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An overview of outdoor visible light communications

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Abstract

In visible light communication (VLC) technology, the outdoor applications are less explored when compared to those indoors. This is due to the fact that: (1) the dual use of light-emitting diodes is not always practicable in the outdoor VLC environment; (2) the level of interference and noise is considerably higher in outdoor VLC; (3) many other communication technologies are available to be used which, due to their specific characteristics, adapt better to the outdoor environment when compared to VLC technology. Nevertheless, several outdoor VLC applications have been identified. They include and are not limited to building-to-building, vehicle-to-vehicle, and road-to-vehicle communications. Deploying light fidelity (Li-Fi) using street and park lights is also feasible. Finally, some applications exploit the ability of solar panels to simultaneously harvest the electrical energy and serve as a VLC receiving antenna. The implementation of these communication systems faces lots of challenges. Most of them are related to environmental factors such as fog, rain, sunlight, haze, snow, dust, and atmospheric disturbances. Some challenges are based on parameters such as the geometrical aspect of the light diffusion, which is Lambertian in most cases. These challenges contribute to lower interest in outdoor VLC to date. However, the environment presents several opportunities. In this article, we explore the outdoor VLC environment, review, and present some promising applications selected from the literature. Furthermore, we underline likely research opportunities based on the actual state-of-the-art and our outdoor VLC characterization experiments.

1 | INTRODUCTION

Visible light communication (VLC) technology can be used in two main transmission environments, namely, indoor VLC and outdoor VLC. Indoor VLC is a challenging topic, which presents the advantage of dual use of light sources.[1] These can simultaneously serve as illumination devices and as transmitting antennas. This advantage is not always available in outdoor VLC since there is no need of an additional light source during daylight because the sun lights up the environment. This situation dictates that many outdoor VLC applications deployed in daylight make use of light sources only for communication. As a result, outdoor VLC is less appealing. However, in the applications deployed at night, these light sources can still be used for both illumination and communication. For example, street and park lights are needed at night, they can simultaneously serve as VLC transmitting antennas and lighting devices. This is also true for automobiles front and back lights. Note that, in most of the outdoor VLC applications, the light sources are still dually exploited, even in daylight. As examples, traffic lights are used in daylight and in the night for traffic control and communication, traffic panels and traffic information displays are also used in daylight and in the night to provide directions and positions and exploited for communications.

The outdoor VLC environment thus provides a mean to several applications. It enables communication between buildings and vehicles and facilitates the use of street and park lights to render communication. It may also facilitate the task of self-driving vehicles and allows traffic lights to become VLC transmitters. The outdoor VLC environment also enables the use of solar panels to harvest energy and receive a communication signal.[2] Finally, the use of light sources as Internet relays is a possibility. It is worthy to emphasize that within these VLC applications, those based on the color shift keying (CSK) scheme[3] may inconvenience humans and animals because the blue light, especially from light-emitting diodes (LEDs), may disturb people's sleep patterns and harm nocturnal animals.[4-6] An exposure to low-intensity blue light in the evening may also provoke drowsiness and suppression of energy metabolism the following morning.[7]

To rapidly develop all these applications, a strong knowledge of the outdoor VLC environment is crucial. This environment has multiple sources of impairment. Each of these may cause message deterioration based on its own mechanism. The signal can be attenuated due to fog, rain, snow, dust, or haze.[8] Scintillation, geometrical losses, and atmospheric interference creating absorption, scattering, and/or turbulence must also be taken into account. Though we must recognize that sunlight is the main source of noise, its effects may be considerably reduced by using lenses and filters.

Against this background, in this paper, we aim to identify, define, and describe the outdoor VLC environment. Some promising outdoor VLC applications and their related practical implementation challenges are discussed. Finally, we present the sunlight profile, knowing sunlight is assumed to be considered as main interference and noise source over the analyzed environment.

The remainder of this paper is organized as follows. In Section 2, we propose a review of the eminent outdoor VLC applications. We firstly provide the state-of-the-art and, afterwards, discuss the applications. Section 3 is reserved to transmission over the outdoor VLC environment. We discuss transmitters' and receivers' structures, transmission link topology, noise, attenuation, distortion and their sources, channel model and capacity are also discussed in this section, which is concluded by a word on the modulation techniques. In Section 4, we propose a sunlight profile, and concluding remarks are provided in Section 5.

2 | PROMINENT OUTDOOR VLC APPLICATIONS

In this section, we discuss some prominent VLC applications. Note that the topics covered are not exhaustive as many other applications of VLC in the outdoor environment are not listed.

2.1 | Quick summary

A great amount of achievements have been reported in outdoor VLC experimentations.[9-20] In most of these, a high-power signal is produced for a short and medium transmission distance. Several outdoor VLC applications are meant for traffic security.[10,16-18,20] These are either vehicle-to-vehicle (V2V)–based or road-to-vehicle (R2V)–based systems. They are deployed using techniques such as on-off keying (OOK), pulse position modulation (PPM)/variable PPM (VPPM),[21] and orthogonal frequency division multiplexing (OFDM). As an example, the latter was implemented in a V2V system utilizing an optical communication image sensor.[22,23] In these systems, an array of photo detectors (PDs)[24] or a camera (fixed on the vehicle)[22] is used as a VLC receiver. These detectors must have outdoor suited characteristics related for instance to the ingress protection as defined by the International Electrotechnical Commission. They must also be provided with day/night, high-speed, antivibration and motion features, and high tracking and zooming capabilities. With the movement of the vehicle, its behavior (as communication node) becomes unstable. This nonstability motivates the models for vehicles in motion proposed in the work of Yamazato et al.[25] To enhance the receiver capacity, detecting algorithms are proposed in the work of Zhu et al.[26] In transmission using color variations, results show that it is possible to achieve an aggregate throughput of about 1.8 Gbps.[27] This is obtained under sunlight using 150, 100, and 125 MHz of bandwidth respectively for the red, green, and blue LEDs. This transmission is based on a wavelength division multiplexing technique, in which the incoming data is firstly mapped to a quadrature amplitude modulation constellation and secondly to a carrierless amplitude phase. The system uses a three-watt red-green-blue (RGB) LED to realize a communication system over 50 m in which a maximum ratio combining is exploited in the square law detector to achieve detection based on a threshold selection (TS) or direct-detection (DD) techniques. Channel models and simulations disclosing practical

