An Overview of Outdoor Visible Light Communications

A. R. Ndjiongue and H. C. Ferreira

Center for Telecommunications, Department of Electrical and Electronic Engineering Science, University of Johannesburg, South Africa.

ABSTRACT

In visible light communications (VLC) technology, the outdoor applications are less explored when compared to those indoors. This is due to the fact that: *(i)* the dual use of light emitting diodes (LEDs) is not always practicable in the outdoor VLC environment; *(ii)* the level of interference and noise is considerably higher in outdoor VLC; *(iii)* 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 (B2B), vehicle-to-vehicle (V2V) and road-to-vehicle (R2V) 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 characterisation experiments.

1. INTRODUCTION

Visible light communications (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, 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 emphasise that within these VLC applications, those based on the colour shift keying (CSK) scheme [3] may inconvenience humans and animals since 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 recognise 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 analysed environment.

The remainder of the paper is organised 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 is 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) 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 example, the latter was implemented in a V2V system utilising an optical communication image sensor (OCI) [22, 23]. In these systems, an array of photodetectors (PDs) [24] or a camera (fixed on the vehicle) [22] are 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 (IEC). They must also be provided with day/night, high-speed, anti-vibration and motion features, and, high tracking and zooming capabilities. With the movement of the vehicle, its behaviour (as communication node) becomes unstable. This non-stability motivates the models for vehicles in motion proposed in [25]. To enhance the receiver capacity, detecting algorithms are proposed [26]. In transmission using colour 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 MHz, 100 MHz and 125 MHz of bandwidth respectively for the red, green and blue LEDs. This transmission is based on a wavelength division multiplexing (WDM) technique, in which, the incoming data is firstly mapped to a quadrature amplitude modulation (QAM) constellation and secondly to a carrier-less amplitude phase. The system uses a three-watt red-green-blue (RGB)-LED to realise a communication system over 50 meters 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 circumstances for the use of VLC technology in intelligent transportation systems (ITS) are proposed in the literature and some characteristics of outdoor VLC are highlighted.

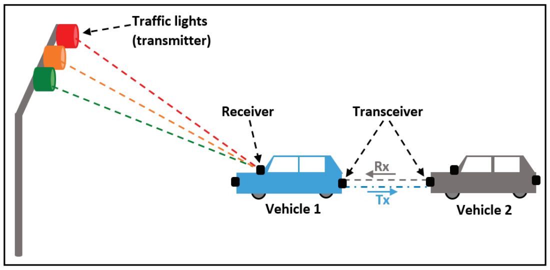

Figure 1. Illustration of road-to-vehicle and the vehicle-to-vehicle scenarios Traffic lights are transmitters and vehicles are receivers, and communication is enabled between vehicles [21].

2.2. Traffic Security

In ITS, traffic security is one of the most investigated topics. It may be implemented using different communication technologies including radio frequency (RF), infrared (IR) 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: *(i)* road-to-vehicles, R2V communications, and *(ii)* vehicles-to-vehicles, V2V, communications. In outdoor VLC, these two applications are the most studied.

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

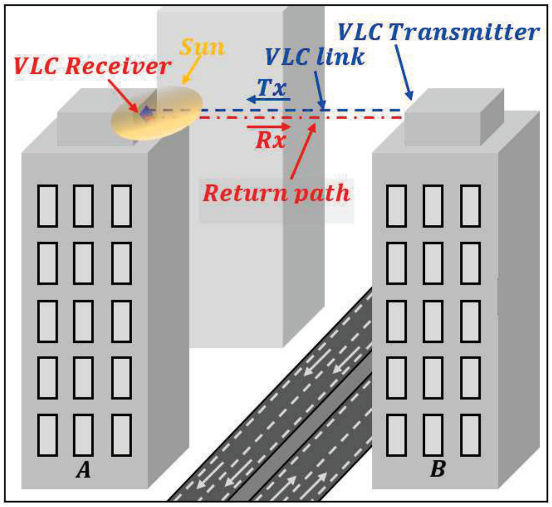

Figure 2. VLC based building-to-building communications. Building *A* exchanges data with building *B*.

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, while, 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. Also, 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 is 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 Fig. 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/OCI 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 meters [21] has reached 110 meters [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 meters link is reported in [31]. This depends on the transmitter's optical power, the overall sensitivity of the receiver and impairment sources present in the environment.

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

Fig. 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 m distance is usually enough for the following vehicle to brake before it reaches the one in front and a minimum of two and a half meters may be allowed as threshold distance.

