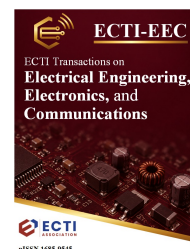


Interference mitigation for indoor proximity-based visible light positioning using receiver's angle diversity

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Interference Mitigation for Indoor Proximity-Based Visible Light Positioning Using Receiver's Angle Diversity

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ABSTRACT

This work considers proximity-based indoor visible light positioning (VLP) in which the user location is specified through the coordinate of the closest light emitting diode (LED) light source. For applications with human users, tilting of a handheld receiver device may lead to positioning errors due to signal interference from an adjacent LED light source. This work investigates the use of multiple photodiodes (PDs) with angular diversity to improve the positioning accuracy in the presence of receiver's tilting, with a unique focus on using multiple PDs to mitigate the problem of signal interference instead of widening the coverage of each LED. First, it is argued that at least four PDs are required on a pyramid structure to effectively mitigate signal interference. Then, performance analysis in terms of the positioning error probability is presented, to be followed by results on the outage percentage defined as the percentage of receiver positions at which positioning error probabilities exceed some acceptable threshold. After evaluating error performances, the error probability expressions are used to optimize the orientation angle of the PDs attached to a pyramid structure. Finally, hardware experiments are conducted to validate the proposed approach.

Keywords: Indoor Localization, Visible Light Positioning, Signal Interference, Angular Diversity, Positioning Error

1. INTRODUCTION

Unlike outdoor positioning, which typically relies on Global Navigation Satellite Systems (GNSSs) including the well-known Global Positioning System (GPS), indoor positioning remains relatively an open problem [1, 2]. Visible light positioning (VLP) is an attractive choice for indoor positioning since it can utilize existing illumination infrastructures that contain light emitting diode (LED) light sources to transmit data signals used for positioning. In addition, compared to radio frequency (RF) based indoor positioning systems, e.g., Wi-Fi and Bluetooth, VLP is immune to signal interferences from RF wireless devices and systems in surrounding environments.

VLP is a special case of optical wireless communications (OWC). For outdoor long-distance and high-rate transmissions, OWC is referred to as free-space optical (FSO) communications, and utilizes lasers for data transmissions. In [3, 4], FSO transmissions are analyzed in terms of the signal-to-noise ratios (SNRs), the bit error rates (BERs), and the Q factors subject to varying channel conditions. In [4], multi-input multi-output (MIMO) transmissions are investigated for reliability improvement from spatial diversity.

When the optical wavelength falls within the visible range, OWC is referred to as visible light communications (VLC). Unlike FSO, VLC typically relies on LED light sources that perform dual functions of illumination and data transmissions [5, 6]. While most VLC systems aim to support indoor spaces, the investigation in [7] considers outdoor VLC and the associated line coding for power spectral control. When VLC is used for positioning, it is referred to as VLP.

Comprehensive surveys of existing works on VLP are available in [8–11]. While VLP can provide detailed position estimation in terms of two-dimensional (2D) or three-dimensional (3D) position coordinates [12, 13], for several applications involving human users, it is sufficient to provide a whereabouts of each user in terms of the position of the closest LED light source. This simplified approach is referred to as proximity-based VLP [8, 11]. With respect to the optical sensor at a receiver, VLP can be categorized into camera-based and photo diode (PD)-based systems [11]. Compared to cameras that capture images, PDs that measure received signal strengths (RSSs) are in general cheaper. In addition, PD based VLP does not require computational resources, both in terms of hardware and processing time, for image processing.

Proximity-based VLP systems have been implemented, both by using cameras [14] and by using PDs [15, 16]. This work focuses on proximity-and-PD-based VLP for potential low-cost system implementation. Its potential applications include tracking of people requiring assistance and indoor navigation for pedestrians. Such a system can operate along a walkway where a user device needs to receive a data signal from just one LED light source for positioning. When multiple data signals reach the user de-

vice, the position of the LED with the highest RSS is detected and used as the position estimate. However, when a user moves towards an adjacent LED light source, signal interference from the further LED may become strong and cause positioning errors. In [15, 16], the effects of signal interference from an adjacent LED light source are analyzed in terms of the positioning error probability. Moreover, time division multiplexing (TDM) for data transmissions from adjacent LED light sources is investigated for interference mitigation.

The interference problem in proximity-based VLP is aggravated when the receiver module in the user device is tilted towards a further LED. While receiver tilting may be limited when the receiver is mounted on top of a moving robot, it may be quite significant for a handheld device used by human. Mitigating the interference problem for proximity-based VLP in the presence of receiver tilting is the main objective of this work. For 3D VLP systems that are not proximity-based, e.g., [17, 18], receiver tilting can be handled through joint estimation of position and orientation of the receiver. However, these joint estimation approaches rely on having data signals from more than two LEDs, e.g., through multilateration, which may not be available for the walkway scenario for proximity-based VLP considered in this work.

The use of multiple PDs with angular diversity has been considered for improving transmission performances from LED light sources [19–21]. In [19], the proposed receiver employs five PDs with a narrow field-of-view (FoV). These PDs are attached on a truncated four-faced pyramid structure, with one PD facing upwards at the top. Results from simulation experiments indicate improvement in the SNRs as well as the BERs from using such a receiver compared to using a single PD with a wide FoV.

In [20, 21], multiple PDs with angular diversity are used together with multiple LED transmitters in the multiple-input multiple-output (MIMO) system to improve transmission performances, i.e., higher data rates or lower BERs, provided to multiple users. In [20], it was pointed out that angular diversity helps make MIMO channels of different users more distinct, leading to less interference and improved data rates for those users. In [21], angular diversity of multiple PDs is achieved through using apertures that are vertically shifted compared to the normal vectors of the PDs. Different designs are compared in terms of the BERs by varying the aperture shape and the vertical distance between the apertures and the PDs.

The use of multiple PDs with angular diversity to handle signal interferences from adjacent LED light sources is considered in [22]. Two physical structures for mounting PDs are considered. The first structure is a pyramid with four attached PDs while the second structure is a hemi-dodecahedron with six attached PDs. Simulation results indicate improvement of the user data rates or the BERs obtained from using multiple PDs with angular diversity.

