Outdoor Optical Wireless Communication: potentials, standardization and challenges for Smart Cities

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***Abstract*— With the growth in number and diversity of devices using RF (Radio Frequency) technologies, e.g. in the frame of IoT (Internet of Things), the available RF spectrum is getting overcrowded with these newcomers. As it is a limited and regulated resource, alternative solutions need to be found to avoid a possible shortage of wireless frequencies. Among the new potential technologies, Optical Wireless Communication (OWC), the family of communication techniques that uses visible, infrared or UV spectra to transmit data, is gaining popularity. Applications of OWC technologies are, for now, related to indoor communications. Nevertheless, outdoor OWC applications are also promising, particularly in the context of smart cities with applications such as outdoor urban Li-Fi (Light Fidelity) or IoT optical interconnections with urban furniture. The aim of this paper is to review the current status of outdoor OWC systems and their standardization, as well as identify their potential and the challenges they face with regard to the deployment of Smart Cities.**

Keywords—Visible Light Communication, Optical Wireless Communication, review, outdoor, smart city

I. INTRODUCTION

Every discipline has its own vision and definition of what a Smart City is. Depending on the considered perspective, a Smart City can be defined as, for example, a hyper-technological city, or as a citizen-centric city where all the services are optimized for a better experience, or even as a city designed to make people feel good [1]. The common denominator of all these definitions is technology, in the broad sense, as the enabler of an energy and transport-efficient city, focused on the citizen experience. Since few decades, communication technology has been developing at a fast rate. People worldwide have joined this evolution and a significant part of the population possesses at least one connected device, centralizing many services. Meanwhile, Smart Cities aim to have efficient traffic, waste or energy management systems to mention just a few. Those applications require the presence of connected sensors or devices in the city. In that context, mobile and network operators must adapt their offer in order to keep up with both the city's technological evolution and the expectations of people. However nowadays, the diversity of devices (e.g. tablets, sensors in the city or smartwatches) is increasing sharply and increasingly taking importance in the use of the telecommunication networks, making it critical to find new ways to connect other devices seamlessly. Furthermore, with the growth in number and diversity of devices in the city, the release of some of the RF (Radio Frequency) spectrum will be necessary to avoid the possible shortage of wireless frequencies. In response to this possible spectrum "crunch" [2] [3], Optical Wireless Communication (OWC) can be part of a solution, as it usually uses the unlicensed ultraviolet, visible or infrared light spectrum bands.

The three main bands of interest for OWC are: the UV band, the visible band and the IR band. Researchers have been working on UltraViolet Communication (UVC) applications for about a decade [4] [5], mainly in the frame of long-distance non-line-of-sight (nLoS) communications [6] [7]. The UV band is defined from 100 to 400 nm [8] and is divided into three zones: UV-A (400 to 315 nm), UV-B (315 to 280 nm) and UV-C (280-100 nm). All three can damage the skin, the importance of their physiological effects depending on the wavelength (the smallest wavelength, the greatest effect). Therefore, this technology has to be avoided and is not discussed in this paper as part of a possible outdoor urban solution to free up the RF spectrum for smart cities users. Visible light covers the 400 to 750 nm range, representing 370 THz of unlicensed spectrum. This is much wider than the 300 GHz [9] of RF range. This corresponds to a very attractive spectrum enhancement factor of 1230 making Visible Light Communication (VLC) a "hot research topic" within the OWC family. The infrared (IR) spectrum extends from the visible nominal red edge at 750 nm up to 1 mm. Optical communications take place in the near-IR and IR LEDs are commercially available until 1720 nm [5]. IR communication is a ripe technique [10] [11], it is mainly used in Free Space Optics (FSO) communications targeting long distance outdoor communication.

Within the framework of cities, OWC applications are good candidates to overcome the future radio frequency shortage. On the one hand, already existing FSO applications can be used to communicate between two distant points using IR LASER beams [12]. On the other hand, since their introduction and adoption, cities are increasingly installing LEDs to enlighten their streets and to reduce their energy consumption [13]. Streetlights therefore become smart thanks to occupancy and ambient light sensors reacting to the presence of people or cars in the environment. With this smart lighting infrastructure in place, an emerging technology can take a step further and combine lighting and Visible Light Communications (VLC).

