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Block network structure layout based on time and space division multiplexing scheme in an indoor positioning system using light-emitting diode

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ABSTRACT

In an indoor positioning system with numerous light emitting diodes (LEDs), one of the most critical issues that must be addressed is the design of a suitable layout for numerous LEDs. In the layout design, the neighbor interference and the long time delay are two of the main factors that limit the positioning accuracy of a moving device. In this study, we propose a novel layout design method of topological block network structure (BNS) based on time and space division multiplexing (TSDM) to accurately locate a large number of moving objects in an indoor environment under the condition of meeting lighting requirement. Performance indicator, the positioning accuracy, was focused on in this paper. The simulation results showed that with a suitable distance between adjacent LEDs adapted to the room height, the various illumination standards can be satisfied and the system time delay can be reduced to less than 500 ms. The results further demonstrated that positioning accuracy of less than 1 cm can be achieved by employing our BNS and TSDM scheme in 2D and 3D positioning algorithm with dimensions of 25 m by 25 m by 3 m.

1. Introduction

Location based services (LBS) have become a topic of intensive research which have been widely implemented in indoor positioning system, global positioning systems (GPS), etc., furnishing enormous convenience to our daily life over past few decades. Currently, many alternatives have been proposed for the indoor positioning system (IPS) such as ultrasonic, Bluetooth, Wi-Fi, ZigBee, and radio frequency identification (RFID). Compared with the above positioning technology, however, Visible Light Communication (VLC), which is characterized by low cost, high precision, license-free operation and unregulated huge (terahertz) bandwidth, apply light-emitting diodes (LEDs) to realize indoor positioning, garnering increasing attention [1–4].

In VLC, LEDs are used both as communication and lighting devices [5]. The potential dual function based on the fast switching of LEDs and the modulation of the visible light waves for free-space communications of LED in the context of VLC has become an interesting research topic [6,7]. Furthermore, compared with radio frequency (RF) system, the indoor positioning system (IPS) based on LED exhibits numerous advantages such as high bandwidth density, security, energy consumption, aesthetics, and immunity to interference from other electromagnetic waves [1,8–13]. Currently, IPS-based services are increasingly applied into position recognition and navigation assistance such as logistic tracking of assets in warehouses, healthcare monitoring for the elderly and children, parking lot management, etc. [7,14].

Moreover, many issues are needed to be addressed in designing a realistic IPS using LED; and those issues are the layout of LED transmitters, the emitting sequence, the channel access mode, the frame structure, the emitting time delay, the illumination, issue of cost versus performance and system reliability, and positioning accuracy concerns.

According to Gu et al., by increasing the coverage area of the LEDs with a suitable layout design, the average positioning error can be decreased [15]. In other words, the layout arrangement of LEDs and the full-range illumination, which can be achieved by adjusting the number of LEDs with the fixed irradiation angle, are vital to the indoor positioning accuracy [16]. A large number of LEDs are used for full-range illumination, which not only causes overlapped illumination that brings heavy intercell interference (ICI) but also contributes to a high-cost system. In the overlapped illumination area, it is a critical point

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that signals transmitted by a lamp are correctly received under ICI [7]. Therefore, the LED network layout and the distance between adjacent LEDs (D_{aj}) are of particular importance in practice; and both, along with the overlapped illumination area, direct the number of LEDs.

To combat the ICI caused by overlapped illumination, the time division multiplexing (TDM) technique is adopted by Zhou et al. and Lee et al., and LEDs are allocated within different time slots [14,17]. However, TDM will cause a long time delay for the LED network to emit signals. Hence, the conventional TDM scheme is not efficient, as short time delay is important to accurately position a moving device [7]. To reduce the long time delay, Hou et al. introduced a novel multiple access scheme based on block encoding TDM. In the proposed block unit composed of nine fixed LEDs, the correlation analysis between D_{aj} and extinction ratio (ER) of received signals were studied; however, the illumination demand and the overlapped illumination area between blocks associated with D_{aj} were not discussed [7]. Improper setting of D_{aj} will cause an unsatisfied illumination demand and heavy ICI. Instead of analyzing D_{aj}, extended BCD code is used to decrease the ICI, but flicker may occur to the LEDs in the corner position [7].

In public indoor environments, such as malls or airports, thousands of LEDs are deployed on the ceiling, which indicates that the LED network is massive. However the research on the LED network of IPS is relatively less common [7]. In this paper, we first propose a new block network structure (BNS) based on the novel time and space division multiplexing (TSDM) channel access scheme, a innovative combination of TDM and space division multiplexing (SDM) which can not only reduce heavy ICI, but greatly decrease the emitting time delay as well, simultaneously, meet lighting requirement. In our proposed BNS, the LEDs network is divided into numerous blocks and each LED acts as a single optical transmitter and is coded with unique physical localization information. In practice, although numerous ways of the emitting sequence can be utilized, a spiral mode, whose signals are uniformly distributed inside the illumination area of one block, is proposed in this paper. Thus, the LEDs of one block emit signals by TSDM scheme in spiral mode, which is a repeating pattern to minimize the ICI. Our TSDM scheme is more efficient compared with other scheme [18]. In addition, illumination demand, time delay, bit error rate (BER) of received signals, and average indoor positioning accuracy were used as evaluation criteria. We then investigated the performance of our proposed BNS in different room sizes with different D_{aj} values using these evaluation criteria.