This work investigates the use of multiple PDs with angular diversity to mitigate the signal interference problem in indoor proximity-based VLP. Different from [22], receiver tilting is taken into account. In addition, this work considers detection of short data frames for the purpose of

positioning instead of continuous transmissions assuming synchronization as considered in [22]. Overall, the use of multiple PDs to mitigate signal interference from adjacent LEDs in the presence of receiver tilting is the unique focus of this work. The investigation is carried out using both mathematical analysis and hardware demonstration to support the analytical results. In particular, the key technical contributions in this work are as follows.

First, the performance of proximity-based VLP using multiple PDs with angular diversity is analyzed in terms of the positioning error probability, taking into account receiver tilting towards an adjacent LED light source. Numerical results are provided to demonstrate the performance improvement from using multiple PDs with angular diversity in terms of reducing the outage percentage defined as the percentage of receiver positions with positioning error probabilities above a present threshold, e.g., 10^{-12} . The results suggest that at least four PDs are needed at the receiver.

Next, the orientation vectors of the PDs attached to a pyramid structure are optimized for the case of a 4-PD receiver to minimize the maximum positioning error probability over all receiver positions along a walkway, and over certain ranges of receiver tilting in terms of yaw, pitch, and roll angles. Finally, hardware experiments are performed to validate the proposed method.

The remaining sections are as follows. The considered proximity-based VLP system model is presented in Section 2. Section 3 argues that at least four PDs are needed for angular diversity at a VLP receiver. Analysis of positioning error probability is presented in Section 4, followed by the definition of the outage percentage. Section 5 presents numerical results for system performances. Optimization of the PD orientations for the receiver is discussed in Section 6. Section 7 presents hardware experiments to validate the proposed approach. Finally, conclusion is provided in Section 8.

2. VLP SYSTEM MODEL

Consider an indoor proximity-based VLP system along a walkway. LED light sources are installed above the walkway on the ceiling at height H . Let W be the spacing between adjacent LED light sources. Consider a user with a handheld device that contains a PD-based optical receiver moving along the walkway. In particular, the user moves from position $(0, 0, 0)$ to position $(W, 0, 0)$, where LEDs 1 and 2 are at positions $(0, 0, H)$ and $(W, 0, H)$, respectively. Fig. 1 illustrates the system scenario considered in this work. Note that the zero height corresponds to the height of the receiver's device from the ground.

The receiver contains L PDs. The path gain from LED k , where $k \in \{1, 2\}$, to PD l , where $l \in \{1, \dots, L\}$, can be modelled based on the commonly used Lambertian emission pattern given by [5, 6]

$$h_{kl} = \begin{cases} \frac{\kappa(m+1)}{d_k^2} \cos^m \varphi_k \cos \psi_{kl}, & |\psi_{kl}| \leq \text{FoV} \\ 0, & \text{otherwise} \end{cases} \quad (1)$$

where κ is the constant of proportionality including the effects of the PD surface area and the optical-to-electrical conversion factor, m is the Lambertian order of each LED light source, d_k is the distance between LED k and the receiver, φ_k is the angle of irradiance from LED k towards the receiver, and ψ_{kl} is the angle of incidence at PD l with respect to LED k , and FoV is the receiver's field of view. The geometry related to parameters d_k and φ_k in (1) is illustrated in Fig. 1, while the geometry related to parameter ψ_{kl} in (1) is illustrated in Fig. 2.

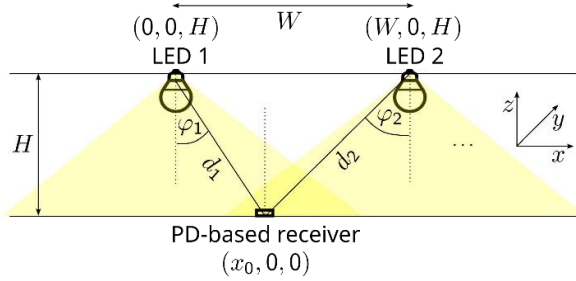


Fig. 1: Scenario for an indoor VLP system along a walkway. The receiver held by a user is at position $(x_0, 0, 0)$, where x_0 varies from 0 to W .

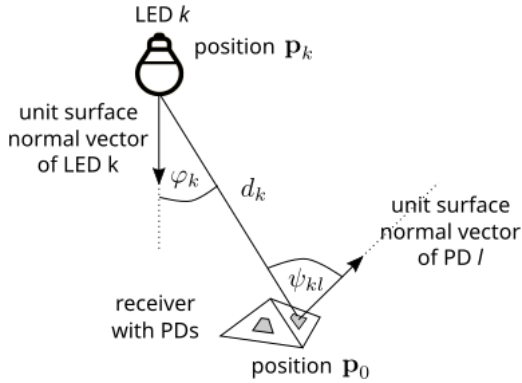


Fig. 2: Geometry of the angle of irradiance φ_k and the angle of incidence ψ_{kl} in (1). The PDs are close to one another such that the distances from LED k to all PDs are approximately equal and denoted by d_k .

Assume that each LED points directly down, i.e., its unit surface normal vector in Fig. 2 is $\mathbf{u}_k = (0, 0, -1)$. Assume that, when the receiver lies flat on the ground and heads towards direction vector $(1, 0, 0)$, referred to as the baseline receiver orientation, the unit surface normal vector of PD l is

$$\mathbf{v}_l = \mathbf{R}(\alpha_l, \beta, 0) \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} \cos \alpha_l \cos \beta \\ \sin \alpha_l \cos \beta \\ -\sin \beta \end{bmatrix}, \quad (2)$$

where α_l is the yaw angle of PD l , β is the pitch angle of each PD, and $\mathbf{R}(a, b, c)$ denotes the standard rotation matrix with yaw, pitch, and roll angles in the counterclockwise direction around the z , y , and x axes equal to a , b , and

c , respectively. In particular, $\mathbf{R}(a, b, c)$ can be expressed as given below.

$$\mathbf{R}(a, b, c) = \mathbf{R}_z(a) \mathbf{R}_y(b) \mathbf{R}_x(c) \quad (3)$$

$$\mathbf{R}_z(a) = \begin{bmatrix} \cos a & -\sin a & 0 \\ \sin a & \cos a & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad (4)$$

$$\mathbf{R}_y(b) = \begin{bmatrix} \cos b & 0 & \sin b \\ 0 & 1 & 0 \\ -\sin b & 0 & \cos b \end{bmatrix} \quad (5)$$

$$\mathbf{R}_x(c) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos c & -\sin c \\ 0 & \sin c & \cos c \end{bmatrix} \quad (6)$$

