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Optical camera communications: concept, marketing, implementation, challenges and applications

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Abstract Optical camera communication (OCC) has emerged as a transformative technology that utilizes light sources, such as LEDs, and camera sensors to facilitate data transmission, offering a low-cost, energy-efficient, and ubiquitous alternative to traditional wireless communication methods. This paper explores the overview of OCC, including its marketing potential, implementation strategies, opportunities, challenges, and wide-ranging applications. By leveraging existing camera and lighting infrastructures, OCC presents unique opportunities for integration into consumer electronics, retail, smart cities, automotive systems, and beyond. However, its adoption faces technical challenges, such as limited data rates, ambient light interference, and camera frame rate constraints, which require innovative solutions in hardware and algorithms. From a marketing perspective, OCC enables enhanced customer engagement, indoor positioning, and context-aware services. This study also examines the future trajectory of OCC, emphasizing the role of interdisciplinary collaboration in overcoming barriers and driving real-world deployment. Through a comprehensive analysis of its strengths and limitations, this paper provides valuable insights for researchers, developers, and stakeholders aiming to harness the full potential of OCC in a connected world.

Keywords optical camera communications (OCC), visible light communication (VLC), light emitting diodes (LEDs), Internet of Things (IoT), image sensor (IS)

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1 Introduction

As technology has become an integral part of society in the 21st century, we have seen a wide spread use of smart devices in all aspects of our lives. As part of the next generation wireless networks (i.e., sixth generation and beyond), Internet of Things (IoT) and Internet of Everything (IoE), smart devices are expected to have multiple functionalities of sensing, processing, localization, and data communication [1, 2]. Both IoT and IoE are finding use in many applications including smart homes, retails, smart industry, smart agriculture, smart healthcare, smart transportation, and other sectors. It is predicted by Cisco that over 500 billion devices (with a projected economic value of over $1377 billion) will be connected

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to the Internet by 2030 reaching 9.7 billion in 2050, where these devices will be able to communicate with each other through IoT networks, allowing device-to-device and machine-to-machine communications [3, 4]. Existing technologies have been successful in addressing the needs of many applications so far, but wide spread use of IoT/IoE devices will impose a few challenges [5] including quality of services, network capacity (i.e., bandwidth and data throughput), energy efficiency and harvesting, sustainability and effective utilization of resources as well as strict key performance indicators on device, sub-systems and systems, thus necessitating the need for new technologies including integrated wireless technologies and a paradigm shift toward intelligent-based distributed systems and networks as well as architecture, routing algorithm, protocol, and spectrum.

IoT technology relies on wireless connectivity to enable large-scale digitization through a paradigm shift from point-to-point monitoring to all-connected systems via the Internet. Because of the diverse applications and multifaceted nature of IoT, there is a need for wireless technologies that can be used in all of these applications. With advances in materials, semiconductors, electronics, photonics, and automation, 5G and 6G communication solutions are becoming smarter, more reliable, robust, energy and spectrum efficient, and more sustainable than ever before. Cellular wireless technology as part of 5G and the emerging 6G and beyond, is a critical enabler of many modern IoT/IoE application scenarios. Current wireless technologies, mostly based on radio frequency (RF), differ in their transmission ranges L, data rates R_b, high-density user scenarios, power usage and latency with a natural trade-off between the latter two [6]. Recent communication technologies adopted for IoT applications in 5G include the following. (i) Short-range (hundreds of meters) and low-power—Bluetooth [7], ZigBee (R_b of 250 kbps over about 100 m transmission link span) [8], and WiFi (at the 2.5–5 GHz band over a 100 m link based on the IEEE 802.11 family of standards) and (ii) long-range: LoRa—a low-power wide-area wireless technologies operating at unlicensed frequency bands, e.g., 433 and 868 MHz in Europe to offer R_b of 0.3 and 27 kbps for energy-constraint devices [9]; SigFox—is a low-power wide area network technology with a 100 MHz bandwidth at 868 and 902 MHz in Europe and USA, respectively for low-throughput IoT and machine-to-machine applications (i.e., smart meters, etc.) [10, 11]; and narrowband IoT—a low-power wide area network RF technology with a 200 kHz bandwidth and orthogonal frequency division multiplexing (OFDM) for indoor applications [12]. Moreover, the need for ultra-low latency for real-time applications, massive connectivity for IoT and beyond, sustainability and energy efficiency, support for new use cases and applications, enhanced artificial intelligence (AI) integration, resilience and security, global connectivity and bridging the digital divide, terahertz communication and convergence of physical, digital, and biological worlds pave the way for 6G to keep pace with the growing demands for faster, smarter, and more inclusive networks while enabling revolutionary applications that redefine the way we live, work, and communicate.

As part of 6G and beyond, it is envisioned that wireless connectivity will be accelerated through increased network agility and integration of AI, machine learning, blockchain (offering security) and edge computing as well as being expanded to include sensing, localization and communications. Moreover, new architectures, routing algorithms and protocols are needed to facilitate large-scale deployments of IoT devices, which will rely on the use of software defined networks, network function virtualization, and edge-fog-cloud continuum. In addition, 6G is opening up the opportunity to explore the use of multiple wireless technologies including millimeter Wave, sub-THz and optical wireless communication (OWC). Using OWC as a complementary wireless technology to RF can release RF spectrum for use in other applications as well as in situations where RF cannot be used [13]. Figure 1 shows the electromagnetic spectrum including the three main optical bands of ultraviolet (UV), infrared (IR), and visible light (VL). Both radio waves and microwaves have a total bandwidth of approximately 300 GHz, whereas IR, VL and UV bands offer a theoretical bandwidth of 20 THz, 320 THz, and 75 PHz, respectively, which are not effectively utilized yet [14–17]. In addition, OWC provides low latency, higher R_b, inherent security at the physical layer as well as improved energy efficiency compared with RF technologies (ZigBee, Bluetooth, etc.) in short-range technologies [14–17]. In IoT/IoE gateways, which manage a vast number of devices and the data between edge devices and cloud servers, data secrecy is highly critical. In addition, since communication is over both public and private networks, a secure network is essential. Therefore, the development of more secure and highly encrypted hardware chipsets and networking solutions is required.

OWC technology includes UV communication, visible light communication (VLC), free space optics (FSO), optical camera communication (OCC), and IR communication, as depicted in Figure 1. The FSO systems based on IR are primarily used for medium- to long-range terrestrial and non-terrestrial applications delivering almost as high R_b as optical fiber communication. Additionally, FSO may be

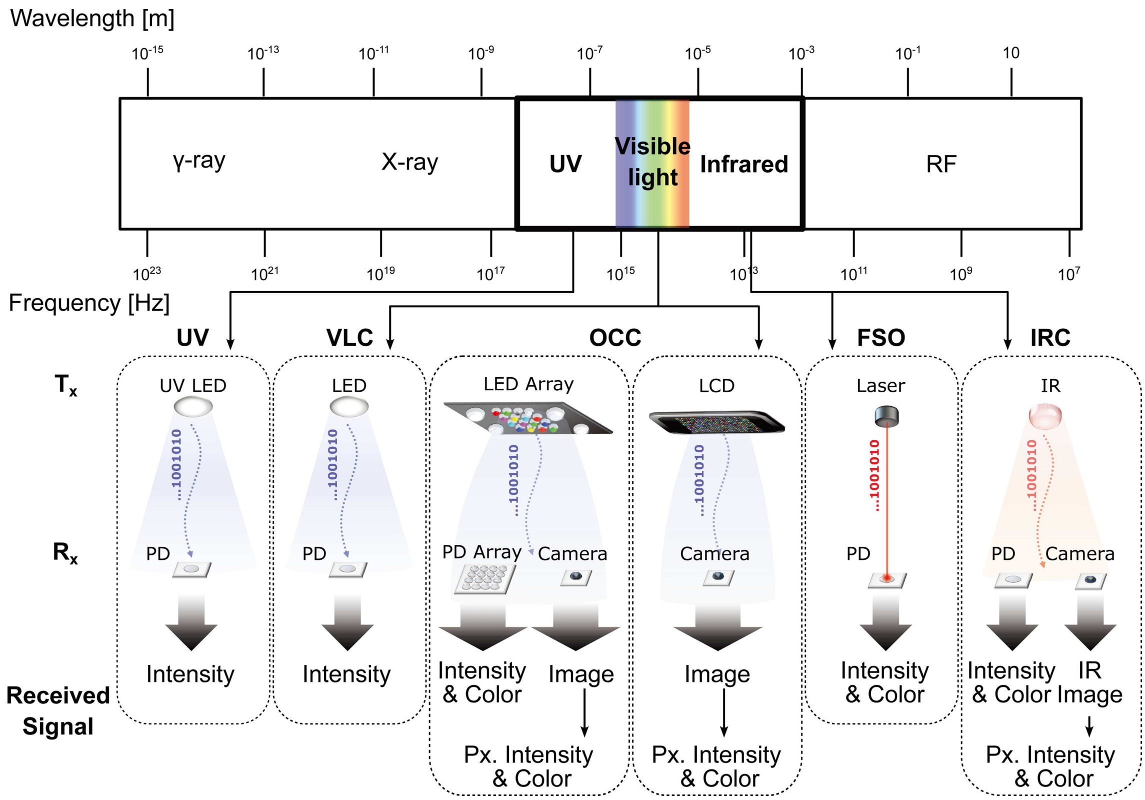

Figure 1 (Color online) Electromagnetic spectrum along with exemplary schemes of OWC.

used in short-range indoor applications (such as data centers) as well as in embedded applications. VLC employing light emitting diode (LED)-based lighting fixtures is mainly used for short-range indoor and, in some cases, outdoor applications (e.g., vehicular communication) [18]. Note that (i) LED lights offer much higher switching speed compared with other light sources, thus allowing them to be simultaneously utilized for illumination, data communication and localization in IoT applications in the next-generation wireless networks [19]; and (ii) the visible band of 370–780 nm provides 400 THz of bandwidth, which is 10000 times larger than the RF bandwidth [20]. Whereas VLC-OCC is mainly for short range and low R_b IoT in 5G and 6G wireless networks [5]. In recent years, VLC has grown in popularity as both a supplement and an alternative to RF communication. This shift is driven by several factors [21]: dwindling RF spectrum, capacity crunch, interference, security, spatial reuse, safety, energy efficiency, moving towards a smart power grid, easy implementation into existing infrastructure, and low cost.

Optical receivers (Rxs) for VLC are generally classified into two types: high R_b, i.e., photodetectors (PDs), and low R_b, i.e., image sensors (IS) (i.e., array of PDs) [22]. The OCC offers new possibilities for the use of VLC systems in a number of applications, including display-based transmission, device to device communications (D2DC)—as part of the Internet of things—and vehicular communications where the IS-based Rx will offer multiple functionalities, including vision, data transmission, localization, and range measurement [14]. In contrast to the single PD-based VLC systems, an IS Rx in OCC, which is composed of an imaging lens and IS, has many unique features, including a wide field of view (FOV) due to the PD array, as well as spatial and wavelength separation of light beams [17]. This development has led to the emergence of OCC, which has gained interest within the researchers and is being considered an option in the IEEE 802.15.7m (TG7m) visible light communication task group [17]. Moreover, unlike VLC which can only capture intensity (one dimension (1D) data) with a single PD Rx, the major advantage of OCC lies in parallel capturing of 2D image data with colors (i.e., spectral resolution). Image processing on the Rx side also provides OCC with advantages to classify shapes and estimate the distance-based depth perception from the vision of cameras. However, in OCC, R_b is limited by the frame-rate R_f of the ISs, i.e., camera. R_b can be increased by using higher R_f cameras, which are very costly and the camera capture speed, which is defined as the physical parameter of the sensor (electronics) and the graphics processor speed in the hardware domain. R_f of the camera is generally confined to either 30 or 60 fps, except for some slow-motion capable cameras with R_f of 120–240 fps. Some specialized high-speed cameras are available with R_f ranging from 1000 to 21000 fps [17]. However, these cameras are not suitable for the use in mobile devices and are less likely to be implemented for OCC applications. Therefore, OCC is further extended to offer massive multiple input multiple output (MIMO) capabilities in order to increase R_b using LEDs and PD arrays in the form of multiple pixels in ISs for IoT applications in both indoor and outdoor environments. Considering the advantages and disadvantages of the IS-based Rxs, in this paper we focus mainly on the IS marketing trends based on the evolution and increasing number of cameras in the form of mobile phones and surveillance usage and its challenges in implementation within OCC technology and applications.

