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Indoor Positioning Systems Based on Visible Light Communication: State of the Art

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***Abstract*—Advances in Visible Light Communication (VLC) technology and the ubiquity of illumination facility have led to a growing interest in VLC-based indoor positioning. Numerous techniques have been proposed to obtain better system performance. In this paper, we survey over 100 papers ranging from pioneering papers to the state-of-the-art in the field to present the positioning technology. Not only the Light Emitting Diode (LED) technology, modulation method and types of receivers are compared, but also a novel taxonomy method is proposed. In this paper, VLC-based Indoor Positioning Systems (VLC-based-IPSs) are classified based on the methods used, (1) mathematical method, (2) sensor-assisted method, (3) optimization method. Different from other survey works, we emphasize and analyze the accuracy of VLC-based Indoor Positioning System (VLC-based-IPS) in the experiment and simulation environments. Meanwhile, the paper illustrates challenges, countermeasures and lessons learned.**

***Index Terms*—Visible light communication, indoor positioning system, sensor-assisted method, positioning optimization method, survey.**

I. Introduction

The indoor positioning technique that relies on in-building communications infrastructure has drawn a lot of attention recently. Its applications cover a wide area and have high demand values. In addition, the growing commercial interest in Indoor Location-Based Services (ILBS) has spurred the development of indoor positioning technique [1]. It is estimated that the indoor positioning market value will be $5 billion in 2018 [2]. At the great museums and shopping malls, users can utilize Indoor Positioning Systems (IPSs) to attain location information and quickly find the exit or the elevator. Combining with some other applications (APPs), indoor positioning technology can also be used to provide Location-Based Services (LBS) and advertisements to users. Subsequently, many researchers endeavor to achieve the finer accuracy and precision.

With the proliferation of mobile devices, wireless technologies are becoming significant parts in embedded systems to provide low-cost, anytime, and anywhere connectivity [3]. However, the wireless signal in the different environments has different characteristics. In an outdoor environment, the signal often propagates in an open and accessible space with a small signal attenuation. However, in an indoor environment, the movements of persons and locations of items may cause different degrees of influence on the indoor wireless signal. For outdoor scenarios, Global Positioning System (GPS) is used extensively. However, the positioning accuracy of GPS is located in the order of several meters [4] which is unacceptably large for indoor scenarios. Therefore, the outdoor positioning technology cannot meet the requirements in the indoor environment. Further positioning techniques must be used to facilitate Indoor Positioning System (IPS).

According to a recent survey [5], there are various indoor positioning technologies proposed such as Radio-Frequency Identification (RFID) [6-7], Ultra-Wideband (UWB) [8], Wi-Fi [9], [10], and fingerprint [11]. These technologies determine the relative position between them by moving targets and communication of the fixed unit and then obtain the actual locations of targets. However, there is usually a need for installing Wi-Fi Access Point (AP) or infrared transmitting equipment. These lead to a significant increase in the cost of the installation, maintenance, and management. Hence, their use is limited to some areas where certain Radio-Frequency (RF) communication is banned such as mines, hospitals, air crafts, and gas stations, etc.

Due to the high transmission capacities, optical wireless networks play an important role in our modern information technology [12]. At present, VLC using Light Emitting Diodes (LEDs) has become a hot topic in wireless communications. The White-LED lighting technology as a type of green lighting technology is considered as the next generation indoor lighting because of the advantage of high luminous efficiency (up to 110lm/W), long service life (up to 50000hours) and fast response speed (up to 10MHZ). Distinct from the older illumination technologies, the LED switches to intensity levels at a very fast rate which is imperceptible by human eyes. Hence, data can be encoded in the emitting light in various ways which mean LEDs can provide illumination as well as communication. An important application of VLC is employed to indoor positioning. Nowadays, plenty of investigations have been attracted to VLC-based positioning, which shows resolutions of a few centimeters [13-16]. There are two features which make lights available for positioning:

- The light strength varies according to different light sources, which can be readily detected by light sensors embedded in Commercial Off-the-Shelf (COTS) devices (e.g., smartphone, smart glass, and smart watch).
- The light strength is stable at different times of a day, avoiding site-survey and database maintenance.

Hence, according to Received Light Strength (RLS) of the light source, a user can locate itself.

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Compared with other systems, the VLC-based-IPS has the following advantages:

- It can be used in RF sensitive areas like hospitals and air crafts because it does not generate RF interference.
- Light emitting diode offers a narrow beamwidth, which enables more precise Angle of Arrival (AOA) information at the receiver side[17].
- VLC has little influence from multipath interference because the primary energy of indoor visible light concentrates on the line of sight link.
- VLC-based positioning systems can be installed inexpensively since they utilize existing lighting systems with very few modifications applied.
- The precision of visible light positioning is higher than traditional positioning. For example, the research shows that the number of LED luminaires is ten times more than Wi-Fi in a typical indoor building [18], which contributes to the higher accuracy.

Previous decade observed a significant research effort directed towards VLC-based positioning system. Hundreds of papers in this field have been issued. However, there are few surveys on VLC-based positioning system [19-22]. Moreover, all of them miss some critical information about the VLC-based-IPS or use the different classification method. We will do a thorough comparison among those surveys in Section III. In our paper, we survey the related knowledge of VLC-based positioning system and compare some pioneering systems in different ways. We utilize two more classification methods: sensor-assisted method and positioning optimization method. This type of classification method can help researchers quickly find the thought of increasing the precision based on the basic mathematical method. It can help researchers to understand which method can be utilized to achieve localization and what type of effect can be achieved, and provide the new ideas of the positioning method. Some challenges regarding VLC-based positioning are further discussed.

This paper presents a comprehensive survey of the VLC-based indoor positioning technology and is organized as follows. We explain various indoor positioning technologies and introduce VLC in Section II. In Section III, we make a comparison among the correlated survey papers and conclude our contributions. The VLC-based positioning technology and classification are shown in Section IV. We provide a qualitative comparison of these algorithms in Section V. Moreover, the challenges, countermeasures, and lessons learned are contained in Section V. Finally, we conclude in Section VI.

II. Indoor Positioning Technologies and VLC

Numerous wireless technologies have been employed to design indoor positioning systems. These positioning systems with their own characteristics have different advantages and disadvantages. Compared with RF technology, VLC as a technology of wireless access has the unique advantages. Hence, in this paper, we mainly discuss the VLC-based-IPSs.

A. Various Indoor Positioning Technologies

To better meet the market demand, indoor positioning technology is quickly developed. Basing on the requirements of the positioning applications, we need to choose a particular technology to realize positioning. In an indoor environment, positioning is mainly achieved through the use of techniques such as Frequency Modulation (FM), Cellular Networks, ZigBee, Wi-Fi, Infrared (IR), Ultrasound, Bluetooth, RFID, and UWB. All of those technologies have been discussed in many other survey papers about IPS. Hence, we will not repeat them, but provide a more detailed table to show the system performance, advantages, constraints of using this technology. We summarize all these indoor positioning technologies used in literature. Different technologies have different transmission ranges, different accuracies, different scalabilities, different costs and different power consumptions. We compare these items and outline the advantages and constraints of these technologies in Table I.

B. VLC

Considering the wireless access, RF technology is mature and widely used. However, now the RF spectrum is becoming increasingly crowded. In other words, facing the rapidly growing demand for wireless access, the available RF bandwidth may fail to meet the requirements. Hence, researchers begin to look for other solutions. Fortunately, by using the existing illuminating devices, VLC can be utilized as one of the promising alternative methods for RF-based communication, especially in indoor communications [23]. The rapid increase in the usage of LEDs has provided a unique opportunity for VLC. With the advantages of lower cost, higher lifetime and energy savings, LEDs are expected to replace older illumination technologies and become the next generation illumination devices. It is anticipated that LEDs will provide nearly 75% of all lighting by the year 2030 [24]. The new LEDs can switch to different light intensity levels at a very fast rate which even can not be perceived by human eyes. Hence, the data can be encoded in the emitting light to realize communication. It makes LEDs be used for both illumination and communication. Using high-speed response characteristics of White-LED devices, at the same time of lighting, LEDs can send information.

Compared with other existing technologies of wireless communications, VLC is an essential communication tool and has the following advantages.

- **Cost Efficiency**: VLC uses the existed lighting infrastructure to communicate, which means such systems can be deployed with few additional devices. In other words, the cost is lower.
- **Broad Bandwidth**: The spectrum of VLC is between 385 and 800THz. It means the possible data carrying capacity of VLC are thousands of times larger than the RF portion of the spectrum [25]. Considering the increasing crowded RF spectrum, many types of research endeavor to use efficient frequency and spatial reuse. However, the current RF spectrum is still too scarce to meet the increasing wireless access demand. VLC with the broad bandwidth is suitable to design high-capacity mobile data networks instead of RF-based communication systems.
- **Energy Efficiency**: LEDs use at least 75% less energy and last 25 times longer than incandescent lighting [26].

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TABLE I
SUMMARY OF VARIOUS WIRELESS TECHNOLOGIES

System	Range	Accuracy	Scalability	Cost	Power Consumption	Advantages	Constraints
GPS	16km	6-20m	Low	High	High	Covers entire earth	(1)Expensive infrastructure, (2)Only outdoor
FM	100km	2-4m	Low	Low	Low	Less susceptible to objects	Signal changes little in small distance
Cellular Networks	80km	2.5-20m	Low	Medium	High	Widely covered scope	Low accuracy
ZigBee	30-60m	1-10m	Low	Low	Low	Low cost and power consumption	(1)Low accuracy, (2)Low data transmission
Wi-Fi	35m	1-5m	Medium	Medium	High	Low cost	If fingerprint is used, environment dependent and high deployment cost for building database
Infrared	Few meters	1-2m	Low	Medium	Low	Low power consumption	(1)Short range, (2)Cost for extra hardware
Ultrasound	Tens of meters	0.01-1m	Low	Medium	Low	Good accuracy	(1)Sensitive to environment, (2)Cost for extra hardware
Bluetooth	10m	1-5m	High	Low	Low	Low cost and power consumption	(1)Cover range is limited, (2)Limitation in user mobility
UWB	Few meters	0.01-1m	Low	High	Low	Good accuracy	(1)Cover range is limited, (2)High cost, (3)Problems in non-line of light
RFID	1m	1-2m	Medium	Low	Low	Low cost and power consumption	(1)Response time is high, (2)Limitation in user mobility

Most of the energy of LEDs is used for illumination. Therefore the VLC system is energy efficient.

- **Communication Security**: Visible light can not penetrate most objects and walls, and links can be kept confidential, which means an internal wireless communication security.

The authors of [23] have concluded the potential application areas of VLC. Initially, as an indoor communication technology, VLC can be used at homes to provide Internet access to residents and realize smart homes. It can be used in shopping malls or museums to attain the wanted information quickly. Because of the security of VLC, it is also probably to be employed in military applications. The authors outline that VLC can also be used in outdoor and underwater environments. In this article, we mainly describe a critical application of VLC, namely IPS.