2.3. Building-to-building (B2B)

VLC technology may be used to connect buildings situated within a reasonable distance from each other. B2B can be deployed in environments such as campuses, bank buildings and headquarters to provide access to information, data and media. As shown in Fig. 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 infra-red technologies. Nevertheless, it is worth emphasising 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 later, 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 centres. In hybrid systems, the information to be retransmitted is provided by a backbone network such as RF or power line communications (PLC), and the message is retransmitted through light. Fig. 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, he receives the signal it broadcasts and under the beam of source 2, he relies on the second beam.

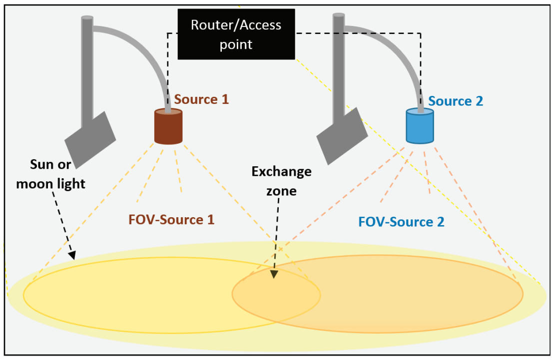

Figure 3. Street and park lights as access points, illustrated by two sources and highlighting the need for a handover mechanism to allows the receiving node to be mobile [32].

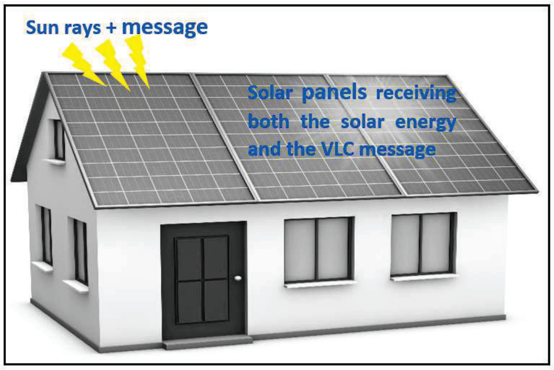

Figure 4. Solar panels used for energy harvesting and as VLC receiving antennas.

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 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.

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.

a)- 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 (PN)-junctions with an un-doped intrinsic (I) region to form a PIN-junction [33]. They can also be avalanche or compound types [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 Aluminium Gallium Arsenide (AlGaAs), Gallium Nitride (GaN) [35], Organic LEDs (OLEDs), Quantum Dots 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 sub-miniature solid LED-lamps with improved brightness and high luminous intensity and are used in optical up-converters. OLEDs and QLEDs have a similar structure, contain thin flexible sheets of an organic electro-luminescent material, and, are utilised 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 (CMOS) 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 which 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 CMOS 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 Fig. 4. This type of VLC receiver is destined to be used only in the outdoor VLC environment since 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 while the nearest satellites, is situated at about 600 km from earth. This could also happen if the solar panel has the capacity of detecting laser lights (open topic for future research). Consequently, at 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 Photo-phone invented by Alexander Graham Bell in 1880 [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.

b)- LDs and the corresponding PDs

LDs are PIN-diodes as they are PN-junctions with an un-doped intrinsic (I) region. Some LDs use charge injection in powering the diode laser (injection LDs [ILDs]). Some use an optical pumping and are called optically pumped semiconductor lasers (OPSL). Most LDs are based on gallium arsenide (GaSa), 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 GaSa with Aluminium GaSa ($\text{Al}_x\text{Ga}_{(s-x)}\text{As}$). We also distinguish quantum well lasers, quantum cascade lasers, inter-band 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 lasers and distributed feedback lasers types, are single frequency diodes and used in optical communications (fibre optics (FO) communications especially). The applications of LDs are not limited to optical communications, they are used in bar-code readers, laser pointers, optical recording and storage (compact disk (CD) and digital versatile disk (DVD) technologies), high definition DVD (HD-DVD) 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 colours).

c)- Combined LEDs and LDs

A combination of LEDs and LDs, at a doping level, produces super-luminescent diodes (SLDs) light sources. They are based on edge-emitting semiconductors. These type 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 fibre 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 modelled using a generalised Lambertian radiation pattern with uni-axial symmetry [39] as shown in Fig. 5-A. It produces a photometric intensity, $I(\phi)$, given by

$$I(\phi) = I_0 \cos(\phi), \qquad (1)$$

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 Fig. 5-A 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 [23]. Hence, it becomes feasible, using lenses, to redirect sunlight towards idle pixels and converge the desired light to the target pixel (see Fig. 5-B [25, 40]).