With respect to the baseline orientation, when the receiver is rotated and tilted with yaw, pitch, and roll angles equal to α' , β' , and γ' , the unit surface normal vector of PD l becomes

$$\mathbf{v}_l' = \mathbf{R}(\alpha', \beta', \gamma') \mathbf{v}_l. \quad (7)$$

Let $\mathbf{p}_k$ denote the position of LED k , and $\mathbf{p}_0$ denote the position of the receiver. Note that, in Fig. 1, $\mathbf{p}_0 = (x_0, 0, 0)$ with $0 \leq x_0 \leq W$. To compute the path gain in (1), the cosine terms can be computed as follows.

$$\cos \varphi_k = H/d_k \quad (8)$$

$$\cos \psi_{kl} = \frac{(\mathbf{p}_k - \mathbf{p}_0)^T \mathbf{v}_l'}{d_k} \quad (9)$$

Each LED light source transmits a reference signal. Assume that reference signals from different LED light sources are chosen to be orthogonal. In particular, assume that these reference signals serve as headers of data frames containing LED position numbers whose data bits are mapped to inverse pulse position modulation (IPPM) symbols, as considered in [15, 16]. These headers can be based on the same signal waveform but are orthogonal to one another through TDM.

Based on intensity modulation at an LED with direct detection at a PD, referred to as IM/DD, the received signal at PD l from LED k transmitting at power P_k is

$$r_{kl} = h_{kl} P_k + n_{kl}, \quad (10)$$

where h_{kl} is the path gain as computed in (1) and n_{kl} is additive white Gaussian noise (AWGN) with zero mean and variance σ^2 .

The receiver combines the signals received from L PDs and then detects the header of a data frame by computing the signal correlation with respect to the common header waveform over an observation window that is longer than one data frame. The position with the maximum correlation determines the frame header. After frame header detection, the corresponding LED position number

is then detected through IPPM symbols contained in the frame.

A positioning error happens when the receiver detects a position number that is not the number of the closest LED. The detection error probability, denoted by P_e , is the ratio between the number of positioning errors and the total number of detections made. In this work, the outage percentage, denoted by P_{out} , is defined as the percentage of receiver positions with P_e above a certain preset threshold, e.g., 10^{-2} .

3. RECEIVER STRUCTURES WITH MULTIPLE PHOTODIODES

This section argues that, to mitigate signal interference from adjacent LEDs, at least four PDs with angular diversity should be used at the receiver. First, the effects of receiver's tilting are demonstrated for a receiver with up to four PDs tilted from their baseline orientations at the pitch angle of $\beta' = 20^\circ$. Note that, when the receiver is closer to LED 1 in Fig. 1, this tilting turns the receiver towards LED 2. Fig. 3 shows the physical structures used to mount 1, 2, 3, and 4 PDs at the receiver together with the baseline orientation of each case.

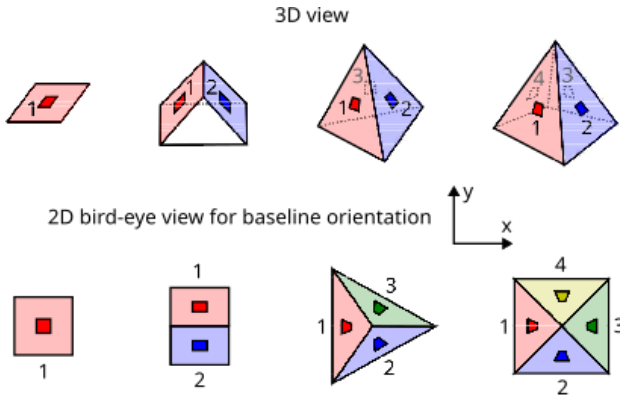


Fig. 3: Physical structures for mounting PDs and their baseline orientations.

In proximity-based VLP, the total path gains from LED 1 and from LED 2 to all PDs can be used to identify which LED yields a stronger RSS and will thus likely be identified as the current receiver position. Note that position detection also depends on noise. Therefore, a higher total path gain will likely but may not always lead to the corresponding LED position being detected by the receiver.

Fig. 4 shows the total path gain from each LED to all PDs for the cases of 1, 2, 3, and 4 PDs in Fig. 3. Each path gain is computed using (1) and the following system parameters: $H = 1.5$ m, $W = 2.5$ m, $\kappa = 1$, $m = 1$, $\text{FoV} = 90^\circ$, and $\beta = -25^\circ$.

In each case of Fig. 4, for $x_0 < 1.25$ m, a positioning error is likely when the total path gain from LED 2 is higher. The percentage of $x_0 < 1.25$ m for which the gain from LED 2 is higher becomes small when 4 PDs are used. Intuitively, for 1 PD and 2 PDs, it can be seen from Fig. 3 that tilting the receiver towards LED 2 will make each PD

look towards LED 2 and thus receives a stronger signal from LED 2. For 3 PDs, tilting the receiver towards LED 2 will make 2 out of 3 PDs look towards LED 2. While the remaining PD looks towards LED 1, the total interference from LED 2 received by the other two PDs can be stronger.

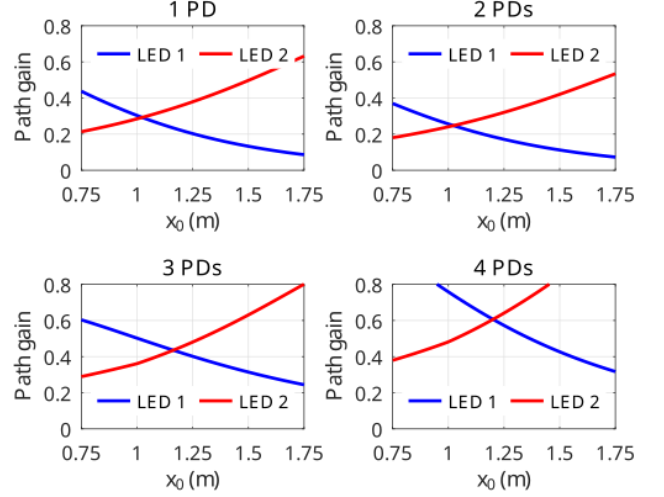


Fig. 4: Total path gains from LEDs 1 and 2 to all PDs for the cases of 1, 2, 3, and 4 PDs with the receiver tilting towards the positive x -axis by 20° .