III. Related Surveys and Contributions

IPS is undergoing a rapid development in recent years. A lot of surveys of IPS can be found [27-30]. And those surveys can help general readers quickly find relevant information and have an obvious contrast with the VLC-based-IPS. Thus we gather some latest surveys of IPS and do a comparison in Table II. Moreover, information of VLC is very important in the design of the VLC-based-IPS. The suitable technology of VLC can efficiently improve the performance of the VLC-based-IPS. Thus we still collect some surveys of VLC [31-34] and do a detailed comparison in Table III. Recently, the VLC-based-IPS get a rapid development, and numerous algorithms have been proposed. However, surveys of the VLC-based-IPS are very few. Here we list four survey papers [19-22] of the VLC-based-IPS and make the comparison in Table IV. With the development of the LED technology, the VLC-based-IPS can achieve better performance with the high accuracy and low cost. Thus, we believe that a detailed survey of the VLC-based-IPS and related knowledge can help improve the development of IPS. Compared with other survey papers, this paper contains the latest papers and numerous references. Relevant knowledge of the VLC-based-IPS is relatively comprehensive. The new taxonomy is proposed. Our contributions include the following:

- We summarize a lot of related knowledge of the VLC-based-IPS which is critical in the design of IPS. According to the specific application scenarios, choosing the right LED technology, modulation method and types of the receiver can improve the performance of the system.
- We provide an updated literature review of the VLC-based-IPS, and the vast majority of the papers which study the VLC-based-IPS are included. A comprehensive comparison of the VLC-based-IPS is provided. About the accuracy of the systems, we discuss two aspects: experimental results and simulation results.
- We provide a new taxonomy method of the VLC positioning technology, and two new classes (called the sensor-assisted method and positioning optimization method) are proposed. The new taxonomy approach can help the researchers quickly understand positioning principle and give a direction to find out the way to improve the performance of the system.
- We compare the survey papers of the VLC-based-IPS and list the different taxonomy method of the survey papers to help the reader quickly find the information of the VLC-based-IPS.

IV. VLC-based-IPSs

As an important application of VLC, positioning systems using VLC have gained a lot of attention. In this section, we discuss the differences between the VLC-based-IPSs and other positioning systems. The key issues (LED technology, modulation method and types of receivers) in the design of the VLC-based-IPS are included. And we classify the VLC-based-IPSs into three classes. In each class, we introduce some papers which use the corresponding methods.

A. *VLC-based Indoor Positioning Techniques*

Compared with other systems, the VLC-based-IPS has many advantages. According to the characteristic of RF, we can see RF-based-IPS is not suitable to be used in the RF sensitive area. The bandwidth of the RF-based-IPS is limited and too scarce to meet the increasing wireless access demand. The device-free-IPS analyzes how a human body changes the pattern of received signal strength to detect and locate human in an indoor environment. It can utilize the Infrared, UWB Radar, Ultrasonic, Wi-Fi, Wireless Sensors, RFID, and FM to detect and track the human body without wearing any device. Compared with device-based-IPS which need a particular smartphone-based or tag-based device, the device-free-IPS is more vulnerable to environmental interference and dynamics. Because the device-free-IPS relies on the human impact on wireless signals to detect and localize people, environmental changes may also require recalibration for the device-free-IPS

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TABLE II
COMPARISON OF SURVEY PAPERS FOR IPSS

Ref.	Taxonomy method	Reference Number	The newest reference	Standard of comparison	The related knowledge
[27]	Passive indoor positioning, Active indoor positioning	Few	2013	Comprehensive (technologies, accuracy, coverage, cost , NLOS ,performance)	Brief (basic measuring principle)
[28]	Inertial navigation systems (INSs), Step-and-heading systems (SHSs)	Medium	2012	Comprehensive (system description, No.Users, evaluation, particle scheme, initialisation, accuracy quoted)	Detailed (indoor positioning systems, smartphone and hybrid systems, open research issues, incorporating map matching)
[29]	Vision systems, Infrared IPSs , Ultrasound IPSs, Wi-Fi IPSs, RFID IPSs, Bluetooth IPSs	Medium	2014	Common (person localization and tracking, object recognition and tracking, Robot navigation, animal tracking)	Brief (enabling technologies)
[30]	System based localization in indoor environments, Cooperative localization and hybrid data fusion, Learning algorithms for localization	High	2016	Brief (wireless positioning systems, localization technique, range,accuracy)	Brief (application)

TABLE III
COMPARISON OF SURVEY PAPERS FOR VLC

Ref.	Survey content	Reference Number	Published year	The related knowledge
[31]	Visible light communication system, Physical layer, Medium access techniques, System design and programmable platforms, Visible light sensing and application	High	2015	Detailed
[32]	Physical layer properties of visible light, Securing visible light communication, VLC security: attacks and opportunities	Low	2015	Brief
[33]	Application of VLC, Architecture of VLC, VLC standardization, Modulation techniques for VLC, Open research issues	Medium	2016	Medium
[34]	Application of VLC, Architecture of VLC, VLC standardization, Modulation techniques for VLC, Open research issues	Medium	2015	Medium

TABLE IV
COMPARISON OF SURVEY PAPERS FOR THE VLC-BASED-IPSS

Ref.	Taxonomy method	Reference Number	The newest reference	Standard of comparison	The related knowledge
Our	Mathematical method, Sensor-assisted method, Positioning optimization method	High	2016	Comprehensive (experiment accuracy, simulation accuracy, cost, complexity, note, positioning technique, modulation)	Detailed (LED technology, modulation method and type of receivers are contained and compared by using table)
[19]	Scene analysis and proximity method, Triangulation method based on RSS, Image positioning	Few	2014	Common (complexity, accuracy, power, synchronization, space dimension)	None
[20]	Triangulation, Scene analysis, proximity	Higher	2015	Brief (receiver, multiplexing, accuracy)	Brief (types of receivers and multiplexing techniques are contained)
[21]	Reference from 3D building models, Reference from images, Reference from deployed coded targets, Reference from Projected targets, Systems without reference, Reference from other sensors	Medium	2011	Comprehensive (coordinate reference, reported accuracy, coverage, CCD size, frame rate, object/camera positioning, camera costs, market maturity)	None
[22]	Photodiode based design, Camera based design	Medium	2014	Comprehensive (multiplexing protocol, positioning error, minimum number of LEDs, database requirement, specific requirements, auxiliary equipment)	Medium (application, system overview)

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to maintain satisfactory performance. The detailed comparison of the VLC-based-IPS, the RF-based-IPS, and the device-free-IPS is shown in Table V.

Many the VLC-based-IPSs with high precision have been proposed. Those systems in [35-39] reported the positioning accuracy up to a few centimeters. However, the accuracy is attained only by computer simulations. In the practical environment, the multipath effects will severely reduce the accuracy. Recent years, other practical VLC-based positioning systems are proposed: Eplison [18], Luxapose [40], LIPS [41], PIXEL [42] and so on. Eplison presents the first practical visible light localization system which 90% of the accuracy can achieve 0.4m, 0.7m, and 0.8m for three different environments. Luxapose achieves a localization accuracy of 0.1m. Experimental results show the average positioning accuracy of LIPS is about 0.4m. It is great stability against interference. PIXEL is a system which wearable can afford. The software program of PIXEL is designed for both Android phones and Google Glass. The main principle of these systems will be presented later. When VLC is used to realize localization, we must consider issues such as LED technology, modulation method, and types of receivers. We will discuss these factors subsequently.

1) LED Technology: With the advantages of lower power consumption and longer lifetime, LEDs are expected to be the next generation illumination device. Because of this, VLC-based indoor positioning has attracted a lot of attention. As illumination is the primary purpose of the LED luminaire, it should not be affected by the communication. How to design the LED luminaire is a crucial part of the VLC-based positioning. The LED luminaire is used for communication, and the driver circuit is modified to modulate the data. Both White-LEDs and RGB-LEDs can be utilized to transmit information in the VLC-based-IPS. Next, we will list the strength and weakness of the White-LEDs and RGB-LEDs respectively.

White-LEDs can be modulated at frequencies up to 20MHz, which means a new opportunity to create a positioning system. We can use the particular technology and manufacturing method to change the emission power and bandwidth of LEDs. Under white light, the colors of the object are likely to be the same as the color under the natural light. That is why the white light is the most common light used in our daily life. Conventionally, there are two ways to produce the white light [31]:

- Blue-LED with phosphor: A yellow phosphor is coated on a Blue-LED. The yellow phosphor can be excited by the blue light and emit yellow light. Therefore combining the blue light and the yellow light can produce white light.
- RGB combination: Three LEDs produce red, green, yellow light respectively. Then mixing the three kinds of lights at a decent percentage can get white light.

The first method is more commonly used because of the easier implementation and lower cost. But using the second method can use Color Shift Keying (CSK) to modulate the data, which means better performance in communication. Now there is a growing interest in using White-LEDs to transmit high-speed data [43] and for localization [13-16], [18], [44-45]. In [43], a 550 Mbit/s real-time VLC-based positioning system of White-LEDs using Non-Return-to-Zero On-Off Keying (NRZ-OOK) modulation is presented. By employing the proposed analog pre-emphasis circuit based on NPN transistors and active post-equalization circuit based on an amplifier, the 3dB bandwidth of VLC link could be extended from 3 to 233MHz with the blue-filter. However, the modulation bandwidth of White-LEDs is still limited, which restricts the modulation rate.

RGB-LEDs have relatively higher modulation bandwidth, data rates, and lower response time. Compared with 40Mbps data rates of White-LEDs, RGB-LEDs can reach up to 100Mbps [23]. In [46], CSK is suggested to be used in RGB-LEDs to meet the high data rate application. This type of modulation scheme can transmit the data by modulating red, green and blue signal separately. Some researchers propose a method that only modulates a single color of RGB-LEDs, while other colors remain to provide white color for illumination. Employing RGB-LED, some outstanding achievements of efficient modulation are concluded in [47]. In [47], the authors employ Carrier-less Amplitude and Phase (CAP) modulation and Recursive Least Square (LS) based adaptive equalization in the high-speed RGB-LED VLC system and achieve a very high data rate of 4.5Gb/s at an average indoor distance. The RGB-LEDs employed to transmit data can provide higher data rate over White-LEDs at the cost of greater complexity. The comparison of the two technologies is presented in Table VI. Some researchers have proposed the VLC-based-IPS using the RGB-LEDs [36], [48].

2) Modulation Method: We have mentioned that LEDs should be taken into account for both illumination and communication purposes. Hence, it is important that a proper modulation method is used to modulate the signal to switch LEDs at desired frequencies which contain the information. It means that the modulation method for VLC should achieve not only the data rate but also to meet the demand of illumination. In other words, there are two questions to be considered: dimming control and flicker control. Sometimes the illumination is low in a room, while we still need to achieve the data rate which can be realized by dimming control. As we know, it is harmful to our eyes when we stay long in the environment of fluctuations of the light intensity, which means the modulation method should support the flicker control.

As an alternative of RF, VLC has some difference from it. Hence, the phase or amplitude modulation method is not suitable for VLC. In VLC, the modulation method encodes the information in the intensity of the light wave. There are lots of modulation methods proposed for VLC. Various modulation methods have been used in the VLC-based positioning. We first introduce some types of modulation methods for VLC, and then we will present some articles which employ the modulation method in VLC-based positioning.

On-Off Keying (OOK) is a type of the simplest technique modulating data through turning the LED on and off to transmit data bits 1 and 0. It is easy to be implemented. Therefore it is widely used in wireless communications. However, this modulation method neither supports dimming control nor provides a high data rate. In NRZ-OOK, the positive and negative signs are used to express the 0s and 1s

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TABLE V
COMPARISON BETWEEN THE VLC-BASED-IPS, THE RF-BASED-IPS AND THE DEVICE-FREE-IPS

System	RF sensitive area	Interference	Cost	Complexity	Precis	Bandwidth	Communication Security	Application Scenarios
VLC-based-IPS	Yes	Low	Low	Low	Higher	Large	High	Residence communities, hospitals
RF-based-IPS	No	Medium	Low	high	Low	Limited	Medium	Residence communities
Device-free-IPS	No	High	Low	Low	Medium	Limited	Medium	Large warehouses and stores, intrusion detection and tracking identify

TABLE VI
SUMMARY OF LED TECHNOLOGIES

Type	Usage Rate	Advantages	Disadvantages
White-LEDs	High	(1) Low cost, (2) Availability	Low data rates
RGB-LEDs	Medium	High data rates	(1) Complexity, (2) High cost

respectively. It also can carry more information. In [43], based on the NRZ-OOK modulation method, authors design optimal analog pre-equalizer and post-equalizer and employ them in the white phosphorescent light LED for practical high-speed, low complexity application, and finally, realize a 550Mbit/s real-time VLC link.