Smartphone cameras are driving a shift in the market size of digital cameras, which is valued at $17.68 billion in 2023 and is expected to grow to $21.66 billion by 2030 (i.e., a compound annual growth rate of 5.2%) [23]. In 2024, 5.12 billion smartphones have been sold to the end users [24]. Further advancements in lens design, IS technology, image processing algorithms, electronics, AI-driven scene recognition and object tracking enable cameras to be used for multiple purposes [24]. With cameras being widely used in a wide range of devices, locations, and products, OCC presents an attractive technology for future IoT/IoE applications within the context of 6G and beyond. As ISs shrink and improve, and smartphones gain the power to enhance images in real time, modern smartphone photos are nearing the quality of high-end interchangeable lens cameras. As smartphone makers are rolling out AI features to their devices, phone cameras will only get more powerful, enabling the users to edit their photos in ways beyond just the photography usage, i.e., use within IoT networks for enabling smartphone cameras based on smart environments.

A single camera cannot often observe an area of interest completely due to its limited FOV and the abundance of occlusions in real scenes. Therefore, it can be seen from Figure 2, that multiple cameras with new features such as zooming, telephoto, depth estimation, improved high definition resolution, portrait modes, 3D and low-light photography can be used in such situations to increase the scope of the active surveillance area. Increasing quality and decreasing cost of widely available cameras have resulted in visual monitoring becoming the dominant paradigm for automated surveillance, which may be enhanced by the inclusion of other features such as sensing, data communication and location.

The size of the image/megapixel captured is given by

$$\text{Size of image} = W \times H, \text{Aspect ratio} = \frac{W}{H}, \tag{1}$$

where W is the width and H is the height of the picture/image in pixels (i.e., resolution). For example, considering (1), we calculated the size of image aspect ratio as listed in Table 1 along with resolution, and capture speed for mostly commonly sold Samsung Galaxy S series, iPhone series smartphones and general closed-circuit television (CCTV) cameras. It can be seen that ultra-high definition (UHD) resolution in terms of pixels with the highest image size, aspect ratio and R_f is supported by Samsung and iPhone series cameras.

The rest of the paper is organized as follows. In Section 2, VLC-OCC technologies are introduced in details. In Section 3, technical challenges in OCC are discussed. Section 4 describes various applications of OCC based on IoT and/or 5G and updates to the IEEE standard. Finally, Section 5 concludes the paper.

2 Visible light communication-optical camera communication

Typical VLC systems use light sources, such as LEDs, to transmit information through the optical wireless channel. The modulated light signal can then be received and converted back into an electrical signal using VLC Rxs. PDs are the most common Rxs due to their sensitivity and fast response times. The use of PDs has been widely reported in the literature for both line of sight (LOS) and non-LOS (NLOS) links mostly in indoor environments. In spite of this, there are some issues such as transmission over long L, shadowing and blocking in LOS links, reduced R_b in NLOS links and the need for the transmitter (Tx) and Rx diversities. However, other Rxs such as IS (CMOS/CCD) cameras [25], avalanche PDs, solar panels, PIN diodes, and quantum dot PDs can also be used depending on the specific application based on L and R_b. The selection of the Rx depends on various factors, including (i) performance metrics involving sensitivity, bandwidth, and signal-to-noise ratio (SNR), (ii) physical constraints such as FOV

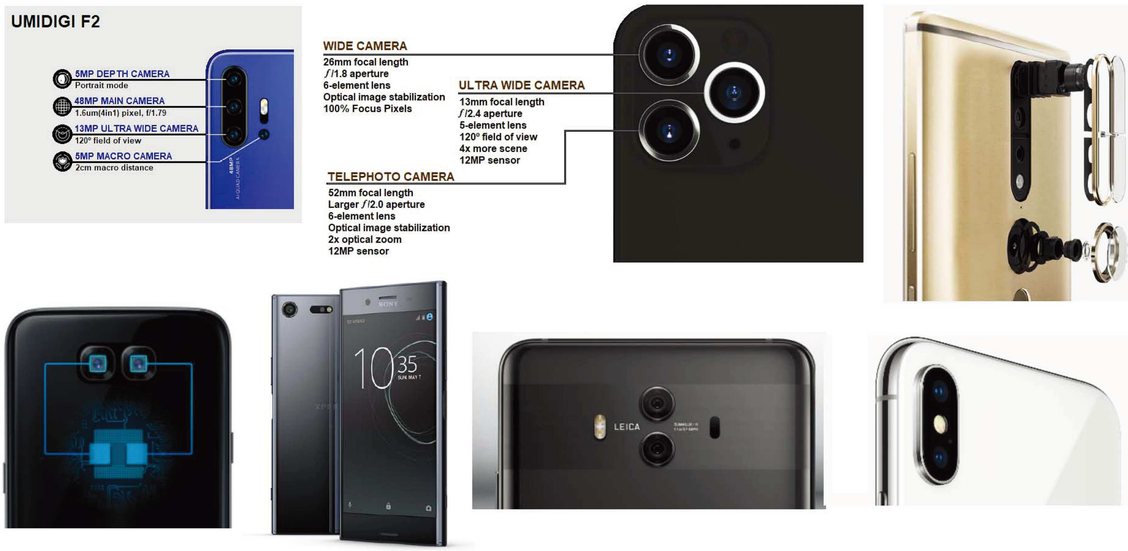

Figure 2 (Color online) Variations, advancements, and number of cameras used in mobile phones.

Table 1 Most commonly sold smartphone and CCTV camera specifications (2023).

Type	Resolution (pixels)	Size of image (megapixels)	Aspect ratio	R_f (fps)
Samsung Galaxy S series	3840 × 2160 (UHD), Not supported by the front camera	8.3 (8294400)	1.78	30, 60
	2560 × 1440 (QHD)	3.69 (3686400)	1.78	30
	1920 × 1080 (FHD)	2.074 (2073600)	1.78	30, 60
	2224 × 1080 (18:5:9)	2.4 (2401920)	2.06	30
	1440 × 1440 (1:1)	2.074 (2073600)	1	30
	1280 × 720 (HD)	0.92 (921600)	1.78	30
	Slow motion	–	–	120, 240, 960
	3088 × 2320	7	–	30, 60
	2576 × 1932	5	–	30, 60
iPhone series	4032 × 3024	12	–	30, 60
	1280 × 960	1.2	–	30

and system size, (iii) power efficiency considerations in terms of power consumption and energy efficiency, and (iv) economic factors such as cost and availability.

The growth in the IS market has presented one of the largest compound annual growth rates of all application markets [26]. This has triggered its use across various industries including motion capturing [26], visionary, sensing, security, machine vision for factory automation, and automotive cameras for driver-assistance and intelligent transportation systems [27], indoor localization, security, virtual reality, and advertising [14]. OCC operates as a subset of VLC, which utilizes ISs to capture and decode the light signals transmitted by LEDs or other light sources. It comprises a group of pixels (i.e., PDs), where the signal strength of each pixel depends on the intensity of incident light [15]. Each pixel can detect signals at different wavelengths over the visible range, e.g., red, green, and blue (RGB), hence offering parallel detection capabilities and an adaptive FOV feature.

Likewise, the transmitted information from many light sources, different directions, and locations via the LOS [16,17], NLOS, and/or a combination of both paths [18] can be captured using a one-dimensional (1D) data single-pixel or a pixel-array IS-based Rx. Hence, it allows a parallel capturing of 2D image data with colors. Furthermore, image processing on the Rx side also provides OCC with advantages to classify shapes and estimate the distance-based depth perception from the vision of cameras. Thus, resulting in a higher SNR, improved mobility, and flexibility over a L of up to hundreds of meters [20]. Also, OCC may offer simultaneous vision and data communication, massive MIMO for both LOS and NLOS as well as spatial separation of multiple Txs (i.e., sunlight, street light, vehicle light) [28–30], improved quality of services under low-light conditions [29], and no need for an additional hardware (i.e., an electronic Rx).

Even though in practical deployments, IS-based receivers offer the advantages such as parallel detection

Table 2 OCC survey studies conducted.

Ref.	OCC major focus	Missing points (categorized)
[25]	Tx and Rx overview; implementation challenges: rolling vs. global shutter; research challenges: modulation schemes, optical MIMO; deployment opportunities in positioning and trends; standardizations.	Link channels: NLOS OCC, long-distance OCC, and dynamic OCC; modulation techniques: advanced modulation schemes; frame capturing: architecture of rolling and global shutters; techniques: hybrid and ANN-based OCC; platforms: image processing (e.g., Android, OpenCV).
[32]	OCC design challenges: synchronization, data rate, flickering, MIMO; comparison of high/low-rate lighting sources; IEEE standardization issues.	Link channels: NLOS techniques, and dynamic OCC; modulation techniques: updated modulation schemes; frame capturing: rolling vs. global shutters; techniques: hybrid, ANN-based OCC; platforms: image processing (e.g., Python).
[17]	OCC in 5G networks and IoT; modulation techniques, sampling schemes; hybrid OCC-PD communication.	Link channels: NLOS OCC, long-distance OCC, and dynamic OCC; techniques: rotation support, ANN-based OCC; platforms: image processing platforms (e.g., Linux).
[33]	OCC system overview: data decoding, illumination models; performance improvements: rolling shutter, MIMO, modulation schemes.	Link channels: NLOS OCC, long-distance OCC, and dynamic OCC; techniques: Hybrid, ANN-based OCC; platforms: Android, Python, OpenCV.
[34]	Existing challenges and limitations; SMARTPHONE as OCC Rx: R_f, exposure control.	Link channels: NLOS OCC, long-distance OCC, and dynamic OCC; techniques: hybrid, ANN-based OCC, rotation support; platforms: image processing on smartphones.
[35]	Standardization, channel modeling, modulation, error detection coding schemes; localization and navigation; brief hybrid schemes.	Link channels: NLOS OCC, and dynamic OCC; techniques: hybrid, ANN-based OCC, rotation support; applications: long-distance OCC; platforms: Android, Python, OpenCV.
[31]	Modulation scheme comparisons; link blockage, NLOS issues.	Techniques: hybrid, ANN-based OCC, rotation support; link channels: long-distance OCC, and dynamic OCC; platforms: image processing (Linux, Android).
[36]	Key issues: mobility, coverage, interference; standardization.	Techniques: hybrid, ANN-based OCC, rotation support; link channels: long-distance OCC; platforms: OpenCV, Android.
[37]	Performance constraints and extended applications.	Techniques: Hybrid, ANN-based OCC, rotation support; link channels: long-distance OCC; platforms: image processing platforms (Python, Linux).

(spatial division), adaptive FOV, and improved SNR, the use of IS, however, introduces key trade-offs compared to traditional PDs. Specifically, IS-based receivers generally suffer from higher latency due to the need for image acquisition and subsequent processing. Power consumption is also typically greater because IS devices need associated processing units typically bigger than microcontrollers, which demand more energy than digital signal processing (DSP) units. Moreover, achieving real-time processing with IS-based systems is more challenging, as the image data must be processed at high speeds to extract communication signals, requiring computationally intensive algorithms [17, 31].