3.2. Topology

As the indoor VLC environment, the outdoor VLC environment accepts both LOS and non-LOS scenarios. A LOS scenario corresponds to rays going straight to the detector. We distinguish a LOS direct (dLOS) and non-direct (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 Aluminium have 75% reflectance while 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

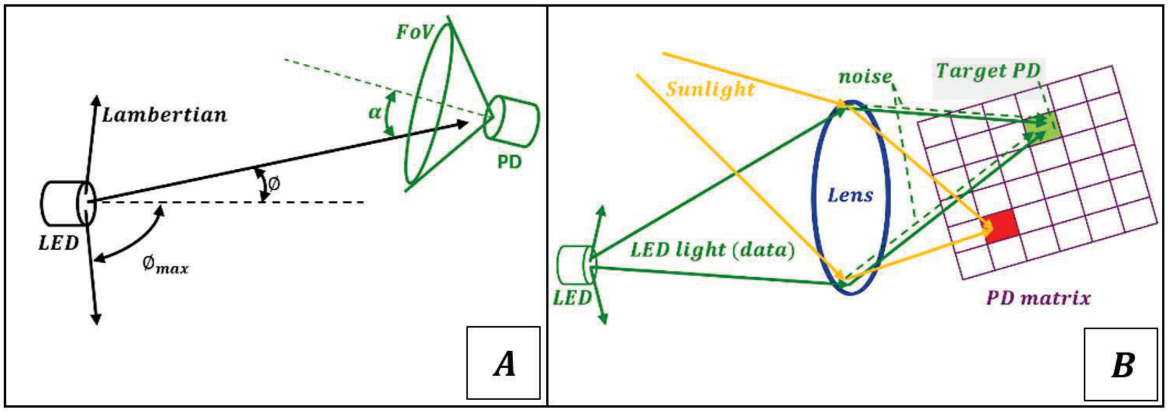

Figure 5. A/-Geometry of a LED model with the Lambertian radiation pattern and receiver model with its field of view, B/-Principle of spatial separation between light suitable for receiver with wide FoV.

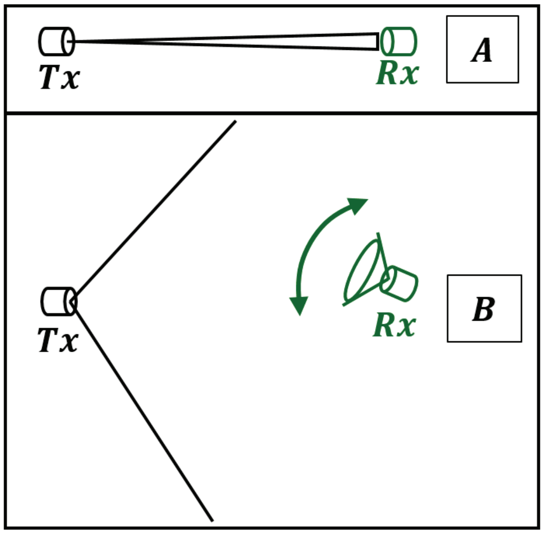

Figure 6. A/-point-to-point topology: transmitter and receiver are locked in a permanent position and oriented towards each other. B/-Diffuse topology: the alignment between LED and PD is not necessary since the receiver can rotate, although, keeping its FoV within the radiation field of the transmitter.

are adopted with regards 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 towards each other (see Fig. 6-A). This topology is characterised by a single transmission path with no dispersion. The P2P topology adapts well in applications such as building-to-building (B2B) communications and corresponds to a typical dLOS VLC link, and, cannot be exploited for general lighting. The diffuse topology is characterised 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 Fig. 6-B. 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 multi-path nature. 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 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 non-negligible 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 Fig. 5-B [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.

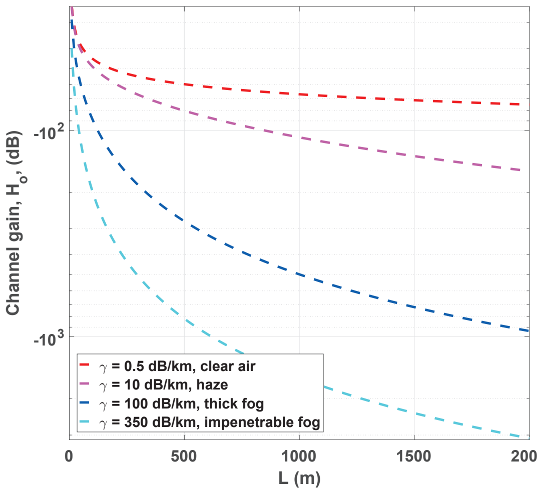

Figure 7. P2P channel gain for clear air and under the influence of haze and fog.