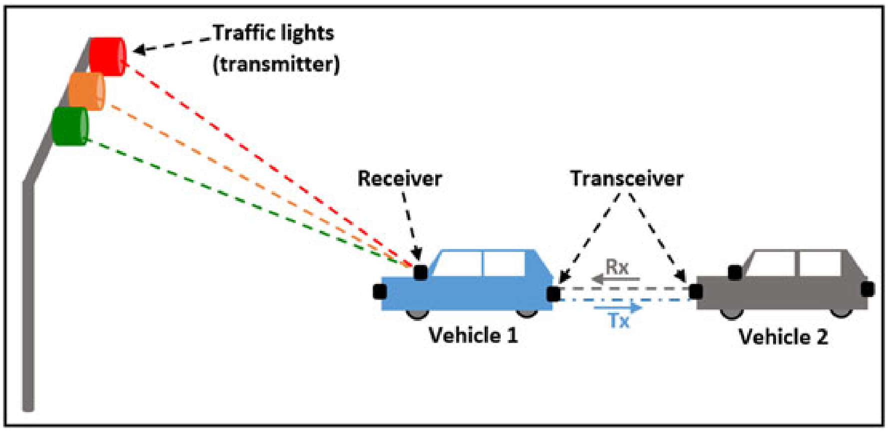

FIGURE 1 Illustration of road-to-vehicle and the vehicle-to-vehicle scenarios. Traffic lights are transmitters and vehicles are receivers, and communication is enabled between vehicles[21]

circumstances for the use of VLC technology in intelligent transportation systems are proposed in the literature, and some characteristics of outdoor VLC are highlighted.

2.2 | Traffic security

In intelligent transportation systems, traffic security is one of the most investigated topics. It may be implemented using different communication technologies including radio frequency (RF), infrared, and laser technology to mention only three. Traffic security is also among the most explored outdoor VLC applications.[9,12,13,19] It has two main scenarios: (1) R2V communications and (2) V2V communications. In outdoor VLC, these two applications are the most studied.

- **Road-to-vehicle (R2V) communications**

In R2V communications, road equipment such as traffic lights, traffic panels, and traffic information displays are exploited to control and/or provide useful information to vehicles, generally for traffic security and safety. Traffic lights are meant to control traffic and avoid blockage or accidents at road intersections in such a way that a vehicle must pass at the green light and stop at the red one, whereas at the orange light, it is recommended to slow down for a prominent stop. Due to many reasons, some drivers do not stop at the red light. Moreover, at peak hours, traffic lights might not be able to handle the number of vehicles present at the intersection. In addition, it seems useless for a vehicle to wait alone under the red light while no other vehicle is in the open direction, the system should give it the green light. Hence, it is necessary that the transportation system becomes intelligent. For example, a vehicle may be given the green light if it has been waiting alone under the red light with no vehicle in the green direction. Using traffic lights as transmitters forms an example of R2V systems, in which roads cooperate with vehicles. An illustration of R2V is shown in Figure 1.

Communication occurs between traffic lights and the vehicle in front. The receiver architecture may use a selective combining technique[21] or high-speed cameras/optical communication image sensor mounted on the vehicle.[22,23,25] The distance from traffic lights to the vehicle in front is set at high value to allow the drivers to have enough time to react according to the purpose of R2V communication system. This distance, initially set to about 25 m (see the work of Lee et al[21]) has reached 110 m (see other works[28-30]), but it must allow communication to take place. With all the improvement that are happening in fields of LED's and laser diodes' (LDs') technologies, this distance may increase again. For example, an experimental demonstration of a 130-meter link is reported in the work of Căilean et al.[31] This depends on the transmitter's optical power, the overall sensitivity of the receiver, and impairment sources present in the environment.

- **Vehicle-to-vehicle (V2V) communications**

Figure 1 also illustrates a V2V system. It shows two vehicles exchanging information. They may, for example, share speeds, next directions, and stops. In V2V systems, front and back lights are used as VLC transmitting antennas, and a VLC receiving antenna is installed on the vehicle. This detector may be a pixel image sensor, single photosensitive element (PD), or a matrix of PDs (camera). Minimum and maximum distances can be set between the tail end of a vehicle and the front end of the one following it. To ensure that the information is efficiently transmitted, 40-meter distance is usually

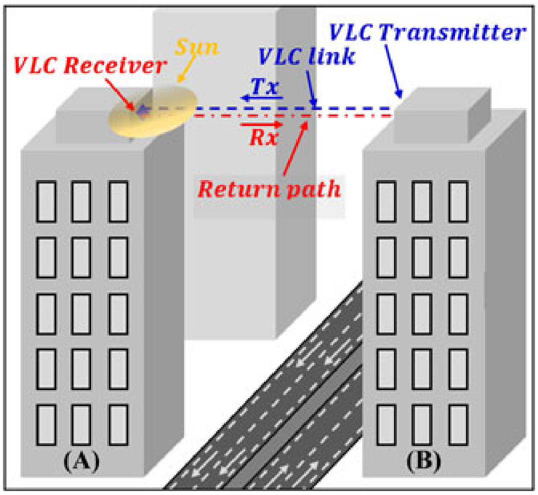

FIGURE 2 Visible light communication (VLC)–based building-to-building communications. Building *A* exchanges data with building *B*

enough for the following vehicle to brake before it reaches the one in front and a minimum of 2.5 m may be allowed as threshold distance.

