA technique difficult to be deployed since it requires a precise synchronization between transmitters and receiver. With TDOA, the synchronization is required only between transmitters, which is easy to be performed since LED panels can share the same clock in the same room. The information of time difference of arrival can be achieved accurately given that we have the proper scheme of transmitting pilot signals. Furthermore, with TDOA, the system just requires the photo diode, which is an inexpensive device, at the receiver. Hence, the technique of TDOA

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appears to be most suitable to use for indoor positioning system using visible light.

Jung et al. [10] also use TDOA technique with visible light for indoor positioning. In this system, all pilot signals are transmitted at the same time and their optical powers are time-domain cosine waves of specific angular frequencies. A complicated technique is used to separate these signals from the mixed received signal. This approach is difficult to be applied in reality because it is very difficulty to control the transmitted optical power of LED precisely. Changing the current frequently also causes the chromatic dispersion problem. Furthermore, choosing angular frequencies for different pilot signals is painful when a large number of pilot signals is used.

In this paper, we use the time difference of arrival of the visible light radiated from LED panels on the ceiling to locate the receiver's position. Since we use TDOA technique, no synchronization between LED panel and receiver is needed. Importantly, our proposed system does not use any complicated modulation technique to embed unique IDs to signals from different LED panels. An inexpensive photo diode is used as the receiver. Thus, our positioning system can be deployed easily and costlessly, yet can achieve high estimation accuracy.

2 Lighting placement and channel model

2.1 Lighting placement

Our system is modeled in the room measuring $5 \times 5 \times 3\,\text{m}^3$. A 3×3 lighting equipment grid is installed at the height of 0.5 m below the ceiling as shown in Fig. 1. Except the center LED panel, which is placed right at the center of the room, other panels have the same distance to the nearest walls. Easily we can see that the position of all LED panels can be specified when knowing the distance from the outer panels to their nearest walls. The receiver is placed anywhere under these LED panels.

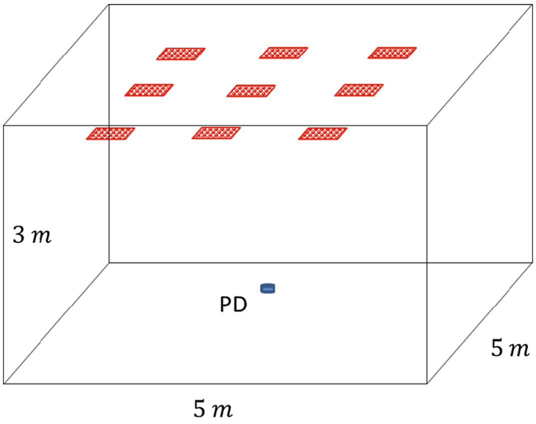


Fig. 1 The model room

2.2 Channel model

Like other positioning system using visible light radiated from LED lamps, our system also has both function of illuminating and positioning. In this paper, however, we just focus on the positioning aspects. Therefore, only things related to positioning performance are explained in this section. The system performance about illumination can be found in [11].

2.2.1 Impulse response

In our system, the photo diode receives the light radiated from LED lamps to find the time difference of arrival of pilot signals. Basically, the light radiated from LED lamp may come to the receiver after any number of reflections in the walls. So both the direct and reflected light should be taken into account when estimating the performance of the system. In the center of the room, the impact of the direct light is much greater than that of higher-order reflected light. But in the regions near the walls, the impact of the reflected light becomes noticeable and degrades the estimation accuracy at these regions. For example, according to [11], the rate of impulse responses of the direct, first and second reflected light at the corner of the room are 95.16, 3.57 and 1.27 %, respectively. For the preciseness of the system evaluation, we take into account the reflected light in the simulation. However, we only consider the first-order reflection for the sake of simplicity. The model of the reflected light is illustrated in Fig. 2. Each LED chip radiates light to all over the walls. And every single point on the wall becomes a diffuse light source, which scatters light to all directions.

The optical wireless channel can be modeled as:

$$Y(t) = \gamma X(t) \otimes h(t) + N(t), \tag{1}$$

where $Y(t)$ is the output signal, $X(t)$ is the input signal, $N(t)$ is the additive noise, γ is the detector responsivity, $\otimes$ denotes convolution and $h(t)$ is the impulse response. Assume that the light radiated from LED and reflected from the walls all have Lambertian radiation pattern, the impulse response at