VLC-OCC technologies can be categorized based on various main factors, including link channels (LOS and NLOS), modulation techniques, frame capturing methods (global shutter (GS) and rolling shutter (RS) architectures), deployments of advanced techniques such as MIMO and the use of machine learning, standardization, performance constraints in synchronization, R_b, perspective distortion, flickering and dimming, and diversity, as well as their practical applications and use cases. Hence, a number of survey papers were established to address these aspects. Table 2 outlines a survey on OCC with major focuses and issues. It also categorizes missing points based on the categorization indicated previously.

Based on the analysis in Table 2, in this paper, we highlighted the major focus on OCC aspects that are already discussed in the surveys and pointed out the missing points that need to be highlighted. In addition to the indicated survey studies, several other studies have attempted to address more advanced aspects of VLC-OCC technologies. These include investigations into the integration of VLC-OCC with emerging technologies like the IoT, 5G/6G networks, and edge computing [5]. Additionally, studies have explored novel modulation schemes for high-speed and high-reliability data transmission, as well as the development of hybrid systems that combine OCC with other OWC paradigms [17].

Further research has been conducted on advanced image processing algorithms leveraging artificial intelligence and machine learning to enhance OCC performance, particularly in challenging environments with high mobility, NLOS conditions, and diverse lighting scenarios [18]. Moreover, recent studies have

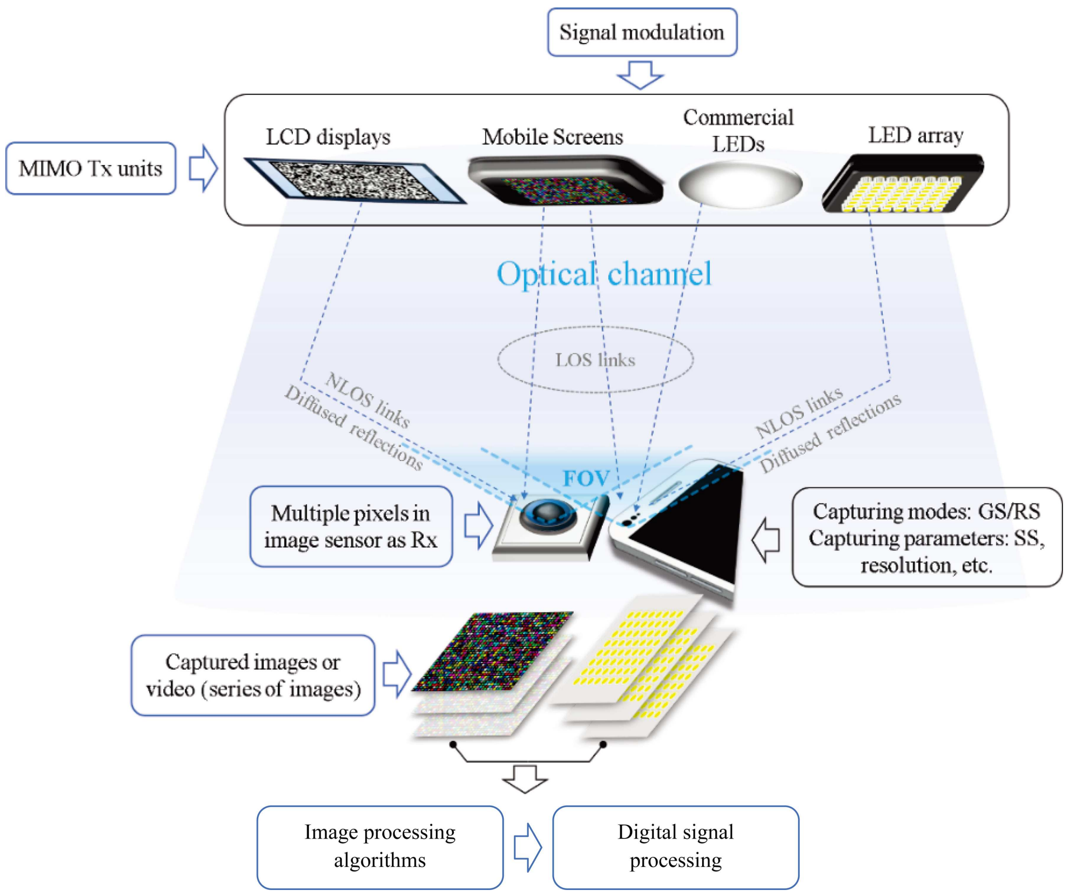

Figure 3 (Color online) General OCC concept.

focused on the practical deployment of OCC systems in real-world applications, such as autonomous vehicles, smart homes, industrial automation, and healthcare monitoring [31–37]. These studies emphasize the need for robust synchronization techniques, adaptive error correction methods, and energy-efficient designs to optimize OCC systems for large-scale, long-term usability.

It can be seen from Table 2 that the current literature is missing important discussions on topics such as marketing trends of smartphones and closed circuit television cameras which we covered in Section 2, OCC link channels (LOS, NLOS), modulation techniques, image processing and various OCC applications. Therefore, in the following subsections of this paper, we will examine the recent advancements made in establishing OCC-VLC communication, including imaging MIMO, LOS-NLOS OCC links, OCC capturing architecture, and noise in OCC.

2.1 Optical camera communication: concept

A general overview of the MIMO-OCC scheme is shown in Figure 3. Recent studies in this area have outlined the use of liquid crystal displays with multiple embedded neopixels [38], mobile phone screen [39] and LED-array [40, 41] together with commercial LEDs as MIMO Txs in applications such as vehicular communications [42]. In MIMO systems, the simple on-off keying (OOK) data formation could be used for intensity modulation of the Tx [19]. Alternatively, complex modulation schemes such as color intensity modulation (CIM) MIMO [43] and undersampled phase shift OOK (UPSOOK) [41] could be adopted to increase the data throughput. At the Rx, a range of CMOS technology-based cameras in the mobile phone (front/rear camera), digital single-lens reflex (DSLRs) cameras with higher capture speeds (ranging from 50 to 1000 fps) and surveillance cameras have been reported [42–44]. CMOS cameras can capture images or record videos in GS and RS modes at different shutter speed (SS) and resolutions. Data evaluation is performed using image processing tools in the software domain (i.e., MATLAB, OpenCV and Python) [45].

The camera-based Rx consists of an imaging lens, an IS along with a Bayer filter and an internal image

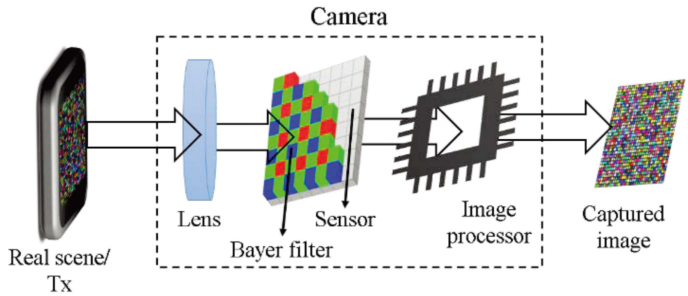

Figure 4 (Color online) Schematic of a digital camera.

processor, see Figure 4. The captured light passes through the focal point of the lens and onto the sensor surface. A Bayer filter on the sensor ensures that each pixel is sensitive to either of the primary colors (i.e., red, green, or blue (RGB)). Note, with no Bayer filter, the sensor only captures a monochromatic image [46]. By using the demosaicing method, the internal image processing creates a colored output image, which is the data image for OCC post processing [47].

$$R_b = \frac{1}{8} NM(\log_2 G) \text{ fps}, \tag{2}$$

where $N \times M$ is the size of IS in terms of pixels, G is the gray scale signal obtained from each pixel and fps is the R_f of the camera. Note, 1/8 is a rate reduction factor for 3D formats. For example, considering a 1000 fps QVGA (320 × 240 pixels) 256 gray scale IS, the maximum achievable R_b is 76.8 Mbps [48]. However, this is too large as each of the pixels in the IS should represent a unique data transmission, which is not practical due to long and varying transmission distance L between the camera and the Tx.

Moreover, the IS resolution with respect to the dimensions (either horizontal or vertical) is given as [49]

$$\text{IS}_{\text{Res}} = 2\left(\frac{\text{FOV}}{\text{smallest feature}}\right). \tag{3}$$

That is, the minimum required IS_{Res} equals twice the ratio of the FOV to the size of the smallest feature. To make an accurate measurement of the captured image, a minimum of two pixels per smallest feature is needed. For the FOV of 200 mm and the smallest feature to be captured is 2 mm, the required IS_{Res} is 200 pixels. Thus, a camera with a resolution of 640 × 480 pixels would be effective because 200 pixels is less than the smallest dimension, which is 480 pixels. In VLC-OCC, data evaluation is performed using image processing tools in the software domain (i.e., MATLAB, OpenCV and Python) [34].

OCC relies on image processing for demodulation of the received data in the form of captured image frames. Thus, robust and reliable image processing algorithms and schemes are essential. In recent years, artificial neural networks (ANN) have attracted considerable attention for solving complex problems related to image recognition using intelligent machine-learning techniques. ANN has been adopted to identify objects' shape in images, transcribe speech into text, match classified items and select relevant results of a search [50, 51]. The use of ANN equalizers in VLC along with image processing can result in high R_b by reducing the effects of inter-symbol interference (ISI) [52]. In indoor VLC-OCC links, a trained ANN can play an important role in motion detection (MD) [53].

2.2 Optical camera communication: capturing architecture

There are two types of camera sensors, i.e., a charge-coupled device (CCD) and CMOS. CCDs are not used in mobile devices (smartphones) due to their larger analog-to-digital converter (ADC) as compared to the CMOS sensors, which are most widely used. The major difference between the two sensors is the capturing modes, i.e., the shutter mode, where GS and RS are used in CCD and CMOS sensors, respectively, as illustrated in Figure 5.

In a GS-based camera the whole sensor is exposed to light, i.e., hold either ON or OFF state of an LED in a single frame [41], see Figure 5(b), whereas in an RS camera, the image is scanned row-by-row (i.e., line wise), where the scanning process is linked to the system clock and is limited by the sampling rate of the ADC. Pixel sensors within the camera continuously integrate the incoming light and each

