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SURVEY

Optical Wireless Communications: Research Challenges for MAC Layer

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ABSTRACT Optical wireless communication (OWC) has emerged as a potential addition to current wireless technologies because of its high capacity, security, and unlicensed spectrum. In addition, owing to recent advancements in optoelectronic components and the industry's globalization, OWC has become a promising solution for addressing upcoming bandwidth requirements and the ''border mile bottleneck''. In 2018, the IEEEE 802.15.7 (updated) standard was released, which proposes physical (PHY) and medium access layer (MAC) layers for OWC-based systems employing visible light (380nm and 780nm) for downstream and infrared spectrum for upstream. Significant research has already been undertaken on the PHY layer; however, the MAC layer must be tailored for application-specific demands. This paper presents a historical overview, summarizes recent works, and offers a broader perspective on OWC-based MAC layer issues, suggesting prospective future research areas. Furthermore, the document aims to provide an overview of the primary technologies necessary to comprehend OWC technology. The document investigates various MAC layer challenges in OWC, including hidden nodes, appropriate guaranteed time slot (GTS) resource allocation, network mobility, and fast link recovery. A comprehensive literature review is performed to identify these MAC layer challenges hindering the widespread implementation of green wireless communication technology. In contrast to previous assessments, this article provides a concise summary of relevant publications on the development of an application-specific OWC-MAC layer.

INDEX TERMS Fast link recovery, GTS allocation, hidden nodes, IEEE 802.15.7, MAC layer challenges, mobility, optical wireless communication, visible light communication, wireless networks.

I. INTRODUCTION

Wireless networking is becoming necessary on par with the provision of water and electricity owing to the rapid growth in the number of mobile devices and volume of data flow. The electromagnetic spectrum inevitably becomes overcrowded, leading to a spectrum crunch. In addition, the exponential growth of Internet data usage has raised concerns regarding energy consumption [1].

In 2007, information and communication technology (ICT) accounted for 3.9% of the world's electricity usage, which increased to 4.6% by 2012 [2]. Concerns related to the power consumption of ICT infrastructure have developed enormously over the past two decades, paralleling the exponential growth in statistics. Despite efforts to reduce energy usage, ICT infrastructure contributed 4.6% of the global electricity demand in 2012 and is expected to continue to increase [3]. Enhanced application capabilities, more data-intensive media, and enhanced data bandwidth given by succeeding generations of network infrastructure contribute to an increase in mobile data traffic [4], [5], [6]. Consequently, global cellular data traffic is predicted to quadruple by 2026, reaching 226 exabytes monthly [6], [7].

We must investigate spectrum segments other than based on radio frequency (RF) to address these impending bandwidth and energy demands. With infrared, visible, and

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ultraviolet working bands, optical wireless communication (OWC) is a convincing alternative for optical transmission in the unguided medium. Its robust characteristics, such as high bandwidth, low cost, and unlicensed spectrum, have the potential to substantially enhance the performance of the existing RF-based wireless technologies [8]. The OWC's downlink data transmission utilizes LEDs as the transmitter, a photodetector or image sensor as the receiver, and an optical channel in free space as the medium. A Wi-Fi, IR, or LED-based visible light communication (VLC) transmitter can be deployed for the uplink [9], [10]

Infrared (IR) wavelengths range from 750 to 1600 nanometres and can be utilized for short-distance wireless connectivity. Moreover, IR communication requires an unobstructed line of sight; hence, it cannot move around or over barriers [11]. Because infrared radiation cannot pass through walls, wired access points are used to connect the rooms.

Furthermore, sunlight, incandescent, and fluorescent lighting can create significant levels of ambient IR noise in various indoor environments [12].

Under OWC, systems that transmit data in the visible light belt (390–750 nm) are designated as VLC networks. VLC technology uses LEDs that can withstand being flashed at high rates of speed without harming the eyesight of humans or the amount of light they generate. It can revolutionize the way LEDs are used for the twin purpose of providing illumination and communication [10], [13]. The most important application domains for VLC are local wireless networks, personal area networks, and the automotive industry [14], [15].

Interest in ultraviolet communication (UVC) has also increased owing to recent developments in solid-state optical components functioning in the solar-blind ultraviolet region (200–280 nm) [16]. A unique UV communication test-bed application based on research-grade semiconductor sources emitting at 275nm is provided in [17]. UV communication devices can be incorporated into existing military transmission networks as core transceivers or relays for localized packet radio networks [18], [19].

This study comprehensively examines OWC technology by reviewing the fundamental principles and applications inherent in this promising field. In addition, this study investigates recent research on the OWC-MAC layer and unresolved concerns that may inspire future research.

Furthermore, as the physical (PHY) layer specifications of OWC and RF-based technologies differ, the channel propagation properties between the transmitter and receiver also differ. The communication environment, such as indoors, outdoors, underground, or underwater, influences the channel conditions of either technology. In the case of the OWC, the positioning of the transceivers and their relative orientations and directions to the reflecting surfaces play a significant role. Compared to the RF link, the optical link fluctuates slowly, causing the radio channel to fade randomly across a few centimeters in a few seconds. Furthermore, unlike RF, OWC channels do not suffer from multipath fading owing to spatial diversity.

On the other hand, using advanced modulation techniques for OWC demands more powerful equalizers in the receiver to counteract interference over a dispersive channel. Furthermore, because users can move in unpredictable ways under LED lights, they can generate a significant OWC channel obstruction. These concerns result in MAC protocols that may differ slightly from RF-based protocols.

The significant contributions of this study can be summarized as follows:

1) We look at how OWC has grown in popularity over the last decade, highlighting the key factors contributing to technology growth. The infrared, ultraviolet, and visible regions of the OWC spectrum are discussed in terms of their communication applications.
2) The survey includes a significant number of graphical representations to improve the reader's comprehension of various OWC-based applications.
3) We provide an overview of the critical technologies required to comprehend OWC technology better. In addition, the OWC literature has been extensively analyzed to identify unresolved MAC layer challenges.
4) We compare and contrast a variety of radio-frequency (RF) and OWC-based systems from a number of different points of view, such as the description of their performance parameters, the types of technology that are used (RF, light-fidelity (LiFi), VLC, optical camera communication (OCC), free space optical communication (FSOC), and Hybrid FSO-RF), the application scenarios (indoor, underwater, vehicular, and space), and the frequencies at which they operate.
5) We highlight the research authors' assumptions and attempt to anticipate potential future work that can be performed to further improve upon these research gaps.
6) We conduct a thorough examination of the significant research platforms that have been developed in the literature.

The remainder of this paper is organized as follows. The second Section examines the background, advantages, and prospective application areas of OWC. Section three describes open research problems associated with the incorporation of OWC into existing MAC-layer systems. Section four to seven dwells into these challenges in detail. Section eight specifies the non-MAC challenges and future perspectives on OWC. The conclusion is presented as a summary in the ninth Section of this paper.

II. ORIENTATION TOWARDS OWC

Clearly, the development of wireless devices and systems depends heavily on RF technology, and the rising demand for RF spectrum is leading businesses and researchers to investigate OWC-based alternatives [20], [21]. The optical spectrum is three times the size of the electromagnetic spectrum, which further motivated us to study this technology [7], [22].

As the OWC's PHY layer is already mature, we must examine the challenges of the MAC layer. However, we must

TABLE 1. Comparison chart for RF, FSO, and hybrid FSO-RF technologies.

Parameter	RF	FSO	Hybrid FSO-RF
Achievable data rates	~Mbps	~Gbps	~Gbps
Modulation	16-QAM	OFDM	Joint-adaptive modulation
Limitation	Spectrum	Environmental	none
Spectrum	3 kHz to 300 GHz.	0.8-1.5 THz	10-100 GHz
Ambient noise	Other RF devices	No	Yes
Electromagnetic	Yes	No	Yes
Security	Low	High	High
Coverage	High	Limited	High
Advantage	No LoS needed	Unlicensed spectrum	Both
Infrastructure	Gateway/access point	FSO transmitters-receivers and backbone network preferably on optical fibers	Retro-fit

first have a solid grasp of the OWC technology. The following subheadings provide background information on the OWC, hybrid FSO-RF technology, and its applications.

A. BRIEF HISTORY OF OWC

Long-distance communication has been facilitated by sunlight since the prehistoric times. The OWC has historically taken the form of beacon flames, smoke, ship flags, and semaphore telegraphs [23]. Ancient Greeks and Romans were the first to use the sun for transmission, using coated shields to reflect sunlight and relay messages during war. In 1810, Gauss devised a heliograph, a device that employs two reflectors to guide a focused high-energy beam of sunlight to a distant location. Alexander Graham Bell invented the first practical wireless telephone system, photophone, in 1880 [24], [25].

Using a GaAs LED, MIT Lincoln Labs established a prototype OWC link to broadcast TV signals for over 30 miles in 1962 [26], [27]. After this invention, numerous tests were conducted to expect the OWC to be the primary installation site for laser diodes. The results were unsatisfactory because of the significant deviation of the laser beams and failure to account for environmental influences. Hence, in the 1970s, limited-loss fiber optics became a natural option for long-distance optical communications.

B. HYBRID OWC-RF

OWC technology can utilize the optical spectrum and deliver high-quality communication characteristics, such as additional security, power efficiency, and resistance to electromagnetic interference [28], [29]. The author demonstrates a 100 Gbps data-transfer rate under typical indoor illumination conditions in [30]. Nonetheless, this intriguing technology has limitations, including a high reliance on line-of-sight and a limited coverage area.