2.3 | Building to building

The VLC technology may be used to connect buildings situated within a reasonable distance from each other. Building to building (B2B) can be deployed in environments such as campuses, bank buildings, and headquarters to provide access to information, data, and media. As shown in Figure 2, buildings *A* and *B* are connected through light. This connection can be simplex or duplex depending on the type of resources to be shared. In a simplex configuration, the return path is not needed as the information goes from one building to another and not vice versa. In a duplex configuration, the information goes from building *A* to *B* and vice versa. The return path, if needed, may use a different technology. Return path solutions are the Ethernet cable, power wires, RF, or infrared technologies. Nevertheless, it is worth emphasizing that, in this outdoor VLC application, LDs adapt better than LEDs, owing to their high transmission range. In this case, the return path is just a different laser light emitted from the receiver side since they have very narrow beams.

2.4 | Street and park light as access points

The use of street and park lights as access points represents part of the outdoor VLC applications under the Li-Fi denomination. Their deployment can be performed in two different ways, namely, hybrid and aggregate systems.[32] In the latter, the message to be transmitted is generated locally. This fits well in some simplex VLC applications, for example, advertisements when the end user is close to shopping centers. In hybrid systems, the information to be retransmitted is provided by a backbone network such as RF or power line communications, and the message is retransmitted through light. Figure 3 depicts a typical street and park light broadcasting scenario. It uses a diffuse topology and is essentially suitable for Internet distribution and allows the user to be mobile. Under the beam of source 1, the user receives the signal it broadcasts, and under the beam of source 2, the user relies on the second beam. Under the exchange zone, the receiver selects the signal detected with the highest signal-to-noise ratio (SNR). Note that the SNR defines the received signal power compared to the detected noise power.

3 | TRANSMISSION IN THE OUTDOOR VLC ENVIRONMENT

In this section, we discuss different types of transmitting and receiving antennas and highlight the ones that may adequately perform better in the outdoor VLC environment. We also review the outdoor VLC channel model and its capacity. The topology related to each application is highlighted. Noise sources and scenarios, attenuation, and distortion are also presented.

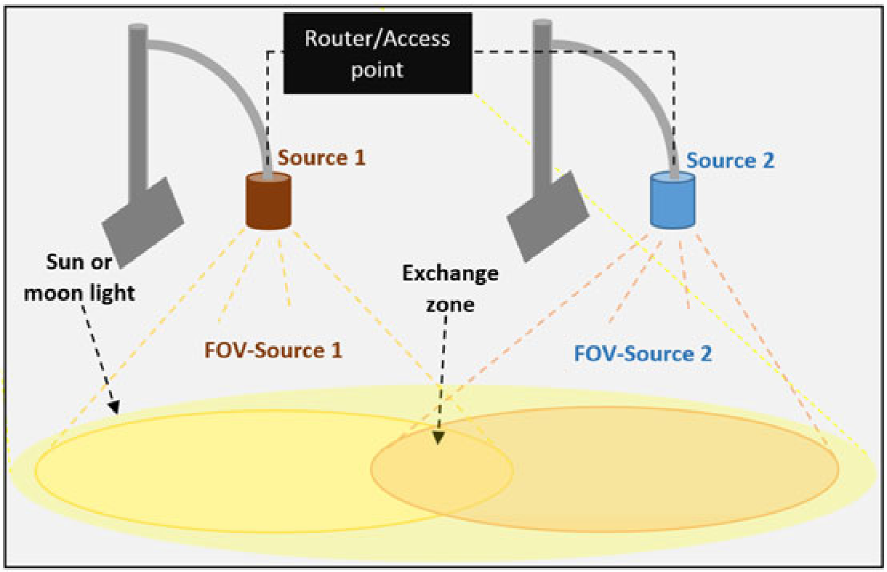

FIGURE 3 Street and park lights as access points illustrated by two sources and highlighting the need for a handover mechanism to allow the receiving node to be mobile.[32] FoV, field of view

3.1 | VLC transmitters and receivers

Two main types of light sources available to be used in VLC are LEDs and LDs. The doping of these two types of diodes may be based on the same type of materials. The difference between them lies on their structures, which is beyond the scope of this paper. Similarly to LEDs and LDs, PDs are manufactured relatively to the light frequency to be detected. Hence, those which are sensitive to LED lights are different from those which detect LD lights. In the following, we present a brief description of LEDs, LDs, and their corresponding PDs. Note that cameras, which are matrices of PDs, are good VLC receiver candidates as they adapt well in many VLC applications, which are also discussed. The simultaneous possible use of a solar panel as energy harvester and VLC receiving device is highlighted.

- **LEDs and the corresponding PDs**

In general, the same types of material are used in doping photo diodes and photo transistors, which may contain positive-negative junctions with an undoped intrinsic (I) region to form a PIN-junction.[33] They can also be avalanche-type or compound-type.[33] The PIN-type has an improved photo current when compared to the avalanche-type.[34] This makes them much solicited in VLC technology. New generations of LEDs such as high-intensity aluminum gallium arsenide (AlGaAs), gallium nitride,[35] organic LEDs, quantum dot LEDs are also available to be used. However, these are destined to specific applications. AlGaAs, which are based on an integration of LEDs and PDs, are subminiature solid LED-lamps with improved brightness and high luminous intensity and are used in optical upconverters. Organic LEDs and quantum dot LEDs have a similar structure, which contain thin flexible sheets of an organic electroluminescent material, and are utilized in visual displays. In outdoor VLC, LEDs (power LEDs) are suitable especially for R2V and V2V applications.

Because they are PD-based, complementary metal oxide semiconductor complementary metal oxide semiconductor–based cameras and image sensors are used in VLC to convert the optically modulated signal into an electrical wave. They exploit DD or TS techniques that are used in VLC detectors. In outdoor VLC, these types of detectors may appropriately fit in applications such as V2V, R2V, and Li-Fi. For example, smart devices (laptops and smart phones to mention only two) are provided with complementary metal oxide semiconductor cameras that can simultaneously be exploited as camera and as VLC receiving antennas.

