Li-Fi: current status, advances and future projection

Li-Fi: estado actual, avances y proyeccion a futuro

Li-Fi: status atual, progresso e projeção futura

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Abstract

Introduction: This literature review is the product of the research on Li-Fi technology entitled "LI-FI: Current status, advances and future projection" carried out in the technological faculty of the Francisco José de Caldas District University from 2018 to 2020.

Problem: The increase in wireless devices connected to the internet, the saturation of the electromagnetic spectrum used by current wireless technologies based on radio frequencies (Wi-Fi, Bluetooth, ZigBee, among others) and the new requirements for bandwidth, speeds and energy efficiency for the new generations of telecommunications have all resulted in the birth of Li-Fi as an alternative and / or complementary technology of wireless telecommunication that is based on the visible light spectrum.

Objective: The objective of this research is to expose the development of Li-Fi technology in the field of telecommunications, covering it in three main aspects such as the current state of technology, recent advances, and future projections.

Methodology: Different types of bibliographic sources were used, including research and opinion articles, marketing studies, forums, books, conferences, among others with a publication date of 2012 onwards (some exceptions are found in the references); using selection criteria for title, authors, date of publication, abstract, results and / or conclusions in relation to the research guidelines (Current Status, Advances and Future Projection of Li-Fi technology)

Results: 61 sources were found including articles, conferences, books, marketing studies, newspaper articles and others that met the research guidelines.

Conclusion: The literature review manages to highlight the importance of Li-Fi in the new generations of telecommunications of the future and its complementarity with current networks, optimally contextualizing the technology, exposing its advantages and recent advances in technical and commercial aspects, as well its disadvantages and weaknesses that should be addressed in the development of this technology in the future.

Originality: The article manages to organize, present and contextualize the development and research of Li-Fi to date. No similar research has been done in Colombia.

Limitations: Certain research and data in bibliographic sources are not freely accessible. Certain alliances and research mentioned in the article may vary over time.

Keywords: Internet of Things, Internet of Everything, LED, Li-Fi, Optical Wireless Comunication, Wireless Networks, Wi-Fi, Visible Light Communication.

Resumen

Introducción: El artículo de revisión de literatura es el producto de la investigación sobre la tecnología Li-Fi titulado " LI-FI: Estado actual, avances y proyección a futuro" realizado en la facultad tecnológica de la Universidad Distrital Francisco José de Caldas durante los años 2018, 2019 y 2020.

Problema: El aumento de dispositivos inalámbricos conectados a internet, saturación del espectro electromagnético usado por las tecnologías inalámbricas basadas en radio frecuencias actuales (Wi-Fi, Bluetooth, ZigBee, entre otras), nuevos requerimientos de ancho de banda, velocidades y eficiencia energética para las nuevas generaciones de telecomunicaciones son causales del nacimiento de Li-Fi como tecnología alternativa y/o complementaria de telecomunicación inalámbrica que basa en el espectro luz visible la cual logra solventar dichos.

Objetivo: El objetivo de esta investigación es exponer el desarrollo de la tecnología Li-Fi en el campo de las telecomunicaciones, abarcándolo en tres aspectos principales como lo es el estado actual de la tecnología, recientes avances y proyección a futuro.

Metodología: Se usaron diferentes tipos de fuentes bibliográficas entre ellas artículos de investigación y opinión, estudios de marketing, foros, libros, conferencias, entre otras con fecha de publicación del 2012 en adelante (se encuentran algunas excepciones en las referencias); tomando como criterios de selección título, autores, fecha de

publicación, resumen, resultados y/o conclusiones en relación con el lineamiento de la investigación (Estado Actual, Avances y Proyección a futuro de la tecnología Li-Fi),.

Resultados: 53 trabajos encontrados entre artículos, conferencias, libros, estudios de marketing, artículos periodísticos y demás que cumplían con el lineamiento de la investigación.

Conclusión: Se logra destacar la importancia de Li-Fi en las nuevas generaciones de telecomunicaciones del futuro y su complementariedad con las redes actuales, exponiendo sus ventajas y recientes avances en aspectos técnicos y comerciales al igual que sus desventajas y puntos débiles que se deberán trabajar en el desarrollo de esta tecnología en el futuro.

*Originalidad***:** El articulo logra presentar y contextualizar de manera organizada el desarrollo e investigación de Li-Fi a la fecha, no se han hecho investigaciones similares en Colombia.

Limitaciones: Ciertas investigaciones y datos en las fuentes bibliográficas no son de acceso libre; ciertas alianzas e investigaciones mencionadas en el artículo pueden variar con el tiempo.

Palabras clave: Internet de las cosas, Internet del todo, LED, Li-Fi, Comunicaciones Ópticas Inalámbricas, Redes Inalámbricas, Wi-Fi, Comunicaciones de Luz Visible.

Resumo

Introdução: O artigo de revisão de literatura é o produto da pesquisa sobre a tecnologia Li-Fi intitulada "LI-FI: Situação atual, avanços e projeções futuras" realizada na faculdade de tecnologia da Universidade Distrital Francisco José de Caldas durante os anos de 2018, 2019 e 2020.

Problema: O aumento de dispositivos sem fio conectados à internet, saturação do espectro eletromagnético usado pelas tecnologias sem fio baseadas nas radiofrequências atuais (Wi-Fi, Bluetooth, ZigBee, entre outros), novos requisitos de largura de banda, velocidades e eficiência energética para o Novas gerações de telecomunicações são a causa do nascimento do Li-Fi como uma alternativa e / ou complementar tecnologia de telecomunicações sem fio baseada no espectro de luz visível que consegue resolvê-los.

Objetivo: o objetivo desta pesquisa é expor o desenvolvimento da tecnologia Li-Fi no campo das telecomunicações, abrangendo-o em três aspectos principais como o estado atual da tecnologia, avanços recentes e projeções futuras.

Metodologia: Foram utilizados diferentes tipos de fontes bibliográficas, incluindo artigos de pesquisa e opinião, estudos de marketing, fóruns, livros, conferências, entre outros com data de publicação a partir de 2012 (algumas exceções encontram-se nas referências); tomando como critérios de seleção título, autores, data de publicação, resumo, resultados e / ou conclusões em relação às diretrizes de pesquisa (Status Atual, Avanços e Projeções Futuras da tecnologia Li-Fi).

Resultados: 53 trabalhos encontrados entre artigos, conferências, livros, estudos de marketing, artigos jornalísticos e outros que atenderam às diretrizes da pesquisa.

Conclusão: É possível destacar a importância do Li-Fi nas novas gerações de telecomunicações do futuro e sua complementaridade com as redes atuais, expondo suas vantagens e avanços recentes nos aspectos técnicos e comerciais, bem como suas desvantagens e fragilidades que devem ser abordada no desenvolvimento desta tecnologia no futuro.

Originalidade: O artigo consegue apresentar e contextualizar de forma organizada o desenvolvimento e a pesquisa do Li-Fi até o momento, nenhuma pesquisa semelhante foi feita na Colômbia.

Limitações: Determinadas pesquisas e dados em fontes bibliográficas não são de acesso livre; Certas alianças e pesquisas mencionadas no artigo podem variar com o tempo.

Palavras-chave: Internet das Coisas, Internet de Todas as Coisas, LED, Li-Fi, Comunicações Ópticas Sem Fio, Redes Sem Fio, Wi-Fi, Comunicações de Luz Visível.

1. INTRODUCTION

Li-Fi (Light-Fidelity) is a data transmission technology that uses the spectrum of visible light to send and transport information. This technology is presented as an alternative to Wi-Fi for the transmission of wireless data, representing a significant increase in capacity, speed, available bandwidth and the necessary security for a world in constant technological growth. Since it was presented in 2011, various researchers and private companies have advanced in the development and implementation of this technology, with the premise of using each existing light bulb as a signal transmitter and receiver through LED lights. The following article will review the background of Li-Fi, the operation of this technology, the current state of the different advances and a future projection of the appropriation of Li-Fi in Colombia and the world in general.

2. CURRENT STATE

To exhibit Li-Fi technology and achieve a quick contextualization, this section is divided into 5 sub-sections which include the elements that make up Li-Fi, Li-Fi architecture, Li-Fi workflow, advantages, and disadvantages of Li-Fi.

