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Passive visible light networks

Taxonomy and opportunities

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Passive Visible Light Networks: Taxonomy and Opportunities

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ABSTRACT

Artificial lighting has been used mainly for illumination for more than a century. Only recently, we have started to transform our lighting infrastructure to provide new services such as sensing and communication. These advancements have two key requirements: the ability to modulate light sources (for data transmission) and the presence of photodetectors on objects (for data reception). These requirements assume that the system has *direct* control over the transmitter and receiver, as in any traditional communication system. But not all lights can be modulated, and most objects do not have photodetectors. To overcome these limitations, researchers are developing novel networks that (i) exploit *passive* light sources that cannot be directly modulated, such as the sun, and (ii) leverage *reflections* from the external surfaces of objects *to create a new generation of sensing and communication networks with visible light that is sustainable and does not require active control over the system*. In this survey, we propose a taxonomy to analyze state-of-the-art contributions. We also identify the overarching principles, challenges, and opportunities of this new rising area.

CCS CONCEPTS

• **Networks → Cyber-physical networks**.

KEYWORDS

Passive visible light sensing, passive visible light communication, taxonomy, applications, opportunities

1 INTRODUCTION

The Internet of Things (IoT) are enabling a new computing era, heavily depending on wireless communication and sensing. These wireless interactions mostly rely on the radio-frequency (RF) band. We argue that in this new era, the visible light spectrum could play a far greater role than that it is currently playing. To achieve this goal, we must investigate new methods for *passive* visible light

sensing and communication. Visible light is present everywhere and is gaining significant interest as a medium to connect things. Thanks to advances in visible light communication (VLC), LEDs can now be modulated to transmit data without affecting the illumination. Thus we can piggyback wireless communication on top of LED illumination almost for free. This breakthrough has created a new range of exciting applications such as accurate indoor localization [9], high-speed Internet [16], interactive toys [20], etc.

Limitations of *active* methods. The above applications are transforming the role of our lighting infrastructure, *but they assume two key requirements: light sources can be modulated to transmit information and objects have photodetectors to receive that information.* These requirements limit how visible light can be exploited for sensing and communication.

1) Limitation at the transmitter (TX) side. Many light sources cannot be directly modulated, for example the sun , but it would be transformative if we could leverage sunlight for communication. Most of the optical radiation in our environments remains largely unused, not only sunlight but also plenty of artificial lighting. Currently, we mainly exploit passive optical radiation to harvest energy, but we should also exploit it to convey information.

2) Limitation at the receiver (RX) side. Most objects do not have photodetectors. Furthermore, even objects with photodetectors, such as smartphones, are only useful when held with line-of-sight (LOS) toward luminaries. This limitation is not present in RF systems. Visible light systems would be more impactful if we could interact with objects that do not have any photosensor.

Focus on *simple* photosensors and *incoherent* light. There are two main types of sensors used for applications related to visible light: photodiodes and cameras. *The focus of this paper is on systems working with simple photodiodes.* Cameras are more powerful devices, however, they are power hungry, more expensive, and pose threats to users' privacy. *Another focus of this paper is on incoherent visible light.* Coherent light, such as laser light, has been exploited for sensing, such as Lidar. However, generating coherent light is more expensive compared to exploiting existing incoherent ambient light and artificial light from LEDs. Therefore, there is an increasing interest in the system's community to develop low-end IoT systems with simple photosensors and incoherent light.

2 TAXONOMY

To build passive visible light networks, researchers are studying methods for scenarios with (i) *passive light sources*, which do not modulate information; and (ii) *passive objects*, which do not have photodetectors. These efforts however are loosely connected. *To consolidate this nascent area, it is necessary to have a framework to identify the principles, challenges and opportunities of passive methods* for exploiting visible light.
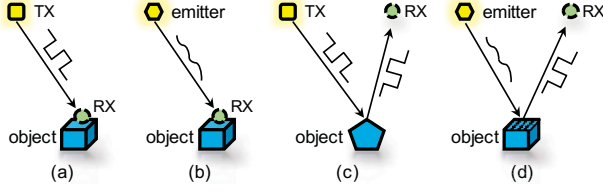
Qing Wang and Marco Zuniga

Figure 1: A taxonomy of visible light networks: (a) *full-active*; (b) *passive-src*; (c) *passive-obj*; (d) *full-passive*.