A solar panel is another device that may be exploited as VLC receiving antenna. It can be simultaneously used as a power harvester and detector for VLC technology.[2] This is illustrated in Figure 4. This type of VLC receiver is destined to be used only in the outdoor VLC environment because the presence of sun rays is compulsory for energy harvesting. In VLC systems using a solar panel as a receiving antenna, the transmitted message could be generated by a satellite to provide VLC technology with a long-distance transmission, but the longest lighting range is about few hundred meters, whereas the nearest satellites are situated at about 600 km from the earth. This could also happen if the solar panel has the capacity of detecting laser lights (open topic for future research). Consequently, at

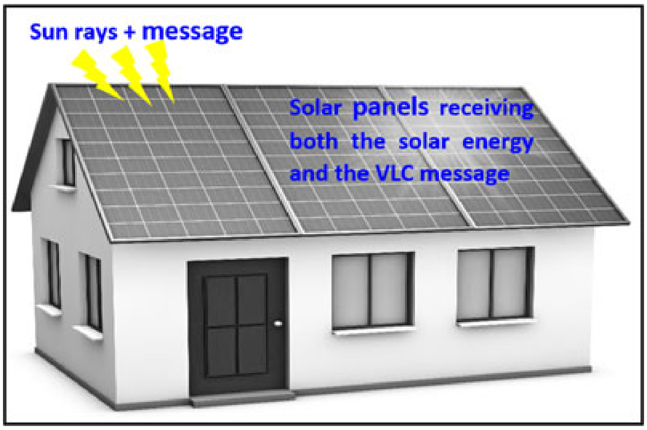

FIGURE 4 Solar panels used for energy harvesting and as visible light communication (VLC) receiving antennas

its actual state, the solar panel is constrained to be used in applications such as B2B communications. Nevertheless, using solar panels as VLC receivers is an interesting area open for further research. It may resurrect investigations related to the photophone invented by Alexander Graham Bell,[36] which, seen as the precursor of outdoor VLC, transmits a sound on the sunlight beam. This technique may be used to provide VLC technology with a long distance and access communication system. Sunlight will be exploited for lighting, data transmission, and as a power source while solar panels will simultaneously serve as a PD and power harvesting device.

- **LDs and the corresponding PDs**

Laser diodes are PIN-diodes as they are positive-negative junctions with an undoped intrinsic (I) region. Some LDs use charge injection in powering the diode laser (injection LDs). Some use an optical pumping and are called optically pumped semiconductor lasers. Most LDs are based on GaAs, indium phosphide, gallium antimonide, or gallium nitride. They are all compound semiconductors. In practice, there exist different types of LDs. The double heterostructure lasers are generally made of a combination of GaAs with AlGaAs ($Al_xGa_{(s-x)}As$). We also distinguish quantum well lasers, quantum cascade lasers, interband cascade lasers, separate confinement heterostructure lasers, distributed Bragg reflected lasers, distributed feedback lasers, vertical-cavity surface-emitting lasers, vertical-external-cavity surface-emitting lasers, and external-cavity diode lasers.[37] Some of these LD-types, such as distributed Bragg reflected laser and distributed feedback laser types, are single frequency diodes and used in optical communications (fiber optics communications especially). The applications of LDs are not limited to optical communications, and they are used in bar-code readers, laser pointers, optical recording and storage (compact disk and digital versatile disk technologies), high-definition digital versatile disk, and laser absorption spectrometry. There are industrial applications using high power lasers and medical applications (laser surgery and laser medicine). Finally, lasers are used in blu-ray technologies exploiting violet lasers among the available visible lasers (red, green, blue, and violet colors).

- **Combined LEDs and LDs**

A combination of LEDs and LDs, at a doping level, produces superluminescent diodes (SLDs) light sources. They are based on edge-emitting semiconductors. These types of diodes combine the high power and brightness of LDs with the low coherence of LEDs.[38] Nevertheless, they have technical challenges related to the optical feedback.

From this description of LEDs', LDs', and PDs' structures, it is justified to say that no LEDs, LDs, and PDs (unless the LDs typically made for fiber optic communications) are originally manufactured for communication, even less for VLC and outdoor VLC in particular. However, most implementations are performed using off-the-shelf components. For example, cameras[22] and image sensors[23,25] have been used in outdoor VLC receivers. On the one hand, a VLC transmitter is essentially made of a signal processing unit, a power allocation module, and an antenna (LED, LD, or SLD). Most of these light sources (LED, LD, or SLD) are modeled using a generalized Lambertian radiation pattern with uniaxial symmetry,[39] as shown in Figure 5A. It produces a photometric intensity, $I(\phi)$, given by

$$I(\phi) = I_0 \cos(\phi), \tag{1}$$

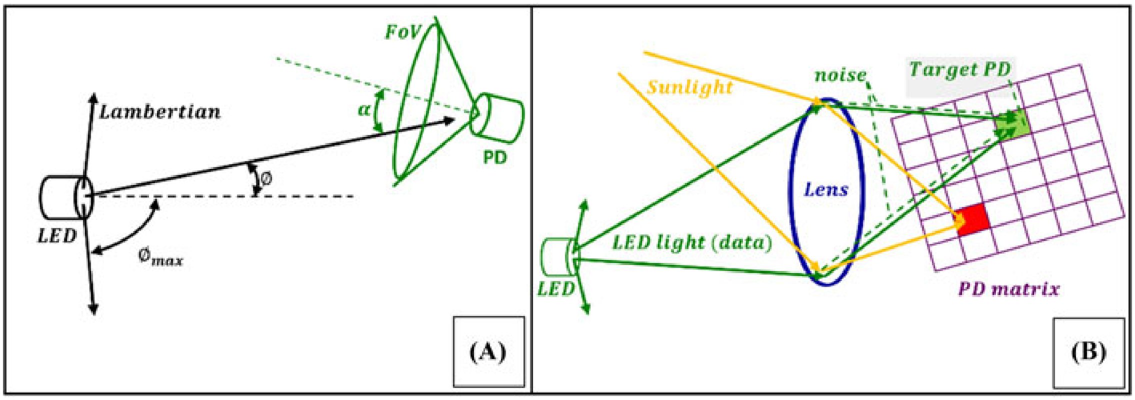

FIGURE 5 A, Geometry of a light-emitting diode (LED) model with the Lambertian radiation pattern and receiver model with its field of view; B, Principle of spatial separation between light suitable for receiver with wide field of view. PD, photo detector

