electronics

Review

Visible Light Communications for Industrial Applications—Challenges and Potentials

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Abstract: Visible Light Communication (VLC) is a short-range optical wireless communication technology that has been gaining attention due to its potential to offload heavy data traffic from the congested radio wireless spectrum. At the same time, wireless communications are becoming crucial to smart manufacturing within the scope of Industry 4.0. Industry 4.0 is a developing trend of high-speed data exchange in automation for manufacturing technologies and is referred to as the fourth industrial revolution. This trend requires fast, reliable, low-latency, and cost-effective data transmissions with fast synchronizations to ensure smooth operations for various processes. VLC is capable of providing reliable, low-latency, and secure connections that do not penetrate walls and is immune to electromagnetic interference. As such, this paper aims to show the potential of VLC for industrial wireless applications by examining the latest research work in VLC systems. This work also highlights and classifies challenges that might arise with the applicability of VLC and visible light positioning (VLP) systems in these settings. Given the previous work performed in these areas, and the major ongoing experimental projects looking into the use of VLC systems for industrial applications, the use of VLC and VLP systems for industrial applications shows promising potential.

Keywords: industrial communications; visible light positioning; localization; LiFi; VLC; VLP

1. Introduction

The ongoing research in optical wireless communications has opened the door for many uses of the optical spectrum that ranges from ultra-violet to infrared (IR) communications. The developments of solid-state lighting and the subsequent advancements in light-emitting diodes (LEDs) have paved the way for the use of the visible spectrum for communications referred to as visible light communications (VLC). VLC systems are envisioned to serve as a complementary technology to the already crowded radio frequency (RF)-based technologies, where VLC would help alleviate some of the increasing demand for high-speed data transmission. While there has been a significant amount of research examining the use of VLC in a variety of environments, the use of VLC systems in industrial environments is still considered a new research area. There has been a growing number of research work characterizing VLC and optical channel models in industrial settings but there remains a few gaps and areas that deserve to be further investigated in detail given the unique nature of industrial environments.

Utilizing VLC for indoor localization is one of the most promising applications. Visible light positioning (VLP) systems are capable of providing high-accuracy localization for a variety of applications. However, there is no significant work examining the use of VLP systems in industrial environments nor is there a study of the challenges that would hinder its performance when adopted in these environments. VLC and VLP have great potential considering that high power white LEDs are replacing existing lighting infrastructure in indoor and outdoor environments to achieve low-cost and energy-efficient illumination systems as part of the global green technology. In addition to illumination, an LED-based system offers data communication using the license-free spectrum [1]. In the last decade, a great amount of research has been carried out on developing and optimizing the performance of VLC systems. Most of the research focuses have been on VLC applications for indoor environments (i.e., home and office environments [2,3]), aircraft cockpits [4–6], underwater applications [3,7], and vehicle-to-vehicle (V2V) communications [8,9]. However, there has been limited work reported in the literature on the application of the VLC technology systems in industrial environments. The developing trend in the industry best known as the "fourth industrial revolution" (Industry 4.0) envisages a substantial increase in operational effectiveness along with the development of new products and business models [10]. Several similar initiatives are also taking place globally, such as 'Factories of the Future', 'Made in China 2025', and work performed by institutions such as the Fraunhofer Institute and the National Institute of Standards and Technology [11]. The fourth industrial revolution is still in its early stages and therefore more research and development on the VLC technology will promote its use in the industry.

The integration of cyber-physical systems (CPS) in the value chain serves as the foundation of Industry 4.0 [12] and would enable the interconnectedness of the supply, manufacturing, maintenance, delivery and customer service processes all through the internet. This will allow real-time data exchange to optimize the production processes. The key element in achieving this is the availability of a high-speed, low-latency and reliable data communications link [13]. Current radio frequency (RF)-based wireless technologies can be used but have drawbacks including lower data rates, proneness to electromagnetic interference (EMI), and multipath reflections impairing the signals for applications on the production floor [14]. Moreover, in certain applications such as hospitals, petrochemical and nuclear power plants, the use of RF-based wireless technologies are restricted due to EMI [15,16]. Alternatively, optical wireless communication (OWC) technologies including VLC can be deployed in Industry 4.0 applications as they offer a wide bandwidth using the license-free electromagnetic spectrum, low latency, inherent security and free from RF-induced EMI. Furthermore, the LED-based lighting infrastructure in buildings, offices and manufacturing areas can be used for simultaneous illumination and data communication, thus potentially reducing the operational costs significantly and the carbon footprint significantly.

The LED-based VLC technology can also be used for indoor positioning and detecting people [17,18], products, and machinery. For example, unmanned aerial vehicles (UAVs), also known as drones, offer a safe and cost-effective way of carrying out inspections, especially in hard-to-reach areas. Currently, their use in warehouses for conducting physical inventory is gaining increasing attention. In such cases, both navigation and data communication (up and downlinks) can be provided by the LED-based lights (i.e., VLC and VLP) [19].

Though significant development has been achieved in VLC for many applications, limited research works on the application of VLC in industrial environments have been reported in the literature. These applications range in their intended use in different types of environments (i.e., mines, pipelines, warehouses, etc.). The work in [20] investigated time synchronization schemes for orthogonal frequency-division multiplexing (OFDM)-based VLC system with low-latency requirements suitable for machine-to-machine communication. Channel impulse response simulations were conducted in [21] for a flexible manufacturing cell based on a VLC system, where an LED cube consisting of six transmitters (Txs) was located at the head of the robotic arm, and eight receivers (Rxs) were placed on the safety screen surrounding it. Significant multipath reflections were observed due to the room's size and the presence of metallic objects as well as the other Txs. The work in [22] investigated a novel communications system while considering industrial requirements such as reliability and robustness. The paper proposed and experimentally validated the use of plastic optical fibers for distributed MIMO LiFi systems. In [13], channel measurements of a distributed 8×6 multiple-input-multiple-output (MIMO) VLC system for use in robots in a manufacturing cell were reported. The results indicate that the link availability was achieved with sufficient signal-to-noise ratio (SNR) for the LOS transmission. However, the link availability was effected with sudden drops in the signal level by 10-20 dB due to the LOS path being blocked by the movement of robot arms. A spatial diversity scheme was then proposed to address this issue. The work in [23] presented a VLP system for location-based services in Industry 4.0. The authors proposed the use of a specific VLP technique that uses active receivers and a fixed low-cost infrastructure. Further discussions on some of these works will follow in the following sections.

The use of LEDs and smart lighting for illumination in industrial contexts offer numerous advantages as highlighted in [24], which includes lower long-term cost, higher productivity and reduced accidents. Moreover, the illumination requirements set by governing bodies [25] must ensure that the work areas are well-lit (i.e., using more LED lights), which ensures adequate coverage for the VLC system. The wide adoptability of VLC will not only depend on advancements in the achieved transmission rates, but also on their ability to comply with common illumination requirements [26].

Considering the limited amount of research works reported on the application of VLC for industrial environments, this paper sets out to provide an overview of this emerging new wireless technology in industrial settings and examine its full potential. The VLC/VLP technologies can be adopted in different industrial settings such as warehouses, mines, and manufacturing halls, etc. Some experimental works demonstrating the potential of the VLC technology in manufacturing cells and VLP in mines have been reported. In this work, we also highlight the potential of VLP for use in autonomous aerial and ground vehicles, a largely unexplored area. The paper also discusses the possible challenges facing VLC and VLP in industrial environments including transmission range, multi-reflection induced dispersion, duplicate position estimates, tracking and blocking. To the best of the authors' knowledge, this is the first survey paper which outlines the use of VLC technology in industrial applications.

The remainder of the paper is organized as follows: Section 2 gives a brief overview of industrial communications. Section 3 presents potential industrial applications using VLC and relevant research work. The unique challenges for these types of environments are presented and discussed in Section 4. Section 5 concludes the paper.

2. Communication Technologies for Industrial Environments

Until recently, industrial communications were a combination of Fieldbus systems, Ethernet cables, and some limited wireless solutions [27]. Fieldbus systems were used to overcome the shortcomings of parallel transmission using cables between different actuators, controllers and sensors, which was followed by Ethernet-based networks. However, the lack of a real-time implementation using standard Ethernet prohibited the development of a single Ethernet-based solution for automation purposes, which ultimately led to the development of dedicated solutions [28,29]. While wired networks offered enhanced reliability and modest data rates, they failed in terms of scalability, cost efficiency and efficient network deployment [30]. The use of wireless sensor networks (WSNs) in modern industrial automation environments offers flexibility in terms of moving machines and devices around with no restricting cables [27], thus leading to lower cost, improved production line efficiency and better use of the resource. However, the use of wireless networks in industrial applications did not take hold because of the most critical issue of the system's reliability [31]. The recent trend in using CPS in industrial environments has resulted in everything being interconnected via a shared ecosystem. The latest push in adopting wireless communication technologies is expected to grow considering the increased global competitiveness.

Companies have been actively seeking ways to further improve efficiency using automated processes to meet market demand and gain a competitive advantage. However, due to the dynamic nature of modern industrial applications, traditional technologies are not adequate in fulfilling the requirements [32], particularly in harsh environments. Existing wireless industrial standards, such as ISA100.11a [33] and WirelessHart [34], are based on a centralized network management scheme, which is not suitable for dynamic large-scale networks [35]. The wireless communication technologies adopted for industry usually use the 2.4 GHz frequency band, which offers a relatively low data rate up to 250 kbps [30], which is not sufficient for some industrial applications. Note that the 868 and 915 MHz bands used in industrial applications offer even lower data rates, 20 and 40 kb/s per channel for the 868 and 915-MHz bands, respectively [36].