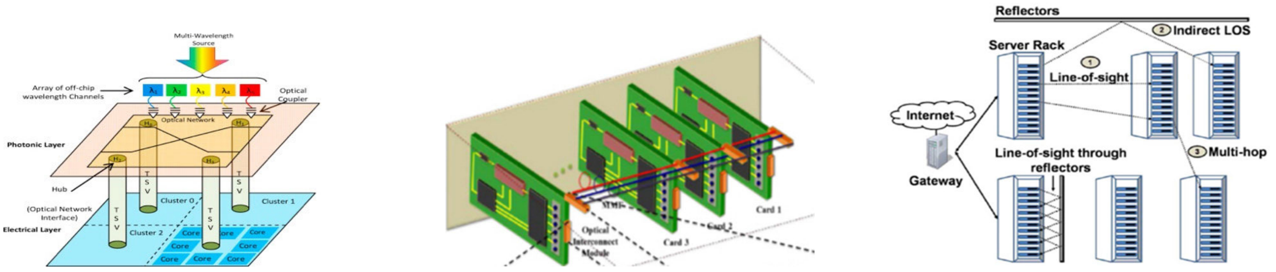
As established in [31], [32], converging RF and OWC as heterogeneous networks (HetNets) is crucial for displaying superior QoS. HetNet enables the concurrent operation of two or more access technologies, including microcells, femtocells, and attocells. These networks can survive in the same environment without interfering with one another. Table 1 compares these technologies with their related parameters.

For instance, hybrid FSO-RF communication systems combine an RF link with an OWC link to enhance reliability and data transmission rates.

FSO is a high-data-rate communication method that uses a comprehensive bandwidth. FSO demands line-of-sight (LoS) transmission between transmission and reception [33], [34], [35]. A point-to-point (P2P) optical connection is highly susceptible to poor weather conditions, such as snow, fog, and atmospheric turbulence. When the FSO link becomes unreliable because of moisture or cloud coverage, an RF link is employed. Nevertheless, hybrid switchover FSO-RF systems are subject to transient environmental disturbances such as atmospheric turbulence [36], [37], [38].

Together, OWC and RF may identify various targets and barriers. Additionally, this technology can be utilized for vehicle-to-vehicle (V2V) and backhaul communications, enhancing the future mobility of networks. As demonstrated in [39] and [40], mobile users can remain connected using a hybrid OWC-RF wireless LAN. Hence, the combination of various wireless technologies makes it possible to establish dependable and easy-to-install communication networks.

In [41], the author compares the advantages of hybrid RF-VLC-based vehicular communication networks to those



(a) (b) (c)

FIGURE 1. Ultra-Short-range, (a) Inter-chip communication using O-NoC technology. (b) Free space optical interconnects, (c) Inter-rack FSO-based network with high flexibility (FIREFLY).

of RF-only systems. The article claims that the hybrid system can meet rugged ultra-high reliability (99.99%) and ultra-low latency (3 msec) requirements, making it a suitable contender for 6G intelligent transportation systems (ITS). In addition, the study analyses the problems and potential future prospects of a hybrid RF-VLC system implementation for advanced V2X communications.

In [42] too, the author also compares the significant benefits of the combined performance of VLC and RF on the behavior of individual technologies. Adaptive to illumination conditions, this study presents an energy-efficient hybrid RF-VLC system. The suggested model employs retrofit LED bulbs and conventional RF access points to create a system that is energy-efficient and more adaptable to changing ambient light levels. The approach identifies the problem as NP-complete, and simulations demonstrate that the proposed system consumes 75% less energy than WiFi and VLC, individually.

The document [43] studies the merits and limitations of hybrid RF-VLC systems, which is quite helpful to both beginners and professionals in this area of research. The author discusses the aspects of the history, objectives, deployment areas, channel model, network structure, and performance parameters of the VLC, RF, and hybrid RF-VLC system design. The report also provides insight into the prominent applications, challenges, and potential research directions for hybrid RF-VLC system deployment.

C. APPLICATIONS

OWC is an innovative technology that offers an appealing option in specialized application domains, where optical fiber and RF alternatives are costly to implement, generate undesirable interference, or are not viable. Moreover, the cost of implementing OWC systems is substantially lower than that of optical fibers, which in a heavily populated area can easily surpass $1 million per mile [44].

In addition, OWC installation simply involves the synchronization of two free-space optical transponders instead of digging trenches or repairing road surfaces.

OWC's diverse application portfolios of OWC range from high-speed Internet connectivity via LED light bulbs to intergalactic telecommunication. Existing state-of-the-art personal communications, gigabit infrared (Giga-IR), function at data rates ranging from 512 Mbps to 1.02 Gbps across a short distance. An additional application area that supports data transfer rates of hundreds of megabits per second over a typical transmission range of only a few meters is underwater OWC [45], [46], [47]. Furthermore, the OWC can add a new dimension to existing applications that use alternative technologies. This section discusses various ongoing and prospective applications within this transmission range.

1) ULTRA-SHORT-RANGE APPLICATIONS

Today's supercomputers, robust data-centers (DCs), and system-on-a-chip (SoC) devices require specialized inter-and

Intra-chip means of communication. In recent decades, the optical network-on-chip (O-NoC) concept has been developed to build multicore devices with higher performance and reduced power consumption. Fig.1(a) shows the inter-chip communication using O-NoC technology.

Optical interconnects have been suggested to replace copper-based interconnections in DCs due to their excellent attributes, including high bandwidth, reduced latency, and low power consumption, as stated in [48] and [49]. There may also be significant industrial interest in ultrashort-scale wireless optical interconnects. Furthermore, the design of guided optical interconnects is dominated by the waveguide loss and bend radius.

Free-space optical interconnects (FSOI), which connect multidimensional device arrays, provide a flexible alternative, and a high level of concurrency can be seen in Fig.1(b) [50], [51]. The share of FSOI in the optical connection industry is defined mainly by effectively solving the misalignment tolerance.

An FSO-based cross-rack network with considerable flexibility, named FIREFLY, is presented in [52] and [53], in which OWC-based architectures replace the DC. FIREFLY is an idea for a wireless steerable DC network based on FSO. It was initially offered as a state-of-the-art design with a fully flexible inter-rack fabric that utilized FSO linkages. As shown in Fig.1(c), DC switches with directional FSO transmitters are used to link the shelves.

2) SHORT-RANGE APPLICATIONS

The classic short-range (a few centimeters) OWC application can be a wireless body area network (WBAN) that incorporates wearable sensors to retrieve physical and biochemical information. It provides consumers with mobility and eliminates the need for patients to remain in hospitals to monitor and lower healthcare costs. A typical WBAN (Fig.2(a)) in the human body can monitor and gather vital medical indicators, such as blood pressure, electrocardiogram (ECG), stress, blood glucose, and even SPO2 levels [54], [55], [56].

Another short-range OWC use case is in innovative smartphone communication. It utilizes a phone camera as an optical sensor to enable diverse machine-to-machine (M2M) and phone-to-phone (P2P) communication, as shown in Fig.2(b). OCC refers to wireless transmission of information between optical sources and cameras (image sensors). Data from light-emitting diodes are collected using camera image sensors, and this technique is compatible with all cameras and smartphones that support image processing, as depicted in [57] and [58].

Further applications of narrow-range OWC are for domestic use. Most current indoor examples of augmented reality (AR) are based on smartphone applications [58], [59], [60]. A typical innovative phone application based on AR in an interior environment is shown in Fig.2(c).

In addition, [33] demonstrates the application of AR as a museum guide by utilizing two functionalities, namely artwork appraisal and advice. ''Artwork appreciation'' refers to educating the visitor about the work to notice and appreciate its qualities. ''Guidance'' refers to the process of directing a visitor around an exhibition space in a logical manner.

3) MEDIUM RANGE APPLICATIONS

WLANs are the most common application of medium-range (in meters) wireless communication. Substantial research has been conducted on indoor infrared communication as a viable WLAN solution under LiFi [61], [62]. LiFi takes advantage of the predicted ubiquity of LED-based light infrastructure, as illustrated in Fig.3(a). The diagram shows how LED bulbs, with minor modifications to their driver circuitry, can be used to link our smart gadgets to the Internet [63].

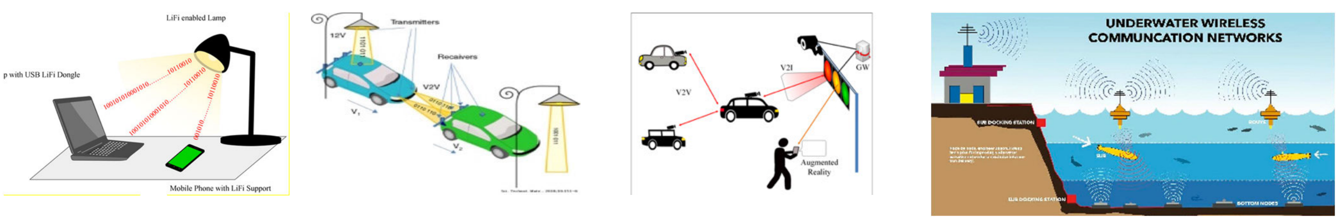
A framework for effective hybrid cloud architecture coupled with LiFi connectivity for a human-centric Internet of things (IoT) network is presented [64], [65], [66]. The author introduces the local cloud architecture, which reduces latency and bandwidth costs while enhancing security and reliability.

Additionally, the paper discusses the communication modulation techniques utilized in LiFi and illustrates the applicability of the suggested model using real-world scenarios. Other researchers have also presented a LiFi-based IoT architecture based on data collection from surrounding LiFi-equipped devices [67]. The data generated by the LiFi can be evaluated and processed to make intelligent judgments to improve the underlying services.