where I_0 corresponds to the incident ray, which is parallel to the LED axis ($\phi = 0$). I_0 is the maximum photometric intensity that will be transferred to the PD when both the LED and the PD are locked in a direct-line-of-sight (dLOS) position. On the other hand, the receiver model consists of an optical lens system or concentrator, a PD, and a signal processing unit. These elements are specified by the receiving effective area, A, the responsivity, R, and the field of view (FoV). The receiver's FoV represents a cone in which any incoming light ray is detected by a PD (refer to Figure 5A for a VLC link model highlighting a FoV). In outdoor VLC communication systems design, the FoV represents one of the key parameters as it directly influences the quality of the service rendered. Generally, if the receiver is made of a single PD, it must have a narrow FoV because single PD elements are vulnerable to direct sunlight.[25] On the contrary, in the case of a wide FoV, an array of PDs such a camera is recommended because the use of a wide FoV combined with a matrix of PDs makes it easy to spatially separate light from different sources as demonstrated in the work of Goto et al.[23] Hence, it becomes feasible, using lenses, to redirect sunlight toward idle pixels and converge the desired light to the target pixel (see Figure 5B).[25,40]

3.2 | Topology

As the indoor VLC environment, the outdoor VLC environment accepts both line-of-sight (LOS) and non-LOS scenarios. A LOS scenario corresponds to rays going straight to the detector. We distinguish a LOS direct (dLOS) and nondirect (non-dLOS) links. The difference between dLOS and non-dLOS lies on the incidence angle of the light ray going from the light source to the PD. A non-LOS is made of rays reaching the surface of the PD after one or many reflections. As an example of non-LOS scenario, sunlight is scattered by the ozone and other layers, and many rays are additionally reflected by objects disposed over the environment such as cars and buildings. The index of this reflection is related to the nature of these objects. For instance, white paper or Aluminum have 75% reflectance, whereas concrete has 15%.

Three main topologies can be deployed over the outdoor VLC environment: the point-to-point (P2P), the diffuse, and the quasi-diffuse topologies. The difference between these lies on the scattering level of the light beams. They are adopted with regard to the application of the designed communication system. For example, only a single light ray is necessary in P2P since both transmitter and receiver are locked in a permanent position and oriented toward each other (see Figure 6A). This topology is characterized by a single transmission path with no dispersion. The P2P topology adapts well in applications such as B2B communications and corresponds to a typical dLOS VLC link and cannot be exploited for general lighting. The diffuse topology is characterized by a Lambertian pattern of the light beam with a panoramic solid angle and bears both dLOS and non-dLOS links. The alignment between the LED/LD/SLD and the PD is not necessary since the receiver can rotate but keeping its FoV within the radiation field of the transmitter, see Figure 6B. This topology enables the dual use of LEDs and is suitable for applications such as Li-Fi, V2V, and R2V; although, several path losses are expected because of its multipath nature. The P2P and diffuse topologies can be combined to form a quasi-diffuse topology.[41]

3.3 | Noise

Several noise sources are present over the outdoor VLC environment. Among them, sunlight represents the most severe noise source.[30] Its effects on the received data are destructive, even if, considerably, reduced with the use of lenses and

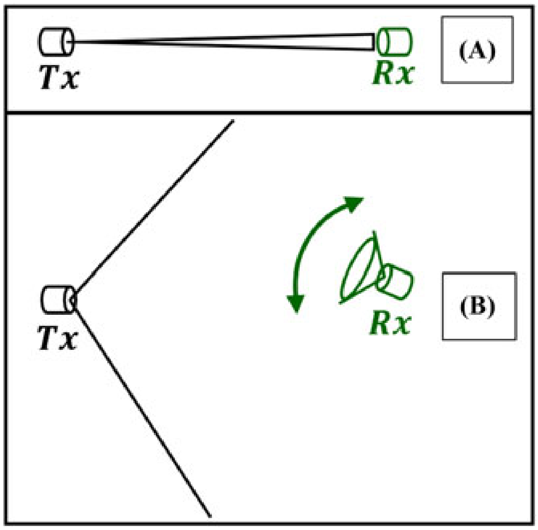

FIGURE 6 A, point-to-point topology: transmitter and receiver are locked in a permanent position and oriented toward each other; B, Diffuse topology: the alignment between light-emitting diode and photo detector is not necessary since the receiver can rotate, although keeping its field of view within the radiation field of the transmitter

filters. In the case of multichannel transmissions, these lenses and this filter also reduce the effect of crosstalk. Like in indoor VLC, shot and thermal noise are the most important noise in the outdoor VLC environment.[30] Note that most shot noise in this channel emanates from sunlight but a nonnegligible part of shot noise is produced by the message itself.

Shot noise is well described by Bose-Einstein statistics when it is generated by a coherent light. If it is engendered by a thermal light, it is best represented by Poisson statistics. Note that both Bose-Einstein and Poisson distributions have the same expectation and exhibit a Gaussian fit for large values of interacting photons. Two shot noise scenarios are identified over the outdoor VLC environment. In the receiver's structure, the lens is simultaneously used to concentrate the desired light to the targeted pixel and to distract sunlight from the target pixel (see Figure 5B).[25,40] After having been scattered by the lens, a small portion of sunlight is detected by the PD and converted to shot noise. Its effects remain noticeable as it may increase the incident light power arriving on the PD, forcing this to work in the saturation region. This may confuse the transmitted signal and make it undetectable. Note that within the sun rays arriving on the PDs' surface, some lights come from diffused and others from reflected sun rays. The second shot noise scenario is due to the light carrying the transmitted message.