Pulse Position Modulation (PPM) is a type of modulation method based on pulse position. The pulse position identifies the transmitted symbol. The symbol duration is divided into t slots of equal duration, and a pulse is transmitted in one of the slots. The position of the pulse identifies the transmitted symbol [31]. The PPM is simpler but with lower spectral efficiency and a lower data rate. Therefore lots of other PPMs have been proposed such as Variable PPM (VPPM) [49], Overlapping PPM (OPPM) [50], Multi-Pulse PPM (MPPM) [51], Overlapping MPPM (OMPPM) [52], Expurgated PPM (EPPM) [53], Multilevel EPPM (MEPPM) [54], and Differential PPM (DPPM) [55]. These modulation methods have their advantages and weaknesses. When we introduce them to VLC-based positioning, we should take these pros and cons into consideration and choose the most suitable one.

Orthogonal Frequency Division Multiplexing (OFDM) can be used in VLC to reduce the inter-symbol interference and increase the utilization of bandwidth. In OFDM, the channel is divided into multiple orthogonal subcarriers which transmit parallel data streams simultaneously [31]. However, it is sensitive to the frequency deviation. OFDM needs some modifications because the conventional OFDM method can use the complex and bipolar signals which do not directly suit VLC whose signals are unipolar and real. We can use the Hermitian symmetry to generate real-time signals for implementation at the cost of doubling the required bandwidth. Some articles have presented some schemes such as Asymmetrically Clipped Optical OFDM (ACO-OFDM) [56], DC-biased Optical OFDM (DCO-OFDM) [57] and Asymmetrically clipped DC-biased Optical OFDM (ADO-OFDM) [58]. These schemes are described in detail in above articles.

Color Shift Keying (CSK) is designed for VLC to solve the problem of lower data rate and support the dimming control. CSK uses the intensity of the red, green, and blue colors in the LED source to modulate the signal. This type of the scheme relies on the color space chromaticity diagram. Recently CSK has attracted significant attention, and some research results have been presented in [59-61].

Carrier-less Amplitude and Phase (CAP) is efficient to increase the VLC link capacity under limited bandwidth and high spectral efficiency. The CAP scheme is composed of two orthogonal signals but has no need for overhead and carrier [62]. Commonly, CAP is much simpler than OFDM and can be implemented without FFT and IFFT blocks. However, it is less flexible than OFDM. In [63-65], some characteristics are studied.

We compare these modulation methods in spectral efficiency, system complexity, power efficiency, data rate, dimming control and flicker effect in Table VII.

3) Types of Receivers: As we know, a receiver is an important part of VLC-based positioning because a large amount of information needs to be obtained by it, such as IDs, the base station position, signal strength, RRS, TOA, or geometric information and so on. According to the positioning algorithm, different information is required. Otherwise, various types of receivers can affect the data rate which is important in VLC. We divide the receivers into two classes: Photodiode (PD) and image sensors. Both of them receive the modulated signals and decode the data. Next, we will present the strength and weakness of the two classes.

PD: Using the property of PD that it is highly sensitive to the light, many PD-based VLC positioning systems are proposed. This type of technique is easy to be implemented and can achieve a relatively high data rate. The response time is a lack, which can contribute to measuring TOA of the signal at high accuracy. In other words, the PD-based VLC positioning system is the most likely to choose the method of RSS, TOA, and TDOA algorithms. However, image sensors based approach can get better results when using the vision analysis algorithms. Otherwise, the multiplexing technique is needed in the PD-based positioning system because it cannot separate light source. In [13], [66], the PD-based-IPS has been proposed.

Image Sensors: Compared with Photodiodes (PDs), it is less expensive. The camera is equipped with most hand-held devices while PDs are not, which means utilizing PDs as the receiver needs additional cost. Using image sensors, the multiplexing techniques are not necessary because the image sensor can spatially separate light sources. Moreover, the positioning accuracy is not subject to the multipath effect. Therefore, the image sensor techniques can be developed quickly. Some studies can be found in [39], [40], [67], [68]. In

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TABLE VII
SUMMARY OF MODULATION METHODS

Modulation Method	Spectral Efficiency	System Complexity	Power Efficiency	Data Rate	Dimming Control	Flicker Effect
OOK	High	Low	Low	Low to moderate	Yes	High
PPM	Low	High	Moderate	Moderate	Yes	Moderate
CAP	High	High	Moderate	Moderate	Yes	Low
OFDM	High	Moderate	High	High	No	Moderate
CSK	Moderate	Low	High	High	Yes	Low

[67], the authors use image sensors to capture LEDs and infer the position of an image sensor according to the relationship between the known three-dimensional (3D) coordinates of LEDs in the real world and two-dimensional (2D) coordinates of LEDs in the image. Utilizing the available data, the authors can determine the position using different methods [67].

B. Taxonomy of the VLC-based-IPSs

With the development of wireless technology, research results have been applied into IPS with various wireless technologies. Different VLC-based positioning systems have been presented in these papers. To evaluate the state-of-the-art the VLC-based-IPSs, a taxonomy should be defined, and various algorithms should be compared and analyzed within the groups with common characteristics. In this paper, the VLC-based-IPSs are classified based on three key features: mathematical method, sensor-assisted method, and positioning optimization method.

We put the general three categories: proximity, triangulation, and fingerprint, into a class called the mathematical method. We add two more categories: sensor-assisted method and positioning optimization method. The sensor-assisted method mainly focuses on how the additional sensor can help the VLC-based-IPSs to achieve better accuracy. In this approach, we discuss four types of sensors: image sensor, accelerator, light sensor and multiple optical receivers. The positioning optimization method concentrates on how to improve the accuracy and track-ability after the positioning algorithm. We take the filtering technique, spring model and normalizing method as the positioning optimization method. Taxonomy of VLC-based positioning systems is illustrated in Figure 1.

C. Mathematical Method

In this section, we will present the mathematical method which includes the proximity, triangulation, and fingerprint. Some survey papers have concluded these positioning algorithms. Therefore, we simply describe the principle of these algorithms but mainly discuss the performance of these papers which use the mathematical method for positioning. We compare these mathematical methods in Table VIII.

1) Proximity: As the simplest positioning method, proximity can provide characteristic relative location information based on the range of a known station or a near AP. In detail, if there is just one beacon detecting the mobile device, it will be considered as being collocated with a mobile device. When more than one beacon can identify the mobile device, we can derive the position of the mobile device according to the beacon whose signal is the strongest, because we think the signal strength is positively related to the distance. From this, we can also conclude that the number of beacons determines the positioning accuracy. However, the variance of proximity is high such that sometimes it cannot meet the demand of localization. In [69-74], some results that VLC-based positioning uses the proximity to realize the localization are presented.

In [69], an indoor navigation system is proposed, which employs LED lights and a geomagnetic sensor. It can provide the accurate position and travel direction. The geomagnetic sensor is used to obtain the route information. This system can provide voice navigation and can be naturally divided into three steps. The accuracy of the scheme is approximately 1-2m. To optimize the cost and implementation, VLC-based positioning using LED lamps as beacons is shown in [70]. The system consists of mobile phone and LED lights, where the lamps repeatedly send ID or coordinate, and then the mobile phone can derive the exact position using the received data. Two types of beacons: passive beacon and active beacon are proposed in this article. Error free range for communication is up to 4.5m.

A hybrid system with VLC and ad-hoc wireless network infrastructure can provide accurate and convenient position information in [71]. Two designs of non-carrier and 4MHz carrier VLC-based hybrid positioning technology have been shown. For the initial design, the error-free communication range is about 0.33-0.403m which is suitable for the low data rate scene. However, for the second one, it is about 0.0057-0.479m, which can be used in the high data rate and wide-range reception scene.

A system that uses VLC and 6-axes sensor can provide higher accuracy than the simple VLC-based positioning system [72]. A Switching Estimated Receiver Position (SERP) scheme can decrease the estimated error distance in the paper. The authors of [73] employ the rotation matrix and Support Vector Machines (SVMs) to calculate precise Field of View (FOV) limit, and the possible azimuth and tilt angulations are also defined. The paper simulates the model which uses the 6-axis sensor to support the azimuth and tilt information and then proves that this model can reduce at least 80% of computations during the Geometric Optics (GO) calculation.

In [74], a system that can achieve long range indoor positioning is presented. The system is a hybrid system where the five-hop ZigBee wireless network is employed to unite with VLC to positioning. The advantages of the system are low power, high security, and extensive area.

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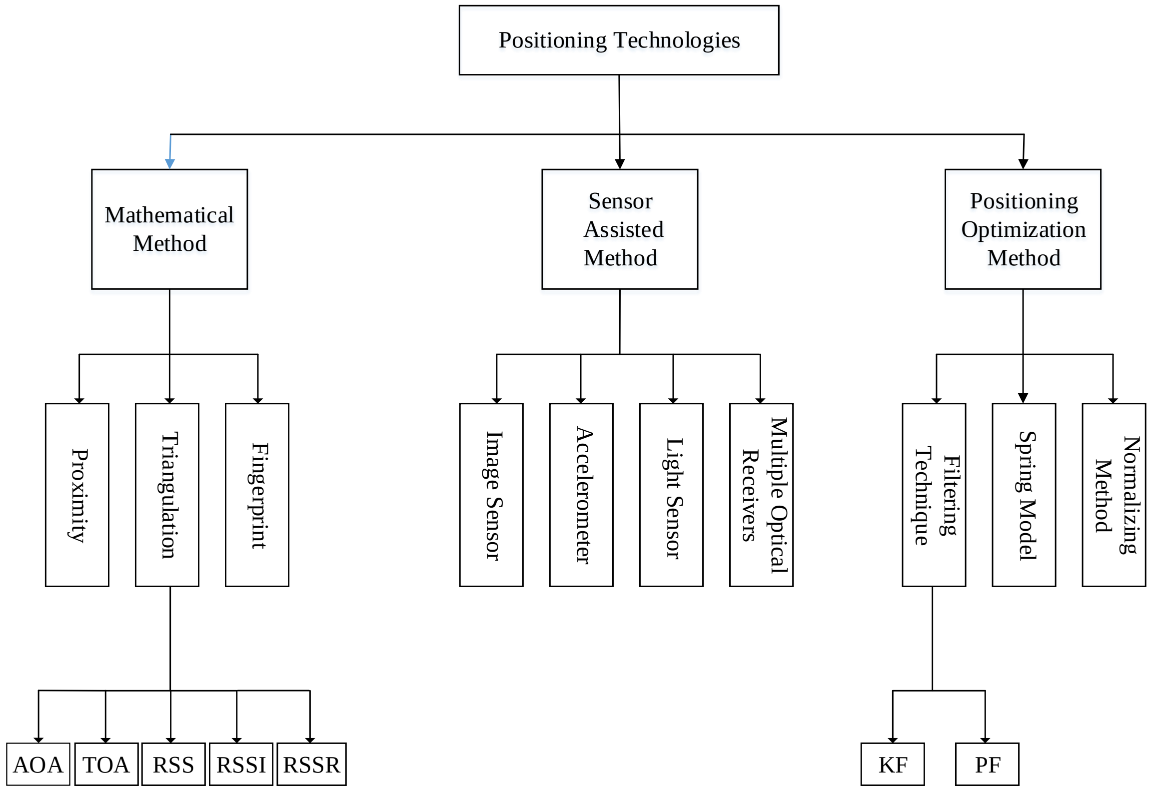

Fig. 1. Taxonomy of positioning technologies

TABLE VIII
TAXONOMY OF MATHEMATICAL METHODS

Method	Accuracy	Coverage	Cost	Multipath Effect	Additional Hardware	Strength	Weakness
Proximity	Low to high	Good	Low	No	No	Low cost	Low accuracy
AOA	Medium	Good	High	Yes	Yes	Do not take up the bandwidth	(1) High cost, (2)Complexity, (3) Need of the antenna array
TOA/TDOA	High	Good	High	Yes	Yes	High accuracy	(1)High cost, (2)Time synchronization
RSS	Medium	Good	Medium	Yes	No	Low cost	Low accuracy
Fingerprint	High	Good	Medium	No	No	Low cost	(1)Need of heavy calibration, (2)Map maintaining is complex

2) Triangulation: Triangulation employs the geometric properties of triangles to estimate the location of the mobile device. Through measuring the distance to the fixed known measurement points, or the received signal angle, and using the geometric properties of triangles, we can derive the location. According to the different methods using the position estimate, we divide the triangulation into three classes: AOA, TOA, and RSS. We will introduce them in detail subsequently.

