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Indoor positioning systems based on visible light communication

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Abstract. Indoor positioning systems (IPS) are crucial in the ever-expanding landscape of wireless communication systems. These systems can generally be classified into four categories based on the underlying positioning technologies. One of them is based on visible light technology using Light Emitting Diodes (LEDs). In this paper, we first present a simple transmission model from the sender to the receiver in a visible light system. Subsequently, we construct a higher-precision, cost-effective model based on the technology proposed by Epsilon. Next, we introduce the most commonly used fingerprint recognition method and triangulation method in visible light indoor positioning. Traditional fingerprint recognition methods have issues such as significant errors. Recent studies have proposed various improvements based on different problems. To address the problem of high position errors, new research introduces an accurate Visible Light Positioning (VLP) method based on location fingerprinting and meta-heuristic. The method presented in this paper addresses the issue of position errors being affected in special cases. A typical IPS is an indoor positioning system utilizing dual-tone multi-frequency (DTMF) technology. The system design involves arranging LED lamps in a rectangular grid shape and using a basic positioning unit. The research discussed in this paper also explores the calculation of channel gains and simulation results of positioning errors. In the proposed positioning system, the coarse position is obtained through the ID acquisition process. When the mobile unit receives one or more LED signals, the ID acquisition process is used to obtain the nearest LED's ID based on the highest Received Signal Strength Indication (RSSI). Simulation results indicate an average positioning error of 18 millimeters at a Signal-to-Noise Ratio (SNR) of 10 dB. Through the results of our research, we conclude that the wide applicability of VLC technology makes it a cornerstone in many fields. In our daily lives, optical communication positioning technology continues to improve, promising broader applications in the future.

Keywords: component, Indoor Positioning Systems, Visible Light Communications, Triangulation method, dual-tone multi-frequency technique, RF Carrier Allocation Technique

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1. Introduction

In recent years, location awareness in indoor environments became a popular topic. Whether the application is asset tracking, location detection of personnel or simply finding a way around an unfamiliar building, there is a great need for IPS [1]. In indoor environments where satellite-based positioning becomes impractical, indoor positioning technology is employed as a supplementary means of augmenting satellite positioning, addressing the challenge of weakened satellite signals upon ground arrival and building penetration limitations. Consequently, this approach facilitates the precise determination of an object's current location. These systems also play a pivotal role in addressing the escalating demands for extensive data traffic and connections while mitigating the challenges of radio frequency (RF) saturation.

These systems can generally be classified into four categories based on the underlying positioning technologies. These include indoor positioning systems based on computer vision technology, indoor positioning systems based on wireless communication technology, indoor positioning systems based on light emitting diodes (LED) visible light technology, and indoor positioning technology based on magnetic matching.

Most navigation systems based on computer vision use cameras carried by the subject, which represents the mobile entity (e.g., person, robot) that requires positioning or tracking. [2]. First, the system collects data from the surroundings based on cameras or sensors, and then the system extracts useful features from them in order to recognize and track the target. The location of the target is determined by comparing the features in the sensed data with the features in the previously captured images or models. This usually involves feature matching algorithms such as feature descriptor matching. Based on the results of characterization, matching and attitude estimation of sensory data, localization algorithms are used to compute the 3D position and orientation of the target. This can be done using techniques such as triangulation, camera calibration, and structured light scanning.

As far as wireless technology is concerned, the IEEE 802.11 data network (Wi-Fi) offers good support for a positioning system: it is already widely deployed for other services (Internet connection, multimedia applications, IP telephony, etc.) and the equipment is quite inexpensive [3]. Multiple WiFi Access Points (APs) are deployed inside a building or area and they are used to transmit WiFi signals. Each AP has known location coordinates. A user device, such as a smartphone, laptop, or other WiFi-enabled device, scans the surrounding WiFi signals and obtains information about the signal strength from different APs. The user device scans the surrounding WiFi signals and measures the signal strength of each AP. Since WiFi signal strength decreases with distance, the signal strength of each AP can be used to estimate the distance between the device and the AP. By using the signal strength information from three or more APs, triangulation can be performed to determine the location of the device. Triangulation utilizes three APs with known locations, and by measuring the distance to these APs, the location of the device can be cross-located. This is a similar method to the GPS principle, but uses WiFi signals instead of satellite signals.