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Most VLC and IR systems are mainly designed for indoor applications, but research interest is nowadays shifting to outdoor environments. This paper presents what are the challenges of VLC and OWC systems are in outdoor environment scenarios, as well as their benefits and applications in the frame of Smart Cities.

First, a brief description of a generic point-to-point unidirectional VLC system is sketched (section II), followed by an overview of the possibilities of outdoor OWC (section III). Then, the specific challenges for the outdoor environment are discussed (section IV). Finally, some conclusions are drawn about the future of VLC outdoor communications in the frame of Smart Cities (section V).

II. Schematics of a VLC System

This section deals with VLC communication systems as it is identified as having high potential of application in the context of Smart Cities. It presents each component of this communication link on a generic point of view. Whether the VLC system is designed for indoor or for outdoor environments, both have the same main components except for the voltage levels handled by the drivers and for the number of LEDs used to communicate. A VLC system has the same schematics as any telecommunication system. Fig. 1 presents the main components of this communication link from a generic point of view. The rest of the section deepens the description of each of them.

A. Transmitter

Any standard off-the-shelf LED can be used to communicate through light. The current of the LED is controlled thanks to a driver circuit, of which the switching speed is enough for the target application keeping the average intensity of the light constant for the comfort of the eyes. The capacity of the LED to send data is linked to its switching capabilities. The time needed for an LED to go from a low level to a high level or the opposite is the rise time and fall time. These parameters are given in datasheets. The simplest modulation schemes used are OOK (On-Off-Keying) and the group of VPPM (Variable-Pulse-Position-Modulation) techniques [14]. Nowadays, the scientific literature shows investigations of more complex modulation schemes like CAP (Carrierless Amplitude Phase) [15][16], optical OFDM (Orthogonal-Frequency-Division-Multiplexing) [17] as well as futuristic schemes such as FBMC (Filter-Bank-Multi-Carrier) [18]. Spread spectrum transmissions are also envisaged [19].

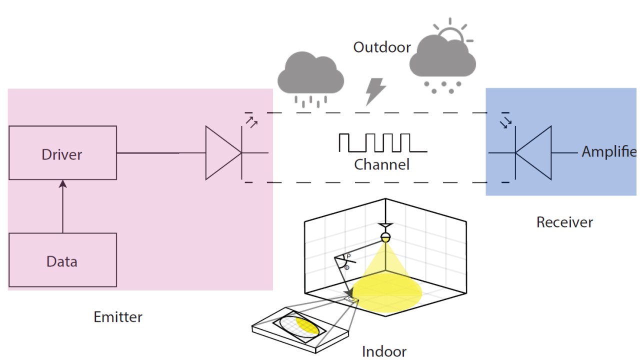

Fig. 1. Indoor and outdoor VLC channel

As for any communication systems, signal processing is added, e.g. to enable error correction codes to improve performance [20], or to increase the transmission security and privacy by using steganography [21].

B. Channel

The transmission channel is the free space between the LED and the receiver. Fading can disrupt the communication depending on the location of both TX and RX devices and other factors, especially in outdoor environments. Their impact on the communication results in an overall increase of the attenuation. As Fig. 1 illustrates, there are two main types of possible environment: indoor and outdoor. Regarding the outdoor environment, the main perturbations on the communication channel come from the weather conditions as opposed to the indoor channel where the main challenge is to deal with the signals reflected from the walls and any obstacles and the nearly mandatory presence of Line-of-Sight (LoS). Outdoor, there usually is LoS between the emitter and the receiver due to the envisaged short transmission distance. Some researchers are focusing on modelling fog, rain and snow to analyze their impact on near-infrared free space communication [22][23][24][25][26]. The conclusions and models can be generalized for visible light communication as near infrared and visible spectra are close in frequency [27]. The weather variability's main effect is an increase of attenuation in the channel. On the other hand, solar irradiance and artificial light induce an increase of noise at the receiver side [28] [29].