We propose a **taxonomy** that arranges all the efforts related to visible light into **four cases**. This taxonomy allows us to identify the main challenges and research opportunities of different applications that exploit visible light for passive sensing and communication. Next, we first describe the traditional scenario (active light sources and objects), and then describe unique properties of passive and semi-passive scenarios. Our taxonomy is illustrated in Fig. 1, where we refer to active sources as *TXs*, and passive sources as *emitters*.

Case A: full-active (active source, active object). This is the most popular VLC application. The goal is to transmit information from an LED to an object. This goal is simple to attain because the light source can be modulated and the object can decode this data reliably thanks to having a photodetector with LOS toward the source.

*Case B: passive-src (**passive source**, active object).* Passive light sources change the problem fundamentally. Since we cannot modulate them as in Case A, the goal is *not* to transmit information from LEDs to the object. The goal now is for the object to *get information about the environment* by measuring *uncontrolled* changes in illumination. The information can still be measured directly by the object because it has a photodetector, but the amount of information is limited and depends solely on the dynamics of the scenario at hand.

*Case C: passive-obj (active source, **passive object**).* Passive objects also change the problem fundamentally. Objects can no longer get information about the environment as in Case B, because they have no photodetectors. With passive objects, the photodetectors need to be placed in the environment. Thus, the goal changes: instead of having objects getting information about the environment, now the environment *gets information about objects*. Having active sources means that we can send fine grained pulses to get information about objects, but these pulses are reflected by the objects' external surfaces, and thus, the received signals will be noisy. There is no-line-of-sight (NLOS) between light fixtures and RXs.

*Case D: full-passive (**passive source, passive object**).* This is the most complicated case. The presence of passive objects (photodetectors in the environment, not on the object), means that the goal is the same as in Case C: *get information about the object.* However, we don't have an active source to modulate information. Thus, the only source of information are the reflections caused by the object's surface. This scenario leads to a compound problem: a noisy generation of information, because there is no active source; and a noisy reception of information, because the signals are reflected (NLOS).

In this paper, we refer to the cases *passive-src*, *passive-obj*, and *full-passive* as **passive** systems. Furthermore, we classify them into two groups based on their main objective: sensing or communication. Next, we will first discuss **Visible Light Sensing (VLS)** and then **Communication (VLC)**.

Table 1: Applications based on passive VLS

|	**Active light source**	**Passive light source**
Active object	- Indoor localization [9]	- Indoor localization [30, 31]
Passive object	- Localization [24] - Virtual trackpad [29] - Reconstruction of users' skeleton [10, 11]	- Localization [4, 18, 19, 32] - Occupancy detection [27] - Gesture detection [13] - Event detection [5, 6]

3 PASSIVE VISIBLE LIGHT SENSING

3.1 System Architecture and Applications

The architecture of passive VLS typically consists of three elements: *light source, object,* and *receiver (RX)*. The *light source* can be anything: an LED (which can modulate information), an incandescent bulb (which cannot modulate information) or natural light sources such as the sun (uncontrollable). The *objects* can be of any form: people, cars, etc. The *RX* is a tiny box containing simple photodetectors, such as photodiodes. Passive VLS is enabling many applications, see Table 1. We describe them below based on our taxonomy.

Case B: passive-src. If the RX is placed on the object, Fig. 1(b), the information is obtained from default changes in the light intensity of emitters. A typical application in this case is *passive indoor localization*, where there is no need to modify existing artificial illumination infrastructures. For example, Pulsar [31] uses two PDs (with different field-of-view) to exploit Angle-of-Arrival (AoA) methods. The differential response between the two PDs follows a nonlinear function with the AoA, and that function can be used to derive the PDs' relative location to the emitters. Pulsar can achieve a median error of 5 cm for 2D localization.

Case C: passive-obj. If the RXs are placed in the environment and the light source can be modulated, Fig. 1(c), the information is obtained from the objects' reflections. Research studies show that many objects can be monitored with this type of architecture: fingers, cars and people, *enabling applications such as trackpad, traffic monitoring, occupation detection, among others*. In Okuli [29], the goal is to track a finger over a pad. A small LED (active source) and two photodiodes are placed at one side of the pad, and the system maps the location of the finger based on its reflected light intensity with a median error of 0.7cm. Passive VLS systems are also being used to monitor people [10, 11]. In this case the RXs are embedded in the floor and ceiling luminaries send modulated signals. Based on the distortions measured at the RXs, the system can reconstruct a person's posture.

