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Review article

Visible light backscattering with applications to the Internet of Things: State-of-the-art, challenges, and opportunities☆

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ABSTRACT

Visible light backscatter (VLB) is an innovative optical transmission paradigm to enable ultra low-power passive communication and localization for the Internet of Things (IoT), by overcoming some of the limitations of conventional (i.e., active) visible light communication (VLC) as well as active/passive radio-frequency (RF) technologies. In this paper, we provide a comprehensive survey of recent research activities in the VLB field. After describing the principles of operation and the main enabling technologies, we classify the existing VLB techniques according to several features, discussing their merits and limitations. Moreover, we introduce the potential applications of VLB techniques in several IoT domains. Finally, we present the main open challenges in this area and delineate a number of future research directions.

1. Introduction

The adoption of radio-frequency (RF) communication technologies to support large-scale connectivity for the Internet of Things (IoT) exhibits severe scalability issues, related to energy constraints, as well as spectral efficiency limitations and RF spectrum congestion (so called "spectrum crunch"). Another drawback of RF communications is the leakage through walls and obstacles, which not only complicates interference management, but also poses serious security and privacy concerns. Moreover, in some scenarios, such as aircraft/spaceship cabins and hospitals, or hazardous environments, such as chemical or nuclear plants and oil ducts, usage of RF technologies must be limited or completely avoided.

To cope with the aforementioned drawbacks, a viable solution is to employ *visible light communication* (VLC) techniques [1], which work in the portion of the wavelength spectrum that is visible to human eyes (from about 400 nm to 700 nm), offering a huge unlicensed bandwidth for the potential support of a massive number of IoT nodes. The key idea of VLC is to jointly carry illumination and data, by modulating the light generated by *light emitting diodes* (LEDs), which allows one to reuse the existing lighting infrastructure for communication or localization. In a typical VLC deployment, a LED, connected to the data network infrastructure via a wired/wireless link, performs downlink (DL) transmission to one or multiple client devices. Several types of modulations, starting from the base *on–off keying* (OOK), can be superimposed on lighting, provided that the switching frequency is large enough to avoid an annoying *flickering effect*.

Visible light (VL) can also be used for localization purposes, leading thus to *visible light positioning* (VLP) systems [2–9], which can easily achieve centimeter-level accuracy. A VLP system operating indoors typically comprises several LED sources, acting as reference

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nodes or *anchors*, each one transmitting a VL signal to a *target* node, using one of different multiplexing protocols, such as *time-division multiplexing* (TDD) or *frequency-division multiplexing* (FDD). The transmitted VL signals convey data related to the anchors, such as their identity, coordinates, timestamps, and the transmitted power, which are needed to perform positioning. The target node decodes the data and measures some position-related parameters of the received signals, such as the *received signal strength* (RSS), *time-of-arrival* (TOA), *time-difference-of-arrival* (TDOA), or *angle-of-arrival* (AOA) [4]. Finally, the target node determines its own position (so called *client-based* localization) by using both the decoded data and the measured parameters, adopting algorithms such as proximity, fingerprinting, trilateration, multilateration, or triangulation [3].

In IoT applications, VL-based techniques offer several advantages over RF-based ones. However, a fundamental limitation of existing VL-based techniques is their inherent *one-directional* DL transmission (from the LED to the client devices), usually lacking a return channel for uplink (UL) [10]. A common workaround is to employ RF technologies in UL, which however requires availability of RF spectrum and must again cope with the aforementioned scalability issues. A more interesting solution would be to adopt optical communications also for UL transmission, such as, e.g., VLC itself, infrared (IR) or near-ultraviolet (near-UV) communications, which however requires integration of a power-hungry active light source (a LED or a laser) in the client devices. Similar limitations affect VLP systems, forcing them to resort to client-based localization (i.e., made by the target nodes). This could represent a bottleneck in large-scale IoT applications, where device capabilities are limited and it is thus desirable to transfer the heavy computational burden of real-time positioning and tracking to the anchor nodes, so called *server-based* positioning.

To overcome the aforementioned limitations of *active* VLC and VLP systems, many recent papers have resorted to *visible light backscattering* (VLB) for ultra low-power *passive* communication and localization. The backscatter/backscattering (BS) paradigm has been first proposed for RF communications, allowing a device to transmit data by reflecting towards the source, after modulating it, a portion of the received electromagnetic field. Systems based on RF BS have been designed for the purposes of communication, identification, or localization, the most popular one being the *radio-frequency identification* (RFID) [11] one. A recent evolution of RF-based BS is *ambient backscatter* [12–15], wherein passive communication leverages existing RF signals (such as, e.g., cellular, TV, or WiFi ones) without requiring dedicated illuminators.

In this paper, by extending our previous conference paper [16], we provide a comprehensive survey of current research activities on VLB systems, which leverage BS principles in the optical domain to perform data communication and/or localization. Many survey papers regarding conventional (i.e., *active*) VL-based systems are available in the literature (see, e.g., [1,10,17,18] for communication and [2–4] for localization). To the best of our knowledge, there are only a few surveys dealing with *passive* VLB systems, such as [19,20]; additionally, many research papers discuss the state-of-the-art on VLB, but without a systematic and comprehensive view. In [19], passive VL networks are discussed, which exploit either artificial light sources (e.g., LEDs) or natural ones (e.g., the sun) for sensing or communication purposes. A taxonomy is proposed to describe the different scenarios, and research challenges and opportunities are outlined. However, [19] does not discuss in detail VLB-enabling techniques and presents only some of the VLB techniques proposed so far.

In [20], the authors present a high-level survey on the integration of tunable optical devices (e.g., metasurfaces) in optical wireless communications, including the VL band. The review is wider in scope than our contribution and neither addresses the VLB case specifically, nor discusses the related technologies and techniques.

In particular, our paper has several objectives:

1. the VLB principles are introduced and the most interesting enabling technologies are discussed in a simple physics-based manner;
2. the existing VLB techniques are reviewed and their applications in several IoT domains are considered, by focusing on weaknesses and strengths, and introducing the main open challenges;
3. a number of original and promising research developments in this field are presented.

The paper is organized as follows. In Section 2, a short introduction to VLB principles and systems is provided, and some enabling technologies are presented in Section 3. In Section 4, VLB channel models are discussed. In Section 5, the state-of-the-art of VLB research is outlined and the VLB techniques are classified and compared. In Section 6, potential applications of VLB techniques to different IoT domains are presented. Open challenges and future research developments are introduced in Section 7. Finally, conclusions are drawn in Section 8.

