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Review

The Role of Optical Wireless Communication Technologies in 5G/6G and IoT Solutions: Prospects, Directions, and Challenges

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Featured Application: Future 5G, 6G, and IoT.

Abstract: The upcoming fifth- and sixth-generation (5G and 6G, respectively) communication systems are expected to deal with enormous advances compared to the existing fourth-generation communication system. The few important and common issues related to 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. Of course, 6G communication will provide several-fold improved performances compared to the 5G communication regarding these issues. The Internet of Things (IoT) based on the tactile internet will also be an essential part of 5G-and-beyond (5GB) (e.g., 5G and 6G) communication systems. Accordingly, 5GB wireless networks will face numerous challenges in supporting the extensive verities of heterogeneous traffic and in satisfying the mentioned service-quality-related parameters. Optical wireless communication (OWC), along with many other wireless technologies, is a promising candidate for serving the demands of 5GB communication systems. This review paper clearly presents how OWC 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.

Keywords: 5G; 6G; IoT; heterogeneous networks; optical wireless communication; small cell

1. Introduction

In recent years, optical wireless communication (OWC) technologies have attracted extensive research interest because of some of their excellent features [1–5]. Wireless connectivity based on the optical spectrum is termed "OWC". OWC has become a favorable complementary technology to radio frequency (RF)-based wireless technologies for future communication networks, including fifth- and sixth-generation (5G and 6G, respectively) communication systems. OWC technologies possess a number of prominent features such as wide spectrum, high-data-rate, low latency, high security, low cost, and low energy consumption, addressing the highly demanding requirements of 5G-and-beyond (5GB) (e.g., 5G and 6G) communications. Aside from this, the Internet of Things (IoT) network is becoming increasingly important. A large number of end-user devices or sensors are connected in IoT. Moreover, tactile internet will be the essential feature of the future IoT. It will enable real-time communicating systems with a range of societal, industrial, and business use cases. To envision the idea of IoT, the number of end-user physical devices connected to the internet is exponentially growing [6]. Therefore, the IoT generates a large volume of data. The OWC technologies can play an important role of sensing, monitoring, and resource sharing in massive device connectivity of IoT networks [2,6]. Moreover, the OWC can also meet the low-power consumption and high security requirements of the IoT.

The 5G communication system specification is already completed, and 5G is expected to be fully deployed by 2020 [7]. The upcoming 5G communication will offer new services with a very high quality of service (QoS). The main features of the 5G communication services will include ultra-high system capacity, ultra-low latency, ultra-high security, massive device connectivity, ultra-low-energy consumption, and extremely high quality of experience (QoE) [7–11]. The launch of the 6G communication system is anticipated to be between 2027 and 2030. The 6G specification has not yet been exactly identified, but many researchers are working on it [12–16]. Among the many research issues are capacity improvement, increase in the number of connectivities, latency reduction, security improvement, energy efficiency improvement, user QoE level enhancement, and reliability improvement, which will be addressed by both 5G and 6G communication systems. The 6G communication system is expected to be a global communication facility, with the service level being several folds better compared to 5G.

RF is currently widely used for different wireless connectivities. RF-based wireless communication faces several limitations, such as limited spectrum, great interference effect, and strict regulation. Only RF-based wireless communication technologies are insufficient in meeting the demand of 5GB and IoT networks. Therefore, researchers are working hard to determine a new spectrum that would fulfill the exponentially growing demands. A very large optical band is considered to be a promising solution for the development of 5GB and IoT networks with high-density and capacity. In comparison to RF-based networks, OWC-based network technologies offer unique advantages, such as high data rate, low latency, high security, and low-energy consumption [1–3,6]. Communication distances ranging from a few nanometers to more than 10,000 km are possible through the deployment of different OWC systems [2]. The main technologies of OWC networks include visible light communication (VLC) [6,17–19], light fidelity (LiFi) [20–22], optical camera communication (OCC) [23–27], and free space optics (FSO) [28–30] communication. The differences and similarities among these technologies are briefly discussed in another section. Each of these technologies has individual excellent features and some limitations. The verities of services are offered by different OWC technologies in indoor, outdoor, and space communications. Hence, the OWC technologies can play a vital role in achieving the goals of 5GB and IoT systems.

Our previous review paper related to OWC [2] provides a detail comparative study of various optical wireless technologies to acquire clear idea about the differences among them. The aim of this review paper is quite different. The detail explanation of OWC technologies is not the main goal of this study. It clearly presents how the OWC technologies will be an effective solution for the successful deployment of 5G/6G and IoT systems. We provide herein possible detailed 5G/6G and IoT solutions using different OWC networks. The contributions of this paper can be summarized as follows:

- The key characteristics of the 5G and IoT networks are discussed. The possible 6G requirements are also briefly presented.
- Different OWC technologies are briefly discussed in the 5GB and IoT systems' points of view.
- The scope of the OWC technologies to meet the 5G/6G and IoT requirements is explained in detail.
- Recent works on the OWC technologies for the 5GB and IoT solutions are surveyed, and the research trends are discussed.
- The challenging issues related to the OWC deployment for the 5G/6G and IoT solutions are discussed.

The rest of the paper is organized as follows: Section 2 provides a brief overview of the 5G, 6G, and IoT requirements; Section 3 describes different OWC technologies; 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 OWC-based 5G/6G and IoT solutions. Section 6 draws the conclusion of this paper. Various abbreviations used in this paper are summarized in Table 1.

Table 1. List of acronyms.

Acronym	Definition
5G	Fifth generation
6G	Sixth generation
5GB	5G-and-beyond
BLE	Bluetooth Low Energy
DSRC	Dedicated short-range communications
eHealth	Electronic health
EH	Energy harvesting
FSO	Free-space optics
HBC	Human bond communication
HMD	Head-mounted displays
IoT	Internet of Things
IR	Infrared
LD	Laser diode
LED	Light emitting diode
LiFi	Light fidelity
LOS	Line-of-sight
MBS	Macrocellular base station
NR	New radio
OCC	Optical camera communication
OWC	Optical wireless communication
P2P	Point-to-point
P2mP	Point-to-multipoint
PD	Photodetector
NLOS	Non-line-of-sight
QoE	Quality of experience
QoS	Quality of service
RF	Radio frequency
UV	Ultraviolet
V2V	Vehicle-to-vehicle
V2X	Vehicle-to-everything
VL	Visible light
VLC	Visible light communication
WiFi	Wireless fidelity

2. Brief Overview of the 5G, 6G, and IoT Requirements

5G will provide an order of magnitude improvement in some key characteristics compared to 4G to efficiently support the increasing heterogeneous multimedia applications with a diverse set of requirements [11]. The 5G requirements are already specified, and the 5G system is expected to be fully deployed in 2020. The 5G key requirements are summarized as follows:

High traffic volume: The mobile data volume per area will be 1000 times compared to that of the 4G wireless networks, and the number of connected wireless devices will be 100 times higher.