While the introduction of wireless technologies for use in industrial automation resulted in improved flexibility in the utilization of resources, the high-reliability was the major issue [27] that needed addressing. The evolution to wireless communications for industrial automation meant that cables did not restrict machines and devices, which in turn facilitated their movement and ease of connections. However, wireless communication did not take off as expected as the high-reliability advantage outweighed the need for flexibility [27], further highlighting the need for robust and reliable links. The success and persistence of digital Fieldbus systems and industrial Ethernet thanks was owed to their robustness and their ability in ensuring precise control for factory automation processes, but at the same time, it is not keeping up with the newer demands of Industry 4.0 and Internet of Things (IoT).

RF-based wireless systems, which have been adopted in industry, face several challenges due to their use in extreme conditions such as dust, EMI (from motors and generators) and heat, which needs addressing [31,37]. One of the major problems is the multipath reflections from highly reflective surfaces and objects, which results in both link failures and reduced data rates. In the literature, work has been reported on characterization of wireless channels for RF-based system within industrial environments. Early work in [38] reported on wide-band multipath measurements at 1300 MHz in five different buildings and showed a root mean square (RMS) delay spread within the range of 30 and 300 ns. It was shown that the median values for all factory sites for line-of-sight (LOS) and non-line-of-sight (NLOS) paths were three times higher than for two-story office buildings. Measurements of large-scale fading and temporal fading at 900, 2400, and 5200 MHz in wood processing and metal processing industrial environments were reported in [39,40]. The results showed that the path loss was high compared with the data reported in the literature, with maximum measured path losses of 98, 105, and 96 dB at the center frequencies of 900, 2400 and 5200 MHz, respectively. The radio channel measurements in a single room of $20.4 \times 22 \times 4.8$ m^3 dimension with brick walls, concrete slabs, steel plates and doors, and glass windows reported in [41] showed lower absorption compared with the office environments by 16 to 22%. Similarly, it was shown in [42] that multipath components can be measured up to 1000 ns following the detection of the main component in highly reflective environments. In [43], several channel measurements were performed in different industrial settings (warehouses, manufacturing, automation labs, storage areas, production lines, and robot cells). The measurements conducted were in the wide-band radio spectrum of 5.8 GHz and the 2.2 GHz region along with some additional measurements in the optical domain (the red wavelength at 478 THz). It was shown that multiple antennas must be used to meet the packet error rate (PER) requirements.

The deployment of wireless local area networks (WLANs) in industrial environments is often challenging due to the size of the area and the presence of highly reflective surfaces [39], which requires a detailed site survey prior to the deployment of such systems. The work in [44] compared two network planning approaches; an experimental and software-based automated planning in a large factory warehouse containing 224 installed warehouse racks. The authors concluded that (i) combining the automated network planning with a limited validation site survey resulted in a reliable network at the low cost; and (ii) increased intra-network interference due to a large number of installed access points even using a frequency planning algorithm. However, in such environments, the deployment of VLC technologies offers several advantages including the use of the existing LED-based lighting fixtures for data communications and sensing with no need for additional equipment. In addition, VLC systems offer high-level of security, which is highly desirable in modern industries to avoid malicious attacks, eavesdropping, information tampering, etc. [30,45]. For a thorough discussion of the challenges that industrial wireless sensor networks face, the reader can refer to [30].

Industry 4.0

Ever since the term 'Industry 4.0' was introduced, there has not been a consensus on its definition. This led the authors in [46] to review the different used meanings of the Industry 4.0 concept. According to the authors, the Industry 4.0 concept is an umbrella term for a new industrial paradigm which embraces a set of future industrial developments including CPSs, the IoT, the internet of services, robotics, big data, cloud manufacturing and augmented reality [46].

Given that the wireless communication technologies currently used in factory settings cannot fulfill the requirements for modern use cases, 5G is seen as an enabler that can deliver reliable links with low latency and low jitter for Industry 4.0 and smart manufacturing [47]. Deploying 5G in warehouses and factories would benefit manufacturers by bringing reliable communications between machinery, sensors, and computing systems [48].

The Industry 4.0 paradigm encompasses a wide variety of applications and ideas, which means that there are no specific set of technical specifications that need to be met as it would depend on the use case. As the work in [49] states: "the task of defining requirements that encompass all types of industrial control applications is impossible to achieve due to the wide variety of use cases". Each user needs to understand the requirements of their respective systems before embarking on any wireless enhancement [50].

For a more detailed list of specifications, we refer to the technical specification (TS) produced by the European Telecommunications Standards Institute (ETSI) 3rd Generation Partnership Project (3GPP). Contrary to what is commonly thought, 3GPP is an engineering organization that develops technical specifications and not standards. These specifications are then used by the multiple global standards setting organizations. Based on 3GPP's technical report (TR) 22.804 [51], a mapping of the considered use cases to application areas is shown in Table 1. There is a multitude of potential use cases for each of these application areas and a few are shown in the table as well. Discussions and definitions on each of these areas can also be found in [52]. The five main application areas listed by the 3GPP for vertical "Factories of the Future" are:

- Factory automation: Factory automation is generally seen as a key enabler in providing a cost-effective way of providing high-quality mass production. It includes automated control, monitoring and optimization of processes in factories. In the future factories, novel modular production systems will replace static production systems as they are capable of offering flexibility and versatility. These systems require reliable links that have low latencies.
- Process automation: Process automation refers to the control of production and handling of substances like water, foods, and chemicals. These substances require efficient production systems that automatically control and process several parameters along the production process. The controllers interact with actuators such as heaters and pumps, while sensors are used for measurements (e.g., pressure, temperature, humidity, etc.).
- Human-machine interfaces and production IT: Human-machine interfaces (HMIs) refer to the different types of devices meant for the interaction between people and production facilities (e.g., panels attached to a machine or production line). This also includes standard IT devices, smartphones, laptops, and augmented and virtual reality applications that are projected to have increasingly important roles in the future.
- Logistics and warehousing: Logistics and warehousing refer to the organization and control of the flow and storage of materials and goods. As one aspect of logistics is to ensure an uninterrupted supply of material, there is great potential for utilizing mobile robots in this area. The other aspect

here is warehousing. Warehousing would mainly refer to the storage of goods and material. It is an area already seeing an increase in the adoption of automated processes through the use of conveyors and automated storage systems.
- Monitoring and maintenance: Certain processes and/or assets can be monitored without having an immediate effect on it, unlike automated closed-loop control systems in factories. Applications in this area include predictive maintenance based on the data being fed from the sensor. Big data analytics can also be used to optimize future parameters for a certain process. In industrial factories, this allows manufacturers to gain insights into environments and adjust accordingly.

Table 1. Application areas and use cases in a smart factory as defined in 3GPP TR 22.804 [51]. Reprinted with permission from 3GPP™, © 2020.

		Use Cases									
		Motion Control	**Control-to-Control**	**Mobile Control Panels with Safety**	**Mobile Robots**	**Massive WSNs**	**Remote Access & Maintenance**	**Augmented Reality**	**Closed-Loop Process Control**	**Process Monitoring**	**Plant Asset Management**
Application Areas	Factory automation	×	×		×	×					
	Process automation				×	×			×	×	×
	HMIs & Production IT			×				×			
	Logistics & warehousing		×		×						
	Monitoring & maintenance					×	×				

The ETSI TS 122 104 (3GPP TS 22.104) and TR 22.804 also list service performance requirements, which were used to make Table 2 [51,53,54]. The table shows a few use cases and their corresponding requirements. The performance requirements vary in different scenarios but it can be seen that there is a high demand for reliability (>99.99%), and low cycle times. Reliability, defined here within the context of network layer packet transmissions, is “the percentage value of the amount of sent network layer packets successfully delivered to a given system entity within the time constraint required by the targeted service, divided by the total number of sent network layer packets” [55]. And the cycle time includes “the entire transaction from the transmission of a command by the controller to the reception of a response by the controller. It includes all lower layer processes and latencies on the air interface as well as the application-layer processing time on the sensor/actuator” [55].

Table 2. Three application scenarios and their requirements as defined in 3GPP TR 22.804 [51] and ETSI TS 122 104 [54]. Reprinted with permission from 3GPP™, © 2020.

Use Case		Availability	Cycle Time	Message Size	No. of UEs	Typical Service Area
Motion control	Printing machine	>99.9999%	<2 ms	20 bytes	>100	100 m × 100 m × 30 m
	Machine tool	>99.999%	<0.5 ms	50 bytes	∼20	15 m × 15 m × 3 m
	Packaging machine	>99.9999%	<1 ms	40 bytes	∼50	10 m × 5 m × 3 m
Mobile robots	Cooperative motion control	>99.9999%	1–50 ms	40–250 bytes	≤100	≤1 km^2
	Video-operated remote control	>99.9999%	10–100 ms	15–250 kbytes		
Mobile control panels with safety functions	Assembly robots, milling machines	>99.9999%	4–8 ms	40 to 250 bytes	4	10 m × 10 m [51] 50 m × 10 m × 4 m [54]
	Mobile cranes, mobile pumps, fixed portal cranes	>99.9999%	12 ms	40 to 250 bytes	2	Typically 40 m × 60 m; max 200 m × 300 m
Process automation (process monitoring)		>99.99%	>50 ms	Varies	10,000 devices per km^2	

In addition to the high requirements on latency and reliability in modern manufacturing systems, there is also an emphasis on security that was not seriously considered or required by previous industrial revolutions [56]. There are other applications that have even more stringent requirements. The authors in [57] reviewed available and future wireless standards and suggested that none of them can meet the required performance demanded by an ultra-high performance wireless network for industrial control which aims for Gbps data rates and 10 µs–level cycle time [57].

While 5G is seen as the enabler for Industry 4.0 and smart factories, the authors in [58] noted that relying solely on 5G to support all use cases is highly risky, and instead advocated for the use of a set of different wireless communication technologies. The authors then briefly discussed other technologies with certain requirements, such as VLC, to free the spectrum for data-hungry and reliability critical applications. Similarly in [59], the authors noted that it would be rational to combine 5G with OWC to offload ultra-reliable and low latency communications traffic and free the radio spectrum for other services.

