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

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challenges in this area and delineate a number of future research directions. 

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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, of 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 [2], 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 emitted 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 can also be used for localization purposes, leading thus to visible light positioning (VLP) systems [3, 4, 5, 6, 7, 8, 9].

VLC techniques offer several advantages over RF ones in IoT applications. However, a fundamental limitation of existing VLC techniques is their inherent one-directional DL transmission (from the LED to the 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 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), which however requires the integration of a power-hungry active light source (a LED or a laser) in the client devices. To overcome such limitations of active VLC, many recent papers have resorted to visible light backscattering (VLB) for ultra low-power passive communication and localization.

The backscatter (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 backscattering have been designed for the purposes of communication, identification, or localization, the most popular one being radio-frequency identification (RFID) [11]. A recent evolution of RF BS is ambient backscatter [12, 13, 14, 15] wherein passive communication lever-
ages existing RF signals (such as, e.g., cellular, TV, or WiFi ones) without requiring dedicated illuminators.

In this paper, we provide a comprehensive survey of current research activities on VLB systems, which leverage backscatter principles in the optical domain to perform data communication and/or localization. Survey papers regarding conventional (i.e., active) VLC are available in the literature (see, e.g., [2, 10, 16, 17] for communication and [3, 4, 5, 6, 7, 8, 9] for localization). However, to the best of our knowledge, this is the first survey paper specifically addressing passive VLB systems. In particular, this 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 presented and their applications in several IoT domains are discussed, by focusing on weaknesses and strengths, and the main open challenges are introduced;
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 is provided, and some enabling technologies are presented in Section 3. In Section 4 channel models are reviewed. In Section 5, the state-of-the-art of VLB research is discussed 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”), equipped with a retroreflector (see Section 3.1), performs passive UL transmission by reflecting the light, after modulating it, back towards the source. Optical modulation is usually performed by means of simple LCD shutter
devices (see Sec. 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 [18]. Cheap photodiodes (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.

VLBP systems work on similar principles, where tag localization is usually performed by the transmitting LEDs on the basis of some measured parameters, such as the time-of-arrival (TOA), time-difference-of-arrival (TDOA) or received signal strength (RSS), 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. One distinct advantage of VLBP techniques over active/passive RF ones, like those based on WiFi, is that the number of LED luminaries and their power is generally much higher that that of WiFi access points [2].

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 [19]. 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, nondirected 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 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, stands between the source and the tag. Compared to their LOS counterparts, NLOS link designs ensure greatest robustness and ease of use (see also Section 4 for further details).

3. VLB-enabling technologies

In this section we describe two main enabling technologies for VLB system: 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 [20, 21, 22], satellite communications [23], and low-powered sensor networks [24, 25, 26]. Cheap RR materials are commonly available (e.g., Scotchlite™ manufactured by 3M) and are used for road signs, bicycles, and clothing for road safety [27].

One popular type of RR is the corner-cube retroreflector (CCRR) [28], 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 built as a high index-of-refraction
Figure 2: Working principle of a CCRR based on ray optics.

transparent sphere with a reflective backing [29]. A less common implementation is the phase-conjugate mirror [30], 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 RRs, as further discussed in Section 7.3.

Disregarding the actual implementation, it is common to describe [29] the behavior of a RR device by means of two angles (Fig. 3): the entrance angle $\beta$, which is the angle between the illumination direction and the normal to the RR surface, and the observation angle $\alpha$, which is the angle between the illumination direction and the viewing direction. High-quality retroreflectors work over fairly wide entrance angles, up to 45° or more (up to 90° for
Figure 3: Geometrical description of a RR: $\beta$ is the entrance angle, $\alpha$ is the observation angle.

The performance of RRs can be measured by several coefficients, the most common ones [29] are $R_I$ and $R_A$. The first one is the coefficient of retroreflected luminous intensity:

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

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:

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

where $A$ is the area of the retroreflector. Values for $RA$ of several hundred (cd/m$^2$)/lux are not uncommon [29]. Both coefficients are functions of the angles $\beta$ and $\alpha$.

It should be noted that RRs can also be used as optical modulators, by controlling the reflection mechanisms with micro-electromechanical systems.
(MEMS) [22] or semiconductor *multiple quantum wells* (MQW) technologies [27].