Using 4 PDs mitigates the interference problem caused by tilting the receiver, as can be seen by the last case of Fig. 4. In the next section, the positioning error probabilities will be quantified, and then used to evaluate the outage percentages for the considered scenario in Fig. 1.

4. POSITIONING ERRORS AND OUTAGE PERCENTAGES

Assume the use of orthogonal reference signals with respect to LEDs 1 and 2. In particular, each reference signal consists of p pulses each with amplitude A in an interval containing a fixed number of timeslots, e.g., $2p$, with one timeslot for each possible pulse position. In particular, when $p = 4$ and there are 4 pulses in the first 4 timeslots, the reference signal can be written in terms of the pulse amplitudes in 8 timeslots as $(A, A, A, A, 0, 0, 0, 0)$. Accordingly, the reference signal from the other LED is $(0, 0, 0, 0, A, A, A, A)$ for orthogonality. These signal values are transmitted using IM/DD. With the path gain h_k from LED k , where $k \in \{1, 2\}$, the received pulse amplitude with respect to LED k is $h_k A$.

With L PDs at the receiver, let $h_{k1}, \dots, h_{kL}$ denote the path gains from LED k to PDs 1, $\dots$, L , respectively. When the receiver detects a reference signal based on the maximum correlation with the frame header signal waveform, under LED 1, a positioning error corresponds to the following event in which the sum of correlations as received by the L PDs for reference signal 1 falls below the sum of correlations for reference signal 2, i.e.,

$$pA^2 \sum_{l=1}^L h_{1l} + \sum_{l=1}^L n_{1l} < pA^2 \sum_{l=1}^L h_{2l} + \sum_{l=1}^L n_{2l}. \quad (11)$$

In (11), $n_{11}, \dots, n_{1L}$ are AWGN values in the correlations with respect to reference signal 1 at PDs 1, $\dots$, L , respectively. Similarly, $n_{21}, \dots, n_{2L}$ are AWGN values with respect to reference signal 2. Note that, after correlation computations with respect to the orthogonal frame header signal waveforms, these noise values are independent and identically distributed (IID) Gaussian noise with mean 0 and variance $pA^2\sigma^2$. Under LED 2, a position detection error corresponds to the following event, where the noise values are as previously defined.

$$pA^2 \sum_{l=1}^L h_{1l} + \sum_{l=1}^L n_{1l} > pA^2 \sum_{l=1}^L h_{2l} + \sum_{l=1}^L n_{2l}. \quad (12)$$

As pointed out in [15], positioning errors are dominated by header detection errors (as described above) in comparison to symbol detection errors that can possibly happen later on in detecting the position number from the associated data frame.

It follows from (11) and (12) that a positioning error happens with the following conditional error probabilities given that the receiver is under LED 1 and under LED 2, denoted by $P_{e,1}$ and $P_{e,2}$, respectively.

$$P_{e,1} = Q\left(\left(\sum_{l=1}^L h_{1l} - \sum_{l=1}^L h_{2l}\right) \sqrt{\frac{p}{2L}} \frac{A}{\sigma}\right) \quad (13)$$

$$P_{e,2} = Q\left(\left(\sum_{l=1}^L h_{2l} - \sum_{l=1}^L h_{1l}\right) \sqrt{\frac{p}{2L}} \frac{A}{\sigma}\right) \quad (14)$$

In (13) and (14), Q denotes the complimentary cumulative distribution function (CCDF) of a standard Gaussian random variable, i.e., $Q(x) = 1/\sqrt{(2\pi)} \int_x^\infty \exp(-u^2/2) du$.

In the considered scenario in Fig. 1, the error probability depends on the receiver position $(x_0, 0, 0)$. Accordingly, $P_{e,1}$ and $P_{e,2}$ are used when $x_0 \leq W/2$ and $x_0 \geq W/2$, respectively. For performance evaluation, the outage percentage is defined as the percentage of positions obtained from $0 \leq x_0 \leq W$ at which positioning error probabilities are above a preset threshold denoted by $P_e^{\max}$.

5. PERFORMANCE EVALUATION

Using the expression of $P_{e,1}$ in (13), the error probabilities are computed for the receiver at $(x_0, 0, 0)$, where $x_0 \leq W/2$. By symmetry, the results based on $P_{e,2}$ in (14) yield similar trends for $x_0 \geq W/2$ and are therefore omitted. The considered system parameters are listed in Table 1. Note that, without loss of generality, the proportional constant κ is set to 1 in Table 1. The ratio A/σ is set such that the electrical signal-to-noise ratio (SNR) is equal to 30 dB at a PD located directly below an LED and facing upwards. In particular, from (1) and Table 1, when a pulse of amplitude

A is transmitted, the electrical signal power detected by a PD directly below an LED is equal to $(2A/1.5^2)^2 \approx 0.7901A^2$. For SNR = 30 dB, the ratio $0.7901A^2/\sigma^2$ is set to 1000, yielding $A/\sigma \approx 35.58$, which can be substituted in (13) to compute $P_{e,1}$.

Table 1: System parameters for performance evaluation.

Parameter	Notation	Value
Ceiling height (from receiver)	H	1.5 m
LED spacing	W	2.5 m
Gain constant	κ	1
Lambertian order	m	1
Receiver FoV	FoV	90°
PD pitch angle	β	-25°
Number of pulses in each reference signal	p	4
SNR below each LED	—	30 dB

Fig. 5 compares the error probabilities for the receivers with 1, 2, 3, and 4 PDs with and without tilting at 20°. In Fig. 5, while using a single PD (facing upwards) yields the best performance without receiver tilting, it yields the second worst performance with tilting. As expected from the previous section, using 4 PDs provides significantly better performances with receiver tilting compared to the other cases.

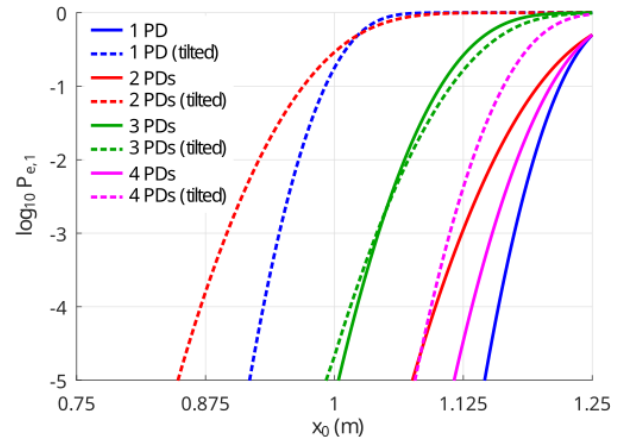


Fig. 5: Error probabilities for the receivers with 1, 2, 3, and 4 PDs with and without tilting at 20°.