The receiver circuitry generates thermal noise. This happens regardless of the voltage source used to power the circuit. It is modelled using a central limit theorem. Finally, shot and thermal noise are modelled using a normal distribution, therefore, the additive white Gaussian noise (AWGN) model may be used in outdoor VLC channel modelling. However, after a square law detector, the noise maybe modelled 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, thought 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 while 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

a)- **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 modelled as Gaussian since shot and thermal noise are modelled using the normal distribution. This is illustrated by Eq. 2. In this equation, the channel impulse response $h(t)$ is characterised 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 modelled 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]. Fig. 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 Fig. 8 which shows that the paths which 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 Eq. 3, but multiplied by $\cos\alpha$, α been the rotation angle of the receiver main axis from the transmitter direction. This gain can also be modelled taking into account other system parameters such as aperture diameters and optical efficiency factors of both the transmitter and the receiver as presented in [47].

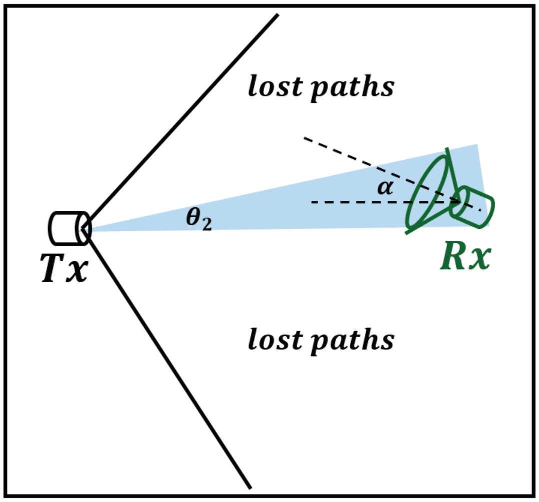

Figure 8. Diffuse link model assuming the reflection does not reach the receiver, which has rotating capabilities.

b)- 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 (RSRP) may be used based on the threshold selection technique. The received signal is measured by comparing its intensity to that of the set RSRP 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 characterised 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 capacity of the transmission channel is given by [1]

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

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

c)- 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 non-fading channel is analysed 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 [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. ACO- [23] and DCO-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 (MPPM) provides the advantage of an improved average power efficiency [52] and does not require any adaptive threshold when compared to OOK. MPPM 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 (DPPM) [48, 53], differential amplitude PPM (DAPPM) [48, 54], pulse interval modulation (PIM) [48, 55], dual header PIM (DHPIM) and overlapping PPM (OPPM) [48, 56–58]. Another modulation scheme that may be used in outdoor VLC is the optical sub-carrier modulation scheme (SIM) which needs a DC bias to meet the non-negative aspect of VLC. SIM may improve the BER 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 (BPSK) and the differential PSK (DPSK), 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 colour 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 [30] focusses 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. *(i)* SNR: As underlined in [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 [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). *(ii)* 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. *(iii)* Mobility: A good detection is always obtained in VLC when transmitter and 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 transmitter and receiver [30]. Hence, the applicability of VLC outdoor is decreased since mobility is a feature required in many applications. The equipment exploited in both transmitter and receiver must also have day/night, high-speed, anti-vibration and motion features with high tracking capabilities. *(4i)* Another challenge is related to the development of hybrid systems involving VLC and other communication technologies such as RF and PLC. In this case, an efficient strategy needs to be implemented. It can be amplify-and-forward (AF), decode-and-forward (DF) or DF with incremental and incremental selectivity options. *(5i)* Modulation and coding schemes: Most modulation and coding schemes, except few such as CSK and colour codes, are borrowed from other communication technologies. Their adaptability in outdoor VLC in particular are not straight forward since the channels are different. For example the usual OFDM cannot be exploited over the VLC channel. Its non-negative versions DCO- and ACO-OFDM have then been developed for the VLC channel.