3.2. LCD shutters

LCD shutters are employed in consumer 3D TV glasses [31] and act as modulator devices in most VLB prototypes. An LCD shutter is characterized by a multilayer sandwich structure [32], with two linear polarizers at the ends and one liquid crystal (LC) layer in between.¹ Each polarizer obeys the *Malus law*:

\[ I_\theta = I_0 \cos^2 \theta \]  

where \( I_0 \) is the intensity of light impinging on the polarizer, \( I_\theta \) is the intensity of light that is passed through the polarizer, and \( \theta \) is the angle between the polarization direction of the polarizer and the polarization of light. If the polarization of the incident light is parallel to that of the polarizer, i.e., \( \theta = 0^\circ \), no attenuation will occur and the light will pass unaltered through the polarizer. When, instead, the two directions are perpendicular, i.e., \( \theta = 90^\circ \), 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 [33]. 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),

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¹A 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.
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.²

The most interesting features of LCD shutters are, among others, compatibility with non-coherent white light [35], low power consumption (sub-mW [27]) and low cost (0.03 $ per cm² [36]). 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 [31, 34], which limits the achievable data-rate to sub-kbps level and complicates equalization. In [31] a rising time of 1.096 ms and a falling time of 0.533 ms have been measured, whereas in [34] 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 [31]. However, LCD shutters exhibit an asymmetric response and a marked nonlinear behavior [37, 34], which make them very difficult to generate multilevel modulated signals [27]. Finally, the slow switching rate of LCD shutters might induce

²Some LCD shutters employ orthogonal polarizers at the two ends [34], in which case the encoding of voltage levels to bright/dark states is simply reversed.
flickering.

4. Channel modeling for wireless optical communications

A considerable amount of work has been carried out about channel characterization, covering both experimental measurements and computer modeling of indoor and outdoor optical wireless communications systems. In this section, we focus on indoor scenarios, which are in our opinion the most appealing ones for VLB techniques. For the characterization of outdoor optical wireless channels we directly refer to [38].

The channel characteristic of an optical wireless link is fixed for a given position of the source, tag, and surrounding reflecting objects. It changes only when these components are moved by distances in the order of centimeters [39]. Due to high bit rates and the relatively slow movement of objects and people within a room, the optical wireless channel typically varies only on a time scale of many bit periods and, hence, it may be considered quasi-static [40].

For LOS links, reflections are negligible and, consequently, the path loss is easily calculated from the knowledge of the transmitter beam divergence, receiver size, and separation distance between the source and the tag [39]. NLOS links, particularly in indoor applications, are subject to the effects of multipath propagation, similarly to RF systems. Multipath propagation causes the received signal to suffer from severe amplitude fades on the scale of a wavelength. However, optical receivers are typically equipped with large-area PDs, whose surface area is orders of magnitude larger than the transmission wavelength. In this case, the total photocurrent generated at the
receiver is proportional to the integral of the optical power over such a large
surface, thus providing an inherent spatial diversity that averages out fading
effects [39]. Although indoor optical links are inherently robust against the
effects of multipath fading, they suffer from the effects of multipath-induced
dispersion, which causes *intersymbol interference (ISI)*, thus adversely affect-
ing link performance.

Several experimental channel characterizations have been carried out [41,
42, 43, 44, 45, 46], by considering both LOS and NLOS configurations. Re-
sults have shown that the optical channel response is sensitive not only to
the position of the PD, but also to its orientation and rotation. Different
models have been proposed, e.g., ceiling bounce [47], Hayasaka-Ito [48], and
spherical [49], which are however targeted at the *infrared (IR)* region of the
electromagnetic spectrum. An accurate channel characterization for VLB
applications is still lacking (see Section 7).

Optical transceivers operating in typical indoor environments 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. The DC background photocurrent generated by the am-
bient light acts as a noise source in the receiver, referred to as *shot noise*,
which degrades the link performance. The sunlight is typically the strongest
source of shot noise and represents an unmodulated source of the ambient
light with a very wide spectral width and a maximum power spectral density
(PSD) located at about 500 nm.

All artificial ambient light sources are modulated, either by the mains fre-
quency or, in the case of some fluorescent lamps, by a high-frequency switch-
ing signal. The background current due to artificial illumination is only a 
few tens of µA, which is well below that produced by sunlight, which could 
be as high as 5 mA [50]. Incandescent lamps have a maximum PSD around 1 
µm and produce an interference signal, which is a near-perfect sinusoid with 
the same frequency of the AC grid. Only the first few harmonics carry a sig-
nificant amount of energy, and interference effects can be effectively reduced 
by using a high-pass filter (HPF) [51, 52, 53]. The interference produced 
by fluorescent lamps driven by conventional ballasts is a distorted sinusoidal 
and extends up to 20 kHz. The spectrum of the interference depends on 
the switching frequency. In this case, the interference can be modeled using 
a high-frequency component and a low-frequency component, and it can be 
effectively reduced using an HPF with a cut-off low frequency [52].