2. Visible light backscattering

We classify VLB-based systems as *visible light backscatter communication* (VLBC) ones, targeted at data communications, and *visible light backscatter positioning* (VLBP) ones, aimed at localization purposes. In a VLBC system, light is typically used for both DL and UL communications. In the simplest point-to-point scenario of Fig. 1, a LED acts both as light source and active DL transmitter (TX), while a device (called a "tag"), typically equipped with a *retroreflector* (see Section 3.1), performs passive UL transmission by reflecting the light, after modulating it, back towards the source. A variant of these scheme, referred to as *ambient light* or *sunlight BS communication*, assume that the light source cannot be controlled nor used for DL data transmission, which occurs either when artificial sources (e.g., LED bulbs) are used only for illumination, or when natural light sources (e.g., the sun) are exploited. In this case, communication is inherently one-directional (i.e., restricted to UL).

In many VLBC schemes, optical modulation at the tag is usually performed by means of simple *liquid crystal display* (LCD) *shutter* devices (see Section 3.2). Due to power and complexity constraints, very simple *intensity* modulations, such as OOK, are generally employed in UL, whereas DL transmission could employ more sophisticated spectrally-efficient modulations [21]. Cheap photodiodes

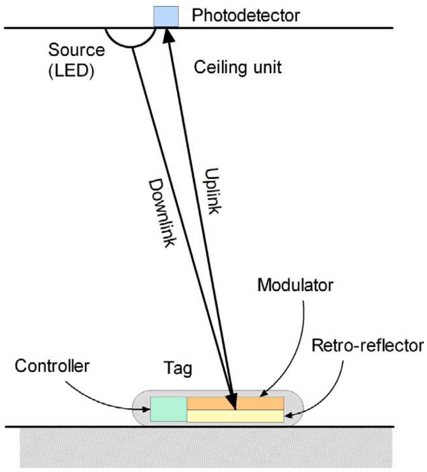

Fig. 1. A pictorial view of a point-to-point VLBC system.

(PDs) are used at the receiver (RX) for signal detection both in DL and UL, even though more expensive *imaging* sensors, such as cameras, can be employed.

Differently from client-based VLP systems, where the target node carries the heavy burden of localization, in VLBP systems localization is usually performed by the transmitting LEDs on the basis of some measured parameters (such as RSS, TOA, TDOA, or AOA) together with some information backscattered by the tag itself, such as the tag identity, timestamps, or the transmitted power. Such VLBP systems are generally used indoors, where the GPS signal is often not available. In this survey, we refer to VLBP systems wherein the tag can modify (by modulating it) in some way the light it receives, in order to leverage the localization task. A different approach is *device-free localization* [7], where the position of a target is determined by measuring its modifications to the light impinging on it, but without assuming that the target can intentionally modify the properties of light (this approach is sometimes referred to as *passive localization*).

One distinct advantage of VL-based positioning techniques over active/passive RF-based ones, such as RFID, WiFi, Bluetooth or ultra-wideband (UWB) ones, is the high localization accuracy attainable and the lack of the need to install a dedicated infrastructure, since they can leverage the existing lighting systems. Moreover, compared specifically with WiFi-based positioning, the number of LED luminaries and their power is generally much higher than that of WiFi access points [1]. Finally, different from conventional VLP systems, the presence of a return (UL) channel in VLBP systems allows one to implement not only client-based localization techniques, but also server-based ones, paving also the way for cooperative/collaborative localization systems [22,23], where the target nodes exchange information via VLB links to ease the localization task.

3. VLB-enabling technologies

In this section we describe two main enabling technologies for VLB systems: *retroreflectors* and *LCD shutters*.

3.1. Retroreflectors

An optical retroreflector (RR) is a device that, unlike a mirror, reflects the incident light back towards the direction of the source, with minimal scattering. RRs can be implemented with different technologies and are used in many fields, including free-space optical communications networks [24–26], satellite communications [27], and low-powered sensor networks [28–30]. Cheap RR materials are commonly available (e.g., Scotchlite™ manufactured by 3M) and are used for road signs, bicycles, and clothing for road safety [31].

One popular type of RR is the *corner-cube retroreflector* (CCRR) [32], which is composed by three mirrors arranged in a 90° corner geometry. Light rays are sent back towards the source regardless of the relative orientation of the incoming beam direction, after undergoing three reflections, as depicted in Fig. 2. Another common type of RR is the *spherical retroreflector* (commonly known as "cat's eyes"), which is build as a high index-of-refraction transparent sphere with a reflective backing [33]. A less common implementation is the *phase-conjugate mirror* [34], which exploits nonlinear optics phenomena, such as four-wave mixing or stimulated Brillouin scattering. It is worth noting that innovative materials such as *metasurfaces* can also be used as (tunable) RRs (see also Section 7.3).

Disregarding the actual implementation, it is common to describe [33] the behavior of a RR device by means of two angles (Fig. 3): the *entrance angle* β, which is the angle between the illumination direction and the normal to the RR surface, and the

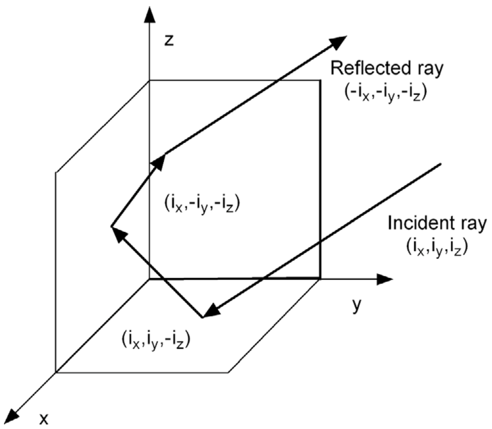

Fig. 2. Working principle of a CCRR based on ray optics.

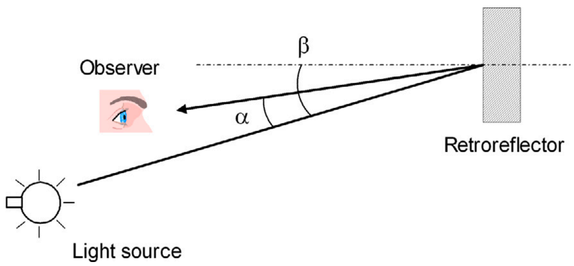

Fig. 3. Geometrical description of a RR: β is the entrance angle, α is the observation angle.

observation angle α, which is the angle between the illumination and viewing directions. High-quality RRs work over fairly wide entrance angles, up to 45° or more (up to 90° for pavement marking), with very small observation angles (<1°).

The performance of a RR can be measured by several coefficients, the most common ones [33] being R_I and R_A. The first one is the *coefficient of retroreflected luminous intensity:*

$$R_I = \frac{I}{E_\perp} \qquad [\text{cd/lux}] \tag{1}$$

where $E_\perp$ is the illuminance (in lux) on a plane normal to the direction of illumination, and I is the intensity (in cd) of the illuminating light. The second one is the *coefficient of retroreflection*:

$$R_A = \frac{I}{E_\perp A} = \frac{R_I}{A} \qquad [(\text{cd/m}^2)/\text{lux}] \tag{2}$$

where A is the area of the retroreflector. Values for R_A of several hundred (cd/m^2)/lux are not uncommon [33]. Both coefficients are functions of the angles β and α.

