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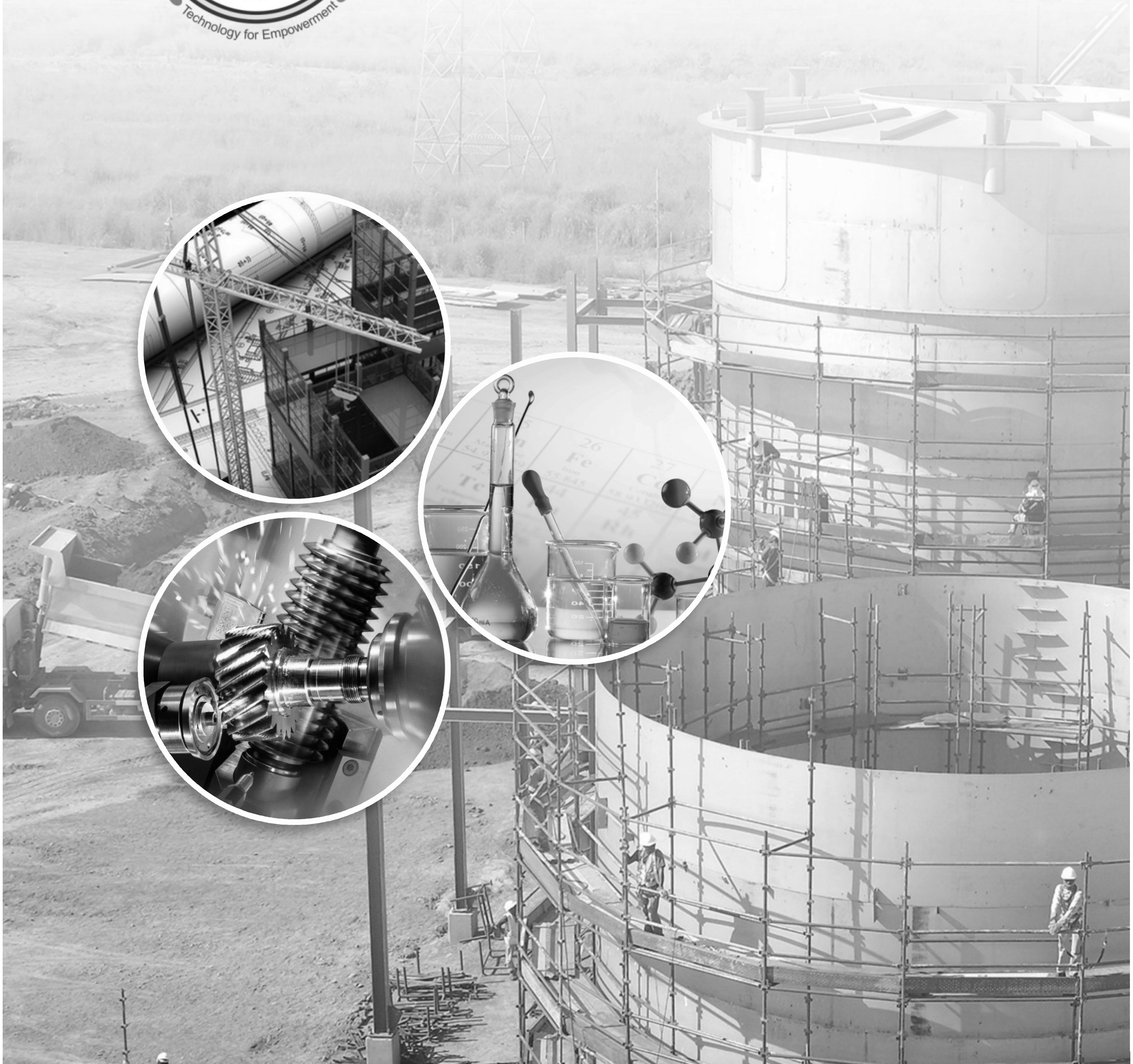

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APPLICATION AREAS OF OPTICAL WIRELESS COMMUNICATION TECHNOLOGIES IN 5G, 6G AND INTERNET OF THINGS: EXPECTATIONS, DIRECTIONS, AND THREATS

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Abstract

Optical Wireless Communication (OWC) systems are indispensable in the actualization of the expected 5G and 6G wireless communication systems. The significant issues concerning the quality of service of 5G and 6G communication systems are high capacity, high security, high quality of experience, low-energy consumption, low latency, massive connectivity, reliable and effective connectivity. 6G in comparison to 5G communication will offer better performance in regards to the stated performance metrics It is very important to emphasize that the Internet of Things (IoT) based on internet data is an integral part of 5G and beyond. This review is a presentation of how OWC technologies, such as free-space optics communication(FSO), infrared light communication(IRC), light fidelity(LiFi), optical camera communication(OCC), and visible light communication(VLC) will be an effective solution for the successful deployment of 5G, 6G, and IoT systems with inherent challenges of supporting the extensive varieties of heterogeneous traffic and in satisfying the mentioned quality of service-related performance metrics

Keywords: Diffused Spots Communication Links, Hybrid RF-Visible Light Communication, IoT, LiFi, Line of Sight Communication Links Optical Small Cell.

INTRODUCTION

In the past few years, the request for high data rate services has increased dramatically. The congestion in the radio frequency (RF) spectrum (3 kHz ~ 300 GHz) is projected to limit the exponential growth of future wireless systems until and unless new segments of the spectrum are opened. Even with the use of advanced engineering, for example; signal processing and advanced modulation schemes, there are still threats to meet the demands of the users in the fifth generation (5G)/and sixth generation (6G) technologies of a wireless network using the existing carrier frequencies as only radio frequency-based wireless communication technologies are not adequate in meeting the requirements of Fifth Generation and beyond and also Internet of Things networks that is according to (Jatau, *et al*., 2020).

Hence, the need for more research work to determine the usage of the new spectrum that would fulfill the high data rate needs(Masroor *et al*., 2021; Wei *et al*., 2021) through hybridized RF/optical or optical/optical wireless systems that can provide an optimal solution for recovering the shortcomings of individual systems as well as ensuring better performance indicators of each of the technologies.

The potential band of spectrum available can give tens of Gigabit per second to Terabit per second(Gbps-Tbps) for users shortly (Chow *et al*., 2020). Optical wireless communication (OWC) systems are also key to effective solutions to bandwidth problems, power/interference management issues, strict regulation, and low-speed problems in radio frequency systems. This paper gives a tutorial survey of the most important setbacks in OWC systems that operate at short ranges such as indoor systems which can support future technologies and also talked a little about free-space optics (FSO) technology that can transmit over a long distance (that is an open space optical technology) for future wireless signal transmission and reception. We also considered the challenging issues facing the implementation of 5GB (i.e 5G and Beyond) and designed of embedded small optical wireless cells (attocell) to support RF signal within a definite size of building geometrics using different optimization algorithms such as illustrated by (Coelho *et al*., 2021). The Internet of Things (IoT) network is extremely important since higher data rates (speed of download/upload) demand by end-users are expected in the nearest future as a large number of end-user devices or sensors would be connected in IoT. Tactile internet will be a critical feature of the upcoming Internet of Things (IoT) which of course required ultra-high frequency and low latency for efficiency, It will allow for real-time communication systems within society, industry, and business use cases, since IoT would generate a large volume of data optical wireless systems will also play important role. The optical wireless communication technologies have applications in monitoring, resource sharing, and sensing in rapid device connections of IoT system networks (Saeed, *et al*., 2019; Pathak *et al*., 2015; Katz & Ahmed, 2020; Menaka *et al*., 2021)

In addition, optical wireless communication can achieve the low-power requirements and ultra-high security requirements of the Internet of Things (Lai *et al*., 2020; Masroor *et al*., 2021; Rahman *et al*., 2016). The 5G communication system specification is already completed, and 5G was expected to be fully deployed by 2020 is according to (Chowdhury *et al*., 2019). The novel 5G communication which has already been launched in some American, European, and Asia countries and was also approved for use in Nigeria by FGN on Wednesday, September 8, 2021, 5G will provide a very good grade of service (QoS). This review aims to present the areas of application of OWC technologies that complement RF technologies to solve the problems that are associated with deployment of 5G/6G and IoT systems. This review provide herein possible detailed 5G/6G and IoT solutions using different optical wireless communication systems. The outline of this paper can be summarized as below:

i. A brief discussion of types of OWC technologies.
ii. Explanation of the main features of 5G and IoT system networks. 6G requirements are also briefly presented.
iii. The scope of diffused spots links as a solution for mobility problems in indoor optical wireless communication systems and different optimizations techniques employed in recent works on small optical cells as a means of densifying the network were surveyed.
iv. Some projects recently carried on the optical wireless communication technologies that improve system support for the 5GB and IoT solutions are captured, and the research trends are discussed.
v. Threaten issues in Optical Wireless Communication as it affects the deployment for the 5G,6G, and IoT solutions are also captured.