The remainder of this paper is organized as follows. In Section 2, the VLC LPS channel model is briefly discussed. Section 3 describes in detail our proposed BNS based on TSDM channel access scheme. Section 4 presents the simulation results and discusses the illumination distribution, emitting time delay, BER distributions, and positioning accuracy of our proposed BNS in different values of D_{aj}. Finally, Section 5 concludes our paper.

2. Background

To provide a theoretical analysis and simulations of the proposed scheme, a VLC LPS channel model was established [7]. In VLC, the influence of the directed light is large and greatly influences the performance of the system [6]. Hence, only the line of sight (LOS) link was included in our analysis. The LED-based IPS channel model we investigated in an LOS environment can be well characterized by channel DC gain, which is given as [19]:

$$H(0) = \begin{cases} \dfrac{(m+1)A}{2\pi d^2} \cdot \cos^m(\Phi) \cdot T_s(\psi) \cdot g(\psi) \cdot \cos(\psi), & 0 \le \psi \le \Psi_c \\ 0, & \psi \ge \Psi_c \end{cases} \quad (1)$$

where A is the physical area of the detector, Φ is the angle of irradiance with respect to the transmitter perpendicular axis, d is the distance between transmitter and receiver, and ψ is the angle of incidence with respect to the receiver axis. Considering the orientation of transmitter and receiver, $\cos(\Phi) = \cos(\psi) = (h - h_0)/d$, where $h - h_0$ is the vertical distance between transmitter and receiver. Moreover, h is the positioning room height, and h_0 is the height of receiver above ground. $T_s(\psi)$ is the transmission of optical filter, and $g(\psi)$ is the concentrator gain. For a compound parabolic concentrator (CPC), $g(\psi)$ is defined as [19]:

$$g(\psi) = \begin{cases} n^2/\sin^2(\Psi_c), & 0 \le \psi \le \Psi_c \\ 0, & \psi \ge \Psi_c \end{cases} \quad (2)$$

where n is the refraction index, and Ψ_c is the concentrator field-of-view semi-angle. The Lambertian order m in Eq. (1) is given by $m = -ln2/ln(\cos\Phi_{1/2})$, where $\Phi_{1/2}$ is the half power angle of LED.

The received optical power is given by

$$P_{r0} = H(0) \times P_t \quad (3)$$

where P_t represents transmitted power of the LED, and P_{r0} is the received optical power [6,7,15]. The distance between the transmitter (i.e., LED-i optical source) and receiver is denoted as:

$$\hat{d_i} = \sqrt[4]{\frac{(m+1)\cdot(h-h_0)\cdot AT_s(\psi)g(\psi)P_t}{2\pi P_r^{(i)}}} \quad (4)$$

where $P_r^{(i)}$ is the received optical power of the LED-i. For the system that the transmitter and the receiver fixed, $\hat{r}_i$ is the horizontal distance between the transmitter and the receiver which can be expressed as

$$\hat{r}_i = \sqrt{\hat{d}_i^2 - (h-h_0)^2} \quad (5)$$

and $\hat{r}_i$ satisfy

$$(X_i - \hat{x})^2 - (Y_i - \hat{y})^2 = \hat{r}_i^2 \; (i = 1,2,3,4) \quad (6)$$

where (X_i, Y_i) is the horizontal coordinate of the signal source of the LED-i, and $(\hat{x}, \hat{y})$ is the estimated horizontal coordinate of the receiver.

In view of the influence of noise, the received signals can be expressed as follows:

$$P_r = \gamma P_{r0} + n \quad (7)$$

where γ is the detection coefficient, and n is the additive white Gaussian noise [7].

Shot noise and thermal noise limit the performance of the IPS and are mainly induced by the channel and the receiver. Other types of noise are not included in this paper [7]. The total system noise variance is

$$\sigma^2 = \sigma_{shot}^2 + \sigma_{thermal}^2 \quad (8)$$

The shot noise, which is mainly caused by incident light signals and ambient light, is given by

$$\sigma_{shot}^2 = 2q\gamma P_{r0}B + 2qI_{bg}I_2B \quad (9)$$

where q is the electronic charge, B represents channel bandwidth, and I_{bg} is the background current. According to Komine, Nakagawa and Wu et al., the noise bandwidth factor is typically given as $I_2 = 0.562$ [1,6].

The thermal noise variance is given by

$$\sigma_{thermal}^2 = (8\pi kT_k/G)\eta AI_2B^2 + (16\pi^2kT_k\Gamma/g_m)\eta^2A^2I_3B^3 \quad (10)$$

wherein the two right terms represent feedback-resistor noise and field effect transistor (FET) channel noise, respectively. Here, k is Boltzmann's constant, T_k is absolute temperature, G is the open-loop voltage gain, η is the fixed capacitance of photo detector per unit area, Γ is the FET channel noise factor, I_3 is the noise bandwidth factor, and g_m is the FET transconductance. In our numerical examples, the parameter values are shown below [1]: