Passive Visible Light Positioning Systems: An Overview

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Abstract

Localization is one of the key applications of visible light communication (VLC) using which sub-centimeter level positioning accuracy is possible. Many visible light-based positioning (VLP) systems have been designed by industry and the research community. Their commercial viability is hampered by the requirement of significant changes in the deployed lighting infrastructure, resulting in a prohibitive increase in the cost and overhead of deployment. In this paper, we review passive VLP systems an emerging paradigm that offers hope to overcome this challenge and thus can catalyze commercial adoption of a new wave of VLP systems. Unlike active systems, passive ones provide unprecedented flexibility and can enable new potential applications and scenarios such as ability to track users not carrying photosensors. Both natural light sources e.g., sunlight and artificial man-made sources can be used to transmit location information. This paper provides a taxonomy of recently proposed passive VLP systems which is supported by several examples from the recent research literature. A comparative performance of these systems based on factors like accuracy and infrastructure changes is provided along with their limitations.

CCS Concepts

• **Hardware** → *Wireless devices*; • **Information systems** → **Location based services**.

1 Introduction

Advances in the Internet of Things (IoT) have accelerated development of a smart digital world around us. A plethora of sensors and actuators are steadily and seamlessly integrating into our daily lives in our homes, retail stores and factories. For the purpose of monitoring, controlling and interacting with these devices, it is becoming even more important to know their exact location with high accuracy. Thanks to the advances in VLP, it is possible to locate humans and objects with very high accuracy. The technology uses omnipresent light sources and visible light to send data wirelessly while piggybacking location information. Typically, this requires light-emitting diodes (LEDs) or fluorescent light (FLs) bulbs to modulate the light for transmitting the positioning beacons. At the reception side, a light-sensing device such as a photodiode (PD) or a camera is needed to sense the changes in light. However, not all the light sources can be modulated and not all the target objects or humans can carry a light-sensing device.

A VLP systems in which the light sources are actively modulated to transmit data to light sensors are known as active VLP systems. Existing active VLP systems, however, suffer from several limitations resulting in low commercial interest. Some of them are listed below:

- **High infrastructure changes:** On the transmitter side, these systems demand custom-designed light sources with a controller capable of modulating the light. Updating existing light fixtures with these controllers incurs extra cost and deployment effort, making commercialization difficult.
- **The burden on the user:** The users of an active VLP system require carrying an optical sensing unit for positioning. Although mobile phone cameras are pervasive and abundant, users are confronted with their high power consumption and privacy concerns. Furthermore, the requirement of holding the mobile in the direction of light sources to receive location estimates is a cumbersome task.
- **Complexity:** Many active VLP systems need to collect different light features and perform extensive signal processing to accurately estimate the position. Complex hardware on both ends of communication link increases the overall cost.

Furthermore, it is impossible for active VLP systems to modulate the natural light sources e.g. sunlight, a flexibility passive VLP systems can provide. In addition information can be sent even without modulating the light source and the user may or may not have to carry a light-sensing device for receiving the beacons. The passive VLP systems offer the following benefits:

- **Device-free localization:** Passive VLP systems enable localization without requiring users to carry any light sensing device. Light reflection or shadows caused by their body are used for locating them.
- **Security:** In passive user systems, there is no need for users to keep personal gadgets like mobile phones for estimating their position.
- **Energy efficiency:** Most of the passive VLP systems capture the light signals using photodiodes (PDs), which consume significantly less power (μW) than cameras. Moreover, in passive VLP systems either the transmitter end or the user is passive resulting in more energy-efficient design compared to the active systems in which both sides have active elements.
- **Less infrastructure changes:** In passive VLP systems, there is no need for specially designed light sources with a controller. The already installed lighting fixtures can be used as a source without any modifications.
- **Cost-effectiveness:** The use of low-cost PDs and the need for fewer infrastructure changes make passive VLP systems cost-effective alternatives to active systems.

Contributions: To the best of our knowledge, this is the first paper that provides an overview of emerging passive VLP systems with

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its focus on localization. Firstly, we propose in Section 2 a classification of passive VLP systems according to passive elements and receiver types, which is similar to the classification used by [11] for passive VLC systems in general. We present a comprehensive survey of the most recent work done in passive VLP systems based on our classification. Secondly, the paper discusses in Section 3 multiple applications of commercial importance and the ways in which recently proposed passive VLP systems meet the needs of such applications. Moreover, to give readers a comparative overview of the capabilities of different passive positioning systems, we analyze the performance reported from their real-world system implementations presented in recent literature in Section 4. We then conclude the paper while pointing out the challenges yet to be overcome by passive VLP systems for wider acceptability in commercial settings.