High accuracy positioning is expected to become essential in modern manufacturing environments as mobile vehicles would increase productivity. These systems also have strict requirements that must be fulfilled prior to their adoption. The work in [60] discussed several use cases for unmanned vehicles (UVs) while considering their respective requirements within the context of Industry 4.0. The authors concluded by noting that the strictest requirements for UV uses are on latency and reliability, which wireless technologies, such as WiFi and LTE, are struggling to meet.

The 3GPP TR 22.804 technical report [51] also lists indoor and outdoor positioning service performance requirements for "Factories of the Future" in vertical domains for the future 5G systems. Three selected use cases are listed in Table 3 along with their respective requirements. There is a high-reliability requirement for all the use cases, but the latency requirements differ depending on the use case. Augmented reality in smart factories requires a latency less than 15 ms, whereas inbound logistics in manufacturing for the storage of goods allow latencies below 1 s. There are also requirements on the maximum speed to ensure maintained service during mobility [60]. In terms of positioning accuracy, two of the service levels specify horizontal accuracies of below 1 m but inbound logistics would require higher horizontal accuracy. The interested reader can refer to [55] for the "Corresponding Positioning Service Level in TS 22.261" column and additional metrics such as the coverage, environment, and vertical accuracy requirements.

Table 3. A selection of positioning performance requirements for industrial use cases with reference to service levels. Adapted from TS 22.104 [54]. Reprinted with permission from 3GPP™, © 2020.

Scenario	Horizontal Accuracy	Availability	Heading	Latency for Position Estimation of UE	UE Speed	Corresponding Positioning Service Level in TS 22.261
Augmented reality in smart factories	<1 m	99 %	<0.17 rad	<15 ms	<10 km/h	Service Level 4
Mobile control panels with safety functions in smart factories (within factory danger zones)	<1 m	99.9 %	<0.54 rad	<1 s	N/A	Service Level 4
Inbound logistics for manufacturing (for storage of goods)	<20 cm	99%	N/A	<1 s	<30 km/h	Service Level 7

There are also many standards already in place along with the ongoing work from various standardization bodies which is outside the scope of this paper. The reader can refer to [11,61] for a detailed discussion on the current standards landscape for smart manufacturing systems and automation.

It should be noted that the requirements listed in this section, and similarly adopted by others in the literature [62,63] should be revisited as the technical reports are constantly being updated. Hence, there are differences in the values used between the papers that cite these performance requirements. The 3GPP technical report even refers to them as "potential requirements".

3. Industrial Applications

This section discusses VLC applications in industrial environments, which are based on the works already reported.

3.1. Manufacturing

There has been a steady expansion in the robot market since 2012 and with a rapid growth beyond 2017. According to the International Federation of Robotics, there were almost 254,000 global robot installations in 2015. The number increased to almost 300,000 and 382,000 in 2016 and 2017, respectively [64]. In 2018, the number was 422,271 (6% increase) with China leading the world with a higher number of robots than Europe and the Americas combined. The largest end-users were the automotive industry and the electrical/electronic industries with market shares of 30 and 25%, respectively. This increase is against the backdrop of the fourth industrial revolution with the forecast increases of 12% per year from 2020 to a total of 583,520 units by 2022. Besides, we have seen retrofitting of existing manufacturing equipment with CPS capability [65,66], which is driven by sustainable manufacturing and modernizing of existing facilities in developing countries [65,67].

Robotic manufacturing cells are highly complex systems that usually consist of industrial robots, conveyors, programmable logic controllers, and physical barriers [68]. They are widely used in the manufacturing industry for a variety of applications with the aim of integrating CPS in Industry 4.0. Production lines, which utilize novel assembly lines, are expected to boost the reconfiguration of automated manufacturing systems for improved operation and reduced production life-cycles [69]. This has led to modern manufacturing cells that are designed for small, compact areas with higher flexibility, facilitating modifications and modernization to achieve customized product features [70]. The use of indoor OWC in industrial scenarios will require reliable data transmission links with moderate data-rates and low-latency over a coverage range of 3–4 m [13]. In addition, VLC can be used with the existing wired and RF wireless networks as a part of a hybrid solution in industrial environments [71].

The OWICELLS (Optical WIreless networks for flexible car manufacturing CELLS) project, which was a collaboration between Fraunhofer Heinrich Hertz Institute (HHI) and BMW in 2018, investigated the use of LED-based VLC systems in manufacturing cells for the automotive industry. The trial was successful and reported low-latencies [72], but requires further improvement for full commercialization. The project did switch to the use of an IR LEDs as it offered an increased data rate compared with phosphor-coated blue LED chips [73], which limits the bandwidth of white LEDs. For a more detailed discussion of this limitation, refer to [74]. Alternatively, red, green, and blue (RGB) LEDs can be used to achieve high data rates [75,76].

In 2019, Signify released Trulifi Securelink 6013, which is capable of delivering an aggregated physical layer speed of 750 Mbps up to a range of 8 m [77,78]. Securelink, with plug and play design features, is designed for use in machine-to-machine communications, network to device communications, and the Internet of things [79]. Wieland Electric is currently investigating the use of the system at its high-quality electronic components production line [80]. The device's point-to-point connection enables transmission rates of 250 Mbps for both downlink and uplink communications.

The use of VLC and OWC in manufacturing is one of the better-researched areas in the literature thanks to the OWICELLS project. The introduction of a LiFi system by Signify is another indicator on the potential of OWC systems in this area. Moreover, there are ongoing research projects that continue to explore the potential of VLC/LiFi systems in an industrial environment. The 'Visible Light in Production' Project by Fraunhofer IOSB-INA and the Ostwestfalen-Lippe University of Applied Sciences and Arts [81] is examining the use of VLC in factories and industrial environments [82]. Project ELIoT (https://www.eliot-h2020.eu/) (Enhance Lighting for the Internet of Things) is another project led by Fraunhofer HHI and is funded by the EU Horizon 2020 program. One of the goals of the ELIoT project is to develop an open reference architecture for future connected lighting infrastructures to facilitate the integration of VLC into IoT applications. There is also the SESAM project with

Fraunhofer HHI, which aims to develop a holistic concept for reliable, low latency and secure wireless communication for future Industry 4.0 scenarios. The project has published a concept that combines RF's large area coverage with optical wireless' high-speed connections to provide a reliable full-area coverage of moving robots in the production facilities [83]. As these projects are still ongoing, we expect a number of publications relating to the use of VLC and OWC for industrial applications in the next few years.

3.2. Mines, Pipelines, Tunnels and Downhole Applications

In the oil and gas industry, 'downhole applications' generally refer to wells or boreholes, which requires an efficient and reliable communication link. The commonly used technologies are (i) wired systems of coaxial cables and fiber optics, which offer high data rates and reliability at the cost of a higher complexity and not being scalable [84]; and (ii) wireless systems with lower data rates such as mud-pulse telemetry [85] and systems that employ low-frequency electromagnetic waves [86,87].

Alternatively, OWC including VLC could be employed offering much higher data rates at low costs. However, only a few simulation works on the use of VLC for downhole monitoring have been reported in the literature [88]. The work presented in [87] examined the use of LEDs and single photon avalanche diodes (SPADs)-based photodetector for gas well downhole monitoring, where it was shown that using a large SPADs array, only 8 dBm of transmit power is needed to send a monitoring signal over a 4 km long gas well pipe. However, in the analysis of the work, several assumptions were made, including an ideal Lambertian source, purely diffuse reflections, and a pipeline without flowing gas. In [89], a ray tracing-based investigation of the downhole VLC channel was carried out, where a cylindrical pipe with the length and diameter of 22 m and 1 m was considered, see Figure 1. Results showed that the path loss is less severe for white and blue LEDs compared with red LEDs as the minimum transmittance of methane gas is in the red band (i.e., 617–631 nm). The results also indicated that a bit error rate (BER) of 10^{-6} can be achieved using pulse amplitude modulation (PAM) up to the order of 8, while the maximum achievable distance is reduced to 19 m for 16-PAM. In other pipeline applications, an experimental investigation of in-pipe image transmission based on the visible light relay communication (VLRC) technique with both analogue image signal relay transmission (AISRT) and digital image frame-relay transmission (DIFRT) modes was presented in [90]. Experimental tests were performed for an empty and half-submerged pipeline in water. Results show that DIFRT has advantages in terms of transmission speed, strong image reconstruction capability, and transmission range compared with AISRT. In [91], an asymmetrically clipped optical-OFDM (ACO-OFDM)-based VLC system using commercially available LEDs and photodiodes for an underwater pipeline was investigated. The system's performance was evaluated for twelve different scenarios with different modulation methods (quadrature phase-shift keying and 16-quadrature amplitude modulation), different sampling rates, and various OFDM parameters. Experimental results showed that a BER of 10^{-6} over a 6.5 m long underwater pipeline can be achieved.

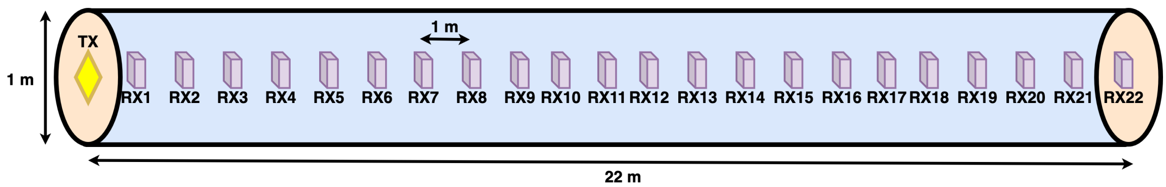


Figure 1. A recreated illustration of the gas pipeline simulated in [89]. An LED is located at the head of the pipeline and 22 Rx test points placed within it.