The receiver circuitry generates thermal noise. This happens regardless of the voltage source used to power the circuit. It is modeled using a central limit theorem. Finally, shot and thermal noise are modeled using a normal distribution; therefore, the additive white Gaussian noise model may be used in outdoor VLC channel modeling. However, after a square law detector, the noise maybe modeled using the Chi-square statistic, which corresponds to a scenario where non-Gaussian components of noise are dominant. Thence, to use the Gaussian model, it is recommended to use biased PDs to increase thermal noise (more Gaussian components) and improve signal detection. Biasing PDs is already adopted in the literature; hence, transmission in outdoor VLC is governed by[39]

$$r(t) = Rs(t) \otimes h(t) + \omega(t), \tag{2}$$

where $r(t)$ and $s(t)$ are received and transmitted signals, respectively. Here, $h(t)$ is the channel impulse response and $\omega(t)$ the AWGN.

3.4 | Attenuation and distortion

Numerous sources of attenuation and distortion are classified in the outdoor VLC environment. The main ones are snow, fog, rain, dust, and haze. Rain, dirt, and dust create light distortion and result in a poor detectability of the desired signal. Fog and rain considerably attenuate the transmitted light, although the effects of dust and snow may be worse. For clear air and at ambient temperature, the signal attenuation is less than one dB/km but can reach 70 dB/km for fog, whereas haze creates an attenuation of about 8 dB/km.[42-44] Outdoor VLC may also suffer from atmospheric interaction owing to the fact that the propagated light passes through the atmosphere and mechanisms related to absorption, scattering, and turbulences may occur. Absorption supervenes when the molecules, in the air, interact with the transmitted wave. Scattering will increase and distort the light beam, which reduces the light intensity, affects the inverse square law principle, and leads to a poor signal detection, although without any loss of energy. This is generally caused by fog, smog, and sandstorms as they contain small particles. The effects of atmospheric interaction can be neglected in short distance communications although this might not be the case for turbulence which groups the effect of air humidity and temperature.

3.5 | The outdoor VLC channel, its model and capacity

- **Outdoor VLC channel model**

The outdoor VLC channel typically depends on the topology describing the transmission link but also significantly varies throughout the day. Considering that sunlight is the dominant noise source, the total noise may be modeled as Gaussian since shot and thermal noise are modeled using the normal distribution. This is illustrated by Equation (2). In this equation, the channel impulse response $h(t)$ is characterized by the system topology. It is obvious that the channel characteristics for a P2P topology are different from those of a diffuse link. Since a P2P channel does not include any diffuse path, has a small angle beam, and the transmitter and the receiver are locked in a permanent position, it can be modeled as a single mode Gaussian beam stochastic channel expressed as[45]

$$H_0 = \frac{2A_l e^{-\gamma L}}{\pi \theta_1^2 L^2}, \tag{3}$$

where A_l is the effective receiver area, θ the small angle beam divergence, L the transmission range, and γ the intensity attenuation coefficient. It is to be noted that γ depends on the phenomena such as haze, fog, snow, and rain.[46] Figure 7 depicts the channel gain H_0 for specific outdoor VLC environment including clear air, haze, and fog. The diffuse link has a channel different from that of the indoor VLC environment. The difference is that in outdoor VLC, the diffuse path barely reaches the receiver since reflection may not even take place. In the case it takes place, the reflected rays do not automatically reach the receiver. This is illustrated Figure 8, which shows that the paths that do not reach the receiver field of view are lost. Since this topology is suitable for some R2V and V2V applications, the receiver has rotating capabilities as the node is always in movement. Assuming that all rays reaching the receiver FoV have the same power, the link gain is also model using Equation (3), but multiplied by $\cos\alpha$, α has been the rotation angle of the receiver main axis from the transmitter direction.This gain can also be modeled taking into account other system parameters such as aperture diameters and optical efficiency factors of both the transmitter and the receiver as presented in the work of Esmail et al.[47]

- **Outdoor VLC channel capacity**

The outdoor VLC channel capacity is the highest value of the rate at which information can be reliably transmitted over the outdoor VLC environment. It is influenced by the noise amplitude and the signal strength at the receiver. To provide outdoor VLC with high quality of service (QoS), a reference signal received power may be used based on the TS technique. The received signal is measured by comparing its intensity to that of the set reference signal received power and its power is compared to that of the noise. For a constant transmitted signal, the SNR varies with the time of the day, the period of the year, and the position of the system on earth. For a full day analysis, the SNR is high at night and during the morning period. Progressively, the SNR decreases to one dB or less. The worse SNR is obtained around noon. Note that the use of high power LEDs (required for lighting) combined with optical filters having a high attenuation factor and added to a lens improves the SNR. Lenses must have an improved low-light performance and characterized by a high f-stop. The f-stop characteristic of a lens determines how much unwanted light goes through the lens. Optical filters also play an important role in the outdoor VLC as they are designed to attenuate the intensity of interference and noise signals while allowing the transmitted signal to go through. The angle between sun rays and rays carrying the message is to be considered as it directly affects the SNR and the QoS, hence, the bit error rate. This spherical angle defines the position of the transmitter-receiver link with reference to sunlight. Consequently, an efficient disposition of the communication system is necessary to scale down the effects of sunlight and provide the system with an acceptable SNR, a good channel capacity, and improved QoS. If the alignment is not perfect, then the system may face geometrical losses. Finally, the

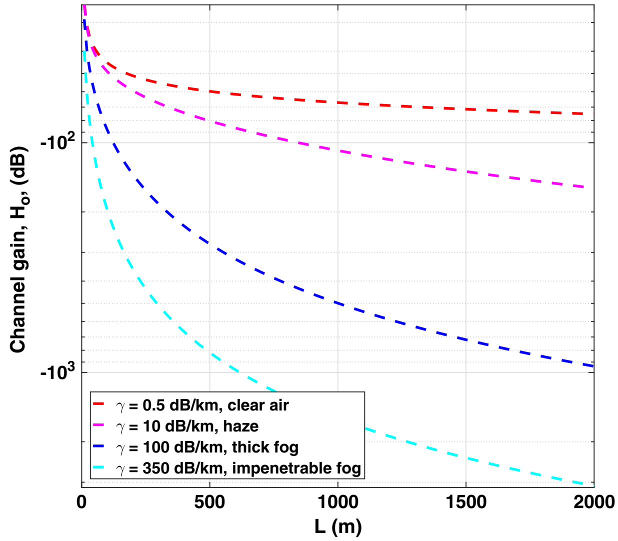

FIGURE 7 Point-to-point channel gain for clear air and under the influence of haze and fog