As indicated previously, LEDs are also extensively deployed in outdoor illumination, traffic signboards, advertisement displays, and automotive taillights/headlights, as shown in Fig.3(b). The VLC can also pave the way for vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) connectivity through LED-based front and rear lights. As demonstrated in Fig.3(c), these lights may communicate with one another and other street lighting equipment to offer safety-related data to the vehicles on the road [68], [69], [70].

(a) (b) (c)

FIGURE 2. Short-range (a) OWC in Wireless Body area networks, (b) Phone to phone and Machine to Machine applications using OWC, (c) OWC-based augmented reality in WPAN.



(a) (b) (c) (d)

FIGURE 3. Medium-range (a) LiFi application in IoT, (b) Vehicle to vehicle communication, (c) Vehicle- infrastructure Communication, (d) Underwater communication.

New research avenues exist for developing this domain, including seamless connection, edge computing, fog computing, software-defined and named data networks, and security [71], [72], [73].

In [74], the authors describe the structure, implementation, and performance of the OWC system used in the third-generation Smart CornerTM exhibit at the 2019 Consumer Electronics Show. This system, which uses OFDM modulation, maintains a nil packet error rate over two meters at over 100 Mbps and fifteen meters at 14 Mbps, suggesting it can serve as a critical alternative communication connection in a range of automotive application scenarios.

Another potential area for VLC in the medium range is underwater communication (see Fig.3(d)). Acoustic communication has historically been utilized underwater for a range of several kilometers. With limited capacity, this technology can carry data at hundreds of Mbps over small distances (less than 100 meters), complementing long-range acoustic communication [75], [76].

In [77], the authors describe the use of self-adapting transceivers to design efficient algorithms for energy consumption for transmitter/receiver localization and beam synchronization.

4) LONG-RANGE APPLICATIONS

Hybrid FSO-RF systems have the potential to be exploited in a variety of long-range transmission scenarios, such as those represented in Fig.4(a). These scenarios include the deployment of mobile access networks and wireless metropolitan area network (WMAN) deployments. The diagram explains how RF and an optical link that complements it are used to carry out cross-border wireless communication.

While FSO links were used primarily for stationary installations, they can now be established in mobile applications with trustworthy acquisition-tracking protocols.

This facilitates the implementation of FSO links for airplane-to-airplane and airplane-to-ground systems, as shown in Fig.4(b). The illustration depicts the FSO connection between the aircraft and ground base station, whereas RF can be utilized for local connections. In [78] and [79], the author discusses the technological characteristics that drive the development and deployment of these hybrid FSO/RF communication lines.

Several operations are described in [80] to develop novel wireless communication capabilities using dynamic spectrum access, wideband and narrowband radio systems, and free-space optical networks operating in the long-wavelength infrared spectrum. Fig.4(c) illustrates the hybrid FSO-RF in defence and military organizations. The diagram depicts how an FSO link connects the space station to a ground-based laser weapon and a high-altitude airship. Ground-based weapons can be deployed to destroy enemy weapons via OWC-based linkages via relay mirrors on the airship. In [81], [82], and [83], the author summarizes these capabilities of radio-optical hybrid communication systems applications in military environments.

5) ULTRA-LONG-RANGE APPLICATIONS

OWC has various applications in aerospace operations, particularly in space-to-ground, space-to-air, and space-to-space links [84]. Fig.5(a) portrays OWC implementation as a robust ultra-long link (10,000 km) for ground-satellite communications. NASA demonstrated lunar laser communication in

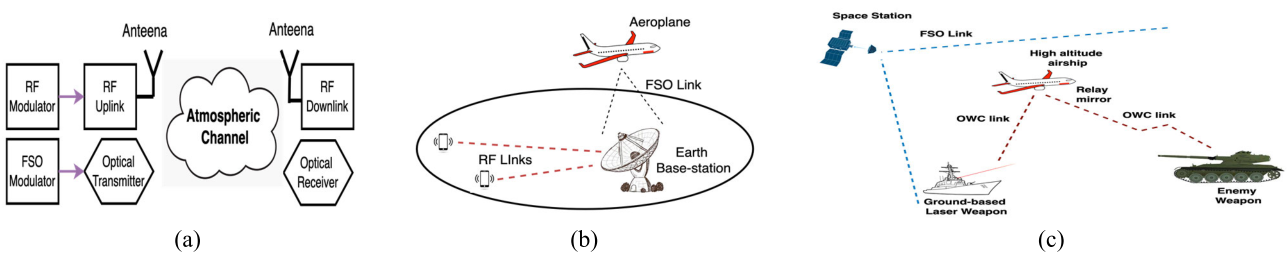


FIGURE 4. Long-range (a) Hybrid FSO-RF In WMAN, (b) Aircraft-ground communication,(c) Hybrid FSO-RF in military applications.

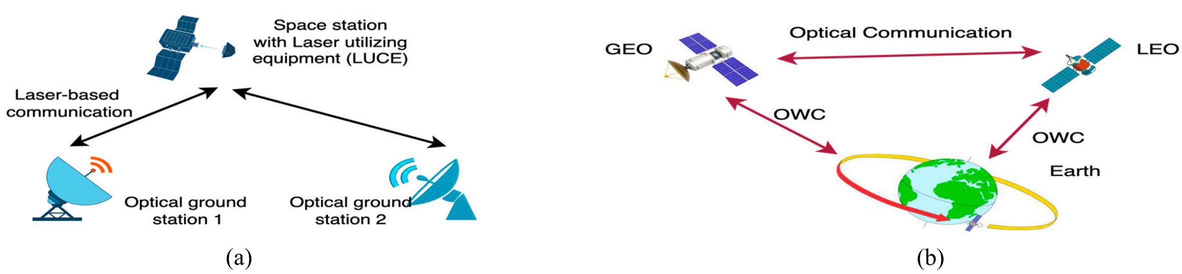


FIGURE 5. Ultra-long-range (a) Aerospace communications (b) Space communication with laser links.
Figure (1-5): OWC Application areas: current and future.

2013 by transmitting data at 622 Mbps over 384,600 kilometers via an FSO link between the Moon and Earth [85].

An inter-satellite OWC (IS-OWC) network using a laser beam as the carrier wave is delineated in [86], [87], [88], and [89]. The system highly depends on several characteristics, including the laser light's wavelength, transmission strength, modulation technique, and transmitter and receiver antenna dimensions.

While both RF and optical signals are electromagnetic light radiations, optical waves have several advantages when employed in space. These benefits include lower equipment bulk, increased data speeds, and no regulatory constraints [90], [91]. Satellite communication in space using an OWC is shown in Fig.5(b). As the next stage for optical communication systems in space, a series of comprehensive tests of high-speed laser-based satellite connections must be conducted to ensure that future needs for satellite-to-satellite communication can be addressed with the appropriate technology.

III. RESEARCH CHALLENGES

We now discuss four critical MAC layer challenges that must be addressed in the near future for broad deployment of OWC-based networks. This work is based on a review of the most recent research on OWC and other leading wireless communication technologies. In addition, we review existing plans and strategies to overcome these challenges.

The following OWC- MAC challenges are covered in this paper:

1. Hidden Node problem
2. Efficient GTS Allocation
3. OWPAN Cell Design and Mobility
4. Fast Link recovery

We'll begin with the problem of hidden nodes in OWC-based networks. Hidden nodes occur when a sensor node (for example, a mobile phone) may connect to the LED bulb (which acts as an access point) but cannot interact directly with other sensor nodes communicating with that AP. Multiple sensors transmitting data packets to the AP may cause congestion and packet drop, thereby reducing the network throughput. There are solutions to this issue; however, they may impose overhead, latency, and cost, particularly for small packet sizes. Therefore, this topic requires careful consideration.

The second issue we will examine is the efficient distribution of transmission slots to sensor nodes. The superframe structure is defined by the IEEE 802.15.7 standard and includes separate transmission periods for contention-based (CSMA) and contention-free (TDMA) transmissions. Guaranteed time slots must be assigned to TDMA-based applications with bandwidth use considered. Numerous solutions have been proposed in the literature, but low-bandwidth wastage is yet to be achieved. The methodologies and approaches used for efficient guaranteed time slot (GTS) utilization are described in this paper.

The third issue addressed in this study is the need for mobility in OWC-based networks. For instance, if we move from under one light bulb to another indoors, the link is disrupted, and we must reconnect to the new light source. Furthermore, mobility permits the use of several access points within an OWC-based PAN and establishes a wireless network between different light sources. However, the mobility and handover procedures in OWPAN must strike a balance between cost, speed, and complexity. Our literature summarizes the strategies that have already been utilized for this objective.

The fourth research challenge addressed in this paper is rapid connection recovery. In OWC-based networks, there must exist a direct line of sight between the mobile device and the access point; a medium obstruction can disrupt the connection. Therefore, the IEEE 802.15.7 standard proposes different fast-link recovery strategies to quickly restore connectivity following an interruption. Here, we summarize the schemes from the standard and available research literature, as well as the implementation challenges necessary for the quick restoration of disrupted connections.

The following sub-sections thoroughly examine existing approaches to mitigate each of these challenges.

IV. HIDDEN NODE PROBLEM

The hidden node problem (HNP) is a fundamental issue that affects all wireless networks, whether RF- or OWC-based. HNP occurs because nodes cannot hear one another due to their short transmission range. This results in collisions, and thus frame loss [92], [93]. Fig.6 illustrates a hidden node scenario in which node one is hidden from node two because the former is outside the latter's carrier-sense range. As a result, both will fail if node one and node two attempts to access the channel simultaneously to relay their data to the coordinator. Table 2 summarizes the comparison of the available methodologies for HNP.