2.1. Elements that make up Li-Fi technology

VLC (Visible Light Communication) systems are short-range optical wireless communication systems that make use of the visible light spectrum. In a general scheme it is composed of 3 simple elements (see Figure 2) [1]:

a) Light Emitting Diodes (LEDs)
b) Photodetector
c) Encoders / Decoders of light pulses, (Modulator - Demodulator), Signal amplifier.

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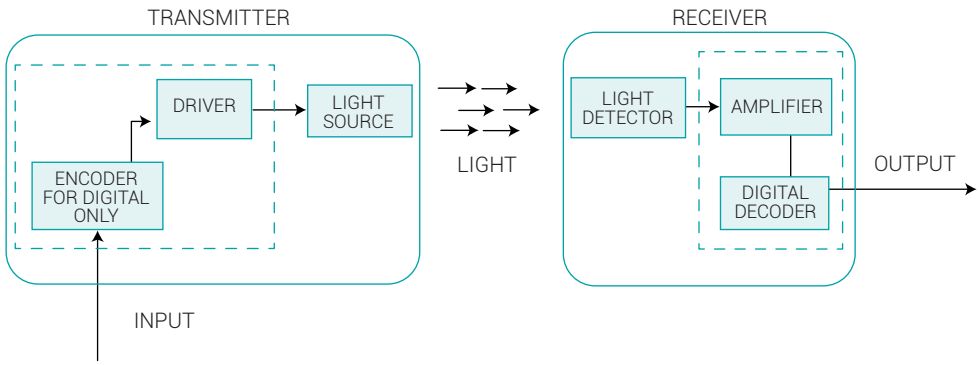

Fig. 1. General VLC Scheme.
Source: Adapted from [1]

Figure 1 shows the operation through each of the elements that make up a VLC system, starting from the input of an initial digital signal from the data source, being processed to encode it within the processing circuit of the transmitter device. This is then converted by a controller into light pulses to be emitted by a light source, so that said signal is sent to the receiving device, where a light detector captures the signal. Later it is redirected to the receiver's processing circuit. There it performs the inverse process of converting light pulses into a digital signal and is finally delivered as an output to the device that makes use of the connection through VLC.

2.2. Li-Fi architecture

The Li-Fi architecture described in the IEEE 802.15.7 standard identifies two layers: physical layer and MAC layer [1].

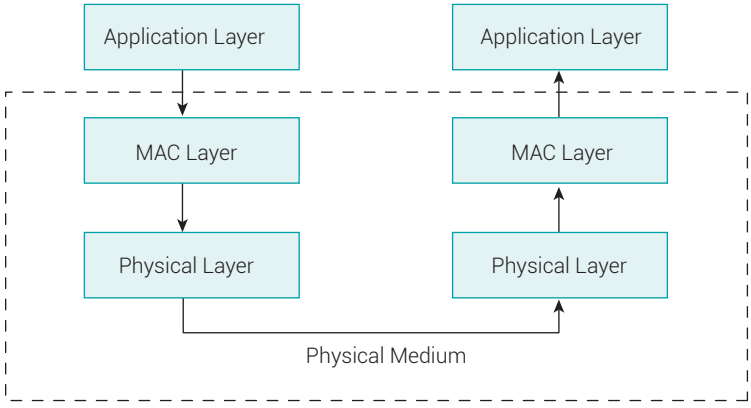

Fig. 2. VLC Layered architecture.
Source: Adapted from [2]

- Physical layer

The physical layer involves turning the optical transceiver on and off (On, Off) as the main task, checking the channel status (active, inactive, busy), data transmission and response (Data Flow) [3].

- MAC layer

The tasks designated to the Medium Access Control (MAC) layer in Li-Fi technology are Mobility Support, Dimming Support, Security Support, Flicker Mitigation Schemes, Visibility Support, Color Function Support, VPAN Decoupling (Virtual Personal Area Network) and association support, generation of network beacons when the device is a coordinator in a link between two pairs of MAC entities. The network topology is also described thanks to the MAC layer. For Li-Fi there are three types of topology, Peer to Peer (P2P), star, Broadcast[2], [4].

Observing the Li-Fi operation with respect to the propagation channel, two methods of propagation exist: propagation in the line of sight (LOS) and propagation in the line of no sight (NLOS). LOS describes the channel between the source and the unobstructed destination, that is, direct line between the light emitting device and the light detector in the receiver. The NLOS channels describe the path of light propagation through reflections in obstacles (walls, ceiling, among others.) [3], [5].

2.3. Li-Fi Work Flow

Harald Hass in 2013 proposed a high-speed block diagram through the allocation of signal bits between subcarriers, applying the OFDM modulation technique [6]. Christophe Jurczak adapts this diagram as follows (see Figure 3) showing in more detail all the elements and subsystems that intervene in the Li-Fi workflow such as modems, signal amplifiers, analog and digital signal converters, filters, among others:

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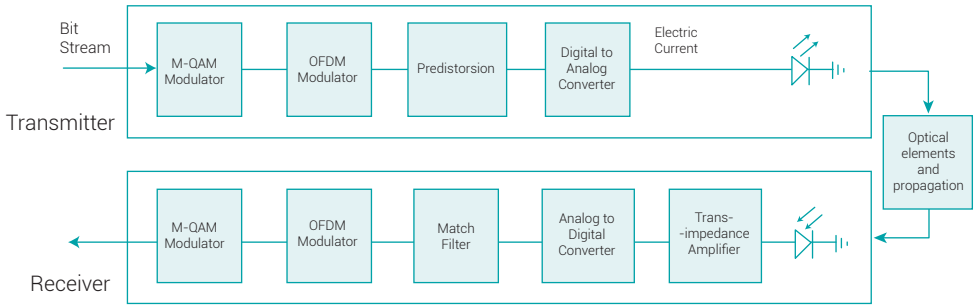

Fig. 3. High speed block diagram via signal bit allocation between subcarriers.
Source: Adapted from [7]

2.4. Advantages and disadvantages of Li-Fi

One of the greatest advantages of Li-Fi is the property that this technology has to overcome the limit of the electromagnetic spectrum that currently has wireless networks based on radio frequencies. The bandwidth used by devices that implement Wi-Fi or other technology based on the radioelectric spectrum are being completely saturated; the increase in devices that use this wireless technology to communicate on the network is estimated at more than half a billion new devices according to cisco in the range from 2015 to 2020 [8]. There are several examples of this phenomenon in homes, companies or places where the use of devices that access the network wirelessly converges; there are interferences in connections, low latency and connection problems to the network by presence of multiple networks that use the same radio frequency spectrum to communicate.

Currently, there are quite simple and useful applications to analyze the traffic and saturation of the channels in which the internet is connected wirelessly. Just install these applications on smartphones and observe the congestion of the medium and the number of devices that exchange data in it [9].

The advantages of Li-Fi arise from the problems that RF-based wireless technologies face today. To evaluate them in a general way, there are advantages at the level of capacity, availability, efficiency and security.

Capacity and Availability

- The availability of electric light sources today provides a great infrastructure for the implementation of Li-Fi anywhere, large and small cities have electric lighting, in many cases already with LED light, where the deployment of Li-Fi technology will only be in the implementation of the LED bulbs

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suitable for the use of Li-Fi and its access to the network, granting internet connections with multiple APs (Access Points) in the public space.

Efficiency

- There are more than 1.4 million cellular radio masts worldwide [10]. These masts consume enormous amounts of energy, where they are used to a greater extent to cool the station at the site of radio wave transmission. In fact, the efficiency of such stations is only 5% [11]. The implementation of Li-Fi stations is not only cheaper for making use of LED lights, they adapt the current LED light sources with those that cities, companies or homes have. Not only do they have better electrical efficiency and consumption, but also a greater deployment of stations that provide Li-Fi connections for access to the network.