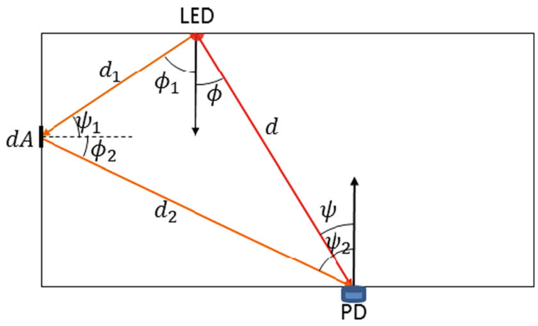


Fig. 2 Model of diffused link

the receiver of the direct and reflected light from LED lamp is given by

$$h(t) = h^{(0)}(t) + \int_{\text{walls}} h^{(1)}(t) \tag{2}$$

where $h^{(0)}(t)$ is the impulse response of the direct light given by Eq. (3), and $h^{(1)}(t)$ is the impulse response of the first reflection given by Eq. (4):

$$h(t) = \begin{cases} \frac{m+1}{2\pi d^2} A\cos^m(\phi) T_s(\psi) g(\psi) \cos(\psi) \\ \times \delta(t - \frac{d}{c}),\ 0 \le \psi \le \Psi_c \\ 0, \quad \psi > \Psi_c \end{cases} \tag{3}$$

$$h^{(1)}(t) = \begin{cases} \frac{(m+1) A \rho d A}{2\pi^2 d_1^2 d_2^2} \cos^m(\phi_1) \cos(\psi_1) \cos(\phi_2) T_s(\psi_2) \\ \times g(\psi_2) \cos(\psi_2) \delta(t - \frac{d_1+d_2}{c}), 0 \le \psi_2 \le \Psi_c \\ 0, \qquad \psi_2 > \Psi_c \end{cases} \cdot \tag{4}$$

In the equations above, ϕ and ϕ_1 are the irradiance angles of the light from LED, ψ and ψ_2 are the incidence angles of the light coming to PD, d is the distance between the LED and the PD, c is the speed of light, A is the physical area of the detector in the PD, $T_s(\psi)$ is the gain of the optical filter, $g(\psi)$ is the gain of the optical concentrator, and Ψ_c is the field of view at the PD, δ is the delayed Dirac delta function, ρ is the wall reflectance, dA is the reflective area of small region in the wall, d_1 is the distance between LED and reflective point, d_2 is the distance from reflective point to receiver, ψ_1 is the incidence angle of the light coming to the wall, ϕ_1 is the irradiance angle of the reflected light from the wall and m is the order of Lambertian emission, which is related to the semi-angle at half power $\Phi_{1/2}$ by the equation:

$$m = -\ln 2 / \ln(\cos(\Phi_{1/2})). \tag{5}$$

2.2.2 Noise

According to [11], the values of shot noise variance and thermal noise variance are given by Eqs. (6) and (7), respectively

$$\sigma^2_{\text{shot}} = 2q\gamma P_r B + 2q I_{bg} I_2 B, \tag{6}$$

$$\sigma^2_{\text{thermal}} = \frac{8\pi k T_k}{G} \eta A I_2 B^2 + \frac{16\pi^2 k T_k \Gamma}{g_m} \eta^2 A^2 I_3 B^3. \tag{7}$$

All of the parameters used in Eqs. (6–7) are listed in Table 1.

Table 1 System parameters

Parameters	Value
Detector responsivity	$\gamma = 0.54$ (A/W)
Electronic charge	$q = 1.602\text{e}{-19}$ (C)
Boltzmann's constant	$k = 1.38066\text{e}{-23}$
Absolute temperature	$T_k = 295$ (K)
Open-loop voltage gain	$G = 10$
FET channel noise factor	$\Gamma = 1.5$
Fixed capacitance	$\eta = 112$ (pF/cm^2)
Background light current	$I_{bg} = 5{,}100$ (μA)
Data rate	$B = 100$ (Mb/s)
Noise bandwidth factor	$I_2 = 0.562$
Noise bandwidth factor	$I_3 = 0.0868$
FET transconductance	$g_m = 30$

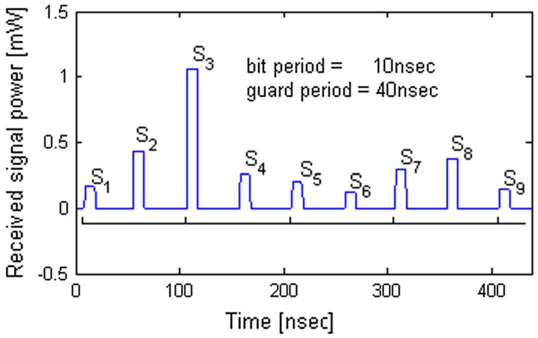


Fig. 3 Received pilot signals

3 Proposed positioning technique

3.1 Pilot signal generation scheme and detection method

Each LED panel sequentially transmits a single rectangular pulse of pilot signal after every guard time period. All pilot signals have the same pulse width. Thus, after a period of time, the receiver receives a series of pilot signals from all LED panels in the room. Figure 3 shows a series of pilot signals coming to the receiver where S_i indicates the pilot signal from the i-th LED panel.