Other noise sources like IR audio headphone transmitters and a TV re-
move control unit can be viewed as sources of the noise as their operating 
wavlengths of coincide with optical wireless transceivers [48]. The aforemen-
tioned studies again pertain IR communications and the impact of ambient 
light on VLB systems deserves further investigation (see Section 7). Another 
form of noise - which is distinctive of VLB systems - is represented by the 
auto-interference: the illuminating source acts as a strong interference on the 
weak backscattered signal at the UL RX. To mitigate such a phenomenon, 
some form of shielding can be used [32]. Time-varying metasurfaces can 
also be an innovative solution for countenancing auto-interference (see Sec-
tion 7.3).
5. Existing VLB techniques

In this section, a survey of the existing VLB techniques is provided, whose main features are also summarized in Tab 1.

5.0.1. Retro-VLC [32]

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.

5.0.2. Ambient light BS communication [31]

This VLBC system exploits either ambient light or a dedicated illuminator for UL transmission. The design is similar to [32] and the developed prototype achieves a data-rate of 100 bps over a 10 cm range. Another VLBC system for UL communications is devised in [54], where 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 the system proposed in [54] is the dynamic encoding
of data, which can be performed by adopting advanced materials (such as e-ink screens or LCD shutters) whose reflection properties are adjusted in real-time.

5.0.3. Pixelated VLC-backscatter [55]

The VLBC scheme proposed in [55] employs multilevel modulation to improve the data-rate of the simple OOK-based Retro-VLC technique [32]. 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 [55] 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 throughput 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.
5.0.4. PassiveVLC [27]

The technique proposed in [27] tries to improve the design of Retro-VLC [32] 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 meoryless Manchester coding scheme employed in [32] 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, 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.

5.0.5. RetroArray [56]

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.

5.0.6. Poster [35]

It 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 [36], 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.

5.0.7. RetroI2V [57]

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.

5.0.8. RetroTurbo [34]

A VLBC prototype is implemented in [34], 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 OOK [32]. The range increases to 10 m
if the data-rate is decreased to 4 kbps. The Authors also designed a real-time demodulation algorithm and claimed a 128x rate gain (32 kbps) via emulation.

5.0.9. RETRO and PassiveRETRO [58, 59, 60]

In [58, 59, 60] several VLBP systems for localization are proposed. The RETRO system [58, 60] 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 received signal strength (RSS) measures and trilateration to achieve ultra low-power centimeter-level positioning. An improvement is the RR-based PassiveRETRO system [59], which retains the advantages of RETRO [58, 60] 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\(^3\) is used for mitigating interchannel interference and improving 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.

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\(^3\)Optical rotatory dispersion is a property of some materials that rotate the polarization of light to different extents depending on the wavelength.
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 [62, 63], 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) [64], composed by wearable or textile sensors aimed at long-term health monitoring. Indeed, WBAN 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 [65], 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 [66, 67] 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 [68] 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 [57] 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 controlling/harvesting circuitry, actually converting conventional road signs into smart, dynamic transmitters. Several usage scenarios are discussed in [57], 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 [57], 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. 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 of is 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 in ITSs [69].
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 congestonate the RF spectrum in urban environments. Possible application of interest could be, for instance, in smart parking (detection of free spaces in parking lots), environmental sensing (i.e., for pollution checking) and cultural heritage. To enable long-range communications, it is envisioned that unmanned autonomous vehicles (UAVs) can be used to relay the information gathered by VLB sensors to a central unit [70].

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 [71] (vacuum cleaners, monitoring devices, lawn mowers, etc.). 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-introsion systems, as well as into systems devoted to energy efficiency [72].
6.5. Logistics and industry

Wireless technologies, such as RFID and wireless sensor networks, are among the important enabling technologies for smart logistics [73] and industrial IoT (IIoT) [74]. 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 [54], 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 RSSI [58, 59, 60] 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 precise positioning and navigation aids in indoor environments.

The advantage of VLC and VLB techniques with respect to RF-based ones (such as RFID, WiFi, Bluetooth or 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, the presence of a return (UL) channel allows one to implement not only client-based localization, but also server-based one.
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 or 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 [75]. 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.