It should be noted that RRs can also be used as optical modulators, by controlling the reflection mechanisms with *micro-electromechanical systems* (MEMS) [26] or semiconductor *multiple quantum wells* (MQW) technologies [31].

3.2. LCD shutters

LCD shutters are employed in consumer 3D TV glasses [35] and act as modulator devices in most VLB prototypes. An LCD shutter is characterized by a multilayered sandwich structure [36], with two linear polarizers at the ends and one *liquid crystal* (LC) layer in between.[1] Each polarizer obeys the *Malus law:*

$$I_\theta = I_0 \cos^2 \theta \tag{3}$$

where I_0 is the intensity of light impinging on the polarizer, I_θ is the intensity of light that is passed through the polarizer, and θ is the angle between the polarization direction of the polarizer and the polarization of light. If the polarization of the incident light is

[1] A liquid crystal (LC) is a special material whose properties are between those of a liquid and those of a crystal. The most common type of LC is a *nematic* liquid crystal, whose optical behavior can be modified by applying an electric field to it.

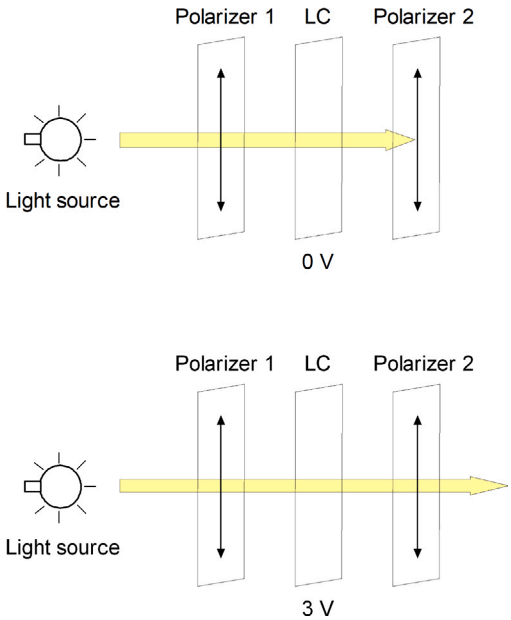

Fig. 4. An LCD shutter operating as an OOK modulator. When no voltage is applied to the LC (top), the polarization of the light is rotated by 90 degrees and is blocked by the second polarizer. When a certain voltage (3 V) is applied to the LC (bottom), the polarization of the light is not rotated and passes trough the second polarizer.

parallel to that of the polarizer, i.e., $\theta = 0°$, no attenuation will occur and the light will pass unaltered through the polarizer. When, instead, the two directions are perpendicular, i.e., $\theta = 90°$, the entire incident light is blocked by the polarizer.

Modulation of bits in a LCD shutter is based on polarization properties of light. In Fig. 4, the working principle of a *twisted nematic* (TN) LCD shutter is explained [37].[2] A variable voltage is applied between the layers of a TN LC, which determines a twist/untwist (realignment) of the LC molecules. In most commodity TN LCs, when no voltage is applied (normal or uncharged state), a light beam passing through the LC layer undergoes a rotation by 90°. Thus, polarizer 2 can entirely block the light if placed parallel to the incident light. Therefore, when the voltage is increased, untwisting of LC molecules will happen and polarizer 2 will become brighter. Over a certain voltage level, such as 3 V, complete untwisting of LC molecules occurs (charged state) and this result in the brightest state of polarizer 2. Hence, the intensity of the light can be modulated by tuning the applied voltage so as to encode bits using bright and dark states.[3]

The most interesting features of LCD shutters are, among others, compatibility with non-coherent white light [40], low power consumption (sub-mW [31]) and low cost (0.03 $ per cm^2 [41]). These features make LCD shutter the best choice for large scale IoT deployment, in comparison to RR-based modulators. However, LCD shutters exhibit a slow (in the order of ms) and asymmetric impulse response [35,39], which limits the achievable data-rate to sub-kbps level and complicates equalization. In [35] a rising time of 1.096 ms and a falling time of 0.533 ms have been measured, whereas in [39] the corresponding values of 0.3 ms and 4 ms were found. The rising time is much smaller than the falling time because of the slow discharging property.

A simplified model for the response of the LCD shutter is that of a first-order RC filter with a cutoff frequency in the order of 300 Hz [35]. However, LCD shutters exhibit an asymmetric time response and a marked nonlinear behavior [39,42], which makes very difficult to generate multilevel modulated signals [31]. Finally, the slow switching rate of LCD shutters might induce flickering.

4. VLB channel modeling

Channel modeling for optical wireless communications has been carried out in several papers, both for indoor and outdoor scenarios [43], especially for the IR region of the electromagnetic spectrum [44,45]. Characterization of the VLB channel is less explored, and many papers consider only experimental results without performing analytical studies. A simple model for VLB links has been recently developed in [46]. However, as also pointed out in Section 7, further results regarding channel characterization for VLB applications are still needed. In this section, we focus on indoor scenarios, which are in our opinion the most appealing ones for VLB techniques.

2 Further details on working principles and mathematical modeling of single- and dual-cell TN LCD shutters can be found in [38].

3 Some LCD shutters employ orthogonal polarizers at the two ends [39], in which case the encoding of voltage levels to bright/dark states is simply reversed.

VLB propagation links can be classified according to the degree of directionality of source and tag, and the existence of a *line-of-sight* (LOS) path between them [47]. *Directed* links employ sources and tags with narrow radiation and illumination patterns, respectively, which have to be aligned in order to minimize path loss effects and reception of ambient light noise. On the other hand, *non-directed* links employ wide-angle sources and tags, which do not require such an accurate alignment. *Hybrid* links are also possible, which combine sources and tags having different degrees of directionality.

The presence of a LOS path between the source and the tag allows VLB link designs with maximum power efficiency and minimum multipath distortion. *Non-line-of-sight* (NLOS) links – also referred to as *diffuse* links – generally rely upon reflection of the light from the ceiling or some other diffusely reflecting surface, such as people or cubicle partitions, standing between the source and the tag. Compared to their LOS counterparts, NLOS VLB link designs trade-off power efficiency with greater robustness, coverage, and ease of use.

There are three key issues that are relevant for VLB channel modeling: reflection patterns of the RR, duplexing techniques, and noise characterization.

4.1. Reflection patterns

Besides the presence of obstacles between the LED and the tag, which might absorb some power while scattering the rest, the VLB channel heavily depends on the reflection characteristics of the RR located at the tag. The reflection pattern of the RR can be approximated by using the *Lambert model* [45]. With reference to Fig. 1, according to Lambert model, the shape of the reflection pattern depends on the observation angle α. This fact allows to develop simple reflection models, which are easy to implement via software. However, the model of Lambert does not accurately approximate the reflection pattern of the RR around the specular reflection direction.