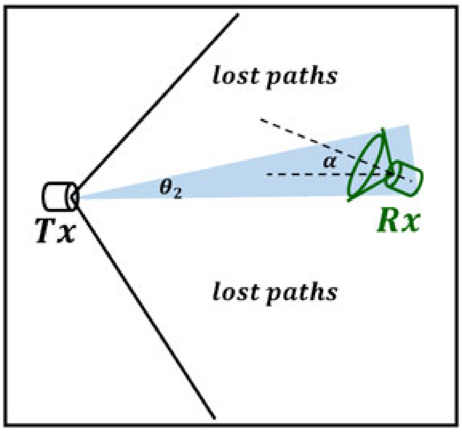

FIGURE 8 Diffuse link model assuming the reflection does not reach the receiver, which has rotating capabilities

capacity of the transmission channel is given by[1]

$$C = \log_2\left(1 + \frac{g^2 P_t}{\sigma^2 B}\right), \tag{4}$$

where P_t denotes transmit power, B the bandwidth, σ^2 the variance of AWGN, and g the channel gain. It is worth noting that turbulence and other impairment sources considerably affect this channel capacity.

- **Transmission performance measurement**

The performance measurement of the outdoor VLC is typically related to the type of impairment source found in the environment. Hence, a Chi-square, a Rayleigh, a Gamma-Gamma, or a Log-normal distributions can be used. These are all fading models and the choice depends on the channel characteristics, especially the type of impairment source. For example, some factors may not be considered in the short distance while they play an important role in the long-range transmission and vice versa. The choice of the channel model also depends on the type of fading (small-scale fading versus large-scale fading). Note that the performance of a nonfading channel is analyzed using the normal distribution. Considering scattering, the signal amplitude may follow the Rayleigh distribution in some types of scattering. Rician, Nakagami, or Weibull distributions may also be use.

3.6 | Modulation techniques

Multiple modulation techniques are carried over from other communications technologies, RF and other optical wireless communications (OWC), and used in outdoor VLC. As pointed out in the work of Kaushal and Kaddoum,[48] the choice of these modulation schemes depends on both optical power efficiency and bandwidth efficiency. Among them, the most solicited ones are OOK,[21] VPPM,[21] and OFDM. Asymmetrically clipped optical OFDM[23] and direct-current-biased optical OFDM are variances of OFDM[49] used in VLC, which could be adapted to the outdoor VLC environment. The most popular binary schemes are OOK and PPM. Generally, OOK requires adaptive threshold under strong turbulences in the atmosphere of the transmission environment[50] and uses the maximum likelihood detection rule in the detector.[51] On the other side, M-ary PPM provides the advantage of an improved average power efficiency[52] and does not require any adaptive threshold when compared to OOK. M-ary PPM is famous as it exhibits a lot of variances. They are all obtained by modifying the original PPM.[48] In the literature, the studied variances of PPM are VPPM,[21] differential PPM,[48,53] differential amplitude PPM,[48,54] pulse interval modulation,[48,55] dual header pulse interval modulation, and overlapping PPM.[48,56-58] Another modulation scheme that may be used in outdoor VLC is the optical subcarrier modulation scheme (SIM), which needs a DC bias to meet the nonnegative aspect of VLC. SIM may improve the bit error rate when it is used in conjunction with a diversity technique.[48,59] The outdoor VLC environment may also accept coherent modulation techniques like binary phase-shift keying and the differential phase-shift keying, which provides the system with a power intensity efficiency at 3.0 dB in respect to OOK. On the other hand, CSK is a typical VLC modulation technique proposed for high data rate. It uses color variation to convey information. Other techniques, such as the wavelength division multiplexing technique, have also been proposed.

3.7 | Challenges in outdoor VLC transmissions

Even though Căilean and Dimian[30] focus on the current challenges related to the use of VLC in vehicle applications, it is clear that these challenges are also those of outdoor VLC in general. We restate these challenges in a general way by choosing those which will probably affect all outdoor VLC applications. (1) SNR: As underlined in the work of Căilean and Dimian,[30] unwanted sources of light represent one of the hardest impairment sources in the outdoor VLC environment. An example of outdoor VLC channels affected by multiple undesired light sources is provided in the work of Cui et al.[60] These light sources added to other impairment sources such as sources of attenuation may lead to low SNR, which can even reach negative values (if the noise is greater than the signal). (2) Transmission coverage: In addition to unwanted signals and attenuation sources, transmission in outdoor VLC is limited to the lighting range of the light source used. At long-distance transmission, the system will again experience a low SNR. (3) Mobility: A good detection is always obtained in VLC when the transmitter and the receiver are in a LOS configuration. This allows the receiver to operate under a narrow FoV. Although this is good for efficient data transmission, it reduces the mobility of both the transmitter and the receiver.[30] Hence, the applicability of VLC outdoor is decreased because mobility is a feature required in many applications. The equipment exploited in both the transmitter and the receiver must also have day/night, high-speed, antivibration, and motion features with high tracking capabilities. (4) Another challenge is related to the development of hybrid systems involving VLC and other communication technologies such as RF and power line communications. In this case, an efficient strategy needs to be implemented. It can be amplify-and-forward, decode-and-forward, or decode-and-forward with incremental and incremental selectivity options. (5) Modulation and coding schemes: Most modulation and coding schemes, except a few such as CSK and color codes, are borrowed from other communication technologies. Their adaptability in outdoor VLC in particular are not straightforward since the channels are different. For example, the usual OFDM cannot be exploited over the VLC channel. Its nonnegative versions direct-current-biased optical OFDM and asymmetrically clipped optical OFDM have then been developed for the VLC channel.