$i)$ **AOA**

AOA realizes locating according to the angle between the base station and the mobile device. The principle of positioning is that using the intersection of multiple directions of the wireless signal estimate the location of the mobile device. The AOA method requires at least two base stations. If we can attain two or more angles of incidence, it is possible to calculate the intersection of multiple lines using geometric relationships while this intersection is the location of the mobile device, as shown in Figure 2.

Supposing the angles of incidence between the azimuth line of wireless signal and the base station, namely BS1 and BS2, are denoted by θ_1 and θ_2 respectively. The coordinate of the mobile device is (x_0, y_0), and the coordinate of the base station is (x_i, y_i). Then they satisfy the following formula:

$$\tan\theta_i = (y_i - y_0)/(x_i - x_0), i = 1, 2 \quad (1)$$

AOA is very susceptible to the external environment, and its positioning accuracy is lower than TOA. Otherwise, the positioning accuracy of AOA will decrease when the distance between the mobile device and base station increases. Meanwhile, AOA needs the additional hardware which increases the cost.

Next, we will introduce the AOA method mentioned in some papers. A high accuracy system using AOA is shown in [40],

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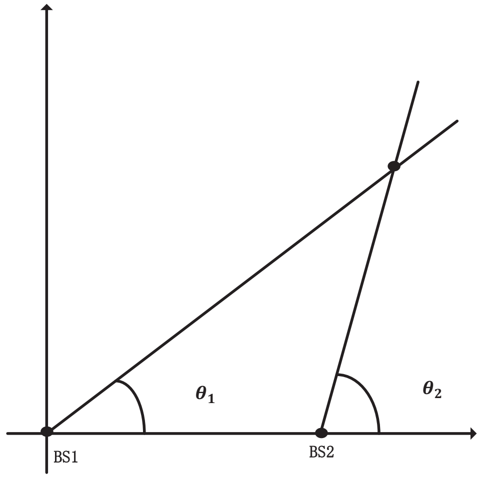

Fig. 2. Positioning based on AOA

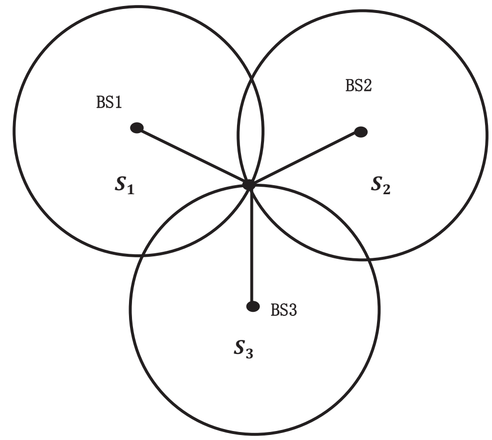

Fig. 3. Positioning based on TOA

where the accuracy is about 0.1m. Based on AOA, a system which wearables can afford is presented in [42]. In this paper, a polarization-based modulation is suggested, which is flicker-free and can provide a low pulse rate. To handle the uneven sampling problem, an adaptive down sampling algorithm is employed. The authors consider the numerical optimization of the positioning algorithm and this system can be used in smartphone and Google Glass. The accuracy of the system is about 0.25m in [75]. The light sensor and accelerometer are used to estimate the position of the mobile device.

The number of PDs in a circular-PD-array which can affect the accuracy of the AOA-based positioning system is verified [76]. Then the truncated-weighting method is employed to enhance the estimate performance of AOA where the simulations show the truncated-weighting can provide better accuracy than the average and Max method. In [77], the authors consider that it is harder to determine the precise position information when the straightforward information provides tracking for the blind user. Hence, the authors utilize the sensor angles to calculate the user's exact location. For testing the system in the real experiment, the accuracy is as small as 10cm.

A LOSOWC system for tracking is proposed in [43]. In this article, the reference LED corresponds to the unique identifier which is represented by a single tone. Then the receiver detects the number of the reference LEDs and computes their positions.

In [78], the AOA-based VLC positioning system whose accuracy can reach 8cm in the simulation is shown. The authors derive the expression of the Cramer-Rao bound (CRB) in detail. The system [79] uses photoreceiver which consists of three PDs to facilitate differential photocurrent sensing of the incident light AOA. AOA is not sensitive to the power and alignment imbalances of the beacon grid, and the comparison experiment shows that the accuracy of the RSS method is four times higher than AOA which can reach 5cm. The authors also report that the three factors, which can affect the accuracy of AOA-based positioning, are systematic errors, angular precision, and geometry on position uncertainty.

$ii)$ **TOA**

In an actual environment, the distance between the mobile device and each base station is not the same. Hence, the distance between the mobile device and nearby base station is calculated according to the time which the signal uses to arrive at the base station. In a 2D-plane, when the distance between an object and three non-collinear reference points is known, the position of the target can be achieved.

Suppose that the propagation time between the mobile device and the ith base station is t_i, and the propagation speed is v. Then the distance s_i between the mobile device and base station can be estimated as $v * t_i$. We suppose that the coordinates of the mobile device and base station are (x_0, y_0) and (x_i, y_i) respectively. Then, we can derive the following formula:

$$(x_i - x_o)^2 + (y_i - y_o)^2 = s_i, i = 1, 2, 3 \dots n \quad (2)$$

where n is the number of detected base stations. Then we draw three circles whose centers are different base stations and the radius is the distance s_i. In the ideal case, the three circles will intersect at one point, and this point is the spatial position of the target point in Figure 3.

This method requires that transmitter and receiver have accurate time synchronization. The positioning result is heavily dependent on the hardware which may significantly increase the cost.

Because the TOA method needs strict time synchronization, there is relatively small amount of research. In [16], a system based on the TOA method has been presented. It assumed that the synchronization between the transmitter and receiver is perfect. In this system, white-LEDs are used for illumination and signal transmission. The device (receiver) receives the signals and estimates the distance of each LED. The range can be obtained by measuring the TOA signal from LED. The CRB of the TOA-based-IPS is discussed in this paper.

TDOA is a method to improve TOA, and this method only requires time synchronization between the base stations that participate in positioning without the need for time-critical synchronization between the base stations and target. TDOA method measures the propagation time difference between the mobile device and base stations, then converts it into the

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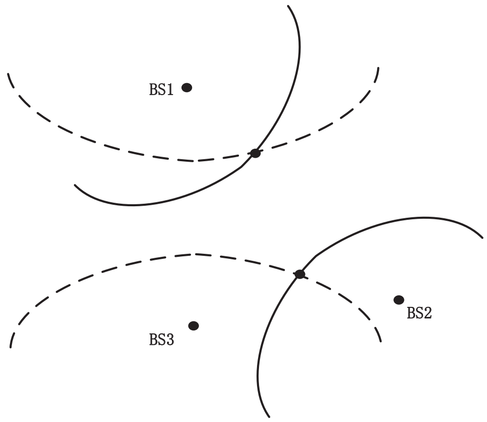

Fig. 4. Positioning based on TDOA

distance by multiplying the speed of propagation.

Then we can attain the location of the mobile client using the hyperbolic positioning method. As Figure 4 shows, the distance difference between the base station BS1 and BS2 is $s_{12} = v * (t_1 - t_2)$. It is sure that the mobile device must lie in the hyperbola whose focuses are the two base stations and the focal length is the distance difference s_{12}(see the solid line of Figure 4). Meanwhile, another hyperbola can be drawn whose focuses are the BS1 and BS3, and the focal length is their distance difference s_{13} (see the dotted line of Figure 4). Then the intersection of the two hyperbolas is the location of the mobile device. We suppose that the coordinates of the mobile device and the base station are (x_0, y_0) and (x_1, y_1) respectively. Then we can derive the following formula

$$s_{1i}=\left(\sqrt{(x_1-x_o)^2+(y_1-y_o)^2}-\sqrt{(x_i-x_o)^2+(y_i-y_o)^2}\right)^2,i=2,3 \quad (3)$$

Equation (3) represents two solutions corresponding to the two intersections of the hyperbola. When putting it into the application, we take advantage of prior knowledge to distinguish which is the real-world coordinates. Compared with TOA, it is less affected by the environment. Therefore, a higher positioning accuracy can be provided by TDOA.

We have previously introduced the system in [14] which provides a very high accuracy within 1cm. The positioning algorithm used in this paper is the TDOA method. Using the TDOA method, the synchronization between the LED panel and receiver is not necessary but requires the synchronization between transmitters [80]. The system of [80] utilizes TDOA of the pilot signals to estimate the position of the device. The average of the location error of 0.14m is proposed in [81]. In the paper, the authors use the Intensity Modulation/Direct Detection (IM/DD) and subcarrier BPSK schemes to modulate the optical signal. To estimate the position of the device, the TDOA method and the nonlinear LS algorithm are employed into this system.

The authors of [82] consider Gaussian noise and provide the VLC-based positioning mathematical model which contains three steps: distance estimation, position estimation, and error minimization. To minimize the errors, a Two-Step Approximate ML algorithm (TSAML) is shown in this article. As for the noise error, an average filter is used to mitigate it. In [83], a TDOA-based system using IM/DD with two LEDs is proposed. The algorithm of the system measures not the phase, but the peak-to-peak amplitude. The experiment has been conducted, while the accuracy is not clearly shown in this paper.

iii) **RSS**

RSS is an alternative approach to estimate the distance between the mobile device and the base station using the attenuation property of emitted signal strength. With increasing distance, the signal strength decreases which means that RSS can obtain the distance. Some researchers try to utilize the signal attenuation-based methods to calculate the signal path-loss due to propagation. However, the path-loss models may fail because of the severe multipath fading. Of course, there are many improved methods to achieve better positioning accuracy. Some systems presented previously also use RSS to positioning such as the systems of [13], [15], [18], [35], [66]. OFDM applied in VLC-based positioning to mitigate the multipath effect is introduced in [66]. The performance of OFDM as a multi-carrier modulation scheme and IM/DD as a single-carrier modulation scheme is compared, and the results show that the positioning accuracy of OFDM is much better. The effect of subcarrier numbers is discussed.

In [44], CRB is used to analyze the theoretical accuracy of the VLC-based-IPS. It shows that the limited accuracy of 4.78cm can be obtained. The influences to CRB of different parameters are discussed in detail. Otherwise, the results indicate that the positioning accuracy with the square LEDs is lower than that of the triangle LEDs. The state estimation model is employed in the system of [45] for positioning. User mobility and dynamic device orientation are taken into account. The Kalman Filter (KF) recursive estimation is employed in this paper. The results show that the location error is about 5cm. In [84], the authors propose a Gaussian Mixture Sigma-point Particle Filter (GM-SPPF) in the RSS-based system to reduce the positioning error.

In [85][86], the authors mainly concentrate on the impact of multipath reflections on the RSS-based system performance. The Combined Deterministic and Modified Monte Carlo method (CDMMC) is employed to calculate the impulse response [85]. Hence, calibration methods are employed to reduce the positioning error that the accuracy of this system can reach 0.558m. In [86], a system using the OOK modulation method and the CDMMC method is suggested. The accuracy of this scheme can be 0.8064m.