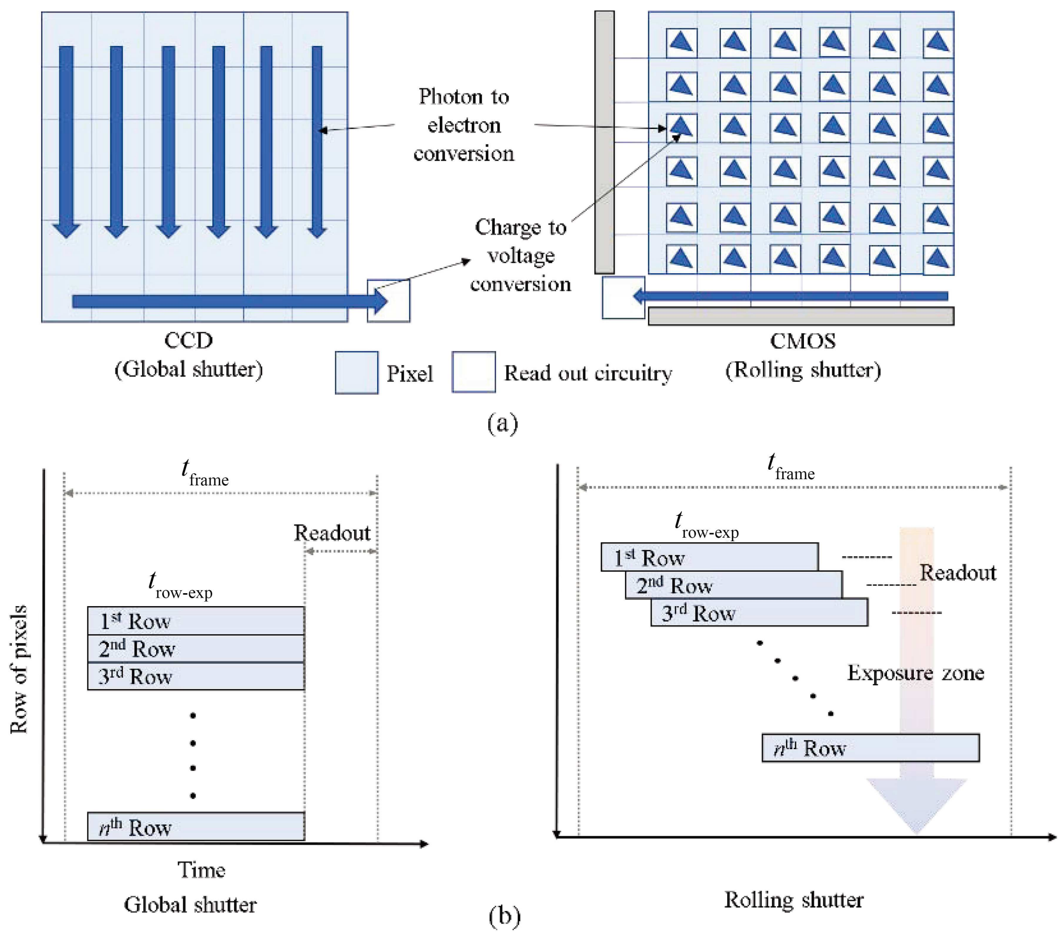

Figure 5 (Color online) (a) CCD and CMOS ISs and (b) GS and RS mechanisms.

row of pixels is exposed simultaneously at T_{exp}. Note, (i) the readout time protects the rows of pixels from overlapping, and (ii) in a single captured image, RS facilitates multiple exposures, enabling multiple incoming light states to be obtained at the same time in a single frame. In GS the image capturing and processing time is longer for the entire frame compared to RS. Therefore, CMOS is used in high-speed cameras with a capture rate beyond 1000 fps [54]. Therefore, RS-based cameras offer flicker-free OCC and relatively higher R_b compared with the GS-based cameras [55]. This feature of RS enables multiple LED states (ON/OFF) to be captured at the same time. Therefore, the captured image will contain a collection of black and white stripes if the LED flickers ON and OFF in accordance with the modulating binary bit stream [56]. The stripes' widths depend on the modulation frequencies, and the number of strips depends on the distance between the camera and the LED [55].

As the text above suggests, the role of specific camera configurations such as ISO, shutter speed, and aperture is critical in real-world applications. It is commonly expected that increasing gain (ISO) would degrade the SNR due to amplified noise. However, we have experimentally demonstrated that in highly attenuated conditions, increasing the analog gain can reduce the impact of quantization noise, thus improving the SNR [57]. Moreover, short exposure times are mandatory to use RS OCC effectively. In contrast, for global shutter cameras, longer exposure times can improve the SNR by integrating more light and reducing noise, as also analyzed in [13]. Additionally, a smaller aperture generally leads to lower light intake, reducing SNR, but it increases what is known as the depth of the field. Atmospheric aerosols, such as those present in polluted environments, can attenuate the received optical power. Nevertheless, scattering effects can magnify the projected ROI on the sensor, as reported by [58].

2.3 Optical camera communication links

2.3.1 *Line-of-sight OCC*

LOS communication is a fundamental aspect of VLC systems. LOS refers to the direct path between the Tx and Rx without any obstructions [59]. This direct path is crucial for maintaining high signal quality and minimizing interference [60]. In VLC systems, LOS communication ensures that the light signals are received with minimal distortion, leading to higher data R_b and improved reliability. The direct path with precise alignment between the Tx and the Rx ensures that the signals are received with minimal distortion, leading to clearer and more reliable communication [61]. This is essential for achieving high R_b and low bit error rates (BERs). However, this also means that any obstruction in the path can significantly degrade the signal quality. Therefore, maintaining a clear LOS is critical for the optimal performance of VLC systems [62].

LOS scenarios present several challenges, including interference from ambient light, strict alignment requirements, and the need for robust signal processing methods. Ambient light can introduce noise and distortions in the received signals, affecting the overall performance of the VLC system [63]. To address these challenges, various techniques such as optical filters, adaptive algorithms, and error correction methods are used to enhance the robustness of LOS communication [64]. LOS VLC systems have a wide range of applications, including both indoor and outdoor positioning and navigation, vehicle-to-vehicle communication, and augmented reality (AR) integration [65, 66]. In indoor positioning, LOS VLC provides high-precision location tracking, which is essential for applications such as asset tracking and indoor navigation [67]. In vehicle-to-vehicle communication, LOS VLC enhances automotive safety systems by enabling reliable and low-latency communication between vehicles [68]. For AR and IoT integration, LOS VLC offers immersive and interactive experiences by providing high-speed data transmission and low-latency communication [66, 69].

State-of-the-art performance metrics for GS and RS OCC systems are summarized in Table 3 [51,57,70–78], which presents the most relevant performance metrics of recently published LOS OCC systems (GS and RS). These systems have very different characteristics, features and target applications, but showcase the diversity of compromises that can be implemented under different constraints and by resorting to different subsystems (Txs, Rxs, and signal processing schemes). In the following sections, these metrics, constraints and subsystems are discussed, both for GS and RS OCC.

Performance of LOS GS OCC. Performance in GS-OCC systems is generally accessed by identifying the maximum data-rate for which communication is considered possible, i.e., with a BER below the FEC limit. This maximum attainable R_b depends on many system parameters, but is ultimately limited by the camera's R_f. Because most conventional commercial cameras today have 30 to 60 fps, most people consider GS-OCC to be restricted to low R_b applications. However, current professional or scientific digital CMOS GS cameras have maximum R_f over 100 Mfps [79], making the future much more promising for OCC as the technology matures. Moreover, high-performance OCC (HP-OCC) cameras have recently been proposed to overcome data-rate bottlenecks [75]. HP-OCC encompasses on-sensor edge processing, dynamic resource allocation on the edge, a frameless sensing principle, and seamless pixel switching to achieve up to 6 Mbps of throughput per pixel, which is comparable to other state-of-the-art OWC techniques.

For a given camera fps, throughput can be further increased by exploring the amplitude and color dimensions, taking advantage of multi-level and multi-wavelength signaling, respectively. The performance is then limited by the Rx's noise, interference, distortion and uncertainty in sampling the state of the light source. These effects are directly related to camera parameters, the most relevant of which are the dynamic range (bit-depth) and the exposure time T_{exp}. While the bit-depth impacts noise levels, the exposure effect impacts conversion speed, distorts received waveforms and introduces ISI, leading to decreased OCC reliability [70]. Added to this, OCC is further impacted by synchronization problems [37] non-linear response, blooming effect, and extinction ratio [80], which has pushed researchers to propose increasingly complex modulation, coding and decoding schemes, based on traditional and learning-based algorithms, most of which can be applied with minor variations to other OWC schemes [72].

Amplitude and color dimensions can also be explored in PD-based VLC, with similar challenges, but OCC can further take advantage of the IS spatial degrees of freedom, enabling MIMO, quadrature-amplitude-modulation (QAM), and orthogonal frequency division multiplexing (OFDM) solutions to be explored. Authors in [81] demonstrate a 7.76-Mb/s LOS OCC system, using a CMOS-driven micro-LED projector and a high-speed camera, with a BER of 7.9×10^{-4}, over a few centimeters. 4-pulse amplitude

Table 3 Performance of LOS OCC.

Ref.	Camera	Shutter	Throughput	R_f	Chans.	Mod.	Range	Mobility
[70]	HP-OCC	GS	294 Mbps	n.a.	49	OOK	Medium	1.5 mps
[71]	CMOS	GS	7.76 Mbps	80 kfps	100	4PAM	<5 cm	NO
[72]	CMOS	GS	1.92 kbps	60 fps	48	OOK	20 m	NO
[73]	CMOS	GS	500 bps	50 fps	2	1024QAM	1.5 m	NO
[74]	CMOS	GS	30.72 kbps	30 fps	16×3	4QAM	3 m	3 mps
[51]	CMOS	GS	3.84 kbps	60 fps	54	OOK	2 m	10 mps
[75]	CMOS	GS	38.4 kbps	15 fps	52	OOK	1 m	NO
[76]	CMOS	RS	250.96 kbps	30 fps	8	8PAM	10 cm	NO
[57]	CMOS	RS	2.4 kbps	30 fps	1	OOK	4.5 m	NO
[77]	CMOS	RS	960 bps	30 fps	16×3	OOK	1 m	NO
[78]	CMOS	RS	500 bps	25 fps	1	OOK	1.5 m	NO

modulation (PAM) signals are applied to 100 individual pixels, captured by a high-speed camera operated at R_f of 80 kfps. Considering a commercial smartphone camera with R_f of 960 fps, a R_b of 12.58 Mb/s can be potentially realized. Other researchers focused their efforts on increasing the attainable distances and demonstrated an MIMO OCC system operating up to 20 m with a R_b of 1.920 kbps, using an 8×8 LED array [74]. With a simpler 2 LED Tx, authors in [73] experimentally demonstrated a 1024-QAM GS-OCC system to achieve a R_b of 500 b/s using a 50 fps commercial camera over L of 1.5 m. Because they use a low R_f camera, special techniques were required to enable flicker-free data transmission, such as undersampled QAM subcarrier modulation (UQAMSM). In [71], the color dimension was combined with the spatial dimension to implement a 4-QAM OFDM modulation scheme, where each LED represents a different transmission channel through specific colors. The system was evaluated at a speed of 2 and 3 m/s over various distances, achieving R_b of 30.72 kbps, over 16 LEDs, and a minimum BER of 10^{-4} with a 30 fps camera.

A significant advantage of GS-OCC over RS-OCC is the ability to capture accurate images in medium to high mobility scenarios. In [51], authors describe a real-time LOS GS-OCC MIMO system that can communicate in high mobility conditions, for indoor environments. They use an 8×8 LED array in the Tx and advanced image processing (machine learning models and adaptive algorithms for LED detection and segmentation) to offer high data rates with a low fps camera (60 fps). The system is validated with camera movement speeds of up to 10 m/s at 2 m, achieving a BER of 10^{-2}. In [82], the color dimension is further explored in an 8×8 LED array, combined with LIDAR distance information, to enable both point-to-point and bidirectional communication in mobile environments, avoiding the typical broadcast fingerprint of OCC. The bidirectional communication demonstrated a R_b up to 38.4 kbps and a BER of 0.03. These state-of-the-art performance metrics are summarized in Table 3.

Performance of LOS RS OCC. In OCC, the RS mechanism in CMOS cameras enables data transmission by encoding information in spatially varying light intensity captured as strip patterns [31]. Under LOS conditions, this mechanism excels by capturing uninterrupted, well-defined patterns, leading to higher R_b [83]—as the RS can detect rapid changes in light intensity, LOS conditions ensure minimal data loss and support higher R_b; and improved SNR [32]—direct LOS minimizes interference, enabling cleaner signal detection. Unlike RF-based communication, OCC usually relies on the direct propagation of VL signals between the Tx (e.g., LEDs) and the Rx (i.e., a camera).

