Hybrid LiFi and WiFi Networks: A Survey

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***Abstract*—In order to tackle the rapidly growing number of mobile devices and their expanding demands for Internet services, network convergence is envisaged to integrate different technology domains. For indoor wireless communications, one promising approach is to coordinate light fidelity (LiFi) and wireless fidelity (WiFi), namely hybrid LiFi and WiFi networks (HLWNets). This hybrid network combines the high-speed data transmission of LiFi and the ubiquitous coverage of WiFi. In this article, we present a survey-style introduction to HLWNets, starting with a framework of system design in the aspects of network architectures, cell deployments, multiple access and modulation schemes, illumination requirements and backhaul. Key performance metrics and recent achievements are then reviewed to demonstrate the superiority of HLWNets against stand-alone networks. Further, the unique challenges facing HLWNets are elaborated on key research topics including user behavior modeling, interference management, handover and load balancing. Moreover, the potential of HLWNets in the application areas is presented, exemplified by indoor positioning and physical layer security. Finally, the challenges and future research directions are discussed.**

***Index Terms*—Light fidelity (LiFi), wireless fidelity (WiFi), visible light communication (VLC), radio frequency (RF), optical wireless communication (OWC), hybrid network, heterogeneous network, network convergence, handover, load balancing.**

I. INTRODUCTION

THE RECENT visual networking index published by Cisco Systems predicts that by 2022, mobile data traffic will account for 71 percent of Internet protocol traffic, and more than 80% of mobile data traffic will occur indoors [1]. This drives short-range wireless communication technologies such as wireless fidelity (WiFi) to become a key component in the fifth generation (5G) and beyond era. Globally, there will be nearly 549 million public WiFi hotspots by 2022, up from 124 million hotspots in 2017 [1]. Due to the limited spectrum of radio frequency (RF), the dense deployment of WiFi hotspots will result in intense competitions for available channels. This challenges the RF system to meet the exponentially increasing demand for mobile data traffic, which will increase seven-fold between 2017 and 2022 and reach 77.5 exabytes per month by the end of 2022.

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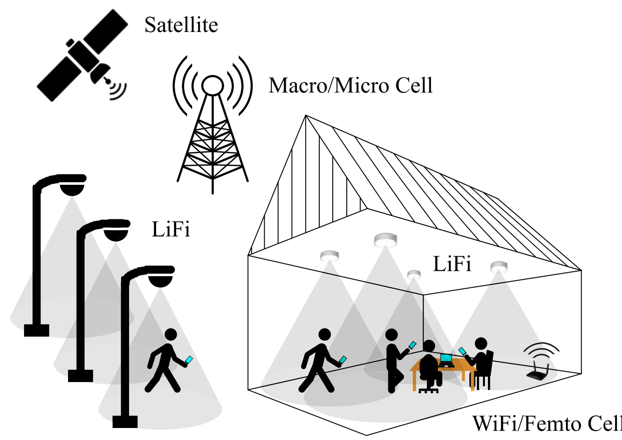


Fig. 1. Vision of network convergence in 5G and beyond.

In order to tackle the looming spectrum shortage in RF, wireless communication technologies employing extremely high frequencies have drawn significant attentions. Among these technologies is light fidelity (LiFi) [2]. Using light wave as signal bearers, this relatively new technology is able to exploit the vast optical spectrum, nearly 300 THz. LiFi access points (APs) can be integrated into the existing lighting infrastructure, realizing a dual purpose system which provides illumination and communication at the same time. Recent research demonstrates that with a single light-emitting diode (LED), LiFi is capable of achieving peak data rates above 10 Gbps [3]. LiFi offers many other advantages over its RF counterpart, including: i) a licence-free optical spectrum; ii) the ability to be used in RF-restricted areas such as hospitals and underwater; and iii) the capability of providing secure wireless communications, as light does not penetrate opaque objects. LiFi also has some limitations as it: i) covers a relatively short range, usually a few meters with a single AP; and ii) is susceptible to connectivity loss due to obstructions.

Combining the high-speed data transmission of LiFi and the ubiquitous coverage of WiFi, the concept of hybrid LiFi and WiFi network (HLWNet) was first mentioned by Rahaim *et al.* in 2011 [15]. Soon later, Stefan and Haas [16] extended the research to the integration of LiFi and femtocells. These hybrid networks are proven to achieve a better network performance than a stand-alone LiFi or RF system [17]. Fig. 1 presents

TABLE I
A COMPREHENSIVE LIST OF THE EXISTING SURVEY PAPERS ON THE TOPIC OF OPTICAL WIRELESS NETWORKS. NOTATIONS: ●: SCATTERED DISCUSSION (I.E., THE CORRESPONDING CONTENT IS MENTIONED BUT NOT IN A DEDICATED SUBSECTION). √: PARTIAL DISCUSSION (I.E., THERE IS AT LEAST ONE DEDICATED SUBSECTION BUT LACKS AN IN-DEPTH REVIEW). √√: DETAILED DISCUSSION

Ref.	Year	System design						Performance metrics	User behavior modeling	Interference management	Handover	Loading balancing	Applications	
		Network architectures	Cell deployments	Multiple access	Modulation	Illumination requirements	Backhaul						IPS	PLS
[4]	2013				√	√		√		●			●	
[5]	2014				√√		●	●		●				●
[6]	2014	√		√	●		√√	●						
[7]	2015			√	√	●		●		√	●			
[8]	2016		●	√	●	●		●		●	√		●	●
[9]	2017	√√			●							●		
[10]	2017				●			●					√	
[11]	2018		√	√	√√	√	●	●		●	√	√	√	
[12]	2018	●			●	●	●	●		●			●	
[13]	2019		●	√	√	√		√√	●	√	●	√		√
[14]	2020	√		●	●	●	√	√√		●	√	√	√	●
This paper		√√	√√	√√	√√	√√	√√	√√	√√	√√	√√	√√	√√	√√

TABLE II
A CLOSE LOOK INTO THE SURVEY PAPERS ON THE TOPIC OF OPTICAL WIRELESS HYBRID NETWORKS

Ref.	Year	Remark
[5]	2014	Briefly discussing the optimal signaling and routing in hybrid RF/FSO systems
[8]	2016	Summarizing medium access and modulation schemes for the coexistence of LiFi and WiFi
[9]	2017	Overview of the networking technologies supporting hybrid optical wireless networks
[11]	2018	Briefly discussing load balancing and handover in VLC-aided hybrid networks
[13]	2019	Studying the optimization of hybrid VLC/RF networks
[14]	2020	Discussing vertical handover and load balancing in hybrid RF/OWC systems
This paper		Being the first comprehensive overview of hybrid LiFi/WiFi networks, with detailed literature reviews and discussions on system design, performance metrics, user behavior modeling, interference management, handover, load balancing and application services

a vision of integrating the mainstream wireless networks and LiFi in 5G and beyond environments. In outdoor scenarios, mobile users can be served by satellites, macro/micro cells or LiFi-enabled street lamps. When moving indoor, they are shifted to a HLWNet for higher quality of service.

So far a number of survey papers have been reported on the topic of optical wireless communications (OWC) and the relevant networks. A comprehensive list of these papers is presented in Table I, in a comparison with our paper. Among these papers, only a few are related to optical wireless hybrid networks. In [5], RF/FSO (free-space optical communication) hybrid systems were briefly discussed, focusing on optimal signaling and routing. The authors in [8] summarized the opportunities and challenges with respect to the coexistence of LiFi and WiFi, particularly in terms of medium access and modulation schemes. Sarigiannidis *et al.* [9] focused on the network level of hybrid networks and gave an overview of the enabling technologies including network function virtualization (NFV), software-defined ratio (SDR) and software-defined networking (SDN). The authors in [11] discussed load balancing and handover in visible light communication (VLC)-aided hybrid networks. Obeed *et al.* [13] elaborated the topic of optimizing hybrid VLC/RF networks, with the impact of field of view emphasized. In [14], an overview of hybrid RF/OWC systems was provided, addressing the issues of vertical handover and load balancing. The noted surveys are summarized in Table II. However, these surveys lack a comprehensive overview of optical wireless hybrid networks and do not provide in-depth classifications of research work on the significant topics such as interference management, handover and load balancing.

This article is focused on reviewing the state-of-the-art research in the field of HLWNets, addressing the unique challenges and discussing the key research directions. The main contributions are:

- providing a framework of system design, which covers network architectures, cell deployments, multiple access and modulation schemes, illumination requirements and backhaul.
- summarizing key performance metrics and reviewing the reported performance of HLWNets to highlight their advantages.
- introducing the user behavior modeling and its impact on the performance of HLWNets, which is underexplored in the existing literature.
- reviewing and classifying the existing studies on three key research topics in HLWNets: interference management, handover and load balancing.
- studying the benefit of HLWNets to application services including the Internet of Things (IoT), indoor positioning and physical layer security.
- discussing the trends, challenges and research directions towards practical implementation and future prosperity of HLWNets.

The remainder of this article is organized as follows. The framework of system design for HLWNets is introduced in Section II, and key performance metrics are summarized in Section III. User behavior modeling is studied in Section IV.

TABLE III
LIST OF ACRONYMS

Acronym	Description
ACO-OFDM	Asymmetrically Clipped Optical OFDM
ADR	Angle Diversity Receiver
AP	Access Point
ASE	Area Spectral Efficiency
CDT	Cell Dwell Time
CSI	Channel State Information
CSMA/CA	Carrier Sense Multiple Access/Collision Avoidance
DCO-OFDM	Direct Current-Biased Optical OFDM
FFR	Fractional Frequency Reuse
FoV	Field of View
HHO	Horizontal Handover
HLWNet	Hybrid LiFi and WiFi Network
ICI	Inter-Cell Interference
IPS	Indoor Positioning System
LB	Load Balancing
LED	Light-Emitting Diode
LoS	Line of Sight
MPTCP	Multipath Transmission Control Protocol
NOMA	Non-Orthogonal Multiple Access
OFDM	Orthogonal Frequency-Division Multiplexing
OFDMA	Orthogonal Frequency-Division Multiple Access
OWC	Optical Wireless Communication
PD	Photodiode
PLS	Physical Layer Security
QKD	Quantum Key Distribution
QoS	Quality of Service
RF	Radio Frequency
RSS	Received Signal Strength
RWP	Random Waypoint
SDMA	Space-Division Multiple Access
SDN	Software-Defined Networking
SFR	Soft Frequency Reuse
SINR	Signal-to-Interference-plus-Noise Ratio
TDMA	Time-Division Multiple Access
VHO	Vertical Handover
VLC	Visible Light Communication

The present research related to interference management for LiFi is reviewed in Section V. Handover and load balancing in HLWNets are elaborately discussed in Sections VI and VII, respectively. The advancements of HLWNets in application services are investigated in Section VIII. The challenges and future research directions are addressed in Section IX. Finally, conclusions are drawn in Section X. The acronyms used in the paper are listed in Table III.

II. Framework of System Design

In this section, a framework of HLWNets is introduced in five aspects: network architectures, cell deployments, multiple access and modulation schemes, illumination requirements and backhaul. The aim of this section is to provide guidelines for designing HLWNet systems.

A. Network Architectures

In general, LiFi can be incorporated into the existing WiFi system in two basic ways: autonomous and centralized. The first approach is to extend the current autonomous network structure of WiFi to LiFi. The user can freely choose an AP from either network domain, and the AP can employ any unoccupied channel. While this approach offers low complexity of network management, the network performance is compromised. Alternatively, it is feasible to manage the LiFi and WiFi APs that belong to the same owner via a central control unit. Optimal routing and resource allocation can be achieved in the network level. This architecture is based on SDN, which decouples the control plane from the data plane of forwarding devices. The schematic diagram of implementing HLWNets on an SDN platform is demonstrated in Fig. 2. An SDN-enabled switch connects LiFi and WiFi APs and extracts key performance indicator information from these APs through SDN agents. This information is then sent to an SDN controller, which makes decisions on the routing of each incoming data packet. Currently, the experimental development of HLWNets is still in its infancy. Relevant research projects and their status on the implementation of HLWNets are summarized in Table IV.