Phong [48] developed a reflection model, mostly adopted in computer graphics, employing both the entrance angle β and the observation angle α. The diffuse and specular components are suitably weighted by a modeling parameter $0 < r < 1$, which can be fitted to the RR characteristics. The *Phong model* is more complex than the Lambertian one and subsumes the latter as a special case when $r = 0$. Existing validations of the Phong's model mainly consider IR applications (see, e.g., [49]).

4.2. Duplexing

The bi-directional communication system of Fig. 1 can be further classified according to the connectivity between the LED and the tag. The possible connections are termed *half-duplex*, *out-of-band full-duplex*, and *in-band full-duplex*.

The half-duplex connection is a VLB link whereby DL and UL transmissions cannot be made simultaneously. This can be implemented by resorting to TDD, according to which UL and DL transmissions are separated in time [46]. In the case of TDD, during the UL phase, the LED does not transmit data, thus acting as a conventional monochromatic illuminator.

The LED and the tag operate in out-of-band full-duplex when they transmit and receive over different VL bands. An innovative solution for implementing out-of-band full-duplex VLB systems is represented by the use of time-varying metasurfaces (see Section 7.3), which could enable the implementation of a FDD connection, where DL and UL transmissions proceed simultaneously over non-overlapping VL bands. In this case, VLB channel models have not been developed yet.

In-band full-duplex operation enables the LED to transmit and receive simultaneously over the same frequency band, hence improving throughput and reducing latency. A compact and flexible solution for implementing an in-band full-duplex VLB system might consist of replacing the LED and the photodetector in Fig. 1 with a single multiple-quantum-well (MQW) diode [50]. When approximately biased, the MQW-diode emits a broad spectrum of light. As a dual-functioning device, the MQW-diode also acts as a photodiode that absorbs photons to liberate electron–hole pairs. In this case, the UL channel model complicates with respect to TDD/FDD.

4.3. Shot noise

VL indoor transceivers are subject to intense *ambient light*, emanating from both natural and artificial sources. The main sources of ambient light are the sunlight, incandescent lamps, and fluorescent lamps [51–54]. The DC background photocurrent generated by the ambient light acts as a noise source in the receiver, referred to as *shot noise*, which degrades the link performance.

Besides ambient light, the performance of VLB systems is also adversely affected by the inherent *auto-interference* at the photodector, which receives in UL both the backscattered signal from the tag and the light emitted by the LED to illuminate the tag. Such an auto-interference yields a photocurrent shot noise that, unlike ambient light, may be a non-stationary random process. Specifically, the auto-interference has a constant intensity in the TDD case, while it exhibits a time-varying intensity in the case of full-duplex connections. In the case of FDD, interference effects can be effectively reduced by using linear time-invariant filtering. On the other hand, in the case of in-band full-duplex more advanced interference cancellation techniques have to be employed.

5. Existing VLB techniques

In this section, a survey of the existing VLB techniques is provided, whose main features are also summarized in Table 1. The techniques are presented mainly in chronological order.

Table 1
A summary of existing VLB techniques.

Scheme	Technology	Light source	Modulation	UL data-rate [bps]	Range [m]	Tag power consumption	Applications	Main advantages	Main limitations
Retro-VLC [36]	RR + LCD shutter	LED	OOK w/ Manchester coding	500	2.4	234 μW	Communication (IoT)	Bidirectional, low-power, analog implementation	Low data-rate, narrow FoV
Ambient light BS communication [35]	RR + LCD shutter	LED/ambient light	OOK	100	0.1	N/A	Communication (IoT)	Ambient light source or dedicated illuminator	Low data-rate, low-range
MobileVLC [55]	Reflective surface	Ambient light	OOK w/ Manchester coding	50	1	N/A	Identification and tracking (IoT)	Ambient light source, mobile node	Very low data-rate, low-range, static encoding of information
Pixelated VLBC [56]	Multiple LCD shutters	LED	OOK, 4-PAM, 8-PAM	600	2	200 μW	Communication (IoT)	High data-rate, rate adaptation	Complexity
PassiveVLC [31]	RR + LCD shutter	LED	TBM w/ Miller coding	1000	1	150 μW	Communication (IoT)	High data-rate, flexible range of orientations	Reduced immunity to noise
RetroArray [57]	Multiple LCD shutters	LED	DSM	4000	3	N/A	Communication (IoT)	High data-rate	Complexity
Poster [40]	RR + LCD shutter	LED	PQAM	N/A	2	N/A	Communication (IoT)	Flicker-free, robust to TX/RX orientation	Complexity
LuxLink [58]	LCD shutter	Ambient light	FSK	80	4–60	~20–30 mW	Communication (IoT)	Ambient light source, flicker-free	Low data-rate, narrow FoV
ChromaLux [59]	Multiple LCD shutters	Ambient light	Polarization-based	1000	50	28 mW	Communication (IoT)	Ambient light source, high data-rate, long-range, flicker-free	Sensitivity to LCD manufacturing inaccuracies
PhotoLink [60]	DMD	Ambient light	4-FSK	80 000	4	45 mW	Communication (IoT)	Ambient light source, high data-rate	Cost
SunBox [61]	Smectic LCoS + camera RX	Ambient light	Polarization-based	10 000	0.1	110–180 mW	Communication (IoT)	Ambient light source, high data-rate, flicker-free	Very short-range
RetroI2V [62]	Retroreflective coating	LED (headlight)	OOK	N/A	~100	~2–20 μJ/bit	Communication (I2V)	Decentralized MAC protocol, flicker-free, long-range	One-way communication, only vehicular scenario
RetroTurbo [39]	Modified LCD	LED	PQAM + DSM	8000	7.5	0.8 mW	Communication (IoT)	High data-rate, real-time demodulation algorithm	Complexity
RETRO [63,64]	RR + LCD shutter	LED	OOK	N/A	1.5	Ultra low-power	Localization (IoT)	Centimeter-level positioning (based on RSS and trilateration)	N/A
PassiveRETRO [65]	RR + linear polarizer	LED	PQAM	N/A	1	Ultra low-power	Localization (IoT)	Mitigation of interchannel interference, completely passive tag	RX complexity
RetroMUMIMO [66]	LCD shutter	LED	OOK with pulse diversity	800	2.50	0.2 mW	Communication (IoT)	Scalable, low-latency, near-far resistant	RX complexity
RetroFlex [67]	Multiple PDLCs + camera RX	LED (flashlight)	OOK	60	2.5	18 mW	Communication (robotics)	Flexible tag, wide FoV	Low data-rate

DL = downlink, UL = uplink, RR = retroreflector, FoV = field-of-view, DSM = delayed superimposition modulation, TBM = trend-based modulation, DMD = digital micro-mirror device, PDLC = polymer dispersed liquid crystal LCoS = liquid crystal over silicon.