C. Receiver

The receiver includes a photodiode (PD) [5][27], a solar panel [30][31] or an image sensor (e.g. a smartphone camera) [32] [33]. The system designer should pay attention on the wavelength detection range of the photodiode and to an amplification stage large enough to include the data's electrical bandwidth (linked to the rise and fall time of the PD) [14]. In order to decode data with a solar panel, a circuit that considers the AC (Alternating Current) component is required. The solar panel on its own is only working in DC mode. The optical receiver of a smartphone is its integrated CMOS (Complementary Metal-Oxide-Semiconductor) image sensor, also known as the camera. The image sensor is a matrix of cells capable of converting the light into a colored pixel to build a digital image. To decode the pulses of data sent by a VLC emitter, the "rolling shutter" process is used. This technique involves sequentially triggering each array to capture the presence of light or not. Each sequence of data is then stored into an image which will be decoded into the digital signal [34].

III. Outdoor Applications of OWC in Smart Cities

Thanks to the use of LEDs along with the miniaturization of circuits, the outdoor lighting infrastructure can provide an added functionality: communication. Several applications classified into high and low data rate requirements are presented below.

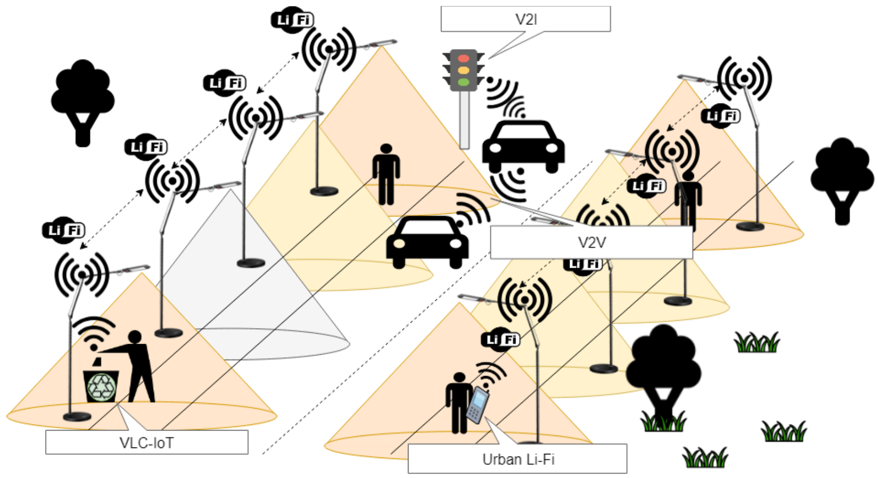

Fig. 2. Summary of outdoor VLC applications

A. High data rate applications

- Urban Li-Fi

Li-Fi (Light Fidelity) aims to combine internet connection and lighting into one device in order to reduce the overall energy consumption [14]. It is typically used in indoor scenarios to deliver internet connection through visible or infrared lights. Regarding outdoor scenarios, this technology can be implemented in LED streetlights with the same principle as for indoor Li-Fi. Fig. 2 illustrates the concept of outdoor Li-Fi. The LED streetlight is equipped with a Li-Fi modulator encoding the internet data and a LED driver shapes the current of the light. This internet data is routed to the streetlight thanks to PLC (Power Line Communication) [35] [36] or PoE (Power over Ethernet) [37]. For the uplink communication, several solutions exist such as using Bluetooth or infrared. This Li-Fi application can also be used in more dynamic scenarios such as moving buses and trains. Ultra-dense connected areas can be created with femtocells and picocells thanks to small Li-Fi hotspots. These systems can also provide a high capacity backhaul with FSO with a low power consumption [4].

- Positioning system

VLC can be implemented for indoor or outdoor geolocation purpose. Each LED lamp is given a unique ID that triggers relevant location-information on the end-user's receiver. This can be scaled in an outdoor environment to receive information at a bus stop or at a smart signboard like cities already do with QR codes [38][39].

