Li-Fi and Visible Light Communication for Smart Cities and Industry 4.0: challenges, research & market status in 2023

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ABSTRACT
The development of technologies that use cellular Radio Frequency (RF) networks to transmit information wirelessly has increased dramatically over the last decade. These technologies include mobile phones, tablets, connected gadgets and the Internet of Things (IoT). The simultaneous use of all these devices quickly saturates the available network. As the RF spectrum resource is limited and regulated, it is important to find alternative connectivity. To reply to this shortage of wireless connectivity, Li-Fi (Light Fidelity) and Visible Light Communication (VLC) are good candidates. Li-Fi is the high data rate bidirectional application of VLC. VLC uses visible and infrared light to transmit data wirelessly. Over the last decade, interest in VLC grew in the scientific community and on the market. However, most scientific works and products are focused on the indoor environment. The external environment for VLC applications, which would be very relevant for smart cities as well as some industrial applications, is very little covered in the literature. This sixty minutes tutorial aims to present the advances of these technologies, their challenges and their relevance in these two environments.
Keywords: Visible Light Communication, Li-Fi, market analysis, Smart City, Industry 4.0

1. INTRODUCTION

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. Furthermore, since their introduction and adoption, cities are increasingly installing LEDs to enlighten their streets and to reduce their energy consumption. 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 communicating. LEDs are also being deployed massively in industry to light offices as well as workshops and warehouses. As RF type wireless technologies do not always work in workshops or on the factory's site, it is relevant to look at how VLC can address these constraints. For example, there are automatic laser-guided vehicles and mobile workstations that could benefit from the existing LED installation to send information and enlighten at the same time.

This tutorial paper provides an overview of VLC and the challenges it faces in outdoor and industrial environments. Then, the strategy to mitigate those undesirable effects is presented. Afterwards, a market review will present the main challenges that Li-Fi and VLC technologies face for their massive deployment for private consumers and private companies.

2. VISIBLE LIGHT COMMUNICATION

Visible Light Communication is part of the Optical Wireless Communication (OWC) family of technologies. These technologies use the near-infrared, visible and ultraviolet bands of the electromagnetic spectrum to transmit data. Visible light covers the $400\,\mathrm{nm}$ to $750\,\mathrm{nm}$ range, representing $370\,\mathrm{THz}$ of unlicensed spectrum. This is much wider than the approximately 300 GHz of RF range [5]. This corresponds to a very attractive spectrum enhancement factor of 1230 making Visible Light Communication (VLC) a relevant technology within the OWC family. The infrared (IR) spectrum extends from the visible nominal red edge at $750\,\mathrm{nm}$ up to $1\,\mathrm{mm}$. Optical communications take place in the near-IR and IR LEDs are commercially available up to $1720\,\mathrm{nm}$ [6]. As the UV band can damage the skin, this technology has to be avoided and is not discussed in this work as part of a possible solution to free up the RF spectrum. Within the framework of cities and industries communication, OWC applications are good candidates to overcome the future radio frequency shortage. Figure 1 displays the different applications behind OWC which VLC is part of. On part *A* of the figure, there is the Li-Fi (Light Fidelity), which is a bidirectionnal high data rate optical communication system [2]. The downlink is usually in visible white light and the uplink in infrared light. However the current commercial trend is towards systems that are in infrared lighting in both communication ways. The receiver of each link is a photodiode designed for the proper wavelength range of the emitting LED. In part *B* of the figure, a VLC application is illustrated [3]. It has only one communication link, usually in visible light to use the existing LED infrastructure to illuminate and send data. The receiver, in this case, is again a photodiode. Optical Camera Communication (OCC), in part *C* of the figure, stands out by using a camera as a receiver. A camera is generally an integrated Complementary Metal-Oxide-Semiconductor (CMOS) image sensor. This image sensor is a matrix of cells capable of converting the incident light into a coloured pixel to build a digital image. It is thus able to build an image copying the changing states of the LED emitter into a frame [7]. Finally, part *D* presents Free Space Optics (FSO) applications which can be used to communicate between two distant points (up to several kilometers) using IR LASER beams [8].