The performance degradation caused by HNP in 802.11ah wireless networks is analyzed in [94]. To overcome this issue, the author proposes a unique grouping technique known as hidden matrix-based regrouping (HMR). The scheme operates by locating hidden node pairs at the Access point (AP)

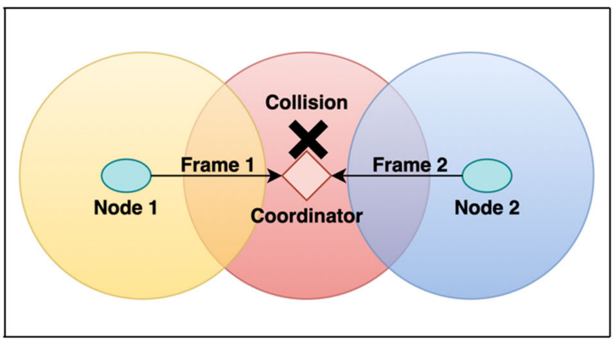


FIGURE 6. Collision occurrence due to hidden node problem as node1 is not in carrier sense range of node 2.

TABLE 2. Summary of comparison of available methodologies for HNP.

Journal, Year of publication [reference]	Authors	Implementation (Simulation platform/ experimental set-up)	Research contribution	Performance metrics considered
Computer Networks (Elsevier Journal), 2016, [94]	S-G Yoon et al.	Event-driven simulator written in C++	Matrix-based regrouping algorithm for hidden nodes	No. of hidden node pairs before and after TBTT Spatial reuse
IEEE Transactions on Mobile Computing, 2020, [95]	S Liu et al.	NS-3 network simulator	Two different ellipse models for interference and carrier-sensing for full-duplex CSMA networks	Throughput with different network densities and impact of self-interference cancellation
14th International Wireless-Communications & Mobile-Computing Conference (IWCMC), 2018, [96]	P Campos et al.	NS-3 network simulator	LAA and Wi-Fi-based heterogeneous networks considered Channel quality index (CQI) distribution to locate hidden nodes	CQI distributions UE rate satisfaction as the ratio between achieved and demanded throughput
Computer Networks (Elsevier Journal), 2020, [97]	P Campos et al.	NS-3 network simulator	presents a method for detecting UEs infected with HNP in LAA networks	Truncated CQI RSRQ RSRP
Software and Systems Modelling, Springer journal, 2020, [98]	E Coronado et al.	Coloured Petri Net (CPN) Tools simulator engine	Coloured petri nets (CPNs) employment to build a customizable IEEE 802.11 model to consider HNP with a wide range of traffic patterns and services.	Collision rate and packet loss (with and without RTS/CTS)
International Conference on Computer, Information & Telecommunication Systems (CITS), 2015, [99]	C L Bosch et al.	OMNET++ simulation framework	HNP analysis in VLC-based PAN networks (IEEE 802.15.7) Confirms the presence of hidden nodes in the upstream CAP (star topology considered)	End-to-end throughput packet error rate Avg collisions and transmission failures
16th IEEE Annual Consumer-Communications & Networking Conference (CCNC), 2019, [100]	K Maesako et al.	Commercial network simulator Scenargie 2.0	A novel asymmetric HNP-aware routing metric is proposed that improves throughput without sacrificing network fairness. The effect of HN interference and the impact of a new flow on a current flow is explored.	Flow throughput fairness (FTF) Throughput of individual flow
International Conference on Information & Communication Technology Convergence (ICTC), 2015, [101]	J Muvlla et al.	MATLAB (licensed software platform)	The work investigates spatial reuse and equitable channel sharing in WLANs where each station has a different carrier sensing capability	Per-STA throughput Unfairness with symmetric and asymmetric hidden nodes

by comparing power-saving poll transmission (PSPT) times. It then constructs an array from which the values of each element can be readily determined using PSPT timings. Finally, it places the nodes encountering the HNP into a different group inside the sequence, where they discover hidden nodes.

This approach dramatically minimizes the number of hidden nodes, which results in improved performance with respect to the PSPT end time and retransmissions. According to the future IEEE 802.11ax protocol, the carrier sensing threshold (CSTH) value should be enhanced to improve WLAN spectrum utilization via spatial reuse.

In [95], the author demonstrates how the asymmetric HNP arises when older devices with lower CSTH reside alongside new devices with greater CSTH and contend to access the channel. The causes of this problem are examined from two s: carrier sensing asymmetry and binary exponential backoff operation. This research investigates the challenges of spatial reuse and fairness in heterogeneous WLANs.

The third Generation Partnership Project, named 3GPP, was initiated in 1998 to develop new technology for 3G cellular networks. 3GPP has completed the standardization of licensed assisted access (LAA) for LTE deployment in the unlicensed 5 GHz band. This method utilizes the listen-before-talk (LBT) protocol, which is comparable to the Wi-Fi MAC mechanism. Identifying hidden nodes and interpreting the essential metrics that reveal how their presence impacts the network's performance inside LAA enables intelligent decision-making if done wisely. The channel quality indicator (CQI) distribution metric enables the detection of nodes in concealed areas.

The coexistence of LAA and Wi-Fi infrastructures is explored in [96]. The author investigates how HNP impacts the LAA network and demonstrates how the presence of LTE user equipment (UE) and Wi-Fi stations (STA) in locations where the two networks overlap affects both networks.

Collision detection can determine whether a node is influenced by collisions and whether it is at a hidden location.

This is demonstrated by displaying various interference levels, simulated network parameters, and users inside the hidden region [97]. This article examines the reference signal received power (RSRP), channel quality indicator (CQI), and reference signal received quality (RSRQ) parameters in the framework of LAA for UE confronting differing degrees of interference. The observations indicate that it is possible to determine with high precision if collisions impact a node and whether it is in a hidden area.

The IEEE 802.11e protocol supports QoS in situations where QoS differences can cause extensive collision loops and delays. The Colored Petri Net (CPN) model presented in [98] analyzes the protocol's behavior in the presence of hidden nodes to determine the performance of RTS/CTS transmission. Using CPN Tools' modeling and monitoring capabilities, the paper then evaluates the efficacy of this approach. The author quantifies the performance of the IEEE 802.11e amendment under various system operating conditions and highlights its shortcomings. In the presence of hidden nodes, the proposed parameter setting for the priority method imposes significant limitations. This study is particularly applicable to the IEEE 802.11-based wireless networks.

The investigation of the influence of hidden terminals on a VLC star topology is done in [99]. The author develops a simulator and analyses the packet loss rate and throughput of VLC networks. By modeling situations with and without hidden nodes, the paper investigates the effect of HNP on network performance. Owing to the directive nature of the optical channel's LoS propagation model, simulations for upstream contention access period (CAP) transmissions vary based on whether or not hidden nodes are present. In all simulations, concealed nodes affect network operation, and the results indicate that they also degrade IEEE 802.15.7 upstream CAP functionality

An experimental asymmetric HNP Aware routing Metric (AHAM) is introduced in [100], enabling a new flow to construct a source-destination path that avoids hidden nodes of existing flows and nodes on that path that interfere with current flows. The HNP can have an unbalanced effect on the volume of fresh flows. AHAM seeks to assess the impact of these nodes properly and to balance new and existing flows. Simulations demonstrate that AHAM maintains fairness in the network while delivering high throughput

Further, [101] highlights the HNP as an unfairness issue that emerges with older devices having a lower Carrier sensing threshold (CSTH) (CSTH). The author tries to lower the CSTH to improve spectrum efficiency in heterogeneous IEEE 802.11ax-based wireless networks. The study demonstrates that the RTS/CTS protocol does not solve the HNP issue, and investigates the trade-off between spatial reuse and fairness for CSTH. The paper indicates that the RTS/CTS protocol does not resolve the HNP problem and examines the trade-off between spatial reuse and equality for CSTH.

This was the most recent and pertinent study on OWC's HNP solutions and other cutting-edge technologies. HNP has been discovered in wireless mesh networks, heterogeneous WLANs, IEEE 802.11ah and 802.11e based WiFi networks, full-duplex WiFi networks, LTE networks, and IEEE 802.15.7 based VLC networks. All simulation results indicate that the impact of hidden nodes dramatically reduces the performance of these network conditions, particularly in uplink CAP.

Furthermore, because nodes in energy-saving mode wake up simultaneously to broadcast frames immediately after receiving a beacon from the AP, the HNP can worsen, resulting in more frequent packet collisions, and thus, performance loss.

A. ASSUMPTIONS MADE BY THE RESEARCHERS

Let us now explore the assumptions made by the authors while solving for HNP. The first is a saturated traffic condition, in which the hidden nodes continuously broadcast data. Another claim is that RTS/CTS messages will be received by all nodes within the same transmission range, ignoring the issue of channel access fairness. Some studies have assumed bidirectional communication, in which all nodes receive the ack of the coordinator in the cluster. It is also anticipated that nodes can simultaneously send a busy tone and receive data in the same frequency range. Some researchers have considered stationary nodes, which are currently not valid for mobile wireless communications.

B. STRATEGIES FOR THE OUTSTANDING ISSUES

Based on this research, it is evident that there is still a lot of work to be done. For instance, researchers can focus on handshaking methods and routing schemes to determine the best path with zero or a small number of hidden nodes. Furthermore, because mobility is vital in OWC, future research must focus on dynamic carrier sensing and, as a result, active hidden node detection. Again, increasing overheads, power consumption, and latency can all be improved.