Case D: full-passive. Like the previous case, in this system, the information comes from reflections. But the information is less accurate because the system does not use modulated light sources, Fig. 1(d). Still, researchers are developing interesting applications leveraging people and hands as passive objects, *enabling applications such as gesture recognition, event detection, occupation detection, among others*. CeilingSee can estimate the occupancy of rooms using ceiling luminaries that also act as receivers [27]. The changes in reflection perceived at the ceiling indicate the number of people present in a room. With a similar approach, we could track a single person within a room by deploying a grid of receivers on the ceiling [5, 6]. Besides monitoring people, passive VLS can also be used to monitor hand gestures. SolarGest exploits ambient light and transparent solar panel on a smartwatch to recognize six hand gestures with an average accuracy of 96% [13].
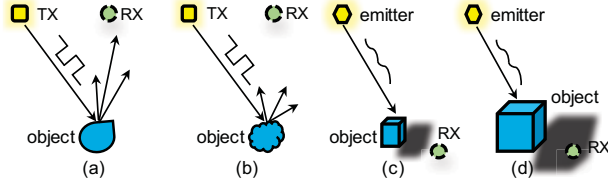
Figure 2: Challenge 1. The object's shape and reflection properties determine the direction and intensity of reflected light, *(a-b)*; its size determines the amount of light blocked over the floor, *(c-d)*.
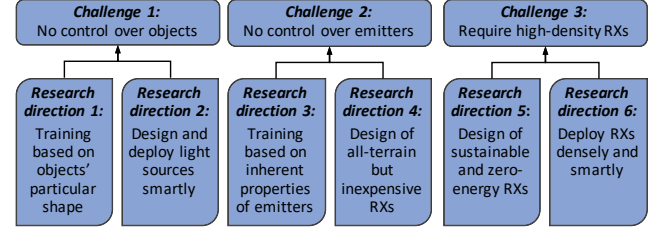
3.2 Research Challenges

Based on our taxonomy and analysis of the SoA, below we describe the three most important challenges.

Challenge 1: No control over the objects' shape, implies no one-size-fits-all solutions. In *active* scenarios, it is customary to use *predefined* modulation methods to communicate with *any* object that carries photodetectors. However, in scenarios where objects do not carry a photodetector (cases C and D), we can only rely on the object's external surface for sensing. In these scenarios, the system performance is largely determined by the object's properties, but objects have different shapes, sizes and reflection coefficients, as shown in Fig. 2. The object's shape determines the direction of reflected light; its size determines the amount of blocked light; and its reflection coefficient, or even cleanness, affect how much light is reflected to the RX. There is no 'standard' object to be sensed. Thus, *before designing a passive VLS system, it is central to gain a deep understanding about the object at hand, to design a tailored system*. It is challenging to design one-size-fits-all solutions that can monitor different objects accurately.

Challenge 2: No control over the emitters, requires designing more flexible and robust methods for reception. In scenarios with *active* light sources, RXs are designed to focus on the specific range of frequencies and intensity-levels modulated by the active light fixtures. The effect of other (passive) light sources is filtered out via hardware or software. Passive VLS systems, on the other hand, cannot filter out these passive light sources because *it relies on them for sensing* (cases B and D). But we cannot control the intensity, location or any other property of emitters. Thus, receivers in passive VLS need to work well under a wider range of optical frequencies and intensities. Furthermore, similar to Challenge 1, where the lack of control over objects requires a deeper understanding of reflections; in this case, the lack of control over emitters requires a deeper understanding of the expected illumination conditions (to *fine-tune* the design of algorithms). Overall, loosing the ability to modulate (control) a signal in passive VLS, creates challenges that can only be tackled with a more flexible and robust design at the reception end.