The effect of the diffuse light reflection on the performance of the RSSI-based system is discussed in [87]. This paper shows that the diffuse reflection has a significant effect on the positioning error so that the error can increase considerably. The ICE effect of the VLC-based-IPS using the RSS technology is presented in [88]. Later we will discuss ICI in detail.

The authors of [89] focus on the problem of the effect of the tilted receiver angle, and a compensated scheme is designed in this paper. It shows that the estimated location changes in the same direction with the receiver tilted. In this paper, the error compensated scheme utilizes multiplying the weighting factor to correct the shape of the estimated position and shifting the

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estimated position to minimize the error using a gyroscope. The simulation and experiment show that the error is 0.7424cm and 1.6226cm respectively.

The Optical Orthogonal Codes (OOCs) are applied to distinguish different signals at the receiver in [90]. Then the RSS technology is used to estimate the position of the mobile device. Otherwise, the reusing/combining codeword is employed in this system to expand the system and use the code resource efficiently. The simulation results show that the system can achieve an excellent accuracy of 0.08m and the receiver structure is simple.

In [91], the Dual-Tone Multi-Frequency (DTMF) technique is employed in the RSSI-based positioning system. As we presented before, LED has its ID encoded into DTMF signal in this system. The LED lamp, as a transmitter, sends the DTMF signal periodically. Then the receiver can utilize the received DTMF signal to calculate the channel gain of the different LED lamp. Finally, solving the Lambertian equation group can obtain the position of the mobile phone. The simulation results show that the positioning error is about 18mm.

The work in [92] shows a positioning algorithm which contacts the received light intensity at the receiver with the pre-calculated light intensity at a given position. The LED AP sends a location tracking request message, while the mobile device measures the received light intensity and sends the response message back to the LED AP for position estimation. The process is called the message exchange between the LED AP and a mobile receiver. The simulation can show the performance of the system, i.e., the accuracy is about 30mm.

An accuracy of 0.5mm of IPS is shown in [93]. In this system, the authors use visible light to recover the VLC channel feature and estimate the position of the mobile device by solving the Lambertian transmission equation group. The system can be considered as a cost-efficient and higher resolution system. The paper shows that increasing transmitting power improves noise tolerance and the receiver height cannot affect the performance of the algorithm.

A Received Signal Strength Ratio (RSSR) is applied in the system of [94]. As usual, LED lamps are used to transmit the information. Using the received signal contained in each time slot, RSSR is easy to be obtained. According to RSSR, we can derive the distance ratio and then at least three equations could be built.

The authors of [95] use the adopting framed slotted ALOHA protocol in the RSS-based positioning system and state that the synchronization is not required between LEDs. In this system, four LEDs can transmit the own code, and the modulation scheme is OOK. Hence the system is easy to deploy, and the accuracy is about 5cm.

3) Fingerprint: Fingerprint means the feature or characteristic of signals that are location dependent. In most times, RSS is considered as a type of fingerprint. It is assumed that in different areas the features of signals are different. The fingerprint uses the difference to correspond to the particular position.

There are two types of fingerprint: radio-map based on fingerprint localization and map-free fingerprint localization. The map based fingerprint localization contains two stages: offline stage and online stage (or run-time stage). In the offline stage, the site survey is performed in an indoor environment and a radio-map is generated. The location positioning technique uses the currently observed signal strengths and radio-map to estimate the position of the target. However, the diffraction and reflection can affect RSS, which leads to poor accuracy. Map-free fingerprint methods as another fingerprint can reduce the complexity of mapping maintaining. Next, we will introduce some papers that use fingerprint technology to achieve positioning.

In [96], LED lamps with a unique address transmit the signal. The signal is modulated using the NRZ-OOK modulation method. The mobile device receives the signal, then the coordinates of the device can be estimated by the correlation of the received signal and predetermined addresses. Further, the authors define a Combination of Correlation Values (CCV) to obtain the position of the device. The accuracy is about 4.38cm.

The iterative Maximum Likelihood (ML) approach is employed in the positioning algorithm in [97]. The ML solution cannot be obtained in the closed form of the regular model. However, the iterative method does not require the variance of the measurement noise distribution. The LS method can obtain the solution quickly but not always optimal. Of course, the computational complexity will increase because of the iterative process. Some papers have shown that the accuracy of the system using the iterative approach highly relies on the initial guess. Fortunately, the iterative ML method has a complete initial guess as for the LS solution. The simulation shows that a positioning error lower than 10cm can be obtained when the SNR is 15dB.

A self-localization method and high robustness system are shown in [98]. The system uses the Bayesian signal model and considers the inherent sparsity to detect the LED lamps, which means little complexity. Because the system does not need synchronization among the beacons, it allows LEDs to be fully autonomous. The authors use a suitable probabilistic model to achieve positioning whose accuracy is about 0.81cm.

The system in [99] designs the transmitter and receiver to enable them to utilize the visible light for localization. In the transmitter, before being sent to LEDs, the voltage or current is modulated with the continuous waves. LEDs transmit visible light where a sinusoidal wave modulates the intensity. Otherwise, modulating frequencies of different LEDs are different. Then the receiver calculates the received power spectral density, extracts the power of each modulating frequency as the metric, and connects with the parameters of the fingerprint map which is corrected in the offline stage. The simulation and experiment show that the accuracy of the system reaches 15-20cm.

In [100], the authors propose a solution of Localization, Access, and Transmission (LAT). It can be explained as follows: i) the indoor localization system uses a power measurement database, ii) MIMO architecture supports VLC and provides high data rate by PPM, iii) Time Division Multiple Access (TDMA) is used in VLC connectivity links. The numerical experiment has verified the performance.

The uniform deployment of infrared LED devices is also

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regarded as a transmitter, and the information of impulse responses is used to achieve indoor positioning in [101]. The positioning algorithm is fingerprint that the map collects, namely the power samples of the transmitters and time samples for the impulse responses in the offline stage. In the online stage, compared with real-time impulse response peaks in the map, the position of the mobile device can be obtained.

An IPS based on White-LEDs which uses the correlation method is proposed in [102], and the accuracy is about 0.651cm. In [103], to mitigate interference, Time-Division-Multiplexing (TDM) is employed. Otherwise, the TDM scheme can selectively receive signal. As a result, the average error distance is 1.689cm. The system in [104] also employs TDM to remove ICI. However, the error range is 1.5787cm which is lower than that of [103]. In [104], the Extinction Ratio (ER) distribution is employed, and NRZ-OOK modulates the location information of the transmitter. The VLC-based positioning using fingerprint technology and the image sensor is presented in [105-110]. In Section V, we will introduce these articles in detail.

Based on the mathematical method of positioning systems, a lot of papers are contained and presented in detail. Further, we summarize these articles that use the numerical method to achieve the positioning in Table IX. We mainly compare the system cost, complexity and the accuracy of these systems. Otherwise, some individual points will be presented in the note column in Table IX.

D. Sensor-assisted Method

As an IPS, the ability to provide high accuracy is necessary. To achieve high precision, many sensors are used to assist positioning, which has been proved to be efficient. The sensor is embedded in the mobile device such as a smartphone. Of course, the additional sensor can be applied in positioning. Lots of sensors can be used in VLC-based positioning. In this subsection, we just consider four types of conventional sensors: image positioning/image sensor, accelerator, light sensor and multiple optical receivers. Then we will describe these articles which use the sensor-assisted method to obtain better positioning performance.

1) Image Sensor: Commonly, image positioning uses the image sensor or camera to capture images, and then detect the presence of the luminaires in the image, decoding their transmitted identifiers for and/or locations. The location and orientation of the luminaires can be derived in [40]. In this positioning technology, the number of image sensors and how to obtain the position of the mobile devices may be different.

In [40], Luxapose consists of the visible light beacon, smartphone, and a cloud server. The smartphone is unmodified, and LEDs are slightly modified. The system requires overhead lights with known positions and nearby beacons to have relative positions. The AOA positioning process contains two steps: using the image sensor to capture a picture, and detecting at least three beacons with known 3-D coordinates. Assuming that the camera geometry is known and it can be determined by the pixels of the beacons projected. Then utilizing the properties of similar triangles, we can derive the position of the mobile device respect to the beacon's coordinate system. The experiments show that the accuracy is about 0.1m.

The authors of [67] use a single image sensor to estimate distance and use the intervals to build a set of equations to obtain the position of the mobile device. The image sensor noise which is ignored in most of the research can reduce the accuracy of the positioning. An image sensor noise model and noise reduction mechanism are proposed in [67]. The results show that the positioning error can almost keep stable at all levels of noise added to the image. The accelerometer sensor is also employed in this system. As a result, mobile devices can have arbitrary orientation and the positioning error is about 10cm.

Two image sensors used in positioning are shown in [68] where the two image sensors are placed in the same plane. Through the lens, the two image sensors receive the signal from all LEDs and utilize the geometric relationship to calculate the distance between LEDs and the unknown position. Then the authors employ the LS estimation and vector estimation method to determine the position respectively. A few centimeters of accuracy can be reached.

In [105], a system that can measure the position and direction of the mobile device is proposed. It is pointed out that the position can be measured outside in this paper. An image sensor receives the signals and demodulates the coordinate information, and then the fingerprint method is used to positioning. The accuracy is about 7cm in the simulation environment.

A system using the image sensor and accelerometer sensor to estimate the location of the mobile device is proposed in [106]. The experimental results reveal that the positioning error is about 5cm. The positioning process can be described in three steps: finding color LEDs, obtaining camera inclination constraint and estimating position. The image sensor captures images with two LEDs lights and inputs the world positions of LEDs to the position estimate program. Then the position estimation can determine the location by finding the colors and utilizing the relation between light color and light position. Moreover, using the acceleration sensor can obtain the camera inclination.

In the system in [107], the positioning algorithm needs at least three LEDs to transmit their 3D coordinate information. Then the two image sensors with unknown position receive the signal through the lenses and demodulate the position information of LEDs. Finally, utilizing the geometrical relations can derive the unknown position. In this system, two image sensors are used and installed in the same plane, and the lenses need identical properties. Therefore, the positioning error distance is about 10cm.

In [108], four single LEDs with different colors are used as transmitters because of the installation easiness and lower cost. Different colors can identify the position information of four LEDs. Two PC cameras receive the signal of LEDs and demodulate the position information. From calculating the geometric relationship of the images on the two image sensors, the position can be obtained. In this system, a vector estimation algorithm is employed to calculate the four quadratic equations

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TABLE IX
SUMMARY OF MATHEMATICAL METHODS

Algorithm	Reference	Accuracy		Cost	Complexity	Note
		Experiment Results	Simulation Results			
Proximity	[69]	1-2m		Low	Low	Provide voice navigation for visually impaired people
	[70]	4.5m		Low	Low	
	[71]	Narrow-range 0.33-0.4m, Wide-range 0.01-0.48m		Medium	Medium	Hybrid system using VLC and ad-hoc wireless infrastructure
	[72][73]		0.3-0.6m	Low	Low	
	[74]		0.4m	Medium	Medium	Achieve a long-range localization
Triangulation (AOA)	[36]	1-2m		Medium	Medium	Provide a data rate between 300-400Mb/s within a illuminate angle of 90^0
	[40][42][75]	below 0.3m		Medium	Medium	
	[76]		5-30cm	High	High	Employ the truncated-weighting method
	[77]	10cm		High	High	
	[78]		8cm	High	High	
	[79]		5cm	Medium	Medium	
Triangulation (TOA)	[16]		2-5cm	High	High	
Triangulation (TDOA)	[14]		1cm	Medium	High	No additional infrastructure
	[80]		3.9cm	Low	Medium	No ID information is required to be transmit along with the pilot signal
	[81][83]		below 0.3m	Medium	Medium	
	[82]		2cm	High	High	
Triangulation (RSS)	[13][121]	2.4cm		Low	Medium	Use the adjustment method to reduce the positioning error
	[18]	0.4m		Low	Medium	
	[35]		5.9cm	Medium	Low	
	[45]		5cm	Medium	Medium	KF technology
	[66][87]		0.3m	Low	Medium	
	[84]	9cm		Medium	Low	
	[85][86]		below 0.9m	Low	Low	Investigate the impact of multipath reflections
	[88]	6cm		Medium	Medium	Mitigation ICI
	[89]	1.66cm	0.74cm	Low	Low	Titled receiver angle error compensated
	[90]		0.08m	Low	Low	Utilize OOCs
	[92]		30mm	Medium	Medium	
	[93]	0.5-7.3mm		Low	Medium	OOK
	[95]		5cm	Low	Low	OOK
	[114]	4cm	1-2mm	Low	Medium	Multiple optical receivers
	[124]		6cm	Low	Medium	Spring model
Triangulation (RSSI) Triangulation (RSSR)	[15]	1.5cm		Medium	Medium	Multiple optical receivers
	[44][91]		below 5cm	Medium	Medium	
	[94]		1.12cm	Low	Low	
Fingerprint	[96][104]	below 5cm		Low	Low	
	[97][109]		below 10cm	Low	Medium	
	[98][102]		below 10cm	Low	Low	
	[99]	15-20cm		Low	Medium	
	[100]		1-2cm	Medium	Medium	Utilize PPM technique
	[101]		20-80cm	Low	Low	Infrared LED devices
	[103]		1.69cm	Low	Medium	TDM scheme
	[105]		7cm	Low	Low	Image sensor
	[106]	5cm		Low	Medium	Image sensor
	[107][110]		below 10cm	Medium	Medium	Two image sensor
	[108]		85cm	Medium	Medium	Two image sensor

derived from the geometric relationship.