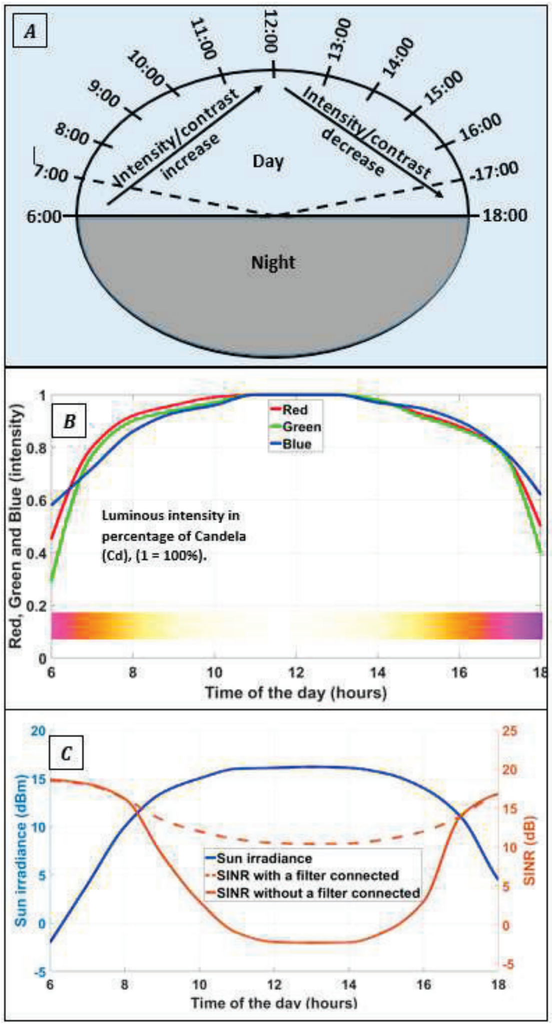

Figure 9. Outdoor VLC system profile using the OOK and CSK transmission techniques. A/- Variation of the intensity of sunlight throughout the day, B/- Variation of the RGB components of sunlight throughout the day, C/- Effects of sunlight radiation on an outdoor VLC communication.

4. OUTDOOR VLC CHARACTERISATION

We set up a simple experiment VLC system to numerically characterise 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 colour 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. The system allows frequencies up to 10 MHz. OOK, using a single white colour LED, is exploited in the determination of the outdoor intensity variation and the SNR while CSK is exploited to determine the daylight colour profile.

The experiment is conducted in the metropolitan municipality of Ekurhuleni near Johannesburg, South Africa, latitude 26.09044^o S and longitude 28.2293^o 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/CPD detects a very low light because moonlight includes more ultraviolet and less visible waves. An hour before six, a blue-grey colour is detected, it quickly becomes violet and dark-orange. From six, the sunlight colour turns into orange and from eight or nine, it quickly changes to white. This colour 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 towards evening. From 17:00, we start getting an orange colour, and, from eighteen the blue-grey colour returns to announce the night. Fig. 9-A shows the variation of sunlight intensity throughout the day. Its colour variation is depicted in Fig. 9-B and its effects on a VLC transmission are shown in Fig. 9-C. Fig. 9-A shows that intensity and contrast are correlated and are null at night, while in Fig. 9-B, the colour composition of sunlight throughout the day is given. The RGB based variation of sunlight is shown in the top part of Fig. 9-B while corresponding colours are shown in the bottom part. Before 08:00 and after 16:00, outdoor VLC is characterised 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 Fig. 9-C 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 Fig. 9-C 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.