The length of guard time period is chosen so that the previous pilot signal causes no or very little interference to the next pilot signal. In this paper, the bit period of every pilot signal is 10 ns. With considering the period of pilot signal as well as the room size, the guard period is chosen to be 40 ns.

The cross-correlation is used to detect each single pilot signal in the series of pilot signals. Then, the information of arrival time of pilot signals can be obtained. Figure 4 shows how the pilot signal can be detected using cross-correlation.

We see that with this scheme, the pilot signal comes to the receiver without any information about the LED panel where it is radiated. As a result, the receiver has no idea about the source of pilot signal it receives. This simple scheme for generating pilot signal allows us to implement the system easily. However, it will take more time to estimate the receiver position due to the process of guessing signal IDs. As it can be seen in the next section, the procedure of estimating receiver position is still fast given that the number of LED panels is not so many.

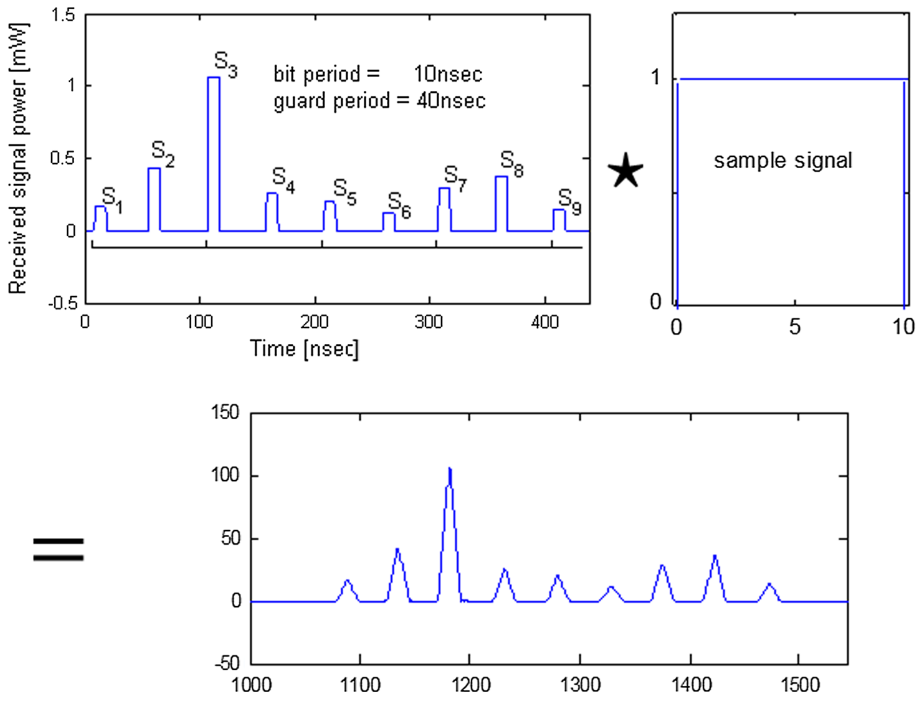


Fig. 4 Pilot signal detection

3.2 Estimate receiver's position

3.2.1 Estimate receiver's position with known signal ID

By using cross-correlation, the time difference of arrival of pilot signals is obtained. From the time difference, the difference of distances from receiver to LED panels can be calculated easily by multiplying the time differences to the speed of light. Given that the signal ID is known, the position of transmitters is known also.

Basically, the distance difference from the receiver to two transmitters with known positions specifies a unique hyperboloid that the receiver lies in. Figure 5 shows a hyperboloid we can draw when knowing the position of the two LED panels and the distance difference from the receiver to these two LED panels.

Assuming that the height position of the receiver is known, we can find the intersection of the hyperboloid and the Z-plane of receiver height, which is the unique conic in 2-D plane containing the receiver. Thus, with two or more time differences, we have two or more conics that the receiver lies in. The intersection of these conics is the receiver position.

3.3 Estimate receiver's position with unknown signal ID

Usually, the signal ID as well as the position of transmitters is compulsory to be known to estimate the receiver's position. In most positioning system, pilot signal is transmitted with an ID embedded. This requires the costly system implementation.

We see that with the transmission scheme of pilot signal described in the previous section, signals come to the receiver without any information about where they are from. However, given the number of transmitters is sufficient, the solution described later allows us to estimate the receiver's position without knowing the signal ID.