5.1. Retro-VLC [36]

This bi-directional VLBC system performs DL transmission by employing conventional VLC techniques, whereas UL transmission is based on VLBC. The UL TX employs a RR device coupled with an LCD shutter as modulator. Several power optimization solutions are proposed, together with an implementation based on purely analog techniques to reduce energy consumption at the tag. The Retro-VLC prototype employs Manchester-encoded binary signals, achieving a data-rate of 10 kbps in DL and 0.5 kbps in UL over a range of 2.4 m in an office environment.

5.2. Ambient light BS communication [35]

This VLBC system exploits either ambient light or a dedicated illuminator for UL transmission. The design is similar to [36] and the developed prototype achieves a data-rate of 100 bps over a 10 cm range in a typical office environment.

5.3. MobileVLC [55,68]

In the VLBC system for UL communications (later referred to as MobileVLC) proposed in [55], information is statically encoded in a tag composed by a reflective surface. Such a surface is mounted on a mobile object (like a car or truck), and can be read by illuminating it with an unmodulated source (artificial or natural) and detecting the reflected light with a PD-based RX. The system works similarly to a bar-code reader, but without using energy-consuming cameras for reading, since the power consumed by the PD is very low (about 1.5 mW). One possible improvement of MobileVLC is the dynamic encoding of data, which can be performed by adopting advanced materials or devices (such as e-ink screens, LCD shutters, or metasurfaces) whose reflection properties can be adjusted in real-time. Further studies and optimizations [68] allow one to improve the performance of MobileVLC, by increasing data-rate, range, and mobile object speed, as well as improving robustness.

5.4. Pixelated VLC-backscatter [56]

This VLBC scheme employs multilevel modulation to improve the data-rate of the simple OOK-based Retro-VLC technique [36]. Since the highly nonlinear characteristic of the LCD shutter prevents modulating a single LCD-shutter with more than two levels, the proposed solution employs *multiple* LCD shutters, whose number is equal to $\log_2(M)$ (with M denoting the cardinality of the modulation), which are independently switched by the modulation bits. A RR and a LCD shutter form a *pixel* that can be switched independently from the others. Hence, the overall reflected light is proportional to the number of activated pixels, which allows one to obtain multilevel pulse amplitude modulation (PAM) signals. The prototype in [56] employs up to three pixels and works at the symbol rate of 200 symbols/s, implementing OOK, 4-PAM, and 8-PAM modulations, with an achieved data-rate of 600 b/s at 2 m, 400 b/s at 3 m, and 200 b/s at 5 m. Rate adaptation should be performed, where lower-order and more robust modulations, such as OOK, are used when the range is higher and viceversa. A possible improvement to this scheme, mentioned by the same authors, is the adoption of orthogonal frequency-division multiplexing (OFDM) modulation techniques.

5.5. PassiveVLC [31]

This VLBC technique tries to improve the design of Retro-VLC [36] by specifically focusing on the modulation/coding schemes. In particular, to solve the problem of long consecutive stream of zeros/ones, it is proposed to replace the memoryless Manchester coding scheme employed in [36] with the Miller one, due to its better spectral efficiency. The choice of a modulation scheme with memory slightly complicates the decoding algorithm, which can be formulated as an optimization problem and solved by means of dynamic programming methods. Another innovation of the PassiveVLC technique is avoiding to completely charge/discharge the LCD shutter, in order to reduce the switching time (from 4 ms down to 1 ms). The resulting solution is called *trend-based modulation* (TBM), since the information is mapped on the "trend" of the voltage change, avoiding hence the slower complete charge/discharge of the LCD, at the price of a reduced immunity to noise. The PassiveVLC prototype achieves up to 1 kbps in UL over 1 m for a flexible range of orientations and different ambient light conditions.

5.6. RetroArray [57]

This technique exploits the nonlinear behavior of the LCD shutter to improve the data-rate of existing VLBC systems. Indeed, LCD shutters exhibit an highly asymmetric response, with 0.5 and 4 ms charging and discharging time, respectively. The RetroArray prototype employs an array of LCD shutters and encodes the information only on the rising (i.e., charging) edges, resorting to time interleaving between different shutters to achieve multilevel modulation. The technique, called *delayed superimposition modulation* (DSM), allows one to achieve an UL data-rate of 4 kbps over 3 m using an array of 16 LCD shutters.

5.7. Poster [40]

This VLBC scheme employs *polarization-based quadrature-amplitude modulation* (PQAM) to overcome the problem of flickering, associated to the low switching rate of the LCD shutter. Similarly to the PIXEL technique [41] proposed for active VLC communications, the LCD TX employs only one polarizer, thus mapping the information on two orthogonal polarizations, which are controlled by the LC layer. This completely avoids flickering, since the intensity of the backscattered light is not changed. At the RX, a second polarizer is capable of detecting the different polarizations. The PQAM design is robust to the cases where TX and RX are not perfectly aligned, in terms of polarization angle.

5.8. Sunlight BS communications [58–61]

The research works belonging to this class are oriented to the use of natural light sources, such as sunlight, for VLBC. This scenario has some specific issues, since it works outdoors with no control on the source, and is restricted to UL transmissions. Moreover, the presence of clouds might severely affect the availability and characteristics of the link. Differently from of Fig. 1, where light source and PD are co-located, in sunlight-based communications they are obviously placed at different locations. One advantage of this approach is the high illumination that can be obtained with sunlight (of the order of tens of thousands of lux), which paves the way for potentially very high-rate/high-range transmissions. One of the pioneering contributions in this area is the aforementioned MobileVLC system [55], which can work both indoors (with artificial light) and outdoors (with artificial light or sunlight).

LuxLink [58] works with any ambient light source (either artificial one or sunlight) and adopts *frequency-shift keying* (FSK) modulation to avoid flickering. It achieves a very low data-rate (80 bps) at ranges of 4 m indoors and 10–60 m outdoors. Another work in this area is ChromaLux [59], which exploits the *birefringence*[4] property, by stacking up to 6 LC shutters to increase the contrast without changing the transition period, which allows one to design particular constellations aimed at increasing the data-rate/range. The developed prototype works indoors with ambient light, reaching 1.55 kbps at 5 m and 1 kbps at 10 m, with BER values below 0.01.

PhotoLink [60] employs for BS transmission *digital micro-mirror devices* (DMDs), which are optical systems composed by a large number of highly-reflective microscopic mirrors (with linear dimension less than 10 μm each), whose orientation can be electrically controlled. They are typically used in consumer electronics to implement high-quality displays, but their control logic can be modified to make them act as high-speed optical modulators. The system proposed in [60] adopts flicker-free FSK modulation and achieves very high data-rates, up to 80 kbps outdoors working with sunlight.