Massive connectivity: 5G will provide massive connectivity. Ten to 100 times more devices will be connected compared to the 4G communication system [11].

High user data rate link: The 5G networks must have the capability to support a very high user data rate; the user will achieve up to 10 Gbps data rate, which will be 10 to 100 times higher compared to 4G.

Low-energy consumption: Low-energy consumption is an important requirement in the 5G communication system. It will reduce energy consumption by more than 90% (i.e., 10 times lower compared to 4G networks) [11].

Extremely low latency: The end-to-end latency will be within only a sub-millisecond level to a few milliseconds [11].

Researchers are focusing on standardizing the requirements of 6G networks [12–16,31–34]. The ultra-high bit rates per device (e.g., 10s of Gbps to Tbps) are expected to be one of the key requirements of 6G [12,31]. Moreover, 6G is expected to be characterized by 1000 times higher simultaneous wireless connectivity than that of 5G. An ultra-long-range communication with ultra-low-power consumption and ultra-low latency of less than 1 ms is expected for the user experience [13]. The other key expected characteristics of 6G are featured spatial multiplexing, higher spectral efficiency (100 bps/Hz), ultra-high wireless security, ultra-reliability, ultra-low-power consumptions, and massively connected complex networks.

The networks will have some special type of characteristics to support the demands of 5GB wireless communication systems. The key characteristics of future 5G and 6G networks are summarized as follows:

Ultra-high-dense network: To provide uniform QoE, massive connectivity, and high capacity demands, 5GB network deployments are expected to be much denser and comprise ultra-dense heterogeneous networks compared to 4G networks.

Small-cell networks: The concept of high-dense small-cell networks has been pointed out as a core characteristic for the 5GB communication systems.

Higher spectral efficiency: 5GB systems are also expected to guarantee an efficient use of the frequency spectrum by using multiple-input and multiple-output, advanced coding and modulation schemes, and a new waveform design. The spectral efficiency on 5G should be at least three times higher than that on the 4G networks.

Low cost: 5G systems are targeted to be 100 times more efficient compared to the 4G systems by delivering 100 times more data traffic using the same energy over the network. As a consequence, they will require low-cost network equipment, lower deployment costs, and enhanced power saving functionality on the network and user equipment sides [35].

Offloading of heavy traffic to indoors: Nearly 80% of the mobile traffic volume is generated indoors [36]. Offloading this volume of data to indoor dense small cells can release expensive and valuable resources of macrocells. Hence, offloading of data to indoor small cells will be another important characteristic of 5G and 6G networks.

The IoT networks also have important characteristics. Some key requirements of IoT systems are low device cost, low deployment cost, high energy efficiency, high security and privacy, and support for a massive number of devices [11].

3. Brief Overview of the OWC Technologies

The four main OWC technologies, namely visible light communication (VLC), light fidelity (LiFi), optical camera communication (OCC), and free space optics (FSO), are considered to be promising in meeting the demands of 5G/6G and IoT networks for their special features. Figure 1 illustrates brief architectures of these technologies. In terms of infrastructure, these technologies have differences in the type of transmitter, receiver, and communication media. The VLC uses light-emitting diodes (LEDs) or laser diodes (LDs) as transmitters and photodetectors (PDs) as receivers. Only visible light (VL) is used as the communication medium in the VLC. LiFi is similar to the wireless fidelity (WiFi) technology. It provides high-speed wireless connectivity along with illumination and uses LEDs or defuse LDs as transmitters and PDs as receivers. It uses VL for the forward path and infrared (IR) as the communication medium for the return path. However, it can also use VL as the communication medium for the return path. The receiver devices in most user equipment, such as smartphones, are not equipped with high-power LEDs; thus, the uplink communication in the VLC and the LiFi cannot perform well [37–39]. Moreover, they also cannot perform well in return path if the uplink is a diffused light and faces serious interference affected by the downlink lights. The OCC uses LED array or light as a transmitter and a camera or image sensor as a receiver. The built-in complementary metal-oxide semiconductor cameras facilitate the ability to capture photos and videos [40]. The camera can be either global shutter or rolling shutter [41] type. OCC normally uses VL or IR as the communication medium. However, ultraviolet (UV) spectrum can also be used as the communication medium. The FSO technology usually uses LD and PD as the transmitter and the receiver, respectively. However, heterodyne optical detection receiver is also used in FSO communication. It is normally operated using the IR as the communication medium but can also be operated using VL and UV. Table 2 presents the performance metric comparison among the various OWC technologies. The differences among these technologies are very specific. The unique characteristic of VLC is the use of visible light as communication media. A LiFi system must support seamless mobility, bidirectional communication, and point-to-multipoint, as well as multipoint-to-point communications. Only the OCC system uses camera or image sensor as a receiver among all the OWC technologies. Due to the narrow beams of focused light from an LD transmitter, an FSO system can form a very long distance as well as a high-data-rate communication link. The detail differences among the OWC technologies can be found in our previous work in [2].

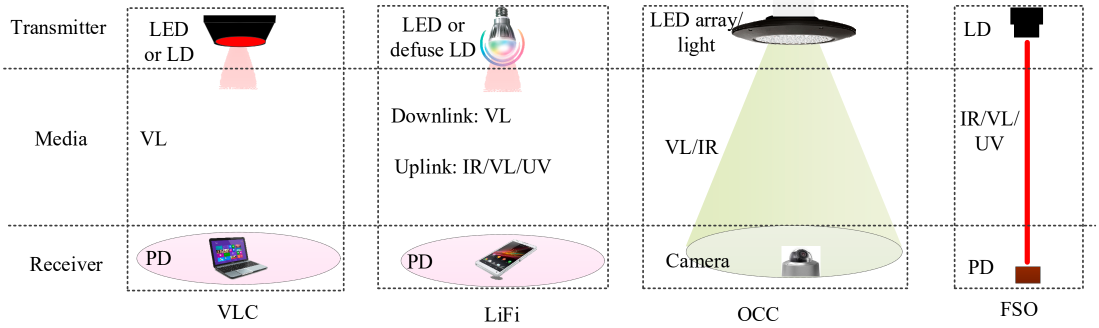

Figure 1. OWC technologies for the 5G/6G and IoT systems.