Due to the high transmission capacities, optical wireless networks play an important role in our modern information technology. At present, VLC using LED has become a hot topic in wireless communications [4]. Multiple light emitting sources, usually LEDs or infrared emitters, are deployed within a building or area. These sources emit light signals, each with known location coordinates. User devices are usually equipped with light receivers, such as cameras or light sensors, to capture light signals from different light sources. By analyzing the signals emitted from multiple light sources, the user device can calculate its distance or direction from each light source. Using triangulation or polygonal measurements, the location of the device can be cross-located.

The accuracy of an optical communication positioning system is usually affected by factors such as the propagation characteristics of the optical signal, the accuracy of the receiver, and the accuracy of the location of the light source. This technique has a wide range of applications in indoor localization, indoor navigation, location identification, and in some special environments such as wireless optical communication systems.

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2. Advancements and Applications of Visible Light Communication (VLC) Using LEDs

Optical Wireless Communication (OWC) technology, utilizing Light Emitting Diodes (LEDs), presents a broadband wireless communication methodology. This technology exploits LEDs for amplitude and frequency modulation at frequencies beyond human visual perception, thereby transmitting information via visible light while concurrently serving lighting purposes. This information is receivable through photodetector devices, such as cameras or photodiodes, in a process commonly referred to as Visible Light Communication (VLC). VLC systems, in comparison with their infrared and ultraviolet wireless communication counterparts, offer significant benefits, including elevated signal power and an absence of health and safety hazards.

Moreover, the human visual system typically lacks the capability to discern brightness fluctuations at frequencies in the order of several tens of MHz or higher. This characteristic enables the modulation of light at these elevated frequencies for data transmission purposes, without adversely impacting the visual experience. This aspect is a pivotal consideration in the design and application of Visible Light Communication (VLC) systems, as it ensures that the high-frequency modulation essential for data transmission remains imperceptible to the human eye, thereby maintaining the primary function of lighting without visual disruption.

Visible Light Communication (VLC) positioning techniques are primarily categorized into two types: Photo Diode (PD)-based systems and Image Sensor (IS)-based systems. PDs are often preferred due to their high sensitivity to light and cost-effectiveness. In contrast, IS systems have the unique capability to spatially separate light sources, providing a distinct advantage.

Despite the cost-effectiveness and high sensitivity of PDs, IS-based positioning techniques are increasingly favored. This preference stems from their ability to operate without the need for complex multiplexing techniques. Additionally, IS-based systems demonstrate a robustness against ambient light interference, ensuring that positioning accuracy remains uncompromised.

The efficacy of VLC is further enhanced by the characteristic rapid on/off capability of LEDs. This feature is exploited through a technique named Epsilon, which is instrumental in enabling the dimming of LEDs via Pulse Width Modulation (PWM). PWM not only aids in light intensity control but also facilitates the transmission of digital information within the VLC framework.

Epsilon is meticulously engineered to balance precision, cost-efficiency, and ease of use. It is specifically designed to leverage existing illumination infrastructure for localization purposes, thereby optimizing the utility of VLC systems in a diverse range of applications. This integration illustrates the versatility and adaptability of VLC technologies in modern communication and positioning systems.

The channel transmission model of visible light communication system is shown in the Figure 1.

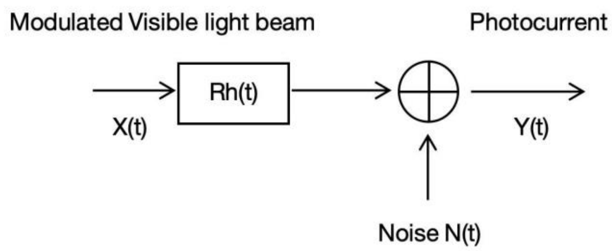

Figure 1. Channel transmission model of visible light communication system.