When a series of signals is received, the possible ID combinations of these signals can be guessed. Since the pilot signals from different LED panels are transmitted in a sequential way, there is only n possible combinations of signal ID if n LED panels are used.

With k received pilot signals, we have $k - 1$ time differences of arrival. Then, the same number of unique conics that the receiver is supposed to lie in can be specified. Ideally, these conics all intersect at the same point, which is the exact position of the receiver. These conics, however, usually meet in more than one point due to noises. In this case, there are up to $\binom{k-1}{2}$ intersections between these conics can be found. With the correct guessed IDs of pilot signals, these intersections are supposed to be converged. On the contrary, we are expected to get divergent intersections if the guessed signal ID is incorrect.

Figure 6 shows two cases of guessing signal IDs. Figure 6a corresponds to the case when the guessed IDs are correct. All intersections are closed to each other. In the case of Fig. 6b, the guessed signal IDs are incorrect and the each intersection is remote from the others.

From the foregoing, we see that the exact signal IDs as well as receiver's position basically can be found by comparing the

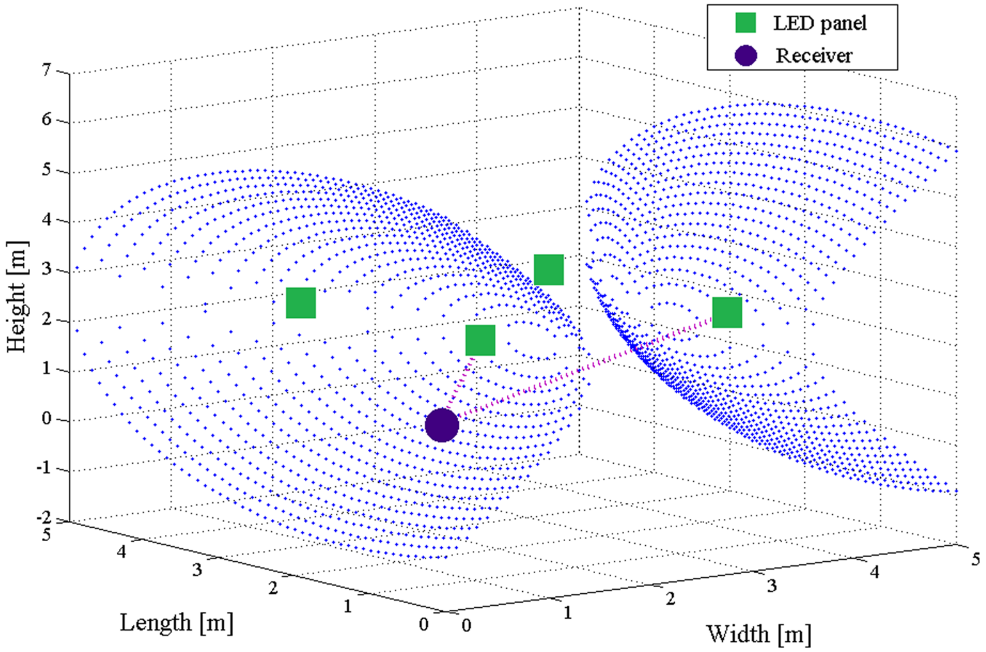


Fig. 5 Hyperboloid defined by distance difference

variation in conic's intersections. In most cases, the information about intersection variation is sufficient to decide which combination of signal IDs is correct. In some of rare case, the wrong signal ID combination, however, gives smaller variation in conic's intersection compared to the correct one. Therefore, besides the variation in intersections, the information about signal strength is also utilized to determine the correct signal IDs. Figure 7 describes our proposed procedure of position estimation in detail.

Suppose that we have *n* LED panels, then we have the iteration of *n* times guessing signal IDs. A combination of signal IDs is assumed in each iteration. According to that assumption, intersections of conics that the receiver possibly lies in are found. The current estimated position is the mean point of these intersections.

To determine which signal IDs' combination is correct, we need two kinds of information, which are mentioned before. The first information is the variation in intersections. The second one is the error which is calculated based on received signal strength (RSS).

To calculate RSS-based error, firstly we sort all received signals in the order of increasing signal strength. Thus, we have a list of signal IDs sorted based on RSS. Note that the IDs in this list are just guessed IDs. Now that we know the exact position of LED panels, we can calculate the distances from the current estimated position to these LED panels. After that, the list of LED panels is sorted in the order of increasing of estimated distances. Thus, we have a second list of panel IDs, which are also signal IDs, sorted based on distances from the receiver to LED panels. Because the received signal strength is proportional to the distance, these two list of signal ID should be identical if the guessed signal IDs are correct. The RSS-based error can be calculated simply as the number of pair of IDs in the two list that do not match each other. For example, if the signal IDs list sorted based on RSS is 2, 1, 3, 5, 8 and the one sorted based on distance is 2, 1, 4, 5, 6, the RSS-based error is 2. If the two lists are identical, the RSS-based error is zero.