Table 2. Comparison of the performance metrics in various OWC technologies [2,18,20,24,28,42].

Issue	VLC	LiFi	OCC	FSO
Communication topology	Unidirectional or bidirectional	Must be bidirectional	Unidirectional	Unidirectional or bidirectional
Communication distance	20 m	10 m	60 m	Greater than 10,000 km
Mobility support	Optional	Must	Optional	No
Environmental effect	Indoors: No Outdoors: Yes	Indoors: No Outdoors: Yes	No	Yes
Interference level	Low	Low	Zero	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
Security	High	High	High	High

4. OWC Technologies for the 5G, 6G, and IoT Solutions

4.1. Why Choose OWC Technologies?

The RF band lies between 3 kHz and 300 GHz of the electromagnetic spectrum [2]. However, the range (3 kHz, 10 GHz) is widely used by the existing wireless technologies because of favorable communication properties in this range. This band is almost exhausted and insufficient in providing the high demands of the 5G/6G and IoT networks. It is also strictly regulated by the local and international authorities. The OWC has excellent features in providing for fulfilment of the strict requirements. The OWC can be used for a wide range of applications. Various types of communications, such as machine-to-machine, device-to-device, chip-to-chip, vehicle-to-vehicle, vehicle-to-infrastructure, infrastructure-to-vehicle, point-to-point, and point-to-multipoint, can be accomplished using different OWC technologies [2,6,29]. Light allows connectivity over various ranges (nanometers to greater than 10,000 km) of communications, such as ultra-short-range inter-chip interconnects using FSO system and in-body networks using VLC, OCC, or LiFi systems; short-range LiFi, vehicle-to-everything (V2X) communications, and indoor positioning; medium range inter-building networks; long-range inter-city backhaul connectivity; and long-range satellite-to-satellite communications. It can also provide a high-data-rate communication link. The other key features of the OWC include high unregulated bandwidth, high level of security, low-power consumption, low infrastructure and device cost, no interference with RF devices and networks, high achievable SNR, and easy integration into existing lighting infrastructures. The most important limitation of the OWC systems is the blocking of transmission by obstacles. The coexistence of the RF and OWC networks can effectively solve most of the limitations of individual RF-based and optical wireless communication systems. Figure 2 presents a few important 5G/6G and IoT platforms using the OWC technologies. The OWC networks can support each and every platform of our lives, such as V2X communications, underwater communications, cellular connectivity support, space communication, smart shopping, electronic health (eHealth), and smart home. This section explains how the OWC networks can provide effective solutions for the 5G, 6G, and IoT deployment.

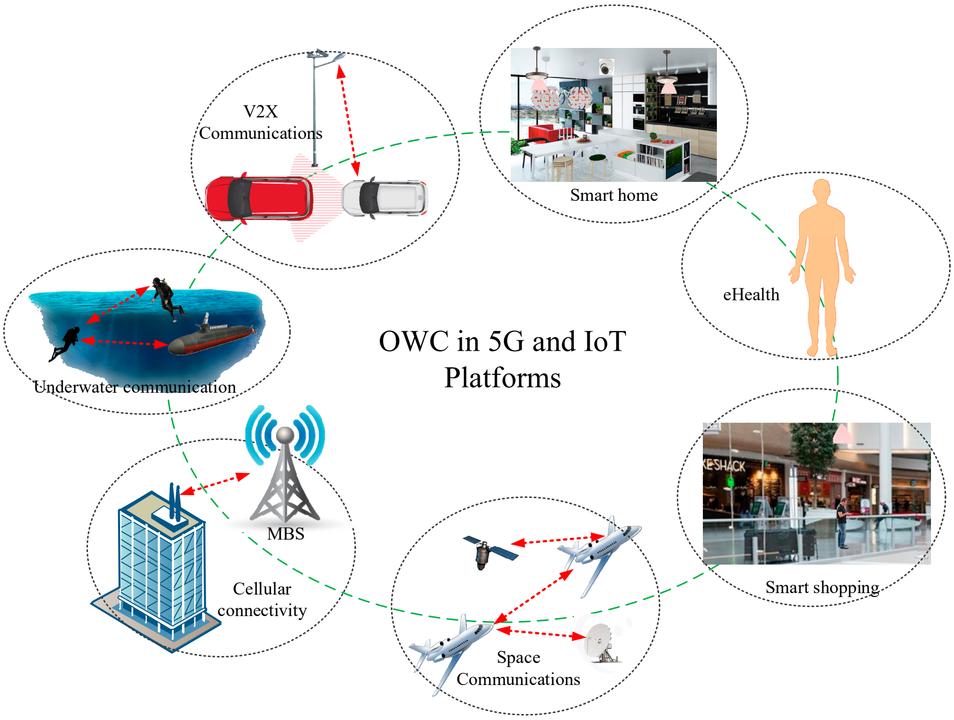

Figure 2. OWC networks for the 5G/6G and IoT platforms.

4.2. Fulfilling the Service Quality Characteristics

High volume of capacity: A much higher bandwidth is essential to realize thousand-fold capacity enhancements in 5GB networks. This desirable higher bandwidth is available in the optical spectrum. Table 3 lists the RF and optical frequencies in the electromagnetic spectrum. The RF band consists of only 300 GHz of the huge electromagnetic spectrum. The optical band (300 GHz to 30 PHz) is considerably very high. However, only a small portion of the optical spectrum (a part of visible light, near infrared, and middle ultraviolet) is currently being used. Future research will increase the use of the optical spectrum portion as well as improve the efficient use of it. The terahertz band (0.3–3 THz) situated in infrared is expected to be used for future high-data-rate cellular communications [31]. The availability of a wide optical spectrum through different OWC technologies opens the opportunity to support a high volume of data capacity. 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.

Table 3. RF and optical spectra [2–6,21,29].

