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OPTICAL WIRELESS COMMUNICATIONS FOR INTERNET OF THINGS: APPLICATIONS, ISSUES AND CHALLENGES

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ABSTRACT

Visible light communication (VLC) is a novel paradigm that has the potential to completely alter wireless communication in the future. In VLC, data is transferred by modifying the 400–700 nm visible light spectrum, that is employed for lighting. It has been demonstrated via analytical and experimental study that VLC has the ability to offer high-speed data transmission with the added benefits of increased energy efficiency and communication security/privacy. As part of future smart environments, VLC with its expansive frequency spectrum and IoT integration can enable a variety of indoor and outdoor applications. An overview of optical wireless communications for the Internet of Things (OWC-IoT) is presented in this research, focusing on VLC based potential applications and challenges.

Keywords: (IoT) Internet of Things, Visible Light Communications (VLC), Light Fidelity (LiFi), Optical Wireless Communications (OWC), Optical Camera Communications (OCC).

الاتصالات اللاسلكية البصرية لشبكة إنترنت الأشياء: التطبيقات والقضايا والتحديات

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ملخـــــص البحـــــــث

الاتصال بالضوء المرئي (VLC) هو نموذج جديد ينطوي على إمكانية التغيير الكامل للاتصالات اللاسلكية في المستقبل. فيVLC ، يتم نقل البيانات عن طريق تعديل طيف الضوء المرئي 400–nm700 ، الذي يستخدم للإضاءة. وقد ثبت من خلال دراسة تحليلية وتجريبية أن VLC لديها القدرة على عرض نقل البيانات بسرعة عالية مع الفوائد الإضافية لزيادة كفاءة استخدام الطاقة وأمن الاتصالات/الامتيازات. وكجزء من البيئات الذكية في المستقبل، يمكن لمركبات VLC مع طيف ترددها

الموسع وتكاملها في مجال تكنولوجيا المعلومات أن تتيح مجموعة متنوعة من التطبيقات داخل المباني وخارجها. ويرد في هذا البحث عرض عام للاتصالات اللاسلكية البصرية من أجل شبكة الإنترنت للأشياء (OWC–IoT) مع التركيز على التطبيقات والتحديات المحتملة المستندة إلى VLC .

الكلمات المفتاحية: إنترنت الأشياء(IoT)، الاتصالات الضوئية المرئية (VLC)، دقة الضوء (LiFi)، الاتصالات اللاسلكية البصرية (OWC) ، الاتصالات بالكاميرا البصرية (OCC).

1. Introduction

The Internet of Things (IOT) is a ground-breaking technology that connects individually identifiable smart items to bring the physical and digital worlds together. The IoT age imposes a fundamental paradigm change in our knowledge of nearly all areas, including research, education, industry, public health and safety, business, energy, transportation, media, logistics, and so on by opening the door for a wide range of applications, such as, smart home, smart city, smart hospital, smart hospitality, smart grid, smart car, etc.[1], [2], [3] . Transforma Insights[1] has released data indicating that the number of connected IoT devices worldwide is anticipated to increase from 7.6 billion in 2019 to 24.1 billion in 2030, resulting in revenue of more than $1.5 trillion. McKinsey & Company[2] estimates that the IoT may produce $5.5 trillion to $12.6 trillion in value globally by 2030. The International Data Corporation's estimates that IoT connected devices is expected to reach 41.6 billion in 2025, generating 79.4 zettabytes of data [4], [5]. The number of connected IoT devices continues to grow at an exponential rate putting a significant strain on the radio spectrum [2]. Wireless communication can operate on electromagnetic (EM) spectrum, which is illustrated in Figure 1 with various bands along with corresponding frequency ranges and wavelengths.