Security

- One of the strengths of Li-Fi technology is with the indoor connections and the confidentiality component at the physical level of the network. Although light does not have the ability to penetrate objects, walls or non-translucent surfaces, in a closed environment where it is sought to provide network connections to a certain group of devices that are only found in said closed space, Li-Fi is the solution ideally, avoiding data leaks outside the place as current RF-based wireless networks do (see Figure 4), it is very common to hear of data interception by third parties in places where the wireless network has coverage; the result of non-authorized access if the security of the network can be decrypted. Despite attempts to improve the encryption algorithms and protocols that are implemented in RF-based wireless networks, the exponential growth of devices with greater processing capacity puts at risk the preventive and access control that these algorithms and protocols provide to the wireless networks, as was recently exposed to the WPA2 protocol vulnerability - with PSK and TKIP / AES encryption [12].

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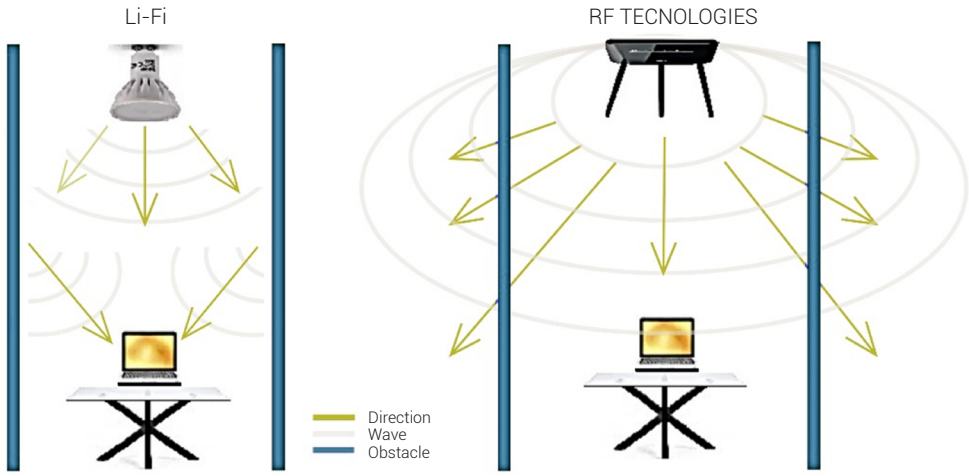

Fig. 4. Li-Fi vs Wi-Fi propagation mode.
Source: own work

The disadvantages found in this technology are based in the same way on the benefits that it has. It is mentioned that one of the advantages of Li-Fi with respect to security is the property that it has of not penetrating walls or opaque materials, avoiding the interception of data; but that limits the use of Li-Fi as a method of propagation of access to the network in a homogeneous way, as RF-based technologies do. For several offices or closed sites, the device that wants to make use of the connection through Li-Fi must be almost directly with the Li-Fi AP (Access Point) so that the connection is stable, creating a disadvantage in terms of accessibility.

Security problems with respect to technology are not yet taken as a priority in recent research, although studies focus on optimization to achieve improvements in speeds, latencies, bandwidth, among others. Not enough attention has been paid to the risks and vulnerabilities that may arise as an emerging technology, although Li-Fi achieves a better level of physical security than RF technologies, it still does not achieve a much higher level of deterrence against security issues presented by wireless technologies [13].

Regarding modulation, Li-Fi technology has different challenges to meet to achieve stability and speed in its connections. The technical difficulties that this technology encounters today is the mitigation of non-linearity, as a consequence of the variations that are applied to the intensity of the light causing the LED temperature to rise and therefore memory effects are generated [11]. Li-Fi has a limited bandwidth in the communication channel which gives way to the generation of Inter-Symbolic Interference (ISI). This concept is understood *as a distortion of the signal that generates noise, as a result of the extension and / or propagation of the pulse beyond the*

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assigned time interval, increasing the error rate in the receiver [14]. For this, the modulation techniques studied to date limit the bandwidth modelled under an electronic filter that allows the lower frequencies to pass and attenuate the higher frequencies, known as the Low Pass Filter, allowing the selection of the channels of frequencies that oscillate between 2-20MHz in the LEDs that are popularly marketed, but that limit the potential of LI-FI reducing it to a cut-off frequency of 3dB. Therefore, future modulation techniques have the challenge of breaking this limit without sacrificing system efficiency and without forgetting the primary requirement of generating illumination first, rather than just a data transmitting device.

3. ADVANCES OF LI-FI TECHNOLOGY

In the last decade, various researchers in various university institutions and private entities around the world have achieved important experimental advances, with practical laboratory results. Here are some of the most important investigations:

3.1. Li-Fi in Europe:

- At the University of Oxford, researchers managed to reach a transmission speed of 224 Gbps using a prototype of bidirectional Li-Fi of around 3 meters, divided into 6 aggregated links of 37.4 Gbps to cover a field of view of 60 °. They also managed to reach 112 Gbps with a configuration of 3 links added at 37.4 Gbps, with which they managed to cover a field of view of 36 °. This configuration was the first demonstration of a wireless link that could have a practical coverage of a room greater than 100Gbps and routes for these types of networks. [15]
- At the Fraunhofer Heinrich Hertz Institute in Berlin, Germany, researchers succeeded in creating a prototype of a bi-directional Li-Fi system under realistic conditions, made with low-cost hardware, which adapted the data sending rate according to the conditions. of light. In a distance of approximately 2 meters, the system reached 200 Mbps per user. Using the same configuration, but with a narrower beam of light, speeds of 100 Mbps were reached over a distance of 20m; reducing the distance resulted in a peak of 500 Mbps being achieved[16]. Despite achieving a lower send rate than the Oxford researchers, this model represents a system closer to a commercial one, which can be optimized to achieve more shipping capacity at a lower cost.

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- Researchers from the University of Edinburgh, including Professor Harld Haas, conducted an experimental study that looked at the transmission capabilities of LED lights compared to RGB-type laser diodes (LDs). Their results revealed that this type of LD exhibits a much higher modulation rate than LEDs, with sufficient efficiency to cover $1m^2$ at a distance of 2.88m, with a sending rate of 3.43 Gb / s with a single RGB triplet. This means that fulfilling a double task of lighting and sending data, these LDs can reach a rate of 14GB/s in well-lit areas. Furthermore, LDs have the advantage, over LEDs, of having a much narrower emission profile, which makes it possible to improve the efficiency of the use of the visible light spectrum. This can achieve over 100 Gb/s with standard lighting, following the same pattern but under wavelength division multiplexing. [17]
- At Motol University Hospital in Prague, Czech Republic, a group of German researchers carried out the first measurement tests of a Li-Fi channel in a neurosurgery room to demonstrate the capabilities of this technology in spaces where Wi-Fi cannot be achieved, bringing the entire hospital network structure to the degree of "smart hospital" by combining individual channels in a multi-user virtual MIMO link. The results of the experiment were based on measuring the performance of the network according to the predetermined systems for data transmission such as TDMA (Time Division Multiple Access), SDMA (Space Division Multiple Access) in addition to the method ZF (Zero Forcing) for interference control. The results show that the combination of TDMA + SDMA + ZF achieved a higher performance for this case. These were the first experimental tests in a medical setting, and they reveal an important basis for defining the following Li-Fi systems in similar environments. [18]

These advances have led to the establishment of several commercial Li-Fi solutions companies such as pureLifi, Global LiFi Tech or Signify. These companies, in the company of various collaborators, have managed to design and assemble Li-Fi systems in various environments:

- The pureLifi Li-Fi-XC system, comprised of 9 Li-Fi-enabled LED bulbs, was deployed at O2 Telefonica's UK headquarters in a 'scan room'. The system allowed data to be sent through an LED bulb at high speeds by setting the light level of the bulb. The result was a high-speed, two-way wireless

network for communication. This network has the potential to provide all the necessary elements for a future implementation of 5G technology [19].