Using VLC/VLP systems in mines for tracking people, machines, etc. has gained a fair amount of attention in recent years due to health and safety regulations [92,93]. The work in [93] proposed the use of a VLC-based positioning system based on Cell-ID in underground mines with an accuracy of 1.6 m with no inter-cell overlapping. However, the accuracy can be improved to 0.32 m by introducing a maximum of 5 overlapping cells. The work in [94] presented a 3D trilateration system for localization in underground mining. The system was tested under three different scenarios. The first scenario reported an average positioning error (PE) of 16.4 cm as the photodetector's location was in a corner and only had a strong signal from one Tx. Bringing the Rx closer to the LEDs lowered the average. A short discussion on the use of VLP in underground mines was presented in [92]. The authors further concluded that range free positioning algorithms are most suitable for VLP system in underground mines as these methods are robust to LOS link shadowing and multipath effects.

Robots have been used for pipeline inspections as they offer more convenience, compared with manual inspections, especially in hard to reach areas and hazardous locations. To overcome the limited inspection range due to the use of cables, a preliminary study using the VLC technology for gas pipeline inspections was reported in [95,96], where the pulse-width modulation (PWM) signal transmitted from a spotlight was used to control the robot. The results showed great potential in replacing traditional wireless communications, which suffer from EMI and low energy efficiency, with VLC technology. VLC can also be used in the construction industry. The work in [97] proposed the use of VLC in the construction of tunnels within the framework of the Industry 4.0. The authors characterized the optical channel while taking into account the reflections. It was shown that the quality of the channel depends on the angle of incidence of the receiver. They proposed a reconfigurable photodetector to ensure a LOS transmission path.

The use of VLC and VLP systems in mines and downhole applications seems promising given the reported simulation results. However, whether these results are replicated in real-life conditions will require further experimental results under realistic conditions.

3.3. Indoor Positioning for Unmanned and Autonomous Vehicles

Current solutions for indoor positioning in manufacturing and storage facilities usually employ a large set of sensors such as radio frequency identification (RFID) tags [98], RF-based solutions such as ultra-wideband (UWB) [99,100], or would employ a set of vision-based solutions using cameras. An industrial VLC-based positioning system can prove to be beneficial for both customers and suppliers, as asset tracking in large industrial warehouses is mandatory to optimize the logistic supply chain processes [101]. The harsh conditions in industrial environments have hindered the adoption of RF-based solutions that proved to be unreliable in these conditions and reported positioning accuracies in the range of meters. This was demonstrated in [102] by experimentally testing a localization system in office environments and in an industry-like factory environment. The results showed that RF-based localization solutions degrade considerably in large-size industrial indoor environments with metal obstacles that causes the signals to have significant reflections with multipath effects. For the industry-like factory environment, an average error of 6.41 m was achieved using the received signal strength indicator (RSSI) method, and 6.66 m when using the time-of-arrival (ToA)-based method. This further highlights the difficulty of achieving a highly accurate indoor localization system in industrial environments. The work in [101] performed an experimental comparison using four received signal strength (RSS) algorithms for indoor localization between Bluetooth Low Energy (BLE) and long-range technologies. The tests were performed in a large open industrial environment measuring 69 m $\times$ 69 m and obtained a median accuracy of 15 meters with four BLE beacons without relying on additional information such as the transmit power and the path loss exponent. However, the test environment was empty without any objects, which presence can degrade the system through signal reflections and object movements [103].

The use of VLC for self-driving vehicles in manufacturing and storage facilities has been briefly discussed in [19], where features such as providing indoor location must be considered prior to the technology being adopted. A description of a system was presented where dedicated Rxs will be integrated with the self-driving unit for a better-optimized system. The highlighted shortcoming was that for a better positioning resolution, the number of Txs/luminaires will have to be increased, and industrial environments do not usually employ a large number of high-bay luminaires. Using unmanned ground vehicles (UGVs) for industrial applications is an area where VLC can contribute to [104,105]. UGVs are vehicles that operate while in contact with the ground and without an onboard human presence. When a UGV is automated, it is referred to as an automated ground vehicle (AGV). UGVs and AGVs in the context of industrial environments can be forklifts, cranes, or ground robots that are usually used to move inventory [106,107]. One of the current ways used for directing these robots is by using RFIDs that are placed on the ground to function as 'roads' for them to follow by scanning the tags. See [108] for a thorough review on AGV technologies, challenges, and requirements for 5G-Based smart manufacturing applications.

There has been limited work examining VLP for industrial applications. The work in [23] proposed the use of a specific VLP technique that uses active Rxs and a fixed low-cost infrastructure for location-based services in Industry 4.0 applications. The authors argued that an infrastructure-based positioning system is the best way forward as a multitude of mobile Rxs can utilize the system and position themselves. This would cut the cost and maintain the computational processing at the Rx's side. In addition, it was outlined that Industry 4.0 devices such as robots, machines, or augmented and virtual reality headsets can be included as part of the VLP system. In [109,110], a 3D positioning algorithm method for use in industrial environments was presented and further examined the effect of Rx tilt. Experimental results showed that an Rx tilt of 10° increased the 3D median positioning accuracy from 10.5 to 21.6 cm. Researchers in [104] employed two different designs to reduce the storage and computational effort for a model-fingerprinting-based RSS VLP system. Sparse propagation models were computed for an AGV and it is shown that model-fingerprinting-based RSS positioning only requires modeling less than 1% of the grid points in an elementary positioning cell. In [111], a design and demonstration of an indoor robot controlling and positioning system based on visible light was presented, with WiFi being adopted for the uplink. Experimental results reported an average PE of ≈10 cm. The work in [105] presented a flexible and efficient VLC network architecture that would decrease the outage duration arising from handovers due to the high mobility of AGVs in indoor industrial environments. Their proposed system has been shown to reduce the handover latency to a few tens of milliseconds. In [112], a phase-difference-of-arrival (PDOA)-based positioning system was experimentally tested in a smart factory area measuring 2.2 m × 1.8 m × 2 m. The Rx was mounted on a movable material buffer station and was tracked along a trajectory achieving an average positioning accuracy of around 7 cm.

Using UAVs, or drones, for industrial applications is another area that is gaining momentum and is being actively pursued as they provide several advantages. Using UAVs in industrial environments has been utilized for a while for different applications [113]. It is mainly used by companies to perform visual inspections for a variety of indoor and outdoor settings as UAVs provide a safe and cost-effective way to inspect heights and hard to reach areas, and eliminate the need for manual inspections [113–115]. The areas can range from oil rigs, power plants, buildings, and sewers [113,116]. They have also been adapted for patrolling and surveillance purposes [117,118]. UAVs and micro air vehicles (MAVs) can also be used for warehousing and inventory management/physical stock-taking [119]. The drone can gather information either by reading RFID tags or by scanning the barcode of the inventory using a mounted camera [120,121]. The market has already a few companies that provide drones for warehouse management such as DroneScan [122], Eyesee [123], Infinium Scan [124], and InventAIRy® [125]. Another envisioned use for drones is material handling in manufacturing environments where drones can pick and drop-off goods to the production line [117,126,127]. Project 'UAWorld' researchers in [127] have successfully implemented the use of drones for manufacturing purposes in a larger than 400 m^2 setting with fifteen indoor satellites to enable accurate positioning. Their experimental test results in [117] of their hybrid positioning system showed that it was capable of providing the location of the UAV with sub-centimeter accuracy. The use of VLP systems for drone positioning has the potential of offering centimeter-level accuracies at a lower cost compared to using a dedicated system solely for localization purposes.

While there has been no experimental work examining the use of UAVs with VLC systems, one of the first references on indoor UAVs localization using the optical spectrum was by researchers in [128]. The researchers proposed, implemented, and evaluated the use of an IR-based positioning system for an indoor UAV. The system consists of directional Rxs scanning the indoor environment for active tags that emit a unique IR signal. The system was constructed using off-the-shelf components and requires no room calibration when introduced to new environments, unlike some RF-based systems. Experimental testing in a large open space environment achieved a localization error of less than 1 cm at 2 m covering a range of 30 m. The work in [129] presented a high-precision UAV positioning system that is interconnected with an unmanned ground robot (UGR) aimed for automated warehouse inventory management applications. The tested system fuses 2D Lidar sensors, a camera, and an ultrasonic system for localization. The localization of the UAV is based on an adaptive active IR marker system to achieve reliable flight on different heights and light conditions. The achieved accuracy of their UAV localization system was 1.25 cm. An actual implementation of a drone using VLP has already been demonstrated by Philips Lighting (now known as Signify). An autonomous indoor drone was developed by Blue Jay and was capable of providing position information using light fixtures that transmit the luminaire's ID to the drone using VLC [130]. A summary of some of the discussed work is shown in Table 4. The referenced papers are classified depending on their environments and intended application.

The autonomous mobile robot market is rapidly growing [131]. Future industrial requirements call for high centimeter accuracies for automated mobile robots. Systems that guide AGVs have so far been infrastructure-dependent and usually require using tags to guide vehicles from one point to another [132]. While these systems are reliable, they are unadaptable and time-consuming to install. The latest technological advances are moving towards autonomous and infrastructure-independent navigation [131]. This navigation is enabled by progress in simultaneous localization and mapping (SLAM) algorithms, which is usually based on Lidar, cameras, and the integration of different sensors. The integration or fusion of VLP systems with a SLAM system is likely the required path that needs to be taken to have mobile vehicles suitable for automated movement-based tasks.

Also, while both types of UVs (i.e., UAVs and AGVs) require highly reliable links and accurate positioning, UAVs are more challenging due to their speed and additional degrees of freedom, which would require a lower latency for the communication technology used [60,133]. AGVs on the other hand, might require higher data rates for video transmission in remote control applications.

Table 4. A selection of some of the VLC work performed in different industrial settings.