A. Wireless Communication

Given the constraints and difficulties of wired infrastructure, wireless communication technologies have emerged as the only viable method of connecting IoT devices. The electromagnetic (EM) spectrum, which is shown in Figure 1 with distinct bands and their accompanying frequency ranges and wavelengths, is currently used for wireless

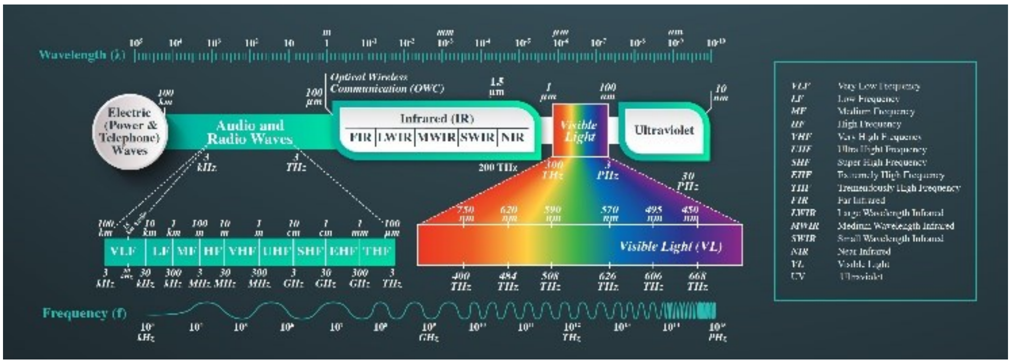

Figure 1: Electromagnetic spectrum and bands along with corresponding frequency and wavelengths

communication. The properties of signal propagation as well as hardware complexity and size, which are primarily influenced by the size of the radio front-end, antenna, and battery, all depend on the inverse relationship between frequency and wavelength. Due to their ability to penetrate objects (such as windows, walls, ceilings, etc.), existing wireless technologies are primarily built to extensively exploit the sub-6 GHz region of the microwave bands (300 MHz - 30 GHz) [5]. This leads to interference and coexistence issues among devices operating on the same band. Because of this, regulatory agencies (such the Federal Communications Commission and the Body of European Regulators for Electronic

Communications) carefully enforce restrictions on the usage of sub-6 GHz bands. Only the industrial, scientific, and medical (ISM) bands, which are widely used by today's most popular and established wireless technologies like Wi-Fi, Bluetooth, ZigBee, etc., are allocated worldwide for license-free usage in the sub-6 GHz range [5]. The ISM band is a first choice if the inexpensive cost and low complexity of IoT devices are taken into account, but as the number of IoT devices grows, it gets overcrowded and interference limited. Due to the fact that there is no more free space in the ISM band. Reaching the end of the radio frequency Spectrum , is forcing the industry to explore new directions, such as Optical Wireless Communication.

B. Optical Wireless Communications (OWC)

As the information era has progressed since the 1970s, fiber optic communications (FOC) has revolutionized the telecommunications sector due to its advantages over electrical transmission in terms of high bandwidth, long range, or immunity to electromagnetic interference (EMI). Optical wireless communications (OWC), in contrast to FOC, has gained popularity over the past 20 years in order to fully capitalize on FOCs and the adaptability of wireless communications. Instead of using radio waves to send data or communicate, the OWC devices instead send modulated visible/invisible light beams across an unguided medium [5].

OWC technology offers some impressive benefits over RF-enabled networks, such as ultra-high data rate transmission capacity spanning from nanometers to several kilometers for both indoor and outdoor applications. OWC also addresses the high demand needs of 5G/B5G communications with broad spectrum, extremely low latency, cheap cost, and decreased power consumption. Additionally, by utilizing a wide optical spectrum, OWC technology has the ability to offer some exceptional communication advantages including dependable security, electromagnetic interference-free transmission, and high system efficiency [6]. OWC technology is capable of providing energy-efficient connectivity and can reach 100 Gb/s at indoor lighting standards. The fundamental benefit of OWC technologies is that they don't need a substantial infrastructure, which lowers installation costs while preserving the green agenda for high-speed communication [7].

The present illumination structure is used to implement wireless data transmission through visible light communication (VLC) and light fidelity (Li-Fi) techniques under OWC technology. Due to the fact that light waves cannot pass through the enclosed walls, OWC offers a higher level of data protection. As propagation medium, typically visible light (VL), infrared (IR), or ultraviolet (UV) spectra are employed. These three optical bands constitute the foundation for the development of the most promising wireless technologies in OWC, including VLC, LiFi, optical camera communication (OCC), and free space optical (FSO) communication. However, there are certain parallels and differences between VLC, LiFi, OCC, and FSO technologies in terms of communication protocol, propagation media, architecture, and applications [5]. This paper aims to provide an overview of advancements and applications, issues and challenges in OWC-based IoT. The remainder of the paper is organized as follows. Section II Gives an overview of wireless technologies used by IoT. Section III introduces OWC and Section IV describes the OWC for IoT. Section V discusses OWC-IoT applications and challenges and finally the conclusions are drawn in Section VI.