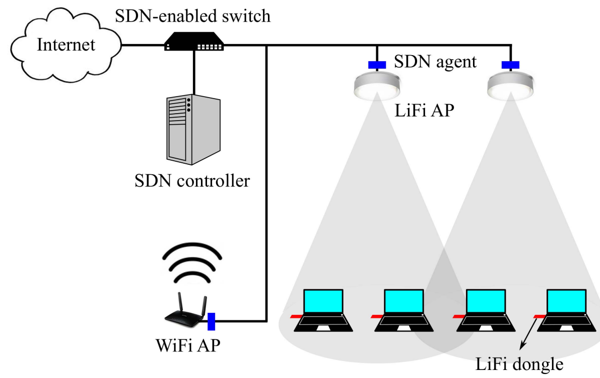


Fig. 2. Schematic diagram of an SDN-enabled HLWNet.

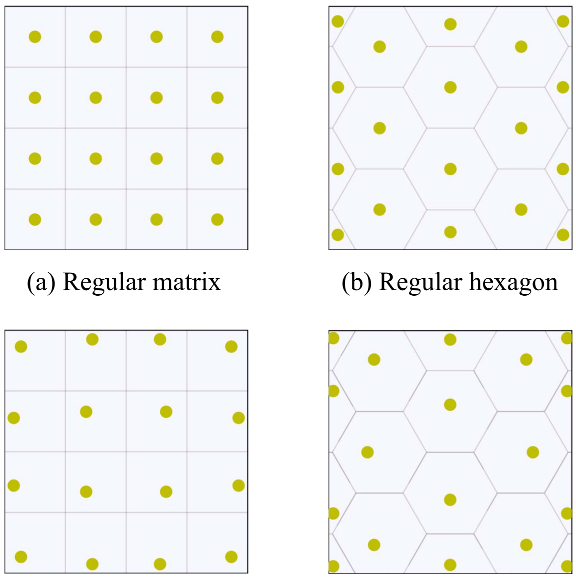
B. Cell Deployments

While WiFi APs can reach up to 50 m indoors, LiFi APs usually cover a relatively small area, only a few meters in diameter. A proper placement of the LiFi APs, which are normally integrated into the ceiling lamps, is important for achieving high-quality network performance. In practice, the cell deployment is subject to environmental constraints, e.g., room shapes. In the current literature, three cell deployment models are usually considered: hexagon, matrix and Poisson point process (PPP).

- The hexagon deployment is an ideal structure of cellular networks. It is proven to provide the highest signal-to-interference-plus-noise ratio (SINR) coverage probability in LiFi [18]. Although it is not common to find such a structure of lamps in daily life, the hexagon deployment offers an upper bound analysis of performance.
- The matrix deployment of lamps is widely used due to the simplicity of installation. This deployment is considered in most studies related to VLC and HLWNets. It is able to obtain an SINR coverage probability very close to the hexagon deployment [18].

TABLE IV
HLWNET-RELATED RESEARCH PROJECTS

Year of start	Project title	Funder	Status of HLWNet implementation
2014	TOUCAN	EPSRC	Demonstrated an SDN-enabled multi-technology experimental platform
2017	INITIATE	EPSRC	Plan to create a distributed test-bed and integrate end-users as part of the experimental process
2019	5G-CLARITY	Horizon 2020	Plan to demonstrate an AGV positioning application in a factory near Barcelona



(a) Regular matrix (b) Regular hexagon

(c) Optimized matrix (d) Optimized hexagon

Fig. 3. Optimized placements of LiFi APs.

- The PPP deployment is employed to simulate randomly located APs. It is however difficult to achieve uniform illumination with this deployment. Apart from that, the PPP offers the worst SINR coverage probability among the three deployments [18].

Given a deployment topology, the distance between APs renders a trade-off between the handover rate and coverage probability. The impact of AP separation was studied for the matrix deployment in [19], showing the optimal separation as a function of the handover overhead and the average speed of users. It is concluded that a 3 meter separation is optimal in most scenarios. In [20], the gradient projection method is used to find the optimal placement of APs. The regular and optimal placements for the matrix and hexagon deployments are presented in Fig. 3. For both deployments, the optimal placement shifts the APs outwards modestly in comparison to the regular placement. This optimal placement can improve the system throughput by up to 70% [20]. In addition, the locations of WiFi APs affect the distribution of LiFi users and thus influence the network performance of HLWNets. Recent research shows that compared with a random deployment, a regular matrix deployment of WiFi APs can increase the system throughput by up to 20% [21].

C. Multiple Access and Modulation Schemes

The multiple access and modulation schemes related to LiFi and WiFi have been broadly discussed in [8]. Here these schemes are summarized from the perspective of standardization in Table V. With respect to multiple access, carrier sense multiple access/collision avoidance (CSMA/CA) and time-division multiple access (TDMA) are considered for the current LiFi standards. Allowing only one link to be active at a time, CSMA/CA can reduce inter-cell interference (ICI) to a negligible level. However, the access process for users is random and not always fair, especially in dense deployments. Also, unlike WiFi using time division duplex, LiFi usually adopts visible light for downlink and infrared for uplink. This might cause overwhelming collisions when the existing CSMA/CA is used for LiFi. Broadcasting a channel busy tone was suggested in [22], which can largely reduce the collision probability. Compared with CSMA/CA, TDMA is superior in terms of power consumption and bandwidth utilization but relies on synchronization and interference management. Orthogonal frequency-division multiple access (OFDMA) and non-orthogonal multiple access (NOMA) have also been extensively studied for LiFi. These schemes carry out a tight coordination of resource assignment in the entire network and thus require relatively high system complexity. In OFDMA, time-frequency resource blocks are allocated among users to enable concurrent transmissions. In NOMA, grouped users are served at the same time and frequency but at different power levels depending upon the channel condition. The performance gain of NOMA over OFDMA increases when the difference in channel conditions is large. Yin *et al.* [23] found that the LED semi-angle also has a significant impact on the performance of NOMA in LiFi. It is proven that the performance gain of NOMA over orthogonal multiple access can be further increased by pairing users with distinctive channel conditions.

TABLE V
STANDARDS FOR WIFI AND LIFI

Technology	Standard	Multiple access	Modulation
WiFi	IEEE 802.11 series	CSMA/CA	OFDM [1]
LiFi	IEEE 802.15.7	CSMA/CA	VPPM/OOK/CSK
	ITU-T G.vlc	TDMA	DCO-OFDM [2]
	IEEE 802.11bb	CSMA/CA	OFDM-based

In regard to modulation, IEEE 802.15.7 adopts variable pulse-position modulation (VPMM) and on-off keying (OOK) in physical (PHY) I and II, and color shift keying (CSK) in PHY III. As single-carrier modulation schemes, OOK and VPMM have relatively low complexity and can support low/medium data rates, from ∼10 kbps to ∼100 Mbps. CSK is similar to frequency shift keying but uses multiple optical

[1]The 802.11 standards prior to 1999 adopt direct sequence spread spectrum (DSSS), and those after 2009 employ MIMO-OFDM.

[2]The PHY layer of G.vlc is still under discussion.

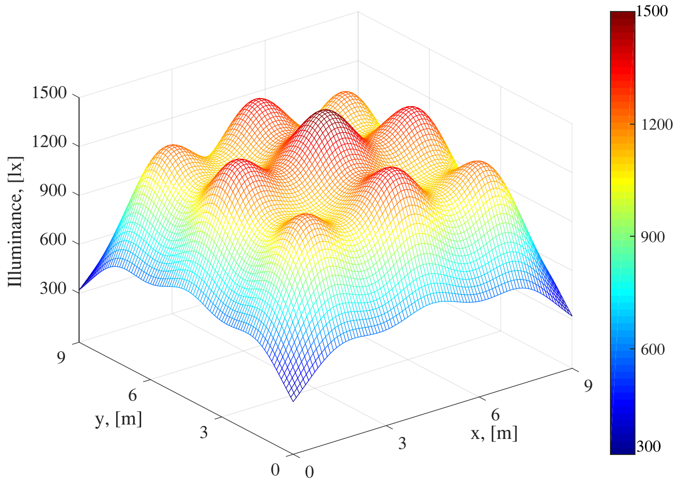


Fig. 4. Example of illuminance distribution in a room.

sources with different wavelengths. This modulation method is specially tailored for LiFi, allowing PHY III to operate between 12 and 96 Mbps. The three above modulation techniques can be directly used for LiFi, as they fit the real and non-negative optical signals. On the contrary, orthogonal frequency-division multiplexing (OFDM) yields complex and bipolar signals. Real OFDM signals can be built by constraining the input vector of the inverse fast Fourier transform to have Hermitian symmetry. This process is termed optical OFDM (O-OFDM). ITU-T G.vlc (i.e., G.9991) is now considering two forms of O-OFDM: direct current (DC)-biased optical OFDM (DCO-OFDM) and asymmetrically clipped optical OFDM (ACO-OFDM). In DCO-OFDM, signals are made positive by adding a DC bias. In ACO-OFDM, signals are clipped at zero and only the positive parts are transmitted. ACO-OFDM is more power efficient than DCO-OFDM, except for large constellations such as 1024 quadrature amplitude modulation (QAM) [24]. With respect to IEEE 802.11bb, there are two main proposals for PHY: i) to shift the central frequency of the output signals of existing IEEE 802.11 chipsets, or ii) to use the PHY layer from G.vlc. The key advantage of using the existing PHY is that it requires the least amount of change to the existing WiFi silicon. The hope is that this will greatly reduce any barriers to entry.

D. Illumination Requirements

The system design of LiFi must comply with illumination requirements. International organization for standardization (ISO) on light and lighting specifies illuminance of 300 to 1500 lx for office work. Komine and Nakagawa [25] mathematically derived the illuminance distribution in a room. An example is demonstrated in Fig. 4, where the locations and output power of LiFi APs are designed in a way so that the minimum requirement of 300 lx is satisfied at the corners, while the peak illuminance does not exceed 1500 lx. As shown, the illuminance peaks in the center of the room but is significantly low at the corners.

Optimizing LEDs for better network performance under illumination requirements is tricky. This process involves a number of factors related to LEDs, including their locations, orientations, field of view, emission pattern, output power, bandwidth, color temperature, etc. In [26], a power allocation scheme was proposed to maximize the multi-user sum rate under lighting constraints. It is found that higher data rates can be achieved with higher color temperatures. Alternatively, the process can be formulated as a multi-objective optimization problem, which obtains the Pareto front of the spectral efficiency-illumination region. The authors in [27] discovered that giving a large weight to the spectral efficiency maximization causes the photometric flickering to increase. This signifies that it might be necessary to consider a control mechanism in the system design, to keep flickering within a permissible level for eye-safety and productivity.

TABLE VI
SUMMARY OF BACKHAULING TECHNOLOGIES

Technology		Capacity	Cost	Flexibility	Ref.
Wired	PLC	1 Gbps	Low	Low	[28], [29]
	POE	1 Gbps	Low		[30]
	POF	3 Gbps	Medium		[31]
Wireless	mmWave	Multi-Gbps	Medium	High	[32]
	VLC				[33], [34]
	IR				[34]

E. Backhaul

Backhaul is necessary for connecting APs to the core network. The backhaul for HLWNets is challenging due to three main factors: i) there are a relatively large number of APs; ii) the heterogeneous structure of the network; and iii) considerable network capacity, where a single AP is capable of providing link data rates in the range of Gbps. A number of technologies have been proposed as a backhaul solution for indoor wireless networks, including power-line communications (PLC), power over Ethernet (PoE), plastic optical fiber (POF), millimeter wave (mmWave), infrared (IR) and VLC. These technologies, which are summarized in Table VI, can be classified into two categories: wired and wireless backhaul.