Ref.	Environment	Application
[13,72,134–136]	Manufacturing cell	Communications
[87]	Gas pipeline	Downhole monitoring
[89]	Gas pipeline	Downhole monitoring
[91]	Underwater pipeline	Communications
[93]	Mines	Localization
[94]	Mines	Localization
[95,96]	Pipeline	Inspections
[97]	Tunnel construction	Communications
[110]	Warehouse	UV localization
[104]	Factory/Warehouse	AGV localization
[112]	Smart workshop	AGV localization

A Standard Benchmark for Evaluating VLP Systems

The lack of consensus on metrics, procedures, and definitions used in evaluating the performance of VLP systems has made it difficult for fair comparisons, even though several indoor positioning frameworks have been proposed in the literature. Outlining a comparison of the proposed systems using an established benchmark would be beneficial. The PE, which is the Euclidean difference between the estimated and the real positions, is usually used to measure the accuracy of these systems without taking into account pre-calibration requirements. In the literature, there is no unified way of reporting the PE. It has been referred to by using the median, mean, RMS error, or a chosen percentile error. Moreover, the difference between *accuracy* and *precision* is not clearly defined in the reported works in the literature [137].

The use of the mean should not be relied on, as the presence of outliers may not accurately reflect the performance of the system [138,139]. The disparity between the mean and median values can be seen in [140] as an example. By using percentiles, it reflects how often the system gives an accuracy below, or above, a reported error [141]. The work in [141] even suggests the use of the 0.5, 0.75, 0.9, and 0.95 percentiles. As a result, the lack of a unified measured metric has affected survey and review papers. Review papers generally resort to classifying work published in the literature based on the *stated* accuracy of VLP systems, which sometimes results in pitting median against mean values.

There are three major benchmark frameworks for evaluating indoor positioning systems. (1) EvAAL (http://evaal.aaloa.org/) (Evaluation of Ambient Assisted Living) framework—for benchmarking and evaluation metrics with the recommendation of the use of 75th percentile error (third quartile of point Euclidean error) [139]. (2) International Organization for Standardization and the International Electrotechnical Commission (IEC) [142]—the ISO/IEC 18305 standard for testing and evaluating indoor positioning systems using several accuracy score metrics, which uses the median and the 95th percentile error. However, the standard has some limitations as discussed in [141]. (3) EVARILOS (Evaluation of RF-based Indoor Localization Solutions for the Future Internet)—defines a set of evaluation metrics for evaluating indoor positioning systems [143,144]. While originally aimed for RF-based systems, the EVARILOS framework can apply to other indoor positioning technologies as well. All of the aforementioned benchmark frameworks emphasize the testing environment. One of the core criteria of EvAAL is that the system needs to be evaluated in a realistic setting. EVARILOS and the ISO/IEC standard noted that evaluating a single environment is not representative of other environments and therefore test and evaluation must be carried out in multiple environments [143]. EVARILOS also notes that the test points should include a wide range of measurements at different locations in a room, such as near walls and the center of the room [143].

As for industrial settings, the work in [145] specified two prerequisites that are deemed necessary: (1) the evaluation method must be postulated making it possible to have comparable results and to benchmark systems; and (2) testing must be carried out in an industrial environment under real-life conditions. In addition, checking whether the designed system is fit for the intended application is another important issue, which has not been reported in the literature when evaluating VLP systems. Each intended application would require a different accuracy depending on the task at hand. Figure 2 demonstrates the required accuracies for a variety of applications [146]. For example, it has been reported that AGVs would require a 2D positioning system with PEs within the range of 1 and 10 cm [147].

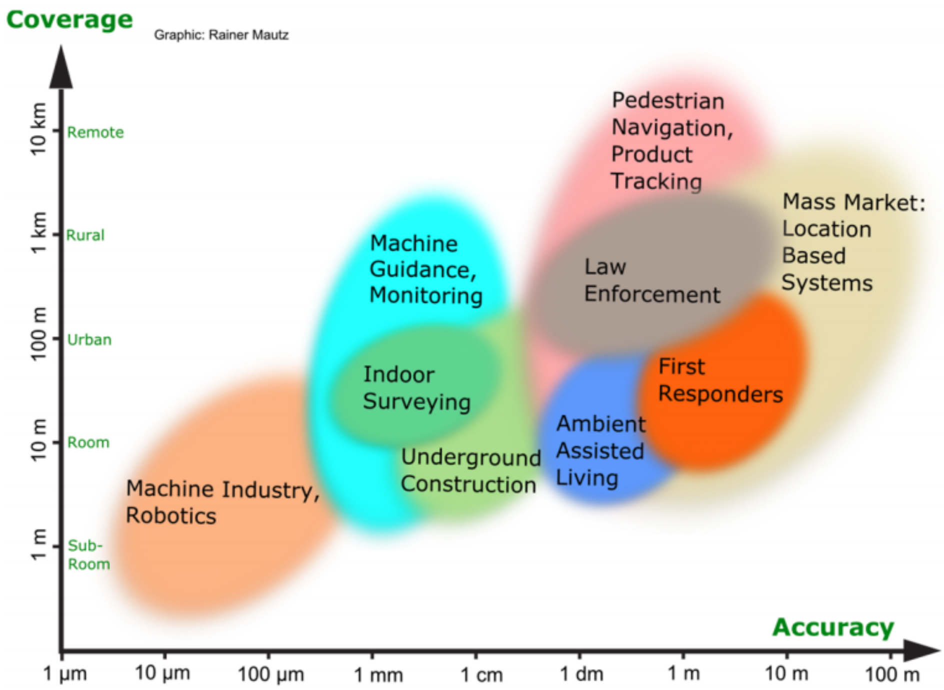


Figure 2. Overview of positioning requirements in terms of accuracy and area coverage. Adopted from [146].

The variation in testing procedures, pre-calibration requisites, and differences in experimental testbed sizes makes it difficult to fairly compare between VLP systems. Thus, there is a need for a standardized framework for testing and evaluating VLP systems. Researchers may not adopt all of the evaluation guidelines, but at least there should be an agreed-upon metric used when reporting the positioning errors of the VLP systems. For example, the IPIN indoor localization competition used the third quartile for their 'accuracy score' [138].

4. Unique Challenges

When implementing VLC systems in industrial environments, there are some unique challenges which can generally be divided into five areas (listed in Table 5):

Table 5. Challenges for Visible Light Communication (VLC) systems in industrial environments.

	Causes	Effects	Solutions
Greater link distances	Increased ceiling heights	• Weaker link budget (i.e., low SNR) • Overlapping cells, which can lead to CCI and ICI	• Relay schemes • Certain multiplexing schemes
Indoor attenuation	Particles from dust, coal, water and oil vapor	Signal attenuation through photon absorption and scattering	Increase the transmit optical power
Severe multipath reflections	High reflective surfaces (e.g., metallic fixtures)	• Signal time dispersion (i.e., ISI) • Reduced data rates	• Using OFDM and its variants • Forward error correction • Using multiple Txs to ensure at least one LOS signal
Multiple position estimates	• Linear placement of LEDs • Using lattice-shaped layouts • LED configurations (i.e., sparsely spaced or closely spaced)	• Flip-ambiguity • Duplicated points • Increased PEs	• Hybrid localization algorithms • Non-lattice shaped LED layouts • Using Rxs with wide FOV
Signal loss & blockage	• Movements or objects blocking the LOS • The Rx venturing into areas outside its and the Tx's range	Loss of a signal	• Antenna diversity • Wider FOV angles

4.1. Greater Link Distances

In most indoor VLC applications (e.g., homes, offices, etc.), the transmission distance between the Tx and Rx is in the order of a few meters, whereas in larger places such as warehouse and industrial facilities the linkspan is much longer [148]. For warehouses, ceiling heights increased from 25 feet (7.62 m) in the 1990s to 32.3 feet (9.84 m), with 36 feet (10.97 m) being common, reaching 40 feet (12.19 m) in some cases [149,150]. The longer link spans result in higher path losses and lower data rates due to multipath dispersion, thus affecting the system's performance. In addition, a higher number of lights sources on the ceiling will result in increased levels of interference between them, which will affect the link performance [151,152]. Additionally, research work over a long distance link is usually restricted to V2V communications and these results cannot be extended to indoor applications due to the different design characteristics of the luminaires which aim to deliver a more focused illumination distribution as opposed to a wide illumination distribution similar to the ones being used for indoor illumination.

There has been limited work examining LED-based VLC systems with link distances over 4 m. Table 6 lists some of the experimental work performed over a variety of distances.

Table 6. Some of the VLC work performed at different distances.

Ref.	Distance	Data Rate	Tx's Type
[76]	1.5 m	>10 Gb/s	RGB LED
[153]	2 m	60 Mb/s	RGB LED
[154]	40 cm	500 Mb/s	Blue LEDs
[155]	1.4 m	84 Mbit/s	White LED
[156]	6 m	100 kb/s	RGB/White LEDs
[157]	5 m	125 Mbit/s	White LED
[158]	1.5 m	1 Gb/s	White LED
[159]	0.5 m	3.5 Gb/s and 5 Gb/s	micro LED

Experimental work performed in [157] reported 125 Mbit/s over a distance of 5 m with bit-error-ratios below 2×10^{-3} in a lab setting using on-off keying (OOK). In [156], the authors noted that a majority of VLC systems in research are limited to short link ranges and then presented an embedded VLC platform. The system is capable of achieving 50 kbps effective throughput at a distance of up to 6 m with 99% link reliability under normal ambient light conditions. The system is also capable of achieving 100 kbps aggregate throughput under full duplexing with its transceivers.

The link range can also be extended through the use of relays. The work in [160] experimentally tested a link relay-based VLC scheme for links that span longer than 5 m. The researchers reported a data rate of 16 Mb/s at 10 meters using an amplified-and-forward scheme.

There are also other byproducts of higher ceiling heights such as increased inter-symbol interference (ISI) and inter-cell interference (ICI) influences [151]. As the luminaires will be placed even higher, this will increase the number of objects they encounter on the way to the Rx, and bigger light-cones would have more instances of overlapping coverage, which can also lead to ICI and co-channel interference (CCI) [152,161]. This gap can be addressed by testing a VLC/VLP system in an actual industrial setting using commonly-used light fixtures as opposed to lab setups with custom focused designs.