The remaining parts of this paper are programmed as follows: Section 2 describes different OWC technologies; Section 3 provides a brief overview of the 5G, 6G, and IoT requirements; and Section 4 describes the potential of the OWC technologies to meet the demands of the 5G, 6G, and IoT systems. Section 5 presents a few key challenging issues of optical wireless communication in the implementation of 5G/6G and IoT and solutions. Section 6 concludes this paper.

2. BRIEF OVERVIEW OF THE OWC TECHNOLOGIES

The optical broadband includes the infra-red (IR) spectrum, the visible light spectrum, and the ultraviolet spectrum benefits from an almost unlimited 800 THz bandwidth when compared to the 300 GHz RF spectrum (Gautam *et al*., 2021). Infrared light spectrum (1 mm – 750 nm for infrared) usage was discovered, considered, and tested over time, the usage of the visible light spectrum (380 – 780 nm) is still undergoing laboratory testing because the spectrum almost new to both industries and researchers.

Light Visible Communication technology was introduced in the early 2000s with performing experimental prototypes being presented several years after (Chowdhury *et al*., 2020; Masroor *et al*., 2021). Starting from the 2010s, the technology became more popular and the laboratory experiment sh1Gb/s data rate was reached and exceeded soon after (Eltokhey *et al*., 2019). The technology has been further developed and today's papers report experimented data rates that exceed 10 Gb/s though, mobility of the system caused blockage of signal (total signal loss) due to the LoS nature of light Khalid *et al*., 2021) presented that, the proper (field of view) FOV adjustment is very important for achieving good lighting efficiency and higher data rate in a VLC link, with envisioned data rates of few hundreds of Gb/s (Rahman *et al*., 2018). In parallel with the improvement of the data rates, as the VLC technology was developing, new applications were identified and VLC has become a worldwide business (Pathak *et al*., 2015). The intensive research efforts have also led to the standardization of optical communications using visible light by IEEE (Wei *et al*., 2021). Lifi is the modernization of VLC which implements bi-directionality, multiuser access, and handover capabilities.

Light Fidelity (LiFi) OWC system was first introduced by Professor Harald Haas at TEDGlobal 2011, LiFi is similar to wireless fidelity (WiFi) technology.

Optical Camera Communication (OCC), and free-space optics (FSO) Optical communication systems-

They are not expensive to imbed into routine use, manufacture of dedicated infrastructure is not required, instead they both (i.e FSO & OCC) relied on the innovation/modifications of existing ones. Despite the pros of optical wireless communication systems, it also has some demerits. For example; Optical wireless communication system is mostly dependent on line-of-sight (LOS), effective in a small coverage area because it is sensitivity to sudden blockage of a connection as the device orientation affects the channel gain significantly, other light sources caused interference, outdoor atmospheric conditions cause performance degradation and transmitted power is limited due to eye/ skin safety regulations.

To surpass the aforementioned demerits, seamless OWC usage is a threatening issue. OWC Technologies are all designed to complement RF communication technology, with high security, enormous and unregulated bandwidth, and not to replace it (RF), but there are indications that optical wireless technologies are good for usage in the future 5G and beyond (Haas *et al*., 2020). The transmitter, receiver types differ depending on the technology used and also depend on the communication media as in Wang *et al*. (2021) shown in Table 1.

Transmitter used in OWC system (photodiodes)- LED and LD are the commonest transmitters often used in optical wireless communication systems, they are based on either white light generation, or quantum techniques, and related color conversion techniques to achieve higher conversion efficiency.

According to Haas (2011) improvements in the use of optical transmitters are based on the following; i. The multichip-based white light generation ii. The Resonant Cavity LEDs (RCLED) iii. The Super Luminescent Diode (SLD) iv. Narrowing down the LED diameter, v. The quantum dots methods and lastly, Tx characteristics in an indoor scenario with the characteristics such as; the room size and model, the reflection characteristics of the environment, the placement of windows and doors, the layout of optical transmitters, and their parameters. Hence, optimizing the above parameters can improve the performance metrics of OWC systems. There are lots of efforts on how to achieve higher capacity and reliable OWC channels through modulation schemes because the device orientation affects the channel gain significantly Katz (2020).

a. Receiver (photo-detectors) there are two types of receivers namely; APD photo-detectors and PIN Photo-detectors. APD PDs are good for high-speed, long-haul communications but it is not cost-effective. While PIN PDs are known for their high reliability for all categories of communication and are cost-effective solutions for OWC. The higher sensitivity of the APD is due to the choice of a higher number of layers and a smaller depletion region, this makes it a long-distance communication receiver. The PIN PD is more applicable for indoor short-distance scenarios because of the high ambient brightness available in indoor environments.

b. Transmission Media- Visible Light Communication uses visible light (VL) only as of the communication medium, Optical Camera Communication employs either Infrared Light or Visible Light as a communication medium, Free Space Optics use any of the three media namely; Ultraviolet Light, Visible Light, and Infrared Light as media and Light Fidelity used VL for downlink while at the uplink it employed either of UL, VL or IR.

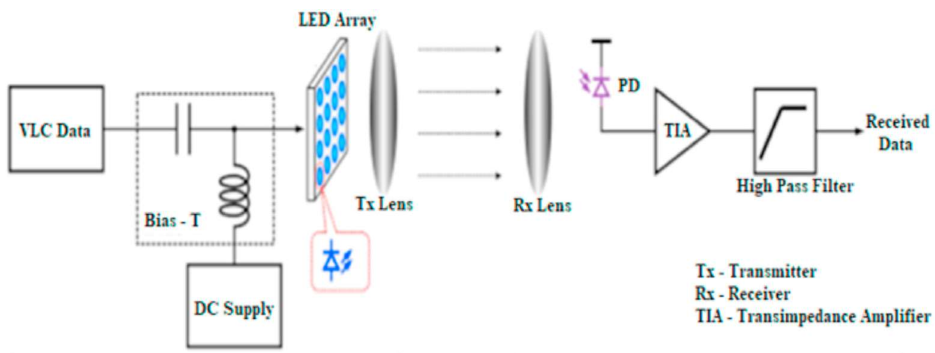


Fig.1. Structure of a Typical VLC System Masroor, (2021)

Table 1: OWC Technologies for the Future Heterogeneous Networks

Transmitter	Diffused Laser Diode /Light Emitting Diode	Light Emitting Diode spread Light	Laser Diode or Light Emitting Diode	Laser Diode
Media	Downlink: VL Uplink: UV/ IR/VL	Infrared/Visible Light	Visible Light	Ultraviolet/ Visible Light/ Infrared
Receiver	Light Detector	Camera	Light Detector	Light Detector
OWC Technologies	Light Fidelity	Optical Camera Communication	Visible Light Communication	Free Space Optics

2.1 Data Transmission Techniques / Modulation Techniques

Traditional Radio Frequency Communication links differ from Optical Frequency Communication links as such different methods of modulation are used. Modulation schemes that worked perfectly in RF links may not necessarily do well in the optical domain. Therefore, four (4) criteria that determine the choice of a particular modulation technique for OWC systems of specific interest are-: (1) The average power used (power efficiency) of a given modulation format, this is considered because of eye hazards and power consumption in mobile terminals. (2) The complexity of the modulation format (and power consumption in portable devices). (3) The third factor is the available channel bandwidth and receiver bandwidth requirements. (4) The criteria relating to the physical limitations in the transmitter (i.e. LD or LED) which the modulation format may have to take into account.

Modulation in OWC systems is comprised of two stages: (i) the information is coded as a waveform(s) (ii) The waveforms are modulated onto the continuous high sinewave power of the (carrier frrequency) Intensity modulation (IM) and direct detection (DD) is the preferred transmission technique in OWC systems according to Chow *et al*. (2020).

Intensity Modulation can be obtained by changing the bias current of either Laser Diode or Light Emitting Diode. For Optical Wireless Communication systems, the transmitted signal had always been positive in intensity. Direct detection (DD) is also the simplest method that is used to detect an intensity-modulated signal. The light detector generates a current which is proportional to the incident of optical power intensity. Below is the expression of the IM/DD channel as given by Haas *et al* , (2020)

$$z(t) = R(x)\, t \otimes h(t) R n(t) \qquad (1)$$

where R is the light detector responsivity, $z(t)$ is the instantaneous photocurrent received, t is the absolute time, $\otimes$ denotes convolution, $h(t)$ is the channel impulse response, $x(t)$ is the instantaneous transmitted power and $n(t)$ is the background noise (BN), which is modeled as white Gaussian noise and is independent of the received signal.

Delay Spread is an important parameter in wireless communication (i.e Spread of time in which signal energy arrived at the receiver due to the temporal dispersion of the incoming

Signals). The delay spread of an impulse response is given by (Abdelrahman, 2019):

$$DS = \sqrt{\frac{\int (t-\mu)^2 (h(t:T_f;R_f))^2\, dt}{\int (h(t;T_f;R_f))^2\, dt}} \qquad (2)$$

And μ is the mean delay, which is given by:

$$\mu = \frac{\int t(h(t;T_F;R_F))^2\, dt}{\int (h(t;T_F;R_F))^2\, dt} \qquad (3)$$

Note: $h(t:T_f;F_f)$ is the channel impulse response LOS while at diffuse spot or a Lambertian surface rth reflection order impulse response of $h_r(t{:}T_f;R_f)$.