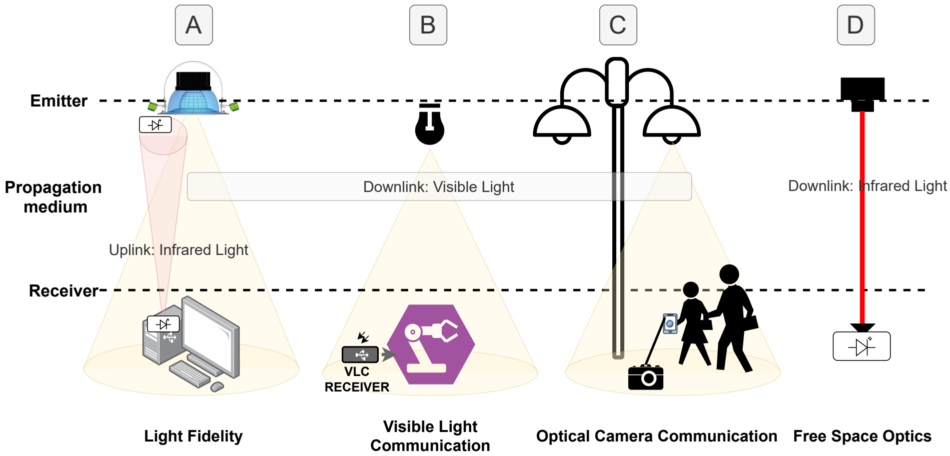

Figure 1: The technologies behind VLC systems

3. The outdoor and industrial environments challenge

The amount of dust or particles in the air in indoor environments is much lower than in outdoor or semi-confined areas like tunnels or mines. The concentration of dust particles emanating from cars and industrial areas is higher near massively industrialised environments and then near major roads and higher than in residential environments. It is therefore normal that the amount of dust particles is lower in indoor environments. Because of these particles in outdoor environments, two phenomena can occur that increase the medium's total attenuation: absorption which happens when atmospheric particles transform the incident radiant energy into other forms of energy (such as heat), and scattering which is the re-radiation in all directions (sometimes with a preferred direction) of the incident light wave by the atmospheric particles. Figure 2 illustrates the loss of optical power due to scattering, absorption and the distance L between the emitter and receiver. The different weather conditions that can affect the amount of particles in the air are typically fog, smoke, sandstorm, rain and snow. Sunlight on the other hand impacts the receiver by increasing its noise level as the sunlight is located in the same spectral bandwidth as the data sent. One way to overcome this issue is by designing narrowband optical filters.

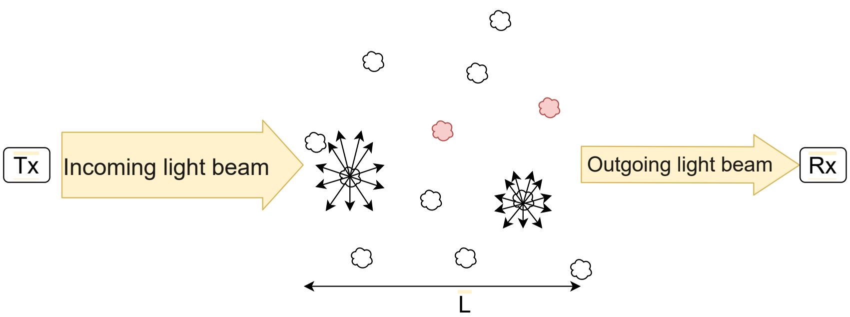

Figure 2: Particles in the air interacting with the incoming light wave

4. Mitigation of undesirable effects

The transmission channel is the space between the emitter and the receiver. To characterise at best the VLC system, the phenomena that can occur between the light wave and the space surrounding it, a simulator has been developed using open-source tools. The simulator includes the characteristics of the emitter, the receiver as well as the overall space configuration such as the presence or absence of walls in the studied space. The simulator enables now the use of any LED lighting taken from actual optical power measurements (making it closer to real use cases instead of using mathematical models for the light's power distribution). The outdoor environment has been thoroughly explored thanks to different weather condition models and a novel smoke model has been developed and added in the simulator [4]. These models inform us of the attenuation the optical signal undergoes from the emitter to the receiver. The reflection properties of the walls in the space studied are flexible as well as their relative configuration. These tools will be presented during the tutorial. Once the channel is characterised, it is possible to assess the performance of the system in simulation. A modulation scheme is a process by which the signal is transformed from its original form into a form suitable for the transmission channel. Three different schemes have been explored which follow the evolution of VLC standards: OOK (On-Off-Keying), OFDM (Orthogonal Frequency Division Multiplex) and UFMC (Universal Filtered Multi-Carrier). The first one is a single-carrier scheme and the two last ones are part of the multicarrier communication schemes. The challenge of using a multicarrier modulation scheme is the necessity of an adaptation of the signal processing for VLC as the requirements are different compared to RF communications. The main results of the study of these advanced modulation schemes is that it is possible to optimise VLC systems to have more information in the same bandwidth.