Challenge 3: Monitoring passive objects, requires a high-density of receivers. In scenarios where photodetectors are placed on top of objects, the RX moves along with the object, and thus, can provide continuous sensing. In scenarios with passive objects, the RXs have fixed locations and can only provide information when objects move under their limited field-of-view (FoV). To cover a large sensing area and/or provide fine-grained results, more RXs are indispensable. These denser deployments require not only a careful analysis to reduce the number of RXs while guaranteeing a minimum performance level, but also require designing more energy-efficient RXs to minimize the overall energy footprint.

Figure 3: Map the research opportunities to the challenges

3.3 Research Opportunities

As discussed in the previous section, passive VLS systems expose unique challenges. Below, we describe the research directions from the community to tackle these challenges. Fig. 3 summarizes our findings by mapping challenges to research directions.

Research Direction 1: Train the system based on the particular shape of the object-of-interest with low overhead. This approach is applied to Cases C and D, where the object is passive. To cope with the unique reflecting properties of different objects (Challenge 1), researchers first create a training database. For example, in CeilingSee [27], the authors analyze the correlations between the number of people present in a room and the subtle light distortions they cause. These correlations are then used to estimate occupancy levels. Similarly, SolarGest relies on training for hand gesture recognition [13]. These two examples work on scenarios with passive lights (Case D). But scenarios with active lights (Case C) can also benefit from a training phase. Okuli [29] exploits the fact that fingers have circular shapes and reflect light uniformly, to create a database mapping RSS with 2D locations on a pad. The main limitation of training is the overhead involved in creating and maintaining training sets. There are research opportunities to reduce this training overhead (or even better, to remove it), without affecting sensing performance greatly.

Research Direction 2: Design and deploy light sources in a smarter manner. This approach is applied to Case C, where the light is active but the object is passive. To compensate for the lack of control over the passive object (Challenge 1), the design and deployment of *active* lights can be *tailored* to improve the system performance. For instance, a *cross-like* deployment of active ceiling lights is used to monitor human postures [10]. And not only can standard luminaries benefit from a smart design and deployment. In Okuli [29], an LED light is mounted on a custom-made structure to control the light reflected by a finger on a tracking pad. There are two important aspects to be considered with these approaches: (i) the overhead and costs associated with modified light fixtures, and (ii) the balance between sensing and illumination. Contrary to RF systems where changes in output powers are not perceived by users, the changes of lighting infrastructure must not affect user experience.

Research Direction 3: Train the system based on the inherent properties of some passive emitters. This approach is applied to Case B, where the light source is passive, but the object carries a photodetector. Some light sources have *inherent* properties that can be sensed by the object's photodetector. LiTell uses this approach to achieve sub-meter indoor localization based on unmodified (passive) fluorescent bulbs [30]. First, photodiodes are used to measure the specific frequency of each fluorescent bulb in an indoor space.

These measurements are stored in a database. Later, users with smartphone cameras capture the frequency of nearby fluorescent bulbs and look for a match in the database.

While training can boost the sensing performance, it comes at the cost of increased overhead (similar drawbacks to Research Direction 1). For example, the characteristic frequency of fluorescent bulbs depends on the surrounding temperature, which means that LiTell may require frequent training updates. Still, the idea of exploiting the inherent properties of passive sources is an exciting direction that has not been explored much (cf. Table 1). Many research opportunities are present at the intersection of exploiting these inherent properties while reducing (or removing) training overheads.

Research Direction 4: *Design of all-terrain but inexpensive receivers.* This approach is applied to Cases B and D, where light sources are out of the system's control. The receiver thus needs to cope with a wide range of optical frequencies and intensities (Challenge 2). There are receivers with advanced optical filters that can work in various environments, but they are expensive (upwards of 300 USD, such as the Thorlabs-PDA100A). Given that some passive VLS scenarios will require a high density of RXs (Challenge 3), researchers are looking for ways to design *inexpensive* all-terrain RXs. One such approach is to use LEDs for the dual purpose of emission and reception of light. CeilingSee [27] for example modifies standard luminaries to emit light but also to sense light. In this way the lighting infrastructure is used not only to provide illumination but also to monitor occupancy. Another approach is to combine simple photodetectors, with different receiving characteristics, into a single RX. For instance, The work [23] combines a photodiode and an LED acting as a receiver. The photodiode works well under low illumination conditions, but saturates under high illumination. The LED has the opposite trade-off. The authors use this dual RX mainly for passive communication, which is explained in the next section, but some of their experiments include passive sensing, such as detecting the type of cars present in a parking lot by analyzing the unique optical signatures reflected by the cars' surfaces. There are not many efforts targeting at the design of new RXs suited for passive sensing. Most of the existing works rely on RXs used in traditional VLC. There are thus research opportunities in this direction.