The most commonly used light source in OCC systems is the LED, valued for its ability to rapidly modulate light intensity, which is crucial for transmitting data [84]. Beyond single LEDs, LED arrays and LED strips are frequently employed to enhance R_b and increase spatial resolution by encoding multiple signals simultaneously across different regions of the light source [85]. These configurations are particularly advantageous in scenarios requiring high throughput or wide-area coverage, such as digital signage or vehicle-to-vehicle communication [86]. Additionally, innovative solutions like LED-coupled side-emitting optical fibers extend OCC applications to flexible and wearable designs, enabling light emission along curved paths or edges [87]. Screens, such as those found in smartphones, tablets, or PC monitors, are another versatile light source, capable of transmitting data by modulating pixel brightness or color [88].

Recent advancements in OCC have demonstrated diverse approaches and applications, significantly pushing the boundaries of performance. In high-speed OCC, a record throughput of 250.96 kbit/s was achieved through a R_f adaptive fractionally spaced equalization algorithm, effectively mitigating ISI and timing offsets [76]. OCC has also shown potential in outdoor environments. For instance, an OCC-based wireless sensor network was implemented in a farm-like setting with scalable, low-cost communication over a 100 m range at R_b of 7.5 bps, showcasing its feasibility for agricultural applications [57]. Similarly, indoor experimental setups have demonstrated reliable performance for health monitoring and IoT applications. In one study, a single white LED transmitted electroencephalogram (EEG) data over an LOS link to a smartphone, achieving error-free R_b at 2.4 kbps with a power consumption of 3 W over a 4 m range [89]. Another setup using a 4×4 RGB LED panel transmitted vital sign data with a low BER of 1.2×10^{-4} at a rate of 960 bps over 1 m using an RS camera [77]. Furthermore, color shift keying has emerged as a promising modulation technique, enabling efficient data encoding and enhanced R_b [90, 91].

Maintaining LOS in OCC systems poses several challenges. (i) Alignment sensitivity [78]: even slight misalignments between the light source and the camera can lead to partial signal capture or complete failure; furthermore, the limited angular field-of-view of standard CMOS sensors and/or any obstruction or misalignment can disrupt the RS effect and reduce the system's efficiency. (ii) Motion artifacts [92]: when either the Tx or the Rx is in motion, maintaining LOS becomes difficult, leading to distortions in the RS pattern. (iii) Ambient light interference [17]: strong ambient light can interfere with the modulated light signal, making LOS communication more susceptible to noise. This dependency on the LOS path differentiates OCC from other VLC methods, where PDs can sometimes be used in NLOS OCC links, albeit at reduced R_b [93].

Overall, when comparing RS and GS-based OCC, RS-based OCC achieves higher data rates by exploiting the line-by-line scanning method, and embedding several symbols per image; however, this requires a combination of short link distances, large transmitter areas, and long focal length optics to ensure the ROI covers a substantial portion of the FOV (at least, in the scanning direction of the IS). This necessity, combined with the lower exposure times required, limits the simultaneous capture of multiple transmitters or environmental features (video monitoring). On the other hand, GS-based OCC, while offering much lower achievable data rates, works effectively with smaller transmitters, longer link distances, and short focal lengths, enabling a wider FOV and the simultaneous communication and video monitoring [51, 81, 85].

2.3.2 *Non-line-of-sight OCC*

OCC-based ITS can be categorized into LOS and NLOS configurations. LOS-based OCC has been extensively investigated in the literature. However, in some scenarios, Txs may not be within the FOV of the LOS path or LOS paths may be blocked, thus the need for transmission via NLOS paths. The following are some examples of NLOS-based VLC-OCC links.

(1) Supermarkets—LOS paths being blocked by the shelves.

(2) Offices and homes—LED lights not covering all parts of an indoor environment, shadowing and blocking.

(3) Pedestrians—LOS access to cars and street lights being blocked at crossroads.

In NLOS links, reflected lights normally have a large illumination footprint, thus offering an increased level of mobility and link tolerance to the Rx's (i.e., cameras) positions but at the cost of reduced received optical power level at the Rx, i.e., lower SNR and, therefore, higher BER and higher levels of inter-channel crosstalk. Note that NLOS OCC links offer a lower probability of outage, improved reliability and the quality of service, as well as enhanced flexibility in lighting fixtures.

In order to reduce the impact of channel crosstalk, different multiple access/multiplexing techniques have been proposed in OCC. In [37], an RS camera and Manchester coding were employed to avoid flickering while capturing the reflected lights from the floor surface. Frequency shift keying was adopted in [46] for an RS-based OCC using reflected lights from surfaces. R_b of 10 bps was achieved using a camera with R_f of 30 fps for an MIMO system in an indoor environment. However, this approach is not efficient for OCC in terms of the bitrate. A long-distance RS-based OCC approach was proposed in [39], which was based on the reflections from the floor surface at L of 1.5 m. Multi-level illumination [11] and Manchester coding with variable pulse widths are other techniques that are used in NLOS RS-based OCC. A novel spatial multiplexing scheme for NLOS RS-based OCC with PSK was proposed in [41], where R_b of 4.5 kbps was achieved at L of 1 m.

In [30], a $2 \times N$ NLOS OCC system with a small overlap illumination region was proposed for street light-to-vehicle communications. It was shown that, for an overlap area above a certain level the information could not be extracted. Hence, in scenarios where the overlap region increases provided all the lights

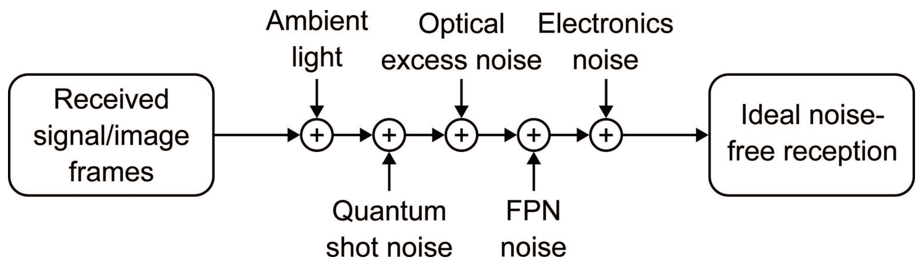

Figure 6 Noise sources in OCC.

transmit data simultaneously, then the information cannot be retrieved successfully. In [43], a space- and time-division multiplexing was proposed for NLOS OCC with large overlaps of the illumination footprints. However, using time division multiplexing (TDM) the system throughput is reduced [44], more specifically in areas with a large number of light sources. In this situation, since the camera R_f is low, selecting TDM as a multiple access technique is not the most efficient option. In addition, in cameras the IS, which is a massive matrix of PDs, channel inversion (CI) can be used, while the channel access is based on space division multiplexing (SDM). In [45], two algorithms based on CI are used for NLOS MIMO OCC systems for interference cancellation and for extracting the payload in the presence of gamma correction, noise, and interference. The CI-based algorithms are proven to tolerate higher levels of interference compared with hybrid selection/equal gain combining.

In order to alleviate the limitation of the LOS requirement, reconfigurable intelligent surfaces (RIS) are adopted as a viable solution that allows to redirect the impinging beam toward the PD in case of blockages. RIS for OWC is taking place as a cutting-edge technology, thanks to its several benefits [94]. Indeed, RIS can dynamically adjust the reflection angle and intensity of light, focusing on the optical signal toward the camera-based Rx. This ensures a stronger and more reliable signal, even in NLOS conditions or areas with obstructions. As a result, by controlling the light reflection and scattering, RIS can help minimize interference from the ambient light or other OCC Txs. Also, RIS can enable signal propagation to areas where transmission via LOS paths is challenging, increasing the system's spatial flexibility, and extending the coverage area of OCC by reflecting light beams to previously unreachable locations, such as shadowed regions or around obstacles.

Traditionally, RIS is comprised of tunable low-cost nearly passive reflecting elements that can be strategically deployed to control the propagation environment. Each RIS element can be configured individually, and in real-time, to induce controllable manipulation of incident signals. For OWC, the use of mirror-arrays is largely adopted; they are made of glass with a flat or curved surface and a reflective coating, which allows only reflections of the impinging optical signal. Each mirror is equipped with a mechanical control system to move the mirrors according to specific yaw and roll angles.

3 Optical camera communications: technical challenges

3.1 Noise sources in OCC

The noise in ISs for photography can be categorized as either temporal or spatial noise. The spatial noise is known as the fixed pattern noise (FPN), see Figure 6. In a CMOS IS, FPN in dark conditions is mainly due to the dark current non-uniformity, whereas under illumination, it is a result of the gain variation of the active transistors inside each pixel. The number of dark current charges can be calculated via [95]

$$\sigma_{\text{dark}}^2 = \frac{I_{\text{dark}} T_{\text{exp}}}{q}, \tag{4}$$

where I_{dark} is the dark current produced in the PD, T_{exp} is the exposure time, and q is the electron charge.

The main temporal noise sources in an IS are thermal noise, photocurrent shot noise, and flicker noise.

(1) Thermal noise in a camera mostly occurs in the form of readout and reset noise and is a result of thermal agitation of electrons in the resistance of the circuits in a Bandwidth of B. The variance of the

thermal noise can be calculated as follows [95]:

$$\sigma^2_{\text{thermal}} = 4KTB\left(R + \frac{1}{4C} + \frac{\overline{\boldsymbol{\varpi}}}{g_m}\right), \tag{5}$$

where K is Boltzmann's constant, T is the temperature in kelvin, R is the resistance, C is the capacitance at the reset gate, g_m is the transconductance of the MOS transistor, and $\overline{\boldsymbol{\varpi}}$ is a coefficient, which depends on the modes of the MOS transistor operation.

(2) Photocurrent shot noise occurs mainly due to the stochastic nature of the photo conversion process in the PD. The probability that N_e number of photoelectrons released in a T_{exp} time interval has a Poisson distribution with a mean of $\overline{\boldsymbol{N_e}}$ is [95]

$$P_{Ne} = \frac{\overline{\boldsymbol{N_e}}^{N_e}\exp(-\overline{\boldsymbol{N_e}})}{N_e!}. \tag{6}$$

Hence, the variance of the photocurrent shot noise $\sigma^2_{\text{thermal}} = \overline{\boldsymbol{N_e}}$.

(3) In MOS transistors, there is another source of noise called flicker noise (also referred to as $1/F$ noise) and is calculated via [96]

$$v^2_{1/F} = \frac{K_F}{C_{ox}W_{\text{mos}}L_{\text{mos}}}\cdot\frac{\Delta F}{F}, \tag{7}$$

where K_F is a constant which depends on the device parameters such as transistor size, F is the frequency, ΔF is the bandwidth, and C_{ox}, W_{mos}, and L_{mos} denote the gate capacitance, width and length of the MOS gate, respectively.

In addition to intrinsic sensor noise sources, the image signal processing (ISP) pipeline introduces additional distortions relevant to OCC. As detailed by Cossu et al. [97], JPEG encoding acts as a nonlinear low-pass filter, attenuating high-frequency content and introducing quantization noise. Furthermore, gamma correction nonlinearly alters the pixel intensity values, leading to harmonic distortion in the frequency domain. These ISP-induced effects can reduce the effective bandwidth and degrade the SNR of the received OCC signal. Therefore, even under constant optical conditions, image compression may significantly impact OCC performance.

For the intensity modulated LOS transmission link, the received signal is given by [98]

$$y(t) = \eta x(t) \otimes h(t) + n(t), \tag{8}$$

where $x(t)$ is the intensity modulated signal, $h(t)$ is the combined impulse response of the channel and camera, η is the quantum efficiency of the IS, $\otimes$ is the time domain convolution, and $n(t)$ is the additive white Gaussian noise including the ambient light induced shot noise and the noise in the camera i.e., fixed pattern, thermal, photocurrent shot (optical excess and electronics), and flicker noise sources [99], see Figure 6. Note, we utilize a part of the image for data processing. Therefore, these noise sources can be reduced and have minimal effect on the received signal.