REFERENCES

1. Ndjiongue AR, Ferreira HC, Ngatched T. Visible light communications (VLC) technology. *Wiley Encyclopedia of Electr. and Electron. Eng.* Jun 2015; :1–15.
2. Wang Z, Tsonev D, Videv S, Haas H. On the design of a solar panel receiver for optical wireless communications with simultaneous energy harvesting. *IEEE J. Sel. Areas Commun.* Aug 2015; **33**(8):1612–1623.
3. Association IS, *et al.*. IEEE Std. for Local and metropolitan area networks-Part 15.7: Short-Rang Wireless Optical Communication Using Visible Light. *IEEE computer Society* 2011; .
4. Mats-Olof Mattsson and Jung T and Proykova A. Health effects of artificial light. *Scientific Committee on Emerging and Newly Identified Health Risks (SCENIHR)* Mar 2012; :1–118.
5. Alina Bradford, LIVE SCIENCE. How blue LEDs affect sleep Feb 2016. URL https://www.livescience.com/53874-blue-light-sleep.html.
6. Louis J Kraus, AMERICAN MEDICAL ASSOCIATION. Human and Environmental Effects of Light Emitting Diode (LED) Community Lighting 2017. URL http://darkskyarkansas.com/wp-content/uploads/2017/01/DarkSideBlueLight.pdf.
7. Kayaba M, Iwayama K, Ogata H, Seya Y, Kiyono K, Satoh M, Tokuyama k. The effect of nocturnal blue light exposure from light-emitting diodes on wakefulness and energy metabolism the following morning. *Environmental health and preventive medicine* Sep 2014; **19**(5):354–61.
8. Navidpour SM, Uysal M, Kavehrad M. BER performance of free-space optical transmission with spatial diversity. *IEEE Trans. Wireless Commun.* Aug 2007; **6**(8):2813–2819.
9. Căilean AM, Cagneau B, Chassagne L, Dimian M, Popa V. Novel receiver sensor for visible light communications in automotive applications. *IEEE Sensors J.* Apr 2015; **15**(8):4632–4639.
10. Căilean AM, Dimian M, Popa V, Chassagne L, Cagneau B. Novel DSP receiver architecture for multi-channel visible light communications in automotive applications. *IEEE Sensors J.* Feb 2016; **16**(10):3597–3602.
11. Căilean AM, Dimian M. Impact of IEEE 802.15. 7 standard on visible light communications usage in automotive applications. *IEEE Commun. Mag.* Apr

2017; **55**(4):169–175.