Spectral Category/Sub-Category			Frequency Range
RF (3 kHz to 300 GHz)	Very low–super high frequency		3 kHz to 30 GHz
	Microwave		225 MHz to 100 GHz
	Millimeter wave		30–300 GHz
Optical (300 GHz to 30 PHz)	IR (300 GHz to 394.7 THz)	Far infrared	0.3–20 THz
		Thermal infrared	20–100 THz
		Short-wavelength infrared	100–214.3 THz
		Near infrared	214.3–394.7 THz
	VL (394.7–833.3 THz)	Red	394.7–491.8 THz
		Orange	491.8–507.6 THz
		Yellow	507.6–526.3 THz
		Green	526.3–600 THz
		Blue	600–666.7 THz
		Violet	666.7–833.3 THz
	UV (750 THz to 30 PHz)	Near ultraviolet	0.750–1 PHz
		Middle ultraviolet	1–1.5 PHz
		Far ultraviolet	1.5–2.459 PHz
		Hydrogen Lyman-alpha	2.459–2.479 PHz
		Extreme ultraviolet	2.479–30 PHz
		Vacuum ultraviolet	1.5–30 PHz

Ultra-high user data rate: The transmission rate of the 5G mobile communication systems is expected to reach an average of 1 Gbps at a 10 Gbps peak rate [8]. Accordingly, 6G will later support tens of Gbps to Tbps bit rates per device. The VLC and LiFi technologies have the capability to support very high-data-rate services at the user level. Moreover, LiFi can support a complete network system (i.e., point-to-multipoint, multipoint-to-point, and bidirectional communications) such as WiFi. A data rate of 100 Gbps has already been confirmed using the VLC [18,43]. The FSO can also support high-data-rate services indoors and outdoors. An outdoor remote high-speed connectivity is possible using the FSO network. The OWC based on the UV band can provide high-data-rate, non-line-of-sight communications [4]. In addition, extensive studies aimed at increasing the data rate in the OWC technologies are ongoing. Hence, the OWC technologies are a good complementary solution for supporting high-data-rate connectivity in 5G and 6G and more advanced communication systems. Figure 3 illustrates a scenario of high-speed connectivity using different OWC technologies. High-data rate connectivity is provided to indoor and outdoor users and in V2X communications.

Ultra-low latency: Low latency is a crucial criterion for any kind of communication system and is a more critical factor in 5GB communication systems. OWC systems normally follow line-of-sight (LOS) paths and, hence, the communication distance is minimum with no loss due to the obstructions. However, the RF-based communications use both LOS and non-line-of-sight (NLOS) paths. There is a significant loss due to the obstructions in NLOS paths. Moreover, the communication distance is not minimum due to the NLOS path. 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 [44]. Additionally, the processing time in an optical system is short. A fraction of millisecond end-to-end delay communication services can be provided using the OWC technologies. Hence, these OWC-based network technologies that can offer services with negligible latency in the 5GB communication systems.

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 if it is used for illumination as well. Compared to RF sensors, LED sensors consume very little energy. The OWC technologies can provide communication systems that consume very little power; hence, the OWC-based communication technologies can provide energy-efficient communication systems that are an important requirement for the 5GB and IoT deployments.

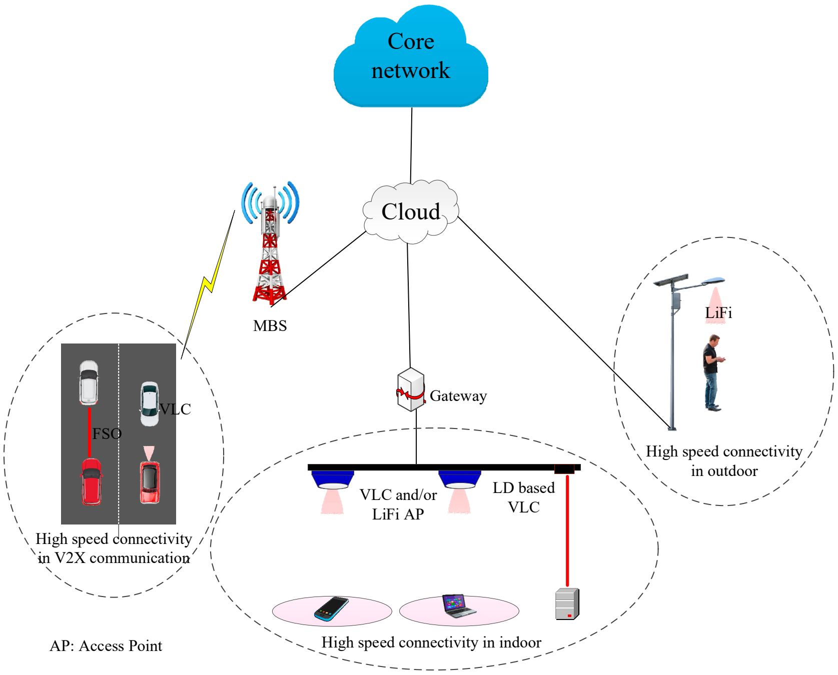

Figure 3. High-speed connectivity using different OWC technologies.

Reliable connectivity: A reliable connectivity is an important criterion for any kind of communication system. The OWC systems assure a very high level of SNR, especially for indoor users. Even for outdoor scenarios, the OCC can provide non-interference communication and a high SNR. Moreover, a stable performance is achievable even when the communication distance increases. The FSO also provides a good SNR level for outdoor long-distance communications. The OWC networks yield an opportunity of providing an extra tier network for indoor users, which surely increases the reliability of a communication system. Therefore, the OWC systems can increase the connectivity reliability for users in the 5G/6G and IoT networks.

Ultra-high security: The OWC technologies can provide a secure communication, as is required by the 5G, 6G, and IoT networks. The OWC signal cannot penetrate an obstacle; therefore, outside people cannot hack the information. It is impossible for a network hacker device that is outside to pick up the inside optical signal. The information can be exchanged in a highly secured manner, especially for health purposes. Hence, the OWC systems offer a higher level of security for the 5G/6G and IoT networks.

4.3. Fulfilling the Network and Infrastructure Characteristics

Network densification using highly dense heterogeneous networks: Three primary means can be used to add capacity to a network—densifying the network, making the spectrum more efficient, and using more frequency spectra. Network densification is defined as the adding of more cell sites to increase capacity. Network densification includes the dense deployment of small cells and the increase of frequency utilization. Cell sites are placed in capacity-stressed areas to add more capacity and offload traffic from the surrounding sites. Densely populated areas, where a huge traffic volume is generated, are considered for network densification. The high system capacity and the high per-user data rates in the 5G/6G communication systems necessitate the densification of access networks and/or the deployment of additional network infrastructures. The traffic volume can be increased by increasing the number of small cells. Moreover, shortening the access network to the user distance improves the achievable data rate. Hence, network densification in terms of the dense deployment of small cells is a must to meet the requirements of 5G/6G paradigms. Along with macrocells and other wide-area networks, different indoor and outdoor optical or RF small cells will be the networks in this dense deployment. Each and every indoor can contain many optical small cells (e.g., VLC, LiFi, and OCC networks) along with RF small cells. Moreover, many outdoor applications, such as vehicular networks and street lighting, will also use many optical small cells for communication. Therefore, the dense deployment of the OWC networks meets this network densification criterion. The facility of high-capacity FSO backhaul connectivity also ensures the backhaul densification. Figure 4 indicates that the OWC-based small-cell networks along with the RF small cells create highly dense network deployment.