The SNR was given by

$$SNR = \frac{(R\,P_r)^2}{\sigma_{total}^2} \qquad (4)$$

Where P_r is the average optical receiver power and σ_{total}^2 is the total variance of the noise which was given by:

$$\sigma_{total}^2 = \sigma_{PA}^2 + \sigma_{BN}^2 \qquad (5)$$

Where σ_{PA}^2 is the noise variance of the pre-amplified signal and σ_{BN}^2 is the ambient lights noise variance. Three broad types of modulation schemes can be applied in OWC (a) baseband modulation, (b) multicarrier modulation, and (c) multicolor modulation Ghassemlooy *et al*. (2017)

a. **Baseband Modulation**

The main baseband modulation techniques considered in OWC include (i) pulse amplitude modulation (PAM), (ii) pulse position modulation (PPM), (iii) pulse interval (PIM) modulation, and (iv) carrier less amplitude phase (CAP) modulation.

b. **Multicolor Modulations**

Multicolor modulation has recently been considered to provide high data rates or multiple access for users by (Z. Wang, et al, (2018). White light can be generated from blue, green, and red (BGR) kinds of LEDs which means data can be transferred through each color or wavelength. The multiplexing used here is wavelength division multiplexing (WDM). In addition to the above, this author, Huang et al.,(2018) achieved white light from four-color LDs which provide a better result compared to three colors LEDs in terms of multiple access and higher data rates due to the improved modulation capabilities of LDs. However, the slow response of phosphor, which reduced the modulation bandwidth of white LEDs to a few MHz is a challenging task, these effects can be improved upon but, it requires complex signal processing and advanced modulation formats.

c. **Multicarrier Modulation**

Subcarrier modulation (SCM) is another advanced modulation technique that can be used in OWC systems to transmit multiple carriers. This can provide multiple access for concurrent users at high speed (data rate). SCM is not power-efficient, unlike the single carrier technique. For example, one quadrature phase-shift keying (QPSK) or binary PSK subcarrier requires about 1.5 dB more power than OOK.

According to Rahman *et al*. (2016) reducing the average power requirements in SCM modulation gives a high data rate in orthogonal frequency division multiplexing (OFDM) when applied in indoor OWC systems to achieve high data rates over a noisy channel and to reduce Inter Symbol Interference, but according to Wei et al., (2021) did not achieve a high SNR. OFDM's because of challenges due to frequency sensitivity and offset and phase noise as well as the high peak to average power ratio (PAR) while Performance improvement of the OWC systems depends on the use of complex modulation schemes to mitigate the effect of ISI and increase the data rates. But these modulation techniques require a complex transmitter-receiver (transceiver) on the need for more optimization techniques. Abdelrahman *et al*. (2019).

2.2 Medium Access Control Protocols

The concurrent support of many mobile terminals from just one access point in OWC wireless networks is very important. The mobile terminals may have different service requirements. In the case of production plants, the transmission delay may be more important than the peak data rate. Developing optimum multiuser access techniques which avoid multiuser interference and achieve high-frequency efficiency must be first considered. Fundamentally, the total data rate of an access point is greater when supporting many users as compared to a single-user scenario. A promising access technology in OWC that can achieve this is non orthogonal multiuser access (Chowdhury *et al*., 2020). The uses of OWC are shown in the following articles are related to multiuser access in OWC networks (Chowdhury *et al*., 2018; Dehghani Soltani, 2019; Wang *et al*., 2021; Pathak *et al*., 2015; Masroor *et al*., 2021).

2.3 Interference Mitigation and Mobility Support

Many access points which are spatially distributed is one of the characteristics of the wireless network. A certain area is covered by one access point when a user equipment or mobile device enters the coverage zone of an access point, the system performs a seamless handover from the access point to which the UE device was previously connected to the new access point. The main merit of optical wireless networking is that atto-cells (very small cells) can be generated where a cell is defined by the coverage area of an access point. The same transmission resource can be reused many more times because of the small size of the coverage area, it is a very important opportunity for frequency reuse if compared to large area cells in RF systems. This principle of cell shrinkage is the main reason why Radio Frequency communication needed improvements (more interference due to large cell size) which could affect data rates (speed) significantly. But interference is kept at minimal levels even as the size of the cell gets smaller in OWC.

2.4 Network Topology is the arrangement of the elements (links, nodes, etc.) of an OWC network. It is used to define or describe the arrangement of various types of wireless communication networks, including command and control of optical networks. Topology is the physical or logical depiction of the structure of the network.

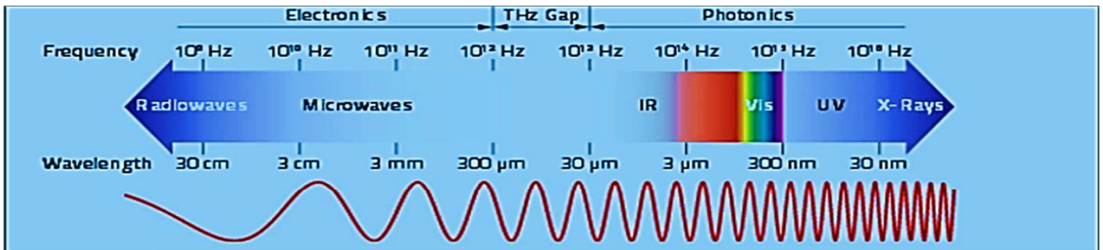
2.5 Communication Distance is the distance between OWC Tx and Rx that, allows for effective communication. Performance metrics e.g SNR, SNIR, interference level, signal strength, latency rate, and data rate etc can be used to determine the effective distance in the communication system.

Table 2. Comparison of the Performance Metrics in Various OWC Technologies

Challenges	**VLC**	**LiFi**	**OCC**	**FSO**
Information Security	High	High	High	High
Communication Topology	Unidirectional or bidirectional	Must be bidirectional	Unidirectional	Unidirectional or bidirectional
Communication Distance	20m	10m	60m	Greater than 10,000km
Mobility support	Optional	Must	Optional	No
Environmental effect	Indoors: No Outdoors: Yes	Indoors: No Outdoors: Yes	No	Yes
Interference level	Low	Low	No	Low
Data rate	10 Gbps using LED and 100 Gbps using LD	10 Gbps using LED and 100 Gbps using LD	55 Mbps	40.665 Gbps

3. Important Characteristics of the 5G and IoT Networks and the Possibility of 6G Requirements :

5G networks will deliver an extensive variety of services comprising ultra-reliable and low-latency communications (uRLLC), massive machine-type communications (mMTC), and enhanced mobile broadband (eMBB) as presented in Fig. 2. In order to achieve all of the aforementioned characteristics of 5th generation networks (i.e existing cellular towers), must be complemented by a modern system called small cells with multi-inputs/ multi outputs MIMO antennas technology. For more information on the requirements, core properties, and vision of 5G wireless cellular mobile communication networks, we refer the reader to Gohar *et al*. (2021). However, wireless data traffic volume and the momentousness of connected devices are expected to surge to hundred times of equipment in a given shape's meter. Moreover, data-thirsty applications such as sending heliographic videos require a special frequency band that is currently not available in the mm-wave spectrum. The above situation would be task-oriented and a challenging one in the area space or frequency efficiency as such, higher frequency spectrum bands are required for connectivity. Hence, a broader radio frequency spectrum bandwidth has become a necessity and can only be found at the sub-terahertz bands (terahertz –terahertz) frequency bands systems. Moreover, the recent upturn of assorted mobile applications, specifically those supported by programable smart systems and Artificial Intelligence (AI) technology, is challenging / exciting deliberations on the future expansion of wireless communications.



Frequency (THz)	Wavelength (μm)	Propagation mechanism	Attenuation effects	Supported link distances (m)	Approximate Bandwidth (THz)
0.3-3	1000-100	LOS, Reflection	Free Space Loss	< 10	Up to 0.3
3-30	100-10		Molecular Absorption High H_2O Peaks	< 1	> 1

Fig. 2. Electromagnetic Spectrum and Wavelength of Terahertz and Millimeter Waves (Alsharif *et al.*, 2020)

The followings are among the expected expansions of hybrid of RF and optical wireless communications to support the implementation of 5GB multi-layer heterogeneous networks such as; basic vehicular communications which covered vehicle-to-vehicle (V2V), vehicle-to-road/infrastructure (V2R/V2I) communications and was extended to models and services in V2X umbrella, for example, vehicle-to-power grid (V2G), vehicle-to-pedestrian (V2P) - direct communication, vehicle-to-vulnerable road user (VRU), vehicle-to-network (V2N) - including cellular networks and Internet, Vehicle to sensors (V2S), and vehicle-to-home (V2H). V2X allows vehicles to directly communicate with each other, also to other road users and roadside infrastructures, for the purpose of actualizing smart mobility, environmental sustainability, traffic efficiency, driver convenience, and better road safety. For the aforementioned provisions, V2X contributes to fully autonomous driving development through its unique non-line-of-sight sensing capability which allows vehicles to detect potential hazards, traffic, and road conditions from longer distances.