2 Architecture and Taxonomy of Passive VLP Systems

2.1 Architecture

The architecture of passive VLP systems consists mainly of three components: a light source, user, and receiver. The light source can be man-made like incumbent FLs, LEDs or natural light sources like the sun. The receiver is a light-sensing device usually a photodetector or camera referred to as 'Rx' in this paper. The user can be a human, robot or any object like a carton box in warehouse, etc.

2.2 Taxonomy

We classify the passive VLP systems based on types of transmitter and users' involvement into three categories: passive source, passive user and fully passive VLP systems as shown in Figure 1. Like the work presented in [11], we define a light source as *passive* if it only provides illumination and *active* if it *also* modulates data. The user is considered active if it carries a light-sensing device and passive otherwise [1]. Figure 1 (a) represents an active VLP system in which user is localized with the help of one or multiple deployed active light sources and an active light sensing device carried by the user. Based on the received modulated information, the user locates its position. On the other side, passive VLP systems do not always need an active light source. The light operation and user involvement solely depend upon the type of passive VLP system. We further classify passive VLP systems into types of receivers namely PD-based systems and camera-based systems as shown in Figure 2. We now briefly explain each type of passive VLP systems with examples from research literature.

2.2.1 Fully Passive In fully passive systems, neither the light fixtures modulate the positing beacons nor users carry any photosensor. Instead, typical unmodulated light sources present in indoor spaces such as bulbs and sunlight from windows, etc, are used for positioning purposes. As a user moves around, it blocks the light and produces a shadow. Shadows of the users are of varying intensity. This causes a change in the light intensity at different points in the room. The light sensors placed in room measure these changes and estimate user's actual position and/or room occupancy status. Such light sensors can be placed at different places in the room.

[1]Passive user localization is also synonymous to *device-free localization* or *non-cooperative localization.*

Systems: LocaLight [1] is a fully passive localization system that embeds co-located PDs and RFID sensors on strategic points on the floor to localize users using their shadows. The receivers are battery-free that harvest energy intermittently from the incident RF signals generated by RFID readers. Due to a lack of continuous energy supply real-time positioning is not possible. For the same reason, the performance of successfully detecting a target depends on its speed. SmartWall [2] also exploits shadows but embeds PDs on the wall to estimate the user's location based on a fingerprinting technique and machine learning. Specifically, Weighted k Nearest Neighbor (WKNN) classification is employed on the received signal strength (RSS) values to predict real user position at the inference stage. The system only located the objects and was further extended in WoW [3] to track moving targets. However, both systems require extensive manual effort on fingerprinting. To reduce the dependency on labeled training data and fingerprinting, FieldLight [5] makes use of artificial potential fields along with light sensors to localize the target. While all the above systems exploit shadows other fully passive systems use reflections. CeilingSee [14] converts the ceiling LEDs so that these can also sense energy reflected back from the targets. Variance in diffuse reflection only helps the LEDs to detect occupancy but not estimate the target location. Presence of multiple targets under field of view (FOV) of light causes interference and thus can degrade detection of occupancy. To overcome this problem, CeilingSee employ machine learning algorithms.

2.2.2 Passive User In passive user systems, the user is not equipped with any light sensing device. The user's involvement in locating its position and occurrence is passive. However, the light source modulates the data and transmits positioning beacons. The light reflections and shadows caused by the user body are used to locate its position. Compared to the fully passive systems, the passive user systems dominantly exploit reflections. The reflected received data is decoded by the receiver circuitry to retrieve the user position. The receiving sensors can be placed anywhere in the targeting area similar to fully-passive systems.

Systems: The work done in [4] is an example of a passive user system which modifies the light driver circuit to send a time-multiplexed signal to recognize the source of reflected light at each sensing device and based on a threshold user occupancy is detected. Similarly, EyeLight [10] sends on-off modulated data through the lighting device to check if the target has crossed the light barrier or not. Instead of modulating the one LED, the StarLight [8] approach modulates each LED in a custom-designed light panel and embed the sensing device on the floor. Based on the shadow it measures the frequency power changes, based on which the user's movement and gesture are detected.