5. Market players

Some Li-Fi and VLC products are already available on the market mainly in Business to Business (B2B) but also Business to Consumer (B2C) segments. Consumers can buy some Li-Fi products but they are generally overpriced compared to their equivalent products in RF. This chapter presents a market analysis of the different products available and discusses how VLC can still be a good potential in smart cities and industrial environments. The company pureLiFi offers Li-Fi products where the downlink channel is in visible light and in the uplink channel is in infrared light. Nowadays, pureLiFi proposes mainly Li-Fi products that can be used with laptops and smartphones. In 2019, they presented the Gigabit Li-Fi at the Mobile World Congress. More recently, in April 2021, pureLiFi started offering for sale the Kitefin, a product that enables the large-scale deployment of Li-Fi [1]. To the best of our knowledge, their main customers are office spaces, private individuals and schools who want an alternative to Wi-Fi. Around 2016, the first products available from Oledcomm were mainly a desk lamp capable of delivering a broadband internet connection using white light in downlink. Over the years their product range has evolved and they have now as their current motto "High-speed Internet through invisible light". That is, the products they are now selling under the name Li-Fi are actually infrared for bidirectional (not visible light in the downlink and infrared in the uplink channel as the first Li-Fi systems). Their latest product, the LiFiMax equipment is able to reach 100 Mbit/s in indoor environment but its outdoor version does not exist yet. In May 2016, Philips Lighting N.V. becomes Signify. Signify is not a company that only makes Li-Fi equipment. They offer a range of smart lights (controllable and with sensors) as well as Li-Fi but this is not their main focus. The products they offer are in the same idea as Oledcomm and are under the brand "Trulifi" [9]. In their early days they offered white light panels with Li-Fi but now they have focused on two-way infrared communication. There was not enough information to know where their projects were mainly used. Nevertheless, they promise a net data rate of about 845 Mbit/s on their website. Fraunhofer IPMS (Institute for Photonic Microsystems) is a German research institute that develops electronic and photonics microsystems since 2007 in several fields such as industrial or health. As part of their Li-Fi catalog, in 2018 they offered the "Li-Fi HotSpot Evaluation kit " capable of transmitting up to 100 Mbit/s bidirectionally in infrared. The product is composed of 2 Infrared emitter/receiver capable of communicating in both directions. There is one master and one slave to enable point-to-multipoint communication. Those devices maintain high performance within a range from 0,5 m to maximum 5 m indoor. Nowadays, their website proposes the same product but capable of transmitting $1\,\mathrm{Gbit/s}$ [11]. The company Velmenni also started out with visible light solutions but soon moved on to high-speed infrared solutions. Today his company offers, like the others mentioned before, equipment dedicated to indoor connectivity (a Li-Fi dongle as well as an Access Point). It also proposes a solution for the outdoor environment for backhauling but it is not specified if they use a laser or LEDs as the product is called "LC" [12].

For now, most commercialized VLC products are either Li-Fi with visible light or infrared light, thus mainly focusing their design activities on high data rate applications [13]. These products are now available on the market by multiple companies worldwide. The market research highlighted the larger customer base including private companies and schools for indoor products. In order to summarise the performance of the different players, Figure 3 provides a graphical representation of the distance and throughput offered by the different brands. It can be seen that when the products are for VLC, the proposed distances are from 3.5 to 5 meters.

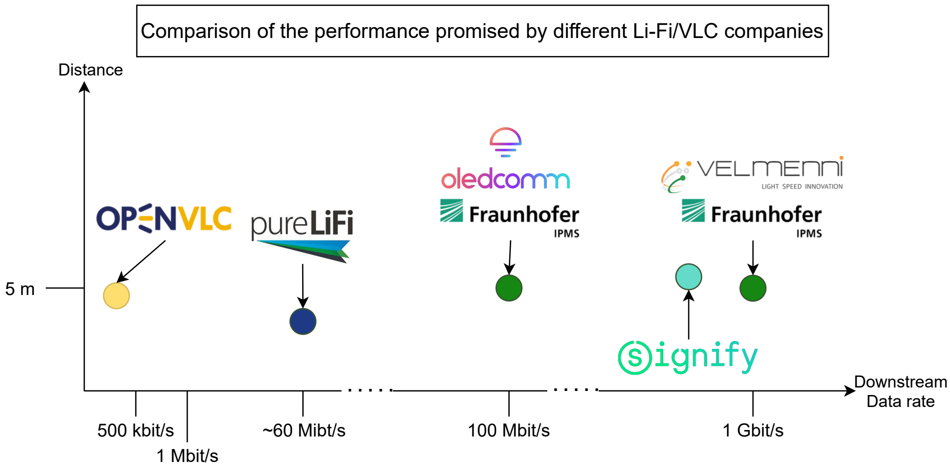

Figure 3: Comparison of Li-Fi/VLC main market actors

6. Conclusion

There is no single standard for Li-Fi and VLC. This makes it hard for manufacturers of end devices and light manufacturers to comply with just one norm. Furthermore, this technology has not reached its maturity level yet. As VLC requires the use of LEDs as its emitter's front-end and since they were adopted a relatively short time ago, it makes this technology relevant but still needs some time for the light market to stabilize itself. Nevertheless, VLC and Li-Fi have a bright future ahead and this tutorial will conclude with practical examples of their use in smart cities and smart industries.

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