12. Liu J, Chan PWC, Ng DWK, Lo ES, Shimamoto S. Hybrid visible light communications in intelligent transportation systems with position based services. *IEEE GLOBECOM WORKSHOPS (GC Wkshps), Anaheim, CA, USA*, 2012; 1254–1259.
13. Kumar N, Lourenço N, Terra D, Alves LN, Aguiar RL. Visible light communications in intelligent transportation systems. *Proc. IEEE Symp. Intell. Vehicles (IV), Alcala de Henares, Spain*, 2012; 748–753.
14. Lourenço N, Terra D, Kumar N, Alves LN, Aguiar RL. Visible light communication system for outdoor applications. *Proc. 28th IEEE Int. Symp. Commun. Sys., Netw. & Digital Signal Processing (CSNDSP), Poznan, Poland*, 2012; 1–6.
15. Căilean A, Cagneau B, Chassagne L, Topsu S, Alayli Y, Blosseville JM. Visible light communications: Application to cooperation between vehicles and road infrastructures. *Proc. IEEE Symp. Intell. Vehicles (IV), Alcala de Henares, Spain*, 2012; 1055–1059.
16. Căilean AM, Cagneau B, Chassagne L, Popa V, Dimian M. A survey on the usage of DSRC and VLC in communication-based vehicle safety applications. *Proc. 21st IEEE Symp. Commun. Vehicular Technol. Benelux (SCVT), Delft, Netherlands*, 2014; 69–74.
17. Căilean AM, Dimian M. Toward environmental-adaptive visible light communications receivers for automotive applications: a review. *IEEE Sensors J.* Feb 2016; **16**(9):2803–2811.
18. Béchadergue B, Chassagne L, Guan H. Visible light phase-shift rangefinder for platooning applications. *Proc. 19th IEEE Int. Conf. Intell. Transport. Sys. (ITSC), Rio de Janeiro, Brazil*, 2016; 2462–2468.
19. Kumar N, Alves LN, Aguiar RL. Design and analysis of the basic parameters for traffic information transmission using VLC. *Proc. 1st IEEE Int. Conf. Wireless Commun., Vehicular Technol., Inf. Theory and Aerospace & Electron. Sys. Technol., Aalborg, Denmark*, 2009; 798–802.
20. Căilean AM, Cagneau B, Chassagne L, Topsu S, Alayli Y, Dimian M. Visible light communications cooperative architecture for the intelligent transportation system. *Proc. 20th IEEE Symp. Commun. Vehicular Technol. Benelux (SCVT), Namur, Belgium*, 2013; 1–5.
21. Lee IE, Sim ML, Kung FWL. Performance enhancement of outdoor visible-light communication system using selective combining receiver. *IET Optoelectron.* Feb 2009; **3**(1):30–39.
22. Takai I, Harada T, Andoh M, Yasutomi K, Kagawa K, Kawahito S. Optical vehicle-to-vehicle communication system using LED transmitter and camera receiver. *IEEE Photon. J.* Oct 2014; **6**(5):1–14.
23. Goto Y, Takai I, Yamazato T, Okada H, Fujii T, Kawahito S, Arai S, Yendo T, Kamakura K. A new automotive VLC system using optical communication image sensor. *IEEE Photon. J.* Jun 2016; **8**(3):1–17.
24. Nishimoto S, Yamazato T, Okada H, Fujii T, Yendo T, Arai S. High-speed transmission of overlay coding for road-to-vehicle visible light communication using LED array and high-speed camera. *Proc. IEEE GLOBECOM WORKSHOPS (GC Wkshps), Anaheim, CA, USA*, 2012; 1234–1238.
25. Yamazato T, Kinoshita M, Arai S, Souke E, Yendo T, Fujii T, Kamakura K, Okada H. Vehicle motion and pixel illumination modeling for image sensor based visible light communication. *IEEE J. on Sel. Areas in Commun.* Sep 2015; **33**(9):1793–1805.
26. Zhu YJ, Sun ZG, Zhang JK, Zhang YY. A fast blind detection algorithm for outdoor visible light communications. *IEEE Photon. J.* Dec 2015; **7**(6):1–8.
27. Wang Y, Huang X, Tao L, Chi N. 1.8-Gb/s WDM visible light communication over 50-Meter outdoor free space transmission employing CAP modulation and receiver diversity technology. *Proc. Opt. Fiber Commun. Conf. and Exhibition (OFC)*, 2015; 1–3.
28. Saito T, Haruyama S, Nakagawa M. A new tracking method using image sensor and photo diode for visible light road-to-vehicle communication. *Proc. 10th IEEE Int. Conf. on Advanced Commun. Technol. (ICACT)*, vol. 1; 673–678.
29. Okada S, Yendo T, Yamazato T, Fujii T, Tanimoto M, Kimura Y. On-vehicle receiver for distant visible light road-to-vehicle communication. *Proc. IEEE Symp. Intelligent Vehicles*; 1033–1038.
30. Căilean AM, Dimian M. Current challenges for visible light communications usage in vehicle applications: A survey. *IEEE Commun. Surveys Tuts.* 2017; **19**(4):2681–2703.
31. Căilean AM, Dimian M, Done A. Enhanced design of visible light communication sensor for automotive applications: Experimental demonstration of a 130 meters link. *Proc. 1st Global LIFI Congress, Paris, France*, IEEE, 2018; 1–4.
32. Ayyash M, Elgala H, Khreishah A, Jungnickel V, Little T, Shao S, Rahaim M, Schulz D, Hilt J, Freund R. Coexistence of WiFi and LiFi toward 5G: Concepts, opportunities, and challenges. *IEEE Commun. Mag.* Feb 2016; **54**(2):64–71.
33. Campbell J, Dentai A, Qua G, Ferguson J. Avalanche InP/InGaAs heterojunction phototransistor. *IEEE J. Quantum Electron.* Jun 1983; **19**(6):1134–1138.
34. Hata S, Kajiyama K, Mizushima Y. Performance of PIN photodiode compared with avalance photodiode in the longer-wavelength region of 1 to 2 μm. *IET Electron. Lett.* 1977; **13**(22):668–669.
35. Rajbhandari S, McKendry JJ, Herrnsdorf J, Chun H, Faulkner G, Haas H, Watson IM, OBrien D, Dawson MD. A review of gallium nitride leds for multi-gigabit-per-second visible light data