From the results in Fig. 5, the outage percentages can be computed based on receiver locations with $0 \leq x_0 \leq W/2$. Table 2 compares the outage percentages for different numbers of PDs used at the receiver that is tilted at 20° towards the positive x -axis. It can be seen that using 4 PDs significantly reduces the outage percentages for both values of the error probability threshold ($P_e^{\max}$). In particular, the outage percentage below 10% can be achieved for $P_e^{\max} = 10^{-2}$.

Table 2: Outage percentages for different numbers of PDs with receiver tilting at 20° .

$P_{e,\max}$	1 PD	2 PDs	3 PDs	4 PDs
10^{-2}	22.7%	25.8%	14.3%	9.28%
10^{-3}	24.3%	28.3%	16.7%	11.0%

Fig. 6 shows error probabilities for the 4-PD receiver with different values of the pitch angle β for the PDs. For $\beta = -35^\circ$, the PDs face towards the ceiling the most. On the contrary, for $\beta = -15^\circ$, the PDs face away from the ceiling and towards the four sides the most. When the receiver is not tilted, having the PDs towards the ceiling (i.e., $\beta = -35^\circ$) yields the lowest error probabilities. With receiver tilting, having the PDs towards the four sides (i.e., $\beta = -15^\circ$) yields the lowest error probabilities. Since the receiver may or may not be tilted in practice, the choice of $\beta = -25^\circ$ provides a compromise such that the error probabilities are kept low with and without receiver tilting.

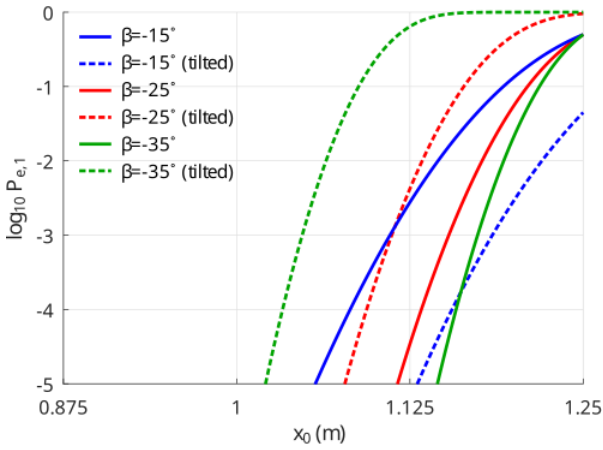


Fig. 6: Error probabilities for the 4-PD receiver with and without tilting at 20° .

Since the error probabilities significantly depend on the pitch angle β of the PDs attached to a pyramid structure. The next section covers optimization of the value of β taking into account receiver tilting.

6. OPTIMIZATION OF THE PITCH ANGLE FOR PHOTODIODES

6.1 Optimization over Receiver Positions and Tilt Angles

Choosing the pitch angle β for the 4-PD receiver can be formulated as an optimization problem whose objective is to minimize the maximum error probability ($P_{e,1}$) over a range of receiver position ($x_0, 0, 0$) and a range of tilt angle β' . For the purpose of optimization, assume that the target ranges are $0 \leq x_0 \leq 0.45W$ and $-20^\circ \leq \beta' \leq 20^\circ$. In other words, the target outage percentage is 10% while the target tolerable tilt angle is $\pm 20^\circ$.

In the expression of $P_{e,1}$ in (13), note that the factor $\sqrt{(p/2L) \times A/\sigma}$ is a constant independent of x_0 and β' . Since Q is a decreasing function of its argument, it follows that

minimizing the maximum of $P_{e,1}$ over x_0 and β' is equivalent to maximizing the minimum of $\sum_{l=1}^L h_{1l} - \sum_{l=1}^L h_{2l}$ over x_0 and β' . Therefore, the optimization problem for choosing β can be written as follows. First, define the objective function to be maximized for $L = 4$ (i.e., 4 PDs) as

$$f(\beta) = \min_{x_0, \beta'} \sum_{l=1}^4 h_{1l} - \sum_{l=1}^4 h_{2l} \quad (15)$$

The corresponding optimization problem is given below.

$$\begin{aligned} & \max f(\beta) \\ & \text{subject to } -90^\circ \leq \beta \leq 0^\circ \end{aligned} \quad (16)$$

Since the path gain expression of h_{kl} in (1) is a complicated nonlinear function of x_0 and β' , the optimization problem cannot be solved using standard algorithms. Therefore, the problem in (16) is numerically solved using the grid search. For the grid search, assume that $x_0 \in \{0, 0.225W, 0.45W\}$, $\beta' \in \{-20^\circ, 0^\circ, 20^\circ\}$, and $\beta \in \{-90^\circ, -89^\circ, \dots, 0^\circ\}$.

Fig. 7 shows the values of $f(\beta)$ in the optimization problem in (16) for $\beta \in \{-90^\circ, -89^\circ, \dots, 0^\circ\}$. It can be seen that the optimal value of β is -21° . Fig. 8 shows the error probabilities obtained from the 4-PD receiver optimized at $\beta = -21^\circ$, assuming the system parameters in Table 1.

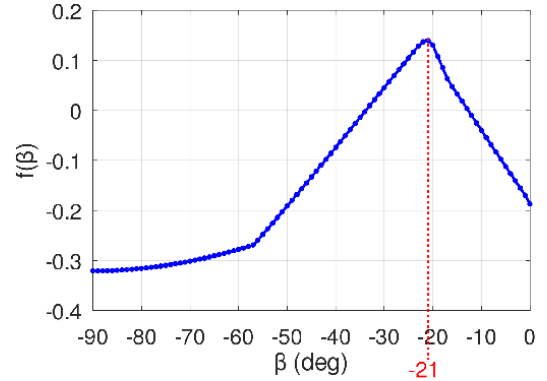


Fig. 7: $f(\beta)$ versus β for the objective function in (15).