If the definition of power is scaled by the number of points in the signal, it will give the mean squared error (MSE). This notion can be extended in OCC for actual transmitted and received images by summing up twice the rows and columns of image vectors or stretching the entire image into a single vector of pixels and applying the 1D definition. Therefore, in OCC signal images, the SNR can be given as [99]

$$\text{SNR(dB)} = 10\log_{10}\frac{\Sigma_{m=1}^{W}\Sigma_{n=1}^{H}I_{Tx}(m,n)^2}{\Sigma_{m=1}^{W}\Sigma_{n=1}^{H}[I_{Tx}(m,n) - I_{Rx}(m,n)]^2}, \tag{9}$$

where $I_{Tx}(m,n)$ and $I_{Rx}(m,n)$ denote the intensity of the pixel of the transmitted and received image frames, respectively, at the location (m,n). In (9), $[I_{Tx}(m,n) - I_{Rx}(m,n)]^2$ corresponds to the squared error between the original and corrupted signals as $\left|y(t) - x(t)\right|^2$. The size of the image is $W \times H$. High values of SNR show that the estimation error is small and, therefore, among various image fusion methods, the ones that exhibit higher SNR values can be considered to improve performance. The peak SNR (PSNR) and the MSE are measured similarly to the SNR, which are defined as [100, 101]

$$\text{PSNR(dB)} = 10\log_{10}\frac{I^2_{\text{peak}}}{\text{MSE}}, \tag{10}$$

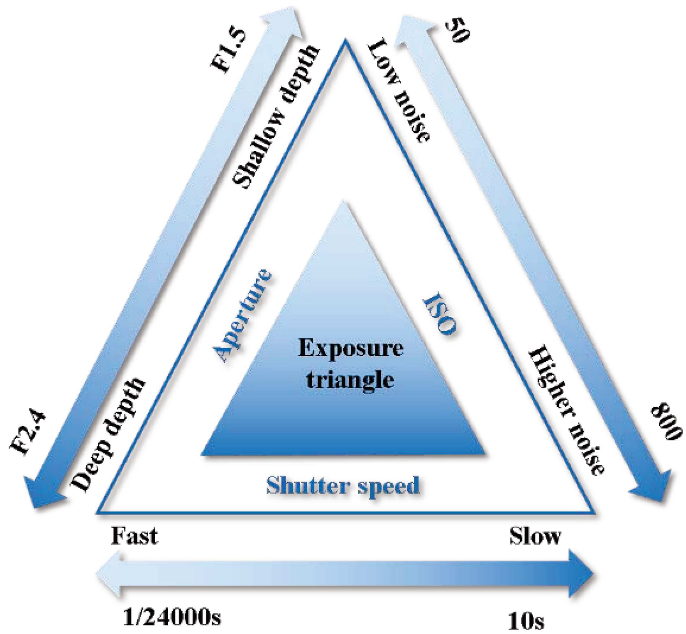

Figure 7 (Color online) Camera exposure triangle.

$$\mathrm{MSE} = \frac{\Sigma_{m=1}^{W}\Sigma_{n=1}^{H}[I_{Tx}(m,n) - I_{Rx}(m,n)]^2}{N_{\text{column}} \times N_{\text{row}}}, \tag{11}$$

where I_{peak}^2 denotes the squared peak intensity of the measured frame, and N_{column} and N_{row} are the number of columns and rows of the images, respectively. In PSNR, the key parameter is I_{peak} of the measured frame, which determines the signal bandwidth or number of bits to represent the signal. Therefore, the major issue is how the high-intensity regions of the image will be affected by the noise. This is much more content-specific than the SNR, which can be adopted in many applications, such as image compression.

3.2 Exposure triangle for camera capturing

There are a number of image processing techniques that can be used in OCC including (i) image acquisition, enhancement, segmentation, and histogram, (ii) image pattern detection (shape, size, etc.), (iii) image transform and filtering (i.e., noise), and (iv) image data compression and decompression. In order to understand the image capturing process, the focus should be on the exposure triangle [102], as shown in Figure 7. T_{exp} sets the amount of light that reaches the IS, which determines how light or dark an image will appear. Note, too much light captured will overexpose (too bright/no details) images resulting in the blooming effect, while less light results in underexposed (dark/grainy/less details) images. The blooming effect means that the number of photons reaching the detector exceeds its maximum capacity, and the excess photons will either spill and merge to adjacent pixels or are not counted, thus leading to non-precise intensities [103]. The camera's exposure is based mainly on three camera settings: aperture, ISO and SS [104, 105], as shown in Figure 7.

A camera's SS is typically measured in fractions of a second. Slow SS allows more light incident and is used for low-light and night photography, while fast SS helps to freeze [104, 105]. The aperture or also called as f-stop controls the amount of light being captured through the lens as well as controls the depth of field, which is the portion of a scene that appears to be sharp. Note that for very small and large apertures the depth of fields is large and small, respectively. In photography, the aperture is expressed by F number (i.e., the focal ratio), which represents the ratio of the diameter of the lens aperture to the length of the lens [104, 105]. Higher ISO (i.e., sensitivity of camera) means faster light absorbed by the IS, but at the cost of increased noise level.

The choice of exposure time, ISO and aperture is critical for OCC signal fidelity, and needs to be considered along with the encoding and non-linear effects applied by the subsequent ISP pipeline that is applied to the image signal after capturing. As shown in [97], shorter exposure times lead to higher bandwidth and better temporal resolution, which is essential for capturing signals in RS-OCC. However, increasing ISO to compensate for shorter exposure introduces amplified noise and may trigger nonlinear effects due to the camera's gamma correction.

3.3 Data rate enhancement and equalization in OCC

As OCC captures data in the form of images, the modulated bit streams can be carried by either color, intensity and spatial coordinate. Unlike PD-based VLC systems, which capture only the intensity of light, OCC captures multiple colors simultaneously due to the employment of the Bayer filter along with spatial separation of multiple Txs because of its 2D coordinates in the image. Furthermore, an image also contains another interesting feature, i.e., the shape, which can be interpreted differently. Therefore, based on the carrier for the modulated bits, the OCC data can be modulated through the entities of color, intensity, spatial coordinate, and shape.

As mentioned above, low R_b of OCC is due to the low R_f of the camera, typically 30 or 60 fps. Several methods have been proposed to enhance R_b, including equalization, MIMO, and complex modulation schemes. In [106], an OCC system utilizing RS and colour shift keying was investigated achieving R_b up to 5.76 kbps, whereas in [107] PD-based VLC employing multi-pixel photon counters was demonstrated with R_b of 18 Mbps [107]. An OCC system utilizing color pulse width modulation and pilot-aided demodulation has been investigated to enhance R_b to 7.2 kbps over 2 m as well as mitigate ISI [59, 108]. PAM is also a popular scheme used in OCC to increase R_b, e.g., up to 10 kbps with a 30-fps camera [109, 110]. However, generating a complex modulation scheme requires a digital-to-analogue converter (DAC). In [111], a superimposed PAM technique was proposed, which relaxed the need for a DAC and achieved R_b of 16 kbps. An MIMO system employing an array of 88 LEDs was introduced in [17] to achieve R_b of 13.44 kbps. On the other hand, to exploit the full bandwidth of RS-based OCC, equalizers have been used to mitigate the slow rise time of the signal due to long T_{exp}. The study in [17] has described OCC modulation schemes in five different categories of Nyquist sampling-based modulation (NSM), high-framerate NSM, RS-based OCC, region-of-interest (ROI) signaling and hybrid camera-PD modulation. These categories mainly depend on the tight relation between the parameters of Txs and the limitations on the camera-based Rx (i.e., the limited fps). Table 4 [17, 19, 21, 29, 53, 55, 109–117] gives an overview of recent advancements in OCC modulation schemes.

Using a high-speed camera Rx, NSM can be further implemented for high-framerate NSM-based OCC schemes. Using a high-framerate NSM the modulation frequency can be >200 Hz (i.e., a maximum flickering time) [113]. A space shift keying (SSK) and hierarchical rate adaptation techniques with a 1000 fps high-speed camera were proposed in [118] for long range communications, see Table 4. However, high-speed cameras are costly and are not commonly used in smart devices. In order to implement flicker-free communications, OCC takes advantage of the high-sampling rate of the RS mechanism, which sequentially exposes pixel lines to the incoming light [17]. Note, RS-based OCC offers flicker-free transmission for both LOS [113] and NLOS [116] links. Moreover, RS-based OCC systems using MIMO and combination of UPSOOK and wavelength division multiplexing (WDM), and multilevel intensity modulation have been investigated for long range and high-speed, respectively [55, 115]. To reduce the overall processing time on the Rx side, a smaller portion of the image containing only the Tx, i.e., ROI, needs to be determined. Since processing is carried out for a much smaller portion of the image, the processing time is considerably shortened and the efficiency of the image processing can be increased. This technique is useful to detect the exact Tx image captured in the outdoor scenarios that contain many other noise sources. A spatial 2-phase shift keying (S2-PSK) was developed considering the spatial separation capacity of the camera to fully decode a bit within a randomly sampled image [117].

For high-rate data streams, single-carrier modulation or multiple-carrier modulation, such as hybrid-spatial-PSK (HS-PSK) or variable pulse-position modulation (VPPM) [114], can serve as viable solutions. An alternate form of the ROI sampling modulation, termed as selective capture, was also proposed for pre-processing to shorten the frame capture period in a study and produce the overall higher efficiency [53]. A hybrid camera-PD-based link was proposed in, where the IS consists of both pixels for image capture and PD cells specifically for communications. The hybrid scheme can achieve a huge B of up to 10 MHz due to the use of PD cells within the IS. On the other hand, in [27] a hybrid VLC-OCC link using both PD and camera-based Rx was demonstrated to receive light signals from the same Tx simultaneously. Hybrid modulation formats such as multilevel OOK intensity shift keying (ISK) and Manchester coding over VPPM have also been investigated to provide low-rate OCC R_b ranging from 1–4 kbps and high-rate

Table 4 Overview of recent advancements in OCC modulation schemes.

Group	Modulation schemes	Ref.	IS	Flicker-free	R_b (kbps)	L (m)
NSM	OOK	[21]	GS	No	0.24–1.28	0.3–2
	DC-biased optical OFDM (DCO-OFDM) for vehicle-to-everything	[55]	GS	Yes	55×10^3	60
	CIM	[112]	GS	No	11.52–317.3	0.2–1.4
	Cell modulation	[19, 109]	GS	No	0.48–112.5	0.1–1.2
High R_f NSM	SSK	[110]	GS	Yes	1	30
	Hierarchical rate adaptation	[111]	GS	Yes	42.7	65
RS-based OCC	OOK for NLOS-MIMO space and time division multiple access	–	RS	Yes	1	10
	Rolling OOK	[17, 113]	RS	Yes	0.896–2.88	0.1–0.25
	Multilevel IM	[29]	RS	Yes	>10	2
	Rolling UPSOOK	[113]	RS	Yes	0.15	60
	Combination of UPSOOK-WDM and MIMO scheme	[29]	RS	Yes	0.15	60
ROI signaling	S2-PSK	[113]	GS	No	0.01	1.5
	HS-PSK and VPPM	[114]	GS	Yes	0.03	100
	Selective capturing	[115]	GS	No	6.9	1.75
Camera-PD	Manchester coded optical communication image sensor (OCI)	[116]	GS	Yes	10×10^3	7.7
	Optical-OFDM OCI	[117]	GS	Yes	55×10^3	1.5
Hybrid VLC/OCC	Hybrid multilevel OOK-ISK	–	RS	Yes	4.2 (OCC), 2.75×10^3 (VLC)	3
	Hybrid Manchester coding and VPPM	[53]	RS	Yes	1.67 (OCC), 100 (VLC)	5.8

VLC R_b from 100 kbps to 2.75 Mbps over a range of R_b, see Table 4.