The concept of using the existing electrical wires within buildings as backhaul for VLC was initially proposed by Komine and Nakagawa in 2003 [28]. A recent work in [29] introduced a hybrid PLC-VLC architecture to support multi-user downlink communications, with the backbone capable of handling data rates up to 1 Gbps. PoE is another approach to provide data transmission and power supply at the same time. Using a cascaded system of PoE and VLC, a dual-hop relaying transmission was proposed in [30], also with a 1 Gbps backbaul. The third option of wired backhaul is POF, offering a data rate of several Gbps. In [31], a wide-band signals distribution network was reported by combining POF and LED-based VLC, where frequency division multiplexing is used on a 50 m POF to transmit signals to different APs.

Compared with wired backhaul techniques, wireless solutions provide a more flexible installation at a higher cost of hardware. The authors in [32] demonstrated a multi-Gbps point-to-point backhaul connectivity on the basis of millimeter wave (mmWave). In [33], a VLC-based backhaul solution was proposed for LiFi, using the in-band full-duplex technique for the access and backhaul links. In this work, relaying protocols such as amplify-and-forward and decode-and-forward are used to realize dual-hop transmission. In [34], both visible light and infrared bands are employed to compose the backhaul solution, with the interference between inter-backhaul and backhaul-to-access network characterized. With respect to HLWNets, resource allocation and network optimization across LiFi and WiFi is feasible when they share the same backhaul. For instance, given a power budget, the power allocation can be optimized between LiFi and WiFi to enhance the network performance [35].

III. Performance Metrics

A number of metrics are used to evaluate the performance of wireless networks, including SINR coverage probability, spectral efficiency, area spectral efficiency, energy efficiency, network capacity, quality of service, and user fairness. These metrics and relevant studies with respect to HLWNets are reviewed in this section.

A. SINR Coverage Probability

The SINR coverage probability, i.e., the probability that the user's SINR is above a certain threshold, is crucial for providing stable connectivity. In regard to the RF system using omnidirectional antennas, the received signal power is dependent on the link distance and shadowing. As for LiFi, the user's orientation also plays a decisive role. Specifically, normal incidence gives a peak received signal power, while no signal will be received for incident directions beyond the field of view (FoV) of photodiodes (PDs). For this reason, changes in the user's orientation can significantly reshape the coverage areas of LiFi APs [36]. While the PD with a large FoV widens the range of receiving orientations, it results in receiving more interference. Alternative to using a single PD, the angle diversity receiver (ADR) comprised of multiple narrow-FoV PDs is able to greatly improve the user's SINR, by 20 dB $\sim$ 50 dB depending on the combination scheme chosen [37]. Research has been also conducted to analyze the SINR coverage probability of HLWNets. In [38], it shows that HLWNets can effectively improve the SINR coverage probability over stand-alone LiFi or WiFi networks, especially for single-PD receivers with a half angle of view below 45°.

B. Spectral Efficiency

Spectral efficiency measures how efficiently a certain amount of frequency spectrum is used. An experimental VLC system was reported in [39], achieving a spectral efficiency of 4.85 bit/s/Hz. This system is based on carrierless amplitude and phase modulation (CAP), a variant of QAM. In [40], generalized spatial modulation with dimming control is used for VLC to obtain a spectral efficiency above 10 bit/s/Hz. To further enhance the spectral efficiency, the authors in [41] combined DCO-OFDM with adaptive bit loading and experimentally demonstrated a link data rate of 15.73 Gbps. As for HLWNets, it is feasible to transfer the users from one network to another for a higher value of SINR, and consequently a higher spectral efficiency. With this approach, HLWNets can effectively improve the spectral efficiency than operating the two networks in a stand-alone fashion, with an increase between 10% and 30% [17].

C. Area Spectral Efficiency

In contrast to WiFi, LiFi can highly reuse the spectral resource in space, since a single LiFi AP only covers a confined area with a 2-3 meters diameter. To fairly compare the spectral efficiency of LiFi and its RF counterparts, area spectral efficiency (ASE) is defined, which measures the sum of the maximum average data rates per unit bandwidth per unit area. Stefan *et al.* [42] showed that LiFi is able to provide an ASE at least 10 times higher than the RF femtocell system. As for the hybrid LiFi and RF femtocell system reported in [16], it can increase the ASE by at least two orders of magnitude over the stand-alone RF network. Considering the impact of light-path blockages, Wang *et al.* [43] analyzed the ASE of HLWNets. It is surprisingly found that modest blockages may have a beneficial effect on the ASE, because the obstacles can block more interference than the desired optical signals.

D. Energy Efficiency

While increasing the deployment density of APs could improve the ASE, the cost of energy consumption also rises rapidly. Energy efficiency has thus become a focal point in ultra-dense networks. There exists a trade-off exists between energy efficiency and spectral efficiency, as a higher spectral efficiency requires more energy per bit. The authors in [44] analyzed the energy efficiency of OFDM-based VLC systems. It is showed that ACO-OFDM is more energy efficient than DCO-OFDM, when the spectral efficiency is low, e.g., below 2 bit/s/Hz. Due to the feasibility of switching users between different networks, HLWNets have the potential to improve energy efficiency. This can be formulated as an optimization problem of bandwidth and power allocation to maximize the energy efficiency of HLWNets. Using this approach, the authors in [45] demonstrated the superior performance of a hybrid RF/VLC network in comparison to an RF-only system, with an improvement up to 75%. In [46], end-to-end energy efficiency for a heterogeneous LiFi and RF network was analysed. This work shows that deploying LiFi attocell APs can reduce the overall power consumption by almost 10% compared to the mmWave indoor wireless technology.

E. Network Capacity

Regarding wireless networks, network capacity measures the maximum achievable sum data rate that a network can handle under certain constraints, usually a requirement on bit error ratio. This metric is paramount for guaranteeing decent network performance. Thanks to the integration of wireless technologies of different spectra, HLWNets are capable of boosting the network capacity, especially in a scenario where WiFi APs are densely deployed. In addition, the existence of WiFi can relieve the capacity degradation of LiFi caused by light-path blockages, as demonstrated in [43]. Maximizing the network capacity of HLWNets has attracted a massive amount

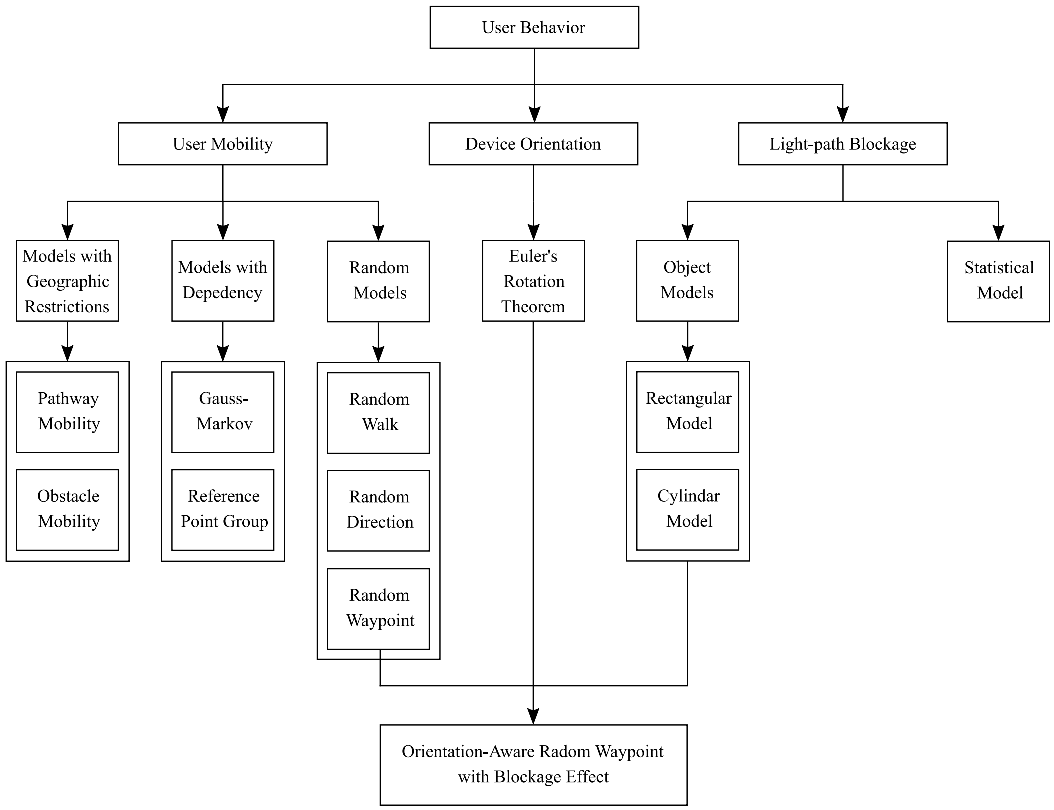


Fig. 5. Taxonomy of user behavior modeling in LiFi-related networks.

of research attention in recent years. Due to the coverage overlap between LiFi and WiFi, This optimization process essentially involves load balancing, which is elaborated in Section VII.

F. Quality of Service

While the metrics in the PHY layer are focused on bits, in the network layer packets are the unit of data. Several aspects of packets, including throughput, packet loss ratio, latency and jitter, are usually considered for measuring the quality of service (QoS). Future indoor wireless network is expected to support applications with diverse QoS requirements. For instance, holographic 3D display requires very high data rates above 10 Gbps [47], whereas automated guided vehicle (AGV) positioning needs ultra low latency below 1 ms [48]. In the meantime, the prevalence of IoT is significantly increasing the number of devices. The more dense the population of devices, the higher the average latency and jitter, limiting the types of applications that can be supported by high-density WiFi.[1] The research work in [49] shows that with the participation of LiFi, HLWNets can greatly improve the maximum packet arrival rate as well as decreasing the latency.

G. User Fairness

The above metrics are all concentrated on the overall network performance. In practice, users may have different requirements on throughput, latency, user experience, etc. Hence, it is necessary to ensure that each user receives a fair share of system resources. Typical measures include Jain's fairness index, max-min fairness and quality of experience (QoE) fairness. Among them Jain's fairness index, which assesses the throughput fairness among users, is widely used in the current literature. Maximizing network capacity only will result in a resource allocation preference for users with sound channel quality. This unfairness becomes particularly pronounced in HLWNets when a large number of users are competing for limited WiFi resources. In order to enhance the user fairness, proportional-fairness schemes are usually considered for allocating the resources in HLWNets. Detailed discussions are given in Section VII.

[1]A location can be classified as high density if more than 30 users are connecting to an AP.

IV. User Behavior Modeling

As mentioned earlier, the system performance of LiFi and LiFi-involved hybrid networks is substantially affected by user-related factors including user mobility, device orientation and light-path blockage. These factors are collectively referred to as user behavior. A taxonomy of these factors and their modelling methods is presented in Fig. 5. In this section, the models used for characterizing user behavior in LiFi-related networks are summarized.

A. User Mobility

Mobility models have been well studied for examining the features of wireless ad hoc networks. Depending on whether the movement has a memory and/or restriction, these models can classified into three categories: random models, models with dependency, and models with geographic restrictions. Compared to outdoor, indoor mobility is more arbitrary and variable. In [50], advanced mobility models were proposed for indoor scenarios, e.g., a rule-based model which mimics realistic indoor maneuvers inside a building with several rooms, where users move along specific paths from one room to another. However, these models consider specific environments, making it difficult to evaluate the general performance of a wireless network. Alternatively, random models have been widely used in the current literature to measure the network performance of HLWNets. The random waypoint (RWP) model was initially introduced in [51] to model human movements in a random manner. The user moves along a zigzag line from one waypoint to another one, with the waypoints randomly distributed. Between two consecutive waypoints, the user move forward in straight line with a constant speed. With the original RWP model, the user wanders within a large outdoor area and changes its speed when arriving at each waypoint. The distance between two waypoints in an indoor scenario is however relatively short. A modified RWP model is feasible through keeping the speed constant for a short period of time [52]. Research results demonstrate that the user's speed has a great impact on access point selection in HLWNets [53]. In general, fast-moving users prefer WiFi, whereas slow-moving users can be served by LiFi. The movement path also plays a vital role in the handover process [54]. Details are discussed in Section VI.