For comparison, the error probabilities for $\beta = -25^\circ$, as used in Fig. 6, are also shown in Fig. 8 to demonstrate the optimality of $\beta = -21^\circ$. From the results in Fig. 8, for the outage percentage corresponding to the threshold $P_{e,\max} = 10^{-2}$, optimization of β reduces the outage percentage from 9.40% (in Table 2) to 6.53%.

Besides receiver tilting in terms of the pitch angle β' , it is practical to consider more general receiver positions and orientations. In the next section, optimization of β is performed taking into account a position offset in the y -axis (y_0), the receiver's yaw angle (α'), and the receiver's roll angle (γ').

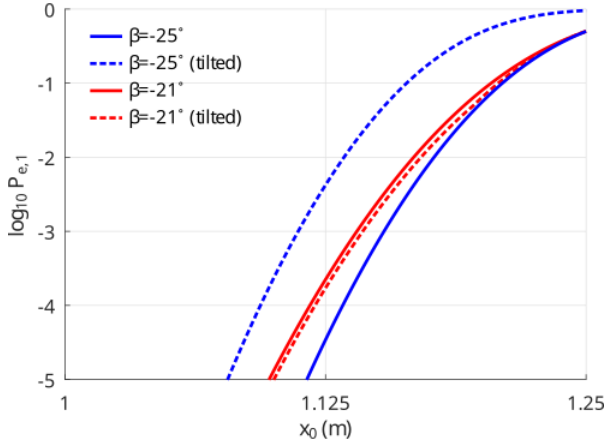


Fig. 8: Error probabilities for the 4-PD receiver optimized at $\beta = -21^\circ$ with and without tilting at 20° .

6.2 Optimization over General Receiver Positions and Orientations

Receiver tilting can be more generally modeled using the yaw, pitch, and roll angles (i.e., α' , β' , and γ') of the receiver orientation. In addition, practical receiver positions along the walkway may involve nonzero offsets along the y -axis denoted by y_0 . In this section, the optimization of β in (16) is generalized to take into account the ranges of parameters $x_0, y_0, \alpha', \beta', \gamma'$, as shown in Table 3. Note that the ranges of x_0 and β' are the same as in the previous section. In addition, due to the rotational symmetry of the 4-PD receiver in Fig. 3, it is sufficient to consider the yaw angle in the range $-45^\circ \leq \alpha' \leq 45^\circ$ to see the effects of rotation.

Table 3: Parameter ranges for optimization of β .

Parameter	Range	Discretized values
β	$[-90^\circ, 0^\circ]$	$-90^\circ, -89^\circ, \dots, 0^\circ$
x_0	$[0, 0.45W]$	$0, 0.225W, 0.45W$
y_0	$[-0.2W, 0.2W]$	$-0.2W, 0, 0.2W$
α'	$[-45^\circ, 45^\circ]$	$-45^\circ, -22.5^\circ, 0^\circ, 22.5^\circ, 45^\circ$
β'	$[-20^\circ, 20^\circ]$	$-20^\circ, 0^\circ, 20^\circ$
γ'	$[-20^\circ, 20^\circ]$	$-20^\circ, 0^\circ, 20^\circ$

Accordingly, optimization of β to minimize the maximum error probability, which is equivalent to maximizing the minimum of $\sum_{l=1}^4 h_{1l} - \sum_{l=1}^4 h_{2l}$, can be expressed as in (16) but with the modified objective function given below.

$$f(\beta) = \min_{x_0, y_0, \alpha', \beta', \gamma'} \sum_{l=1}^4 h_{1l} - \sum_{l=1}^4 h_{2l} \quad (17)$$

For the grid search, the considered discretized values of $\beta, x_0, y_0, \alpha', \beta', \gamma'$ are shown in Table 3.

Fig. 9 shows the values of $f(\beta)$ in the modified objective function in (17) for $\beta \in \{-90^\circ, -89^\circ, \dots, 0^\circ\}$. It can be seen that the optimal value of β is -23° . Compared to the optimal value of β in the previous section, the close values

(-21° vs. -23°) indicate that the optimal value of β is relatively insensitive to the position offset along the y -axis (y_0) and other receiver rotation angles (α' and γ').

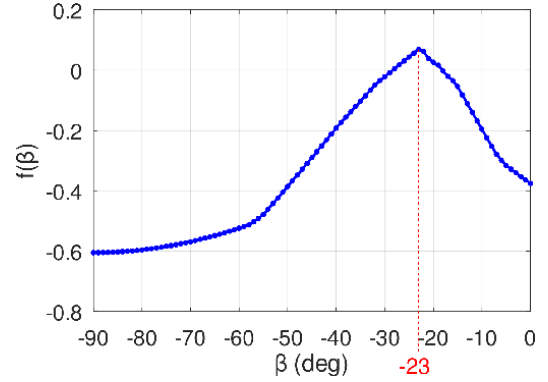


Fig. 9: $f(\beta)$ versus β for the modified objective function in (17).

Fig. 10 shows the contour lines of the maximum of $P_{e,1}$ over angles α', β' , and γ' in Table 3 at each receiver position (x_0, y_0) . Assume the error probability threshold of $P_e^{\max} = 10^{-2}$. The shaded area indicates the outage receiver positions with the error probabilities above the threshold. Notice how the outage region is wider for a higher value of position offset y_0 around 0.

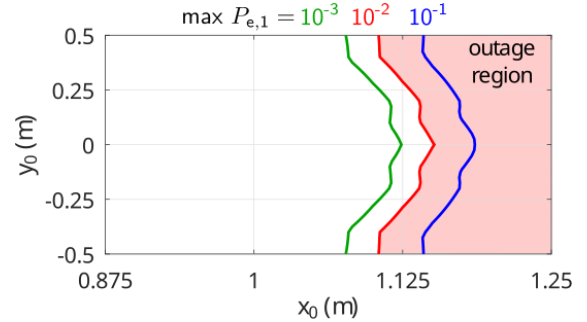


Fig. 10: Contour lines of maximum error probability ($\max P_{e,1}$) over all receiver rotation angles α', β' , and γ' for each receiver position (x_0, y_0) , with the outage region based on the probability threshold of $P_e^{\max} = 10^{-2}$.