- In a joint project of the Scottish government, the University of Edinburgh, the Scottish futures trust and pureLifi, a network of 8 Li-Fi bulbs was implemented in a work area of students and teachers (classrooms) of the Kyle Academy of Scotland. Each student was given a data transmitter / receiver (Lifi-XC Stations) that connects via USB to their laptops. This will considerably improve the downloading and viewing times of multimedia material, the consequence of which was the optimization of study times. These implementations in educational environments will close the technological gap between different schools around the world and open the door to high-quality virtual and augmented reality solutions. [20]
- Babcock international is a company that offers engineering, maintenance and technology coverage services for various types of assets that include navy ships, nuclear submarines, police and fire vehicles, among others. Through the implementation of the communication system based on Li-Fi (Lifi-X) in their facilities in Plymouth (United Kingdom) they managed to overcome the disadvantages of wireless communications they had with Wifi, such as interference, security risks or signal stability. Due to its mission objectives, these aspects are quite critical to guarantee a high-quality service to its clients. With this implementation, Babcock engineers were able to obtain information from sensors that previously could not be achieved due to the various interference of the radio frequencies of the devices and the Wi-Fi network. In addition, they were able to improve the maintenance information display system for customers through portable tablets, obtaining user manuals, work instructions or 3D models instantly. [21]
- The AAL X AAL project allowed the Aviano Oncology Reference Center, Italy, to obtain a wireless communication network based on Li-Fi using the light infrastructure current; not generating electromagnetic pollution that would otherwise affect the operation of medical devices within the institution. This project focused on improving geolocation services to improve pattern compression, resource management and workforce location, in addition to improving the administration and communication processes of critical information from patients and professionals throughout the medical center. [22]
- The Signify company has Trulifi as a solution to the need for a business focused Li-Fi service. In the announcement of its launch, Signify showed its

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experience in this field with two clients. The first is Globalwoth, an institutional investor with offices in Poland and Romania that installed 18 Phillips Trulifi-capable luminaires in its office meeting rooms at the Spektrum Tower in Warsaw, Poland, providing reliable and secure communications for its corporate clients. The second is Claerhout Communication Campus, a Belgian marketing and communications company, which installed Phillips LED luminaires in a large meeting room used by the company and its customers. [23]

3.2. Li-Fi in North America:

- Among the advances of Li-Fi, one can mention the progress of Basic6. This emerging company, founded in the United States, focuses on the development of an indoor positioning system, called GeoLiFi, which uses the lighting infrastructure of stores to anonymously distribute proximity messages, product information, related promotions, and visual shopping lists to customers and employees. This company actively works with other lighting companies that provide physical Li-Fi supplies. [24]
- Researchers from several universities and institutes have worked on the coexistence of Wi-Fi and Li-Fi in hybrid networks, demonstrating experimentally that, through channel aggregation, the performance for users can be tripled. This research was carried out looking for communication solutions for mobile devices in closed places, since 80% of cell phone and tablet communications take place in these places. In addition, it is stated that the stationary users would prefer to use Li-Fi. [25]
- LVX System is a company that offers Li-Fi products and services in the United States that is located in Florida at the Kennedy Space Center. This company is associated with the United States government through an agreement with NASA, where its researchers develop applications for communication through visible light, with potential use of these advances in "deep space" missions such as a visit to Mars, along with various innovations to improve the everyday lives of Americans. [26]
- In the department of electrical and computer engineering at Boston University in the United States, an indoor 3D localization project was developed using low-cost Li-Fi components. This project was aimed at offering a better experience of location and placement of objects in a closed space, using the information transmitted by LED bulbs that were transmitted to a

mobile device through a technique called Ray-Surface Positioning (RSP) on the surface. What this team wanted to demonstrate is that, by using a few LED bulbs in a room, it is possible to make a very detailed mapping of the objects present there by means of Li-Fi in a more economical and precise way than conventional multilateration (or position triangulation) [27]. Although the errors in the results were greater than those expected, this project demonstrated new capabilities of Li-Fi technology at the time of fulfilling its double task of data transmission and lighting, since combining these two characteristics was achieved locating various objects in a closed room.

3.3. Li-Fi in Asia, Africa and Oceania

- Among Lifi's most important advances in the Asian continent is the association between Latécoère, a leading company in the field of aerostructures and interconnection systems, Signify, formerly known as Phillips Lighting, and Huneed Technologies, a South Korean communication company; aerospace tactics and teams that started the industrialization phase to develop and produce the Li-Fi cockpit system to implement wireless internet in airplanes, something impossible with Wi-Fi. [28]
- Hyperion Technologies is a Turkish company focused on optical wireless communication in order to empower next-generation wireless networks at both access and return levels. The company made important contributions to the 802.15.7rl regulatory project and continues to support the 802.11 regulatory group on communication with light and 802.15.13 on optical wireless communication. [24]
- CRRC Corporation, a Chinese state-owned rolling stock manufacturer, at AusRail at the Sydney International Exhibition Center in Sydney, Australia presents futuristic models of trains with the implementation of Li-Fi technology as a means of connection to the network. According to CRRC, with the ease of connection that Li-Fi presents, both inside and outside of the trains, connections can be made between the different trains, tracks and tunnels of the railway system, saving construction and maintenance costs by not requiring large additional ethernet cabling deployments. [29] [30]
- Different investigations developed in institutions of China and India have achieved optimizations regarding hybrid systems between Wi-Fi and Li-Fi, from adaptations to the modulation algorithms for VLC as data processing

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techniques in which both technologies are implemented to achieve connection improvements. In [31], optimization of the multipoint hybrid wireless connection is achieved by balancing the loads between the different clusters and the Li-Fi and Wi-Fi connection systems, maximizing efficiency and reducing interference between multiple APs and user equipment in the previously proposed connection models of Hass and his team [32]. In [33], a parallel transmission is achieved with multiple connections through multiple Li-Fi APs called PT-Li-Fi, a design that helps mitigate the loss of connection of a Host susceptible to intermittent blockages of light paths, achieving an increase in performance; 150% and 15% in fairness of user connections.

- The use of QR codes by smartphone users has increased dramatically in recent years. Its ease and practicality in multiple daily scenarios such as product control, payments, advertising, among others, have managed to position this technology in a very promising place. As a result of this, in Japan a proposal based on Li-Fi called LiQR is presented that helps to replace the active static QR codes with dynamic QR codes generated by Li-Fi connections that increase the security and ease of renewal of the QR code should it be required. [34]
- "LiFi: the solution to radio frequency saturation" is a study conducted at the Federal University of Technology, Minna - Nigeria. This study shows the benefits of Li-Fi technology in simulations developed in MATLAB software, simulating a Li-Fi work environment complementary to a 100m 5G system, obtaining average received power values of 3.87 dBm and 2.28 dBm on the downlink channel, checking that these values are possible in standard interior lighting spaces. [35]

3.4. Li-Fi in Latin America:

- The Sisoft company is a pioneering Mexican company in the production and commercialization of Li-Fi technologies in Mexico and Latin America. For the year 2016 they managed to put on the market a type of LED ceiling lamp called "Lumux" together with the Ledcom USB Dongle Mini receiver. The highlights of this product were [36]:

a) 12 Mbps links both upstream and downstream
b) 2 meter maximum range

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c) infrared system to maintain connection when LEDs are off.
d) 16W Power.

However, the company has not updated its products since 2017, in addition, they have two projects without sufficient funds in Kickstarter where they sought to obtain aid for the construction of 20 LEDCOM Kits made from their own Li-Fi prototype.