B. Device Orientation

Photodiodes have a limited FoV, restricting the angles at which the device can receive optical signals. Within the range of reception angles, the received optical intensity depends on the direction of incident light. This makes the device orientation an important factor that can significantly affect the link performance of LiFi. This issue however was not well addressed in the early research on LiFi and HLWNet. In the existing literature, a fixed device orientation was mostly assumed due to the lack of a valid model. A few studies have been carried out to evaluate the performance of HLWNets with randomly oriented devices, e.g., [55], based on the Euler's rotation theorem. Specifically, any form of rotation in the $\mathbb{R}^3$ space can be uniquely interpreted by composing three axial rotations in a three-dimensional Cartesian coordinate system, as illustrated in Fig. 6.

The first empirical model of the device orientation was reported in [56]. The authors managed to acquire real-time values of axial rotations from smartphones, attributed to the embedded gyroscope. The polar angle (i.e., the angle between the Z-axis and the normal vector of the device) exhibits a Laplace distribution for sitting and a Gaussian distribution for walking. Experimental measurements of the device orientation for uncontrolled activities were presented in [57]. It is found that in this case, the polar angle of mobile devices better fits a Laplace distribution than a Gaussian distribution. In [58], the changes in the device orientation were studied based on the data measurements. It is discovered that the coherence time of the random orientation is in the order of hundreds of milliseconds. Indoor optical wireless channels, of which the typical delay spread is in the order of nanoseconds, can thus be treated as slowly-varying channels. Combining the device orientation model with the RWP mobility model, an orientation-aware RWP model was first introduced in [56] to provide a realistic and accurate framework for analyzing the performance of LiFi. It is demonstrated that this model pronounces the issue of frequent handovers in HLWNets, in comparison to the conventional RWP model [59]. The orientation-aware RWP model was later applied for HLWNets in [60] to support dynamic load balancing and real-time resource allocation for mobile users.

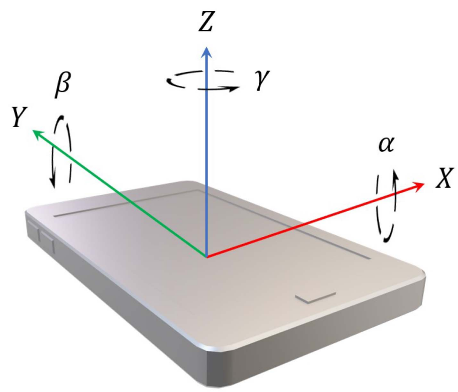


Fig. 6. Axial rotations of a mobile device.

C. Light-Path Blockage

Like millimeter-wave and Terahertz communications, LiFi is susceptible to channel blockages, which are caused by opaque obstacles such as walls, furniture, human bodies, etc. Researchers are particularly interested in the factor of human bodies, since this is closely related to the use of mobile devices. In this case, the light path of a device can be blocked by the person using the device and other persons around it. The human body is usually modeled as a cylinder object or a rectangular one [61]. This blockage model can be combined with the orientation-aware RWP model, establishing a joint model to comprehensively analyze the impact of user behavior. A statistical model of blockage is also available [62]. This model characterizes blockage with occurrence rate and occupation rate, which measure how often the blockage occurs and how long the blockage lasts, respectively. Several methods are feasible to alleviate the performance degradation due to blockage. In [63], the LED with a wider half-intensity angle is used to enlarge the coverage area. However, this method introduces more interference. Alternatively, an omni-directional receiver that employs PDs on each side of the handset can make it robust against blockage [64]. As for HLWNets, the user can be transferred to the WiFi system when experiencing a severe light-path blockage and shifted back once the LiFi connectivity is restored. This process involves vertical handover, which is discussed in Section VI.

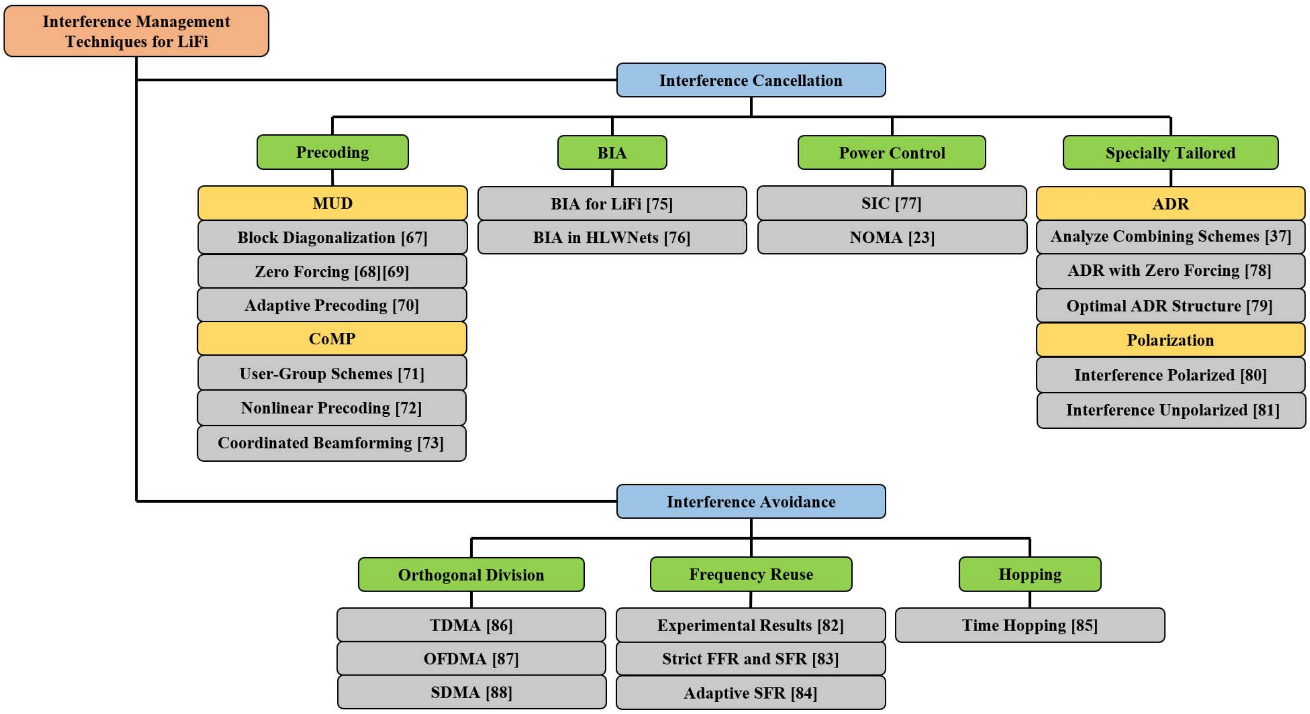


Fig. 7. Taxonomy of interference management in LiFi.

V. Interference Management

Increasing the density of APs is an important aspect of network densification, a key approach for wireless evolution over the next decade, while interference management is of vital importance. Operating at different spectra, LiFi and WiFi do not interfere with each other. Also, the CSMA/CA adopted by WiFi can suppress co-channel interference to a negligible level. Hence, in this section we focus on discussing the interference management for LiFi. These techniques can be classified into two basic categories: interference cancellation and interference avoidance. A detailed taxonomy is presented in Fig. 7, and a summary table of the current literature is given in Table VII.

A. Interference Cancellation

Andrews [65] defines interference cancellation as the class of techniques that decode desired information and utilize this information along with channel estimates to eliminate or reduce received interference from the received signal. This type of technique works at the receiver end, i.e., after the interference-affected signal is received.

1) Precoding: Precoding techniques are widely used to eliminate interfering signals in downlinks. The basic principle is to artificially create orthogonal channels through singular-value decomposition. Due to the non-negativity of optical signals, traditional precoding techniques need to be modified to suit LiFi, e.g., adding a DC biasing vector [66]. Precoding techniques can be divided into two subcategories: multi-user detection (MUD) and coordinated multipoint (CoMP) transmission. MUD aims to cancel interference among co-channel users within the same AP. Using block diagonalization, Hong *et al.* [67] showed that an SINR value of 20 dB can be achieved for two VLC users in the majority of the indoor region, when single LED's power is 10 mW. At the same power level, the zero forcing-based VLC system in [68] can provide an SINR value of 30 dB, with more densely deployed APs. The work in [69] showed that with zero forcing, ACO-OFDM outperforms DCO-OFDM for low optical power, the same trend as no precoding used [24]. In [70], optical adaptive precoding was studied, which only nulls destructive interference. With reduced dependence on CSI, this method is more robust to imperfect CSI than channel inversion precoding. With the aim of eliminating ICI, CoMP requires coordination among APs to exchange the channel state information (CSI) knowledge. Relevant research was carried out for LiFi in [71]–[73], with interests in user grouping and coordinated beamforming.

Precoding methods rely on channel state information at the transmitter (CSIT) of all co-channel users. However, the uplink of LiFi usually employs infrared when lighting is not needed [74], composing a frequency division duplex system. As a result, using precoding techniques for LiFi comes at a cost of hefty feedback. This issue has not yet been well addressed in the current literature. In addition, inaccurate CSI will impair the performance of precoding. This problem becomes more pronounced in LiFi, since rapid changes in the device orientation can cause fast-varying channels. The practicality of adopting precoding techniques for LiFi is yet to be validated.

2) Blind Interference Alignment: When exact CSI is not available at the transmitter, blind interference alignment (BIA)

TABLE VII
SUMMARY OF INTERFERENCE MANAGEMENT TECHNIQUES IN LIFI

Ref.	Approach type	Assumed knowledge	Modulation	System			Remark
				Antenna	AP Density	Topology	
[67]	MUD	Perfect CSIT	OOK	MIMO (2×2)	$0.16/m^2$	Matrix	Use block diagonalization precoding
[68]		Imperfect CSIT	OOK	MISO (9×1)	$0.36/m^2$	Matrix	Use zero-forcing precoding
[69]		Perfect CSIT	O-OFDM	MISO (4×1)	$0.16/m^2$	Matrix	Precoding for DCO- and ACO-OFDM
[70]		Outdated CSIT	OOK	MIMO	$0.25/m^2$	Matrix	Null destructive interference
[71]	CoMP	Perfect CSIT	OOK	MISO (16×1)	$0.17/m^2$	Hexagon	Compare user-grouping schemes
[72]		Perfect CSIT	Space-time	MISO (4×1)	$0.25/m^2$	Matrix	Use nonlinear precoding
[73]		Imperfect CSIT	OOK	MISO (2×1)	$0.04/m^2$	Line	Use coordinated beamforming
[75]	BIA	Coherence time	O-OFDM	MISO (2×1)	$0.06/m^2$	Line	Use the filter pair
[76]			OOK	MISO (2×1)	$0.02/m^2$	Line	Study the use of BIA in a HLWNet
[77]	Power control	Perfect CSIT	-	MIMO	$0.03/m^2$	Matrix	7-LED Tx
[37]	ADR	-	-	SIMO	$0.16/m^2$	Hexagon	9-PD and 20-PD Rx
[78]		Perfect CSIT	-	MIMO (4×7)	$0.16/m^2$	Matrix	7-PD Rx
[79]		-	-	SIMO	$0.08/m^2$	Matrix	3-PD, 4-PD, 5-PD and 6-PD Rx
[80]	Polarization	-	DMT	SIMO	-	Matrix	Differential Rx with 2 polarized PDs
[81]		-	OOK	MIMO (2×2)	-	Line	2 polarized LEDs and 2 polarized PDs
[82]	Frequency reuse	-	QPSK	SISO	$4.28/m^2$	Hexagon	Demonstrate experimental results
[83]		-	O-OFDM	SISO	0.04 - $0.1/m^2$	Hexagon	Compare strict FFR with SFR
[84]		-	-	SISO	0.01 - $0.12/m^2$	Hexagon	Adapt to the density of APs
[85]	Time hopping	-	PPM	SISO	-	Matrix	Strict sync between Tx and Rx

can be achieved by pairing a time-selective user with a frequency-selective user. The concept is to maximize the degree of freedom for co-channel users through masking transmitted signals on the basis of channel coherence. Unlike precoding, BIA can only reduce interference to some extent. Since the condition of channel coherence for BIA may not always be met, channel manipulation is required. In RF systems this is realized by reconfigurable antennas, which enable the receiver to switch among different antennas. As for LiFi, it employs PDs as the receiver antennas. A few studies were conducted to utilize BIA in LiFi. Equipping each user with one PD and multiple optical filters, the BIA scheme in [75] requires 3-5 dB less optical transmit power than TDMA. The performance of BIA in an HLWNet was studied in [76], showing that shifting LiFi cell-edge users to WiFi can allow BIA to obtain a greater gain over TDMA. However, BIA only outperforms TDMA in the range of high optical transmit power, e.g., above 50 dBm in [75]. Such high levels of LED power are not suitable for illumination, restricting the use of BIA for LiFi.