Some practical constraints for real-world deployment of hybrid camera-PD links and advanced modulation techniques include limited access to low-level camera controls in mobile devices (e.g., exposure time, analog gain), inconsistent rolling shutter timing across devices (it depends on the IS), and processing overhead for real-time ROI detection and signal demodulation. Commercial devices have not adopted any OCC functionalities, making it challenging to deploy OCC currently [27, 85, 116].

The data rate in the RS-based OCC is prone to the pixel clock, $T_{\rm exp}$ and R_f of the camera. The pixel clock and camera R_f directly depend on the IS technology. However, $T_{\rm exp}$, which can be controlled through the user interface, defines the bandwidth of the IS in RS cameras. That is in the course of capturing a frame, the camera applies a moving average filter, with a width of $T_{\rm exp}$, to the signal. Therefore, the shorter $T_{\rm exp}$, the higher the bandwidth. However, a short $T_{\rm exp}$ imposes a low SNR and thus higher BER. ANN can be used for R_b and L enhancement, improving image processing and pattern recognition and equalization. In [113], an ANN-based equalizer was proposed for RS-based OCC, which improved the bandwidth of the system nine times to 12 kbps employing a 30-fps camera at a relatively long $T_{\rm exp}$. The proposed method involves a single-time camera calibration and the network can be stored as a look-up table in the camera. ANN-based Rxs can be used for classifying the transmitted symbols separated from the interferences. In addition, this approach enables an intelligent OCC, i.e., using a learning computer vision algorithm to achieve more efficient hybrid VLC-OCC-RF communications, as well as enhances the functionality of OCC to support motion, illumination and communication simultaneously. OCC also enables the development of modulation schemes utilizing unique information from the camera sensor, i.e., shapes, depth (acquired from focus), inter-frame relation and diffused reflection, which is similar to multipath propagation in RF systems. Note that the hardware requirement for building an ANN is adequately provided through recent electronics advances in smart devices.

4 Applications of OCC based IoT and/or 5G and updates to IEEE standard

Camera employing a large array of PDs is a suitable option for an MIMO Rx. The recent advancements on digital displays for TVs, mobile phones, laptops and advertisement boards enabled data transmission through massive MIMO in OCC. The data transfer can be either encoded in patterns such as QR codes or embedded in different images/frames of a video. In [119], a novel detection technique was introduced to achieve R_b of 100 kbps in smartphone display to smartphone camera communications. The advancements in the micro-scale LED (μLED) arrays opened a gate to a global market with a size of $120 million in 2018 and expected to reach USD $53.1 billion by 2025 [4]. μLED arrays offer compact size/high resolution Txs with a significantly higher bandwidth compared to regular LED arrays. In [120], a transmission and a detection technique were introduced to achieve R_b of 122.88 kb/s using a 16×16 micro-LED array and a 960 fps. The other method to transmit information with digital displays is embedding information in pictures, also known as steganography, which is discussed below.

4.1 Positioning

One important application of OCC is on positioning systems. Positioning systems play a key role in modern communications systems, for instance advanced 5G and 6G systems required to know the position of the users to estimate the channel conditions [121]. VLC/OCC-based positioning systems are low cost, have high accuracy (in the range of tenths of cm) and promote the dual usage of LEDs (as reference beacons and normal lighting). OCC-based estimation relies on the estimation of the camera pose. The estimation process relies on two inter-related coordinate systems, the camera coordinates and the world coordinates. Conventional methods employ linear least squares with triangulation algorithms, such as the studies reported in [122, 123]. More advanced methods employ machine learning algorithms such as ANNs [122] to perform this task. Another approach relies on CNNs to classify the patterns received by the OCC Txs and the projective N-point algorithm to estimate the pose [124]. Combination of OCC and standard PDs has been proposed to estimate 3D positioning, where the camera is used to estimate the angle of arrival and the PDs to estimate the received power [125]. The combination of both methods plus a compensation scheme based on single view geometry for situations where the PD distance from the camera is not negligible as proven as a valid approach to accurately estimate 3D position within a room. Another important aspect of position estimation is the orientation of the receiving device, that is, the camera. Combined position and orientation can be estimated using projective geometry and the projective N-point method, such as in [126]. Recently, more sophisticated applications have started relying on OCC for position estimation, such as the case of pedestrian dead reckoning [127], where multiple sensors are used for pose estimation (gravitational sensors), motion direction (gyroscope), step detection (acceleration sensors) and position estimation (relying on OCC). Advanced machine learning methods are used for pose analysis (CNNs) and step length estimation (Long-Short term memory).

Current challenges on OCC-based positioning include (a) camera blockage effects—obstacles may block the camera FOV preventing the correct identification of some of the beacons; (b) complex room configurations— usually the standard assessment of the system performance assumes an empty room [128] and this does not correspond to a real working scenario, where the existence of furniture may hinder optimal performance [129]; (c) frame recovery—it is normally assumed that the beacon identifier can be retrieved in a single camera frame. But depending on the distance between the camera and the beacons, the complete identification may occur distributed between frames [130]; and (d) calibration of the world coordinates—another usual assumption is that the world coordinates are known with absolute precision, so that the position error can be easily evaluated. However, in real-world scenarios, this is not usually true, which will turn the problem of evaluating the position error into a complex one.

In [129] it has been shown that frame drops or partial blockage can lead to positioning errors exceeding 30–50 cm in indoor scenarios, while robust ROI detection under room clutter and dynamic occlusions remains an open challenge for practical deployments. Furthermore, the requirement of maintaining a stable visual line-of-sight to the transmitters significantly constrains OCC positioning accuracy compared to alternative methods [130].

With the rapid development of the IoT [131], location-based services (LBS) are becoming increasingly important, especially in indoor environments (i.e., homes, supermarkets, factories, etc.) [132], where RF-based global positioning systems (GPS) do not perform well since signals are easily obstructed [103]. Therefore, several indoor positioning systems (IPSs) based on different wireless technologies have been proposed, including wireless local area network (WLAN) [133] and Bluetooth [133], which are based on creating and maintaining a radio map frequently [7], RF identification (RFID) [134], ultra-wideband (UWB) [135], and VL [136]. UWB-based PSs have high accuracy but at high costs and are affected by multi-paths [137]. Visible light positioning (VLP) offers high accuracy at lower costs compared to the RF-based PSs [138].

Furthermore, UWB provides robust performance under NLOS conditions and typical accuracies below 30 cm, but at a higher hardware and deployment cost [135]. VLPs are also immune to RF-induced electromagnetic interference, use a free and unrestricted spectrum, and offer a much higher level of security at the physical layer [139, 140]. These features have made VLPs one of the potential candidates for use in various indoor scenarios.

In VLPs, the location information of the beacon is received via VLC links [141]. In VLPs, both PD- and IS-based Rxs as well as hybrid PD-IS could be used [142–144]. Hybrid PD-IS systems, while combining high temporal resolution and spatial selectivity, often require dedicated hardware and are less scalable with consumer devices compared to OCC [116]. In [142], system architectures and algorithms based on type of Rxs (i.e., PD or IS) with auxiliary sensors were classified, whereas in [143] positioning algorithms and hardware structures were outlined. In [144], a new taxonomy method for VLP algorithms classified into three categories of mathematical, sensor-assisted and optimization was considered. For IS-based VLP system architecture, usually an indoor environment (e.g., a room, an office, or a supermarket) fitted with multiple LEDs for lighting purposes is considered and is modelled using a cube-shaped room as shown in Figure 8(a). In Figure 8(a), three LEDs are deployed on the ceiling and a device equipped with an IS-based Rx is located above the floor level facing the LEDs. Generally, a world coordinate system (WCS) is used, which is first set to express the absolute coordinates of each space point. In most VLPs floor plans, i.e., the X-Y plane, is used in an upward direction perpendicular to the X-Y plane as the positive direction of the Z-axis. The origin O of the coordinate system is generally selected at the vertex of the X-Y plane. Figure 8(b) depicts the general architecture of IS-based VLP. At the Tx, the LED coordinates are coded and used for intensity modulation of LEDs via a microcontroller and an optical driver. At the Rx, an IS captures the VL from LEDs followed by image and signal processing to obtain the world coordinates of LEDs and the pixel coordinates of its projection points on the image-by-image processing. Next, the location algorithm is used to estimate the coordinates of IS in WCS using information from the auxiliary sensors.

Most VLP systems are based on one of several typical positioning algorithms, such as proximity, fingerprinting, trilateration, triangulation and vision analysis. Trilateration schemes include received signal strength (RSS), time of arrival (TOA), time difference of arrival (TDOA), and angle of arrival (AOA). These algorithms will, however, be improved to a certain extent by different hardware architectures. In particular, VLPs with ISs often enhance visual analysis methods based on the number of cameras and LEDs as well as the type of auxiliary sensors. Note that (i) ISs do not have the accuracy of PDs, so there are no algorithms based on TOA and TDOA in IS-based VLPs; and (ii) IS-based VLPs can calculate the LED projection position using a computer vision (CV) algorithm based on image processing. There are two main types of CV: solving the characteristic equations that the camera pose, and the perspective-point (PNP) method.

In VLP, there are many challenges that need addressing as follows.

(i) Mobility. May be one of the most important problems in IS-based VLP systems. Due to the RS effect in CMOS cameras, when the object is moving at a high speed, it will move a certain distance during the exposure period of each row of pixels. Thus, the exposure results for each row correspond to different positions of the object in space. The picture will be blurred when the LED is identified in this case. RS compensation algorithm has been used in OCC to solve this problem, but most of them have assumed that the object camera maintains a constant posture. In IS-based VLP scenarios, however, the changing pose is often considered.

(ii) FOV. Determine the angle range of the camera. The real-world scenes often have an FOV that is often too small to capture sufficient numbers of LEDs to meet the requirements of the positioning algorithm, which is also one of the key factors in the robustness of the system. To minimize its impact, consider adding a fisheye lens in front of the camera lens to expand the FOV. Alternatively, a VLP with an NLOS path might be one potential solution, where exact alignment is no longer an issue, where signals can be picked up via reflected lights from any direction.