- Signify, formerly known as Phillips Lighting, presented at the Iberoamerican Meeting of Lighting Design (IMLD) in 2019 in the cities of Bogotá, Colombia and on Colonia del Sacramento, Uruguay, its information transmission system based on Li-Fi, called TruLifi. In these conferences, the operation of this technology was demonstrated and the prototypes of projects with TruLifi in Europe were discussed, as well as a possible expansion into South America through investors and state contacts in both countries. Also, Signify presented its IoT platform "Interact" designed to manage the data collected by each of the connected light points (devices, sensors and lighting systems) including Li-Fi tecnology in is your smart solutions for cities (Interact City), sports lighting (Interact Sports), offices (Interact Office), commercial lighting (Interact Retail) and small and medium enterprises (Interact Pro). [23][37]
- Signify implements, in the city of Buenos Aires, Argentina, one of the first "Interact City" projects to monitor more than 100,000 points of light. The system allows you to remotely manage consumption, create scenes to save energy, verify the optimal functioning of the luminaires and schedule eventual replacements in maintenance tasks. In addition, this company will be in charge of lighting the new "Estudiantes de La Plata" stadium through Interact Sports technology, making it the first 100% LED football stadium in Argentina. Likewise, it will have a control system that will allow it to offer a unique experience to viewers. [38]
- In several Latin American countries, Li-Fi technology has become very important in the field of implementing this technology. Different research groups from Latin American universities have carried out various research on prototypes and designs of telecommunications systems that implement Li-Fi technology as a means of transmitting information. Some of those works are:

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a) "Analysis and study of the use of Li-Fi technology in multimedia playback via streaming for use at medium term in Ecuador" (University "Católica de Santiago de Guayaquil", Ecuador). This research carries out a study of the functionality of the Li-Fi technology applicable at the national level, to reproduce multimedia content through various platforms and websites that offer access via streaming with next-generation video quality, compared to the technologies of wireless networks that are most used in Ecuador for residential and corporate use. [39]

b) "Design of a Li-Fi network for block 4 of the Queri headquarters" ("Universidad de las Américas", Ecuador). The purpose of this work is to design an Li-Fi network for Lot 4 of the Queri Headquarters of the University of the Americas in Ecuador. The activities to be carried out are detailed as follows: the extraction of information from the study site, comparative tables of the network current compared to the network proposed in the design and possible applications of the Li-Fi technology in Ecuador. In addition, it also presents a cost-benefit analysis compared to currently implemented technology. [40]

c) "LI-FI technology, safety and innovation in the home" (University of San Carlos de Guatemala, Guatemala), is a research and analysis of Li-Fi technology that seeks, based on comparisons in the development of the technology and from surveys carried out, to find a pattern of future trends in the technology market regarding the implementation of Li-Fi as a technology transmission of data and information. [41]

d) "Li-Fi technology in communications in Argentina" ("instituto universitario aeronautico", Argentina), This work aims to understand and understand the operation of the new Li-Fi technology to later be implemented in wireless communications in Argentina. This project considers the use of the electromagnetic spectrum in wireless communications, as the main element to improve security in access networks, and also increase the speed and reliability of data transfer. [42]

e) Services based on geopositioned information through the use of Li-Fi technology (Univerisity "Argentina de la Empresa", Argentina), is an investigation on the implementation of information services in digital format whose access has the characteristic of being limited to a geographic area; and it is consumed by users through Li-Fi technology. It also presents the proposals for five business models with the application of this technology. Each of which has its respective economic-financial-technical feasibility

analysis regarding its implementation, which correspond to services that use geopositioned information and are implemented with Li-Fi technology, also exposing the effectiveness of the development of these services and how these concepts can improve or replace existing wireless data transmission services and their contribution to the development of IoT. [43]

Likewise, there are many other works that show the growing participation of Latin America in the development and implemetation of Li-Fi technology.

4. PROJECTION OF LI-FI IN THE FUTURE

This section describes the estimated projections for the development and commercialization of Li-Fi technology worldwide and in a local context, such as Colombia, highlighting innovations in technology, new alliances and investments at the international level, as well as a brief description of the development of the new standard for Li-Fi; taking as a starting point both the current limitations of the technology in question, as well as the challenges to overcome at a technical, strategic, and commercial level.

4.1. Li-Fi projection worldwide

The solutions of the current limitations of Li-Fi will determine how viable and accepted the technology will be in a larger market niche in the future; the low speeds in the initial solutions, weakness in the signal, interference by physical elements between the receiver and the issuer of the signal, among others, filled the market with uncertainty [44], [45]. However, with the investigation of new elements at a technical level, such as new materials and new connection devices, have made it possible to partially reduce these limitations. Recent research on new materials, such as perovskite, as a faster, more reliable and cheaper photodetector than current photodetectors [46] is an example of it.

Other research worth highlighting is the integration of solutions in a LAN (Local Area Network), such as the Enlighint system proposed by Disney research, achieving intercommunication between different bulbs with bidirectional links within the same room with a speed of 600 bps [47], which opens the door to developments of indoor solutions and developments in PAN (Personal Area Network) networks in IoT (Internet of Things) and IoE (Internet of Everything).

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With IoT, IoE and 5G, other markets have also been opened to Li-Fi beyond conventional network connections. In fact, as previously mentioned, the incorporation of Li-Fi technology in the development of future generations of telecommunications is getting stronger; evidence of this can be seen in the new alliances and recent studies in the implementation of the 5G network with the help of Li-Fi and OWS devices [48]. At a strategic level, new alliances have been established that allow Li-Fi to continue in constant growth and development for the future market. LCA (Light Communications Alliance) was born in June 2019 with the aim of promoting research in Li-Fi and promoting new wireless technologies that allow for the development of communication through light. In this alliance you can find large companies and public and private entities such as Nokia, Commissariat for atomic energy and renewable energies CEA, PureLiFi, Lucibel, Institut Mines-Télécom, Liberty Global, Orange, Li-Fi Center - University of Edinburgh, Emirates Integrated Telecommunications Company (du), Velmeni and Zero.1 [44], [49].

Other important recent alliances are the company Getafe and pureLiFi with the aim of exploring solutions for clients in the military, automotive and manufacturing sectors in which Getafe has a large market niche. It is expected that with this alliance it would be possible to implement the advantages of Li-Fi at a more robust level [50]. Signify and Vodafone Germany establish an alliance so that 5G and Li-Fi can provide higher speed and better mobile connectivity to the consumer, taking, as a reference, reliable and secure broadband with low latency for different applications such as cellular connections, solutions for medical communications and applications in autonomous driving on vehicle-to-vehicle (V2V) and vehicle-to-infrastructure networks (V2X) [51], [52]. With the above alliances, the global Li-Fi market is expected to achieve the projected growth of approximately USD 50,985.46 million by 2023; approx. 70.20% of the CAGR (Compound Annual Growth Rate) between 2017 and 2023 [53].

Regarding regulation, norms and standardization, since 2018 the IEEE group has been working on the implementation of a new standard for Li-Fi technology, with the creation of an opinion group of experts and specialists which seeks to establish a new standard involving all stakeholders (researchers, manufacturers, operators and end customers, both corporate and home) of Li-Fi technology, seeking to determine technical specifications and economic guidelines for the use of Li-Fi as wireless communication technology for new network solutions 5G, IoT and IoE; this standard is planned for the year 2021 [54]–[56].

4.2. Li-Fi in Colombia

Currently, Colombia has become the focus of several companies for the possible implementation of Li-Fi. The Signify company chose the country to carry out the first commercial Li-Fi research in Latin America. In the words of Felipe Uribe, Signify's general manager for the North Latin America region: "Expectations are high, as this is an interesting market; it grows, is healthy and demands innovation, so we are very excited to offer innovations like Li-Fi to Colombians" [57]. In August 2019, the Innovation forum dedicated to Li-Fi technology was held in Colombia with the participation of various scientists and entrepreneurs who promote Li-Fi technology, such as Gunter Pauli, founder and director of ZERI (Zero Emissions Research Initiatives) and creator of the Blue Economy concept, Suat Topsu, French scientist, co-creator of Li-Fi, professor at Paris-Saclay University and Saint Quentin University of Versailles, and Franz Otten, Dutch businessman, who has focused on developing a sustainable and ecologically clean business around light. In this forum, proposals such as those of Otten were heard; this extends to the development in Colombia of a business model that allows it to produce Li-Fi-based solutions for the national and regional market, to make it a point of reference in research and innovation in the Worldwide data business through light.

Otten, Topsu and Pauli, are in talks with experts and national investors for the local production of solutions, both for the use of individuals and families in their homes, as well as for government and industry [58]. However, there are still no successful implementations of Li-Fi in the national environment despite the advances made in other countries and the technological needs of the nation. This is expressed in the degree project of Leonardo Rodríguez and Oscar Guevara at the Catholic University of Colombia, entitled "Scope of the development of the new Li-Fi technology for telecommunications in Colombia" where the current situation of technology and the future implementation of a prototype Li-Fi system in the Latin American country are presented. However, the authors analyze the possible implementations of Li-Fi in Colombia in two specific cases [59]:

- A virtual study network for the vulnerable population, where it is proposed to the national government, taking advantage of light and electricity infrastructure, to bring the internet to the poorest populations in the country. Likewise, thanks to the conditions of the sale of the spectrum where the winners are asked to take tablets to the most needy populations of the country, the delivery of the data transmission and reception equipment would be guaranteed.