The shaded area divided by the total service area below LED 1, which corresponds to $0 \leq x_0 \leq 1.25$ m and $-0.5 \leq y_0 \leq 0.5$ m, is the outage percentage. Based on the rectangular grid on the (x, y) plane with the grid spacing of 2.5 cm along each axis, the outage percentage is numerically computed to be 10.6%.

6.3 Performance of Optimized 4-PD Receiver under a 2D LED Structure

To investigate the system performance in a more general setting, consider a 2D LED structure with 9 LED light sources on the ceiling as illustrated in Fig. 11, where the centers of walkways are indicated by straight lines connecting LED light sources. Note that the system model in-

vestigated in previous sections, as shown in Fig. 1, corresponds to having LEDs 1 and 2 only. As before, assume that the receiver moves from position $(0, 0, 0)$ to position $(W, 0, 0)$. The purpose of adding more LEDs is to investigate the effects of signal interference in a more practical setting with a 2D LED structure on the ceiling.

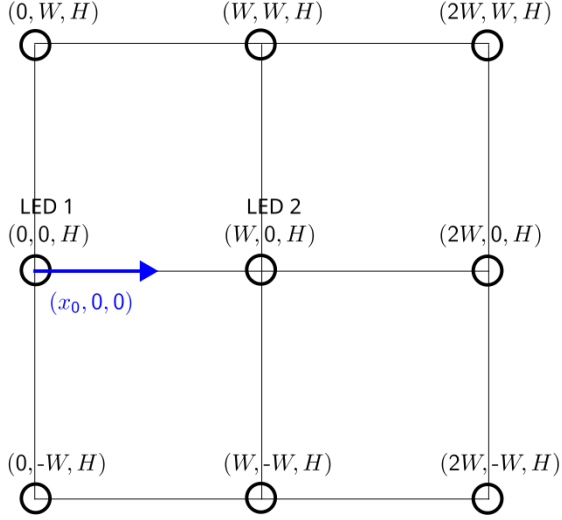


Fig. 11: Top view of a scenario for an indoor VLP system along a walkway under a 2D LED structure with the receiver at $(x_0, 0, 0)$, where $0 \leq x_0 \leq W/2$.

All the system parameters are kept the same as in Table 1. With 9 LEDs, the position error probability when the receiver is under LED 1 can be conservatively estimated using the upper bound based on the sum of pairwise error probabilities based on (13), i.e.,

$$P_{e,1} \approx \sum_{k=2}^K Q \left(\left(\sum_{l=1}^L h_{1l} - \sum_{l=1}^L h_{kl} \right) \sqrt{\frac{p}{2L\sigma}} \right), \quad (18)$$

where $K = 9$. More specifically, in (18), the term indexed by k denotes the probability that the receiver would choose the position of LED k over the position of LED 1.

Fig. 12 shows the contour lines of the maximum of $P_{e,1}$ over angles α' , β' , and γ' in Table 3 at each receiver position (x_0, y_0) . Two cases are considered: 2 LEDs and 9 LEDs being active. Compared to Fig. 10, the range of y_0 is expanded from $[-0.2W, 0.2W]$ to $[-0.5W, 0.5W]$ to demonstrate the effects of signal interference from additional LEDs.

Comparing the top and bottom plots in Fig. 12, the effects of signal interferences from additional LEDs can be seen when y_0 is approaching the halfway vertical distance at either $W/2$ or $-W/2$. However, within the walkway with $-W/4 \leq y_0 \leq W/4$ marked by the dashed boxes in Fig. 12, the interference effects due to additional LEDs are not significant, as can be seen by the similarities of contour lines within the walkway between the two cases.

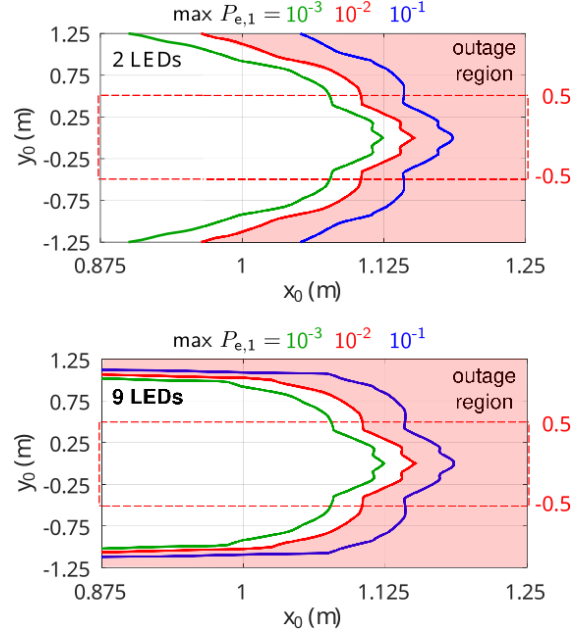


Fig. 12: Contour lines of maximum error probability over all receiver rotation angles α' , β' , and γ' for each receiver position, with the outage region based on $P_e^{\max} = 10^{-2}$ for 2 LEDs (top) and 9 LEDs (bottom).

The numerical results in Fig. 12 indicate that the error performance investigation based on interference signals from adjacent LEDs only, as adopted in previous sections, is reasonable since interference effects from further LEDs are not significant by comparison.

7. HARDWARE EXPERIMENTS

An experimental testbed is set up with the same dimension as in Fig. 1, and is shown in Fig. 13. There are two LEDs on the metallic frame at the height of 2 m and separated by 2.5 m. The receiver is placed on a metallic rail 0.5 m above the floor, making the vertical separation between the LEDs and the receiver equal to 1.5 m.

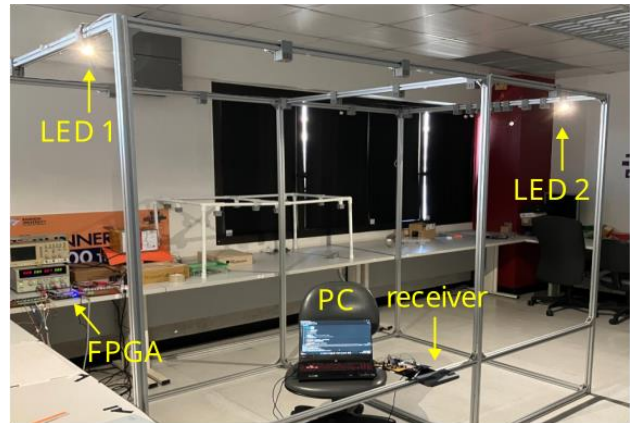


Fig. 13: Laboratory setup for hardware experiments.