4.2. Indoor Attenuation

The transmission medium for indoor VLC systems is normally considered to be clear air. This assumption is not always true in industrial settings. The attenuation contributor depends on the type of industrial environment and it can be oil vapor, water mist, industrial fumes, or coal particles. These particles can affect the VLC signal by causing light signal attenuation due to absorption and scattering. Figure 3a shows a heat treatment facility with oil vapor surrounding the light fixtures.

The oil vapor also affects the shelf life of the luminaires due to the high temperature. Moreover, other sources of attenuation can also come from water mist as some industrial applications require industrial misting systems, also known as industrial fog systems. They are usually employed for dust or odor suppression and share a similarity with the naturally occurring fog, as can be seen in Figure 3b. Its effect has mainly been discussed by outdoor applications of VLC systems and V2V communications [162,163]. The authors in [164,165] similarly noted that particles in polluted environments such as industrial environments can affect the VLC channel.

(**a**) (**b**)

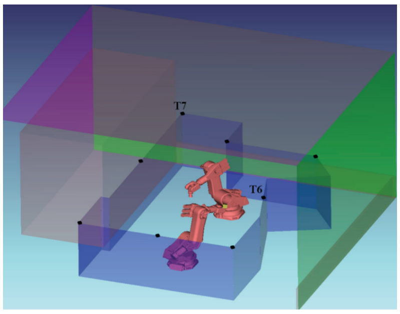
Figure 3. (**a**) A daily occurrence in a heat treatment facility with ambient temperatures of up to 60 °C oil vapors [166]; and (**b**) an industrial misting system [167]. Reproduced with permissions from DIAL and Fogco.

Research work examining the effect of the attenuation on VLC links mostly examined the effect of fog and rain in outdoor and V2V applications. The work in [168] performed a comprehensive channel modeling to quantify the effect of rain and fog on V2V applications. They concluded that the presence of fog reduces the achievable link distance up to 26 m. An experimental evaluation of the effects of fog on camera-based VLC for a vehicular setting was performed in [169] with varying visibility levels due to fog. The results showed a reliable link up to 20 m of visibility for a modulation index (MI) of 0.5 and up to 10 m meteorological visibility for MIs of 1 and 0.75. The link degraded considerably when the meteorological visibility was less than 10 m. However, these results cannot be extended to indoor applications as car headlights are of higher-power and have narrowly focused designs. When it comes to indoor environments, the work in [170] conducted experimental measurements to examine the negative impact of chalk and saw dust that partly obfuscate the photodiode. The tests were meant to represent possible environment dynamics in industrial settings as dust accumulation could obscure the receiver's aperture. When the authors tested a VLP system using a classical RSS-based lateration solution, they reported a median PE of 10.36 cm with an LED current of 300 mA. Scattering chalk dust and sawdust with an LED current of 350 mA increased the median PE to 16.42 and 32.68 cm, respectively.

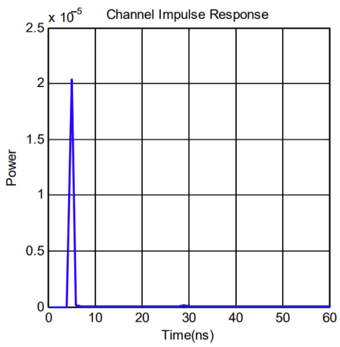
Indoor attenuation also occurs in mine applications. Coal cutters generate large amounts of dust particles that lead to signal attenuation due to absorption and scattering. The effect of coal particles, or coal dust, on VLC optical signals was modeled in [171]. The authors suggested that coal dust can be considered as a condensation nucleus covered by a thin water vapor layer, based on the fact that coal seam water infusion is used as a dust prevention method for these types of applications.

4.3. Severe Multipath Reflections

Considering the effect of multipath reflections is important in VLC system as multipath propagation introduces ISI. ISI is caused by the arrival of light rays from multiple reflectors to the Rx with different path lengths. This is especially problematic for industrial applications as industrial environments usually have highly reflective surfaces such as metal fixtures and equipment. The VLC channels with multipath and ISI have been studied for home and office environments, but only a few works exist for industrial settings. The work in [21] performed channel modeling for a manufacturing cell using Zemax® to obtain channel impulse responses (CIRs). Figure 4a demonstrates the simulated manufacturing cell measuring $8.03 \times 9.45 \times 6.8$ m^3, the robot arm coating material is galvanized steel metal, the floor is considered concrete, the ceiling consists of aluminum metal, and the cell boundaries are Plexiglas. Six commercially available LEDs in a cube shape are placed on the head of the robotic arm. Eight test points were placed on the cell boundaries on top of the Plexiglas. The CIRs from two detectors (T6 and T7) are shown in Figure 4b,c. A heavily scattered signal is received by T7 due to multipath signal from NLOS paths delayed by tens of nanoseconds. The dispersion is also present due to the use of multiple LEDs [172]. In contrast, the signal received by the closer Rx (T6) has a clear peak with a single amplitude. While long delays were observed, the presence of a LOS path to one of the eight Rxs ensures link availability.



(**a**)



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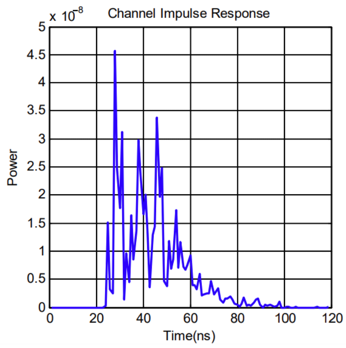

(**c**)

Figure 4. The evaluated manufacturing cell in [21]: (**a**) Manufacturing cell scenario; (**b**) channel impulse response for T6; and (**c**) channel impulse response for T7. The figures were adopted from [173].

The performance of a VLC system that suffers from ISI due to multipath reflections can be improved by using OFDM. However, the traditional OFDM commonly used in RF communications cannot be adopted in intensity-modulated (IM)-direct detection (DD) optical communication as the optical signal cannot be complex and negative. This has led to the introduction to different variants of OFDM, such as DC-biased optical OFDM (DCO-OFDM), ACO-OFDM [174], Unipolar OFDM (U-OFDM) [175] and flip-OFDM [176].

The use of OFDM in VLC systems has been touted and continues to be, as a much superior method that is robust to ISI and capable of delivering high speeds [177–179]. However, a growing amount of work in the literature counters this hypothesis [180].

Analytical results in [181], confirmed by brute-force Monte Carlo simulations, showed that M-PAM outperforms OFDM with the power gain of 3–3.5 dB at a BER of 10^{-3} when 1–4 data bits are transmitted per signal sample. The work in [182] compared the performance of DCO-, ACOand U-OFDM with M-PAM for LED-based VLC systems, where a bandlimited LED with a fixed peak power level and a channel response dominated by the response of the LED were assumed. Numerical results showed that M-PAM offered a higher bit rate by 15% compared with the optimized optical OFDM system. However, optical OFDM outperformed M-PAM in terms of the data rates by 12% for the broadband channel. Theoretical comparisons were performed for an indoor VLC system in [183] using three different modulation schemes. It was reported that PAM with a decision feedback equalizer (DFE) offered the best performance compared with carrierless amplitude–phase (CAP) with DFE and discrete multitone (DMT) modulation (a subclass of OFDM) with bit and power loading. Further experimental comparisons in [184] between PAM, CAP, and DMT showed that 2-level PAM and CAP modulations exhibit better immunity to nonlinear distortions compared to their higher level counterparts. The work in [185] experimentally compared the performance of OFDM and CAP VLC systems employing a commercially available RGB LED. By employing just the blue-chip, data rates of 1.08 GB/s and 1.32 Gb/s were achieved over a distance of 25 cm using OFDM and CAP, respectively. With wavelength-division-multiplexing (WDM), the maximum aggregate data rates were 3.22 Gb/s and 2.93 GB/s for CAP and OFDM, respectively, thus illustrating that the use of OFDM in VLC is not always the most optimal modulation scheme in contrast to the RF systems. Even so, the majority of the highest recorded data rates have been reported for VLC links with OFDM and its variants [76,186,187].

Multipath reflections have also a degrading effect on the performance of VLP systems. The vast majority of papers only consider LOS links when investigating the performance of VLP systems. However, this does not provide an accurate evaluation of the VLP systems due to the substantial effect of reflections. The impact of multipath reflections was examined in [188]. Most of the reported PEs were below 1 m, while errors were up to 1.7 m at some locations. This is in contrast to when an ideal LOS scenario was considered with the sub 1 cm PEs. The positioning accuracy for the systems with multipath reflections achieved a maximum PE of 1.85 m, which is considerably higher compared with 23 cm for the LOS-based scenario. The work in [189] reported similar results. Eight different cost metrics for an RSS-based VLP system with first-order wall reflections was evaluated in [190], where an almost linear increase in the PE and the reflectance coefficient were reported. It should be noted, the works reported in these papers were purely based on simulation. Experimental work examining the effect of reflections on the performance of RSS-based VLP systems in a warehouse was examined in [191]. The results demonstrate that the effect of reflections from the shelf racks and boxes increased the PEs median by an average of 112% in 2D systems and by 69% in 3D systems. Experimental work in [192] showed largest PEs were observed around furniture and near the curtains.

As mentioned previously, OFDM is often employed in VLC systems to mitigate the effect of reflections induced multipath, which has been extended to VLP systems [193]. An OFDM VLP system was proposed with the RMS error of 0.04 m compared to 0.43 m for OOK. An experimental demonstration of an indoor VLC-based positioning system using OFDMA was presented in [194] to overcome ICI, where results showed that the proposed method achieved a mean PE of 1.68 cm while overcoming ICI. The authors noted that an OFDMA-VLC-based positioning system provides high spectral efficiency with high tolerance against multipath-induced distortion.