Finally, SunBox [61] is a short-range (in the order of 10 cm) VLBC system employing artificial light or sunlight. The reflective device is a *smectic* LCoS (LC over silicon) microdisplay, consuming 110 – 180 mW, whereas a low-end smartphone camera (working at 30 FPS) acts as RX. By employing Reed–Solomon codes, the developed prototype achieves a variable throughput of 2–10 kbps, operating indoors with standard lighting, or outdoors with sunlight under different cloud conditions.

5.9. RetroI2V [69]

This system exploits retroreflective coating of the road signs for VLBC in outdoors scenarios. Late-polarization and polarization-based differential reception technique are used to mitigate flickering. Experimental results show that the system exhibits long range (up to 100 m) connectivity. Efficient operation is achieved by using a decentralized multiple-access control (MAC) protocol. A limitation of this scheme is that it can be used only for one-way communication and it is designed for a specific vehicular application.

5.10. RetroTurbo [39]

A VLBC prototype is implemented in [39], which uses PQAM and DSM for IoT-oriented applications. It achieves an UL data-rate of 8 kbps at 7.5 m range, which is 32x higher than Retro-VLC using OOK [36]. The range increases to 10 m if the data-rate is reduced to 4 kbps. The authors also designed a real-time demodulation algorithm and claimed a 128x rate gain (32 kbps) via emulation.

5.11. RETRO and PassiveRETRO [63–65]

In [63–65] several VLBP systems for server-based localization are proposed. The RETRO system [63,64] performs real-time tracking of location and orientation of passive IoT nodes equipped with a RR and an LCD shutter, which transmit their identity to the network. The prototype exploits RSS measures and trilateration to achieve ultra low-power centimeter-level positioning. An improvement is the RR-based PassiveRETRO system [65], which retains the advantages of RETRO [63,64] but eliminates the LCD shutter at the tag. This design choice completely avoids the necessity of any electronic component on the IoT devices. Polarization-based modulation and bandpass optical filters are used as means to identify and separate the signals reflected by different IoT devices. Moreover, *optical rotatory dispersion*[5] is used for mitigating interchannel interference and improving the signal-to-interference-plus-noise ratio (SINR) for each node. Specifically, the PassiveRETRO system splits the LCD shutter present in RETRO into two parts: one linear polarizer and one LC layer are installed on the light source for performing polarization-based modulation, while another linear polarizer is placed on top of the RR to modulate the backscattered light.

5.12. RetroMUMIMO [66]

To support low-latency concurrent transmissions, the RetroMUMIMO system [66] exploits the different shapes of the pulses emitted by LCD shutters (due to changes in position, orientation, manufacturing, etc.), so called *pulse diversity*, as well as conventional RX diversity, The transmission of up to 8 tags is modeled as a MIMO-like problem, where demodulation is based on maximum-likelihood (ML) decoding, whose complexity is reduced by a preliminary pulse feature extraction and dimensionality-reduction technique based on singular value decomposition (SVD). A larger number of tags is accommodated by means of a centralized, slotted, and contention-based MAC protocol. The power consumption of the tag is 0.2 mW during transmission, and the testbed achieves concurrent transmission of 8 tags, each transmitting at 800 bps in a typical indoor environment with different ambient light conditions. The testbed is robust to ambient light and to the near-far effect, supporting the given rate with BER values less than 0.01 at 2.50 m for 8 tags, at 3.25 m for 6 tags, and at 3.75 m for 4 tags. Moreover, extensive simulations are reported to benchmark the proposed system in different operative simulations, in comparison with the RetroTurbo [39] system, showing a marked reduction of the network latency and a good scalability of latency performance with the number of tags.

[4] Birefringence is the optical property of certain non-isotropic materials, whose refractive index depends on the polarization and propagation direction of light.

[5] Optical rotatory dispersion is a property of some materials that rotate the polarization of light to different extents depending on the wavelength.

5.13. RetroFlex [67]

This system performs bi-directional VLBC-based communication with robots, leveraging the properties of *polymer dispersed liquid crystal* (PDLC) technology to implement VLB modulation, and using a smartphone both as a source light (flashlight) and RX (camera). The flexible nature of PDLCs make them readily deployable on irregular surfaces, such as those of robots. An array of 4 PDLCs is used to encode the information to be transmitted in UL. The system achieves up to 60 bps at 2.5 m with a view angle of 70° in several lighting conditions, ranging from day light to artificial light. The power consumption of the tag is around 18 mW, and the UL data-rate is mainly limited by the camera frame-rate, as typically occurs in camera-based RXs.

6. Main applications of VLB in IoT

VLB techniques can be employed in several IoT domains, mainly to supplement or replace VLC and/or RF technologies when extreme energy efficiency is pursued. In the following, some fields of application are discussed.

6.1. Healthcare

In e-Health and m-Health applications [70,71], sensors of different nature are used to monitor some physiological parameters of the patients (such as, e.g., temperature, pulse, blood pressure, or oxygen saturation) and transmit them in real-time to a collection unit. The use of RF communication technologies to this aim presents two main drawbacks: (i) long-term overexposure to RF fields, which amplifies the risks to human health; (ii) electromagnetic interference (EMI), which affects the accuracy and reliability of medical equipments. Optical-based VLC and VLB techniques allows one to overcome the previous drawbacks, and can be used in many different healthcare setups, including operating and emergency rooms, intensive care units, imaging and pathology labs, and hospital wards. In particular, the use of VLB techniques is particularly appealing in *wireless body area networks* (WBANs) [72], composed by wearable or textile sensors aimed at long-term health monitoring. Indeed, WBANs must inherently adopt energy-efficient devices and protocols for sensing and communication. Moreover, wearable devices are equipped with low-capacity batteries, whose recharging or substitution might be cumbersome.

In [73], a VLBC system for health monitoring applications is studied, which exploits the light emitted by a LED to transmit, by means of a CCRR, OOK-modulated data acquired by wearable sensors to a central unit. The RX at the ceiling employs an imaging sensor to detect the transmitted data. A link budget analysis is proposed, aimed at assessing the theoretical performances of the system, in terms of BER, achievable range, and data-rate. This solution is further generalized in [74,75] to an *hybrid* system providing two different operation modes: an *active* one based on IR and a *passive* one employing VLBC. The active mode is used when VLBC cannot be used, that is, when the LED light is turned off or the user is too far from the source.

6.2. Transportations

Intelligent transportation systems (ITSs) are critical components to make transport safer, more efficient, more reliable, and more sustainable. They make widespread use of IoT technologies to enable automated collection of transportation data and information exchange between vehicles/passengers and infrastructures.