2. Overview of RF Technologies

The use of radio frequency to send signals and commands, exists in nearly every aspect of modern life. Applications of wireless technology are widely known, such as cell phones, radio-controlled toys, wireless headsets, wireless printers, etc. for personal or home use to medical use as in Magnetic Resonance Imaging (MRI) and wireless monitoring implants. Table 1. Lists some RF technologies that are used in these applications.

Wireless Fidelity. is a wireless communication protocol that enables appliances to connect without using direct cables. When many devices are linked to a Wi-Fi router, it delivers data packets to computer networks, giving those devices

Table 1: Rf Communications Technologies

Radio Wireless Communications Technologies					
Technology / **Characteristic**	WiFi	Bluetooth	ZigBee	NFC	LoRa
Frequency	2.4–5 GHz	2.4–2.485 GHz	2.4 GHz	13.56 MHz	Sub – 1 GHz
Coverage	100 m	10 m	100 m	4 – 20 cm	10 Km
Data rate	11 Mbps	1 Mbps	250 Kbps	106 - 424 Kbps	~38.4 Kbps
Spectrum	ISM	ISM	ISM	ISM	ISM
Power	Low	Low	Low	Low	Low
Interference	Yes	Yes	Yes	Yes	Yes

which uses the FHSS or DSSS encoding technique, Wi-Fi has a 2.4GHz spectrum and a data throughput of 1 to 2Mbps. The 802.11a IEEE standard, which uses the OFDM encoding technique and operates in the 5GHz range, has a maximum data throughput of 54Mbps. This network is convenient because it offers constant connectivity, increased productivity from allowing multiple users to use the network, mobility, and simple reconfiguration for new users. However, it also presents security risks, has constrained bandwidth availability, which adds to the network's workload, and poses risks to the health of living things. It is mostly used in workplaces, academic institutions, and IoT [8].

Bluetooth. It is a wireless technology standard utilized to exchange data between fixed and mobile devices over a short range making use of short-wavelength UHF radio waves in the industrial, scientific and medical radio bands, and building personal area networks (PANs).Bluetooth operates at frequencies between 2.402 and 2.480GHz comprising guard bands of 2MHz at the bottom and 3.5MHz at the top. It uses a technique called Frequency-Hopping Spread Spectrum (FHSS) and divides transmitted data into packets, and transmits each packet on one of the 79 designated Bluetooth channels of bandwidth 1MHz. It comes with the benefit of low power consumption, cost of Bluetooth devices being cheap, connectivity through obstacles, and voice and data exchange over Bluetooth enabled headphones, speakers, mouse, keyboard and so on. It also comes along with drawbacks such as short range communication, less secure, and lower bandwidth [8].

ZigBee. The IEEE 802.15.4 standard for wireless personal area networks uses ZigBee technology primarily for control and sensor networks (WPANs). It works at a range of 10-100 meters at frequencies of 868MHz, 902-928MHz, and 2.4GHz. For periodic and intermediate two-way data exchange between collectors and sensors, a data rate of 250 Kbps is suitable. Compared to previous proprietary short-distance sensor networks, this system is more affordable, easier to use, and consumes less power. It also has longer batteries. Low data rates, security concerns about sensitive data, and impractical outside usage owing to limited coverage are the drawbacks in this situation. It is mostly utilized for smart grid monitoring and home automation [8].

Near Field Communication (NFC). is a wireless technology that enables mobile devices to cooperatively operate with other mobile devices. In order to transfer data between two devices that are 4 cm or closer, NFC is a very short-range communication method. In the unlicensed ISM radio frequency range of 13.56 MHz, it operates. From 106 to 424 kbps are used for data transport. NFC provides an ideal channel for the recognition methods that authenticate secure data transfer [9].