Research Direction 5: *Design of sustainable and zero-energy receivers.* Requiring a high number of RXs to increase the coverage of passive systems, implies a bigger energy footprint (Challenge 3). To sustain the development of passive VLS, it is necessary to design zero-energy cost receivers: RXs should obtain all their energy via harvesting methods. One such approach is followed in LocaLight [4], where RXs are deployed over the floor and powered wirelessly using RF. The receivers pinpoint the location of people based on the shadows they cast over the floor. A key problem faced by zero-energy platforms is the trade-off between energy consumption and operational time. Relying on energy harvesting usually implies intermittent operation. For example, Localight only detects objects 50% of the time due to the limited harvested energy. In general, an important research opportunity for passive VLS is to leverage light as a means for communication and energy. RXs could be designed by default with solar panels, together with complementary harvesting methods for periods with low illumination. And the sensing and

data processing methods running on these RXs should be designed to be energy efficient from inception.

Research Direction 6: *Deploy receivers densely and smartly.* This approach is applied to Cases C and D. Due to the limited FoV of most photodetectors, RXs need to be deployed in higher numbers or be carefully deployed to provide the necessary coverage (Challenge 3). Many studies follow a high-density approach. For example, to monitor people's posture, 324 RXs are deployed in an area of 3×3m. This high density enables the required granularity to track the movements of limbs [10]. Similarly, LocaLight deploys dense RXs on the floor to track the location of people by measuring their shadows [4]. Other studies follow a careful-deployment approach. Okuli places two photodiodes in a custom-designed enclosure to filter out undesirable light while monitoring the location of a finger on a pad [29]. Another example is shown in [5], where the authors place RXs in suitable locations to track specific events such as the state of doors (open/closed).

Deploying a high number of RXs is a relatively simple solution to increase coverage, but increases costs across many dimensions: energy, data processing and infrastructure. A more elegant approach, which also opens more research opportunities, is to design a careful placement of fewer RXs.

4 BEYOND SENSING: PASSIVE VISIBLE LIGHT COMMUNICATION

Passive *communication* is more complex than passive *sensing*, because communication requires sending bits. Thus, to achieve passive communication we need to find ways to modulate visible light without having control over the emitter.

The overarching vision of passive VLC is to have objects sense and process data, but instead of communicating this information actively, e.g. via a radio module, objects will adapt the reflective properties of their external surfaces according to the information they want to convey (like a chameleon). In this way, light waves impinging over the smart surfaces will create distinctive patterns, and photodetectors deployed in the surroundings will decode the reflected signals.

4.1 System Architecture and Applications

The architecture of passive VLC is similar to those of passive sensing. There are *emitters, objects and RXs.* But there are two key differences: one on objects, the other on RXs.

Architectural Difference 1: *Objects are covered with smart surfaces.* Passive sensing exploits the *default* external surface of objects. But as described in Challenge 1, objects have different shapes and materials, making them unsuitable to modulate binary information via reflections. To attain some control over reflections, passive VLC systems cover objects with smart surfaces, including modulated retro-reflectors. These surfaces adjust their reflective properties between two states to send information: a high (low) reflective coefficient to transmit a logical one (zero).

Architectural Difference 2: *RXs do not contain cameras.* Some passive sensing scenarios exploit the presence of cameras in smartphones. But if RXs are to be deployed in high densities and in a sustainable manner, cameras are not suitable. Cameras are costly,

Table 2: Applications based on passive VLC

	Active light source	Passive light source
Active object	- High-speed Internet [16]	
Passive object	- Battery-free IoT [8, 26] - Infrastructure-to-vehicle networking system [22]	- Object identification [23] - Battery-free IoT [2, 3, 23] - Inter-building networking [3]

consume more energy and raise up privacy issues. In passive communication the RX is assumed to be always a simple photodiode.