IoV has advantages of extending from the normal vehicle driving and precaution safety to novel target domains for example enhanced traffic management, road infrastructure construction and repair, vehicle insurance, automobile production, logistics, repair, and transportation.

Note that IoV involves the Internet and includes heterogeneous access networks, therefore IoV is a typical use case of the Internet of Things (IoT); however, IoV contains intelligent "terminals" such as vehicles (it could be - autonomous). The complexity of the V2X/IoV claims for strong support infrastructure.

The 5G slicing technology is considered to be an appropriate candidate. The fifth-generation, sixth-generation mobile network technologies offer compelling ingredients, in terms of capacity, flexibility, services, and speed to respond to the increasing need and threat addressed to communication systems and Internet (Ji *et al*., 2021). 5G can render robust kinds of services to concurrently satisfy different customer/tenant needs in a multi-x fashion (the notation –x stands for the tenant, domain, operator, and provider).

The 5G network slicing concept (based on virtualization and software) enables programmability and modularity for network resources provisioning, adapted to different vertical service requirements (in terms of bandwidth, latency, mobility, etc.) (Soldani, 2021). In a general view, a Network Slice (NSL) is a managed logical group of subsets of resources, organized as virtual dedicated networks, isolated from each other (with respect to performance and security), but sharing the same infrastructure. The NSLs functionalities are implemented by Physical/Virtual network functions (PNFs/VNFs), chained in graphs, to compose services dedicated to different sets of users. The slices are programmable and have the ability to expose their capabilities to the users.

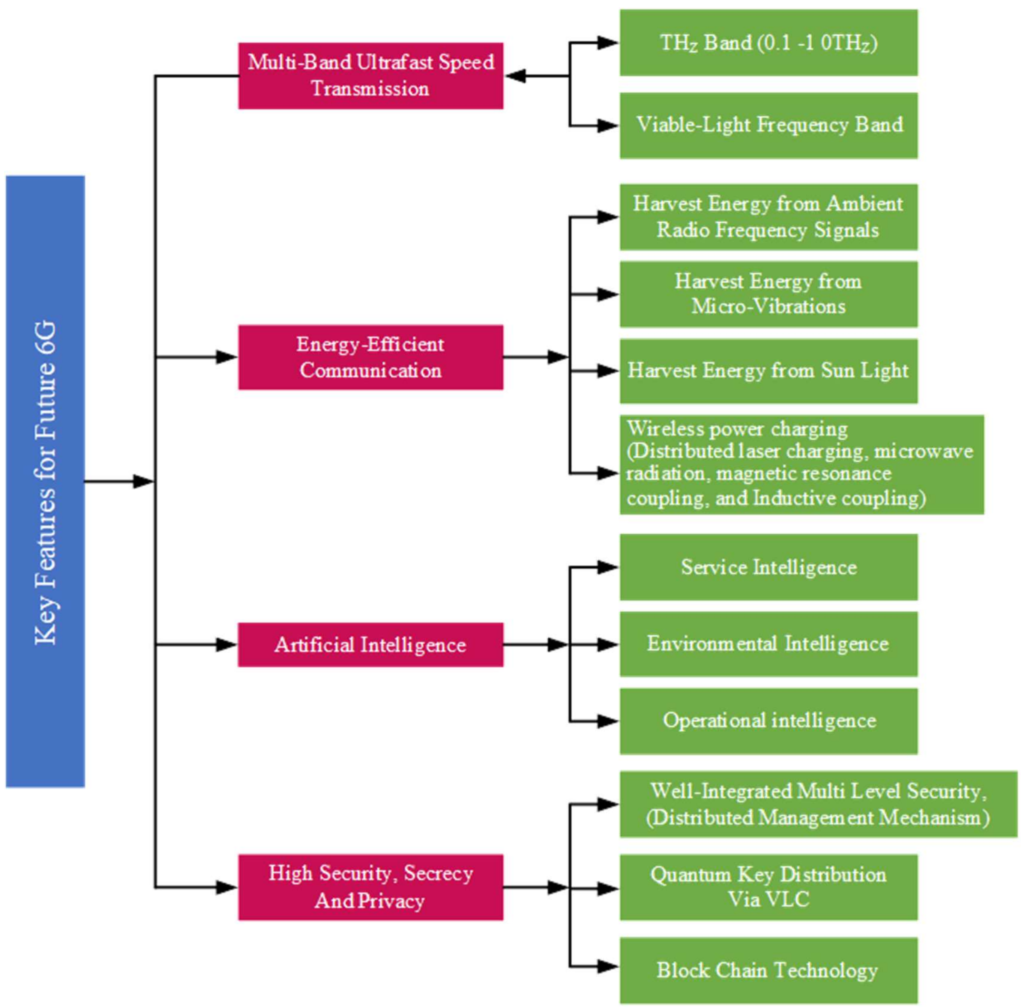


Fig. 3: Main Characteristics For Future 6G (Letaief *et al*., 2019; Zakrzewski & Łaga, 2020; Alsharif *et al*., 2020; Soldani, 2021)

According to Soldani (2021) Fig. 3 illustrates future wireless communication characteristics which include: mssive machine type communication (mMTC); Ultra reliability low latency communication (URLLC); Enhanced mobile broadband (eMBB) According to Obreja *et al*. (2021) the authors also presented two-hop hybrid active-and-passive relaying scheme are to provide concurrent wireless information and power transfer (SWIPT) by considering both time-switching (TS) and power-splitting (PS) receiver architectures. Dynamic modeling that involves dual-hop time-period (TP) metrics was also proposed by Ottersten *et al*. (2021) for energy efficiency in 5G/6G and IoT systems.

4. THE POTENTIAL IN THE OPTICAL WIRELESS COMMUNICATION SYSTEMS TO MEET DEMANDS OF THE FUTURE OF SYSTEMS

Reports have shown that platforms such as cellular connectivity are supported by OWC according to Alsulami *et al*. (2020), OWC systems also support electronic health (eHealth) that is according to (Eltokhey *et al*., 2019), space communication, and smart shopping according to Ghassemlooy *et al*, (2017), and smart home presented by Nencioni *et al*, (2021). underwater communications, V2X communications can be supported by OWC networks according to Zhang, Zhao *et al*. (2020). Very encouraging concepts for which OWC system can be used in the identified 6G verticals, which opens new areas of research for 6G such as VLC, Light- based IoT, Living surfaces, and optical communications through bio-tissues (BAN) RF radiations exposure affects the cells and tissues that, may have effects in human health which is an existing challenging problems, OWC also gives importance to environmentally sustainable safety, this is so, because human bodies are transparent to radio and microwaves frequencies, while they are not transparent to visible light. The above feature makes optical wireless transmission via visible light safe for human health.

4.1 Optical Wireless Communication Systems as a Successor for 5G and 6G Technologies

Network slicing presented a virtualization technology for 5G which could allow OWC to play an important role in a short distance scenario such as V2V, M2M, Hybrid RF, and other OWC indoor scenarios (Arai, *et al*. 2021).

4.2 5G Use Scenarios and Suitability of Optical Wireless Communication

In the year 2014, a 5G research was initiated at the workshop entitled “Research views on IMT Beyond 2020” at Working Party 5D, by International Telecommunications Union Radio Communication Sector. This review focused on the connection of a random number of mobile terminals to an infrastructure that is composed of multiple fixed optical access points, which covers a small area defined by wireless networking with light. The communication channels are expected to be non-line of sight or hybrid (Arfaoui *et al*., 2020).

Furthermore, the connection is supposed to be smoothly maintained as the mobile terminals roam between optical access points and RF access points. Wireless connectivity employing light requires a set of basic technologies, which were mentioned (Chowdhury *et al*., 2020). The main technologies at the outer boundaries, starting with channel models, are the same as in RF networks hence integration with an optical signal is possible since the optical radiation does not interfere with radio waves. The areas of application of OWC can be further extended because it does not use radio waves (Chowdhury *et al*., 2020) and the license-free communication band. Any technology can be used to complements radio waves for user needs. Thus, acceptance of OWC need not be constrained to only post 5G and 6G technologies. However, specific solutions are needed for each category due to the characteristics of light. New solutions are functions of the actual channel models, the optical front-end systems, and the devices types. The optical devices and their components determine the key system parameters such as peak data rates, link distance (Hakeem *et al*., 2020), etc. The optical front-end system has a very significant impact on the actual link budget, which is limited by the maximum optical output power and the receiver sensitivity. The link budget is logically fed into the channel models, which vary largely with the actual deployment scenario (Zakrzewski & Łaga, 2020).