Long Range. The LoRa Alliance promotes the Long Range (LoRa) wireless communication system. It aims at being useable in long-lived battery-powered systems, where the energy usage is of fundamental concern. LoRa can frequently refer to two separate layers: a physical layer employing the Chirp Spread Spectrum (CSS) radio modulation method; and a MAC layer protocol (LoRa WAN) (LoRa WAN). Communications that are long-range, low-power, and low-throughput are made possible by the LoRa physical layer. Depending on the area where it is installed, it runs on the ISM bands at 433, 868, or 915 MHz. When channel aggregation is used, the payload of each transmission can have a range of 2-255 octets, and the data rate can be as high as 50 Kbps. Sem tech's exclusive technology is the modulation method. With the help of the LoRa WAN's medium access control mechanism, several end devices can connect to a gateway and communicate using the LoRa modulation. The LoRa Alliance is creating an open standard for the LoRa WAN even if the LoRa modulation is proprietary [9].

3. OWC Technologies

Infrared (IR), visible light (VL), and ultraviolet (UV) optical carrier transmission each have unique features that enable certain critical communications [10]. Systems for free-space optical communication (FSO) are used in the IR and VL frequency ranges. Contrarily, the UV spectrum enables high-speed LOS and NLOS optical communications. To fulfill the growing need for wireless technology, a number of OWC technologies, including VLC, light fidelity (LiFi), optical camera communication (OCC), light detection and ranging (LiDAR), and free space optical (FSO) communication, have been created. In addition to WiFi, a relatively new technology called LiFi offers fast data rate transfer at the speed of light illumination with the same intended uses [11], [3], a laser diode or a light emitting diode Additionally, they are unable to communicate across vast distances. On the other hand, in the OCC subsystem under OWC, LEDs are employed as transmitters and cameras or image sensors are used as receivers. Even in outdoor conditions, OCC provides exceptional SNR performance and wipes out related disturbance. Additionally, it displays consistent performance over greater link distances, whether the communication is conducted indoors or outside. LiDAR is a remote sensing 3D laser scanning technique that produces high-resolution maps of a target (Jin and Huang, 2020; Zhang et al., 2019). An LD, a scanner, and a specific global positioning system (GPS) receiver make up a LiDAR apparatus. It uses high resolution sensors to detect objects and record data about a landscape in order to analyze conditions and attributes. Free space optical (FSO) communication has recently come to light as a promising option for next-generation light-wave networking, regardless of the environment, whether it be indoors or out. However, the system suffers greatly from channel impairments like atmospheric turbulence. Table 2 displays characteristics of different optical wireless technologies.

NIR's 760 nm-1 mm working wavelength makes it especially ideal for LOS communication, which doesn't require illumination. There are just a few applications for NLOS communication, and it is not always safe for people. Second, for VLC, LiFi, and OCC covering short and medium distances, visible light (VL) is frequently employed. Over the different broadcasting ranges, VL spectrum (with an operating wavelength of 360–760 nm) is occasionally also employed for FSO and LiDAR. The advantages of VL spectrum include safety for people and the possibility of simultaneous use for illumination and communication. Similar to NIR, VL exhibits low data rate for NLOS transmission by a reflection of light but is ideal for LOS communication. Finally, there is a lot of demand for high-speed NLOS/LOS communication lines using UV communication. LiFi's short and medium ranges, as well as FSO systems' ultra-short, short, medium, long, and ultra-long coverage distances, benefit from the UV spectrum (with an operational wavelength of 10-400 nm) [12].

Table 2: Electromagnetic spectrum and bands along with corresponding frequency and wavelengths

Optical Wireless Communications Technologies				
Technology / **Characteristic**	FSO	OCC	VLC	LiFi
Transmitter	LD	LED	LED/LD	LED/LD
Receiver	LD	Camera	PD	PD
Coverage	>100 km	200 m	30 m	10 m
Data rate	40 Gbps	54 Mbps	100 Gbps	60 Gbps
Spectrum	IR/VL/UV	VL	VL	IR/VL/UV
Bio/Unidirectional	Bidirectional	Unidirectional	Bidirectional	Bidirectional
Interference	Very Low	None	Low	Low

4. OWC for IoT

IoT poses a significant challenge for communication network service providers in terms of offering wireless connection that is both affordable and of excellent quality. In some locations where communication may be easily created, a complementary wireless technology of OWC may be used in tandem with RF domain improvements. The three primary bands of light—ultraviolet, infrared, and visible—can be used in OWC. In the latter two bands, optical camera communications (OCC), visible light communications (VLC), and free space optics (FSO), see Figure 2, may be taken into account as a component of the 5G networks for the implementation of IoT [13].