Applications. Given the more complex nature of passive communication, researchers have only make some inroads into the problem. There are two main lines of work in the literature: Retro-VLC/RetroI2V [8, 22, 26] and sunlight communication [2, 3, 23], as summarized in Table 2. Retro-VLC creates a bidirectional link between an active light source and a surface (object). Both of these elements have a photodiode. For the downlink, the active light transmits information to the surface with traditional VLC. For the uplink, the surface replies back by using an LCD shutter to absorb and reflect the impinging light. Retro-VLC can achieve a speed of 10 kb/s, and can enable applications such as object identification, battery-free IoT, infrastructure-to-vehicle networking, etc. It is similar to the backscattering concept used by RFID, but more energy efficient because it piggybacks on lights that are already on, and more secure because light is more directional. Sunlight communication [2, 3, 23], on the other hand, is a fully passive communication system for mobile objects. It leverages sunlight to transmit information. In [2, 23], the objects are cars, whose roofs are covered with barcodes consisting of materials with different reflective properties. These barcodes can contain any information such as the ID of the vehicle or the type of cargo. As the cars pass by, the sunlight impinging on their roofs is modulated by the barcodes and decoded by the RX at a distance up to 4 m. In [3], an LCD is used to backscatter sunlight (ambient light) using the frequency modulation. The envisioned applications are inter-building networking and smart bus stop where their external surfaces could be modified to modulate the impinging sunlight with information about events in a city.

4.2 Research Challenges

Passive VLC creates a new wireless channel that inherits many of the challenges encountered in passive sensing. Below, we first describe the similarities and differences with the three challenges mentioned in Section 3.2, and then, we introduce new challenges that pertain only to passive VLC.

Differences with **Challenge 1**. Compared to passive sensing, which exploits the default surface of objects, passive communication covers objects with surfaces having distinctive reflective properties. Thus, the reflections are not as random as those observed in passive sensing. This ability to control reflections is key to modulate binary information.

Similarities with **Challenge 2**. Similar to passive sensing, passive communication also relies on uncontrolled light sources. Thus, RXs need to be flexible and robust to operate in a wider range of illumination conditions.

Similarities with **Challenge 3**. Passive sensing and communication share the same coverage problem. To collect as much information as possible from *passive* objects, many RXs need to be deployed

and they have to be energy efficient to reduce the overall energy footprint of the system.

Challenge 4: *Modulation of passive light requires control over reflections.* Passive VLC heavily depends on the ability to modulate reflections. Due to this reason, we need to design smart surfaces with three key characteristics: high mutability, fine granularity and high energy efficiency. High mutability is required to change rapidly the reflective properties of the surface between high and low reflection states (in the order of ms or less). Fine granularity is required to encode as much information as possible over the surfaces. A high mutability and granularity would increase the throughput of the system. Finally, the surface should not require high amounts of energy to achieve the required mutability and granularity. Many objects do not have connections to batteries or power outlets, and the energy required to control their surfaces may be obtained from light itself (harvested through solar panels).

Challenge 5: *The object determines the encoding of information, but we have no control over the object.* Compared to existing communication systems, passive VLC faces unique challenges due to the lack of TXs. In traditional systems, the TX controls the packet size and the symbol's period. In passive communication, these parameters depend on the object's size and speed, and these dependencies cause two problems. *First*, the object's size limits the amount of information that can be encoded. Symbols cannot be too narrow, else they may not be detected; but they cannot be too broad either, else too little information is encoded. It is thus essential to estimate the optimal (minimum) symbol width to maximize the channel's throughput. *Second*, changes in the object's speed can distort symbols' periods. Consider a Low-High-Low symbol sequence on top of a mobile object. The object could move faster, slower or pause at any point in time. These dynamics would change the duration of symbols, leading to many possible decoding outcomes: LHHL, LHL, LHHLL, etc. In traditional systems the symbol duration within a packet changes minimally, and different methods have been devised to cope with small drifts. Passive communication requires new decoding methods to overcome the larger variations caused by the speed of variable objects.

4.3 Research Opportunities

Passive communication with visible light is still in its infancy. Below we describe the progress made by the community and the opportunities we foresee.