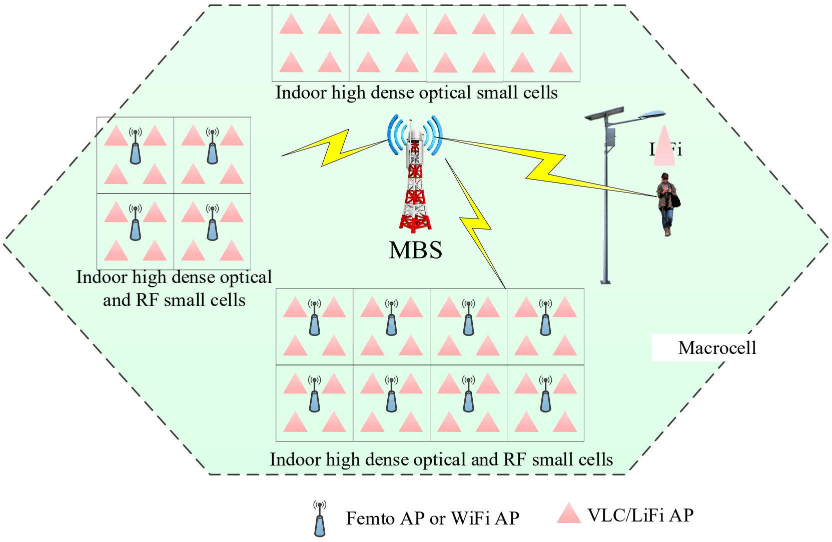

Figure 4. Scenario of heterogeneous multi-tier networks containing an RF macrocell, many RF small cells, and a large number of optical small cells.

Multi-tier architecture and convergence of heterogeneous networks: To meet the demands of future communication, networks will exploit a multi-tier architecture of larger coverage satellite and/or macrocell networks underlying small cells containing RF small cells and optical VLC, LiFi, and OCC networks. The VLC and LiFi even create a tier under RF small cells. Figure 4 presents an example of a multi-tier architecture consisting of macrocells, RF small cells, or optical small cells. The presence of optical small cells, such as VLC and LiFi, creates an opportunity to add additional high capacity in multi-tier wireless heterogeneous networks. As a result of the multi-tier architecture, load will be offloaded from expensive satellite or macrocell networks to small-cell networks. A large number of users can be served by indoor OWC systems. Consequently, outdoor expensive and comparatively low-capacity macrocell and satellite networks can provide better services for outdoor users. Moreover, the limitations of RF-based wireless communication systems are overcome using the OWC technologies in the multi-tier heterogeneous networks. Optical and RF signals do not interfere with each other; hence, the multi-tier networks consisting of RF and optical wireless networks can effectively reduce the interference effect [45]. In other words, the OWC technologies will play a vital role in multi-tier heterogonous networks in 5G, 6G, and more advanced communication systems.

Provision of hybrid network connectivity: Each of the individual RF and optical wireless technologies has limitations and advantages. The coexistence of heterogeneous networks (i.e., hybrid systems consisting of both RF and OWC technologies) can effectively overcome the limitations. The presence of two systems improves the link reliability and provides an opportunity for load balancing. Moreover, for outdoor applications, the hybrid system can overcome the atmospheric effect. Figure 5 illustrates a few possible means of connectivity in the RF/optical hybrid systems. The RF and optical links work together for connectivity. Connectivity from a source to a destination is established directly or through relay. The optical link in the relay system can be established either from source-to-relay or relay-to-destination in a hybrid system. In any or both of these, the links can also be established with the presence of optical and RF links simultaneously. The forward and return communication links may be different or the same on the basis of the application scenario and the hybrid type. Another possibility is the sharing of forward and return paths. The optical links can be used for the forward path, and the RF link can be used for the return path. Hence, the OWC technologies can play an important role in designing hybrid systems to mitigate the limitations and bring a proper solution in the 5G/6G networks.

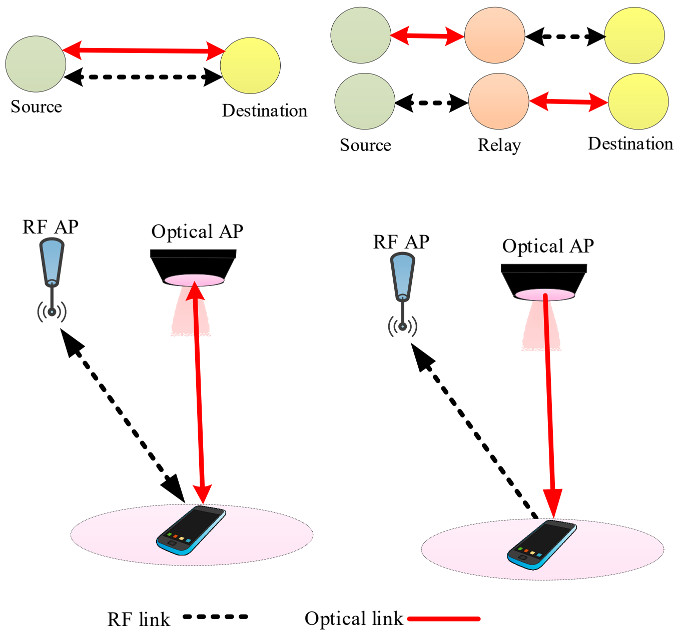

Figure 5. Few possible ways of connectivity using optical and RF hybrid systems.

Massive device connectivity: Massive connectivity is a crucial characteristic of future communication systems. The IoT in 5G is predicted to connect up to 50 billion heterogeneous devices. These devices will be used in not only mobile phones but also in other devices, such as vehicles, household electronics, and medical equipment, to build a smart society [46]. Through the massive connectivity, the IoT supports an integration of various sensors and physical devices, which can monitor and communicate directly with one another without human intervention [47]. In addition, it is expected that the IoT in the 6G paradigm will connect more devices with the capability of being intelligent in nature.