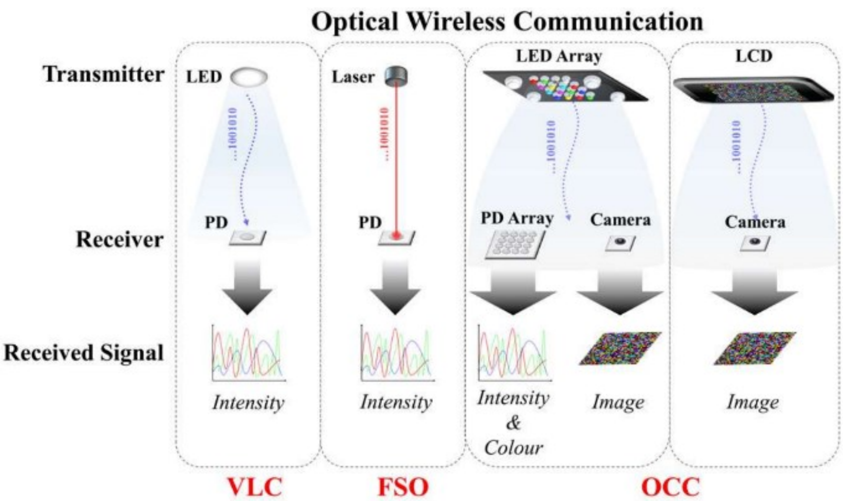

Figure 2: OWC Technologies

VLC, which has a huge frequency spectrum and is connected with IoT, may be used for a variety of indoor and outdoor applications. Figure 3 demonstrates the essential characteristics of OWC-IoT, which are described below:

1) Efficiency and capacity: The RF spectrum (3 kHz – 300 GHz) is becoming crowded as a result of the rising demand for high-speed wireless services, which is causing the bandwidth bottleneck. In order of magnitude more bandwidth than RF is available in the visible light spectrum (400 THz to 780 THz), which may be successfully used in IoT networks. Additionally, it is simple to integrate tiny and compact VLC modules for OWC-IoT into the current lighting infrastructure. Due to its great power efficiency of

80% when compared to conventional lights, LEDs are considered green lighting devices and are utilized extensively worldwide[13].

2) Availability and security: The ubiquitous lighting infrastructure may be reused to create the OIoT system based on visible lights with just a few more modules (modulation unit, digital-to-analog converter, and drive circuit) that can be incorporated into the LED lighting systems. The price of VLC transceivers is predicted to decrease due to the LED industry's rapid expansion. Security is a crucial concern in RF communications since RF signals can pass through walls and other barriers, jeopardizing the physical security of the link. Light transmissions, unlike RF, may be contained within a narrow, well-defined region both inside and outdoors, making eavesdropping nearly difficult unless the receiver is in the transmitter's field of vision. Additionally, as long as the illumination level falls below the advised limit, LED light is harmless for the environment [13].

3) Device connection: By implementing the best handover algorithm to provide uninterrupted communications while mobile devices are moving around within a specific

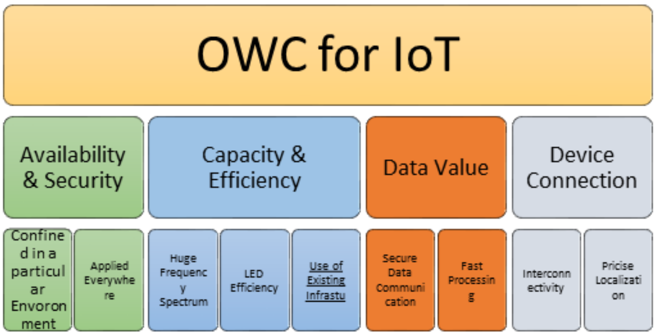

Figure 3: Essential characteristics of OWC-IoT

transmission range, of course, the interconnectivity between various OWC-IoT devices may be maintained. Relay-based OWC-IoT might be used for extended range. Additionally, IEEE 802.15.7 studies protocol advancements for the PHY, Media Access Control (MAC), and higher layer architecture to maximize link dependability. On the other hand, a VLC and OCC system combination may also be used to provide extremely accurate indoor localization. Similar to the GPS, indoor positioning and localization are accomplished by employing LED lighting [13].