V. EFFICIENT GTS ALLOCATION

The coordinator can allocate a portion of the active superframe to an application requiring low latency or high bandwidth. These time slots are classified as GTSs. As shown in Fig.7, the contention-free period (CFP) is formed by the GTSs and always comes at the end of the current superframe and follows the CAP [113]. The coordinator can allocate several GTSs, each of which can fill multiple slots. Each device transmitting in a GTS must guarantee that its transaction is completed before the next GTS or CFP [114], [115], [116]. Table 3 compares the recent state-of-the-art methods related to GTS allocation.

The research presented in [102] describes a dynamic time-slot allocation for a real-time virtual patient care system with fog in the network. To improve the network performance, a minimal-cost, energy-efficient parent selection technique is suggested for data packet routing. The proposed method decreases time-slot squandering and additional network delay while enhancing network dependability and channel utilization.

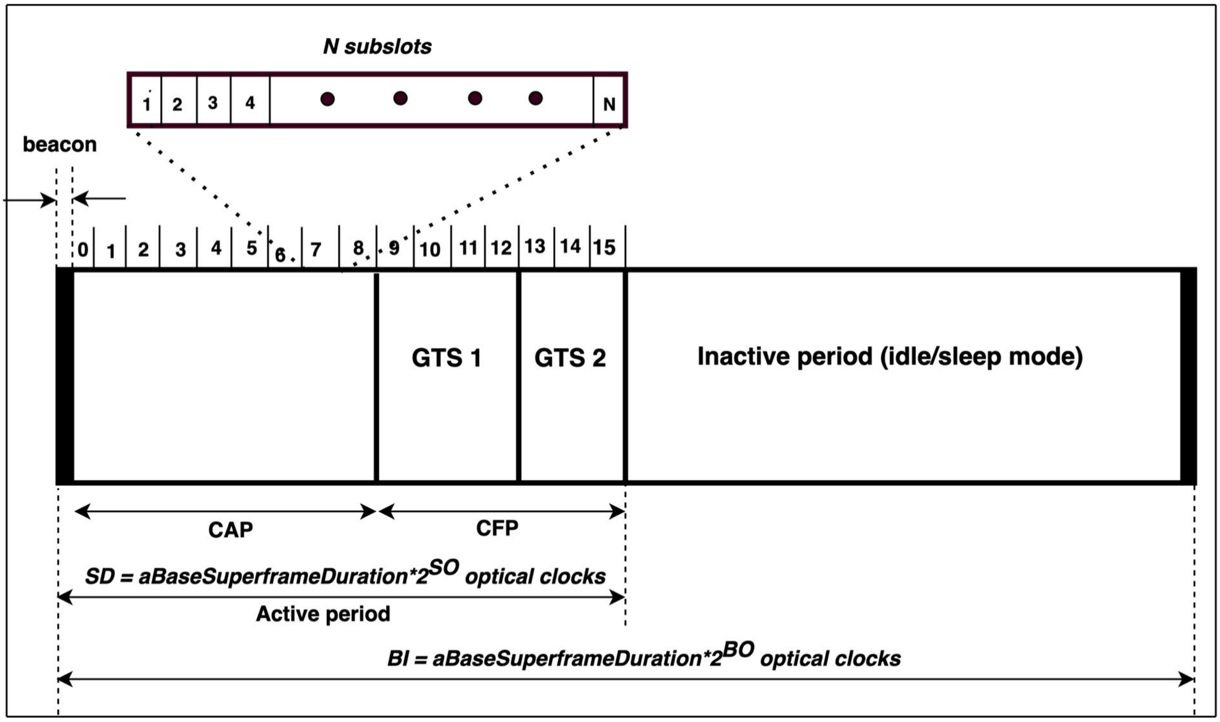


FIGURE 7. Standard superframe structure.

To enhance the effectiveness of IEEE 802.15.4 WPANs in beacon-enabled configurations, [103] proposed a novel GTS allocation mechanism with adaptive resource allocation. This includes the classification of devices and GTS scheduling. During device classification, each data-transmitting device's priority is established. Then, the GTS slots are allocated and planned based on the GTS scheduling priority. The strategy's performance is evaluated by mathematical analysis utilizing Markov chain transition probabilities and simulated trials with Gamma and Pareto distributions.

By investigating GTS performance in QoS-guaranteed transmission, [104] proposed a novel unbalanced GTS allocation scheme (UGAS) to maximize bandwidth resource utilization. The proposed system resolves bandwidth underutilization using network calculus theory and a greedy algorithm. The UGAS divides the CFP into time intervals of varying lengths to satisfy bandwidth requirements. Timing slots are assigned using a QoS approximation approach. The UGAS enables bandwidth allocation with guaranteed QoS, without modifying the current GTS protocol. The numerical results reveal that UGAS can increase the bandwidth consumption by 30 percent compared with the conventional method.

A unique full-duplex MAC to improve CFP spectral efficiency in optical wireless networks is proposed in [105]. The author modifies the beacon frame to facilitate the effective allocation of GTS without introducing additional overheads. Mathematical analysis and simulation models are used to compute network parameters such as throughput and delay.

Reference [106] describes a distributed TDMA algorithm that is topologically ordered for WSNs. By incorporating the verification condition for signal receipt situations and the slot knowledge of peers, the system can be adapted to handle various actual WSN situations.

In [107], the author proposes an approach for optimizing the GTS by reclaiming empty or leftover slots from successful or missed transactions. This implicit allocation technique lets many nodes divide the total number of requested time slots inside a GTS and permits the full utilization of the time slots' bandwidth

Modifying the IEEE 802.15.4 MAC superframe format [108] enables the transmission of priority data with minimal delay and power consumption. The author introduces a novel data-forwarding architecture that allocates GTS by data type to ensure quick and secure data transport. In addition, unwanted channel contention waiting time is lowered in the CAP to reduce power consumption and latency.

WSNs use deterministic and synchronous multichannel extension (DSME) MAC for IoT-based intelligent grids, smart cities, and cutting-edge healthcare applications. During CFP, this MAC system employs a multi-superframe architecture with data flow across many channels. GTS allocation based on DSME, on the other hand, may not be enough in an adaptive traffic network environment with varying throughput and bandwidth. The reference [109] offers a range- and priority-based DSME-GTS allocation approach for two network situations in a WSN with star topology. Scenario 1 assigns slots based on the end-node priorities. Nodes with

TABLE 3. Summary of comparison of available methodologies for efficient GTS allocation.

Journal, Year of publication [reference]	Authors	Implementation (Simulation platform/ experimental set-up)	Research contribution	Performance metrics considered
MDPI Sensors Journal, **2019**,[102]	S Pushpan et al.	NS-2 network simulator	Fuzzy logic-based dynamic slot allocation Fog-based real-time patient monitoring system	Packets delivery ration Avg end-to-end delay Energy consumption
IEEE Transactions on Parallel and Distributed Systems, **2008**, [103]	Y-K Huang et al.	Simulation and analytical modeling	Adaptive GTS scheduling algorithm after node classification Starvation avoidance mechanism for low-priority nodes	Average packet waiting time Fairness (with gamma and pareto distributions as traffic models)
Wireless Pers Communication (Springer Journal), **2012**, [104]	N T le et al.	C++ based simulator Network calculus	Unbalanced GTS allocation scheme with unequal time slot durations	Average bandwidth utilization (*30 percent improvement as compared with the standard scheme) Quality of service (QoS) analysis
IEEE Access, **2021**, [105]	A Gupta et al.	Riverbed Modeller 18.8	Full-duplex MAC with macro and micro beacons and multiple OWC access points	Normalized throughput and average network delay with offered load
IEEE Access, **2020**, [106]	T-T Nguyen et al.	NS-2 network simulator	Message reception status and slot awareness checking based scheduling algorithm	Average transmissions by nodes and network Intermediate trials before GTS allocation
IEEE Transactions on Vehicular Technology, 2016, [107]	C Chen et al.	MATLAB and OPNET	A dynamic scheduling strategy proposed to recover unused GTS spaces from completed or missed transactions	No. of missed transactions GTS utilization delay constraint vs. burst transmission completion time
International Conference on Communication & Electronics-systems, **2019**, [108]	S Banu et al.	NS-2 network simulator	Modified superframe structure for immense preference data forwarding (IPDF) featuring increased throughput and reduced energy consumption and delay	Delay performance with node count and packet size Throughput vs. node count and packet size Energy consumption
Transactions on Emerging Telecommunications Technologies, **2021**, [109]	T Nguyen et al.	MATLAB 2017a programming tool with analytical modeling	End nodes range and priority-based GTS allocation scheme	Packet delivery proportion Packet loss Bandwidth efficiency Latency Energy consumption
IEEE Access, **2019**, [110]	K Kobayashi et al.	Computer simulations	Separate transmission and reception configurations in the CAP and CFP at the node level	Signal-to-noise ratio Control performance with varying network size
IEEE Access, **2020**, [111]	L Yang et al.	Real-time test-bed simulations	GTS allocation for numerous live virtual machines (VMs) a novel compromise among QoS and migration time for multiple simultaneous VM activities	Quality of service with varying bandwidths, deadlines, and data volume Convergence time
Journal of Sensors and Actuator Networks, MDPI, **2021**, [112]	H. Kurunathan et al.	MATLAB 2017a programming tool with analytical modeling	Network calculus-based analytical modeling for GTS utilization. Novel CAP reduction approach to improve network scalability	Throughput Network scalability Impact of CAP reduction on delay

the highest priority receive slots first, followed by those with lower focus. The second scenario sets slots based on an educated assessment of the end node range. The simulation results indicate an increase in packet transmission rate, end-to-end latency, bandwidth utilization, and energy consumption. This GTS approach is appropriate for network applications requiring high throughput and bandwidth utilization.