The guessing error is calculated as the summation of the intersection variation and the RSS-based error. After *n* iterations of guessing and calculating, the correct combination of signal IDs as well as the correct position of the receiver can be identified as the one giving smallest guessing error.

4 Simulation result and discussion

4.1 Simulation environment

We simulate the system with the room model and LED placement described in Sect. 2 by Matlab. The specification of LED and PD used in the simulation is listed in Table 2. Parameters for calculating shot noise and thermal noise are listed in Table 1.

For the accuracy of the simulation, we include all the effects of shot noise, thermal noise and the noise caused by reflected light from the wall. As above mentioned, we only consider the first order of reflection in the simulation. Similar to [11], we assume that all the four walls of the room have the reflectance of 0.54. Each region of $0.2 \times 0.2\,\mathrm{m}^2$ in the wall

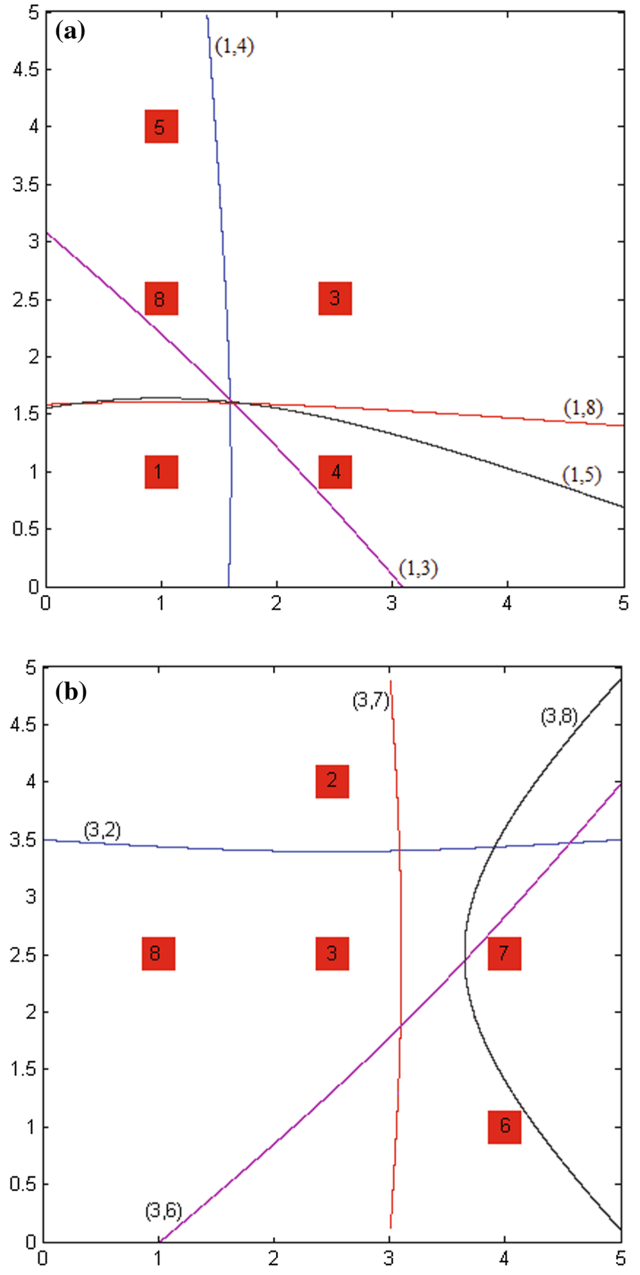


Fig. 6 Two cases of guessing signal IDs. **a** Right guessing of signal IDs, **b** wrong guessing of signal IDs

is considered as a single diffuse light source, which scatters light to all directions following the Lambert's emission law.

We simulate the system performance at 250 × 250 points equally spaced in the room. Each simulated point will be at a distance of 0.02 m from its neighbors.