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- An efficient data transmission network for traffic control where traffic signals, traffic lights and police officers have tools for data reception, which will receive signals transmitted from the lights of the cars; this, with the purpose of having a greater control of traffic violations, reduce accidents and improve safety by obtaining all the information of a vehicle instantly.

Other advances in the nation around Li-Fi have been made from the creation of VLC prototypes, such as the one carried out by the telecommunications systems research group of the Universidad del Valle (SISTEL-UV) [60] where the interference of ambient light on an LED receiver was studied, taking into account the distance and location angle with respect to the emitting signal. The results obtained by this group show that communication is possible and maintains its quality despite the interference of ambient light in a room. This is due to the fact that the power of this interference is weak compared to the potential of the emitting signal. In addition, the angle of reception of the ambient light was greater than 45 °, which does not generate any obstruction, since the angles of greater efficiency are close to 0 °.

Colombia has the same technological implementation needs as other countries thanks to the rise of electronic devices and the limited use of spectrum bandwidth. This means that government entities and the business sector should begin to worry more about the implementation of new communication technologies such as 5G and think about a possible integration of Li-Fi technology, since currently, the competitiveness of companies and economic growth of the nation depend on a correct implementation of new technologies [61].

5. DISCUSSION

The research carried out for the development of this article has allowed us to glimpse the evolution of Li-Fi from its invention to the current development phase in order to make a diagnosis of its future projection. The development of Li-Fi began with the objective of looking for a wireless data transmission technology that could fill all the deficiencies of the current standard; it was even thought that Li-Fi could replace Wi-Fi in the future according to its inventors and first exponents. However, one thing that most of the articles and authors reviewed agree on is that Li-Fi cannot replace Wi-Fi, at least not in its entirety. The current focus of research and development of this new technology has been based on the creation of hybrid networks between Li-Fi and Wi-Fi to provide more personalized solutions according to the infrastructure, users and purpose of the network. For example, for traffic management projects using car

lights and traffic signals, Li-Fi is presented as an ideal and practical solution due to its low installation cost and great utility. On the other hand, in a company network or a solution for a home, the installation of Li-Fi requires a greater effort to cover the distances that the light of the LED bulbs does not reach, in addition to dealing with the disadvantage of Li -Fi of not being able to pass through walls. In this case, we speak of a hybrid network where Li-Fi makes its appearance in large and closed spaces such as meeting and conference rooms, while Wi-Fi will continue to work in other aspects.

This hybrid functionality is described in the concept proposed by Harald Hass: "Li-Fi goes where Wi-Fi cannot go." As an example, we can review the case of hospitals where Li-Fi would be used as a transmission medium in spaces where Wi-Fi can cause interference with medical instruments, but in public spaces this latest technology would be followed in a hybrid network. In the same way, there is talk of underwater exploration ships where Li-Fi has the advantage of traveling more easily through the water or the possible use of Li-Fi to provide internet to airplanes in flight. In this way, research, and development of Li-Fi can establish various uses of this technology in hybrid networks that would work in a complementary way with Wi-Fi.

Observing the technical and commercial limitations that Li-Fi currently has, one could hastily give a negative verdict on the development of the technology, as has been found in some sources of this research; the technology is still at a very early stage of development, in which it is still exploring how to take full advantage of all the technical and commercial advantages that this technology has. Perhaps it has not had the prominence and boom with which it was exhibited in its beginnings today, but that does not mean that it does not achieve the main objective, which is to expand wireless connections, solving the problems of current ones in a complementary way or in replacement of some of these. The results found in the development of this article are clear; examples that there are more achievements, advances and innovations achieved than the difficulties and barriers that have arisen at the same time in the research and development of Li-Fi.

There is still a lot of interest in large organizations worldwide for the development of this technology, which is clear evidence that Li-Fi is in constant development. The current alliances and research groups found in the development of this research show that Li-Fi continues to receive significant economic and intellectual investment from different sectors that ambitiously seek to promote the output of Li-Fi to the consumer market, where not only the business sector (which currently has access to Li-Fi solutions of an initial generation) can make use of this technology but it can be used in homes and in public places increasingly bringing the development of more

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robust and accessible internet connections from anywhere, including places where wireless connection was previously impossible.

6. CONCLUSIONS

Li-Fi technology is an emerging solution with great potential for development and expansion in the telecommunications market, the properties that it has will help expand the connection to the network in a complementary way to the current wireless solutions that are in the market. Despite having the limitations of any emerging technology, Li-Fi is beginning to have a great reception in the business sector, which may encourage this technology to soon reach the consumer market in homes at prices that are more accessible to the general public.

The advantages of Li-Fi help to solve the current problems of bandwidth consumption, limitations of data transmission speed, security and energy efficiency. These would be able to promote other technologies such as home automation, telemedicine, IoT, 5G and Wi-Fi, increasing their current potential and reaching places where it was previously impossible to have a wireless network connection.

Li-Fi is here to stay, the innovative and risky proposal has already managed to awaken interest in network and telecommunications developments in areas that had not been explored before due to the different problems generated by RF-based wireless solutions, such as integration of wireless network connections in the medical sector in sensitive areas, use of the internet in commercial aviation, submarines and space communications, Smartcities, IoT and IoE, among others. With the development of Li-Fi and OWC technologies, it can be estimated that the access and evolution of the Internet will be much more extensive and efficient in the near future, either because these are the leading technologies in said change or, on the contrary, they are complementary technologies to much more robust solutions that implement them.

Observing the alliances and new advances that Li-Fi has had in the last 5 years, a great interest and investment in the development of this technology, in the new generation telecommunication networks by different groups and entities worldwide, can be seen. It is important that countries such as Colombia begin to work hand in hand with experts, such as scientists, researchers and entrepreneurs to, based on the current tests and advances of Li-Fi, implement wireless connectivity solutions through light, taking advantage of the low cost that it represents; its installation and all the capabilities this technology has to offer in a better, more powerful, safe and healthy network infrastructure in family, industrial or government environments.

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The future of Li-Fi will depend on how versatile the research field is and how the market niche of this technology behaves. Although the expected market goal of Li-Fi has not been the expected one, the integration of new companies and new research spaces will allow the technology to reach a state of maturity in which it manages to exploit all its properties and solve the limitations that it currently presents, such as the promised laboratory speeds of 100Gb/s, compatibility with factory devices (without external interfaces), comfort, no dependence on a direct line with the light emitting source, among others, thus achieving and even exceeding the investment and development projections in the market with which it was foreseen in the past.

7. REFERENCES

[1] R. D. Roberts, S. Rajagopal, and S. K. Lim, "IEEE 802.15.7 physical layer summary," in *2011 IEEE GLOBECOM Workshops, GC Wkshps 2011*, 2011, pp. 772–776, doi: https://www.doi.org/10.1109/GLOCOMW.2011.6162558.

[2] L. U. Khan, "Visible light communication: Applications, architecture, standardization and research challenges," *Digit. Commun. Networks*, vol. 3, no. 2, pp. 78–88, May 01, 2017, doi: https://www.doi.org/10.1016/j.dcan.2016.07.004.

[3] S. Nivetha, G. A. Preethi, and C. Chandrasekar, "Performance Evaluation of Modulation Techniques in Li-Fi," *Int. J. Recent Technol. Eng.*, no. 3, pp. 1509–1518, 2019, doi: https://www.doi.org/10.35940/ijrte.C4203.098319.

[4] E. Ramadhani and G. P. Mahardika, "The Technology of LiFi: A Brief Introduction," in *IOP Conference Series: Materials Science and Engineering*, Mar. 2018, vol. 325, no. 1, pp. 1–7, doi: https://www.doi.org/10.1088/1757-899X/325/1/012013.

[5] W. A. Imtiaz and R. Roka, *Design, implementation, and analysis of next generation optical networks: emerging research and opportunities*, pp. 75-76 2019, doi: https://www.doi.org/10.4018/978-1-5225-9767-4.