Another method to lessen the effect of multipath reflections is the selective selection of only the strongest signals. The method selects the strongest signals, which are usually the closest signals, and excludes the faraway ones that are severely affected by multipath reflections [188,189]. In [188], the RMS error across the room was 46.16 cm when 6 LEDs were selected and was then reduced to 31.85 cm when the trilateration algorithm used only 3 LEDs. The authors also noted that the use of LEDs in a dense layout decreased the effect of multipath reflections. Utilizing only the strongest signals have also been observed to improve the link performance when there is shadowing due to the movement of people [195]. The authors reported that in the event of shadowing, the performance improves by using the 3 or 4 LED lights and blocking the optical path that causes ISI. Additionally, promising experimental results in [196] showed that the effect of multipath reflections can be decreased using an integrated VLP system with filtering. There are also works proposing techniques for multipath detection [197].

4.4. Multiple Position Estimates

With VLP being one of the most promoted areas of VLC, it is important to examine any issues that can be problematic. Flip-ambiguity in positioning systems occurs when the Txs (anchors) are collinear or even nearly collinear [198,199]. The installation of lights in a straight line is used in hallways and aisles in warehouses and storage facilities. An example of flip-ambiguity can be seen in Figure 5. The placement of anchors in a collinear fashion causes some positioning algorithms to output two possible outcomes equally placed away on both sides. The presence of noise can also increase the probability of flip ambiguity [200].

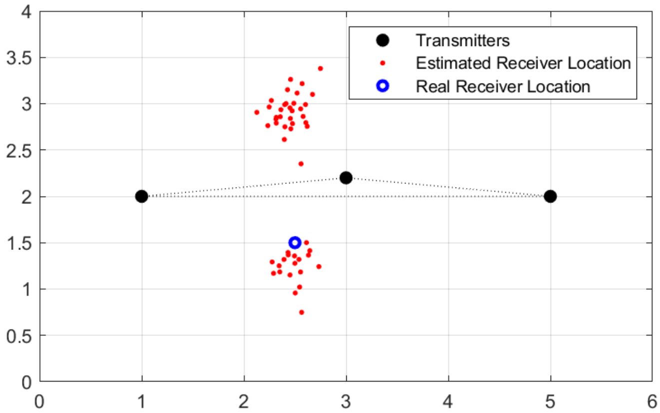

Figure 5. A demonstration of the flip-ambiguity effect when the Txs are placed in a straight or even in a semi-straight line.

As discussed previously, this is especially important as it will affect the use of UAVs and UGVs with VLP systems in warehouses and storage facilities. Flip-ambiguity is also relevant in outdoor vehicle VLP systems given the common straight-line placement of streetlights. There is some limited work examining this subject within the general research of positioning systems as in [201], where a heuristic solution was proposed to minimize the number of flips in trilateration. This issue has received limited discussion in VLP systems.

The work in [202] proposed the use of a VLC-based positioning system using LED streetlights with a fusion algorithm to solve the problem of collinear LED arrangements. The authors tackled this problem specifically as streetlights are generally placed in a collinear fashion. They further proposed the use of an algorithm that uses two cameras placed at different positions in the vehicle to deal with the flip-ambiguity issue. In [203], a VLP system was tested in different office environments, e.g., a corridor with an area of 2×12 m^2 with five collinear LEDs. Multiple tests were conducted at 60 positions and it was demonstrated that the largest errors occur at exactly the positions at the two sides of the corridor, thus suggesting a flip-ambiguity effect. Similarly, the work in [204] noted that the classic multilateration method cannot be used in a scenario where LEDs are deployed linearly, and therefore proposed the use of a rotating multi-face positioning method to address this problem. In [205], the authors did note that traditional trilateration schemes will not resolve due to the system only having information from a single axis. They then proposed the use of their system that consists of fusing an RF localization system with VLP and reported a mean PE of 0.09 m in a hallway.

Singularities have a similar effect to flip-ambiguity and were investigated in [206] for general indoor positioning systems. The authors highlighted that regular lattice-shaped configurations on the ceiling are not optimal for location estimation using trilateration techniques due to the occurring singularities. The use of lattice-shaped LED layouts causes multiple position estimates. This issue is not unique to industrial environments, but similarly to flip-ambiguity, it occurs in indoor environments.

To demonstrate the effect of 'singularities', the widely cited $5 \times 5 \times 3\,\text{m}^3$ room by Komine and Nakagawa [207] has been adopted with the same LED layout. A test point was measured throughout the room every 10 cm and the received powers were recorded, see Figure 6. The power measurements were matched to their duplicated point by up to two decimal points (e.g., 2.77×10^{-16}). Every red point in the figure has a corresponding point at a different location. Alleviating this issue can be done through the use of non-lattice Tx configurations. The examination of the Txs' layouts has been largely missing in VLP literature even though there is earlier work in indoor positioning systems discussing its importance [206,208–210]. The dilution of position (DOP) metric, sometimes referred to as geometric dilution of precision (GDOP) metric, is usually employed as it quantifies the geometrical effects of the transmitters' distribution. The use of this metric, however, is largely absent in VLP work. There has been limited work that utilized it for an optical wireless positioning system in [211–214]. Other DOP parameters can be used to characterize the effect of the transmitters' placements [215–217]. Examining the effect of the transmitters' layout on the accuracy of localization systems is especially important in VLP as the arrangement of the luminaires is dictated by the area and the room's design to satisfy illumination purposes. Which means that, unlike other technologies, the layout of the Txs are usually fixed and cannot be optimized to meet localization purposes as it would affect the primary function of the LEDs, which is for illumination.

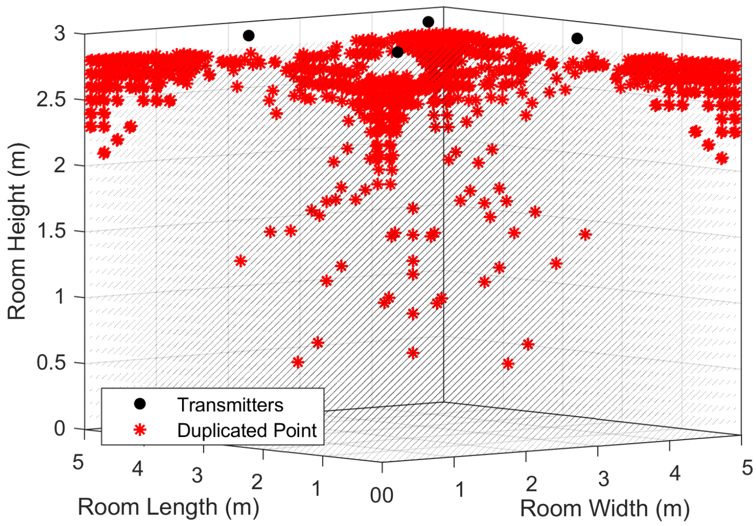

Figure 6. A demonstration of the duplicated points in the room.

The work in [218] used the algorithm developed in [219] to experimentally compare the accuracy of a VLP system under a 'Square' and 'Star' LED layout configuration. 22,801 test points were taken in a $4 \times 4 \times 3\,\text{m}^3$ room for both 2D and 3D positioning systems. Experimental results show that while the 3D median error was over 2 m under a 'Square' configuration, it was 12.7 cm under the 'Star' LED layout (a visualization of the difference can be seen in Figure 7). The increased PE under the 'Square' configuration is caused by the ambiguity in height estimation. A similar effect was also reported in [220] when more than one optimal height was calculated by the algorithm. The authors attributed this to a limitation by the system channel model, but it is more likely caused by their use of only three Tx sources, which results in a height ambiguity as examined in [219]. The Tx's locations have also been shown to affect the accuracy of angle-of-arrival (AOA)-based VLP systems [211,214].

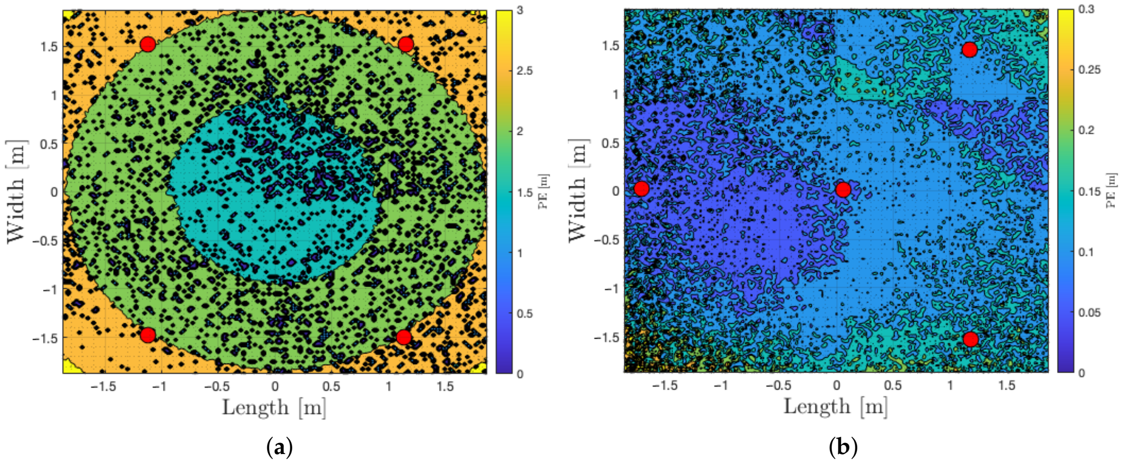

Figure 7. Spatial distribution of the PE for a square and star-shaped LED configuration (red circles denote Tx locations). Based on the work in [218].

The number of duplicated points also has the potential to increase when considering multipath reflections and signal fluctuations. Experimental work in [221] shows that the received illuminance from LEDs changed randomly with time, with amplitude fluctuations reaching up to 38% of the average. This can lead to measurement points at certain positions matching other points at completely different locations. It should be noted that this issue is not specific to trilateration algorithms, but also occurs in RSS-based fingerprinting systems.