3) Successive Interference Cancellation: Successive interference cancellation (SIC) can detect co-channel signals by distinguishing their different power levels. It is worth noting that when power control is implemented in LiFi, illumination requirements must be satisfied. Since only the alternating current (AC) component of optical signals is converted to the effective electrical signal, it is feasible to adjust the amount of the AC component while keeping the same level of the average optical transmit power. In [77], power control was studied when the user is served by multiple APs, with each AP consisting of multiple narrow-FoV LEDs. This method is able to obtain an SINR 2-5 dB higher than TDMA. As SIC detects one user per stage, the computational complexity and latency are proportional to the number of co-channel users. Alternatively, parallel interference cancellation (PIC) detects all users simultaneously and can reduce latency at the cost of increased complexity. In regard to LiFi, SIC is preferable to PIC, since each LiFi AP covers a relatively small area and is likely to serve only a few users. Using SIC to realize multiple access forms the concept of NOMA [23]. Note that SIC-based methods rely on an appropriate pair of the co-channel users, which might not always be satisfied in ultra-dense networks due to the sparsity of users in a single cell.

4) Specially Tailored Methods: There are two interference cancellation methods specially tailored for LiFi: angle diversity receiver (ADR) and polarization techniques. The ADR uses multiple narrow-FoV PDs instead of a single wide-FoV PD, in order to reduce interference at each PD. Chen *et al.* [37] analyzed the performance of different signal combining schemes for ADR, including select best combining, equal gain combining, maximum ratio combining, and optimum combining. This work shows that with optimum combining, ADR is able to achieve an SINR performance close to that of interference-free systems. In [78], zero-forcing precoding was combined with ADR. This approach can noticeably improve the SINR performance, especially for LiFi cell-edge users. In [79], the optimal structure of ADR was studied, depending on the number of PDs and the LED layout. It is shown that choosing an appropriate tilt angle of side PDs can greatly affect SINR, with a fluctuation range of 20 dB. While capable of rejecting interference, narrow-FoV PDs are susceptible to changes in the device orientation. So far the performance validation of ADR in a realistic mobile environment has not been addressed in the existing literature.

The polarization property of light can also be exploited to realize differential detection for interference cancellation. Specifically, two polarized optical signals with perpendicular directions do not interfere with each other, constructing an orthogonal division multiplexing. In [80], at the receiver two PDs with different polarization filters are used to cancel interference. A similar method was proposed in [81] to resist unpolarized optical interference. These approaches do not require extra feedback to exchange CSI. However, they rely on a perfect alignment of polarization directions between the transmitter and receiver. This is feasible in laboratory experiments but much difficult to implement in practice.

B. Interference Avoidance

The interference avoidance refers to the techniques that work at the transmitter end to avoid yielding interference. Among these techniques are orthogonal division schemes including TDMA [86], OFDMA [87] and space-division multiple access (SDMA) [88]. Some studies, e.g., [89], list power control as an interference avoidance method. This type of method is unable to work without SIC, and hence we classify it as SIC-based interference cancellation. Other interference avoidance techniques include frequency reuse and frequency/time hopping.

1) Frequency Reuse: Frequency reuse (FR) is widely used to avoid ICI among neighboring cells, where frequencies are reused in a regular pattern. A few studies have been carried out to apply FR to LiFi [82]–[84]. In [82], experimental work was carried out to demonstrate the use of FR in LiFi among three APs, achieving a sum data rate of 0.5 Mbps. Chen *et al.* [83] analyzed fractional frequency reuse (FFR) for LiFi, including strict FFR and soft frequency reuse (SFR). The former scheme partitions the cell area into three equal sectors, while the latter one provides a two-tier cellular structure. Compared with strict FFR, SFR is more flexible and thus able to achieve a higher reuse ratio with the same capability of suppressing interference. Considering different AP densities, a dynamic SFR scheme was proposed in [84], using an adjustable spectrum allocation. This scheme in essence creates a cellular structure more flexible than SFR.

2) Frequency/Time Hopping: Hopping techniques rapidly switch a carrier among many frequency channels or time slots, using a pseudo-random sequence known to both the transmitter and receiver. A time hopping method for LiFi was reported in [85], where the period and duty cycle of the optical carrier are varied in a pseudo-random manner. While this type of method can reduce the probability of two users occupying the same time-frequency block, it requires a strict synchronization between the transmitter and receiver.

C. Summary and Lessons Learnt

1) Centralized LiFi System: The LiFi APs can be readily managed in a centralized manner, as they are located in the same compartment. This renders LiFi more opportunities in interference management, while WiFi has to rely on sensing carries and avoiding collision. With dedicated backhaul, the centralized LiFi system can ease the implementation of precoding. But LiFi channels could vary rapidly, compromising the performance of precoding. As a result, channel variance must be considered when developing precoding schemes for LiFi. Centralized systems also facilitate spectrum scheduling in FR, which can exploit the wide spectrum available in LiFi. However, an over-complicate structure of FR would worsen the problem of resource allocation.

2) Dense AP Deployment: The LiFi APs are usually densely deployed, with a separation of 2-3 meters. This makes ADR a promising approach for rejecting interference. ADR can also improve the received signal strength, as the PD's sensitivity is dependent on the incident direction. In contrast, a single wide-FoV PD does not perform well when it is significantly tilted. This drives a momentum in using multiple PDs to construct an omnidirectional receiver [64]. The dense deployment of LiFi also boosts the area spectral efficiency when FR is used. In the meantime, there are sparse users in a typical indoor scenario such as office and home. For this reason, adjustable spectrum allocation can make FR more efficient for LiFi.

3) Opportunities in HLWNets: Though WiFi and LiFi do not interfere with each other, it does not mean WiFi has no impact on the interference management for LiFi. On the opposite, a delicate user association in HLWNets can help mitigating interference in LiFi, e.g., based on a conflict graph in [90]. The AP selection between LiFi and WiFi is a key issue in HLWNets and will be discussed in the following sections. After user association is determined, an appropriate resource allocation in terms of sub-channel or time slot can also meliorate the interference situation [91]. In summary, the interference management for LiFi should be in line with user association and resource allocation in a full picture of HLWNets.

VI. HANDOVER

In general, the handover process in a hybrid network falls into two categories: horizontal handover (HHO) and vertical handover (VHO). A HHO takes place within the domain of a single wireless access technology, whereas a VHO occurs between different technologies. With a VHO, the air interface is changed, but the route to the destination remains the same. In some literature, e.g., [92], a third category named diagonal handover is introduced, with the air interface and route to the destination both changed. A significant body of research was conducted on the topic of handover for heterogeneous networks (HetNets). A relevant survey was carried out in [93], summarizing different types of handover schemes including received signal strength (RSS)-based, load balancing-related, and energy-saving. Handling the handover process is more challenging in HLWNets than HetNets, due to the small coverage areas especially of LiFi APs. In this section we review the current literature related to: i) HHO in LiFi, ii) VHO between LiFi and WiFi, and iii) the selection between HHO and VHO. A detailed taxonomy is given in Fig. 8, and the relevant studies are summarized in Table VIII. The considerations and guidelines for implementing handovers in HLWNets are also discussed.

[4]The ratio between the number of LiFi APs and the number of WiFi APs.

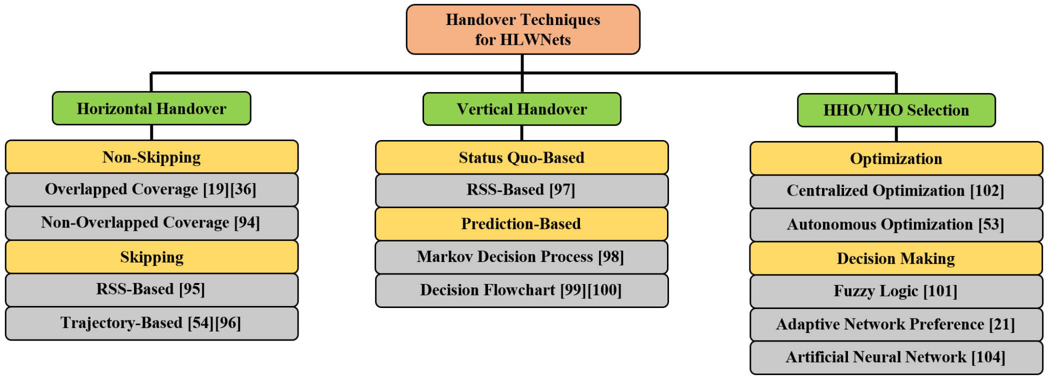


Fig. 8. Taxonomy of Handover in LiFi and HLWNets.

TABLE VIII
SUMMARY OF HANDOVER SCHEMES IN LIFI AND HLWNETS

Ref.	HO type	Required knowledge	Centralize	Predict	Topology	Density [4]	Remark
[19]	HHO	RSS	No	No	Matrix	-	Optimize AP density
[94]			No	No	Line	-	Soft HO for non-overlapping coverage
[36]			No	No	Matrix	-	Consider change of receiver orientation
[95]			No	Yes	Matrix	-	Weigh RSS and its rate of change
[96]		Cell topology, user trajectory	Yes	Yes	PPP	-	With single-AP association
[54]			Yes	Yes	PPP	-	With multi-AP association
[97]	VHO	RSS	No	No	Line	2	Consider change of receiver orientation
[98]		WiFi queue length and LiFi channel condition	Yes	Yes	-	-	Use the Markov decision process
[99]		Message size, delay and interruption duration	No	Yes	One VLC AP per room		Use a decision flowchart
[100]		Queue length, throughput delay, traffic preference	No	Yes	Hexagon	8	
[101]	HHO/VHO	SINR, user speed, data rate	Yes	No	Matrix	4	Use fuzzy logic
[102]		SINR, blockage	Yes	No	Matrix	36	Maximize throughput
[21]		RSS, user speed	No	Yes	Matrix	4	Adaptive network preference
[103]		RSS, user speed, AP density	No	Yes	Matrix	4	Adjust network preference via ANN

A. Horizontal Handover

LiFi has a relatively small coverage range with a single AP, usually 2-3 meters in diameter. The ultra small cell makes LiFi encounter considerably frequent handovers, even when the user moves at a moderate speed. Also, the LiFi channel is related to the PD's receiving orientation, of which the change could be very rapid and sudden. This might lead to frequent and unexpected handovers. Therefore, the handover cost becomes a critical factor to consider in LiFi. Taking handovers into account, the separation distance between APs affects network throughput in two aspects. On the one hand, a smaller separation provides a higher area spectral efficiency. On the other hand, a larger separation reduces the handover rate. Motivated by this, the authors in [19] studied the optimal placement of LiFi APs and concluded that the ideal coverage area of a LiFi AP is 2 to 8 m^2, depending on the user density and handover overhead. While the coverage areas of different APs usually overlap each other, the authors in [94] also investigated the handover procedure for non-overlapping coverage. This study suggests a soft handover for APs with non-overlapping coverage and otherwise a hard handover. The above two papers only consider user mobility with a fixed receiver orientation. In [36], the handover rate was analyzed with both the movement and rotation of user equipment considered. It is found that the handover rate peaks when the user device is tilted between 60° and 80°.