4) Data value: Using visible light as the carrier signal in OWC-IoT allows for the formation of secure data transmission channels. To increase the receiver signal-to-noise ratio and shorten the time needed to determine the position of the VLC receiver, researchers have investigated innovative, quick, and efficient adaption strategies [13].

5) Human value: Smart settings (i.e., homes, hospitals, factories, cities, etc.) might develop cost-effective, environmentally friendly, and efficient OWC-IoT, which delivers faster and safer communications [13].

5. OWC-IoT Applications and Challenges

With the use of light fidelity (Li-Fi) and visible light communication (VLC) methods, wireless data transmission is implemented using the current lighting structure in accordance with OWC technology. OWC provides a better level of data protection since light waves cannot go through the enclosed walls. Typically, visible light (VL), infrared (IR), or ultraviolet (UV) spectra are used as the transmission medium. The development of the most promising wireless technologies in OWC, such as VLC, LiFi, optical camera communication (OCC), and free space optical (FSO) communication, is based on these three optical bands [5]. Table 3 displays a comparison of OWC compared to wireless communication technologies used in IoT.

Table 3: OWC compared to wireless communication technologies used in IoT

Radio Wireless Communications Technologies							
Characteristic / **Technology**	**Range**	**Data Rate**	**Power Consumption**	**Security**	**Advantages**	**Disadvantages**	**Use Cases**
OWC	Short (few meters)	Low to Moderate (Mbps)	Moderate to High	High (inherently secure)	High Bandwidth, Immunity to RF interference	Line-of-sight required, Sensitive to environment	Indoor IoT (Smart Homes, Industrial Automation)
Cellular Networks (2G/3G/4G/5G)	Long (City-wide)	High (Gbps)	High	Moderate	Wide Area Coverage, Reliable	High Cost, Complex infrastructure	Industrial IoT, Connected Vehicles
Wi-Fi	Medium (tens of meters)	High (Gbps)	High	Moderate	Easy Setup, High Bandwidth	Limited range, Prone to interference	Home Networks, Office Automation
Bluetooth	Short (few meters)	Low to Moderate (Mbps)	Low	Moderate	Simple Connectivity, Low Power	Low Bandwidth, Limited range	Wearables, Smart Peripherals
ZigBee	Short (tens of meters)	Low (kbps)	Very Low	High (Mesh Networks)	Low Power Consumption, Secure Mesh Networks	Low Bandwidth, Limited range	Smart Homes, Building Automation
NFC	Very Short (few centimeters)	Low (kbps)	Very Low	High	Secure Data transfer, Touch-based interaction	Extremely short range	Mobile Payments, Access Control
LoRa	Long (kilometers)	Very Low (kbps)	Very Low	Moderate	Long Range, Low Power	Low Bandwidth, High Latency	Industrial Monitoring, Asset Tracking

Applications of OWC-IoT in various contexts are shown in Figure 3. In the beginning, the high-speed VLC can be used in locations with weak or restricted Wi-Fi access, such as hospitals (connectivity of contemporary medical devices, on-body sensors known as wireless body area network, WBAN, etc.) or airlines. Links within chemical and power facilities, where RF usage is restricted, intelligent transportation systems (such as car-to-car communications), submarines, and remotely controlled underwater vehicles can all benefit from connectivity [13].

As a result, a new technology called as the internet of light emitting diode, which makes use of the internet and VLC, was introduced. For instance, this technology is incorporated into contemporary cars' head and tail LED lights as an Automobile Collision Prevention System to avoid accidents, or it is used in department stores' ceiling lights to illuminate the space and advertise products while providing customers with a place to store their mobile devices. In order to provide better customer service and save lives, VLC-IoT has been utilized and is still being used in the healthcare sector to detect, monitor, transmit, and report medical data to user mobile devices, healthcare professionals, or hospital employees [14].