4.2 Basis simulation result

Figure 8a shows the distribution of estimation distance errors in all over the room. It is easy to see that at the region near the

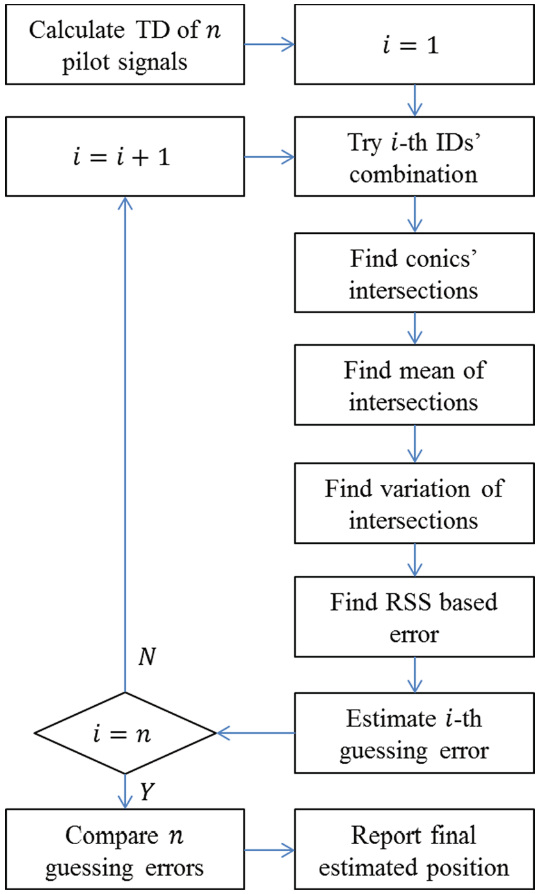
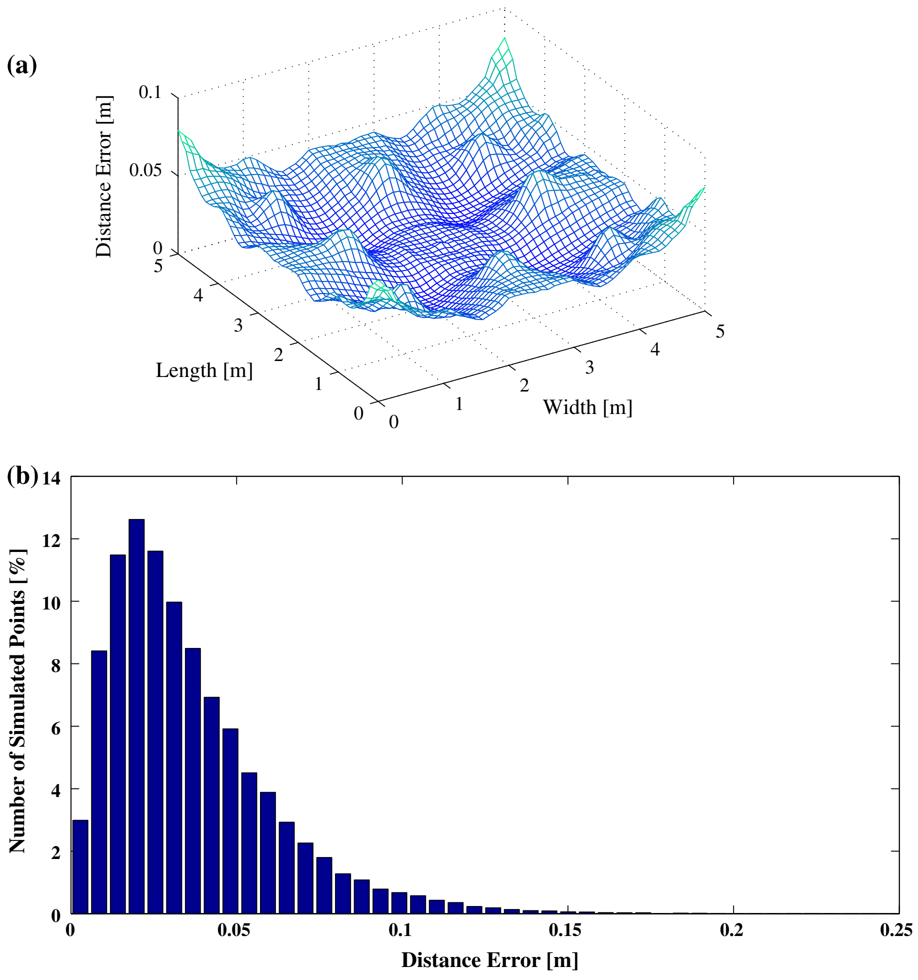


Fig. 7 Procedure of position estimation

Table 2 Simulation parameters

Parameters	Value
Transmitted optical power	20 (mW)
Semi-angle at half power	70 (°)
Refractive index	1.5
FOV at a receiver	60 (°)
Gain of an optical filter	1.0
Detector area in PD	1.0 (cm^2)
Wall reflectance	0.54
Area of each small region in the walls	0.2 × 0.2 (m^2)
Number of simulated points in the room	62,500 (250 × 250)
Interval between two simulated points	0.02 (m)
Number of LED panels	9(2 × 2)
Interval between LEDs	0.01 (m)
Number of LEDs in each panel	1,600(40 × 40)
Bit period of pilot signal	10 (ns)
Guard period	40 (ns)
Number of LED panel	3 × 3
LED panel to nearest walls distance	1 (m)
Clock precision	1 (ns)