4.5. LOS Signal Loss and Blockage

It has been well established that VLC heavily relies on the LOS link, so a clear and uninterrupted path between the Tx and Rx is imperative. When employing robot arms, a signal loss due to the quick movements of the robot arm is likely to happen. This issue was researched by the Fraunhofer Institute for Telecommunications HHI. Experimental work performed by researchers in [13,72,134–136] led to the development of an antenna diversity model that consists of placing the Rxs around a manufacturing cell to ensure that there will always be a LOS signal. The tests were performed in an industrial environment that is part of BMW's robot testing facility. The cell measures 5 × 5.7 m^2 and is surrounded by a metal cage as shown in Figure 8a. The measurements were taken along a typical trajectory (shown in Figure 8b) that has a length of 5 m and involves picking up an object. The results revealed sudden signal fades up to 20 dB that occur even when the robot arm moves by a few centimeters.

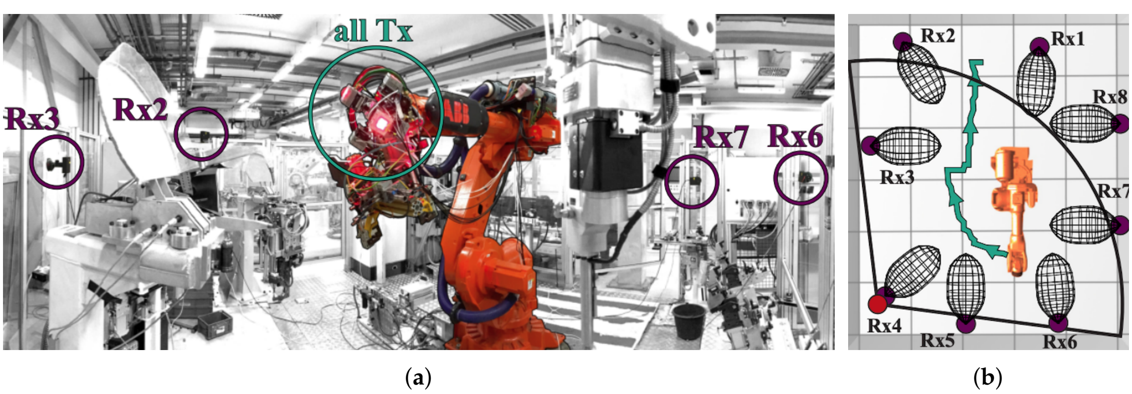

Figure 8. (**a**) The manufacturing cell used for the experiments at BMW's robot testing facility; and (**b**) the robot arm movement trace investigated in [13]. The figures were adopted from [222].

The use of spatial diversity ensures that there is always at least one direct signal connection, meaning that the manufacturing robot arm's process is never interrupted by always having an Rx within the movement range of the robots that have the Txs placed on top of it. The use of multiple Rxs and Txs is important because if only a couple were used then the risk of having an interrupted signal increases. This solution may not always be applicable for different uses and layouts especially when considering collaborative robots, colloquially referred to as cobots. Robots working alongside humans is one of the key drivers in smart factories [223] and a key concept in Industry 5.0 [224]. There could be a risk of the signal being interrupted by an operative if there are several Rxs around the robot arms at the same level, something that can be avoided by placing the Txs/Rxs at higher locations or on the ceiling.

Signal loss is a risk that can also affect VLP systems, especially for receivers such as UAVs as discussed in Section 3.3. VLP systems generally require signals from 3 or 4 spatially distributed Txs, and the height changes affect the number of Txs that the Rx sees. The loss of a signal from one or more Txs due to the signal being outside the field-of-view (FOV) of the Rx occurs when the Rx is closer to the light fixtures, or ventures to an area outside of the light's beam angle as reported in [225,226]. The work in [225] found that the corners and areas close to the ceiling are the locations with poor LOS coverage and would be problematic for tracking receivers. The authors proposed the use of an active zone when benchmarking positioning systems and defined it as the volume in an indoor space in which localization is of higher importance. Likewise, the work in [226] looked into areas where the Rx might lose a LOS signal and identified the corners and edges of the room as the most problematic areas. Mitigating the loss of a signal, in theory, can be achieved by using an Rx with a FOV of 180°. The performance of the 180° FOV Rx with multiple photodiodes was studied in [227,228] and reported to be capable of offering full mobility within a typical home/office environment when compared with a single Rx. There have been some research works that examined the use of a fisheye lens with an ultra-wide FOV (≥180°) [229]. Experimental work in [230] found that the ICI is alleviated due to the high spatial diversity provided by the fisheye lens-based Rx. The results suggest that the fisheye lens-based imaging Rx is a potential candidate for high-speed VLC applications. The work in [231] also concluded that a fisheye lens-based imaging Rx is a potential candidate for high-performance indoor MIMO VLC applications. However, the use of Rxs with an ultra-wide FOV to eliminate dead-zones has not been examined experimentally, nor has the effect of reflections on dead-zones. Another way for VLP systems to operate in areas where there are less than three signals is by employing a system design which can work even in the presence of a single Tx [232]. The use of filters in the event a receiver venturing into a dead-zone has been shown to alleviate to some extent the effect of losing a LOS signal. The works in [233,234] found that the use of an extended Kalman filter (EKF) helps the trackability when there are less than three LOS sources. They also found that EKF helps in cases where there are strong NLOS signals and in the event of shadowing.

5. Conclusions

This paper reviewed several aspects of utilizing VLC systems in industrial settings and discussed existing requirements for industrial communications. The potential for using VLC systems in the industrial settings is examined and existing work was categorized. Historically, the industrial community has always been cautious when it comes to adopting new technologies. Several factors contribute to this, mainly; industrial environments have almost no tolerance for downtime and require highly reliable links. This underscores the importance of having robust links and as such, it should be taken into account for any possible VLC application, even if robustness comes at the expense of high data rates. Moreover, when it comes to proposed solutions for localization, it is important to examine if the developed systems' accuracy meets the specifications for such applications.

The experimental work of a manufacturing cell in collaboration with a car manufacturing company has demonstrated the potential of VLC/OWC systems in industrial applications. While the project proved that it is capable of satisfying important functionalities such as data transfer rate, stability, and low delay, the project's "readiness level" was rated 6 out of 9 (9 would be necessary for general deployment) [235]. The particular issue noted was that significant miniaturization of the transceivers was needed (down to the size of a USB stick) [73].

Nevertheless, the EU's biggest research and innovation program (Horizon 2020) has provided funding to a promising project. The ELIoT project's aim in bringing together different organizations is a significant step to ensure a streamlined process using a unified set of standards. The project brings together research institutes and partners that represent the chipsets, components, systems, and the applications sectors all working together on the commercialization of LiFi for the future IoT [236]. An initial open reference architecture document has already been released and shows a close relation to other standardized references [237]. The project's aim is to facilitate the integration of VLC into various IoT applications for different use cases that range from indoor residential and commercial settings to outdoor applications.

At this stage, experimental work to establish the system's reliability, latency, and suitability in factory environments is needed before it will be considered by the industry. This is especially lacking in VLP work. The parallel work in VLP systems has the potential to breathe new life into the use of UVs due to the relative simplicity in implementing indoor positioning systems compared to other systems, yet this area lacks significant experimental work.

In general, this paper aimed to reflect the current work performed in these areas and to offer potential avenues for other researchers to examine and consider, as well as to highlight the challenges that VLC and VLP systems face in these types of settings. Industrial environments are harsher compared to residential settings, so the results reported in these areas (and lab settings) should not be blindly extended to industrial settings. Evaluations and system characterizations are needed to tailor the use of these systems to fulfill industrial automation requirements.

Given that the research work in this field is still in its early stages, while also considering the ongoing research projects, we expect a significant increase in the number of VLC and OWC work for industrial applications over the next couple of years.

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Abbreviations

The following abbreviations are used in this manuscript:

ACO-OFDM	Asymmetrically Clipped Optical-OFDM
AGV	Automated Guided Vehicle
AISRT	Analogue Image Signal Relay Transmission
AOA	Angle-of-Arrival
BER	Bit Error Rate
BLE	Bluetooth Low Energy
CAP	Carrierless Amplitude–phase
CCI	Co-Channel Interference
CIR	Channel Impulse Response
CPS	Cyber-physical Systems
DCO-OFDM	DC-biased Optical OFDM
DD	Direct Detection
DFE	Decision Feedback Equalizer

DIFRT	Digital Image Frame-relay Transmission
DMT	Discrete Multitone
DOP	Dilution of Position
EKF	Extended Kalman Filter
EMI	Electromagnetic Interference
FOV	Field-of-View
HHI	Heinrich Hertz Institute
HMI	Human-machine interface
ICI	Inter-cell Interference
IM	Intensity Modulation
IoT	Internet of Things
IR	Infrared
ISI	Inter-symbol Interference
LED	Light-emitting Diode
LOS	Line-of-Sight
MAV	Micro Air Vehicle
MI	Modulation Index
MIMO	Multiple-input-Multiple-output
NLOS	Non-Line-of-Sight
OFDM	Orthogonal Frequency-division Multiplexing
OOK	On-Off Keying
OWC	Optical Wireless Communication
PAM	Pulse Amplitude Modulation
PDOA	Phase-Difference-of-Arrival
PE	Positioning Error
PER	Packet Error Rate
PWM	Pulse-width Modulation
RF	Radio Frequency
RFID	Radio Frequency Identification
RGB	Red, Green, and Blue
RMS	Root Mean Square
RSS	Received Signal Strength
RSSI	Received Signal Strength Indicator
Rx	Receiver
SLAM	Simultaneous Localization and Mapping
SNR	Signal-to-Noise Ratio
SPAD	Single Photon Avalanche Diode
ToA	Time-of-Arrival
TR	Technical Report
TS	Technical Specification
Tx	Transmitter
U-OFDM	Unipolar OFDM
UAV	Unmanned Aerial Vehicle
UE	User Equipment
UGR	Unmanned Ground Robot
UGV	Unmanned Ground Vehicle
UV	Unmanned Vehicle
UWB	Ultra-Wideband
V2V	Vehicle-to-Vehicle
VLC	Visible Light Communication
VLP	Visible Light Positioning
VLRC	Visible Light Relay Communication
WDM	Wavelength-Division-Multiplexing
WLAN	Wireless Local Area Network
WSN	Wireless Sensor Network

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