In complementing RF with light wave using principles such as software-defined networking (SDN) are used to integrate the optical wireless networks into existing RF wireless networks, (Zadobrischi et al., 2019). However, the initial application area will be terrestrial indoors since about 80–90% of all Internet traffic originates and terminates indoors (Jenila & Jeyachitra, 2021;Molinaro *et al*., 2020; Storck & Duarte-Figueiredo, 2020). This would also provide a medium for harnessing the lighting infrastructure to build the optical wireless networks on top of the downlink direction, this could be based on white light (standardization as required by existing VLC). The uplink uses the infrared spectrum or RF as a medium for the downlink, this permits for full-duplex operation, which is advantageous for delay-sensitive applications. Arai *et al*. (2021) reported the applicability of OWC to the following use scenarios as follows:

4.2.1 EMBB: Enhanced Mobile Broadband- It is also quite possible to envision, for example, the use of OWC in a limited indoor space; this is the scenario for which Li-Fi, VLC which are consider as post 5G and 6G and they are expected to use higher frequency bands than are currently in use. However, assuming the use of frequencies above 300 GHz, the wavelength would be 1mm or less, making communications more susceptible to absorption in matter and air. Thus, the characteristics of the transmitting radiation would become closer to those of visible light. Because a sufficiently large frequency band is available for the OWC, it may prove to be an excellent solution for implementing the ultrafast communications expected in post 5G and 6G. Therefore, one may consider that OWC is a viable candidate for post 5G and 6G and IoT networks (Chowdhury *et al*., 2020).

Moreover, high-speed network connectivity is required to support massive IoT connectivity. Hence, the optical spectrum has the potential to serve the large volume of data traffic generated by high-data-rate heterogeneous multimedia applications in the 5G, 6G, and IoT networks (Chowdhury *et al*., 2019).

4.2.2 URLLC: Ultra-Reliable, Low-Latency Communication- This scenario assumes wireless operation in the manufacturing industry, telemedicine surgery, smart grids, vehicle automation, etc., and requires precision from the viewpoints of throughput, delay, and reliability. Adoption of OWC is unlikely in this scenario because of the difficulty in ensuring ubiquity as previously described in Section. 4.21 except for the use of Hybrid RF and OWC (Diffused Spots/NLOS Links). However, it may be adopted as an alternative measure in places where radio waves are not used, such as at medical sites. Hence, even though RF and optical signals both propagate at the speed of light, the communication using the optical band is faster than that using RF bands because the propagation is rapid in the optical communication systems. Additionally, the processing time in an optical system is short. Therefore, these OWC-based network technologies can offer services with negligible latency in the communication systems (Chowdhury *et al*., 2018).

4.2.3 MMTC: Massive – Machine - Type Communication- OWC is expected to only find limited use in this scenario. Since this scenario involves low-speed or immobile objects, line-of-sight communication is easily secured. In such an environment, OWC can play a significant role. In particular, VLC and Li-Fi use visible light as a transmission source so that communication paths can be visually determined, which would greatly facilitate designing the communication path. Conversely, the use of OWC would be limited because IoT devices installed outside the line of sight, for example, behind shelves, would be inaccessible according to Haas *et al*. (2020); Katz & Ahmed (2020); Chow *et al*. (2020).

4.2.4 Ultra-Low-Energy Consumption- Among a few important criteria, energy efficiency is one of the most important requirements for all 5G, 6G, and IoT systems. Most OWC system infrastructures are based on LEDs. Currently deployed LEDs consume a very small power. Moreover, huge studies are currently ongoing around the world to reduce the power consumption by LEDs. LEDs can also be used for illumination and communication. Therefore, no additional energy is consumed by an LED transmitter, therefore the OWC-based communication technologies can provide energy-efficient communication systems that are an important requirement for the 5GB and IoT deployments.

4.2.5 Reliable connectivity and Ultra-High Security- As it is expected of 5G, 6G, and IoT networks OWC signal has a high signal to interference noise ratio and cannot pass through an object (e. g wall) so without entering into the building, therefore, security is assured (Silva & Guerreiro, 2020) since the exchange of information would be highly secured and will be free of jamming of data, used especially for health purposes (e.g Body Area Network).

4.3 Achieving Network and Infrastructural Qualities- is another area where OWC, specifically visible light systems play important roles. Since 5GB (5G and beyond) systems are to be used together with 3G applications it will require 3D base stations, hence research into measurement and data-driven modeling of propagation entity is essential which in turn required planning to utilize 3D broad bands. The aforementioned may be complicated at optical wireless frequency band because of the line of sight nature of the system. Obviously, the Poisson point process (PPP) and other mathematical model would be employed Future communication would network demand.

4.3.1 Network restriction using highly restricted heterogeneous networks- That is constrict stationing of atto-cells and the boost of frequency usage. The small cell sites are placed in capacity-starved areas to increase capacity and speed up traffic offload from the neighboring sites stated in this paper (Akhtar *et al*., 2020).

Fig. 4. Shows multi-tier networks using RF/OWC (Tomkos *et al*., 2020)

To increase network capacity these are the 3 main sources require below.

i. Restricting the network
ii. The spectrum should be made more efficient, and
iii. A more frequency band should be used. Hence, all of the above three sources can give high data rate, provision of hybrid network connectivity, and massive device connectivity for 5G, 6G, and IoT communication systems can be achieved (Zhang *et al*., 2020) This is the main focus of our research work. Below are some reviewed work on OWC small cells.

4.3.2 Multi-tier Architecture and Convergence of Heterogeneous Networks: Future communication would demand a high data rate, low latency for the system to achieve, the network will exploit a multi-tier architecture of macro cell networks and underlying small cells containing optical VLC, LiFi, and RF small cells as illustrated in Fig. 4 in section 4 above. The optical technologies of VLC and LiFi build a tier under RF small cells short distance scenario while multi-tier design can consist of larger coverage RF base station, RF small cells, or optical small cells.

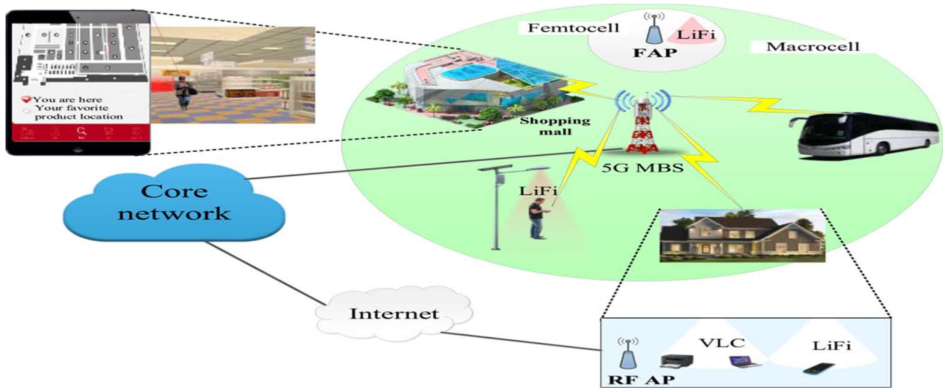


Table 3: Review of other reviewed Papers

S/No	Authors (year)	Title	Methodology	Results
1	Tomkos *et al*., 2020)	Toward the 6G Network Era: Opportunities and Challenges	Reviews the opportunities and challenges of 5G network.	
2	(Tariq *et al*., 2020)	A Speculative Study on 6G	Reviewed possible technologies for the future 6G network. Also, The limitations of 5G network that form the basis of our 6G vision were discussed. The 5G and 6G were compare in terms of use cases.	Identify that 5G is very week in areas such as true AI, time buffer, ultra-sensitive application, satellite integration e.t.c.
3	Wang *et al*., (2020)	An Overview of Key Technologies and Challenges of 6G	Presented the key characteritics for comparing 5G and 6G networks. Also, investigated the vision of 5G soon and contemplates. about the ambitious technologies which will lead to the implementation of 6G networks.	The suggested key performance indicators for 6G network against 5G was highlighted. Also, likely challenges of 6G networks and technology area of the 6G was pointed out. These technologies are artificial intelligence, THz communication along with Radio Stripes and quantum networks.