Fig. 8 The performance of the positioning system. **a** Distribution of estimation distance error, **b** histogram of estimation distance error



walls and especially near the corner, the performance is poor compared to that at the center. This is because the reflected light has more impact than the direct light in these regions. There are also other reasons related to the curvedness of the conics, which will be discussed later.

Figure 8b shows the histogram of the estimation distance error. We see that at most region in the room, the distance error is less than 10 cm.

4.3 Discussion about error in estimation

In this section, we will discuss about the reason causing errors in the estimation. Because there is always noises such as thermal noise, shot noise, or reflected light from the walls, the signal received by the PD always contains measurement errors. Hence, the conic curves we can draw from TDOA information and their intersections are also incorrect. While the measurement error is an unavoidable factor, its effect differs from position to position in the room.

The measurement error is greater when the signal is weaker. The measurement at the corner region contains more error compared to that at the center because of the farther distance to neighbor LED panels.

Another important factor affect the precision of the found intersections is the curvedness of the conics. When the receiver is located at the bisector of two panels, the conic specified by the TDOA information is a straight line. When the receiver moves away from this bisector, the conic get curved. The farther the receiver moves from this bisector, the more curved the conic is. As can be seen in Fig. 6b, the conic (3,7) corresponds to the receiver located in the inside region of panel 3 and panel 7. The conic (3,8) corresponds to the receiver located in the outside region of panel 3 and panel 8. Therefore, the conic (3,8) is more curved than the conic (3,7).

The error caused by the incorrect signals from remote LED panels can be minimized by using only strong signals from near LED panels. The error caused by the curvedness of the conics can also be minimized by moving LED panels to the room corners so that the receiver will locate inside LED panels.

Figure 9 shows estimation error corresponding to different panel positions. In both figures, the receiver is placed at the same position. However, depending on the position of

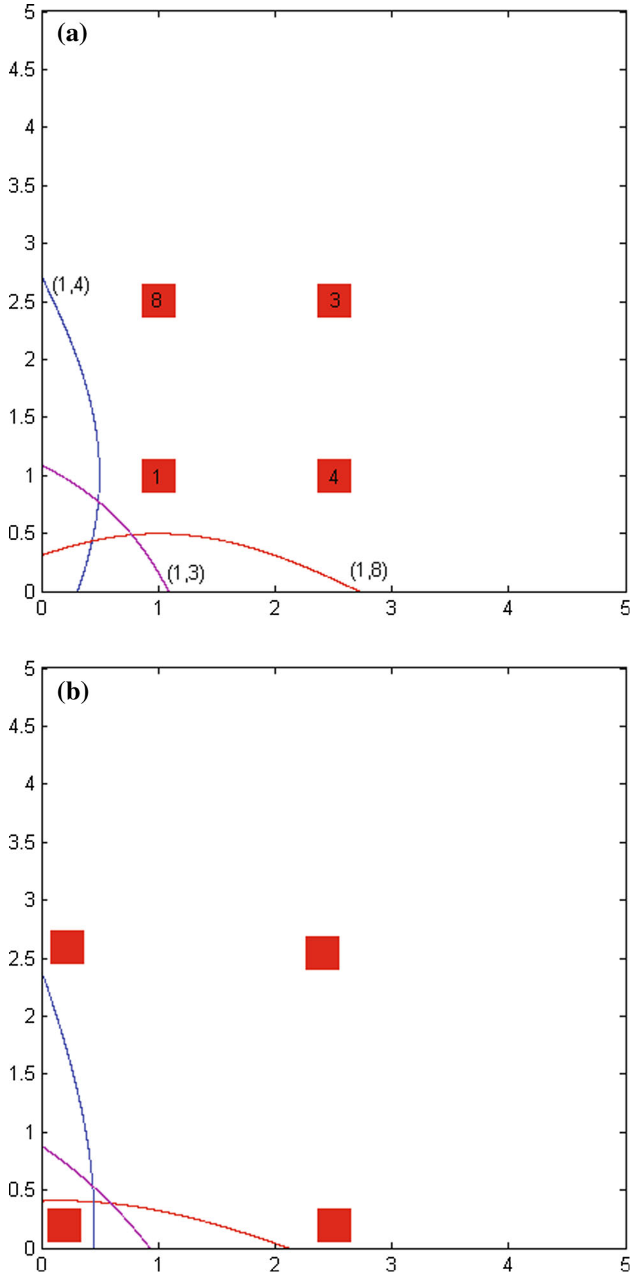


Fig. 9 Error corresponding to different panel position. **a** Error when receiver placed outside panels, **b** error when receiver placed inside panels