Although the optimal placement of APs can relieve the detriment of handovers to some extent, the degradation in throughput is still outstanding for fast-moving users. To further reduce the handover rate, the concept of handover skipping (HS) was introduced in [96], which enables the user to be transferred between non-adjacent APs. In this work, a topology-aware HS scheme was proposed to let the user skip the APs of which the chord length is below a predefined threshold. A similar method was reported in [54], with the research scope extended to multi-AP association. This type of approach relies on knowledge of the user's trajectory and network topology. However, the equivalent network topology of LiFi is dynamic and user-dependant, due to the impact of the PD's receiving orientation. Also, positioning techniques are needed to acquire knowledge of the user's trajectory, and feedback is necessary for sending this information to APs. To circumvent the above stringent requirements, an RSS-based HS approach was developed in [95] by exploiting the rate of change in RSS to indicate whether the user is moving towards a certain AP. Using a weighted average of RSS and its rate of change to make handover decisions, this method does not require extra feedback, since RSS is commonly used in the current handover schemes. More importantly, it does not rely on knowledge of the network topology. It is shown that the RSS-based HS method can improve the network throughput by up to about 70% over the handover scheme employed in long-term evolution (LTE) and 30% over the trajectory-based HS method, respectively.

B. Vertical Handover

The user usually requires a VHO from LiFi to WiFi when losing LiFi connectivity. The loss of LiFi connectivity might be caused by two reasons: i) the light-path is blocked by opaque objects, such as human bodies and furniture; and ii) the PD's receiving orientation is significantly deviated from the LoS path. The authors in [97] analyzed the probability of VHO, showing that a trade-off exists between the number of handovers and their delay. This signifies the importance of an appropriate level of hysteresis in the handover process. A number of studies were carried out to develop VHO schemes for LiFi-involved hybrid networks [98]–[100]. In [98], a VHO scheme based on the Markov decision process was proposed. This method determines whether to perform a VHO on the basis of the queue length for WiFi and the channel condition of LiFi. Another VHO scheme was proposed for hybrid LiFi and LTE networks in [99], which predicts the system state in terms of interruption duration, message sizes and access delays. These parameters, which are recorded by the user equipment in real time, can be used to make handover decisions. A similar approach was developed for hybrid LiFi and femtocell networks in [100], considering multiple attributes including dynamic network parameters (e.g., delay, queue length and data rate) and actual traffic preferences. The above methods have one common point: they adjust the network preference based on channel and traffic conditions. However, they do not consider the handover overhead and user mobility, which impose different impacts on different types of handovers. Without weighing the advantages and disadvantages of VHO and HHO, it is difficult to implement an effective handover process for HLWNets.

C. Selection Between HHO and VHO

Due to the change of air interfaces, a VHO usually needs a much longer processing time than a HHO [104]. Also, the WiFi system has a lower system capacity than LiFi, and an excessive number of WiFi users would cause a substantial decrease in throughput. Thus, the choice between HHO and VHO is critical to HLWNets. Specifically, not all of the users that lose LiFi connectivity should be switched to WiFi, e.g., the users encountering a transient light-path blockage. Apart from that, the user's velocity is also an important factor in deciding whether a user should be served by LiFi or WiFi. In general, fast-moving users prefer WiFi, since they would experience frequent HHOs in LiFi. To solve the complicate problem of choosing between HHO and VHO, Wang *et al.* [101] proposed a handover scheme based on fuzzy logic. This method makes handover decisions by measuring parameters including not only CSI but also the user's speed and data rate requirement. Unfortunately, this method does not address the issue of channel blockages in LiFi. Exploiting the statistical information on light-path blockages, the handover process was formulated as an optimization problem in [102], which maximizes throughput over a period of time. Such a method however requires a relatively high computational complexity. In [21], the concept of handover skipping in LiFi [95] was extended to HLWNets. Specifically, a dynamic network preference that adapts to the user's speed is introduced to adjust the coverage areas of different networks. This approach can reduce 40% of handovers in a walking speed and 70% in a running speed. In [103], the network preference is trained through artificial neural network (ANN), considering the user's speed as well as the network deployment. This method is able to further improve the network throughput, with a gain of 50% higher than the trajectory-based method.

D. Summary and Lessons Learnt

The selection between HHO and VHO can be considered in two parts. The first part is to select an AP without taking into account the handover cost. This is a typical AP selection process which needs to measure channel quality as well as resource availability. A high channel quality means a high spectral efficiency. However, an AP that provides a high channel quality does not necessarily render a high data rate since the resource might be fully occupied. Thus, resource availability must be considered in conjunction with channel quality. The second part is to evaluate the handover cost. Cell dwell time (CDT), which is defined as the time that a user stays with an AP without being disconnected, is a key metric for the handover process, no matter caused by user mobility or channel blockages. In summary, the HHO/VHO selection needs to jointly consider channel quality, resource availability and CDT through optimization or decision-making methods. The handover decision can be made in the interest of: i) a single user or ii) overall network performance. In addition, the user can be served by multiple APs simultaneously, e.g., CoMP. In this situation, the handover occurs in the form of a group of APs. The six factors that need to be considered when designing the handover scheme for HLWNets form a hexagram, as shown in Fig. 9. The issue of choosing between HHO and VHO essentially involves load balancing, which is elaborated in the next section.

VII. Load Balancing

In the area of wireless networks, load balancing (LB) refers to the techniques that distribute user sessions across the APs with overlapping coverage areas. The aims of LB are to optimize resource utilization, to maximize throughput, to minimize response time, and to reduce network congestion. In homogeneous networks, the coverage overlap among APs is restricted to mitigate ICI. As a result, LB only applies to cell-edge users when they impose unbalanced traffic loads to different APs. In other words, LB is not needed when the users' demands for data rates are uniformly distributed in geography. The authors in [105] classified WiFi-related LB techniques into two categories: user-based and AP-based.

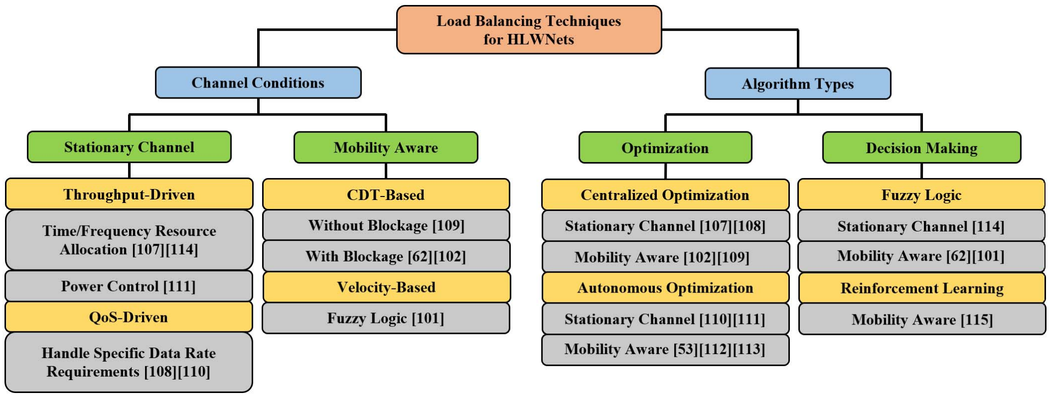


Fig. 10. Taxonomy of load balancing in HLWNets.

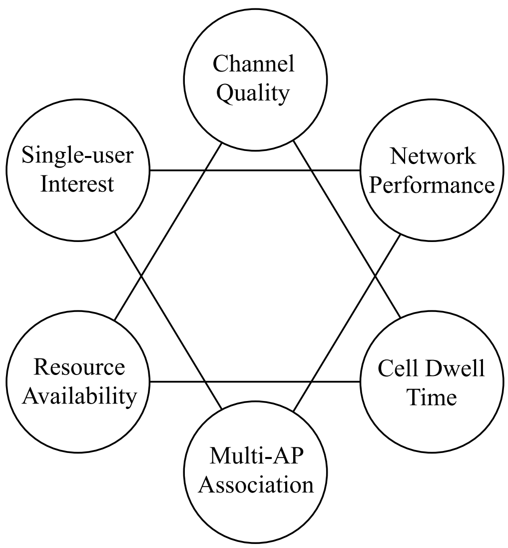


Fig. 9. Factors for consideration in the handover process for HLWNets.

With user-based methods, each user selects the APs according to its own interest, and the optimal network performance is hard to achieve. On the contrary, AP-based methods implement a network-wide LB, which requires a central unit to coordinate APs.

LB becomes essential and challenging in hybrid networks due to two main factors: i) the coverage areas of LiFi and WiFi overlap each other; and ii) WiFi APs have a larger coverage area but a lower system capacity than LiFi APs [18]. This makes WiFi susceptible to traffic overload even if the users' demands for data rates are uniformly distributed in geography. A large body of research was carried out to study LB approaches in the HetNet, including relaxed optimization, Markov decision process, game theory and cell range expansion [106]. Though these methods are applicable to HLWNets, they face a critical issue of user mobility due to the short coverage range of a single LiFi AP. According to the algorithm type, the LB algorithms that have been developed for HLWNets fall into two categories: i) optimization and ii) decision-making. In this section we classify these methods into i) stationary-channel and ii) mobility-aware, depending on whether user mobility is considered. A detailed taxonomy is shown in Fig. 10, and the current literature is summarized in Table IX.

A. Stationary Channel Load Balancing

The wireless channel can be assumed stationary within the coherence time. With stationary channels, the LB problem needs to trade off channel quality with resource availability. In [107], an LB method was proposed to achieve proportional fairness (PF) among users, in forms of both centralized and distributed resource-allocation algorithms. To improve quality of service, the LB issue is formulated as a mixed-integer non-linear programming problem in [108], which considers different data rate requirements among users. The two above methods both construct an NP-hard problem, and solving the problem requires an excessive amount of computational complexity that exponentially increases with the number of APs. To reduce the processing power, an iterative algorithm based on evolutionary game theory was reported in [110], with multiple fairness functions (MFF) considered. In this work, light-path blockages, arbitrary receiver orientations and data rate requirements are characterized to model a practical communication scenario. The authors in [111] also introduced an iterative algorithm but focused on power allocation. This algorithm consists of two states: i) finding the optimal power allocation of each AP to maximize its throughput; and ii) seeking another AP for the user with the minimum data rate to increase the overall throughput and to enhance the system fairness. The above iterative algorithms can be deemed as autonomous optimization, which is carried out individually at each AP.

The centralized optimization needs to solve an NP-hard problem, whereas the autonomous optimization requires a quantity of iterations to reach a steady state. They both need a substantial amount of processing time. In HLWNets, CSI could rapidly vary for mobile users with an even modest speed. This restricts the processing time and thus challenges the practicability of the above methods. Alternatively, direct decision-making methods are applicable, which provide a significantly reduced amount of processing time. Such an LB method was reported in [114], which splits the process into two stages: i) determine the users that should be served by WiFi and ii) assign the remaining users as if in a stand-alone

TABLE IX
SUMMARY OF LOAD BALANCING APPROACHES IN HLWNETS

Ref.	Algorithm type	Mobility awareness	Required knowledge	Fairness	Complexity	Topology	Density	Remark
[107]	Centralized optimization	No	CSIT	PF	High	Matrix	16	Maximize throughput with PF constraints
[108]			CSIT	PF	High	Matrix	16	With different data rate requirements
[109]		Yes	CDT	PF	Medium	Matrix	4	Joint optimization of LB and handover
[102]			CDT, blockage	PF	Medium	Matrix	4	Consider light-path blockages
[110]	Autonomous optimization	No	CSIT	MFF	Medium	Matrix	4 & 16	With different data rate requirements
[111]			CSIT	PF	Medium	Matrix	16	Implement power allocation
[112]		Yes	CSIT, trajectory	PF	Medium	Hexagon	18	Use the college admission model
[53]			CSIT	MFF	Medium	Matrix	4	Different distances between LiFi APs
[113]			CSIT	MFF	Medium	Matrix	5	Joint implementation of AP assignment and resource allocation
[114]	Decision making	No	CSIT	PF	Low	Matrix	4	Use fuzzy logic
[101]		Yes	CSIT, speed	PF	Low	Matrix	36	
[62]		Yes	CDT, blockage	PF	Low	Matrix	4 & 9	
[115]		Yes	CSIT, traffic load	PF	Low	Matrix	4	Use reinforcement learning

LiFi network. Relying on statistical knowledge of data rate requirements and CSI, this fuzzy logic-based method is able to achieve near-optimal performance in terms of throughput and user fairness, while reducing the processing time by over 10 orders of magnitude.