communications. *Semicond. Sci. and Technol.* Apr.; **32**(2).
36. WIKIPEDIA. Photophone 2018. URL `https://en.wikipedia.org/wiki/Photophone`.
37. WIKIPEDIA. Laser diode 2017. URL `https://en.wikipedia.org/wiki/Laser_diode`.
38. WIKIPEDIA. Superluminescent diode 2016. URL `https://en.wikipedia.org/wiki/Superluminescent_diode`.
39. Kahn JM, Barry JR. Wireless infrared communications. *Procc. IEEE.* Feb 1997; **85**(2):265–298.
40. Yamazato T, Takai I, Okada H, Fujii T, Yendo T, Arai S, Andoh M, Harada T, Yasutomi K, Kagawa K, *et al.*. Image-sensor-based visible light communication for automotive applications. *IEEE Commun. Mag.* 2014; **52**(7):88–97.
41. Hranilovic S. *Wireless optical communication systems*. Springer Science, 2005.
42. Beshr M, Aly MH. Outdoor wireless optical communication system attenuation at different weather conditions. *International J. Opt.* 2015; .
43. Kim II, McArthur B, Korevaar EJ. Comparison of laser beam propagation at 785 nm and 1550 nm in fog and haze for optical wireless communications. *Opt. Wireless Commun.*, vol. 4214, International Society for Optics and Photonics, 2001; 26–38.
44. Ali MAA, Mohammed MA. Effect of atmospheric attenuation on laser communications for visible and infrared wavelengths. *J. Al-Nahrain Univ* 2013; **16**(3):133–140.
45. Borah DK, Boucouvalas AC, Davis CC, Hranilovic S, Yiannopoulos K. A review of communication-oriented optical wireless systems. *EURASIP J. Wireless Commun. Netw.* 2012; **2012**(1):91.
46. Chan VW. Free-space optical communications. *IEEE J. Lightw. technol.* 2006; **24**(12):4750–4762.
47. Esmail MA, Fathallah H, Alouini MS. Outdoor FSO communications under fog: Attenuation modeling and performance evaluation. *IEEE Photon. J.* Aug 2016; **8**(4):1–22.
48. Kaushal H, Kaddoum G. Optical communication in space: Challenges and mitigation techniques. *IEEE Commun. Surveys Tuts.* 2017; **19**(1):57–96.
49. Armstrong J. OFDM for optical communications. *IEEE J. Lightw. Technol.* 2009; **27**(3):189–204.
50. Viswanath A, Kaushal H, Jain V, Kar S. Evaluation of performance of ground to satellite free space optical link under turbulence conditions for different intensity modulation schemes. *Proc. SPIE, California, USA* 2014; :897 106–1.
51. Zhu X, Kahn JM. Pilot-symbol assisted modulation for correlated turbulent free-space optical channels. *Proc. SPIE, Sans Diego, CA, USA*, vol. 4489, 2002; 138–145.
52. Hemmati H. *Deep space optical communications*, vol. 11. John Wiley & Sons, 2006.
53. Zwillinger D. Differential PPM has a higher throughput than PPM for the band-limited and average-power-limited optical channel. *IEEE trans. inf. theory* 1988; **34**(5):1269–1273.
54. Gopal P, Jain VK, Kar S. Performance analysis of ground to satellite FSO system with DAPPM scheme in weak atmospheric turbulence. *Int. Conf. on Fibre Opt. and Photon.*, Optical Society of America, 2012; WPo–43.
55. Liu C, Yao Y, Tian J, Yuan Y, Zhao Y, Yu B. Packet error rate analysis of DPIM for free-space optical links with turbulence and pointing errors. *Chinese Opt. Lett.* 2014; **12**(A01):1–4.
56. Choudhary M, Bose R, Jain V. Study of trellis coded overlapping ppm and overlapping multi-pulse ppm schemes for deep space optical communication systems. *Proc. Int. Conf. Optoelectron. Fiber Opt. Photon.*, 2004; 1–10.
57. Georghiades CN. Modulation and coding for throughput-efficient optical free-space links 1993; .
58. Georghiades CN. Modulation and coding for throughput-efficient optical systems. *IEEE Trans. Inf. Theory* 1994; **40**(5):1313–1326.
59. Kaushal H, Jain VK, Kar S. Improvement of ground to satellite FSO link performance using transmit diversity in weak atmospheric turbulence. *IEEE Int. Conf. on Intell. and Advanced. Sys. (ICIAS)*, 2010; 1–6.
60. Cui K, Chen G, Xu Z, Roberts RD. Experimental characterization of traffic light to vehicle VLC link performance. *Proc. IEEE GLOBECOM Workshops (GC Wkshps)*, 2011; 808–812.

AUTHOR'S BIOGRAPHY

Alain Richard Ndjiongue received Masters (M. Eng.) and Doctorate (D. Eng.) degrees in Electrical and Electronic Engineering from the University of Johannesburg, Johannesburg, South Africa, in 2013 and 2017, respectively. He is presently involved in research with the Centre for Telecommunications (CfT), University of Johannesburg. I have authored/co-authored several peer reviewed journals and conference papers and also, reviewed for some notable journals in my field including IEEE Communications Magazine, IEEE Communications Letter (Exemplary Reviewer 2017), IEEE Selected area on Communications, IEEE Systems Journal, IEEE Transactions on Vehicular Technology, and Optical Society of America (Exemplary Reviewer 2017). His research interests include emerging telecommunications engineering, power line communications, visible light communications, outdoor visible light channel, adaptive modulation technique, physical layer security, MIMO communication systems, signal constellation design, hybrid systems involving the radio frequency and the visible spectrum, trellis coded modulations, and coding and forward error correction (FEC) for hybrid and