In the Visible Light Communication (VLC) system, the transmission model involves an LED at the transmitter end emitting an intensity-modulated optical signal. This optical signal is then captured at the receiving end by a photodiode, which converts it into an electrical signal. The resulting photocurrent signal, denoted as Y(t), encapsulates the core dynamics of this transmission and can be mathematically expressed through a specific formula.

$$Y(t) = R(t) * h(t) + N(t)$$

In this formula, R represents the photoelectric conversion efficiency of the photodiode, indicating how effectively the photodiode converts the incoming optical signal into an electrical signal. X(t) is the light signal emitted by the LED, encapsulating the original data or information in its intensity-modulated form. h(t) corresponds to the channel impulse response, characterizing the effect of the transmission medium on the signal. N(t) signifies the additive white Gaussian noise, a common form of noise in communication systems that represents random fluctuations or disturbances that might affect the signal during transmission, thus impacting the fidelity of the received signal.

3. Principle Of Indoor Positioning Technology

In the previous part, we conducted a series of studies on visible light communication technology and indoor positioning technology. Now, according to the research, optical communication technology can be applied to indoor positioning technology, and visible light positioning (VLP) has become a research hotspot of indoor positioning technology, which has advantages over traditional RF technology. They do not require satellite signals or electromagnetic interference to achieve positioning, which is a low-cost, low-power technology, at the same time, visible light positioning has the biggest advantage of high accuracy, and recent research found that the mixing of VLC and Bluetooth hybrid indoor positioning technology has made the final accuracy of up to 0.03 m [5].

In recent years, the most commonly used positioning methods for visible light indoor positioning include fingerprint recognition method and triangulation algorithm. Traditional fingerprint positioning is to install (m+1)×(n+1) LED light source as shown in figure (a) in the location area, and use WKNN algorithm to compare and approximate positioning. However, there are many problems in this traditional method. Accuracy is still not high in special cases to produce large PE at the same time is not suitable for large-scale LED scenes, will produce a lot of useless fingerprints, and some recent studies according to different problems put forward different improvements, according to the PE too high problem, the new study proposes the accurate VLP method based on location fingerprinting and meta-heuristic is proposed. As far as the authors are aware, this is the first time to report fingerprinting weight calculation method based on meta-heuristic algorithm, the result of which is shown in Figure 2 (c, d), Compared with other fingerprint identification and positioning methods, this method solves the problem that PE is affected in special cases [6]. For large-scale scenarios that are not suitable, the researchers proposed a high-precision 3D system based on ELM and proposed a VLP kernel for fingerprint recognition: Coordinate transformation is used to simplify fingerprint positioning, as shown in Figure 2(b). According to calculation and verification, this method reduces the number of samples without affecting the positioning accuracy; so as to reasonably reduces the positioning time [7].

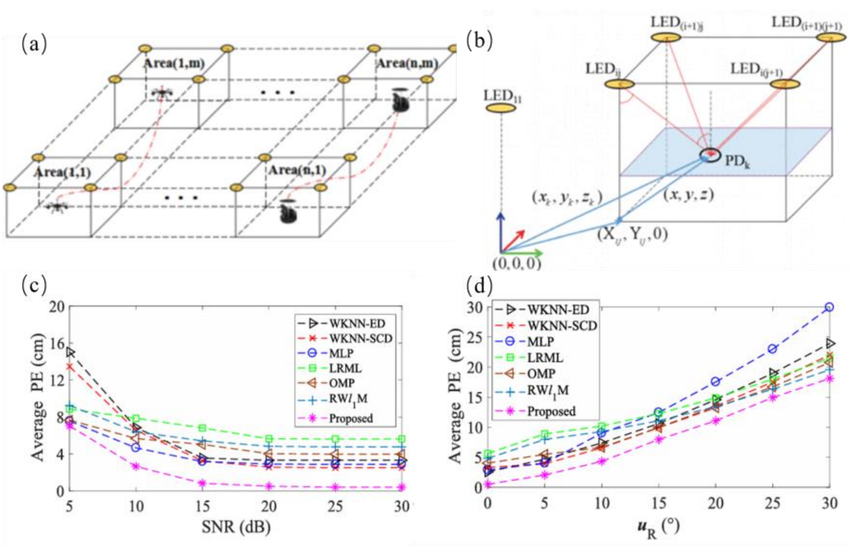

Figure 2. The principle and effect of fingerprint location method. (a) Arrangement of LED light source. (b) Fingerprint location method. (c) The impact of SNR on the average PEs with S = 20 cm. (d) The impact of ur on the average PEs with S = 20 cm [6,7].