The authors use the low-resolution photodiode array and the front camera of the mobile phone to achieve positioning in [109]. By matching the spot information with visual information and position information, the position of the mobile device can be estimated. Meanwhile, a collinear-equation model is derived in this paper. A detailed positioning process is presented, and the simulation results show that the accuracy is in the order of centimeters.

In [110], the LED-aided and encoder-based navigation system is proposed, which can estimate the position and pose of a vehicle moving in a 2D-plane. The authors use LEDs, a high-speed camera, and two encoders to enable the navigation. The high-speed camera and encoders are equipped with the front wheels. The camera can capture the image which may contain LEDs to measure LED coordinates and recover ID of LED. Encoders can gauge the rotation of the front wheels. Finally, the authors use an Extended Kalman Filter (EKF) to fuse measurements of the encoder and camera to obtain a state estimate.

2) Accelerometer: As we know, the received power can be used to derive the distance between the receiver and LEDs. However, the received power can be affected by the distance, the irradiance, and incidence angles. In spite of the fixed position of the receiver, the received power is different when the incident angle of the receiver is changed. To determine the orientation of the receiver, the incident and the irradiation angles, the accelerometer which is embedded in most smartphones are employed in some papers. We will introduce several papers using the accelerometer for positioning and explain the goodness of the accelerometer in these systems.

In [38], the accelerometer is used in this positioning system to provide the measurements of the acceleration of a receiver, and then these measurements can be used to determine the receiver's orientation. The received signal power and the measurements of the accelerometer are used to form a closed-form expression which can estimate the position of the receiver. Meanwhile, the accelerometer measurements can be utilized to remove some assumptions that the angle of a transmitter's irradiance equals the incidence angle at the receiver. Hence the height of the receiver from the ground is not needed. The experiments show that the accuracy is about 0.5m in the simulation environment.

The authors of [38] continue to study IPS by using visible light, accelerometer, and the results shown in [75]. The accuracy is increased to about 0.25m in the experimental environment. Similarly, the height of the receiver from the ground and the alignment of the receiver's normal with LED's normal are not required. LEDs broadcast their known coordinates to the receiver. By using TDMA approaches, the receiver can estimate the received power. The irradiance angles of transmitters can be obtained from the measurements of the accelerometer. Then by using the triangulation technology, the distance can be derived. It can be used to estimate the

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position of the mobile device. In [39], the accelerometer sensor and multiple optical receivers are employed and then the triangulation technology is used to estimate the position of the mobile device.

The accelerometer sensor is used in [67], which allows the mobile device to have an arbitrary orientation. The authors of [67] state that the accelerometer allows low-noise measurement of acceleration in three perpendicular axes, thus it can sense tilt, motion, shock, and vibration in a smartphone. In this system, the accelerometer sensor is used to measure the tilt forward and backward on the x-axis and the tilt side to side on the y-axis. Employing the measurements of the accelerometer sensor, the positioning can succeed in determining the position of the mobile device at arbitrary orientations. Similarly, in [106], both an image sensor and an accelerometer are used in the positioning system. The detailed calibration procedure of the position detector using the accelerometer is shown in this paper. Using accelerometer, the camera inclination constraint can be obtained. By utilizing the results, the direction of the camera can be estimated.

3) Light Sensor: It is found that the light sensor has a deterministic sensitivity to both distance and incident angle of the light signal. Therefore, it is suitable for using the light sensor as the receiver of VLC-based positioning. The light sensor can retrieve the beacon information, measure RSS and then estimate the position of the mobile device. The light sensor can be found on the mainstream mobile devices. Meanwhile, to meet some condition or better performance, researchers can design the light sensor by themselves.

In [18], the authors develop a small light sensor board which contains a light sensor, an amplifier, and low battery. Through the audio jack, the light sensor board is connected to the mobile phone. In the Epsilon, the light sensor is the receiver. Different LEDs and light sensors may have different emission powers and the receiving sensitivities, which result in various measurements to the distance. The system is deployed in different office environments, and the 90th percentile accuracies can reach 0.4m.

A stand-alone sensor connected to a microcontroller in the positioning system is presented in [41]. Firstly, the authors conduct an experiment to demonstrate that the light sensor can infer the distance and angular information from the light signal. The information received by the light sensor may mix the background light signals such as daylight and artificial lights. Hence, a low-end microcontroller is employed to switch on and off at a specified frequency. Then FFT and inverse FFT are used to extract the signal strength at a particular frequency. A Multi-Face Light Positioning (MFLP) algorithm is proposed in this paper. This method needs at least three properly oriented sensors to receive the signal strengths and the sensors' orientation. Combined with the pre-defined RSS model, the measured data provides sufficient spatial constraints to estimate the position of the mobile phone.

In [111], considering the low-power applications, the authors show that how the tags can demodulate the same signals using a light sensor instead of a camera. By employing the Binary Frequency Shift Keying (BFSK) modulation in the system, the data rate has been increased substantially. A fixed differential photosensor is employed in IPS [112]. Incident light of the photosensor can generate the photocurrents which are functions of the incident angle of the light. It means that by utilizing differential photocurrents, the differential photosensors can estimate the AOA of signals from two LEDs. Then the triangulation technology can be used to determine the position of the mobile device. The accuracy is about 4cm.

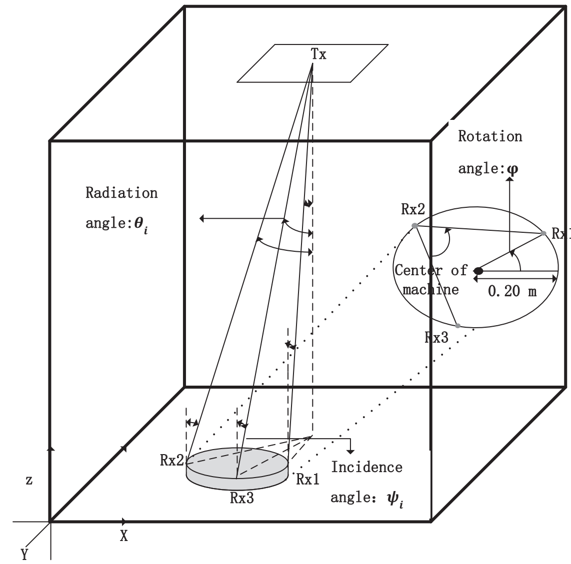

Fig. 5. Positioning system based on single transmitter and multiple receivers

4) Multiple Optical Receivers: the VLC-based-IPS using the RSS technology requires multiple transmitters or receivers. We have presented numerous multiple transmitter systems based on the RSS technology which needs to know the transmission distance between the receiver and at least three transmitters. However, interference such as ICI technology needs to be employed in this kind of system. Another choice is that a single transmitter and multiple receivers are used in IPS. However, additional problems need to be solved efficiently. Next, we will introduce some papers to describe this kind of approach.

In [15], the system with the single transmitter and multiple receivers using the RSSI technology obtains the position of the mobile device. The obvious advantages of this kind of system are not only removing ICI but also extending the positioning range to the single Rx. The system is shown in Figure 5. The radius of the device is 0.2m. When one receiver is selected as the reference assuming Rx_1, the relative positions of Rx_2 and Rx_3 can be expressed as

$$\left.\begin{aligned} Rx_1 &= \left(r\cos\left(\varphi\right), r\sin\left(\varphi\right)\right) \\ Rx_2 &= \left(r\cos\left(\varphi+\tfrac{2\pi}{3}\right), r\sin\left(\varphi+\tfrac{2\pi}{3}\right)\right) \\ Rx_3 &= \left(r\cos\left(\varphi+\tfrac{4\pi}{3}\right), r\sin\left(\varphi+\tfrac{4\pi}{3}\right)\right) \end{aligned}\right\} \quad (4)$$

where Rx_i is the i_{th} receiver, r is the radius of the device, and φ is the rotation angle of the device. Then we can derive the relative position of the receivers. Combined with the distance between LED and receiver, the coordinate of LED and the parameters of the receivers, the position estimation is obtained. A positioning error of 1.5cm is achievable.

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The system of [37] uses a single transmitter and multiple titled optical receivers to estimate the position information of the mobile device. Because a single transmitter is used, ICI can be ignored. However, considering that the RSS difference is induced by the incidence angle difference, the problem that the system needs a minimum separation distance can be solved. In this system, the 2D-positioning is based on AOA, and the 3D-positioning is using RSS. The positioning error is less than 6cm.

In [41], the authors state that their system has the following advantages. For example, the receiver can be mobile, and its heights can be unknown, and its normal does not require to be aligned with those of transmitters and so on. In this system, at least three tilted optical receivers and one accelerometer are required. To receive different light intensities from the same LED, optical receivers should be tilted at different angles. According to the received light intensities and the receivers' orientations, by employing the triangulation technology, the position of the mobile device can be obtained. The accuracy of less than 6cm can be achieved when the average receiver speed is 1.3m/s by experiments with four optical receivers.

In [113] a fixed single optical transmitter and tilted multiple optical receivers consist of the positioning system. Utilizing the coordinates of LED and the received signal power difference between PDs can obtain an accuracy of about 4cm. The authors in [114] focus on the scenario where the multi-PDs terminal device is located. Due to the multiple PDs in a device where their relative positions are known, positioning is different from these positioning scenarios which have the fixed receiving node with the known coordinate. To get better performance, the iterative mechanism is suggested to be employed. The simulation results show that the positioning error can be less than 2mm, while the accuracy of 4cm can be achieved in the experimental environment.

Various sensor-assisted methods are presented previously. Now we compare these papers in the aspects of precision, system cost, system complexity, and some individual notes. We summarize them in the following Table X.

E. Optimization Method

By using the mathematical method and sensor-assisted method, some accuracy is reported. However, the researchers still try to find other ways to improve the performance. Employing some other methods of other subjects or positioning environments, researchers have done some modification to make them suitable for the VLC-based-IPS. There we take the filtering technique, spring model and normalizing method as the positioning optimization method which is mainly concentrated on achieving better accuracy and improving the trackability.

1) Filtering Technique: To achieve better performance in the positioning system, some filter techniques are employed. We can divide these into two classes: KF and Particle Filter (PF). Some papers are collected to show the advantages of the filtering technique in IPS.