4	(Chowdhury *et al*., 2019)	The Role of Optical Wireless Communication Technologies in 5G/6G and IoT Solutions: Prospects, Directions, and Challenges	Presents how optical wireless communication technologies, such as visible light communication, light fidelity, optical camera communication, and free space optics communication, will be an effective solution for successful deployment of 5G/6G and IoT systems.	The results of the reviews shows the 5G, 6G and IoT requirements such as ultra-high bit rates per device, ultra-long-range communication with ultra-low-power consumption and ultra-low latency of less than 1 ms for 6G. also, predicted that the 6G network will hit the market between 2027-2030. The challenges of the service quality of 5G and 6G communication systems are high capacity, massive connectivity, low latency, high security, low-energy consumption, high quality of experience, and reliable connectivity.
5	(Arai *et al*., 2021)	Optical Wireless Communication: A Candidate 6G Technology?	Reviews trends in Mobile Radio Communications and Optical Wireless Communication and the possibility of using OWC for 5G network and beyond.	The results shows that the possibility of using OWC is limited
6	(Alsharif *et al*., 2020)	Sixth Generation (6G) Wireless Networks: Vision, Research Activities, Challenges and Potential Solutions		
7	(Zakrzewski & Łaga, 2020)	Potential use of fiber-optic and Li-Fi systems in private 5G/6G networks dedicated to the industrial IoT	Reviews the potential of using fiber-optic and Li-Fi system for private 5G/6G Networks dedicated to the industrial IoT.	The results of the review suggested that the combination. of private and public network resources will significantly increase the potential of IoT solutions, as this will enable the

				Combination of production, analytical and logistics processes. Also, that fast decision-making systems, efficient transmission of Massive data can be realized by fiber-optic networks. The result also, proposes the Li-fi interface for tunneling of optical fiber path for digitized radio signal in the baseband.
8	(Wang *et al*., 2020)	Wireless Channel Measurements and Models: Trends and Challenges	Presented the vision of the application scenarios, performance metrics, and potential key technologies of 6G wireless communication networks. And then conducted a comprehensive review of 6G wireless channel based on their measurements, characteristics, and models for all frequency bands and all scenarios, with special attention on millimeter-wave (mm-wave), terahertz, and optical wireless communication channels	

Table 4. Summary of Related Reviewed OWC Systems (LOS / Diffused Spots Links)

Reference(s)	**Improvements**	**Limitations**	**Link/Techniques**	**Comments**
(Zhang *et al*., 2020)	channel quality is increased by 0.32% and 6.08%	the advantages are not very prominent	NLoS/ Q parameter	No delay spread.
(Tivig & Borcoci, 2020)	secured network	Only bandwidth 75MHz was considered	ETSI and 3GPP functional architectures for slicing support Genetic algorithm for controlling the optical wireless channel	Low Speed & high latency
(Wang *et al*., 2021)	Simultaneous wireless communication with 4-PAM format and positioning achieved.	No Mobility	LOS Link/ Filter enhance RSS indoor OWC	2.5Gb/s achieved
(Eltokhey *et al*., 2019)	Bit Rate: 50 Mbps Bandwidth:70MHz (Average SNR, & Average Delay Spread respectively) Scenario 1: 17.9881dB 1.0270×10-9s Scenario 2: 19.4327dB 0.9528×10-9s.	The authors developed optimization based on the impulse response, not, considering that the eye safety regulations must be considered. in real practical systems. Need improvement in bit rate.	Diffuse NLOS/ PSO Algorithm.	Shows up to 42% and 23% improvement achieved in the average delay spread and the average SNR, respectively. Also shown was the improvement in the standard deviation of SNR by up to 65% in the presence of the noises & losses.
(Alsulami *et al*., 2020)	The Image Receiver (ImR) provides better results compared to the ADR in terms of the supported data	Increases system complexity, there is an effect of shadowing.	LOS Link/ using RYGB LDs as a transmitter. The proposed data Centre contains 30 racks that are divided into three rows.	A data rate of 8.5 Gbps can be achieved for downlink comm. by using the ImR, while the ADR provides varied data rates between 1.5Gbps and 7 Gbps.
(Aljohani *et al*., 2020)	The use of ADR has improved Data Rate by an average of 35%	To provide an efficient and low complexity power allocation approach, robust Optimization Techniques would be required	NLOS/NOMA (non-orthogonal multiple access (NOMA) visible light communication (VLC) system is investigated)	The outcome shows that ADRs improve the data rate by an average of 35% compared to a system using wide FOV receivers.

5. OPEN AREAS OF RESEARCH AND IMPORTANT CHALLENGING ISSUES IN OWC-BASED 5G, 6G, AND IOT REMEDIES

There are threatening issues that must be adequately addressed to use the optical wireless communication systems for unfolding 5G, 6G, and IoT. Some threatening problems are concisely discussed below:

Frequent Handover: Wireless communication systems in the future as pointed out earlier will comprise of heterogeneous small restricted networks that will cause a very frequent changing of cells by UEs (handovers). The frequent changing from one cell to the other (handover) will be between optical and RF networks and also between optical networks. Due to the very small size of optical cells, they may trigger many unnecessary handovers. Therefore, unnecessary handover and the ping-pong effect avoidance are also important issues.

The inter-cell optical interference: This is an open research issue often caused by the , properties of the data-link layer and physical layer differ in the optical and RF-based wireless networks, thereby bringing about a huge setback for the mobility support in RF/optical hybrid systems. Inter-cell interference: Managing inter-cell optical interference is a serious issue in the deployment of optical VLC and LiFi networks. The restricted use of LEDs for the OWC technologies may create high interference in the 5G/6G and IoT networks. Inter-cell interference of optical hybrid system is a threatening problem.

Natural Atmospheric loss: This includes scattering, air absorption, free space loss, refraction, and scintillation of the weather conditions all affect the performance of the OWC technologies. In the open space environment, dust and fog affect the light signal from the transmitter (LED or LD) to the receiver (Light Detector).

The communication channel nature in the FSO is greatly affected (free space loss) because of bad weather conditions. The mitigation techniques for weather condition losses in OWC systems are threatening the use of the technologies concerning reaching the goal of the 5GB networks, especially in the outdoor conditions.

Inadequate Uplink Communication using OWC technologies: The user equipment is modeled with a low-power LED to suppress the excessive use of power. Due to the low-power LEDs, most optical systems example; visible light communication and Light Fidelity cannot perform well in uplink communication. Most of the user equipment employed LEDs that produce diffused lights with low power that are easily affected by downlink high-power lights. It, therefore, limit uplink communication. In addition, a little deflection or movement of the receiver of a mobile device can easily affect the uplink communication link. Hence, this is an important problem to be solved in the nearest future to efficiently support uplink communication using optical wireless communication systems (VLC and LiFi).

The Low Data Rate: OCC system and the Visible light Uplinks have very low data rate that require improvement according to Chowdhury, (2019), low data rate is a great setback of the existing OCC system, to provide a high data rate is a highly challenging issue due to its low-frame rate and medium of cameras communication. In this reviewed paper, the most recent data rate obtained in the OCC system is only 55 Mbps (Arai *et al*., 2021; Saeed et al., 2019). There is need to increase the speed of downloads to fulfill the demands of service quality in the 5G/6G and IoT networks.

Eye and skin safety regulation: Light energy due to the fluctuations in the brightness of a light can be noticed by humans. This is an important issue in the OWC systems as it affects performance. Different modulation schemes on the OWC systems may cause flickering that harms human health. The modulation of LEDs should be done in such a manner that flickering is avoided, this is a challenging issue.

Data rate improvement of the FSO backhaul system: The backhaul systems in the 5G/6G systems have to handle an enormous volume of data traffic to support high-data-rate services at the user level; otherwise, a bottleneck problem will arise. Hence, increasing the FSO backhaul capacity considering the growth of traffic volume is a challenging task according to Lee *et al*., (2019).

Machine Learning for OWC: Learning-based networking system will be the key requirement in future 6G communication networks. The ever-increasing complex network structure and requirements demand artificial controlling and decision-making in challenging environments. Integrating machine learning in 6G OWC networks enables intelligent network assignment, auto error correction, efficient decision making, and network re-assignment, among others. Moreover, the machine learning approach is a core demand in indoor mobile wireless communication systems, robot-based dense OWC (i.e small owc or hybrid OWC/RF networks) to perform fast and efficient tasks (Soldani, 2021).

5.1 The threats of OWC: the recent development of OWC devices and the strategies for performance enhancement and indoor applications have been discussed in previous sections section 5.1 talked on solutions to the challenging issues earlier mentioned.

In order to achieve the ubiquitous usage of high-performance metrics (High data rate and low latency of OWC systems) for an indoor environment, this is discuss in sub-section 5.1.

5.1.1 Monolithic and solid-state structural arrays of organic semiconductors: This makes the devices flexible with energy-saving low-temperature processes, fabricated from organic thin-film materials known as Organic semiconductors. Since spectrally tunable laser sources can implement the Color Shift Keying (CSK) efficiently, so also an adaptive wavelength allocation can improve the spectral efficiency of the OWC system, therefore, implementation of tunable laser sources in the OWC system should be studied, so that the corresponding limitations should be rectified.

5.1.2 The uplink establishment on the battery-driven user devices: A demodulation of the downlink beams can be used to resolve this threat. To achieve a Gbps data rate, an enhanced modulation scheme must be utilized. Furthermore, the fully networked link installation will enable the green OWC system as an important improvement to future intelligent internet applications.

5.1.3 Safety of Both Eye and Skin: This is a prerequisite requirement and should always be considered while striving to achieve high-performance metrics in OW communication.

5.1.4 Three Security Levels Out of Eight Security Levels: Defined by Lai (2020) denote complete security, namely, encryption and Message Integrity Code (MIC), coupled with this, the non-encrypted MAC header fields may heighten the danger of confidentiality and integrity. Hence the technology made encryption and integrity optional, a sufficient MAC level protection against danger on the physical level must be included in practical applications.