- Building to Building communication

Building to building communication is part of the FSO family applications and uses rather infrared LDs (Laser Diodes) as opposed to LEDs. This application is not new since its first publication in the 1960s [40] [5] but it has regained interest recently as a mean of communication between buildings belonging to a complex like in campuses or banks. This requires a powerful signal and a narrow beam to overcome both the weather conditions and the distance. This technology is mainly used for high data rate backhauling between two fixed points [4]. Despite many challenges related to (i) weather sensitivity (such as rain, fog, haze, snow and sandstorm), (ii) atmospheric turbulence (such as scintillation phenomenon which changes the refractive index of air and leads to intensity fluctuation of the LD beam) [41] and (iii) possible obstruction (new building built, someone intentionally passing by), FSO communication is more secure at the physical layer of the OSI model compared to some RF technologies [42].

B. Low Data rate applications

- VLC for outdoor IoT

IoT has opened a new world of possibilities and monitoring systems when used in Smart Cities. Sensors measuring quantities like air quality, space occupancy or visibility can be distributed everywhere along the streets. They are designed to be energy efficient as they can run on batteries, and to transmit data occasionally using wireless communication mediums up to a gateway. Streetlights can have the role of data collectors from surrounding smart street furniture and sensors, as well as the role of a gateway. As an example, Fig. 2 illustrates the case of a smart bin sending a message when it is nearly full, using infrared light to communicate up to the lamppost. The weather conditions are less critical for this application due to the short communication distance and the scarcity of data exchanges.

- Vehicle to X (V2X) communication

Automotive LEDs can also be used for vehicle to vehicle (V2V) communication [43]. Cars are currently being equipped with LEDs for their headlamps and rear lamps. Some simple warning information coming from the car at the front could be sent to the one at the back, creating a communication path in heavy traffic conditions. Traffic lights can also send messages regarding their state to the incoming cars (V2I or "Vehicle - to - Infrastructure communication"). Furthermore, in dense areas of connected cars, they could form clusters to optimize the traffic on highways. Those V2X applications are illustrated in Fig. 2.

IV. Outdoor VLC challenges

VLC products are now available on the market by multiple companies worldwide such as pureLiFi (UK), OledComm (France), Signify (Netherlands) and Firefly (USA), to name a few. A market analysis led to companies mainly focussing their design activities on high data rate indoor applications. This is justified by the larger customer base including companies and private individuals for indoor applications. The potential is lower for outdoor applications as the key enablers are the cities themselves, but this trend is slowly changing since the introduction of the concept of smart cities.

One can notice that even with specialized companies, VLC/Li-Fi products are not on the mass market yet. The main reason being the lack of a unique standard for those applications. This also inhibits greatly the industrial development of outdoor applications and slows down its time-to-market deployment.

Table 1 highlights the main characteristics of the future or in force standards. Among all of them, only the PHY I physical layer specification of the IEEE 802.15.7 standard [44] is intended for outdoor use cases. As the JEITA-CP 1221 [45] doesn't specify the environment, it could be used for low data rates outdoor communications, but it is not used as much nowadays. Finally, the main trend and focus is now on the promising IEEE802.11bb [46]. Furthermore, the absence of a unique standard for all VLC applications induces confusion among Li-Fi system manufacturers and make interoperability difficult. Furthermore, with the range of RF solutions already installed, it is important to consider other network communication possibilities along with VLC systems. This is the main challenge of hybrid networks such as VLC-PLC [47] or VLC-RF [48][49].

Standardization is not the only obstacle to the development of this technology. The main challenges that future standards should consider are listed below. The main physical challenges for indoor VLC include avoiding flickering [50][51] and supporting dimming [52], maintaining a LoS connection and a communication solution if the lights need to be off [53]. Other more practical challenges are: keeping the communication secure [21], the integration in existing technologies and infrastructure in order to be massively commercialized [54].

Within the frame of Smart Cities and more specifically outdoor environment, VLC systems encounter specific challenges [26].