2.2.3 Passive Source In passive source systems, the light sources do not modulate the positioning beacons instead, an intelligent or smart material chip is placed in an environment to modulate the light. The smart material can be made of a polarizer, LCD and birefringence material, etc. As light passes through these materials it changes the light properties such as polarization, etc. These changes although unperceived by humans are then detected by active receivers to estimate their position. The chip can be placed at suitable locations in the room to modulate room light and even

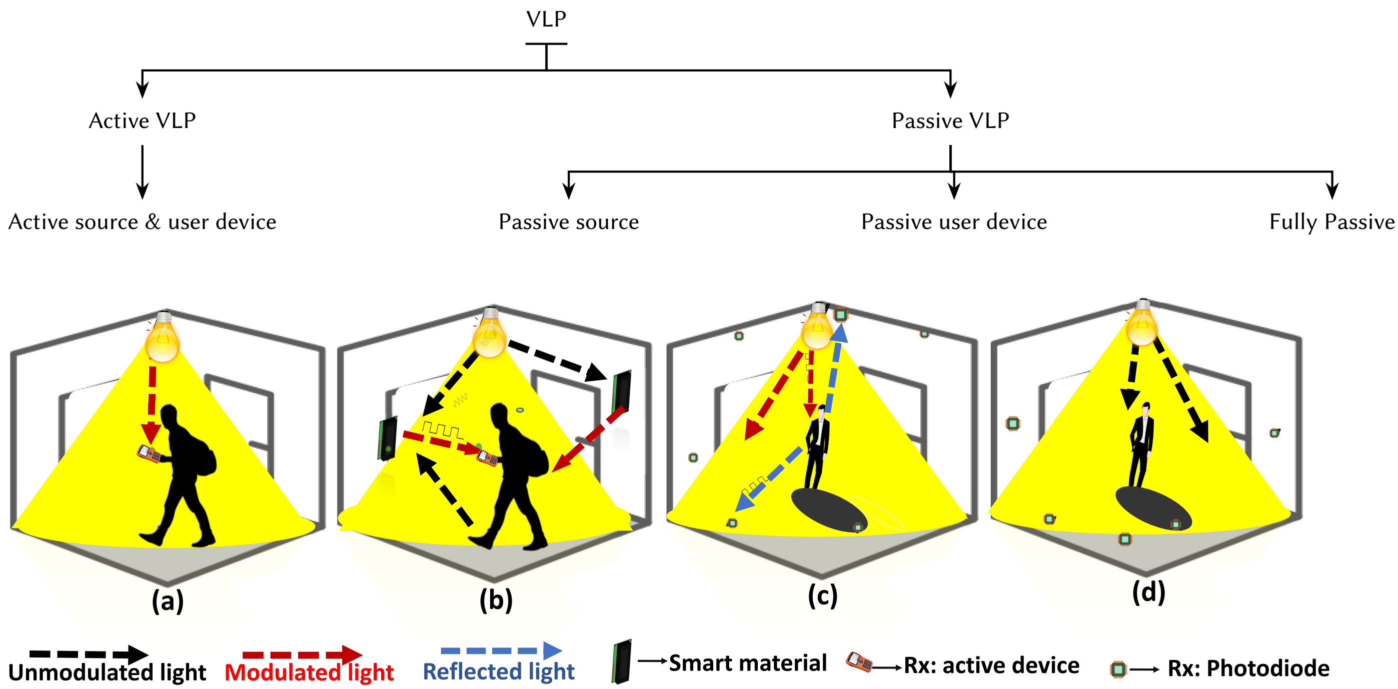

Figure 1: Different classes of VLP systems a)*Active VLP* systems require active modulated light sources and active user device b) *Passive source* systems employ unmodulated light sources but rely on intelligent materials/devices to modulate the light sources c) *Passive user* systems do not require a target to carry an active user device and monitor shadow of the target using modulated light sources and ambient photosensors for localization. d) *Fully passive* systems neither require modulated light sources nor active user devices to track the target albeit through ambient photosensors

close to a window to modulate the natural sunlight. System performance not only depends on the reflection or blockage of light but is also sensitive to user device handling dynamics related to its alignment and orientation towards smart material chips.