Using an IEEE 802.15.4 beacon-enabled network, [110] examines wireless feedback control of several workstations. CAP is more likely to communicate failure than CFP because of packet collisions and backoff intervals. The controller's GTS assignments for the input control and device status must be correct to maximize the wireless control loop. The article presents a straightforward, efficient method for distributing GTSs that considers CAP and CFP feedback management and packet delivery. In addition, the author provides a GTS allocation method that is compliant with IEEE 802.15.4 and improves the control performance. By separating transmission and reception in the CAP and CFP, the proposed technique makes the GTS allocation more efficient. This data request is used to assign the GTSs more precisely.

The document [111] investigates the resource distribution problem for simultaneous live Virtual machine (VM) relocation in edge clouds. Real-time VM relocation implies that the VM continues to provide user services throughout the move. Live VM migration between widely scattered edge clouds is necessary to deliver low-latency and consistent facilities to mobile consumers. Owing to the lower network bandwidth, the migration of virtual machines between edge clouds is more complicated than in cloud computing. The author creates an innovative method for optimizing QoS and migration time for multiple simultaneous live migration operations.

In [112], the author analyzes the worst-case limits of IEEE 802.15.7's VLC-MAC layer. Using network calculus, the author examines GTS use by estimating network throughput and latency bounds. Additionally, the study introduces and analyzes a CAP reduction strategy to boost network scalability without increasing latency.

In life-critical scenarios such as real-time patient monitoring or vehicular networks, it is essential to distribute bandwidth resources efficiently and with the lowest latency. Based on modifying the conventional beacon or superframe structure, researchers have developed novel GTS allocation techniques for WBANs, Zigbee networks, WPANs, IEEE 802.15.7-based OWC networks, WSNs, sensor-based vehicle networks, and live virtual machines. However, the significant latency and lack of security during emergencies make this a pressing issue.

Furthermore, IEEE 802.15.4 and IEEE 802.15.7 have nearly identical beacon frame formats and superframe structures. The primary distinction between GTS allocation for both systems is the utilization of the beacon frame and superframe slots. For example, the inactive section of the superframe can be utilized to make the GTS allocation method adaptive [103]. In addition, the beacon frame can be modified to create a full-duplex communication link [105].

A. ASSUMPTIONS MADE BY THE RESEARCHERS

The following assumptions were made to develop the novel strategies to address this challenge. Incorrectly, the authors estimated the worst-case channel access time based on the idle channel situation. Unrealistically, the authors believe that all nodes can be precisely synchronized. Moreover, an immobile or mobility-restricted position cannot always be the norm.

B. STRATEGIES FOR THE OUTSTANDING ISSUES

We can see that future work can offer significantly more support to existing research. Encryption and authentication can be added to the procedures to improve the security of the system. In addition, a scenario with several access points may be an option for reducing latency and interference. Alternatively, we can concentrate on expanding the network to include more nodes. Last, we can also consider GTS allocation for low and medium preference data

VI. OWPAN CELL DESIGN AND MOBILITY

Mobility management is a challenge that affects all wireless mobile communication networks and is one of the most significant and critical issues to resolve. Mobility permits a serving-service provider network to determine the location of a mobile user to deliver data packets and maintain a mobile connection. [117], [118] investigate the concept of mobility in several wireless communication networks in greater depth.

Fig.8 depicts the mobility requirements for an indoor OWPAN scenario where the uplink is performed via infrared (IR) communication and the downlink via VLC. An LED bulb connects multiple users to a single VLC access point. Multiple interconnected devices require the development of protocols to handle medium access, device-to-access point association, and mobility [119], [120].

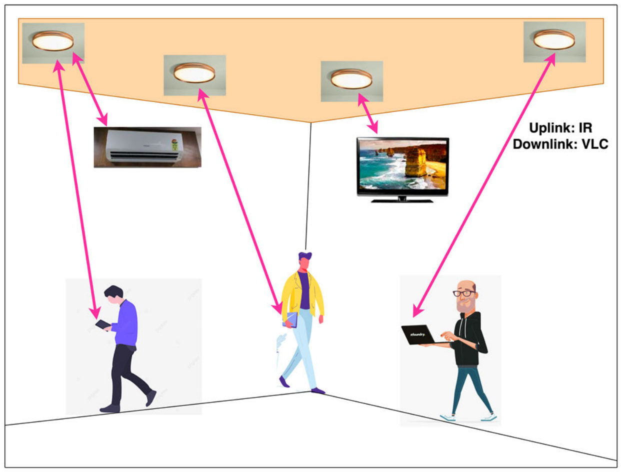


FIGURE 8. Mobility requirements in an indoor Li-Fi scenario.

LiFi is a wireless access network that maintains a connection even when users are in motion by using visible light. Optical sources and detectors are unidirectional; thus, a single LiFi access point (AP) covers a limited area. [121] demonstrates that an omnidirectional User equipment (UE) topology can minimize channel variance caused by user mobility, device rotation, and connection obstruction. The simulation results indicate that the proposed UE design has the potential to improve the quality of connections for mobile users and increase the throughput of the link.

Integrated LiFi and WiFi networks (HLWNets) can be used to increase the bandwidth capacity and overall performance of indoor communication systems. LiFi and WiFi coverage overlap, making load-balancing challenging [122]. It is difficult to decide whether to utilize a horizontal or vertical handover in a mobile environment with ultra-small cells since users move and objects can block the light. Most conventional systems address these issues separately, resulting in frequent handoffs and reduced performance.

In [123], the author presents a new fuzzy logic-based technique for simplifying the resolution of computational optimization issues. The proposed approach increases the system throughput by as much as sixty-eight percent while simultaneously reducing processing complexity.

A similar hybrid network is considered in [124], where the choice between LiFi and WiFi becomes a challenging task. The author proposes a unique handover strategy that adapts the choice between LiFi and WiFi using a flexible coefficient derived from machine learning. This coefficient is learned using an artificial neural network (ANN) for many situations, including user speed, LiFi Access point (AP) separation, LiFi AP height, and LiFi AP-to-WiFi AP ratio. The new technique balances channel performance, resources, and user mobility when considering handover choices. The suggested system can boost user throughput by two hundred sixty percent and fifty percent over RSS- and trajectory-based handovers.

The same HLWNets are presented again in [125] as a viable technique for OWPAN communications, where intermittent light-path obstructions complicate the handover problem. This paper proposes a joint optimization issue for load balancing (LB) and handover in HLWNets. In addition, depending on the receiver's angle of tipping and tilting, the receiver rotation substantially affects handover performance. Compared to the conventional LB approach, the results indicate that the suggested approach can boost network capacity by up to sixty percent.

By considering the impact of mobility and inversion on connected UEs, [126] presents a crucial method for switchover modeling. This study investigates the issue of downlink handovers in a network of indoor optical attocells. The likelihood of handover and handover rate are computed using the random waypoint (RWP) framework for the receiver's motion and a geometric design for its orientation. Significant observations were included in the handover efficiency of indoor optical attocells networks using Monte Carlo simulations. Furthermore, assuming that the user is moving at one m/s, tilting the UE to the right or left has a more significant impact on the handover rate than leaning toward or away from the user.

Parallel transmission (PT) is a unique technology studied in [127] that enables many Li-Fi APs to serve consumers simultaneously. Data transfer remains uninterrupted when a user loses connectivity to one or more APs. The author discusses resource allocation for the PT-LiFi network and a new load balancing strategy for allocating resources among APs. The results indicate that PT-LiFi can efficiently use densely dispersed LiFi APs and provide an adaptable load balancing method. PT-LiFi-based systems allow multiple APs to serve users, optimizing densely deployed LiFi APs simultaneously. Further, PT enhances network performance by permitting flexible load balancing and minimizing handover throughput loss. Compared to a standard LiFi system, the proposed technology can increase user throughput by up to 1.50 times and improve user fairness by up to fifteen percent.

Sojourn time (ST) is a crucial metric for mobile cellular networks. It indicates the length of time a mobile UE stays associated with a serving access point (AP) while progressing within a cell. The ST is influenced by device orientation, cell coverage, and user speed. Hence, ST estimation is crucial for mobility management. Reference [128] analyzed ST for indoor LiFi cellular networks using the RWP mobility model. Monte Carlo simulations evaluate the analytical derivations and provide insights into numerous orientations.

In contrast to RF channels, OWC channels are predictable, reducing feedback and increasing bidirectional user throughput [129]. Two techniques are provided to further reduce feedback in LiFi-based mobile networks. 1) Limited content feedback (LCF) and 2) limited frequency feedback (LFF) based on the interval between updates. LCF exhibits a downlink performance comparable to that of the full-feedback (FF) technique and even less overhead than the one-feedback mechanism. The LFF maximizes the uplink and downlink throughput, and the author also derives and analyzes the optimal notification duration for the RWP mobility pattern.

In a typical OWPAN scenario, a single AP serves many users, and light-route constraints restrict user mobility. This involves frequent handoffs that reduce the service quality. [130] supports the concept of multiple-tier LiFi systems for enhanced mobility management in the real world. The authors offer a supplementary cell coverage strategy based on the half-angle between the primary and secondary AP luminaires. Cross-tier changeover rate and sojourn time are represented as closed-form functions for TTT, AP intensities, and user speed. The effect of system characteristics, such as TTT and user speed, on mobility efficiency is explained, which can aid in planning LiFi networks. The findings can be applied to actual LiFi deployment and planning and optimizing multi-tier network changeover.