[6] H. Haas, "Li-Fi Technical Tutorial 'Li-Fi modulation and networked Li-Fi attocell concept,'" pp. 1–65, 2013, [Online]. Available: http://www.lifi-centre.com/wp-content/uploads/2014/07/131223_Li-Fi_tutorial.pdf.

[7] C. Jurczak, "LiFi: Enlightening Communications," pp. 1–15, 2017, doi: https://www.doi.org/arXiv:1802.01471v1.

[8] Cisco, "Cisco Visual Networking Index: Global Mobile Data," pp. 1-39, 2016. [Online]. Available: https://www.cisco.com/c/dam/m/en_in/innovation/enterprise/assets/mobile-white-paper-c11-520862.pdf.

[9] R. Velasco, "Aplicaciones para monitorizar los equipos de una red en PC, Android o iOS," 2018, p. 1. https://www.redeszone.net/2018/11/18/apps-monitorizar-red-pc-android-ios/ (accessed Mar. 02, 2020).

[10] A. Sarkar, S. Agarwal, and A. Nath, "Li - Fi Technology : Data Transmission through Visible Light," *Int. J. Adv. Res. Comput. Sci. Manag. Stud.*, vol. 3, no. 6, pp. 1–12, 2015, [Online]. Available: https://www.researchgate.net/profile/Asoke_Nath/publication/279530585_Li-Fi_Technology_Data_Transmission_through_Visible_Light/links/559560a608ae21086d206514/Li-Fi-Technology-Data-Transmission-through-Visible-Light.pdf.

[11] H. Hass and M. Sufyan, "Modulation Techniques for Li-Fi," vol. 33, no. 2, pp. 29–40, 2016, [Online]. Available: https://res-www.zte.com.cn/mediares/magazine/publication/com_en/article/201602/458048/P020160512435234985272.pdf.

[12] Xakata, "El protocolo WPA2 ha sido hackeado: la seguridad de las redes WiFi queda comprometi," p.1, 2017. https://www.xataka.com/seguridad/el-protocolo-wpa2-ha-sido-vulnerado-la-seguridad-de-todas-las-redes-wifi-queda-comprometida.

[13] G. Blinowski, "Security issues in visible light communication systems," in *IFAC-PapersOnLine*, 2015, vol. 28, no. 4, pp. 235–239, doi: https://www.doi.org/10.1016/j.ifacol.2015.07.039.

[14] A. Hohendahl, "Interferencia entre Símbolos en Comunicaciones Digitales I.S.I. (Inter Symbol Interference)," 2014. [Online]. Available: http://web.fi.uba.ar/~ahohenda/docs/ISI_Hohendahl2014.pdf.

[15] A. Gomez *et al.*, "Beyond 100-Gb/s indoor wide field-of-view optical wireless communications," *IEEE Photonics Technol. Lett.*, vol. 27, no. 4, pp. 367–370, 2015, doi: https://www.doi.org/10.1109/LPT.2014.2374995.

[16] L. Grobe *et al.*, "High-speed visible light communication systems," *IEEE Commun. Mag.*, vol. 51, no. 12, pp. 60–66, 2013, doi: https://www.doi.org/10.1109/MCOM.2013.6685758.

[17] D. Tsonev, S. Videv, and H. Haas, "Towards a 100 Gb/s visible light wireless access network," *Opt. Express*, vol. 23, no. 2, p. 1627, 2015, doi: 10.1364/oe.23.001627.

[18] S. M. Mana *et al.*, "LiFi Experiments in a Hospital," *2020 Opt. Fiber Commun. Conf. Exhib. OFC 2020 - Proc.*, no. March, pp. 3–6, 2020, doi: 10.1364/ofc.2020.m3i.2.

[19] PureLifi, "O2 Telefonica is ready with LiFi for 5G and beyond," 2019, p. 1. https://purelifi.com/case-study/o2-telefonica-is-ready-with-lifi-for-5g-and-beyond/.

[20] PureLifi, "Kyle Academy becomes one of the first schools to offer disruptive technology, LiFi to their students in the classroom," 2019, p. 1. https://purelifi.com/case-study/lifi-in-a-classroom/.

[21] PureLifi, "Babcock is pioneering leading edge engineering services using LiFi.," 2019, p. 1. https://purelifi.com/case-study/babcock-powered-by-purelifi/.

[22] PureLifi, "LiFi in the healthcare sector," 2019, p. 1. https://purelifi.com/case-study/lifi-in-the-healthcare-sector/.

[23] Signify, "Signify lanza Trulifi: los sistemas comerciales LiFi de alta velocidad más confiables del mundo," 2019, p. 1. https://www.signify.com/es-co/our-company/news/press-releases/2019/20190625-signify-launches-trulifi

[24] Sector de radiocomunicaciones de la UIT, "Luz visible para las comunicaciones de banda ancha," pp. 1-20, 2018. [Online]. Available: https://www.itu.int/dms_pub/itu-r/opb/rep/R-REP-SM.2422-2018-PDF-S.pdf.

[25] M. Ayyash *et al.*, "Coexistence of WiFi and LiFi towards 5G," pp. 1–13, 2015, doi: https://doi.org/10.1109/MCOM.2016.7402263.

[26] Lvx Systems, "LVX Information Page," p. 1. http://www.lvx-system.com/service.php.

[27] E. W. Lam and T. D. C. Little, "Indoor 3D Localization with Low-Cost LiFi Components," *2019 Glob. LIFI Congr. GLC 2019*, p. 14, 2019, doi: https://www.doi.org/10.1109/GLC.2019.8864119.

[28] Signify, "Latécoère, Signify and Huneed Technologies announce strategic partnership on LiFi in commercial airplanes," 2019, pp. 1–3. https://www.assets.signify.com/is/content/PhilipsLighting/Assets/signify/global/news/2019/20191028-latecoere-signify-and-huneed-technologies-announce-strategic-partnership-on-lifi-in-commercial-airplanes.pdf.

[29] Sydney International Exhibition Centre, "AusRail Sydney International Exhibition Centre," *AusRail Sydney International Exhibition Centre*, 2019, p. 1. http://www.xinhuanet.com/english/2019-12/04/c_138604527.htm

[30] ASIA TIMES STAFF, "Subway cars of the future have window screens and Li-Fi - Asia Times," Sep. 11, 2018, p. 1. https://asiatimes.com/2018/09/subway-cars-of-the-future-have-window-screens-and-li-fi/

[31] W. Ma, L. Zhang, and Y. Jiang, "Optimized joint LiFi coordinated multipoint joint transmission clustering and load balancing for hybrid LiFi and WiFi networks," *J. Opt. Commun. Netw.*, vol. 12, no. 8, p. 227, Aug. 2020, doi: https://www.doi.org/10.1364/JOCN.388264.

[32] X. Wu, M. D. Soltani, S. Member, L. Zhou, and M. Safari, "Hybrid LiFi and WiFi Networks : A Survey," no. January, p. 25, 2020.

[33] X. Wu and D. C. O'Brien, "Parallel Transmission LiFi," *IEEE Trans. Wirel. Commun.*, pp. 1–10, 2020, doi: https://www.doi.org/10.1109/twc.2020.3001983.

[34] H. Babar, L. Carson, and Y. C. Patrick, "OSA | Li-Fi based Secure Programmable QR Code (LiQR)," *JSAP-OSA Jt. Symp. 2017 Abstr. (Optical Soc. Am. 2017), Pap. 6p_A409_6.*, p. 1, Sep. 2017, Accessed: Jul. 27, 2020. [Online]. Available: https://www.osapublishing.org/abstract.cfm?uri=JSAP-2017-6p_A409_6.

[35] M. Jatau, M. David, and S. Zubair, "LiFi: The Solution to Radio Frequency Saturation," in *2020 International Conference in Mathematics, Computer Engineering and Computer Science (ICMCECS)*, Mar. 2020, no. Vlc, pp. 1–6, doi: https://www.doi.org/10.1109/ICMCECS47690.2020.240880.

[36] A. Lopez Victoria and B. Ortega Tamarit, "Desarrollo de una herramienta software para redes de comunicaciones e iluminación en interiores basada en tecnología VLC," pp. 1–62, 2019, [Online]. Available: https://riunet.upv.es/bitstream/handle/10251/124615/López - Desarrollo de una herramienta software para el diseño de una red de comunicaciones e ilum....pdf?sequence=1.