Recently, VLC techniques have been proposed to replace RF ones in *vehicle-to-vehicle* (V2V), *vehicle-to-infrastructure* (V2I), and *infrastructure-to-vehicle* (I2V) links, (see [76] and references therein). Their use relies on the ubiquitous availability of LED-based street, traffic and vehicle lights. A distinctive feature of VLC-based vehicular communications is the outdoor operating scenario, characterized by a non-negligible ambient light interference due to background solar radiation. As discussed in Section 4, this type of interference can adversely affect the reliability of VLC and VLB techniques, unless suitable mitigation strategies are performed.

The VLBC system called RetroI2V [69] assures flicker-free I2V data transmission over distances of about 100 m, under different lighting conditions. It works by equipping the road signs with tiles of transparent LCD shutters plus controling/harvesting circuitry, actually converting conventional road signs into smart, dynamic transmitters. Several usage scenarios are discussed in [69], aimed at providing additional information to drivers (i.e., possible accidents or time restrictions) or adapting the messages to road/weather conditions.

Notwithstanding the successful demonstration of [69], we do not envision VLB as a candidate technology for outdoors mission-critical applications, such as autonomous driving or collision avoidance systems. VLB can be used instead to transmit or share low-rate information, such as traffic or road conditions, points-of-interest, or travel suggestions. in non-critical infotainment applications. A sample application of the LuxLink [58] technique is to transmit information to people standing at a bus stop, by modifying the panels of the stop to modulate the impinging sunlight. Other areas where VLB technologies can be fruitfully used is in automatic toll or ticketing systems, to provide information about free parking lots, or as support to green shared-mobility systems, such as bikesharing or scooter sharing systems.

We envisage that VLB technologies are more useful in public transportation systems working in indoor scenarios, such as galleries or metro railway stations, or to provide low-rate communications within vehicles. For example, VLB can be used to provide indoor localization when GPS is absent, or to assist precise stop control of train vehicles to platforms. Another application could be substitution of RF techniques in smart ticketing and access control systems. Moreover, VLB technologies can be used also to support more innovative functions, such as counting people to implement crowd-avoiding functionalities [77] in ITSs.

6.3. Smart cities

The wide availability of outdoor lightning infrastructures in urban environments is a formidable enabler for VLC and VLB applications. Moreover, adoption of VLB-based sensing and communications can avoid to further congestionate the RF spectrum in urban environments. Possible applications of interest could be, for instance, in smart parking (e.g., detection of free spaces in parking lots), environmental sensing (e.g., for pollution checking) and cultural heritage. To enable long-range communications, it is envisioned the use of unmanned autonomous vehicles (UAVs) to relay the information gathered by VLB sensors to a central unit [78].

6.4. Smart home

IR-based device control is common in consumer electronics and equipment: however, IR devices are subject to annoying battery replacement. Since homes and offices are equipped with LED luminaries, IR active devices can be easily replaced by passive VLB system, which assure long times of operation with a limited energy consumption.

Moreover, the indoor positioning capabilities of VLB make it the naturale candidate for *home robotics* applications [79] (such as vacuum cleaners, monitoring devices, and lawn mowers). Other natural applications are in smart lightning systems, where many small inexpensive VLB sensors are deployed in several points of the room to measure the light intensity and report the results to the lightning infrastructures. Moreover, VLB technologies can also be employed in security and anti-intrusion systems, as well as into systems devoted to energy efficiency [80].

6.5. Logistics and industry

Wireless technologies, such as RFID and wireless sensor networks, are among the important enabling technologies for *smart logistics* [81] and *industrial IoT (IIoT)* [82]. Due to the already mentioned limitations, RF technologies can be conveniently replaced by VLC and VLB ones in several applications within this domains.

A promising use of VLB is that of indoor localization and identification of goods in retailers, shopping malls, and supermarkets, as a replacement of RFID or traditional bar codes. An example is the VLB technique proposed in [55], aimed at replacing RFID systems by encoding the information in a reflective surface, which is read by using only ambient illumination (i.e., the sun). More generally, the indoor localization capabilities of VLB can be applied in several industrial and logistics fields, such as real-time location of assets in a facility, i.e., tracking of vehicles in industrial sites or goods in retail shops. Triangulation-based VLB techniques based on TOA, TDOA, or RSS [63–65] can be used to this aim. Thanks to the small wavelength of visible light, these techniques can easily achieve sub-meter or even centimeter-level accuracy. In robotics, VLB can be used to provide communication [67], precise positioning and navigation aids in indoor environments.

Finally, VLBC techniques can also be used in hazardous environments, such as, e.g., petrochemical plants, oil ducts, or nuclear plants, where usage of RF technologies must be limited of avoided at all. VLBC techniques can be used for sensing and monitoring of indoor infrastructures such as galleries, ducts, pipelines, etc.

7. Future research directions

Although VLB is a promising paradigm for IoT, there are some inherent issues to be dispelled, which deserve further developments in order to ensure a widespread use of such a novel technology. In what follows, we delineate the most interesting future research directions.

7.1. Channel modeling for VLB applications

As already pointed out in Section 4, many works dealing with channel modeling of optical wireless communications are targeted at the IR region of electromagnetic spectrum. However, there exist significant differences between VLB and IR communications and those results cannot be applied to VLB channel modeling in a straightforward manner. For instance, an IR source can be approximated as a monochromatic emitter, while a visible light LED source is inherently wideband. This fact implies that wavelength-dependency of the source in VLB channel modeling should be accounted for. Moreover, in IR communications, the reflectance of materials is typically modeled as a constant. In contrast, the reflectance of materials in the VLB spectrum should be taken into consideration due to the wideband nature of VLB links, especially for the reflection process at the tag.

As a matter of fact, a precise characterization of the VLB channel is needed, by also considering the case of multiple sources and/or hybrid PD-based and camera-based tags [83]. Specifically, advantages and drawbacks of the VLB medium have to be compared to those of IR media. Physical characteristics of VLB channels using IM/DD are not fully studied, including path losses and multipath responses. Another key issue is the characterization of natural and artificial ambient VLB noise.

Table 2
Different types of metasurfaces suitable for VLB applications.

Tuning element	Tuning mechanism	Operation spectrum	Maximum modulation speed
Transparent conductive oxides	Electrical	VL	10 MHz
Ferroelectrics	Electrical/Thermal/Optical	GHz to VL	NA
Graphene	Electrical	THz to VL	20 GHz
Phase change materials	Optical	THz to VL	2.77 GHz
Liquid crystals	Electrical/Thermal/Optical	GHz to VL	1 kHz
Semiconductors	Electrical/Optical	THz to VL	1.2 GHz
Elastic materials	Mechanical	GHz to VL	NA
M-NEMS	Electrical	GHz to VL	1.5 kHz

M-NEMS = Micro-NanoElectroMechanical Systems.