The random orientation of the UE is significant in OWC, encompassing millimeter-wave and terahertz systems. At such short wavelengths, the arbitrary direction of the UE influences the angle of arrival or the incidence angle, thereby modifying the channel strength and SNR. Frequent handoffs may negatively impact the user experience. [131] presents a framework that unifies traditional mobility and random orientation models, including UE's random orientation of the UE. The author presents an improved alignment RWP mobility model that considers UE direction during walking and pauses time. The model's metrics are derived from orientation measurements and are relevant to an indoor LiFi network

The author in [132] discusses hybrid LiFi-WiFi networks (HLWNets) for indoor wireless communications. This work aims to provide an optimization algorithm to choose access according to the channel state information (CSI). A collaborative optimization problem is developed to consider load balancing as well as handover in HLWNets at the same time. The simulation results demonstrate that the proposed strategy can boost system throughput by sixty percent when compared to the conventional techniques.

In [133], it is explored how radial user movement and random photodetector orientation can negatively impact the performance of VLC-based systems (3D mobility). The author provides an analytical equation for the bit error rate (BER) of a single LED indoor VLC system with radial user mobility, random receiver orientation, and inadequate channel status information (CSI). The author models receiver orientation via the Laplacian PDF, assuming no radial motion and divides 3D mobility into components representing radial and random orientation. Using the resulting pdf, an approximation of the

TABLE 4. Summary of comparison of available methodologies for OWPAN cell design and mobility.

Journal, Year of publication [reference]	Authors	Implementation (Simulation platform/ experimental set-up)	Research contribution	Performance metrics considered
IEEE International Conference and Communications Workshops, 2019, [121]	C Chen et al.	Computer-based simulations	Enhanced omnidirectional source configuration presented Randomly oriented light sources used for realistic implementation	Instantaneous SNR and link status Coverage probability
IEEE Transactions on Communications, 2020, [123]	X Wu et al.	Monte-Carlo simulations	A novel load balancing scheme is proposed for mobility as well as light path blockages Fuzzy logic application for reducing computational complexity	Throughput and fairness Effect of light path blockage
IEEE Globecom Workshops, 2020, [124]	X Wu et al.	Monte-Carlo simulations	A machine learning-based handover scheme proposed to balance user mobility, resource availability, and channel quality	Average achievable throughput Handover rates
IEEE Wireless - Communications and Networking Conference (WCNC), 2017, [126]	M D Soltani et al.	Monte-Carlo simulations	Models for receiver movement and orientation proposed for calculating handover rate and probability in indoor optical networks	Handover probability Coverage areas with different orientation angles Rate of handover
IEEE Transactions on Communications, 2020, [127]	X Wu et al.	Random wave point model (RWP) Model with Monte-Carlo simulations	Resource allocation for multiple access point-based LiFi networks is examined Comparison with conventional LiFi systems shows a 15 percent improvement in fairness	Effect of receiver orientation, light path blockage, no. of users on mobility Latency and packet loss ratio User fairness
30th IEEE Annual International Symposium on Personal, Indoor and Mobile Radio-Communications (PIMRC) Mobile & Wireless Networks, Track 3 2019, [128]	M D Soltani et al.	Monte-Carlo simulations	Sojourn time is analyzed and derived analytically LiFi based indoor cellular networks Monte-Carlo simulations performed to examine handovers and Random waypoint (RWP) mobility model	Sojourn time w.r.t receiver orientation and user velocity
IEEE Transactions on Communications, 2018, [129]	M D Soltani et al.	RWP Model with Monte-Carlo simulations	A revised CSMA/CA algorithm presented for upstream LiFi networks to optimize the maximum bidirectional throughput Proposed limited-content and limited-frequency feedback-based schemes	Uplink, downlink, and average overall throughput Transmitted overhead with different subcarriers
IEEE Global Communication Conference (GLOBECOM), 2021, [130]	A B Ozyurt et al.	Analytical modeling with computer-based simulations	Multi-tier LiFi network introduced for enhanced mobility management Closed-form analytical formulations provided for cross-tier switching frequency and sojourn time	primary to secondary (P2S) switching rate Average sojourn time within the secondary cell
IEEE International Conference on Communication Workshops (ICC Workshops), 2020, [131]	H Hass et al.	ORWP Mobility model with Monte-Carlo Simulations	An extended random direction-based random waypoint mobility concept is proposed Simulations offer a practical context for analyzing performance	Handover rate SNR with random orientation of user equipment
88th IEEE Vehicular Technology Conference (VTC-Fall), 2018, [132]	H Hass et al.	Monte-Carlo simulations	A joint optimization scheme proposed for dual LiFi-WiFi networking to consider handover as well as load balancing	System's throughput as a function of the number of users and their speed Light-path blockage rate
IEEE Communications Letters, 2021, [133]	K R Sekhar et al.	Computer simulations with analytical modeling	Laplacian pdf considered for radial mobility variations and haphazard receiver direction Results have been verified by channel impulse response (CIR) measurements too	bit error rate (BER) vs. Signal to noise ratio (SNR) Radial mobility of the user arbitrary receiver orientation imperfect Channel-state information (CSI)

BER for a VLC system with 3D user mobility and approximative CSI is generated.

Several functional studies on introducing mobility to wireless networks are described above in Table 4. We observed the need for handoffs and mobility in the LiFi, WiFi, hybrid LiFi WiFi, ad hoc, and VLC network configurations.

Mobility and seamless handover are crucial for delivering a future-based adaptable communication infrastructure, as is evident. To ensure consistent connectivity, the network must be able to provide seamless support handover whenever a user moves. However, the proposed mobility management protocols continue to be challenging to apply at multiple levels of design and decision making. Because optical sources and detectors in OWC-based networks are directional and access points have a restricted field of view, this task becomes more challenging. In heterogeneous networks, researchers focus on load balancing, modeling user behavior, and interference control, among other significant issues.

A. ASSUMPTIONS MADE BY THE RESEARCHERS

Nonetheless, researchers have made the following assumptions to provide solutions to these issues: For instance, it is assumed that there would be no abrupt direction changes and that users will maintain a constant speed, which is impractical. Moreover, several studies on VLC have claimed that user equipment would always be oriented vertically upward, that is, that the receiver plane would always be parallel to the transmission plane.

B. STRATEGIES FOR THE OUTSTANDING ISSUES

Given the above assumptions, it is reasonable to conclude that significant additional effort is required to fill the gaps in this research. Future mobility management in OWPANs can be planned in various ways. Researchers can attempt to conduct a performance investigation of the suggested strategy in a realistic setting with real-time user movement and path blockage. Second, the QoS requirements of indoor applications can be prioritized. Finally, researchers can strive to reduce the complexity of neural network models utilized in hybrid LiFi-WiFi network settings.

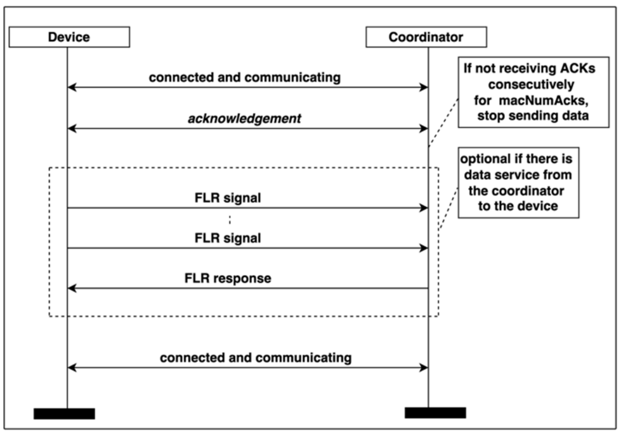


FIGURE 9. Message flow diagram for FLR initiated by device [113].

VII. FAST LINK RECOVERY

Visible LEDs are becoming increasingly efficient, trustworthy, and versatile. These sources are capable of rapid reconfiguration, enabling simultaneous data and lighting exchanges. Because visible light cannot penetrate through solid obstacles such as walls, a line of sight (LoS) is required for most VLC applications.

Temporal obstructions such as walking or inadequate VLC focusing may cause frame faults or link termination. Owing to the directional nature of the VLC, it is challenging to re-establish a connection if one of the devices moves or rotates. FLR is essential for P2P and point-to-multipoint (P2MP) connectivity in VLC systems [134]. Fig.9 and Fig.10 depict the FLR procedure as mentioned in the IEEE 802.15.7 standard.

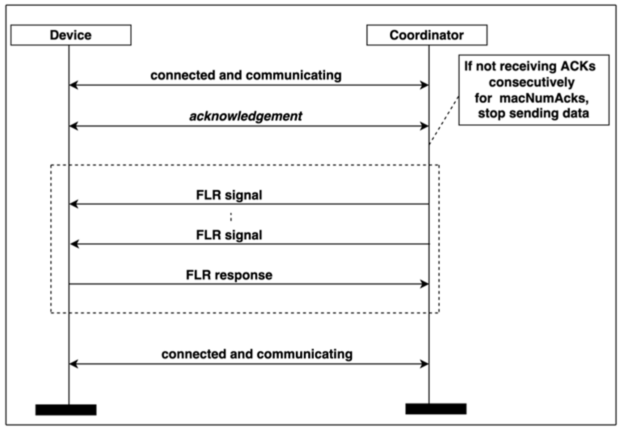


FIGURE 10. Message flow diagram for FLR initiated by coordinator [113].

VLC is gaining importance for offering low-power, Gbps-rate data connections owing to developments in LED technology and the power required to sample and process Gbps data in the baseband for RF systems [135]. The research presents energy-efficient connection recovery techniques for VLC LAN and P2P connections and enhanced communication directions and color bands. The proposed method recovers VLC links rapidly and effectively while preserving the battery life of communicating devices.