(iii) Standards. Currently, there are no defined standards for VLP systems, thus making it challenging to fully evaluate the performance of the system. Although the system architectures are different,

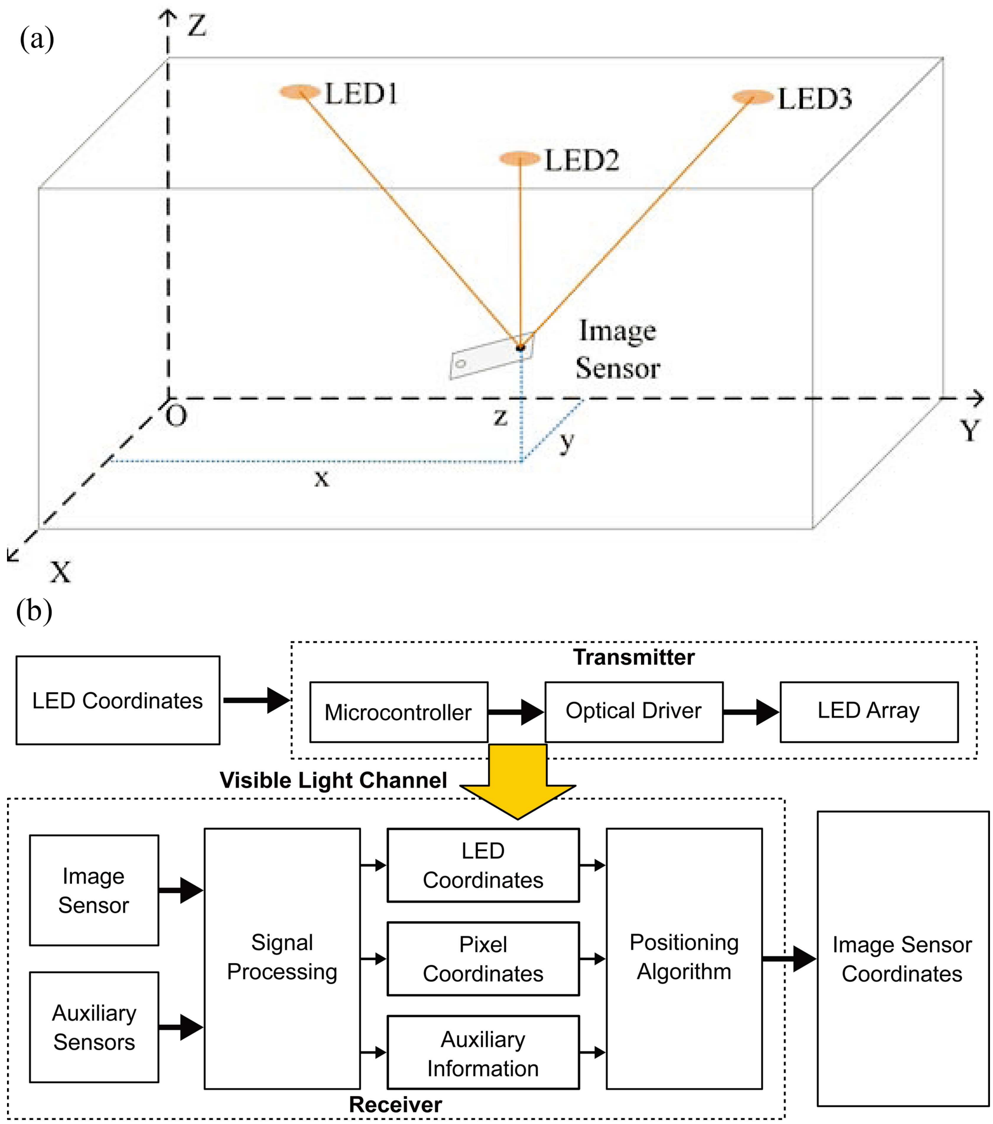

Figure 8 (Color online) (a) A typical geometric model of a VLP system; (b) a general architecture for IS-based VLP.

defining a set of unified standards on the size of the testbed, the type of errors (absolute, relative, or cumulative distribution), and the algorithm complexity calibrated against the running time is critical.

Considering the rapid growth of IS-equipped devices and the maturation of VLC-OCC technology, the IS-based VLP has great potential for use in IoT applications as part of the 5G and 6G wireless networks. As the IS technology improves and the terminals equipped with ISs become increasingly popular, IS-based VLPs have a wide range of hardware choices and, therefore, it is easy to commercialize them. For example, in (i) vehicular positioning, where cameras are widely used. In [145], a technique for determining the position of a moving vehicle using LED-based street lights and a CMOS camera within a vehicle was proposed, where LED identification codes were captured by the camera for estimating the vehicle's position using a CV algorithm. In [146], the IS-based VLP technologies were used in vehicle-to-vehicle distance estimation. And (ii) mapping, where the VLP technology can provide location information for some mapping algorithms in certain indoor scenes. With the integration of existing mapping algorithms, IS-based VLPs are able to correct the deviation of spatial position estimation in real time.

4.2 Steganography

Steganography consists of hiding a file, message, image, or video within another file, message, image, or video. It can be used to conceal sensitive and important information in a picture, such as security codes for a bank note. Steganography can be categorized as spatial domain-, transform domain-, and adaptive-based techniques. In the spatial domain, many techniques have been proposed to embed information in a picture while maintaining the visual quality. The simplest method is the least significant bit (LSB), where the LSB of the selected pixels is substituted by the desired information [147]. However, the embedding capacity of LSB-based methods is limited. Other methods have been proposed to improve the embedding capacity, including pixel value difference, exploiting modification direction, multi-base notation system, pixel pair matching, and edge-based methods. Generally, the performance of the steganography methods is measured in terms of visual quality, embedding capacity, security, robustness, and computational complexity [148], where typically there is a trade-off between the embedding capacity and visual quality of the stego-image.

4.3 Vehicular communications

OCC has also been proposed as a supporting technology for wireless access in vehicular environments (WAVE) [149]. Nowadays many cars have front and rear cameras as a part of their regular equipment, which can interact with existing vehicle LED headlights, taillights, and streetlights, able to operate in both VL and near-IR spectrum and supporting rolling-shutter capture techniques to enhance baud rate. This solution has challenges to be faced, such as low range, limited baud rate and channel limitations as OCC requires a direct line-of-sight between the Tx (LED) and the camera. Obstructions can disrupt communication, while fog, rain, snow, pollution, dust or even mirages due to asphalt heating and direct sunlight can degrade OCC performance, affecting the quality of transmitted data. It should be noted that glare from headlights and streetlights can cause saturation issues in camera sensors. Finally, the effectiveness of OCC decreases as vehicles move at high speeds, reducing T_{exp} for reliable data reception [36, 86]. Nevertheless, OCC also offers interesting opportunities as their worldwide low-cost availability, inherent security and SDMA capacities [150, 151]. OCC can deal with traffic lights, even capable of transmitting dynamic information (speed limits, weather alerts, road closures, etc.). Another interesting possibility is platooning and cooperative driving, when the lead vehicle in a platoon sends lane-keeping and acceleration instructions, detecting also pedestrian and cyclist safety or for navigation inside parking facilities guiding vehicles to available parking spaces over optimized routes. However, in some cases the performance metrics OCC provides are insufficient to deal with the highly dynamic environment and to present enough robustness against changing illumination conditions without affecting communications performance due to their limited dynamic range. In those cases, event cameras can add additional possibilities [149], transforming sensing systems in vehicular technology, providing unique advantages like ultra-low latency and high dynamic range vision, suitable for the dynamic conditions of vehicular navigation [152]. These cameras have been shown to excel in robust and fast obstacle detection, supporting, e.g., forward collision warning (FCW) and automated emergency braking (AEB) functions [88], and traffic condition monitoring, ensuring safety and enabling quicker vehicle responses. The combination of conventional and event cameras with RF technologies in vehicles marks a crucial evolution towards a multi-technology or hybrid approach necessary for modern transportation challenges. This synergy would enhance system adaptability and reliability, ensuring efficient operation under varied conditions.

4.4 Medical

By 2050 almost 2.1 billion people will be at the age of 60 years or above according to the World Health Organization, and by 2030 the death rate due to chronic diseases will be increasing and will reach 66%. Early detection and monitoring will assist medical staff in reducing the death rate and the healthcare cost. Communication between different parts for transmitting data from the patient to the doctor and vice versa can be done using several technologies. There were initial analyses proving benefits of OWC for optical wireless body-area network communication [121]. OCC can be used for monitoring the recovery process of patients following surgery and monitoring elderly people. This can be combined with wearable systems, for example, organic LEDs used in sportswear or linen, even integrated in the textile, which can be used for monitoring sleep in a more comfortable way, or to replace the starting number in athletic competitions, as well as transmitting information about the athlete's or patient medical conditions [153, 154].

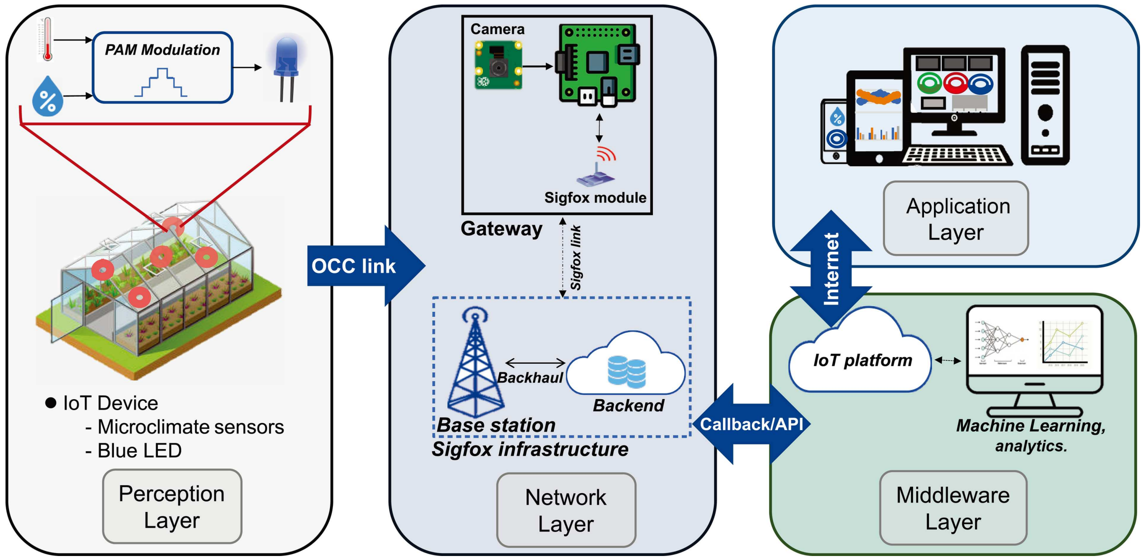

Figure 9 (Color online) Hybrid OCC/RF wireless sensor network architecture for IoT-enabled smart farming. OCC links enable communication between distributed sensing nodes and an RF-based aggregation node equipped with a camera, which processes multiple data streams and forwards them to the cloud [155].

4.5 Farming

VLC has recently been proposed for monitoring the location of sensors and extracting data in farming environments. OCC can be used for remote parallel control and data collection from multiple sensors distributed in both traditional farms and vertical farming (mostly in urban areas). The use of OCC in agriculture offers several advantages, including low cost, ease of deployment, and the ability to operate in environments where RF signals may be obstructed or pose interference issues.

In a recent paper, Luna-Rivera et al. [155] proposed a hybrid OCC/RF system for IoT-based smart farming, where OCC is used to allow wireless communication between distributed sensing nodes and a central RF-based aggregation node featuring a camera for processing multiple data streams before forwarding them to the cloud. The architecture, illustrated in Figure 9, allows unidirectional communication, where sensors periodically upload data without necessarily network access protocols, thanks to the inherent spatial division capabilities of image-forming optics in cameras. By integrating OCC and RF technologies, this and similar architectures offer an efficient and cost-effective solution for collecting environmental, crop health, and operational data in smart farming environments.

5 Conclusion

Based on the analysis presented in this paper, we can conclude that OCC is a promising technology with the potential to revolutionize wireless communication in various applications. By utilizing existing camera and lighting infrastructures, OCC offers a low-cost, energy-efficient, and ubiquitous alternative to traditional wireless communication methods.

The growing market for image sensors, particularly smartphone cameras, presents a significant opportunity for OCC integration in consumer electronics and other applications. However, OCC adoption faces technical challenges, such as limited data rates, ambient light interference, and camera frame rate constraints, which require innovative solutions in hardware and algorithms.

Despite these challenges, OCC has demonstrated its potential in various applications, including positioning systems, vehicular communications, medical monitoring, and farming. Continued research and development efforts are critical to overcome existing barriers and drive real-world deployment of OCC technology.

Future research directions may include the following.

(1) Developing advanced modulation techniques and algorithms to improve data rates and overcome ambient light-induced interference.

(2) Exploring the use of machine learning and artificial intelligence to enhance the performance of OCC in challenging environments.

(3) Investigating the integration of OCC with other emerging technologies, such as 5G/6G networks and edge computing.

(4) Conducting real-world trials and pilot projects to demonstrate the feasibility and benefits of OCC in various applications.

(5) By addressing these research areas, the full potential of OCC technology can be unlocked to pave the way for its widespread adoption in a connected world.

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