4 | OUTDOOR VLC CHARACTERIZATION

We set up a simple experiment VLC system to numerically characterize the outdoor VLC environment using physical measurements. It exploits OOK and CSK techniques to achieve communication. The transmitter is made of two LEDs including three-watt white and RGB LEDs. The receiver, using a single PD and a matrix of color PDs (CPDs), is provided with an angular diversity detector, which helps improving the LOS connection to the transmitter. Both parts are mounted on the same horizontal axis and form a LOS system. The transmitter-receiver axis is flexible with reference to sunlight.

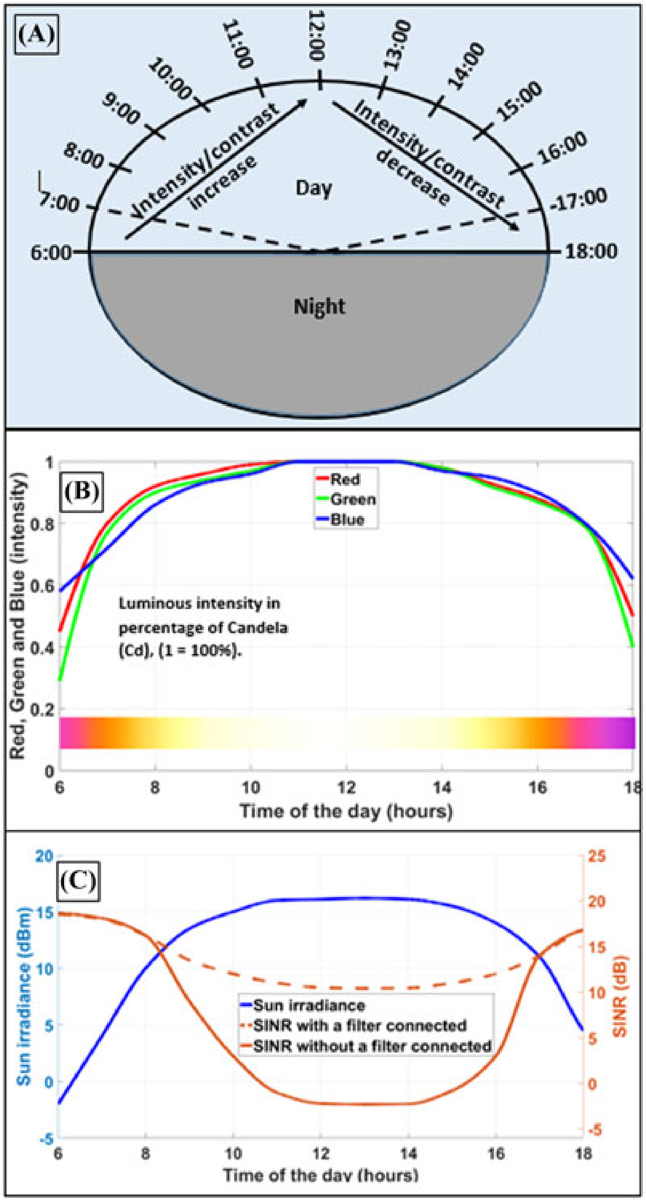

FIGURE 9 Outdoor VLC system profile using the OOK and CSK transmission techniques. A, Variation of the intensity of sunlight throughout the day; B, Variation of the RGB components of sunlight throughout the day; C, Effects of sunlight radiation on an outdoor VLC communication

The system allows frequencies up to 10 MHz. OOK, using a single white color LED, is exploited in the determination of the outdoor intensity variation and the SNR, whereas CSK is exploited to determine the daylight color profile.

The experiment is conducted in the metropolitan municipality of Ekurhuleni near Johannesburg, South Africa, latitude 26.09044° S and longitude 28.2293° E. The measurement is taken during autumn, which is the most temperate season in South Africa falling between months of February and April. During this season, the rainfall is slow with a warm sunshine and cold night.

During the night, the PD/color PD detects a very low light because moonlight includes more ultraviolet and less visible waves. An hour before 6:00, a blue-gray color is detected, it quickly becomes violet and dark-orange. From 6:00, the sunlight color turns into orange and from 8:00 or 9:00, it quickly changes to white. This color is kept with increasing intensity throughout the day until noon. From this time, we observe the reverse operation. Sunlight intensity and its contrast decrease as we progress from noon toward evening. From 17:00, we start getting an orange color, and from 18:00, the blue-gray color returns to announce the night. Figure 9A shows the variation of sunlight intensity throughout the day. Its color variation is depicted in Figure 9B, and its effects on a VLC transmission are shown in Figure 9C. Figure 9A shows that intensity and contrast are correlated and are null at night, whereas in Figure 9B, the color composition of sunlight throughout the day is given. The RGB-based variation of sunlight is shown in the top part of Figure 9B while corresponding colors are shown in the bottom part. Before 08:00 and after 16:00, outdoor VLC is characterized by a high SNR, which decreases as the day goes on until it reaches poor values at noon. It may reach zero or one dB and less, proof of the need of lenses and filters. The lack of a filter is depicted in Figure 9C by the *SNR without a filter in* curve. From noon, the SNR increases progressively until very high values at night. An edge filter was implemented in our prototype owing to its ease in discriminating adjacent wavelengths and controlling the SNR. Its effects are shown in Figure 9C by the *SNR with a filter in* curve, where the SNR is being considerably improved.

5 | CONCLUSION

This paper reviews and presented the outdoor VLC environment. Noise sources and scenarios are identified, defined, and presented. Prominent outdoor VLC applications are classified and depicted. The most important are B2B, V2V and R2V, street and park lights as access points, as well as new systems using solar panels as VLC receiving antenna. They represent interesting open fields for research in telecommunication engineering. We implemented a flexible outdoor VLC data transmission system that uses OOK and CSK with a receiver integrating both an angular diversity detector and an edge filter. This was used to perform an outdoor VLC characterization. Finally, this paper may be used as a guideline and a master plan for the outdoor extension of VLC technology.

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