- Hazardous weather conditions and turbulence

The main difference between indoor and outdoor environments is the instability of the environment (due to weather variations) and therefore of the channel transfer function. Scientists integrate fog and other weather conditions models to study their impact and to find ways to overcome them or study their limitations [22][23][24].

- Ambient disturbances and receiver's sensitivity

The design of the receiver should be resilient to external disruptors like artificial light and solar radiation. For this purpose, their impact is studied in [28] [29] to build custom circuits that filters out the disruptors.

TABLE I. Summary of the current and future standards

Date and Name	Use case	λ range	Carrier frequency	Max. data rate	Modulation scheme
2007 JEITA[1] CP-1221 [45]	VLC system	380nm-780 nm	15 kHz - above 1 MHz	/	/
2007 JEITA[1] CP-1222 [45]	Visible Light ID System	380 nm-780 nm	28.8 kHz	4.8 kbit/s	4-PPM
2011 IEEE 802.15.7[2] [17]	Short-range optical wireless communication	380 nm – 780 nm	PHY I: 0.2 to 0.4 MHz PHY II and III: 3.75 to 120 MHz	PHY I: 11 to 266 kbit/s PHY II: 1.25 to 96 Mbit/s PHY III: 12 to 96 Mbit/s	PHY I: OOK and VPPM PHY II: OOK and VPPM PHY III: 4-CSK and 16-CSK
2018 IEEE 802.15.7[2] [55]	OCC Optical Camera Communication	380 nm-780 nm	PHY I to III: same 2011 PHY IV, V & VI depends on the modulation scheme	PHY I to III: same 2011 PHY IV, V & VI depends on the modulation scheme	FSK, OOK
2019 ITU G.9991[3] [56]	High speed indoor visible light communication	380 nm - 780 nm and 800 nm - 1675 nm	0-50 MHz 0-100 MHz 0-200 MHz	/	OFDM
2021 IEEE 802.11bb[5] [46]	Integration of Li-Fi in IEEE 802.11 LAN protocol	380 nm – 5000 nm band	/	5 Mbit/s to 5 Gbit/s	/
Coming soon IEEE 802.15.13[4] [57]	High speed light communication for industrial environments	190 nm - 10000 nm	/	Multi Gbit/s	/

[1]Japan Electronics and Information Technology Industries Association
[2]IEEE Standard for Local and Metropolitan Area Networks--Part 15.7: Short-Range Optical Wireless Communications
[3]High speed indoor visible light communication transceiver - System architecture, physical layer and data link layer specification
[4]Multi-Gigabit/s Optical Wireless Communications
[5]IEEE 802.11 Light Communication

- Long distance and radiation pattern

An average streetlight pole is about 5m high depending on its location in the street compared to an indoor use case where the ceiling is about 3m high. The radiation pattern is the graphical representation of the angular power distribution emitted by a source. The intensity and shape of the light beam should be adapted to reach the expected spot size and data rates.

V. Discussions and conclusions

Outdoor Optical Wireless Communication is a rising technology that faces many challenges. Nevertheless, a plethora of applications exist that could complement Wi-Fi and other RF technologies in many areas of a Smart City. Furthermore, OWC is gaining interest in both scientific and commercial worlds as more and more international projects, conference talks and workshops on that subject are taking place all over the world. The main challenge induced by outdoor environments is the variability of the weather and distance between emitters and receivers. Another significant challenge is the manufacturing of VLC compliant smartphones and devices due to the lack of a unique standard. The only standard that proposes a guideline for outdoor application is the IEEE802.15.7 which includes data rates of few hundreds of kbit/s which can be enough for general low data rate applications, but not for end-user's connectivity. On the bright side, industries are already developing prototypes and products usable indoors, and considerable research is being carried out for outdoors. Smart Cities can include IoT-VLC and Li-Fi within the existing LED lighting infrastructure as well as infrared light equipment and supplement the services provided. Finally, the future of VLC technologies is promising and has a high potential to stand alongside 5G cellular mobile communication technologies.

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