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Triangulation method is also a common positioning method for visible light indoor positioning, triangulation method uses the geometric properties of triangles for absolute positioning, triangulation method can be divided into two categories: ranging method and Angle measurement method. In this part of the ranging method, the main technology is the signal receiving strength RSS, arrival time TOA, arrival time TDOA. The main core is to measure the position of the predicted mobile signal through the distance, and in the Angle measurement method, there is the signal Arrival Angle (AOA), which needs to measure the receiving Angle between the receiving end and multiple reference light sources, and then locate the target through the intersection of the direction line. Based on VLC technology, TOA, RSS, TDOA and AOA all have their own.

When the receiver is located far from the LED level, the irradiance and incidence are larger, so the accuracy of RSS algorithm will be greatly reduced, while TDOA has improved performance compared with TOA, but the algorithm is too complicated. Although AOA has the highest accuracy, it is too expensive [8]. Therefore, in the current research, a series of integration of these visible triangulation methods are carried out, not only one kind of measurement. In some indoor positioning systems, a method is proposed to measure AOA and RSS at the same time, so as to increase its positioning accuracy. [5].

4. Some typical indoor positioning systems based on visible light communication

Due to VLC fast development and widespread of artificial light source in public and private places, VLC-based indoor positioning has drawn attention from researchers. Various methods have been suggested and confirmed. Some of the systems had been analyzed and discussed.

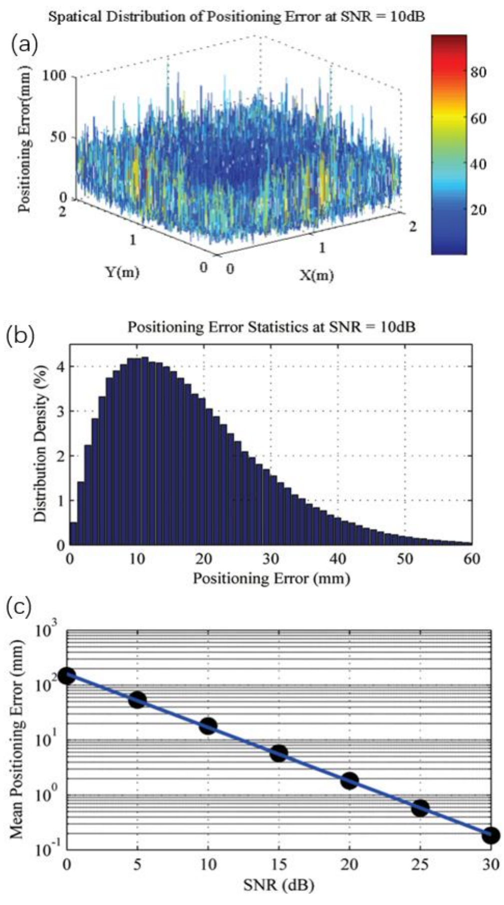

Figure 3. The positioning error characteristics at a SNR of 10dB. (a) Positioning error spatial distribution under SNR = 10dB. (b) Distribution histogram of positioning error at SNR = 10dB. (c) Average positioning error [8].

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One of the typical systems is an indoor positioning system utilizing the dual-tone multi-frequency technique, based on visible light communication; the system design involves arranging LED lamps in a rectangular grid shape and using a basic positioning unit. The technique of DTMF employs 8 distinct signals with different frequencies to symbolize numbers or characters, and it's commonly implemented in the field of systems of telecommunications. Each LED lamp has a unique ID composed of 4-6 digits with the same low frequency component. The ID acquisition procedure is used to acquire the nearest LED's ID based on the highest received signal strength indication (RSSI), allowing for the estimation of the mobile unit's coarse position. The procedure for acquiring coordinates assesses the intensities of various low frequencies to determine the channel gains based on the LED lamp's relative position to the mobile unit. This process allows for precise computation of the mobile unit's coordinates. The research also discusses the calculation of channel gains and simulation results of the positioning error. The coarse position in the proposed positioning system is obtained using the ID acquisition procedure. When the mobile unit receives one or more LED signals, the ID acquisition procedure is used to acquire the nearest LED's ID based on the highest RSSI. Through querying the position information of the ID from a stored database, the mobile unit's rough location can be estimated. The results of the simulation indicate an average positioning error of 18 mm at a SNR of 10 dB as shown in Figure 3 [9].