$i)$ **KF**

Lots of estimators are proposed to be used in mobile positioning and tracking as a location estimators such as KF and EKF. KF requires that the system is dynamic and the measurement model is linear. However, EKF can linearize the nonlinear model. Hence it is suitable for use in these nonlinear systems.

In [45], a state estimation model is used to achieve localization and mobile tracking. The KF recursive estimation technology is employed in this system. In this system, the authors describe the process of operation of KF in four steps: initialization, prediction, measurement, and update. However, considering the KF linear requirement, other methods are presented in this paper: EKF and Unscented Transformation (UT) which propagate system state and covariance information through nonlinear transformations rather than analytically linearizing the transformation. Experiments are conducted to compare the two technologies of EKF and UT.

Before describing the principle of the paper [110], we focus on the EKF technology. In [110], both the motion and measurement models are nonlinear, which means that KF is not suitable. However, EKF is employed to fuse the measurements of the encoder and camera to produce a state estimate. Accurate initialization plays a significant role in the performance of EKF. Therefore this article mainly concentrates on the initialization algorithm which is formulated as a Bayesian estimation problem. Otherwise, various aspects of the initialization and EKF aiding using LED features are discussed, and the experiments are conducted to verify the performance.

Using KF to detect the direction of a robot is presented in [115]. In this paper, the accurate positioning comes from two reasons that the dead reckoning and KF using the output of a geomagnetic sensor and gyro sensor. The experiments show the lowest error comes from KF compared to the geomagnetic sensor and gyro sensor. The maximum directional error of KF is kept to less than 6 degrees. Meanwhile, the positioning error is 10.5cm.

The EKF technology is used in [116], and the detailed mathematical model is shown in this article. The offline calibration method is proposed, and state initialization method is analyzed. In [117], an integrated AOA-RSS localization method is used in positioning, and the EKF estimator is employed to achieve better performance. The EKF estimator is a compensator to reduce the accumulative errors through controlling the mobile robot moving on the specified path. The simulation results prove that EKF can achieve a smaller positioning error and reduce the accumulative errors of the mobile robot.

$ii)$ **PF**

The basic idea of the PF algorithm is adopted by a set of independent random samples from the proposal distribution called particles to represent a posteriori probability. Then obtaining new observations is to update the posteriori probability. Particles pass through a certain way, and Bayes rule updates the weight. The advantage of this scheme is the adaptation to the nonlinear model of Gaussian noise without the assumption of the linear and Gaussian hypothesis of the system.

GM-SPPF technology which combines the Gaussian Mixture Model (GMM) and Sigma approach is employed for higher accuracy [84]. GMM is a Probability Density Function

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TABLE X
SUMMARY OF SENSOR-ASSISTED METHODS

Algorithm	Reference	Accuracy		Cost	Complexity	Note
		Experiment Results	Simulation Results			
Image Positioning	[40]	0.1m		Medium	Medium	
	[67][68]		below 10cm	Medium	Medium	Use accelerometer and propose a noise reduction mechanism
	[105]		7cm	Low	Low	
	[106]	5cm		Low	Medium	Use accelerometer
	[107][110]		below 10cm	Medium	Medium	Two image sensors
	[108]		85cm	Medium	Medium	Two PC cameras
	[109]		7cm	Low	Medium	Front camera
Accelerometer	[38]		0.5m	Low	Low	
	[39]	6cm		Medium	Medium	Multiple optical receivers
	[67]		10cm	Medium	Medium	Use the image sensor and propose a noise reduction mechanism
	[75]	0.25m	7cm	Low	Low	
	[106]	5cm		Low	Medium	Use image sensor
Light Sensor	[18][41]	0.4m		Low	Medium	
	[111]		0.3m	Low	Medium	
	[112]	4cm		Low	Medium	
Multiple Optical Receivers	[15]	1.5cm		Medium	Medium	
	[37]	6cm		Low	Medium	
	[39][113]	below 6cm		Medium	Medium	Use accelerometer
	[114]	4cm	1-2mm	Low	Medium	

(PDF) composed of a weighted sum of Gaussian components which is used to represent a set of particles. Sigma-Point Approach (SPA) is applied to sample the posterior distribution of a set of points. The GM-SPPF approach can reduce the computational cost. Otherwise, the system in [84] uses the OOK modulation scheme and trilateration technique to estimate the position. The experiments verify that employing GM-SPPF can obtain a better performance and the accuracy is about 9cm.

The system in [118] called Lightitude employs PF for its localizing scheme, and then the scheme can be described as the following four parts: initialization stage, attributing weights to particles, continuous walking and achieving convergence. The detailed positioning process is shown in this paper, and a realistic light strength model is proposed. Otherwise, the authors show how the system can coexist with Wi-Fi. Experiments in typical office and library environments confirm the effectiveness and the robustness of Lightitude.

In [119], both EKF and PF technologies are employed in IPS which uses the AOA-RSS positioning algorithm. Compared with EKF linearizing the system model to adapt the nonlinear system, PF is inherently suitable for the nonlinear system, which means that the linearize process can be removed and implemented. When the number of particles is small, the positioning error of PF is larger than that of EKF. However, with an increasing number of particles, the positioning error of PF is less than EKF. Of course, both the two technologies can improve the system accuracy.

Considering the non-Gaussian measurement noise and nonlinear measurement model in [120], PF technology is employed to obtain the position of the robot. The motion model, initialization, and localization method are described in detail by a mathematical formula. The experiment shows that a better trackability can be obtained by using PF. The authors in [121] study the tracking capability using KF and PF. In KF technology, the Gaussian distribution assumption of the state variables is made. Hence, in the scene which does not follow the Gaussian distribution, KF may have poor performance. However, PF does not have the limitation. Hence, the experiment where a wild value is added shows that both KF and PF can estimate the deviation of the real path, while PF is faster than KF in determining the aggregation of the correct path.

2) Spring Model: A Localization Algorithm based on a Spring Model (LASM) method is employed in the system so that the computational complexity may be reduced with the same accuracy [122]. The principle of the algorithm is to simulate the dynamics of the physical spring system and then obtain the position of the node. In this algorithm, the sensor nodes are set as particles and connected with neighbor nodes by virtual springs. As we know, the spring will force the nodes to go back to the stable positions from the other random positions. Hence, the blind nodes can be located by calculating the related forces with the neighbor nodes. The LASM system is simple to be implemented. In [123], Wi-Fi and Bluetooth environment IPSs have used the spring model to collaborative positioning. In this system, the position and distance information are first estimated by Wi-Fi and Bluetooth sensor. Then the confidence scores of the estimated position and distance are measured. Finally, the modified spring model utilizes that information to correct the positioning error.

In [124], an improved spring model is used for collaborative VLC-based indoor positioning. The basic principle is similar to that of the paper [123] where the coordinate position is first estimated. Then the spring model is employed to correct positioning errors. A full scheme of the improved spring model in the VLC-based-IPS is shown in Figure 6. In this system, no additional sensors are needed, except for two types of nodes. One is the unknown nodes which may require positioning services, while the other is nodes used to assist positioning. By using the improved spring model, the system can correct the positioning error, particularly when occlusions occur.

3) Normalizing Method: In [13], a system utilizing IM/DD based on CA-VLC is proposed. ICI can be mitigated by the Carrier Allocation (CA) method. An adjustment process using normalizing method is proposed in this paper, and the experiments show an achievable accuracy of 2.4cm without the adjustment process. The authors investigate the performance of the system efficiency with the normalizing factor n. The optimal value of n relies on the system environment parame-

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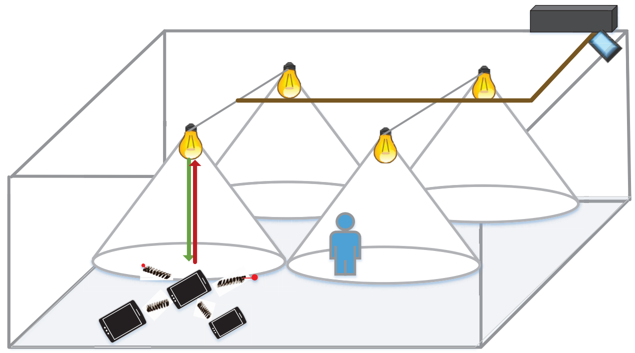

Fig. 6. Schematic of the improved spring model

ters which can affect the received optical power. The authors pointed out that three techniques can be used to determine the optimal value of n, namely mathematical analysis, calibration, and fixed n for transmitter diversity.

The positioning optimization methods mainly focus on the filtering technology, while other methods have attained little attention. However, it is a good idea to employ technology from other subjects for better performance. Through the simple description of the spring model and normalizing method, the researchers can extend the optimization method to other aspects. That is why we will take the positioning optimization method as a class alone. Then we still compare these papers in Table XI.

V. Discussions, Challenges, Countermeasures, and Lessons Learned

We have introduced and discussed various VLC-based-IPSs in Section IV. In addition, a more comprehensive comparison will be presented in this section which contains all of the VLC-based-IPSs that we have discussed in this paper. The challenges and the corresponding countermeasures of the VLC-based-IPSs are analyzed. Moreover, we give a detailed description of lessons learned in this section.

A. Discussions

The VLC-based-IPSs are introduced in Section IV are concluded in Table XII. Different from these tables in Section IV, we compare all these the VLC-based-IPSs at three aspects: positioning technology, modulation method, and accuracy. We divide these positioning systems into four classes. One article may not just use one of them to achieve the positioning. Hence, we collect all types of positioning technologies. As for the modulation, it is unnecessary for some papers, while other documents do not show it. Hence, there is some blank below the modulation method item. Since the accuracy is an important criterion to evaluate a positioning system, it is still shown in Table XI. However, some papers mainly focus on the trackability or the navigation and the exact positioning error cannot be found in them. Otherwise, performances of the proposed systems can be tested by experiments or simulations. Hence, we present the accuracy of research results and simulation results. Note that because the testing environment is different, a significant difference exists in the measurement range. We should not just care about statistical accuracy.

B. Challenges

VLC-based positioning has also attracted much attention. Many technical issues have been solved, and various algorithms have been proposed to obtain better performance. However, there are still some challenges which need the researchers to overcome with great efforts.

Inter-Cell Interference (ICI) in the VLC-based-IPS means LEDs in the same room can cause severe interference to each other [31]. As we know, the smaller cell radius can provide the higher capacity, which means LEDs should be deployed densely. Each cell modulates different information to provide different VLC applications. If the adjacent lighting cells use the same frequency band, ICI problem will be produced. Thus in the VLC-based-IPS which has multiple transmitters (LEDs), ICI should be taken into account in the VLC-based positioning.

Multipath reflection is a major factor which may decrease the indoor positioning accuracy in the complex environment. In a room, the corner area suffers severely from the reflections, while the impact of reflections decreases in the edge areas. The authors have reported their research results in [86], [125], [126]. In [86][126], the authors have analyzed multipath reflection, which shows that the multipath reflection will decrease the positioning accuracy, and the edge and corner areas have the relatively higher positioning error than other areas. In [125], the authors use the Combined Deterministic and Modified Monte Carlo (CDMMC) approach to estimate the channel impulse response considering multipath reflections. The results show that localization error increases from 1.2272m to 2.0989m at the different location of the room when the multipath reflections are taken into account. Note that the center of the room where the multipath reflection is weak has the accuracy with 0.0019m. From the data, we can see multipath reflection will severely decrease the accuracy of IPS.

Lack of fingerprint and effect of the orientation of receiver: The visible light requires fingerprints to identify LEDs uniquely. The similar RLS may be captured at different positions, which means an ambiguity problem that the same RLS may imply multiple possible locations. It leads to wrong estimated position of the person. As we mentioned before, receiving device's orientation and altitude may affect RLS. Some papers need to know the height of the receiver from the ground, while others may fix the receiver at a special orientation. Assuming that the receiver is a smartphone, its orientation and altitude are not fixed during the process of human movement. Therefore, this method will limit the applicability of the VLC-based-IPS.