Systems: RainbowLight [6] and PIXEL [15] are two pioneer passive source systems. Both use polarization-based modulation. PIXEL exploits mobile camera as a sensing unit and an LCD based smart chip to do a binary color shift keying (BCSK) modulation. However, to detect the color light changes a polarizer is also placed in front of the camera. On the other side, RainbowLight's modulating chip consists of a birefringence and polarizer material which produce a specific interference pattern of the light spectrum at different directions to the chip when light passes through it. An initial mapping between chip direction and received light spectrum by a mobile camera at various positions of a mobile device is built. This procedure is done once for every chip and compared with these initial mapping values, the users' 2D position is estimated. Further, to improve the initial mapping an interpolation-based method is proposed. For 3D position calculation of the device, an intersection-based method is developed which makes use of 3 chips to locate the device. The above two systems are camera-based approaches that need to put a special material in front of the camera. To overcome this limitation PD-based receivers are used in other passive source systems such as CELLI [13]. CELLI uses the principle of spatial resolution to find the position of a mobile device. It sends parallel interference-free polarized beams through the LCD pixels to different spatial cells. The transmitted beams are unique to the projected cell. The user in the projected cell carries a PD-based receiver to recover its unique cell coordinates. However, with this the user does not know its actual position for calculating the actual position a two-lens strategy is used which makes this system a complex one.

3 Applications of Passive VLP Technologies

VLP positioning has a wide variety of applications such as asset tracking, autonomous robot navigation, human localization, to name a few. In this section, we describe some applications of the passive VLP system based on our classification and the research work done corresponding to these applications.

3.1 Occupancy Management

Passive user and fully passive systems can be used for occupancy measurement in an indoor space. Occupancy measurement plays a significant role in Smart-building management, e.g., based on occupancy count regulation of heating and cooling in a room can be achieved which will optimize power consumption. Moreover, in shopping malls, retail stores with occupancy measurement, we can predict which location has attracted the most customers.

Systems: EyeLight [10] can measure the occupancy by measuring the deviation in the average received power from the base light level (calculated when the room is empty) and it achieved a 93.7% accurate

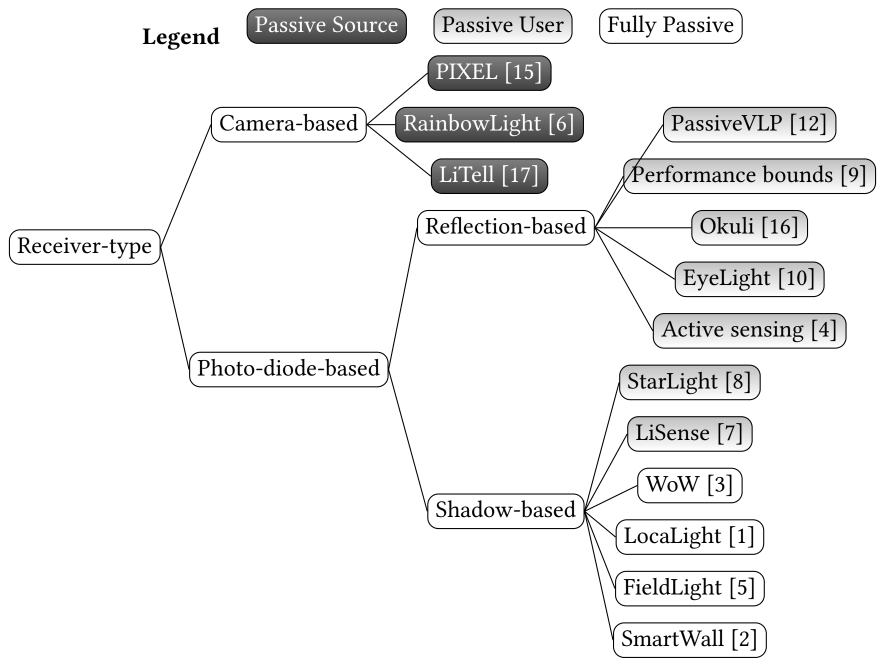

Figure 2: Classification of positioning systems by receiver type and passive components

occupancy count. Another fully passive VLP system CeilingSee [14] has achieved >90% occupancy inference performance.

3.2 Human gesture monitoring and communication

Gesture monitoring benefits those living in assisted environments, for valuable emergency evacuations & aids for visually impaired persons and communicating through gestures is helpful in providing virtual keyboard writing, handwriting-based input for smartphones or smartwatches, virtual-gaming, etc. Due to the light reflection phenomenon and shadow property, passive VLP is a boon for human gesture monitoring.