[37] Sociedad Colombiana de arquitectos, "Luz conectada: el desarrollo que revolucionará la forma de interactuar con la iluminación en Colombia – Sociedad Colombiana de Arquitectos," Jul. 10, 2019, p. 1. https://sociedadcolombianadearquitectos.org/luz-conectada-el-desarrollo-que-revolucionara-la-forma-de-interactuar-con-la-iluminacion-en-colombia/

[38] El Eco, "Ofrecen en Argentina LiFi, internet a través de la luz: más veloz y estable que el Wi-Fi – El Eco," Feb. 18, 2020, p. 1. https://www.eleco.com.ar/interes-general/ofrecen-en-argentina-lifi-internet-a-traves-de-la-luz-mas-veloz-y-estable-que-el-wi-fi/ (accessed Oct. 10, 2020).

[39] V. N. T. Rosero, "Análisis y estudio del uso de la tecnología Li-Fi en sistemas de reproducción multimedia mediante streaming para la utilización a mediano plazo en el Ecuador," Universidad Católica De Santiago De Guayaquil , Guayaquil, pp. 87, 2018, Accessed: Oct. 09, 2020. [Online]. Available: http://repositorio.ucsg.edu.ec/handle/3317/10223.

[40] J. E. A. Aguilar and V. A. L. Lema, "DISEÑO DE UNA RED LI-FI PARA EL BLOQUE 4 DE LA SEDE QUERI," Universidad de las Américas, Quito, pp. 1-87, 2017, Accessed: Oct. 09, 2020. [Online]. Available: http://dspace.udla.edu.ec/handle/33000/7938.

[41] C. A. R. Yoque, "Tecnología Li-Fi, Seguridad E Innovación En El Hogar," Universidad de San Carlos de Guatemala, pp. 1-112, 2016, [Online]. Available: http://www.repositorio.usac.edu.gt/5869/1/Carlos Abraham Yoque Rodríguez.pdf.

[42] L. M. Cerino, "La tecnología Li-Fi en las comunicaciones de Argentina," 2017. Accessed: Oct. 09, 2020. [Online]. Available: https://rdu.iua.edu.ar/handle/123456789/379.

[43] L. R. Bueno, C. A. Bietti, and E. E. Sicre, "Servicios basados en informacion geoposicionada mediante la utilizacion de tecnología li-fi," Universidad Argentina De La Empresa, Buenos Aires, pp. 1-252, 2017, Accessed: Oct. 09, 2020. [Online]. Available: https://repositorio.uade.edu.ar/xmlui/bitstream/handle/123456789/6479/PFI - Leandro Bueno - Entrega Final.pdf?sequence=3&isAllowed=y.

[44] L. Pautasio, "¿Cuánto falta para hacer realidad la conexión a Internet a través de la luz? – TeleSemana.com," *TeleSemana*, 2019, p. 1. https://www.telesemana.com/blog/2019/01/14/cuanto-falta-para-hacer-realidad-la-conexion-a-internet-a-traves-de-la-luz/

[45] G. J. Garcia, "'LiFi': el internet a la velocidad de la luz no se enciende | Innovación | EL PAÍS Retina," *Retina - El Pais*, Nov. 17, 2019, p. 1. https://retina.elpais.com/retina/2019/11/15/innovacion/1573807880_040011.html

[46] C. Bao *et al.*, "High Performance and Stable All-Inorganic Metal Halide Perovskite-Based Photodetectors for Optical Communication Applications," *Adv. Mater.*, vol. 30, no. 38, pp. 1–26, 2018, doi: https://www.doi.org/10.1002/adma.201803422.

[47] S. Schmid, T. Richner, S. Mangold, and T. R. Gross, "EnLighting: An indoor visible light communication system based on networked light bulbs," in *2016 13th Annual IEEE International Conference on Sensing, Communication, and Networking, SECON 2016*, Nov. 2016, p. 1, doi: https://www.doi.org/10.1109/SAHCN.2016.7732989.

[48] M. Z. Chowdhury, M. Shahjalal, M. K. Hasan, and Y. M. Jang, "The role of optical wireless communication technologies in 5G/6G and IoT solutions: Prospects, directions, and challenges," *Appl. Sci.*, vol. 9, no. 20, pp. 1–20, 2019, doi: 10.3390/app9204367.

[49] R. Serrano, "Cuánto falta para que sea una realidad Li-Fi | | Iluminet revista de iluminación," *Iluminet*, 2019, p. 1. https://www.iluminet.com/una-realidad-li-fi/

[50] Getac, "Getac - Getac anuncia una colaboración con pureLiFi para lanzar al mercado dispositivos LiFi robustos," *Getac News*, Oct. 29, 2019, p. 1. https://www.getac.com/latam/news/getac-anuncia-una-colaboracion-con-purelifi-para-lanzar-al-mercado-dispositivos-lifi-robustos/

[51] REDESTELECOM, "La unión hace la fuerza: LiFi y 5G | Noticias | Mercado | Redes&Telecom," *Redestelecom News*, Oct. 03, 2019, p. 1. https://www.redestelecom.es/mercado/noticias/1114463032603/union-fuerza-lifi-y-5g.1.html

[52] Chen. Yining, "Vodafone Partners Signify to Combine 5G and LiFi - LEDinside," *LEDInside*, Oct. 02, 2019, p. 1. https://www.ledinside.com/news/2019/10/vodafone_signify_combine_5g_lifi

[53] Kenneth Research, "Li-Fi Market Industry Players, Revenue And Product Demand Till 2018-2023 - America News Hour," *Global-Li-Fi--Market Kenneth Research*, Sep. 12, 2019, p. 1. https://www.americanewshour.com/2019/09/12/li-fi-market-industry-players-revenue-and-product-demand-till-2018-2023/46630/

[54] Smartlighting, "Avances en la estandarización de la tecnología LiFi - Smart Lighting," *Smartlighting*, 2018, p. 1. https://smart-lighting.es/avances-la-estandarizacion-la-tecnologia-lifi/

[55] P. Nikola Serafimovski *et al.*, "Light Communications for Wireless Local Area Networking - IEEE Future Networks," *IEEE 5G Tech Focus: Volume 2, Number 2*, May 2018, p. 1. https://futurenetworks.ieee.org/tech-focus/may-2018/light-communications-for-wireless-local-area-networking

[56] R. Arellano García, "LiFi: El futuro de las comunicaciones VLC," pp. 1–72, 2019, Accessed: Sep. 05, 2019. [Online]. Available: http://openaccess.uoc.edu/webapps/o2/bitstream/10609/95748/7/rarellanoTFG0619memoria.pdf.

[57] El Tiempo, "Así funciona LiFi, usa la iluminación para conectarse a internet," Bogotá, p. 1, May 21, 2019, [Online]. Available: https://www.eltiempo.com/contenido-comercial/asi-funciona-lifi-la-tecnologia-que-usa-la-iluminacion-para-conectarse-a-internet-364216.

[58] J. H. Rodríguez, "LiFi, una alternativa en plena evolución," *Computerworld Colombia*, 2019, p. 1. https://computerworld.co/lifi-una-alternativa-en-plena-evolucion/.

[59] L. C. Rodriguez and O. A. Guevara Penagos, "Alcances del desarrollo de la nueva tecnologia li-fi para las telecomunicaciones en Colombia," Universidad Católica De Colombia, pp. 2-67, 2014, doi: https://www.doi.org/10.4324/9781315853178.

[60] S. C. Barragan, F. G. Guerrero, U. Valle, and U. Valle, "Design and Implementation of A Visible Light-Based Communications System," *Ing. Solidar.*, vol. 15, no. 28, pp. 1–20, 2019, doi: https://doi.org/10.16925/2357-6014.2019.02.03.

[61] H. Eduardo Díaz Rodríguez, "Tecnologías de la información y comunicación y crecimiento económico," *Econ. Inf.*, vol. 405, pp. 30–45, 2017, doi: https://www.doi.org/10.1016/j.ecin.2017.07.002.