B. Mobility-Aware Load Balancing

The noted LB methods all rely on CSI knowledge, which varies due to user movements and environmental changes. Accordingly, these methods have to calculate their solutions periodically. When the new solutions make a change to the user association, the impact caused by handovers must be taken into account. For instance, with stationary-channel LB methods, users will be transferred between LiFi and WiFi repeatedly when moving across the LiFi APs, leading to frequent and unnecessary handovers.

In order to tackle the above issue, user mobility has to be considered in conjunction with LB. This is referred to as mobility-aware load balancing. In [112], a method based on the college admission model was proposed. Specifically, the achievable data rate and the user's moving direction are used to measure the user's preference, while the sum data rate is used to compute the AP's preference. These two preferences are then iteratively calculated to reach a steady solution. This method however requires to know the user's trajectory, which is not ready to acquire in practice. A dynamic LB scheme was proposed in [53], which also performs an iterative algorithm. In each iteration, AP assignment and resource allocation are sequentially implemented to improve the effective data rates which excludes handover overheads. In [113], AP assignment and resource allocation are jointly implemented. The joint implementation can achieve a network throughput 50% higher than the separate implementation, at the cost of a higher computational complexity by 3 orders of magnitude. In [109], a globally-optimized LB method is realized by using CDT to measure the handover cost. This approach does not rely on CSI and thus suits the scenario of fast-varying channels. Accordingly, it provides a sub-optimal network performance. In [102], light-path blockage is characterized and included in the process of formulating the CDT-based LB problem. This modification can effectively reduce the negative impact caused by intermittent light-path blockages.

To provide low computational complexity for practical implementations, decision-making methods have also been investigated for mobility-aware load balancing. Wang *et al.* [101] developed a fuzzy logic system to balance the traffic loads between LiFi and WiFi, with multiple input parameters including SINR, the user's speed and data rate requirements. Adding light-path blockage as an extra input, another fuzzy logic-based LB approach was proposed in [62] to handle the situation of unbalanced traffic loads caused by blockage. While fuzzy logic can be readily implemented, the logic rules are pre-defined and lack flexibility. Instead, it is feasible to use machine learning to cope with the uncertainties in network deployment, user distribution, traffic situations, etc. A LB method based on reinforcement learning was introduced in [115]. It is shown that this method can outperform iterative algorithms in most scenarios.

C. Summary and Lessons Learnt

Channel variance due to user mobility is not negligible when solving the LB issue in HLWNets. This essentially renders a trade-off between the instantaneous data rate and the handover rate when maximizing the average throughput. Other QoS metrics such as the packet loss ratio, delay and jitter should also be considered, forming a multi-objective optimization problem. To solve the LB problem, the algorithms must compromise optimality for computational complexity. While optimization methods can provide optimal solutions, they need an excessive amount of computational complexity. In contrast, decision-making methods can significantly reduce computational complexity, but the optimality is compromised. In general, it is possible to realize low-complexity LB in two ways. One approach is to exploit the status information on users and APs (e.g., the user's speed and the AP's queuing length) through intelligent control methods such as fuzzy logic, game theory and machine learning. The other way is to construct a decision flowchart with a number of pre-defined

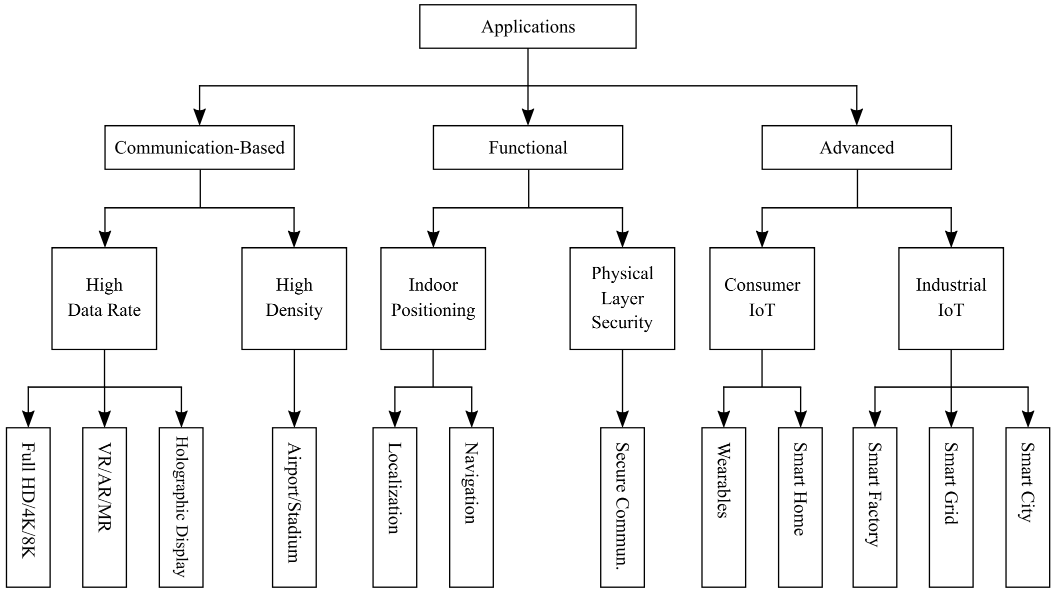


Fig. 11. Taxonomy of applications benefiting from HLWNets.

thresholds. Many of the decision-making methods are examined in specific environments, while the variance of network deployment has not been well studied in the current literature. It is meaningful to develop LB methods with low complexity while being adaptive.

VIII. Applications

The HLWNet can fuel a wide range of applications and services, which can be classified into three major categories: communication-based, functional and advanced applications. A detailed taxonomy is given in Fig. 11. As mentioned, HLWNets are a promising approach to support high-speed wireless communications, e.g., 4K/8K video streaming, VR, holographic display, etc. An integration system of mmWave and LiFi for the transmission of holographic 3D display data was reported in [47]. Also, HLWNets can relieve the resource shortage in high-density scenarios such as airports, stadiums and conference venues. Typical functional applications are indoor positioning system (IPS) and physical layer security (PLS). These functions underlie the advanced applications in IoT, ranging from consumer IoT to industrial IoT. A hybrid VLC/RF indoor IoT system with solar energy harvesting was introduced in [116]. In this section we focus on discussing IPS and PLS, while highlighting the benefits of HLWNets to these applications.

A. Indoor Positioning System

Positioning is an essential tool for providing location-based services such as navigation, creating maps, tracking objects, etc. As a mainstream positioning technology at present, the global positioning system (GPS) is a satellite-based radio-navigation system which provides geolocation information to a GPS receiver. With the latest accuracy enhancement using the L5 band, the accuracy of GPS can be improved from 5 m to 30 cm [117]. However, GPS becomes less accurate in indoor scenarios, as the transmitted signals are degraded and interrupted by obstructions, especially ceilings and walls. Alternatively, IPS can be developed upon short-range wireless communication technologies, e.g., WiFi, LiFi, Bluetooth, radio frequency identification and ZigBee. Multiple surveys have been carried out to summarize LiFi-based positioning techniques, e.g., [118], [119]. In this subsection, we briefly introduce the classification of IPS techniques and focus on discussing the relevant development in HLWNets.

1) Classification of IPS Techniques: IPS methods can be classified from two angles: mathematical algorithm and used information. The main algorithms used for IPS are triangulation, proximity and fingerprint. The triangulation method exploits the geometric properties of triangles by measuring the distance or angle between the device and multiple fixed points, i.e., beacons. This method offers high accuracy at the cost of a sophisticated system structure. With a single receiver, the triangulation method needs at least three beacons for 2-D positioning and four beacons for 3-D. The LiFi beacon can be an LED-based AP or a modulated retro-reflector (MRR) [120], which avoids proactively emitting light. Proximity is the simplest algorithm, which links the device's location to the AP's coverage area. Specifically, when a device is recognized by multiple APs, it is roughly located within the overlapping coverage area of these APs. Due to the dense deployment, LiFi is naturally suitable for using this algorithm. Fingerprint employs location-dependant information such as RSS and requires off-line radio maps. The optimal location is obtained by minimizing the Euclidean distance between the radio map and the real-time measurement. As a result, the positioning accuracy of fingerprint is dependent on the accuracy of the radio map [121].

According to the used information, IPS techniques fall into four categories: RSS, time of arrival (TOA), time difference of arrival (TDOA) and angle of arrival (AOA). RSS-based methods exploit channel attenuation to estimate the distance between the device and the beacon. Among all the signal characteristics, RSS can be readily acquired. The accuracy of such a method depends on a reliable path-loss model and might suffer from uncontrollable errors caused by multipath propagations [122]. TOA-based methods also compute the distance but use the travel time of the signal. This type of method needs rigid time synchronization between the device and the beacon [123]. In order to circumvent this requirement, TDOA-based methods employ multiple transmitters or receivers to obtain the time difference between the received signals [124]. However, time synchronization is still required between the beacons. AOA-based methods measure the angle between the transmitted signal and the normal angle of the beacon. In RF, AOA is usually obtained by detecting the phase difference between antennas [125]. However, AOA cannot be measured directly in LiFi due to the lack of phase information in intensity modulation/direct detection (IM/DD). Instead, AOA can be acquired through two approaches. One approach is called image transformation, which calculates AOA through the trigonometric relationship between the light beacons' coordinates and their imaging locations on a photo [126]. The other one is modeling, which exploits the angular pattern of RSS at the PD [127].

2) IPS in HLWNets: The key metric for positioning is accuracy. The intrinsic shorter coverage range of LiFi leads to a smaller positioning error ($0.1-0.35$ m) than WiFi ($1-7$ m) [128]. Also, LiFi can provide more dense beacons than WiFi. Due to the existing and ubiquitous lighting infrastructures, the installation cost and energy consumption will be relatively low for LiFi beacons. Further, LiFi-based IPS can readily detect the device's orientation via ADRs [129], while it is difficult for WiFi-based IPS to achieve. The challenges facing LiFi-based IPS and WiFi-based IPS are quite different. WiFi signals may experience severely rich multipath fading, especially in some special environments such as factories, underground mines and tunnels. As for LiFi, signals might confront light-path blockage, resulting in a complete loss of connectivity.

A hybrid IPS using both LiFi and WiFi (or other RF technologies) is envisaged to improve the accuracy of indoor positioning. In [130], the proximity positioning concept was applied in a hybrid environment of LiFi and Zigbee. This method however has a relatively low accuracy ($\sim$130 cm). A two-stage positioning system was proposed in [131]. It first determines a possible area via a LiFi-based proximity method and then locates the specific position in that area by using the RSS of the RF signals. Such a system is able to keep the positioning error within 20 cm. Another two-stage positioning system was developed in [132]. In the first stage, RF is used to detect which room the device is currently located in. In the second stage, LiFi is employed to detect the specific position of the device. The estimation error was reported to be only 5.8 cm.

B. Physical Layer Security

Wireless signals are broadcast in the open air and can be received by the intended user as well as an eavesdropper, named Bob and Eve. To enhance the security of wireless communications, PLS has drawn a significant amount of research attention. There are two basic categories: secure key generation and secure data transmission. The former exploits the inherent randomness of wireless channels, e.g., RSS and phase information [133], to ensure the security of keys. As for secure data transmission, the aim is to enlarge the SINR difference between the links of Bob and Eve. In general, Eve's SINR peformance can be weakened in two ways: i) reducing RSS and ii) increasing noise or interference [134]. The first way is focused on optimizing the transmission scheme for Bob through techniques such as beamforming, resource allocation, interference alignment, etc. The transmission power is reduced for Bob and so as for Eve. The second way is to inject artificial noise, which can be generated in the null-subspace of Bob's channel so that only Eve's SINR performance is impaired by the noise. In addition, when Eve's channel is worse than Bob's on average, secure channel coding such as low-density parity-check can effectively increase secrecy [135].