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. Indoor point-to-point (P2P) VLC system throughput has been studied in [76, 77]. Extension of such works to the VLBC case is not straightforward, due to further constraints regarding spatial location and system geometry. The results of [78] 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 [79, 80, 81]. 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 [82], which translates to a second average constraint on the optical power [83]. A third peak constraint also arises due to safety requirements [84] 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 [83].

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 (FOW). 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 [85], 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 [86, 87, 88]. In optics, they have
been used as reconfigurable intelligent surfaces (RISs) for the realization of artificial multichannel communication systems, aimed at improving system performance [61] or for energy efficiency maximization in VLC systems [89]. Moreover, a metasurface can also be used as a RR, albeit with much higher efficiency [90, 91], or as a VLC modulator [92, 93].

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 transmission/reception 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 [94].

Space-time metasurfaces may be used to also overcome the problem of auto-interference in VLB systems. 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 wavelength domain [95].

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 [17] and it has only recently attracted attention [96, 97, 98, 99]. In the literature of VLBC, very few works consider the problems of supporting multiple tag communications. A notable exception is RetroI2V [57], 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.

In our opinion, non-orthogonal multiple-access (NOMA) schemes [100] are more suitable for VBLC 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 NOMA: unlike power-domain NOMA, which attains multiplexing in power domain, code-domain NOMA achieves multiplexing in code domain. A power-domain NOMA scheme has been proposed in [101] for conventional VLC, 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 furnishings) 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 [32]. 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 are useful whenever a strong illumination infrastructure is available and in environments where the lights are always switched on. It is 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 system. 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.

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Figure 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 through the second polarizer.
| Scheme                        | Technology                        | Modulation               | UL data-rate [bps] | Range [m] | Tag power [μW] | Applications          | Main advantages          | Main limitations          |
|------------------------------|-----------------------------------|--------------------------|-------------------|-----------|----------------|----------------------|--------------------------|---------------------------|
| Retro-VLC [32]               | RR + LCD shutter                  | OOK w/ Manchester coding | 500               | 2.4       | 234           | Communication (IoT)  | Bidirectional, low-power, analog implementation | Low-rate, narrow field-of-view |
| Ambient light BS communication [31] | RR + LCD shutter                  | OOK                      | 100               | 0.1       | N/A           | Communication (IoT)  | Ambient light source or dedicated illuminator | Low-rate, low-range |
| Ambient light passive communication [54] | Reflective surface               | OOK w/ Manchester coding | 50                | 1         | N/A           | Identification and tracking (IoT) | Ambient light source, mobile node | Very low-rate, low-range, static encoding of information |
| Pixelated VLBC [55]          | Multiple LCD shutters             | OOK, 4-PAM, 8-PAM        | 600               | 2         | 200           | Communication (IoT)  | Multilevel modulation, high data-rate, rate adaptation | Complexity |
| PassiveVLC [27]              | RR + LCD shutter                  | TBM w/ Miller coding     | 1000              | 1         | 150           | Communication (IoT)  | High data-rate, flexible range of orientations | Reduced immunity to noise |
| RetroArray [56]              | Multiple LCD shutters             | DSM                      | 4000              | 3         | N/A           | Communication (IoT)  | High data-rate          | Complexity |
| Poster [35]                  | RR + LCD shutter                  | PQAM                     | N/A               | 2m        | N/A           | Communication (IoT)  | Flicker-free, robust to TX/RX orientation | Complexity |
| RetroI2V [61]                | Retroreflective coating           | OOK                      | N/A               | ~100      | N/A           | Communication (I2V)  | Decentralized MAC protocol, flicker-free, long range | One-way communication, only vehicular scenario |
| RetroTurbo [34]              | N/A                               | PQAM, DSM                | 8000              | 7.5       | 800           | Communication (IoT)  | High data-rate, real-time demodulation algorithm | Complexity |
| RETRO [58, 60]               | RR + LCD shutter                  | N/A                      | N/A               | 1.5       | Ultra low-power | Localization (IoT)  | Based on RSS and trilateration, centimeter-level positioning | N/A |
| PassiveRETRO [59]            | RR + linear polarizer             | PQAM                     | N/A               | 1         | Ultra low-power | Localization (IoT)  | Mitigation of interchannel interference, completely passive tag | RX complexity |

DL = downlink, UL = uplink, RR = retroreflector, DSM = delayed superimposition modulation, TBM = trend-based modulation