6. CONCLUSION:

The novel 5G communication technologies were launched by 2020 and commercially available in a few cities of the U.S.A, Europe, some Asia countries, and South Africa. The 5G network usage was approved for use in Nigeria by FGN in 2021. The shortcomings of the 5G network such as high interference, existing tower mm-wave of 5G inform the development of a 6G communication network which is expected to be launched in between 2027 and 2030. The advantages of 5G/6G and IoT are challenged by tactile internet. The most important and most challenging issues are the provision of high capacity, massive connectivity, low latency, high security, low-energy consumption, high QoE, and highly reliable connectivity for 5GB communication systems. Only RF-based systems are unable to meet the high demands of future 5G/6G and IoT networks. OWC technologies are the best complimentary solution for RF networks. The coexistence of RF and optical wireless systems can achieve the goals of such networks. This review has presented a detailed observation of how OWC technologies will provide an effective solution for the successful deployment of future 5G/6G and IoT networks. The characteristics of 5G, 6G, and IoT systems and features of OWC technologies were presented alongside their specifications. Therefore, this review presented the understanding of the research contributions in different optical wireless systems for future networks.

REFERENCES

Abdelrahman, Shereen Eltayib. (2019). Enhancing of SNR and Optical Power Distribution in Indoor Visible Light Communications Systems. *Journal of Telecommunication, Electronic and Computer Engineering (JTEC), 11*(3), 23-26.

Akhtar, Muhammad Waseem, Hassan, Syed Ali, Ghaffar, Rizwan, Jung, Haejoon, Garg, Sahil, & Hossain, M Shamim. (2020). The shift to 6G communications: vision and requirements. *Human-centric Computing and Information Sciences, 10*(1), 1-27.

Al Ridhawi, Ismaeel, Otoum, Safa, Aloqaily, Moayad, & Boukerche, Azzedine. (2020). Generalizing AI: challenges and opportunities for plug and play AI solutions. *IEEE Network, 35*(1), 372-379.

Aljohani, Mansourah K, Alsulami, Osama Zwaid, Alazwary, Khulood D, Musa, Mohamed OI, El-Gorashi, Taisir EH, Alresheedi, Mohammed T, & Elmirghani, Jaafar MH. (2020). *NOMA visible light communication system with angle diversity receivers.* Paper presented at the 2020 22nd International Conference on Transparent Optical Networks (ICTON).

Alsharif, Mohammed H, Kelechi, Anabi Hilary, Albreem, Mahmoud A, Chaudhry, Shehzad Ashraf, Zia, M Sultan, & Kim, Sunghwan. (2020). Sixth generation (6G) wireless networks: Vision, research activities, challenges and potential solutions. *Symmetry, 12*(4), 676.

Alsulami, Osama, Hussein, Ahmed Taha, Alresheedi, Mohammed T, & Elmirghani, Jaafar MH. (2018). Optical wireless communication systems, a survey. *arXiv preprint arXiv:1812.11544*.

Alsulami, Osama Zwaid, Saeed, Sarah OM, Mohamed, Sanaa Hamid, El-Gorashi, Taisir EH, Alresheedi, Mohammed T, & Elmirghani, Jaafar MH. (2020). *Data centre optical wireless downlink with WDM and multi-access point support.* Paper presented at the 2020 22nd International Conference on Transparent Optical Networks (ICTON).

Amine Arfaoui, Mohamed, Dehghani Soltani, Mohammad, Tavakkolnia, Iman, Ghrayeb, Ali, Assi, Chadi, Safari, Majid, & Haas, Harald. (2020). Measurements-Based Channel Models for Indoor LiFi Systems. *arXiv e-prints*, arXiv: 2001.09596.

Arai, Shintaro, Kinoshita, Masayuki, & Yamazato, Takaya. (2021). Optical wireless communication: A candidate 6G technology? *IEICE Transactions on Fundamentals of Electronics, Communications and Computer Sciences, 104*(1), 227-234.

Ashraf, Shehzad Ali, Blasco, Ricardo, Do, Hieu, Fodor, Gabor, Zhang, Congchi, & Sun, Wanlu. (2020). Supporting vehicle-to-everything services by 5G new radio release-16 systems. *IEEE Communications Standards Magazine, 4*(1), 26-32.

Borcoci, Eugen, Vochin, Marius, & Obreja, Serban Georgica. On Business Models for Vehicle-to-Everything Systems Based on 5G Slicing.

Borcoci, Eugen, Vochin, Marius, & Obreja, Serban Georgica. On Systematic Identification of Requirements for Vehicle-to-Everything 5G Slices.

Celik, Abdulkadir, Saeed, Nasir, Shihada, Basem, Al-Naffouri, Tareq Y, & Alouini, Mohamed-Slim. (2019). End-to-end performance analysis of underwater optical wireless relaying and routing techniques under location uncertainty. *IEEE Transactions on Wireless Communications, 19*(2), 1167-1181.

Chow, Chi-Wai, Yeh, Chien-Hung, Liu, Yang, Lai, Yinchieh, Wei, Liang-Yu, Hsu, Chin-Wei, . . . Lin, Kun-Hsien. (2020). *Enabling techniques for optical wireless communication systems.* Paper presented at the Optical Fiber Communication Conference.

Chowdhury, Mostafa Zaman, Hasan, Moh Khalid, Shahjalal, Md, Hossan, Md Tanvir, & Jang, Yeong Min. (2020). Optical wireless hybrid networks: Trends, opportunities, challenges, and research directions. *IEEE Communications Surveys & Tutorials, 22*(2), 930-966.

Chowdhury, Mostafa Zaman, Hossan, Md Tanvir, Islam, Amirul, & Jang, Yeong Min. (2018). A comparative survey of optical wireless technologies: Architectures and applications. *ieee Access, 6*, 9819-9840.

Chowdhury, Mostafa Zaman, Shahjalal, Md, Hasan, Moh, & Jang, Yeong Min. (2019). The role of optical wireless communication technologies in 5G/6G and IoT solutions: Prospects, directions, and challenges. *Applied Sciences, 9*(20), 4367.

Coelho, Leandro dos S, Mariani, Viviana C, Goudos, Sotirios K, Boursianis, Achilles D, Kokkinidis, Konstantinos, & Kantartzis, Nikolaos V. (2021). *Chaotic Jaya approaches to solving electromagnetic optimization benchmark problems.* Paper presented at the Telecom.

Dehghani Soltani, Mohammad. (2019). Analysis of random orientation and user mobility in LiFi networks.

Eid, Mahmoud MA, Seliem, Ashraf S, Rashed, AN Zaki, Mohammed, Abd El-Naser A, Ali, M Yassin, & Abaza, Shaimaa S. (2021). High modulated soliton power propagation interaction with optical fiber and optical wireless communication channels. *Indones J Electr Eng Comput Sci, 21*, 1575-1583.

Eltokhey, Mahmoud W, Mahmoud, Korany R, Ghassemlooy, Zabih, & Obayya, Salah SA. (2019). Optimization of intensities and locations of diffuse spots in indoor optical wireless communications. *Optical Switching and Networking, 33*, 177-183.

Gautam, S., Solanki, S., Sharma, S. K., Chatzinotas, S., & Ottersten, B. (2021). <sensors-21-06013-v2 (1).pdf>. *Sensors (Basel), 21*(18). doi: 10.3390/s21186013

Gautam, Sumit, Solanki, Sourabh, Sharma, Shree Krishna, Chatzinotas, Symeon, & Ottersten, Björn. (2021). Hybrid

Active-and-Passive Relaying Model for 6G-IoT Greencom Networks with SWIPT. *Sensors, 21*(18), 6013.

Ghassemlooy, Zabih, Alves, Luis Nero, Zvanovec, Stanislav, & Khalighi, Mohammad-Ali. (2017). *Visible light communications: theory and applications*: CRC press.

Gohar, Ali, & Nencioni, Gianfranco. (2021). The Role of 5G Technologies in a Smart City: The Case for Intelligent Transportation System. *Sustainability, 13*(9), 5188.

Haas, Harald. (2011). Wireless data from every light bulb.

Haas, Harald, Elmirghani, Jaafar, & White, Ian. (2020). Optical wireless communication: The Royal Society Publishing.

Hakeem, Shimaa A Abdel, Hady, Anar A, & Kim, HyungWon. (2020). Current and future developments to improve 5G-NewRadio performance in vehicle-to-everything communications. *Telecommunication Systems, 75*(3), 331-353.

Huang, Yu-Fang, Chi, Yu-Chieh, Chen, Mu-Ku, Tsai, Din-Ping, Huang, Ding-Wei, & Lin, Gong-Ru. (2018). Red/green/blue LD mixed white-light communication at 6500K with divergent diffuser optimization. *Optics express, 26*(18), 23397-23410.

Jatau, Melchi, David, Michael, & Zubair, Suleiman. (2020). *LiFi: The Solution to Radio Frequency Saturation.* Paper presented at the 2020 International Conference in Mathematics, Computer Engineering and Computer Science (ICMCECS).