Long delay is one of the limitations of the positioning system. Nowadays, a lot of applications need the real-time service, especially for the navigation system. If the system cannot provide the real-time positioning information, the moving users may get lost. For the VLC-based-IPS, the data collection, running the positioning algorithm and other measures to decrease the positioning error will cost some time. The

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TABLE XI
SUMMARY OF POSITIONING OPTIMIZATION METHODS

Algorithm	Reference	Accuracy		Cost	Complexity	Note
		Experiment Results	Simulation Results			
KF	[45]		5cm	Low	Medium	KF
	[110]		9cm	Medium	Medium	EKF
	[115]	10.5cm		Medium	Medium	KF/dead reckoning
	[116]	7cm		Low	Medium	EKF
	[117]	4cm		Low	Medium	EKF/AOA-RSS
PF	[84]	9cm		Medium	Low	GM-SPPF
	[118]	1.93m		Medium	Medium	
	[119]		Few centimeters	Low	Medium	EKF/PF
	[120][121]	below 10cm		Low	Medium	
Spring Model	[124]		6cm	Low	Medium	
Normalizing Method	[13]	2.4cm		Low	Medium	

TABLE XII
SUMMARY AND COMPARISON OF VCL-BASED-IPSS

Reference	Positioning technology			Modulation Method	Accuracy	
	Mathematical Method	Sensor-assisted Method	Positioning Optimization Method		Experiment Results	Simulation Results
[13]	RSS		Normalizing method	IM/DD	2.4cm	
[14]	TDOA					1cm
[15]	RSSI	Multiple optical receivers		QPSK	1.5cm	
[16]	TOA			IM/DD		2-5cm
[18]	RSS	Use light sensor		BFSK	0.4m	
[35][95]	RSS			OOK		below 6cm
[36]	AOA			DMT	1-2m	
[37]		Multiple optical receivers		QPSK	6cm	
[38]	Triangulation	Use accelerometer				0.5m
[39]	AOA	Use accelerometer and multiple optical receivers			6cm	
[40]	AOA	Image positioning		OOK	0.1m	
[41]	MFLP/ Triangulation	Use light sensor		OOK	0.4m	
[42][77]	AOA	Image positioning			below 0.3m	
[44]	RSSI					4.78cm
[45]	RSS		KF			5cm
[67]	Fingerprint	Image positioning and use accelerometer				10cm
[68]	Fingerprint	Image positioning				Few centimeters
[69]	Proximity	Use geomagnetic sensor			1-2m	
[70]	Proximity			OOK	4.5m	
[71]	Proximity			OOK	0.33-0.4m/ 0.01-0.48m	
[72][73]	Proximity	Use 6-Axis sensor		No need		30-60cm
[74]	Proximity			NRZ-OOK		0.4m
[75]	AOA	Use accelerometer			0.25m	
[76]	AOA			OOK		5-30cm
[78][79]	AOA					below 10cm
[80]	TDOA					3.9cm
[81][83]	TDOA			IM/DD		below 0.3m
[82]	TDOA		Running average filter			2cm
[84]	RSS		GM-SPPF	OOK	9cm	
[66][85][87]	RSS					below 0.6m
[86]	RSS			OOK		0.81m
[88]	RSS			PSK	6cm	
[89]	RSS				1.66cm	0.74cm
[90][92]	RSS					below 8cm
[91]	RSSI					1.8mm
[93]	RSS			OOK	0.5-7.3mm	
[94]	RSSR					1.12cm
[96]	Fingerprint			NRZ-OOK	4.38cm	
[97]	Fingerprint			OOK		10cm
[98][102][103]	Fingerprint					below 2cm
[99]	Fingerprint				15-20cm	
[100]	Fingerprint			PPM		1-2cm
[101]	Fingerprint					20-80cm
[104]	Fingerprint			NRZ-OOK		1.58cm
[105][107][109]	Fingerprint	Image positioning				below 10cm
[106]	Fingerprint	Image positioning and use accelerometer			5cm	
[108]	Fingerprint	Image positioning				85cm
[110]	Fingerprint	Image positioning	EXF			9cm
[111]		Use light sensor		BFSK	0.3m	
[112]	AOA	Use differential photosensor			4cm	
[113]	AOA	Multiple optical receivers			4cm	
[114]	RSS	Multiple optical receivers			4cm	1-2mm
[115]		Use geomagnetic sensor and gyro sensor	KF		10.5cm	
[116]			EKF		7cm	
[117]		Use gyro sensor	EKF	OOK	4cm	
[118]	Model method		PF		1.93m	
[119]			EKF/PF			Few centimeters
[120]	Fingerprint	Image positioning	PF		10cm	
[121]	RSS		KF/PF		3cm	
[124]	RSS		Spring model		6cm	

positioning system exists for the time delay. Hence, different system models have the different delays.

LED to Internet connectivity will become a trend and challenge when lots of LEDs are deployed indoors. It is nec-

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essary to connect LEDs to the Internet to create a VLC-based broadband access network [31]. However, as we mentioned before, the interference which may reduce the data rate should be taken into account. The cost is an important factor which may affect the use of the system.

Some other challenges such as ambient light noise, synchronization, flickering, receiver design and energy efficiency, uplink and RF augmentation, mobility and coverage need to be addressed shortly. Solving these challenges is essential so that VLC-based positioning systems can be deployed in practice. Researchers try to find new and efficient solutions to these challenges and the performances of systems may be improved, and better service can be provided for the users.

C. Countermeasures

ICI mitigation is critical in the VLC-based-IPS. Some researchers have paid a lot of attention to the ICI reduction in VLC [127-128]. In [127], the Filter Bank-based Multicarrier (FBMC) is employed to mitigate ICI generated in OFDMA-based cell partitioning. A carrier allocation VLC system which adopts different carriers among the system's respective cells is proposed [128]. Then the authors of [128] employ carrier distribution technology to the VLC-based-IPS to mitigate ICI, and the research results are shown in [13], [88], [129]. The frequency band allocation can be used to mitigate ICI. Another way is to design the VLC-based-IPS using multiple optical receivers. We have presented that the VLC-based-IPS using the RSS technology requires multiple transmitters or receivers. Thus if we use a single transmitter and multiple optical receivers in IPS, the interference causing LEDs will disappear. However, the other problems caused by the multiple optical receivers need to be solved.

Mitigating the effect of multipath reflection is necessary for the VLC-based-IPS. A calibration approach is proposed in [85] to reduce the effect of the multipath reflections. An OFDM-the VLC-based-IPS is suggested to mitigate the multipath reflections and provides a high data rate transmission in [66], [126]. Designing new calibration methods to increase the positioning accuracy in the corner and edge areas may be a good way. Deploying LEDs at a suitable layout design to increase the coverage area of LEDs can decrease the average positioning error.

Solution to lack of fingerprint and effect of the orientation of the receiver: The authors in [118] utilize the user's mobility to obtain a RLS set which is spatially related and combines it with inertial sensor data into a PF for positioning. To address the effect of the orientation, in [118], a light strength model is employed to connect every receiving device's status with RLS. We have presented that the sensor-assisted method can help to remove the limitation such as using the accelerometer.

Decreasing delay is one of the important aspects of the positioning system. In the VLC-based-IPS, a solution is presented in [130]. A multiple access scheme based on block encoding TDM verifies that it can shorten the delay time efficiently. In the environment with multiple lamps, it may take a long time to receive signals because every light needs a time slot to transmit the data in the conventional TDM scheme. In [131], nine LEDs compose one block to reduce the system delay and ICI. The simplified localization algorithm, designing new modulation method and suitable design of the system can decrease the delay.

LED to Internet connectivity need to design a novel technology providing high-speed Internet connectivity and reducing the cost. The transmitted data can be dynamic. Through an advanced computer or a microcontroller, the different messages can be sent to different locations to meet various demands. It means the network can control the information of the LED lamp.

D. Lessons learned

Designing a the VLC-based-IPS needs to take many factors into account. When taking the environmental effect into account, the system is more complex. Hence many additional measures should be employed to solve the problem. Here we list some lessons learned.

The multiple transmitters and a single receiver in IPS or single transmitter and multiple receivers in IPS should be considered. The VLC-based-IPS using RSS technology requires multiple transmitters or receivers. Thus how to choose the two different systems and which kind of result will bring are important. In this first kind of system, the multipath reflection interference such as ICI technology needs to be solved. Hence, the detailed method to decrease the multipath reflection and ICI is presented in Section VI Countermeasures. As for the second type of IPS, we have collected this kind of system in the class of sensor-assisted method. Researchers can study these references to find some ideas.

Choosing the suitable LED technology and modulation method can improve the system performance. The RGB-LEDs can provide higher data rate over White-LEDs at the cost of complexity. Moreover, the suitable design of the modulation method can further improve the data rate of the system using the RGB-LEDs. The efficient modulation method can also decrease the effect of the multipath reflection. We have listed a lot of modulation methods in Section IV. Researchers can choose or redesign the suitable modulation method according to the actual application scenarios. Besides, an excellent new modulation method can avoid the flickering and improve the detection performance. Otherwise, a new multiplexing technique can shorten the positioning latency.

Using some sensors reasonably can obtain good positioning precision in the VLC-based-IPS. Using image sensors, the multiplexing techniques are not required and the positioning accuracy is not affected by the multipath effect. Moreover, the system can place two image sensors and use the geometric relationship to determine the position. The accelerometer can be used to determine the orientation of the receiver, the incident, and the irradiation angles. Because the received power can be affected by the distance, the irradiance, and incidence angles, thus using the accelerometer to obtain the orientation of the receiver can improve the estimated accuracy of the distance. The light sensor has a deterministic sensitivity to both distance and incident angle of the light signal. Thus it

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can infer the distance and angular information from the light signal. For the low-power applications, the researchers can use a light sensor instead of a camera. Moreover, the geomagnetic sensor and gyro sensor may be helpful. Also, the researcher can attempt to employ other sensors into the VLC-based-IPS.

Designing suitable calibration methods and using correct optimization method (such as filtering technique) can reduce the positioning error. An efficient calibration method can be designed to adjust the positioning results especially in the corner position which the positioning error is often larger. And the filtering technique is helpful to improve the positioning precision. A running average filter may be efficient to decrease the noise error.

The new mathematical model is a good choice to realize positioning. The TOA-RSS[132], AOA-RSS-based algorithms[117,119,133,134] and triangulation-fingerprint method[135] have been proposed. Comparing with the common mathematical methods(such as TOA, TDOA, AOA, RSS), those methods can combine the respective advantages of the common mathematical methods and provide better performance. Moreover, the dead reckoning and the spring model can be employed in the VLC-based-IPS. Even the range-free positioning method can be combined with the range-based positioning method to realize positioning.

Combining VLC with other wireless technologies such as Wi-Fi, Bluetooth or ZigBee, may be a good choice to realize hybrid positioning. And this kind of strategy may integrate the advantages of different wireless technologies.

VI. Conclusion

With the large requests of LBS, the indoor positioning has attracted an enormous amount of interest in both academic and industrial communities. Numerous research results have been reported. Based on the investigation and universality of VLC, the indoor positioning as an important application of VLC has experienced a fast development. In this paper, we make an in-depth survey of the VLC-based-IPSs. VLC-based indoor positioning technologies such as LED technology, modulation method, and types of receivers are compared. In this paper, we propose a new taxonomy that two new classes, namely, sensor-assisted method and positioning optimization method are addressed. It is convenient for researchers to find a method to improve system performance, to capture the optimized research direction and to understand the degree of the studies in the field. Further challenges are shown in this paper. Tables are listed to compare the positioning systems and the performances of the systems proposed in the pioneering papers.

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