In comparison with WiFi, LiFi has a number of intrinsic advantages in terms of security. First, since light does not penetrate opaque objects, LiFi can be securely used in a compartment space such as conference rooms. Second, LiFi covers a smaller area than WiFi with a single AP. Thus, Eve has to move closer to intercept signals. Third, the LoS path normally contributes over 80% of the received signal power [18]. As a result, the information leakage to Eve from scattered optical signals would be very limited. A quantity of research has been conducted to analyze the secrecy performance of LiFi. Chen and Haas [136] demonstrated that the hexagonal deployment provides the highest secrecy capacity, whereas the matrix deployment performs marginally worse. Ayman and Lampe [137] studied the secrecy capacity of LiFi under amplitude constraints of LEDs, while using beamforming to hinder eavesdroppers in specified areas. In addition, quantum key distribution (QKD) is a specially-tailored approach for OWC-aided PLS [138]. A photon can be readily encoded as a zero/one state, e.g., using horizontal and vertical polarizations. Based on quantum mechanics such as the quantum no-cloning principle, QKD is able to generate and distribute the quantum random key among two parties. A handheld QKD system was demonstrated in [139], to achieve a secret key rate above 30kb/s in the free-space link over a distance of 0.5m.

Studies have been carried out on the topic of PLS in HLWNets. In [140], the secrecy outage performance of an RF uplink was analyzed with solar energy harvesting in a LiFi downlink. In [141], the power consumption of the HLWNet was minimized under the secrecy rate constraint. It is shown that to achieve the same secrecy rate, HLWNets consume a power level 10 dB less than stand-alone networks. In [142], Ucar *et al.* proposed a HLWNet-based security protocol for vehicular platoon communications, where LiFi provides resilience to security attacks and WiFi offers redundancy for link reliability. The authors in [143] analyzed the secrecy performance for dual-hop HLWNets, where the energy harvested from LiFi signals is used to relay data through RF. Similar work was reported in [144], with the aim of finding the minimum transmission power that can achieve a certain amount of secrecy capacity.

C. Summary and Lessons Learnt

Due to the complementarity between LiFi and WiFi, the HLWNet can not only boost the network capacity but also benefit application services such as IPS and PLS. In regard to IPS, the nature of LiFi allows it to offer a much higher accuracy than WiFi for slow-moving users. A typical use case is to navigate the AGV (of which the speed is usually limited to 0.5 m/s) in a factory, where RF-based IPS is significantly inaccurate due to severe multipath fading. As for fast-moving users, outdated information could degrade the accuracy of LiFi-based IPS when the LiFi channel varies rapidly. How to employ HLWNets to improve the positioning accuracy in this case is still an open issue. With respect to PLS, the impenetrability of light has two sides. On the one hand, it offers LiFi a robust security performance in the physical layer as it makes eavesdropping more difficult. On the other hand, the transmission link is susceptible to loss of connectivity due to intended or unintended activities. Therefore, it is important to exploit HLWNets to provide secure and reliable communication links. For example, QKD is able to provide an absolute security for sending keys at a low data rate, while the encrypted data can be transmitted through a high data rate link on WiFi. Further research is still required to understand the use of HLWNets for these applications.

IX. Challenges and Research Directions

The key challenges facing HLWNets are integrating the different wireless technologies in an efficient manner. In the majority of current research, LiFi and WiFi are treated as two individual technologies, and the integration is carried out in terms of network management. In order to lift the restrictions imposed by vertical handovers, it is important to enable LiFi and WiFi to work at the same time, realizing a parallel transmission. To achieve this goal, the integration process must not be contained in the network layer. In this section, we will discuss the challenges and future research directions of HLWNets in different layers.

A. Physical Layer and Hardware Implementation

1) Cost-Effective Hardware Integration: In order to allow the operation of HLWNets, the frond-end circuits of LiFi and WiFi need to be integrated on the same board. There are a number of common electronic components in the signal processing chains, e.g., power amplifiers, up/down converters and analogue-to-digital converters. It is feasible to share these electronic components to provide a compact and economic hardware implementation. The multi-standard RF front-end has been realized with a reconfigurable baseband filter, which is compatible with WiFi and the cellular technologies [145]. The hardware integration of LiFi and WiFi is more challenging as they use different antenna components. To simultaneously process the baseband signals of LiFi and WiFi in the same signal processing chain, they need to be converted to different frequencies. However, this would reduce the system gain and introduce more noise. It is a significant research direction to investigate the hardware integration of LiFi and WiFi to satisfy their respective requirements.

2) Modulation Suitability: While OFDM is the accepted modulation technique for WiFi, now there are a number of candidates for the modulation in LiFi, including O-OFDM, OOK and pulse modulation.[2] Among them, OOK and pulse modulation enable moderate data rates from 1 Mbps to some 100 Mbps. These single-carrier modulation techniques have a relatively low peak-to-average power ratio (PAPR). In contrast, O-OFDM with adaptive bit loading, which allows the use of bandwidth beyond -3dB, can achieve much higher data rates but requires a high PAPR. The modulation suitability relies on the LEDs and PDs used. In practice, commercial LEDs have a limited linear zone of the I-V curve with a restricted bandwidth. This renders a trade-off between the spectral efficiency and energy efficiency. Meanwhile, the PDs affect sensitivity and thus the link budget. It is necessary to study the modulation suitability for realistic LiFi front-ends. Further, the hardware integration will also have a impact on choosing the suitable modulation techniques.

B. Network Layer and Network Management

1) Parallel Transmission: In the existing literature on the topic of HLWNets, it is commonly considered to serve the user by a single AP at a time. This is subject to the conventional transmission control protocol (TCP), which does not support the packets sent from different APs to be reordered at the destination. Since 2013, the Internet Engineering Task Force (IETF) has been working on multipath transmission control protocol (MPTCP) [146], which adds a subflow sequence number in the packet overhead to solve the issue of packet reordering. Enabled by MPTCP, the users can be served by LiFi and WiFi simultaneously. This emerging approach of network management has great benefit on HLWNets in two aspects. First, it can completely avoid vertical handovers, which have been recognized as a key issue in HLWNets. Second, it offers a more flexible way of resource allocation than the single-AP association, since the traffic load of one user can now be distributed among multiple APs. For this reason, parallel transmission is a promising direction for improving the performance of HLWNets.

2) Cell Deployment Optimization: While using parallel transmission in HLWNets can eliminate vertical handovers, horizontal handovers still exist for mobile users. Offering a balance between the handover rate and SINR coverage probability, the cell deployment optimization is fundamental to the network convergence of HLWNets. This optimization process involves a number of factors. The first factor includes the properties of LEDs in terms of their density, locations, FoV, output optical power, etc. Second, the placement of WiFi has an impact on the coverage requirement for LiFi. Third, it is necessary to consider the influence of user behavior. For instance, the optimized cell deployment in [20] would not be ideal when users are seldom located in room corners. Finally but importantly, the cell deployment must meet illumination

[2] Pulse modulation is currently under discussion in IEEE P802.15.13.

constraints. Hence, the optimization on cell deployment is a complicate issue and solving it is challenging. An effective approach to this issue is yet to be developed.

3) Intelligent Network Management: The core component of HLWNets is network management including handover, resource allocation and load balancing. The challenges lie in two main aspects: problem complexity and processing time. As discussed, hybrid networks are much more complex than homogeneous networks, in terms of both the density of APs and their network topology. This significantly increases the complexity of network management. Meanwhile, the processing time is restricted as the mobility of indoor users is relatively high for ultra small cells. Particularly, a drastic change in the device orientation can greatly affect the LiFi channel conditions in a split second. Handling an adaptive network management within a limited amount of processing time is one of the key research topics for HLWNets. One potential approach is applying machine learning, which is capable of solving complex optimization problems where an explicit mathematical model is hard to establish. However, it is difficult to collect sample data in a real-time networking system as the best solution is unknown. Using machining learning in such an unsupervised scenario to realize intelligent network management is still an open issue.

C. Application Layer

1) HLWNet-Facilitated WLAN: In the WLAN domain, there are many different use cases with a wide variety of different requirements. For instance, the data rate of VoIP is around 100 kbps within a 150 ms latency, whereas virtual reality consumes multi-Gbps with a latency requirement less than 20 ms. This results in the demand for high adaptability of the wireless communication system, which HLWNets can well support thanks to the high complementarity between LiFi and WiFi. When using HLWNets to provide service to these applications, it is necessary to consider their different requirements in the network management. In other words, the network convergence of HLWNets is better to be carried out across the physical layer, network layer, transport layer and application layer, rather than being done in each layer separately. The cross-layer design for homogeneous networks has been extensively investigated in the past decade, e.g., [147]. As for HLWNets, there are quite a few unsolved challenges, such as resource description, compatible MAC protocol, prioritized packet routing, etc.

2) HLWNet-Facilitated IoT: Besides WLAN, HLWNets can also contribute to the prosperity of IoT. First, the small cell nature of LiFi allows it to readily support a very high density of IoT devices, while WiFi provides ubiquitous coverage to guarantee connectivity. Second, in some scenarios such as a factory, the radio propagation environment can be quite challenging. This is due to a large number of metallic objects in the immediate surroundings of transmitter and receiver, as well as potentially high interference caused by certain industrial machines. In this case, LiFi can complement WiFi to provide robust and reliable wireless links. Third, many IoT applications have stringent requirements on security and privacy, which can be enhanced by the HLWNet due to its nature of high PLS. Last but not least, IoT requires low power consumption that enables devices to operate for many years on a single charge. Backscatter communications in both RF and VLC have attracted massive research attention to reduce the power consumption and cost of IoT devices. Combining with energy harvesting, it is feasible to develop self-powered IoT devices, which completely avoid the hassle of charging and significantly reduce the maintenance cost.

X. Conclusion

Along with the looming spectrum crunch in RF, LiFi has emerged in recent years as a promising technology for indoor wireless communications. At the mean time, WiFi continues its wide deployment in daily life. The coexistence of LiFi and WiFi is gaining momentum with the roll-out of LiFi commercial products from companies such as pureLiFi and Signify. Located in the same local area, LiFi and WiFi can be readily managed through a central control unit, forming the structure of HLWNets. Combining the high data rate of LiFi and the ubiquitous coverage of WiFi, HLWNets are able to provide greater network performance than a single wireless technology. Research on implementing HLWNets in realistic environments and optimizing the network performance is underway.

This article introduced a framework of system design for HLWNets, followed by an overview of key performance metrics and recent achievements, validating the superiority of HLWNets against stand-alone networks. The modeling work on user behavior was summarized in terms of user movement, device orientation and light-path blockage, highlighting the importance of practical user behavior models to LiFi and HLWNets. Afterwards, the existing studies were classified and analyzed for three key technical topics: interference management, handover and load balancing, with the unique challenges in supporting user mobility identified. Further, we discussed the benefits of HLWNets to application services, exemplified by indoor positioning and physical layer security. Finally, the challenges and research directions for HLWNets were summarized in different layers. It is concluded that parallel transmission has the potential to eliminate vertical handovers for HLWNets, while cross-layer design can further improve network performance. The hope is that this overview paper will push forward both theoretical and experimental research towards the future success of HLWNets in the 6G era.

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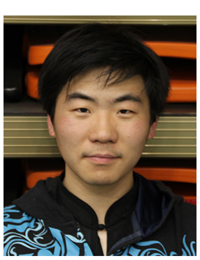

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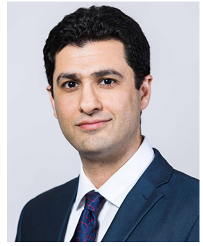

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