Jenila, C, & Jeyachitra, RK. (2021). Green indoor optical wireless communication systems: Pathway towards pervasive deployment. *Digital Communications and Networks, 7*(3), 410-444.

Ji, Baofeng, Wang, Yanan, Song, Kang, Li, Chunguo, Wen, Hong, Menon, Varun G, & Mumtaz, Shahid. (2021). A survey of computational intelligence for 6G: Key technologies, applications and trends. *IEEE Transactions on Industrial Informatics*.

Katz, Marcos, & Ahmed, Iqrar. (2020). *Opportunities and challenges for visible light communications in 6G.* Paper presented at the 2020 2nd 6G wireless summit (6G SUMMIT).

Khalid, Waqas, Yu, Heejung, Ali, Rashid, & Ullah, Rehmat. (2021). Advanced Physical-Layer Technologies for Beyond 5G Wireless Communication Networks: Multidisciplinary Digital Publishing Institute.

Kousaridas, Apostolos, Fallgren, Mikael, Fischer, Edwin, Moscatelli, Francesca, Vilalta, Ricard, Mühleisen, Maciej, . . . Tossou, Bruno. (2021). 5G Vehicle-to-Everything Services in Cross-Border Environments: Standardization and Challenges. *IEEE Communications Standards Magazine, 5*(1), 22-30.

Lai, Chengzhe, Lu, Rongxing, Zheng, Dong, & Shen, Xuemin. (2020). Security and privacy challenges in 5G-enabled vehicular networks. *IEEE Network, 34*(2), 37-45.

Lee, In-Ho, Kim, Jung-Bin, Jung, Haejoon, Kwon, Seok-Chul Sean, & Kurniawan, Ernest. (2019). Advanced Wireless Technology for Ultrahigh Data Rate Communication: Hindawi.

Letaief, Khaled B, Chen, Wei, Shi, Yuanming, Zhang, Jun, & Zhang, Ying-Jun Angela. (2019). The roadmap to 6G: AI empowered wireless networks. *IEEE Communications Magazine, 57*(8), 84-90.

Liu, Baojing, Han, Chenye, Liu, Xinxin, & Li, Wei. (2021). Vehicle Artificial Intelligence System Based on Intelligent Image Analysis and 5G

Network. *International Journal of Wireless Information Networks*, 1-17.

Liu, Qingling, Sarfraz, Shahid, & Wang, Shubin. (2020). *An Overview of Key Technologies and Challenges of 6G.* Paper presented at the International Conference on Machine Learning for Cyber Security.

Masroor, Komal, Jeoti, Varun, Drieberg, Micheal, Cheab, Sovuthy, & Rajbhandari, Sujan. (2021). A Heuristic Approach for Optical Transceiver Placement to Optimize SNR and Illuminance Uniformities of an Optical Body Area Network. *Sensors, 21*(9), 2943.

Menaka, D, Gauni, Sabitha, Manimegalai, CT, & Kalimuthu, K. (2021). Vision of IoUT: advances and future trends in optical wireless communication. *Journal of Optics*, 1-14.

Mizmizi, Marouan, Brambilla, Mattia, Tagliaferri, Dario, Mazzucco, Christian, Debbah, Merouane, Mach, Tomasz, . . . Lombardi, Renato. (2021). 6G V2X Technologies and Orchestrated Sensing for Autonomous Driving. *arXiv preprint arXiv:2106.16146*.

Molinaro, Antonella, Campolo, Claudia, Härri, Jérôme, Esteve Rothenberg, Christian, & Vinel, Alexey. (2020). 5g-v2x communications and networking for connected and autonomous vehicles: Multidisciplinary Digital Publishing Institute.

Pathak, Parth H, Feng, Xiaotao, Hu, Pengfei, & Mohapatra, Prasant. (2015). Visible light communication, networking, and sensing: A survey, potential and challenges. *IEEE communications surveys & tutorials, 17*(4), 2047-2077.

Rahman, MT, Bakaul, Masuduzzaman, & Parthiban, Rajendran. (2018). *Analysis of the effects of multiple reflection paths on high speed VLC system performance.* Paper presented at the 2018 28th International Telecommunication Networks and Applications Conference (ITNAC).

Rahman, Talha, Rafique, Danish, Spinnler, Bernhard, Napoli, Antonio, Bohn, Marc, Koonen, AMJ, . . . De Waardt, Huug. (2016). *Digital subcarrier multiplexed hybrid QAM for data-rate flexibility and ROADM filtering tolerance.* Paper presented at the Optical Fiber Communication Conference.

Saeed, Nasir, Guo, Shuaishuai, Park, Ki-Hong, Al-Naffouri, Tareq Y, & Alouini, Mohamed-Slim. (2019). Optical camera communications: Survey, use cases, challenges, and future trends. *Physical Communication, 37*, 100900.

Silva, Mário Marques da, & Guerreiro, João. (2020). On the 5G and Beyond. *Applied Sciences, 10*(20), 7091.

Soldani, David. (2021). 6G Fundamentals: Vision and Enabling Technologies. *Journal of Telecommunications and the Digital Economy, 9*(3), 58-86.

Storck, Carlos Renato, & Duarte-Figueiredo, Fátima. (2020). A survey of 5G technology evolution, standards, and infrastructure associated with vehicle-to-everything communications by internet of vehicles. *IEEE Access, 8*, 117593-117614.

Tariq, Faisal, Khandaker, Muhammad RA, Wong, Kai-Kit, Imran, Muhammad A, Bennis, Mehdi, & Debbah, Merouane. (2020). A speculative study on 6G. *IEEE Wireless Communications, 27*(4), 118-125.

Tivig, Pantelimon-Teodor, & Borcoci, Eugen. (2020). *Critical Analysis of Multi-Controller Placement Problem in Large SDN Networks.* Paper presented at the 2020 13th International Conference on Communications (COMM).

Tomkos, Ioannis, Klonidis, Dimitrios, Pikasis, Evangelos, & Theodoridis, Sergios. (2020). Toward the 6G network era: Opportunities and challenges. *IT Professional, 22*(1), 34-38.

Turner, Jamie SC, Ramli, Mohd Fitri, Kamarudin, LM, Zakaria, Ammar, Shakaff, Ali Yeon Md, Ndzi, David Lorater, . . . Mamduh, Syed M. (2013). *The study of human movement effect on Signal Strength for indoor WSN deployment.* Paper presented at the 2013 IEEE Conference on Wireless Sensor (ICWISE).

Wang, Cheng-Xiang, Huang, Jie, Wang, Haiming, Gao, Xiqi, You, Xiaohu, & Hao, Yang. (2020). 6G wireless channel measurements and models: Trends and challenges. *IEEE Vehicular Technology Magazine, 15*(4), 22-32.

Wang, Ke, Song, Tingting, Kandeepan, Sithamparanathan, Li, Hongtao, & Alameh, Kamal. (2021). Indoor optical wireless communication system with continuous and simultaneous positioning. *Optics Express, 29*(3), 4582-4595.

Wang, Zhaocheng, Wang, Qi, Huang, Wei, & Xu, Zhengyuan. (2017). *Visible light communications: modulation and signal processing*: John Wiley & Sons.

Wang, Zhaocheng, Wang, Qi, Huang, Wei, & Xu, Zhengyuan. (2018). Multicolor Modulation.

Wei, Zixian, Zhang, Shi, Mao, Simei, Wang, Lei, Zhang, Li, Chen, Chien-Ju, . . . Luo, Yi. (2021). Full-duplex high-speed indoor optical wireless communication system based on a micro-LED and VCSEL array. *Optics Express, 29*(3), 3891-3903.

Zadobrischi, Eduard, Cosovanu, Lucian-Mihai, Avătămăniţei, Sebastian-Andrei, & Căilean, Alin-Mihai. (2019). *Complementary radiofrequency and visible light systems for indoor and vehicular communications.* Paper presented at the 2019 23rd International Conference on System Theory, Control and Computing (ICSTCC).

Zakrzewski, Zbigniew, & Łaga, Bogdan. (2020). *Potential use of fiber-optic and Li-Fi systems in private 5G/6G networks dedicated to the industrial IoT.* Paper presented at the Optical Fibers and Their Applications 2020.

Zhang, Lei, Zhao, Guodong, & Imran, Muhammad Ali. (2020). *Internet of Things and Sensors Networks in 5G Wireless Communications*: MDPI.

Zhang, Xiangyang, Zhao, Nan, Al-Turjman, Fadi, Khan, Muhammad Bilal, & Yang, Xiaodong. (2020). An Optimization of the Signal-to-Noise Ratio Distribution of an Indoor Visible Light Communication System Based on the Conventional Layout Model. *Sustainability, 12*(21), 9006.

Zhou, Yuan, Kim, Minseok, Momose, Hideaki, & Yasukawa, Satoru. (2021). *Device-Free Indoor Location Estimation System Using Commodity Wireless LANs.* Paper presented at the Telecom.