Systems: Okuli [16] develops passive user based system to detect the movement and track human's finger in a defined work-space. It utilizes the fact that fingers are the round and good reflectors of light to build a model-driven solution. With a workspace of 9 x 7 cm, Okuli able to detect and localize a random finger's positioning with an error of 1.43 cm in 90% cases and a median error of 0.7 cm. Another work, LiSense [7] a shadow-based human sensing system that reconstructs 3D human skeleton postures. It uses 324 floor-mounted lighting sensors and modulated lighting sources to reconstruct five main body joints with a mean angular error of 10 degrees. StarLight [8] the extended work of this system reduces the number of receivers used to 20, but with a higher error of 13.5 degrees. The above-discussed examples are passive user system based. Recently, researchers have investigated fully passive systems for localization which can also be used for human gesture monitoring and communication through them e.g. WoW [3] and SmartWall [2].The systems have achieved a high localization accuracy of 7 cm and 7.9 cm, respectively.However, such systems require extensive fingerprinting and labeled training limiting their application usage.

3.3 Assets tracking in factories and logistics

In a factory, any item with a reflective surface can track and monitor through passive VLP. Even robots can be tracked and navigate through Passive VLP. Not only device-free tracking but device identification (ID) is also possible. However, for decoding ID the device/object should have a smart reflecting material or visible-light based barcodes on its surface.

Systems: Recently, a passive user system has been demonstrated in [12]. In which they have modified the external surface of a toy aluminum car (object) to localize, track and identity its ID. The system achieves an average localization error of 0.97 cm with successful decoding of the object's ID.

3.4 Advertising

In shopping malls the designed custom chips as used in passive source systems can be deployed at various positions. The user with a mobile device can extract information about offers, discounts, etc, offered by various vendors corresponding to his location.

Systems: PIXEL and RainbowLight are the two passive source works in this category which can be used for this application by employing their polarizer based smart chips. Among different systems the RainbowLight has achieved a localization accuracy of 3.3 cm and the PIXEL system has a <3cm accuracy for 90% cases, when the receiving device is placed at 3m.

4 Comparative Analysis of Passive VLP Systems

By now, the description of existing passive VLP systems according to our taxonomy has made it evident that the design goals of

Table 1: Summary of recent passive VLP systems

System	Design goal	Key techniques	Testing environment				Performance	Remarks
			Area	Noise	#LEDs	PD		
Okuli [16]	Locate finger on a keypad	On-off, RSS	$9x7cm^2$	Y	1	2 along with LED on dedicated 3D printed shroud	median error 0.7 cm, 1.43 cm (90 % cases)	More infrastructure changes as it needs dedicated hardware & can only track human finger
LiSense [7]	Construct 3D human skeleton	FDM, RSS	$3x3m^2$	Y	5	324 on floor	10 degree mean angular error	Overhead of light sensors deployment and more changes in luminarie design
Starlight [8]	Construct & locate 3D human skeleton	FDM, RSS	$3.6x4.8m^2$	Y	20	20 on floor	10 degree mean angular error, 9.7 cm (95 % cases)	Need to attach laser pen on object for calibration and PD deployment overhead
Eye-light [10]	Detect room occupancy,activity & location	On-off, TDM	$7.5x6m^2$	N	6	24 on ceiling	median error 0.89m, 93.70%	Occupancy detection & work in controlled lighting conditions only
Ceiling-based sensing [4]	Detect occupancy & motion	On-off,TDM, RSS	$2ft$ distance	N	7	3 on ceiling	12%	Do not localize the target only checks if the door has opened or not
Performance bounds [9]	3D Localization	Model object impulse response, Reflection based	$5x5m^2$	N	9	9 on ceiling	RMSE < 10 cm	Model depends upon physical geometry of the room, simulated work only
Passive VLP [12]	Identify objects & locate 1D position	Tailored modulation, TDM	$2.5m$ distance b/w nodes	N	6	Shine+ board, ceiling	avg. error 0.97 cm, max. 5.3 cm	Can only track few points in a path
WoW [3]	2D localization	shadow based-RSS	$2x3.6m^2$	N	NA	14 on wall	7 and 13cm for stationary and mobile target	Need high Fingerprinting & PD deployment overhead
Localight [1]	1D Positioning	Shadow based-RSS	$1.53m^2$ circular	N	NA	5 on floor	NA	Only identifies the person movement static or walking
Field-light [5]	2D localization	shadow based-RSS	$4.8x9.6m^2$	N	NA	14 on wall	68 cm (corridor), 84 cm (lab), 120 cm (foyer)	Assumes constant background ambient light, overhead of PDs deployment
Smart wall [2]	2D localization	shadow based-RSS	$3.4x2.2m^2$	N	NA	7 on wall	7.9 cm	Need extensive fingerprinting & can only locate the target
Ceil-ingSee [14]	Detect occupancy	Reflection based	$5x6m^2$	N	16	16 on ceiling	> 90%	Need more changes in the installed lighting fixtures
Rainbow-Light [6]	2/3D localization	Mapping & Trilateration	$3m$ link	NA	NA	mobile device in user's hand	avg. 3.3 cm in 2D, 9.6 cm in 3D	Initial mapping, 3 chips should be in Rx FoV for 3D localization
LiTell [17]	2D localization	Intrinsic characteristic freq. of CFLs	$2m$ link	NA	NA	mobile device in user's hand	90.30%	Works only when light is on,temp. dependent performance
PIXEL [15]	2D localization	AoA	$2.4x1.8m^2$	NA	NA	mobile device in user's hand	<30 cm in 90% cases	Power inefficient receiver
CELLI [13]	2/3D localization	PPM, spatial modulation, RSS	$2.5m$ link	NA	NA	mobile device with PD module	1.59 cm (2D), 2.65 cm (3D)	Complex design and need of guiding lenses b/w Tx & Rx makes it less suitable for large deployment