Each data frame consists of 9 bits for the LED index followed by 5 bits of cyclic redundancy check with the generator polynomial $x^5 + x^2 + 1$. For the experiments,

LEDs 1 and 2 are numbered using indices 1 and 2. Signal modulation is based on 4-inverse pulse position modulation (4-IPPM). Time division multiplexing is used to mitigate signal interference between the two LEDs. The frame header consists of four consecutive ON timeslots (with pulses) followed by four consecutive OFF timeslots (without pulses).

Fig. 14 shows the signal transmitter that consists of a Terasic DE0-CV field programmable gate array (FPGA) development board for generating 4-IPPM signals, and IRLZ44N MOSFET transistors to turn the LEDs on and off based on 4-IPPM signals. Each LED light source is constructed using a Cree XLamp CMA1306 LED chip.

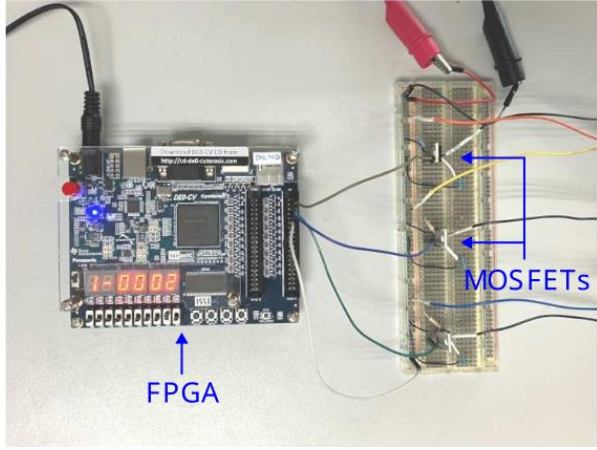


Fig. 14: Signal transmitter using an FPGA development board and MOSFET transistors.

The receiver is shown in Fig. 15. It contains a pyramid structure for mounting 4 PDs, which are OSRAM SFH206K modules. The pyramid is constructed using 3D printing with the PD pitch angles set to $\beta = -23^\circ$, which was found to be optimal in simulation experiments. Each PD is connected to a transimpedance amplifier using an LM358 op-amp module. Each amplifier output is connected to an analog-to-digital converter (ADC) pin of a Teensy 4.1 microcontroller, which performs digital signal processing to detect an LED position number and send the result via a USB cable to a PC. For comparison, the receiver also contains a single PD facing directly upwards. Either 1 PD or 4 PDs are used at any time, but not both.

The system performance is evaluated in terms of the error percentages in detecting LED position numbers. The receiver is placed on the rail at 10, 15, 20, 25, and 30 cm away from the center (on both sides) between the two LEDs. At each position, 100 detections are performed for the receiver in Fig. 15 with the orientation perpendicular to the rail, and 100 more detections with the orientation of 45° towards the center. Two tilt angles are considered, namely 0° and 20° towards the center. Fig. 16 shows the error percentages as measured from hardware experiments. When the receiver is not tilted, there is no significant difference between using 1 PD and 4 PDs. However, with the receiver tilted at 20° towards the center, the use of 4 PDs on the pyramid structure can reduce the error percentages, making positioning more reliable.

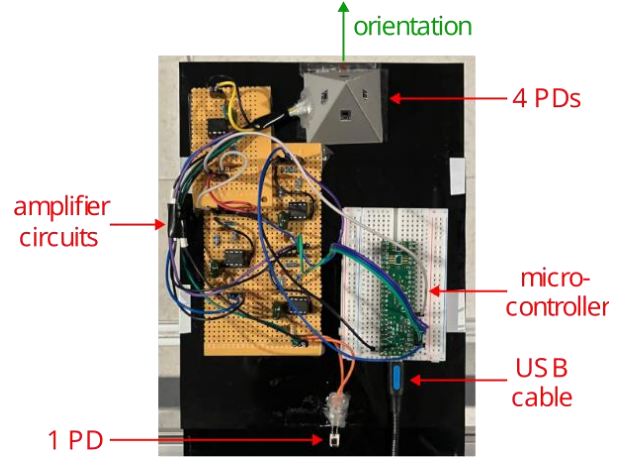


Fig. 15: Receiver using a pyramid with 4 PDs, amplifier circuits, and a microcontroller.

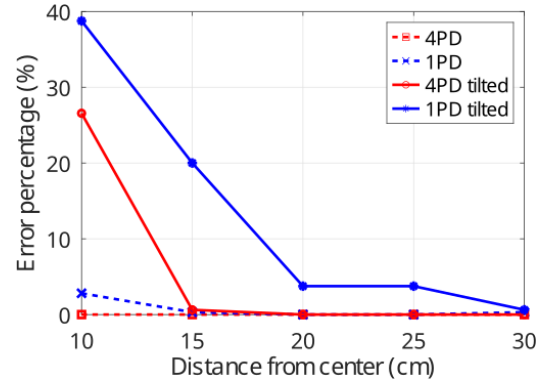


Fig. 16: Error percentages observed by the receivers using 1 PD and 4 PDs at various horizontal distances away from the center position.

6. CONCLUSION

The use of multiple PDs with angular diversity to make proximity-based VLP more resistant to receiver tilting was investigated, with the focus on LED light sources installed above a walkway such that a receiver typically receives signals from at most two LEDs. First, it was argued that at least four PDs should be used on a pyramid structure for angular diversity at the receiver. Assuming the Lambertian model of the optical path gain from each LED to each PD, the positioning error probability was derived and used to evaluate the outage percentage for the receiver service area.

The error performance was next optimized through choosing the pitch angle of the PDs in order to minimize the maximum error probability over a range of receiver orientation angles in terms of yaw, pitch, and roll angles. In addition, the position offset with respect to the middle of the walkway was considered. Finally, hardware experiments were conducted to demonstrate the improved reliability of the proposed receiver structure.

Besides receiver tilting, occasional signal blockages, e.g., due to body shadowing, can affect the positioning ac-

curacy. To handle possible bit errors due to position detection under signal blockages, error detection codes such as cyclic redundancy check can be applied. In the presence of a signal blockage, incorrect position detections will be filtered out and the position information will not be updated until the blockage is over. Incorporating error detection is therefore recommended for practical system implementations.

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