The OWC can play a vital role in providing massive connectivity. The usage of LEDs for different purposes is exponentially increasing because of LEDs' low price, low-energy consumption, and longer life span. The OCC has especially attracted much interest in the area of IoT. Using an existing or a slightly modified infrastructure, the OCC facilitates the development of economically attractive solutions for a wide range of IoT applications. Hence, the OWC technology can provide an enormous number of connections through low-power LEDs to achieve the goals of the 5G/6G and IoT networks. Figure 6 illustrates only a few examples of massive connectivity in different environments through different OWC technologies. The OWC technologies support massive connectivity in homes, healthcare, transportation systems, remote connectivity, and smart grid systems. A smart grid comprises different operational and energy-measuring devices, such as smart meters, smart appliances, renewable energy resources, and energy-efficient resources. Through the massive connectivity among these, smart grids serve as building blocks for energy management of a sustainable environment [47].

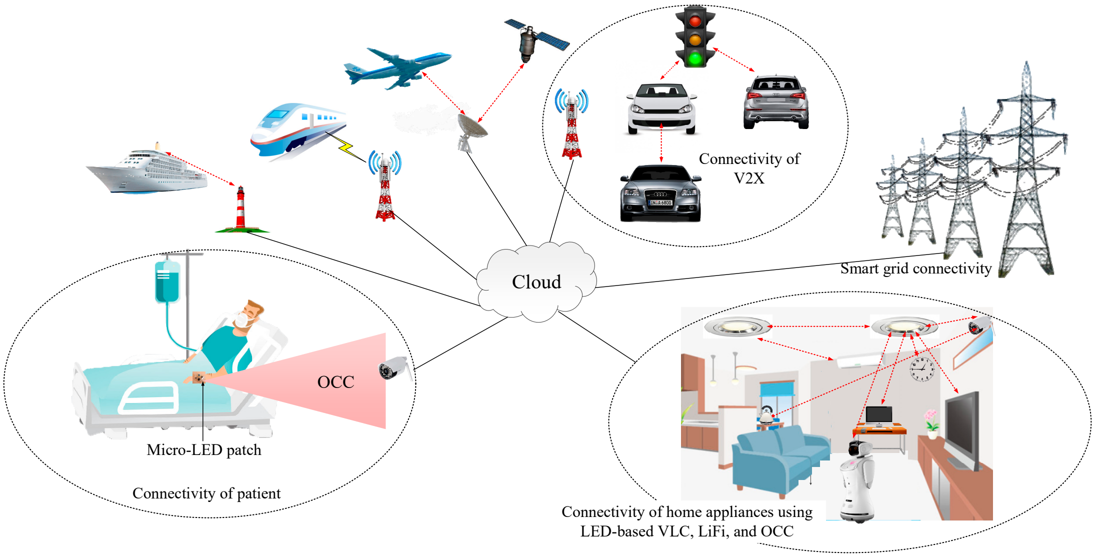

Figure 6. Few examples of massive connectivity using the OWC technologies.

The IoT networks have some important characteristics. Some key requirements of the IoT are low device cost, low deployment cost, high energy efficiency, high security and privacy, and support for a large number of devices. The LED-based OWC systems have all the great features required to support the IoT. The key technologies currently used for the IoT connectivity are Zigbee, Bluetooth Low Energy (BLE), and WiFi. ZigBee is a low-cost, low-power, wireless mesh network standard that has been widely used for IoT applications [48]. Zigbee only supports a low transmission rate, and its security level is not good. The interference is a concern in dense Zigbee networks. The BLE is a smart low-energy version of Bluetooth designed for short-range communication. The BLE currently only supports a single-hop topology, namely piconet, with one master device communicating with several slave nodes, and a broadcast group topology with an advertiser node broadcasting to several scanners [48]. WiFi does not offer any guaranteed QoS and is affected by high interference caused by sharing the unlicensed band with Zigbee, Bluetooth, and many other ISM (industrial, scientific, and medical) band devices. The OWC technologies have a superior capability of meeting the requirements of the IoT networks compared to other existing wireless technologies.

Small-cell networks: An effective method of increasing the area spectral efficiency is to shrink the cell size where a small number of users are served by a cell [49]. To support the cellular connectivity and cope with the demand, the third generation communication system contains only the macrocellular networks; the 4G system added small-cell and microcell along with macrocellular networks, whereas the 5G system will contain ultra-dense small-cells along with macrocellular networks [50]. The shrinking creates an opportunity to provide more spectra to each user. The introduction of indoor small-cell or femtocell has opened a lot of opportunities. The cell radius of an indoor small-cell is around 10 m to serve five to six users [51]. The small-cell deployment is a cost-effective and energy-efficient solution of meeting the coverage and capacity requirement [45]. The peak user data rates of the 5G and 6G communication systems are expected to be 10 Gbs and 1 Tbps, respectively. Heavy data traffic must be handled by indoor small-cell networks because large data are generated indoors. Hence, one of the most important characteristics of the 5GB communication systems will be the deployment of highly dense small-cell networks. The indoor VLC and LiFi create highly dense small cells. Each of the networks under one light source is considered a small cell. Even hundreds of VLC/LiFi-based small cells can be found in a large room. Hence, the OWC networks can fulfill the criteria for the 5G/6G networks.

Seamless movement: Seamless movement is an essential criterion for considering any kind of technology in the 5GB networks. The LiFi system offers complete mobility support to meet the demand of 5G and 6G communication systems.

High-capacity backhaul network: A backhaul is a network that connects the access network to the core network. Current backhaul networks mostly comprise dedicated fiber, copper, microwave, mmWave, and, occasionally, satellite links [8,52]. Backhaul connectivity using satellite link depends on the availability of other options. A high-capacity backhaul network is an essential part in the 5GB systems' ability to exchange a large volume of data traffic between the access and core networks. Without a high-capacity backhaul network, the communication system will not be completed, even though the access networks support the Gbps communication link between the access network and the user equipment. A low-capacity backhaul network will create a bottleneck in the system. Along with the wired optical fiber networks, optical wireless networks, such as the FSO, can effectively solve this issue. The FSO system has excellent features to establish a high-capacity and long-range outdoor backhaul link. Figure 7 presents a few scenarios of the high-capacity backhaul connectivity using FSO communications. High-capacity backhaul networks using the FSO provide connectivity in remote areas, such as underwater, sea, space, and an isolated island. Even the FSO can be used to establish excellent quality connectivity with the macrocellar base stations (MBSs), instead of the existing backhaul network technologies. Table 4 presents a comparison of the achieved data rates and latencies in a few important existing backhaul technologies. The throughput in optical fiber is the highest among all the technologies up until now. However, the throughput in FSO system is comparable with optical fiber. Both the optical fiber and FSO systems use a similar type of transmitter and receiver, and, hence, it will possible to achieve similar throughput in FSO as is the case with the optical fiber system in near future. The latency is calculated for transmission during backhaul connectivity. Hence, the FSO network will be an excellent complementary solution of wired and microwave/mmWave systems to support high-data-rate communications in the 5G and 6G networks.