7.2. VLBC system throughput

A technology can be regarded as "mature" if its performance characteristics are well-understood with well-established design specifications. In this respect, the *throughput* is a measure of the long-term average rate of a VLBC system, which represents a key performance metric for system designs. The indoor point-to-point VLC system throughput has been studied in [84,85]. Extension of such works to the VLBC case is not straightforward, due to further constraints regarding spatial location and system geometry. The results of [86] work well for OOK/PAM modulation and can be applied to VLBC systems. System throughput of optical channels with IM/DD is more complicated due to some additional constraints that differ from the conventional electrical or radio systems [87–89]. Specifically, in IM/DD optical systems, the information is modulated as the instantaneous optical intensity and, therefore, this peculiarity places three constraints on the transmitted signal.

The first constraint arises from the fact that the transmitted signal must be non-negative. Moreover, the eye safety requirements limit the transmit power that may be used. Eye safety limitations are generally expressed in terms of exposure duration at a specific optical power [90], which translates to a second *average* constraint on the optical power [91]. A third *peak* constraint also arises due to safety requirements [92] and, additionally, in order to avoid saturation of the optical power (or the device burns). Evaluation of the system throughput under such three constraints is challenging even for conventional VLC applications, for which closed-form expressions are still unknown [91].

In the case of VLBC applications, calculation of the system throughput is even more complicated due to the additional fact that the UL channel is *double Gaussian* (i.e., it is the product of two Gaussian random variables) due to the reflection process performed by the tag. Therefore, throughput bounds and asymptotics are essential to understand the ultimate performance limits of VLBC systems.

7.3. Metasurface-based VLB

The degree of directionality of the source and the tag significantly impacts on the VLB system performance, especially when the signal transmitted by the source is concentrated in a very narrow beam and/or the tag is characterized by a narrow field-of-view (FoV). Standard mirrors, such as optical RRs, can support only specular reflections (i.e., the incident angle and the reflection angle are identical). Consequently, mechanical change of their orientation is needed in order to reflect the beam in a desired direction.

An interesting alternative is represented by the use of gradient *metasurfaces* [93], which are synthetic materials composed of sub-wavelength metallic or dielectric structures capable of steering the incident illumination toward directions not predicted by Snell's law [94–96]. In optics, they have been used as *reconfigurable intelligent surfaces* (RISs) for the realization of artificial multichannel communication systems, aimed at improving system performance [62] or for energy efficiency maximization in VLC systems [97]. Moreover, a metasurface can also be used as a RR, albeit with much higher efficiency [98,99], or as a VLC modulator [100,101]. Tuning mechanisms of RISs for VLB applications are summarized in Table 2, along with their main characteristics.

Apart from their physical implementation, metasurfaces can be used in VLB systems in different arrangements. They can replace the RR and/or LCD shutter modulator, assuring higher efficiency, focusing capabilities, improved speed and flexibility in implementing more sophisticated modulation/coding schemes. Another usage is to improve *TX/RX efficiency*, possibly solving obstruction problems in LOS links between the source and the tag. However, there are several issues that can hinder the applicability of metasurfaces to VLB systems. First, the mathematical modeling of metasurfaces is generally involved (based on the solution of integral equations), and simple signal models, useful for system-level design, are lacking. Second, switching frequencies of current metasurfaces are inadequate for IoT applications and faster switching mechanisms based on innovative phase transition materials have to be exploited. Third, existing studies rely on space-domain design techniques only, i.e., the phase profile of the metasurface is intentionally varied by changing the state of its sub-wavelength elements at different spatial positions on the metasurface. It would be interesting to also exploit the temporal dimension of the metasurface, by varying in time the phase response of its sub-wavelength elements [102].

Space–time metasurfaces may be used to also realize out-of-band full-duplex VLB systems, for which auto-interference can be readily counteracted. Indeed, they allow to control both spatial (propagation direction) and spectral (frequency distribution) characteristics of the scattered light, thus allowing to separate at the UL RX the signal emitted by the source and the signal backscattered by the tag in the frequency domain [103].

7.4. Multiple access schemes for massive IoT

Massive IoT refers to applications that are less latency sensitive and have relatively low throughput requirements, but demand a huge volume of low-cost, low-energy consumption devices on a network with excellent coverage. The problem of designing multiple access schemes that are able to deal with the limited capabilities of the tags is still an open issue for conventional VLC [18] and it has only recently attracted attention [104–107].

In the literature of VLBC, very few works consider the problems of supporting multiple tag communications. A notable exception is RetroI2V [69], where *ad hoc* signaling protocols have been developed to detect and resolve collisions in DL/UL of an infrastructure-to-vehicle communication and networking system. Another interesting contribution is RetroMUMIMO [66], which combines MIMO-like decoding with contention-based MAC to support low-latency concurrent tag transmissions.

In our opinion, *non-orthogonal multiple-access (NOMA)* schemes [108] are more suitable for VLBC in massive IoT applications than their orthogonal counterparts, since the latter ones may require an unsustainable signaling overhead. NOMA techniques can broadly be divided into two categories, namely, *power-domain* and *code-domain* ones, wherein multiplexing is achieved by transmitting with different powers or different codes, respectively.

A power-domain NOMA scheme for conventional VLC has been proposed in [109], which implements successive interference cancellation to remove interference effects. The benefits of power-domain NOMA for VLBC have not been studied yet. On the other hand, code-domain NOMA schemes exhibit an inherent robustness against ambient reflections, i.e., the interference deriving from light reflected by other objects (such as walls or furnitures) in the ambient, by allowing easy separation of the desired signal from reflections at the RX. However, code-domain NOMA could be difficult to implement with LCD shutter modulators, due to their limitations in switch speed [36]. Use of alternative faster modulators, like RR-based or metasurface-based ones, would allow one to use code-domain NOMA schemes, improving thus system performance.

8. Conclusion

VLB is a new research field, where a number of interesting solutions have been proposed and prototyped, but many challenges and open problems still exist, both theoretical and practical ones. In this paper, we reviewed the characteristics and physical-layer treats regarding VLB, with a focus on IoT indoor applications. In particular, VLB techniques are useful whenever a strong illumination infrastructure is available and in environments where the lights are always switched on. Moreover, VLB techniques can also be profitably used outdoors, due to the availability of a natural source like the sun, which can assure high illumination levels for a significant fraction of time. Shortly, VLB techniques are among the most "biologically friendly" and "green" techniques.

Similar to any wireless communication system, the propagation channel as well as the characteristics of source/tag front-ends dictate the fundamental limits on the physical layer performance of VLB systems. Realistic propagation channel models are therefore of critical importance for VLB system design, performance evaluation, and testing. Moreover, a particularly interesting field is the adoption of metasurfaces in VLB, which could definitely replace simple RRs and LCD shutters by allowing increased flexibility and adaptivity. Finally, the design of multiple access schemes for VLB channels might facilitate the realization of the massive IoT vision, according to which low cost and low energy sensors, devices, objects, and machines communicate with each another.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article

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