Research Direction 7: *Analysis of smart surfaces.* The design of smart surfaces requires a thorough analysis of various materials. Thus far, researchers have only evaluated basic materials such as aluminum foil and black cardboard [23], or screen-based solutions such as LCD shutters [8, 26]. There are however other materials that could be used such as smart glasses or microblinds. These smart materials are being developed to control the amount of sun radiation in buildings, but they could be used to modulate information as well. To further increase the system performance using these advanced materials and techniques, we need to thoroughly understand their performance based on the three metrics mentioned in Challenge 4: mutability, granularity and energy efficiency.

Research Direction 8: *Design of novel decoding methods.* There are no solutions for the research problems introduced in Challenge

5: *finding optimal symbol widths to maximize throughput and designing novel encoding methods to cope with variable speeds.* In [23], the authors drive cars at constant speed and do not provide insights about the maximum throughput that the system can achieve. Furthermore, the experiments did not consider 'collisions' (two objects passing under the same FoV simultaneously) or signal distortions due to damages or dirt on the surfaces. In general, passive communication with visible light is a new area with plenty of opportunities for novel contributions.

5 RELATED TECHNIQUES

Wireless sensing and communication techniques, both active and passive, have been widely investigated in the past decades. In this section, we summarize the most relevant techniques and compare them briefly with the main focus of this work.

Passive sensing with radio. During the past decade, passive sensing with radio signals has been investigated thoroughly. M. Youssef *et al.* introduced the concept of device-free passive localization using Wi-Fi signals in [28]. Through experiments, they show the feasibility of detecting the signal changes caused by people. Investigations in realistic environments are carried out in a follow-up work [15]. Recently, researchers have also been able to track *multiple* objects passively with existing radio signals [1, 17], and can even identify the material type and image the horizontal cut of targeted object with RFID signal [21]. Motivated by these works, researchers are analyzing the unique properties of visible light waves for *passive* sensing, as discussed in this work. Compared to radio waves, visible light waves behave more deterministically (less multipath) but have poorer coverage (light cannot travel through opaque objects). This work has exposed the opportunities of exploiting the external surfaces of objects for pervasive sensing with light.

Passive communication with radio. In passive visible light communication systems, light is modulated by reflective surfaces [2, 23] or LCD shutters [3, 8, 22, 26]. These concepts are mainly inspired by backscatter communication where passive tags modulate the electromagnetic waves emitted by external sources, traditionally used in RFID [25] and recently applied to other radio technologies, e.g. Wi-Fi [7] and TV signals [12]. In the same way radio-backscatter exploits surrounding radio waves, authors in [8, 23, 26] exploit incoherent visible light. Their tags has to deal with visible light waves which have completely different properties compared to radio waves. Wireless barcode [14] has been proposed to embed information into infrastructure such as building walls. The barcode is built with materials of copper/cement into a shape of square-wave. Data is modulated through the barcode's reflection of electromagnetic waves. This barcode does not have electronic devices, similar to the tag used in [23]. However, [14] requires expensive dedicated radio signals impinging on it (unit cost is $220K), while ambient or normal LED light are sufficient for those tags in [2, 3, 8, 23, 26] to work (their prototype cost only dozens of dollars).

6 CONCLUSION

Considering the increasing attention on exploiting visible light as a medium for sensing and communication, researchers are proposing novel *passive* monitoring methods to exploit the external surfaces of people, fingers, hands and cars. In this paper we introduced a taxonomy to classify these various passive approaches. Our taxonomy allowed us to identify five macro challenges and eight general research directions in this nascent area. We envision in the future, passive sensing and communication with light will enable a new generation of IoT systems, one that will connect everyday objects with the vast number of passive light sources in our environments.