Figure 7. High-capacity backhaul connectivity for a remote hill, a remote island, and a remote city.

Table 4. Comparison of the achieved data rates and latencies in the existing important backhaul technologies [2,9,44].

Technology	Peak Throughput	Latency	Option
Optical fiber	100 Gbps	<1 ms	P2P
Microwave	1 Gbps	<1 ms/hop	P2P/P2mP
mmWave	10 Gbps	<1 ms	P2P
FSO	40 Gbps	<1 ms	P2P
Satellite	50 Mbps	300 ms	LOS

Green Communication: Green communication can be achieved by several factors, such as energy awareness in network deployment, choice in communication devices, and design in the communication network protocols. Hence, the green aspects of the future 5G/6G and IoT networks require an energy-efficient communication that can be effectively realized by increasing the use of LED-based OWC technologies. The OWC technologies will support a large portion of the entire wireless data volume. A large amount of energy can be saved if a large portion of indoor users use the OWC networks based on LEDs that are also used for illumination. Moreover, the OWC system can serve for the purpose of energy harvesting (EH). It has been demonstrated that solar cells can be integrated into VLC links to function both as energy harvesters and as optical receivers [53]. Hence, the OWC systems contribute to a built-up green communication system that is one of the most important characteristics of the 5G/6G and IoT networks.

Tactile internet support: The International Telecommunication Union defines tactile internet as the future internet network that combines ultra-low latency with extremely high availability, reliability, and security. The tactile internet will be the next evolution of IoT to encompass human-to-machine and machine-to-machine interactions [54–57]. The OWC technologies have the ability to support the tactile internet. Our previous work in [58] introduced human bond communication (HBC) to enable continuous bidirectional communication among multiple users.

Intelligent transportation: Vehicular communication is an essential part of the modern era that promises to provide ubiquitous connectivity with ultra-reliable and low-latency connectivity [59]. V2X communications improve road safety, traffic efficiency, and availability of infotainment services [60]. The dedicated short-range communication (DSRC) technology, which works in a 5.9 GHz band, is being widely used to support V2X communications, specifically those focusing on vehicular safety applications [61]. The mmWave bands are also attractive for V2X communications to support Gigabits per second date rates, which cannot be achieved in the DSRC [61]. Moreover, the OWC technologies have potential to support a reliable connectivity in LOS conditions. VLC and LiFi can support short-distance inter-vehicle communications, whereas OCC can support communication over a 60 m distance [62]; FSO can support even longer distance communication.

4.4. Surveys of OWC-Based 5G and IoT Systems

A number of researchers around the world are working on OWC-based future communication networks. Table 5 summarizes the key studies on the OWC technologies for the future 5G and IoT systems. No significant work has yet been done on OWC-based 6G communication system. The HBC in [58] is based on head-mounted displays (HMDs). To deploy OCC in HMDs for HBC, the camera of an HMD is used as a receiver, whereas an IR light source is included to the HMD as a transmitter. This work explains the feasibility of HMDs for communication purposes. This system facilitates the users or devices to communicate efficiently with other users or devices using their HMDs. The authors in [63] introduce an LED transmitter and camera receiver-based optical vehicle-to-vehicle (V2V) communication system that can be an emerging technology for Internet of Vehicles. The LED transmitter in a vehicle transmits various data to other camera receivers of a distinct vehicle. An optical communication image sensor is employed in the camera receiver. In [64], the authors present the LiFi/WiFi-integrated architecture that can meet the demands of the 5G system.

The universal traffic management system in [65] provides expressway and ordinary road information to cars. This system uses LED headlight as a transmitter for the uplink and multiple PDs with a lens as a roadside receiver. For the downlink, it transmits signal from an LED on a roadside unit and receives the signal using an optical communication image sensor receiver on vehicle. M.B. Rahaim et al. [66] describe the motivating factors for VLC usage to support highly dense users. They present the VLC integration with RF technologies. Selecting of suitable operating conditions for each of the RF and VLC solutions is important to achieve the best outcome. In the relay-assisted VLC system in [67], an amplify-and-forward relay is used to forward the signals and at the same time transmit its own signals. The relay terminal only assists source terminal in forwarding signals to destination terminal. The signals from source terminal are allocated to even subcarriers, whereas the signals from relay terminal are allocated to odd subcarriers.

Table 5. Summary of the current research trends in the OWC based on the 5G and IoT systems.

Reference	Contribution and Research Direction	OWC Technology
[58]	An HBC method based on head-mounted displays, which enables continuous bidirectional communication among multiple users with or without internet connection is proposed.	OCC
[63]	An OCC-based optical V2V communication system is developed.	OCC
[64]	The primary characteristics of WiFi and LiFi technologies and the possibility for them to coexist for the 5G systems are presented.	LiFi
[65]	The feasibility study of the uplink VLC beacon system for the universal traffic management system is presented.	VLC
[66]	The feasibility analysis to integrate the VLC with the RF networks is presented.	VLC
[67]	A relay-assisted VLC system based on asymmetrically clipped direct current-biased optical orthogonal frequency-division multiplexing for the 5G networks is proposed. An amplify-and-forward relay is used in the proposed system to forward the signals from the source terminal and to simultaneously transmit its own signals.	VLC
[68]	The strengths and weaknesses of the VLC in comparison with RF-based communications, particularly in a spectrum, spatial reuse, security, and energy efficiency for implementing the 5G system, are highlighted.	VLC, OCC, and FSO
[69]	The best cell size for indoor VLC access when users move indoors is investigated. The average rate achieved by the users is maximized.	VLC
[70]	A heterogeneous multi-layer 5G cellular architecture considering three layers, namely the macrocell layer operating below 3 GHz, the picocell layer operating in the mmWave spectrum, and the optical attocell layer operating at the visible spectrum with a control plane and user plane separation scheme, is presented.	LiFi
[71]	A set of critical challenges in advancing 5G networks fueled by the utilization of the network function virtualization and software-defined radio and software-defined network techniques is highlighted.	Generalized OWC
[72]	mmWave and VLC technologies are harmonized and used to create high-speed continuous networks for indoor scenarios.	VLC
[73]	The detailed analysis on path loss and the time dispersion for both mmWave and VLC channels are elaborated. Moreover, comparisons between mmWave and VLC channels and discussions on VLC and mmWave applications are presented.	VLC
[74]	The feasibility of a vertical backhaul/fronthaul framework, where the networked flying platforms transport the backhaul/fronthaul traffic between the access and core networks through point-to-point FSO links, is studied.	FSO
[75]	VLC-based wireless backhaul technologies are studied for high-data-rate access.	VLC
[76]	The integration of a 5G New Radio VLC downlink architecture is proposed and experimentally implemented.	VLC
[77]	The high-capacity and energy-efficient IR-based wireless communication system using low-power laser sources and the retinal hazardless IR region of 1550 nm is designed for smart devices interconnected in the IoT network.	IR-based OWC
[78]	A low-cost hybrid RF/FSO solution, wherein base stations are connected to each other using either an optical fiber or hybrid RF/FSO links, is proposed, considering the combination of RF's and FSO's advantages.	FSO
[79]	The VLC for providing connectivity over the range of a few meters among sensors and luminaires is considered in an IoT smart lighting system.	VLC
[80]	An SDN-assisted VLC system, which is coupled with the WiFi access technology, is presented and experimentally validated.	VLC
[81]	A three-dimensional hybrid VLC/RF indoor IoT system with spatially random terminals with one PD is presented, and the outage performance of the system is studied.	VLC
[82]	An experimental demonstration of optical LED-based OCC system for the IoT is presented.	OCC