Another system is a positioning system for indoor use, which utilizes Visible Light Communication and applies a RF Carrier Allocation Technique, has been implemented. As depicted in Figure 4 (a), the system employs techniques of intensity modulation/direct detection and carrier allocation. It leverages the transmission through three simultaneous channels to ascertain the position of the receiver. Through simulations and experiments, the authors have confirmed the viability of the proposed system. They demonstrate that through the incorporation of an adjustment process using a normalizing method, the average error in the estimated positions diminishes significantly to 2.4 cm, in contrast to a sizable error of 141.1 cm when the adjustment process is not applied. The authors highlight the advantages of using LEDs for VLC, such as reduced cost and absence of electromagnetic interference. They also describe the operational principle and evaluation of fundamental transmission features. of the proposed system. The system's response to radiation and incidence angles was also examined by the authors. The researchers discovered a decline in the power of the received signal as the distance of transmission expanded. leading to a degradation in the SNR. The authors measured error vector magnitude (EVM) values to assess the signal quality, and observed slight differences in the degradation tendencies among the transmitters. The EVM values corresponded to different bit error rates as shown in Figure 3 (b) [10].

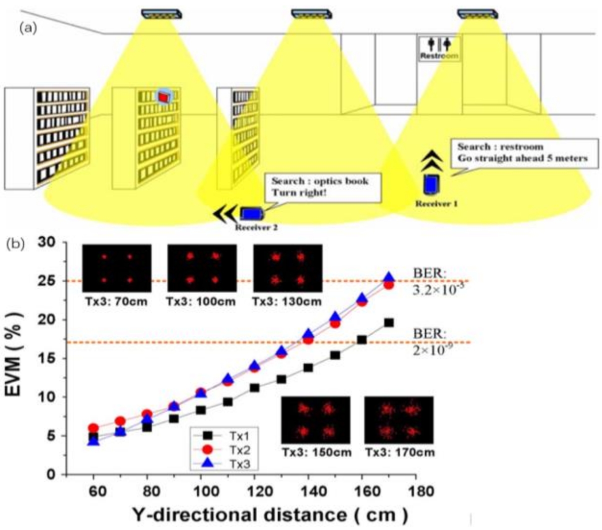

Figure 4. Insights into a positioning system based on VLC (a) An example application of a positioning system based on VLC. Receiver 1 guides the destination. Receiver 2 indicates where the object is. (b)The measured EVM values with respect to Txs by the variation of transmission distance; the insets are the constellation of the Tx3 signal [9].

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5. Conclusion

The indoor positioning system based on Visible Light Communication (VLC) is a vital technology combining indoor positioning with optical communication. Positioning technologies exist in various forms, like wireless LAN, ultra-wideband, and low-energy Bluetooth, each with unique advantages. VLC positioning, in particular, offers promising applications in indoor positioning due to its precision and reliability.

Numerous VLC channel models, including deterministic and stochastic models, have been developed. Stochastic models typically yield better results through the effective operation of scatterers and geometric relationships. VLC technology is advancing, with optical communication transmission gaining popularity. This mode of communication exploits the human body's perception limits of brightness changes to modulate light for data transmission. LED lights are commonly used for this purpose, serving both as information transmitters and light sources. They hold numerous advantages over other light communication methods.

VLC positioning technology is mainly categorized into Photodetector (PD) and Image Sensor (IS) technologies. PD is generally preferred for its high sensitivity and low cost, whereas IS technology is used in specific scenarios to avoid ambient light interference. Combining indoor positioning with optical communication, VLC-based indoor positioning technology offers significant benefits over traditional radio frequency methods, including minimal interference, cost-effectiveness, and low power consumption.

The technology's overall aim is to leverage the properties of visible light to enhance accuracy and overall performance. Through continuous simulation and experimentation, various systems have been developed, each tailored to specific applications. VLC technology's wide applicability makes it a cornerstone in numerous fields. Optical communication positioning technology, pivotal in our lives, continually improves, promising broader applications in the future.

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