The authors of [14] examine and offer numerous technical solutions based on optical wireless communications for diverse application contexts in the tourist sector, as well as their potential for use, potential advantages, and implementation difficulties.

In [15], the work explores how to manage VLC devices (VLC transmitters and receivers) and enable the VLC data transmission in the IoT networks based on the oneM2M standard. It also provides a method for device management and data transport in IoT networks using VLC.

Using a simulator, the impact of the environment and smoke particles on short-range optical communication was examined in [16]. This article includes smoke effects in a short-range outdoor VLC system channel model, from high visibility to 5 m. The visibility tells you how far away an object may still be seen clearly against its surroundings. The effects of smoke and fog were examined in two outdoor VLC situations. Smoke and fog models contain identical equations to describe the optical attenuation they generate using the concept of visibility. The simulator accounts for the real light-emitting diode

(LED) lamp radiation pattern when calculating the power at the receiver side and the channel attenuation coefficients for a selected fog or/and smoke.

In [17], the study suggests brand-new energy-efficient communication plans for LC enabled IoT devices and LiFi users to cohabit. In order to recommend suitable green downlink (DL) and uplink (UL) communication strategies for the coexistence of LiFi users and LC enabled IoT devices, the proposed schemes are compared and studied. The LiFi users need fast data rates and dependable connectivity, but the IoT devices need straightforward, low-power, energy-efficient communication technologies. To meet the aforementioned criteria, a coexistence system at the common LiFi AP that uses multiplexing and modulation techniques is necessary.

A VLC connection provided by a 5G network connects a car to a traffic signal [18]. Data from IoT Road sensors is acquired by the 5G network and transferred to the traffic light, which modulates the light to communicate the information to the car (VLC).

While OWC holds great promise for IoT applications, there are several technical limitations, regulatory obstacles, and implementation problems that researchers and professionals face such as:

- Line-of-Sight Dependence: OWC relies on a direct line of sight between transmitter and receiver. Any obstacles can disrupt communication [19].
- Limited Range: Compared to radio frequency (RF) communication, OWC has a shorter range, especially for outdoor applications [20].
- Sensitivity to Interference: OWC can be affected by ambient light sources and weather conditions like fog or rain [19].
- Power Consumption: Current OWC technology, particularly receivers, can have higher power consumption compared to RF solutions [20].
- Modulation Techniques: Developing efficient modulation schemes that balance data rate, distance, and hardware capabilities is an ongoing research area [20].
- Standardization: Standardization of OWC technologies for IoT applications is still evolving, making interoperability between devices from different manufacturers challenging [20].
- Cost: OWC components like Li-Fi LEDs and receivers can be more expensive than traditional RF modules [20].
- Complexity*:* Implementing and maintaining OWC infrastructure, especially for large-scale deployments, can be more complex compared to RF solutions [20].

6. Conclusion

In recent years there has been increasing research into Optical Wireless Communication (OWC) due to the fact that OWC, is a safe to use technology capable of solving the scarcity problem of the RF spectrum. OWC uses 400 terahertz of secure, unlicensed media for wireless communications, with 10,000 times more capacity than the RF bandwidth. Unlike RF signals, OWC uses visual light making it safe for places that are sensitive to electromagnetic interference like hospitals and airplanes as it does not interfere with electromagnetic signals used by RF devices working in place. OWC does not penetrate walls making it secure and cannot be intercepted by intruders. In this study, we primarily concentrated on OWC-IoT network issues and possible applications based on visual light communication. We concentrated our discussion on prospective uses and difficulties within OWC networks due to the enormous potential of optical communication systems in empowering the next generation of wireless communication networks. Furthermore, we discussed potential applications of OWC-IoT in various sectors like healthcare, transportation, smart cities, and industrial automation and highlighted challenges associated with OWC like technical limitations, standardization and cost and complexity. However, despite these challenges, OWC holds significant promise for future IoT applications. Continued research and development can help overcome limitations and pave the way for wider adoption of OWC in the IoT ecosystem.

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