REFERENCES

[1] ADIB, F., KABELAC, Z., AND KATABI, D. Multi-person localization via RF body reflections. In *USENIX NSDI* (2015).
[2] BLOOM, R., AND ET AL. Tweeting with sunlight: Encoding data on mobile objects. In *IEEE INFOCOM* (2019).
[3] BLOOM, R., ZUNIGA, M., AND PAI, C. Luxlink: Creating a wireless link from ambient light. In *ACM SenSys* (2019).
[4] DI LASCIO, E., AND ET AL. Poster: LocaLight: A battery-free passive localization system using visible light. In *IEEE IPSN* (2016).
[5] IBRAHIM, M., AND ET AL. Visible light based activity sensing using ceiling photosensors. In *ACM Workshop on VLCS* (2016).
[6] IBRAHIM, M., AND ET AL. Light-based occupancy estimation and activity recognition from shadows on the floor. In *IEEE INFOCOM* (2018).
[7] KELLOGG, B., PARKS, A., GOLLAKOTA, S., AND ET AL. Wi-fi backscatter: Internet connectivity for rf-powered devices. In *ACM SIGCOMM* (2014).
[8] LI, J., AND ET AL. Enabling battery-free duplex visible light communication for mobile and IoT applications. In *ACM HotMobile* (2015).
[9] LI, L., HU, P., PENG, C., SHEN, G., AND ZHAO, F. Epsilon: A visible light based positioning system. In *USENIX NSDI* (2014).
[10] LI, T., AN, C., TIAN, Z., CAMPBELL, A., AND ZHOU, X. Human sensing using visible light communication. In *ACM MobiCom* (2015).
[11] LI, T., AND ET AL. Practical human sensing in the light. In *ACM MobiSys* (2016).
[12] LIU, V., PARKS, A., TALLA, V., GOLLAKOTA, S., AND ET AL. Ambient backscatter: Wireless communication out of thin air. *ACM SIGCOMM CCR* (2013).
[13] MA, D., AND ET AL. Solargest: Ubiquitous and battery-free gesture recognition using solar cells. In *ACM MobiCom* (2019).
[14] MOSHIR, F., AND SINGH, S. Wireless barcodes for tagging infrastructure. In *ACM MobiCom* (2014).
[15] MOUSSA, M., AND YOUSSEF, M. Smart cevices for smart environments: Device-free passive detection in real environments. In *IEEE PerCom* (2009).
[16] PURELIFI. *http://purelifi.com/*.
[17] SABEK, I., AND ET AL. ACE: An accurate and efficient multi-entity device-free WLAN localization system. *IEEE Transactions on Mobile Computing* (2015).
[18] SHAO, S., AND ET AL. Passiveretro: Enabling completely passive visible light localization for IoT applications. In *IEEE INFOCOM* (2019).
[19] SHAO, S., AND ET AL. Enabling real-time indoor tracking of IoT devices through visible light retroreflection. *IEEE TMC* (2020).
[20] TIPPENHAUER, N., AND ET AL. Toys communicating with LEDs: Enabling toy cars interaction. In *IEEE CCNC* (2012).
[21] WANG, J., AND ET AL. TagScan: simultaneous target imaging and material identification with commodity RFID devices. In *ACM MobiCom* (2017).
[22] WANG, P., AND ET AL. Renovating road signs for infrastructure-to-vehicle networking. In *ACM MobiCom* (2020).
[23] WANG, Q., ZUNIGA, M., AND GIUSTINIANO, D. Passive communication with ambient light. In *ACM CoNEXT* (2016).
[24] WANG, W., AND ET AL. PassiveVLP: Leveraging smart lights for passive positioning. *ACM Transactions on Internet of Things* (2020).
[25] WANT, R. Enabling ubiquitous sensing with RFID. *IEEE Computer* (2004).
[26] XU, X., AND ET AL. PassiveVLC: Enabling practical visible light backscatter communication for battery-free IoT. In *ACM MobiCom* (2017).
[27] YANG, Y., AND ET AL. Device-free occupancy inference through lighting infrastructure based LED sensing. In *IEEE PerCom* (2017).
[28] YOUSSEF, M., MAH, M., AND AGRAWALA, A. Challenges: Device-free passive localization for wireless environments. In *ACM MobiCom* (2007).
[29] ZHANG, C., AND ET AL. Extending mobile interaction through near-field visible light sensing. In *ACM MobiCom* (2015).
[30] ZHANG, C., AND ZHANG, X. LiTell: Robust indoor localization using unmodified light fixtures. In *ACM MobiCom* (2016).
[31] ZHANG, C., AND ZHANG, X. Pulsar: Towards ubiquitous visible light localization. In *ACM MobiCom* (2017).
[32] ZHANG, R., AND ET AL. Exploiting color sensors to provide optimal lighting and anonymous tracking in stores. In *IEEE SECON* (2020).