LED panels, the estimation error is different. In Fig. 9a, the distance from LED panels to their nearest walls is 1 m. In this case, the receiver is located outside of the four nearest LED panels. In Fig. 9b, the distance from LED panels to their nearest walls is 0.2 m. In this case, the receiver is located inside the four nearest LED panels. We can see that the conics in the first case are more curved compared to that of the second case. The curvedness amplifies the measurement errors in that it makes the conics intersect at remote position from each other. In both figure, the conic (1,3) corresponds to panel 1 and panel 3, which is the farthest panel from the receiver. So the TDOA information from this pair of panel is the least reliable information compared to other two TDOA information (1,4) and (1,8). In this case, we should ignore the conic (1,3) to get better estimation accuracy.

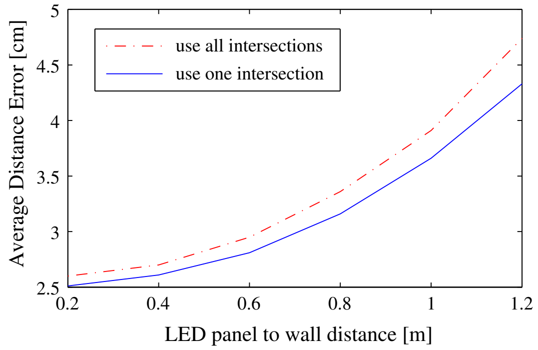


Fig. 10 Estimation accuracy and panel position

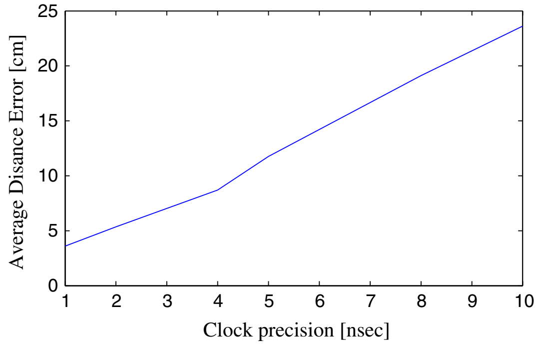


Fig. 11 Estimation accuracy and clock precision

We run the simulation to test the estimation accuracy of the system corresponding to different LED panel position, which is indicated by the distance from the panels to their nearest wall distance. The simulation uses the same setting described in Table 2 except that the LED panel to nearest wall distance now is changed within the range from 0.2 to 1.2 m. The simulation result is shown in Fig. 10.

In the first simulation, all conic intersections are taken into account to estimate the receiver's position. In the second simulation, the intersection of the two conics corresponding to the three strongest signals is used as the estimated position. Through the figure, we see that the closer the distance from the panel to the walls, the higher accuracy of estimation we can get. Furthermore, only using the most reliable intersection always gives higher estimation accuracy than using all intersections.

Our positioning system bases on the time difference of arrival of pilot signals, which is very small due to the high speed of light. The system should be able to measure these time difference precisely to achieve accurate estimation. We found that the precision of the estimation is affected mostly by the precision of the clock. Figure 11 shows the average distance error corresponding to different precision of the clock. The simulation setting is described in Table 2 except that the clock precision now is changed within the range from 1 to 10 ns. Through the figure, we see that if the clock precision is one nanosecond, the average distance error is 3.9 cm. The distance error can grow up to 23.6 cm if the clock precision is 10 ns.

5 Conclusion and future work

In this paper, we propose an indoor positioning system based on TDOA using the LED light. A contribution of our proposed system is that no ID information about the LED panel is required to transmit along with the pilot signal. This makes the modulating pilot signal become simple. Since we use TDOA technique, it is not required that the receiver must have a good clock to retrieve the exact time of arrival of pilot signals. Also, our system uses a cheap photo diode to receive the light from LED panels. Hence, it can be deployed easily and costlessly.

We simulate the performance of the system at all over the room measuring $5 \times 5 \times 3\,\text{m}^3$. For the truth of the simulation, we include the effect of noises such as shot noise, thermal noise and the noise caused by reflected light. The simulation result shows that our system can achieve a high accuracy estimation of 3.9 cm in average giving that the clock precision is 1 ns, which is less than most existing indoor positioning system using LED light.

As a future work, the proposed positioning system will be implemented and experimented.

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