In [76], the authors present the integration of 5G New Radio (NR) with VLC downlink architecture. It combines complementary upcoming 5G NR and VLC wireless technologies. The data transmission of the 5G NR frame over VLC is implemented. The three-dimensional hybrid RF/VLC indoor IoT system in [81], a homogeneous Poisson point process is adopted to model to the distribution of the terminals. The light EH model is considered after introducing the LOS propagation model for VLC. At each of the devices at room, light EH is conducted by using PDs and the harvested energy is adopted for the transmissions over the RF uplink. This paper presents the key advances of OWC technologies to meet the future demands considering 5G, 6G, and IoT systems that are not yet presented in any other review literature. All the OWC technologies are considered and the ways through which each technology can contribute to reach the goal of 5G, 6G, and IoT systems are clearly presented in this article.

5. Challenges of the OWC in the 5G/6G and IoT Solutions

A number of challenging issues must be proficiently addressed to deploy the OWC technologies for the 5G/6G and IoT solutions. A few important challenging issues are briefly discussed below:

Frequent handover: Future communication systems will consist of heterogeneous small dense networks that will create very frequent handovers. A handover will be between optical networks and between optical and RF networks. Optical cells are very small and may trigger many unnecessary handovers. Avoiding an unnecessary handover and the ping-pong effect is also an important issue. The properties of the physical and data-link layers differ in the optical and RF-based wireless networks, thereby bringing about a great challenge for the mobility support in RF/optical hybrid systems.

Inter-cell interference: Managing the inter-cell optical interference is a serious issue in the deployment of optical VLC and LiFi networks. The dense deployment of LEDs for the OWC technologies may create high interference in the 5G/6G and IoT networks. Therefore, the inter-cell optical interference is a challenging issue.

Atmospheric loss: The performance of the OWC technologies is affected by scattering, refraction, air absorption, free space loss, and scintillation of the atmosphere. In an outdoor environment, fog and dust obstruct the optical signal from the transmitter to the receiver. The communication link quality in the FSO is degraded because of bad atmospheric conditions. Hence, the atmospheric loss mitigation is challenging with regard to reaching the goal of the 5GB networks, especially in the outdoor condition.

Limited uplink communication using OWC technologies: Most of the user equipment is designed with low-power LEDs to reduce the drainage of power. Because of the low-power LEDs, VLC and the LiFi cannot perform well in uplink communication. Moreover, most of the LEDs of the user equipment produce diffused lights with low power that are easily affected by downlink high-power lights and, hence, limit the uplink communication. In addition, a little deflection or movement of the receiver of a user equipment can easily hamper the uplink communication link. Hence, this is an important issue to be solved in future to efficiently support uplink communication using VLC and the LiFi systems.

Low data rate of the OCC system: One of the most important drawbacks of the existing OCC system is the low data rate. It is challenging to provide a high data rate because of its low-frame rate cameras. The most recently achieved data rate in the OCC system is only 55 Mbps [27]. This data rate should be increased to fulfill the demands of services in the 5G/6G and IoT networks.

Flickering avoidance: Flickering is defined as the fluctuations in the brightness of a light that can be noticed by humans. This is an important issue in the OWC systems. Different modulation schemes on the OWC systems may cause flickering that has a harmful effect on human health. The modulation of LEDs should be done in such a manner that flickering is avoided. Such 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.

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. We can use supervised learning for several OWC-based applications such as smart healthcare [83], smart home lighting [84], and OWC data mining. OWC data-based analysis, such as correlating, ranking, spatial and temporal analysis, and flow prediction, can be performed more efficiently by unsupervised methods of machine learning. Furthermore, we can use reinforcement learning to enhance the data rate, implement network switching and manage network traffic, among other factors, of the ultra-dense OWC networks for 6G [14]. Integrating machine learning in 6G OWC networks enables intelligent network assignment, auto error correction, efficient decision making, and network re-assignment, among others. Moreover, machine learning approach is a core demand in indoor mobile robot-based dense OWC small networks to perform fast and efficient tasks.

6. Conclusions

The 5G communication is expected to hit the market by 2020. After that, the 6G communication is predicted to be launched in between 2027 and 2030. Achieving the goals of 5G/6G and IoT on the basis of tactile internet is challenging. 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 complementary solution of RF networks. The coexistence of RF and optical wireless systems can achieve the goals of such networks. This study presented a detailed observation of how OWC technologies, such as VLC, LiFi, OCC, and FSO, will provide an effective solution for the successful deployment of future 5G/6G and IoT networks. To do that, we briefly explained herein the characteristics of 5G, 6G, and IoT systems and features of OWC technologies. Each 5G, 6G, and IoT specification is individually explained herein with regard how OWC systems offer such features. The present OWC-related studies on 5G and IoT were also summarized in this paper. Therefore, this paper is highly expected to help in understanding the research contributions in different optical wireless systems for the deployment of future networks.

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