different passive VLP systems vary significantly from each other. Furthermore, it should also be noted that the unique peculiarities of these systems and a lack of common benchmarks, led system designers to test such systems under radically different environments. Table 1 presents a summary of design goals, methods, testing environment and reported performance of passive VLP systems discussed above. The reader can find information about the deployment or testing setup which includes area, the number and arrangement of LEDs and PDs, as well as whether the effect of ambient noise is considered or not. All these factors matter a lot when comparing the accuracy of VLP systems.

We conclude that the fully passive VLP systems are cost-effective solutions due to low-cost receivers and the need for minimal changes in infrastructure. However, most of the designed systems largely rely on fingerprinting that can be a labour-intensive task. A model-driven training method can be employed to reduce the dependence on fingerprinting as proposed in FieldLight [5]. Shadow-based systems achieve higher accuracy than the reflection-based systems provided that the cost of deploying a large number of light sensors can be afforded. Until now, the designed systems have been tested in controlled environments only. The performance of reflection-based methods can be improved by putting reflective material on the surface of objects. However, whether a reflective material can be used depends on the application.

Passive source VLP systems can be deployed in areas where the light source cannot be easily modulated and the user wants to retrieve the information about the environment. The smart material chips can be easily deployed there and the user can use a mobile phone as receiver. These chips can be powered by photo-voltaic cells. Although the power inefficiency of a mobile device is still a problem.

The designed passive user systems are mostly application dependent. It is indeed not easy to find a one-size-fits-all solution. Okuli [16] provides minimum error but its usage scope is limited to extremely small areas. PassiveVLP [12] is the only VLP solution which has decoded the object ID passively while performing localization. Compared to the active VLP system, passive solutions are energy-efficient, cost-effective and less disruptive to previously deployed infrastructure. This makes their commercialization case stronger. However, it is a research area in its infancy and still requires a huge effort from the industry and standardization bodies to push their commercialization.

5 Conclusion and Open Research Problems

There has been a surge of research interest in the passive visible light positioning during the past few years. In this paper, we briefly surveyed the recent passive VLP systems. We proposed taxonomy, and according to it discussed features of each system. The examples of applications where passive VLP offers advantages over active VLP are presented. We believe that as the demand for cost-effective and energy-efficient positioning systems will increase, passive VLP will play a vital role. In general passive VLP is a new research area with plenty of new opportunities. At the same time the design of passive VLP faces multiple open problems some of which we summarize below:

Deployment overhead of light sensors: In shadow-based passive VLP systems the localization accuracy depends on the characteristics of the shadow cast by a user. As the user moves, shadow also moves which necessities the deployment of a large number of light sensors. A careful and smart way of deployment should be adopted to reduce the number of light sensors while getting maximum accuracy.

To get enough received reflected light: The amount of the reflected light from a surface of a target depends on the shape, size, posture and color of the reflecting surface. Therefore, reflected light is often weak and is also subjected to environmental noise. These factors degrade system performance. There is a need to train machine learning models based on the reflectivity of particular shapes.

Localizing multiple targets passively: Until now, the designed passive VLP systems work only for a single user. However, in real-world environments this is not usually the case.

Design of a more robust and flexible receiver: Because passive VLP systems enjoy less control over the environmental light conditions and interference, there is a need to design more sophisticated receivers.

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