The LoS must be guaranteed between VLC transceivers, especially for indoor applications. The Reference [136] presents a new VLC link recovery strategy for IEEE 802.15.7, which uses cooperative communication. The technique aims to maintain the linkage for as long as necessary, thereby boosting overall system reliability. Before the connection is re-established after a connection failure, the sender or receiver must issue a link recovery request and wait for a response. All link recovery techniques swiftly send "link recovery request" and "link recovery reply" packets. Using cooperative communication, a cooperative node sends requests for link recovery to the participating node. This increases the likelihood of the request being granted and reduces the waiting time.

Traditional mobile ad-hoc networks (MANET) MAC and routing algorithms use a faulty link multiple times before reporting or repairing it locally. However, real-time applications require rapid recovery from frequent network disruptions between mobile nodes. In [137], the author offers a cross-layer inference-based speedy link error recovery (CIFLER) algorithm, enabling nodes to pick themselves using neighbor knowledge. CIFLER allows the MAC layer to swiftly detect and repair broken links, thereby stabilizing the path to higher layers. CIFLER is compatible with the source, link state, and RTS/CTS-based MAC protocols, and it can be used in conjunction with other recovery techniques if a route breaks catastrophically.

Massive multiple input multiple output (MIMO) networks are easily obstructed owing to the short wavelength of millimeter waves and directional beamforming. To restore communication, beam switching in the unblocked direction is feasible. Because uncrewed aerial vehicles (UAV) rush, it is difficult to determine which beam they should employ.

In [138], the author describes an FLR technique for the UAV in which spatial correlation, beam reliability, and signal quality are considered while selecting the appropriate beam. Simulations demonstrate that the proposed approach can quickly repair a broken link, and link failures are uncommon when the UAV travels rapidly. The recommended method explores and selects candidate beams using reinforcement learning. Simulation results indicate that the proposed approach can effectively recover the broken link for the high-speed mobile UAV scenario, reducing the probability of an outage to nearly zero. [139] replicates the VLC channel and examines the resource allocation issue in an indoor VLC system. The author examines a VLC system with location-based services and shows how scheduling can optimize resource allocation. The positions of transmitters and receivers must be considered in the solution. The work includes scheduling the possible scenarios, so they do not interfere with one another while ensuring throughput and equity.

A VLC proportional fair (VPF) is introduced to ensure that all users receive the same throughput and fairness. As a centralized system, the coordinator performs most of the work rather than the software or hardware of the receiver. The simulation results confirm that the proposed technique achieves maximum rate scheduling and round-robin regarding user performance and fairness.

Due to the straightness of the LED signal, the VLC system must offer LoS between the transceivers; hence, transient blockage or bad transmitter orientation commonly results in link failure and burst frame defects. In [140], the author studies ways to quickly notify a user of a failing link so that the issue can be resolved by reorienting the transmission signal towards the receiver. The proposed method increases the collision likelihood of the initial access but does not influence channel utilization or system efficiency.

Because of the broadcasting nature of wireless signals, other stations can hear a station's wireless communication. Recent cooperative communications research has focused on enhancing geographical diversity by forcing neighboring stations to resend to overheard information. The article [141] demonstrates how cooperation between WLAN stations can increase throughput and decrease interference. Based on the IEEE 802.11 DCF mode, this study proposes a MAC called CoopMAC, in which high-speed stations assist low-speed stations by forwarding traffic. Because the helper station relays the packet without examining the MSDU, encryption is possible. The new MAC does not affect access fairness because the relaying stations may join without transmission. A related message-flow diagram is shown in Fig.11.

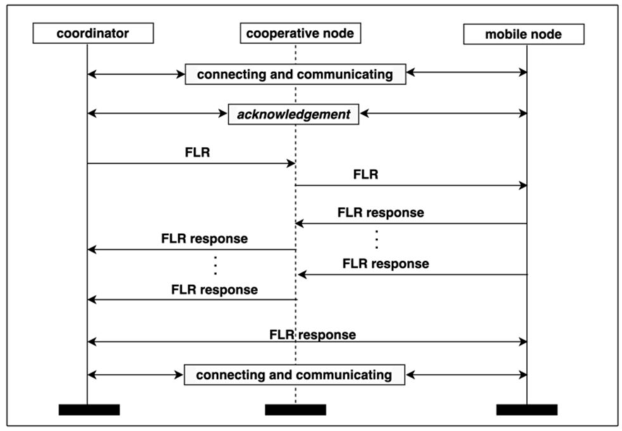


FIGURE 11. Message flow diagram using cooperative communication from the coordinator [136].

We surveyed the literature on fast link recovery in VLC-based WPANs, UAVs, mobile ad hoc networks, and WiFi-based WLANs (as summarized in Table 5). Researchers have proposed numerous techniques for integrating FLR into a network. In addition, the IEEE 802.15.7 standard provides two different FLR algorithms

A. ASSUMPTIONS MADE BY THE RESEARCHERS

While solving this challenge, the researchers have made several assumptions, like a direct line of sight, the absence of hidden nodes, and saturated traffic conditions, which are not always viable in practical situations.

B. STRATEGIES FOR THE OUTSTANDING ISSUES

Regarding unresolved issues, the proposed methodologies have many opportunities for improvement. First, Using color bands, for instance, researchers can coordinate multiple signals. Second, while the broken link is being repaired, one may focus on extending the battery life of the OWPAN devices. Third, researchers may also explore building a MIMO system to increase network throughput significantly. Finally, focusing on minimizing the interference from sunshine and other light sources can lead to exciting results.

VIII. NON-MAC CHALLENGES AND FUTURE PERSPECTIVES ON OWC

This section focuses on the lingering issues of OWC and its future projections. First, as OWC-based indoor links must contend with significantly fluctuating ambient noise, they require inexpensive, sensitive, and dynamic large-range receivers. Researchers must focus on low-cost hardware manufacturing and delicate engineering to achieve the same objective.

Second, because OWC channel modeling is fundamentally distinct from other wireless technologies in terms of

TABLE 5. Summary of comparison of available methodologies for fast link recovery.

Journal, Year of publication [reference]	Authors	Implementation (Simulation platform/ experimental set-up)	Research contribution	Performance metrics considered
7th IEEE Consumer Communications- Networking Conference, 2010, [138]	Y Li et al.	Proposed approach is discussed only	Fast and energy-efficient link recovery schemes proposed for VLAN, P2MP, and P2P communications	Battery consumption for the mobile node
The Journal of Korean Institute of Communications and Information Science, 2012, [139]	N-T Le et al.	Analytical analysis with computer-based simulations	Cooperative communication-based FLR scheme proposed focussing mainly on QoS	Throughput Recovery time requirement
In IEEE Wireless Communications Networking Conference, 2005, [140]	J Yackoski et al.	Qualnet	FLR for ad-hoc wireless systems with a cross-layer interference-based approach presented The technique avoids duplication of messages and incurs no hardware or bit overhead.	RTS success rate Route rediscovery Energy consumption Delay
IEEE/CIC International Conference on Communication in China (ICCC), 2020, [141]	J Wu et al.	Computer-based simulations	Presents link blockage analysis for mm-wave communications (MIMO systems) considering spatial correlation and signal quality	Transmitter beam group distribution Link outage probability
6th International Conference on Wireless-communications and Signal Processing (WCSP),2014, [142]	O Babatundi et al.	MATLAB (licensed software platform)	In VLC broadcast mode, a scheduling-based resource allocation is proposed to overcome FLR and interference difficulties.	Sum data rates with different scheduling algorithms Scheduling decisions Fairness comparison
IEEE Transactions on Consumer Electronics, 2010, [143]	W-C Kim et al.	Markov chain model with computer-based simulations	Three distinct approaches are presented in response to service requirements: VLC-LAN (VL), Broadcast information (BI), and Peripheral interface (PI)	Collision, packet drop, channel utilization, and transmission success rate with varying traffic intensities
IEEE Journal on selected areas in Communication, 2007, [144]	P Liu et al.	Customized C-language event-driven simulator and test-bed experimentation	CoopMAC, a novel protocol based on DCF, features novel data and control plane properties while maintaining backward compatibility with IEEE 802.11 MAC	Throughput performance Cumulative distribution for service delays Energy expense

application-specific constraints, the system designers must develop channel-specific modulation and encoding techniques. In addition, unlike RF-based access points, OWC requires a direct line of sight and a broad spectral spectrum. Therefore, researchers must improve the channel parameters of OWC-based systems operating indoors and outdoors.

Third, even though the IEEE 802.15.7 standard recommends IR for OWC-based uplink, node mobility and interference have a consequence on uplink performance. Researchers can alter the field of view of IR transmitters to prevent scattering and path loss, which can also impede the entire duplex operation.

Finally, while hybrid RF-OWC systems provide high data rates, excellent dependability, and secure communication, they suffer from a low SNR and a limited transmission range. Scholars can work on this integrated architecture and design new and rapid mechanisms to switch between these technologies.

IX. CONCLUSION

In this survey, we examined optical wireless communication technicalities, applications, and existing literature on medium-access layer research problems. We outlined variations in the fundamental principles, designs, and application possibilities of all OWC technologies, including VLC, IR, and UV. As the number of MAC layer protocols for the IEEE 802.15.7 OWC standard is continuously developing, a collection of protocols with the broadest feasible width is chosen for investigation. This study assists the research community in the application-specific MAC layer analysis and OWC system integration. This study is beneficial for protocol designers because it permits a comparison of communication protocols over a wide range of wireless communication networks. We anticipate that our comparative analysis will serve as a helpful resource to encourage the development of OWC systems as essential complements to RF-based solutions and forthcoming 5G and well-transcending heterogeneous wireless networks.

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