# Optical Wireless Hybrid Networks: Trends, Opportunities, Challenges, and Research Directions

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***Abstract*—Optical wireless communication (OWC) is an excellent complementary solution to its radio frequency (RF) counterpart. OWC technologies have been demonstrated to be able to support high traffic generated by massive connectivity of the Internet of Things (IoT) and upcoming 5$^{th}$ generation (5G) wireless communication systems. As the characteristics of OWC and RF are complementary, a combined application is regarded as a promising approach to support 5G and beyond communication systems. Hybrid RF/optical and optical/optical wireless systems offer an excellent solution for recovering the limitations of individual systems as well as for providing positive features of each of the technologies. An RF/optical wireless hybrid system consists both RF and optical-based wireless technologies, whereas an optical/optical wireless hybrid system consists two or more types of OWC technologies. The co-deployment of wireless systems can improve system performance in terms of throughput, reliability, and energy efficiency of individual networks. This study surveys the state of the art and key research directions regarding optical wireless hybrid networks, being the first extensive survey dedicated to this topic. We provide a technology overview of existing literature on optical wireless hybrid networks, such as RF/optical and optical/optical systems. We consider the RF-based macrocell, small cell, wireless fidelity, and Bluetooth, as well as optical-based visible light communication, light fidelity, optical camera communication, and free-space optical communication technologies for different combinations of hybrid systems. Moreover, we consider underwater acoustic communication for hybrid acoustic/optical systems. The opportunities brought by hybrid systems are presented in detail. We outline important challenges that need to be addressed for successful deployment of optical wireless hybrid network systems for 5G and IoT paradigms.**

***Index Terms*—5G, optical wireless communication, radio frequency, hybrid, small cell, visible light communication, light fidelity, and free-space optical communication.**

## NOMENCLATURES

| | |
|---|---|
| 5G | 5$^{th}$ Generation |
| AP | Access Point |
| AHP | analytic Hierarchy Process |
| ASE | Area Spectral Efficiency |
| ASER | Average Symbol Error Rate |
| BER | Bit Error Rate |
| BLE | Bluetooth Low Energy |
| BP | Blood Pressure |
| CATV | Cable TV |
| CDF | Cumulative Distribution Function |
| CG | Cooperative Game |
| CSMA/CA | Multiple Access with Collision Avoidance |
| DSRC | Dedicated Short-Range Communications |
| D-VHO | Dwell Vertical Handover |
| E2E | End-to-End |
| EEG | Electroencephalogram |
| eHealth | Electronic Health |
| EMG | Electromyography |
| EXP3 | Exponential Weights for Exploration and Exploitation |
| FAP | Femtocell Access Point |
| FMC | Fixed Mobile Convergence |
| FOV | Field-of-View |
| FSO | Free-Space Optical |
| HetNets | Heterogeneous Networks |
| IoT | Internet of Things |
| IR | Infrared Radiation |
| I-VHO | Immediate Vertical Handover |
| LD | Laser Diode |
| LED | Light Emitting Diode |
| LiFi | Light Fidelity |
| LOS | Line-of-Sight |
| MBS | Macrocellular Base Station |
| mmWave | Millimeter-Wave |
| MGF | Moment Generating Function |
| MIMO | Multiple-Input and Multiple-Output |

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| | |
|---|---|
| MT | Mobile Terminal |
| NLOS | Non-Line-of-Sight |
| OCC | Optical Camera Communication |
| OFDMA | Orthogonal Frequency-Division Multiple Access |
| OWC | Optical Wireless Communication |
| PD | Photodetector |
| PDF | Probability Density Function |
| PLC | Power-Line Communication |
| QoE | Quality of Experience |
| QoS | Quality of Service |
| RF | Radio Frequency |
| RSS | Received Signal Strength |
| sBS | Small Cell Base Station |
| SINR | Signal-to-Interference-Plus-Noise Ratio |
| SNR | Signal-to-Noise Ratio |
| UE | User Equipment |
| UV | Ultraviolet |
| UWC | Underwater Communication |
| UWOC | Underwater Wireless Optical Communication |
| V2X | Vehicle-to-Vehicle, Vehicle-to-Infrastructure, and Infrastructure-to-Vehicle |
| VL | Visible Light |
| VLC | Visible Light Communication |
| WiFi | Wireless Fidelity. |

## I. INTRODUCTION

THE MULTIMEDIA applications are increasing exponentially day-by-day, producing a high volume of mobile data that requires high-data-rate wireless connectivity. The forthcoming 5th generation (5G) communication will offer many new services with ultra-high system capacity, massive device connectivity, ultra-low latency, ultra-high security, ultra-low energy consumption, and extremely high quality of experience (QoE) [1]–[6]. The support of the extremely high volume data poses a great challenge for the future 5G and beyond communication systems. Hence, the exponentially growing usage of mobile data demands efficient technical solutions to guarantee quality of service (QoS) for end users.

It is well established that communications based on radio frequency (RF) are becoming more restricted owing to the limited spectrum resources in wireless networks [7]–[9]. Hence, to support the growing demand, many researchers currently consider license-free optical spectrum [1 mm–10 nm] as a promising complementary technique of RF. Optical wireless communication (OWC) is such a system that uses optical spectrum as the communication medium [10]–[17]. Due to the rapid progress of light emitting diodes (LEDs), OWC has become a promising solution [18]. OWC technology can use a vast optical spectrum as well as provide high-quality communication features such as electromagnetic interference free, high security, and high energy efficiency [19]–[23]. Using OWC, a data rate of 100 Gbps is demonstrated at standard indoor illumination levels [24]. To realize wireless data delivery, some OWC technologies, e.g., visible light communication (VLC) and light fidelity (LiFi), use existing illumination infrastructure [25]–[27]. Moreover, OWC technologies completely support the growing trend toward energy efficient communication [28]. As most of the OWC technologies do not require an extensive infrastructure, an all-important green agenda can be sustained and the installation costs can be minimized [29]. Since light does not penetrate the surrounding walls, OWC can support improved data security. In OWC, visible light (VL), infrared radiation (IR), or ultraviolet (UV) spectra are used as propagation media. Numerous wireless systems are being developed on the basis of these three optical bands. The most promising OWC technologies are VLC, LiFi, optical camera communication (OCC), and free-space optical (FSO) communication [30]. The propagation media, communication protocol, architecture, and application scenario for each of these technologies are different. VLC, LiFi, and OCC have some similarities and differences that are briefly discussed in the subsequent section. In spite of the advantages of OWC systems, some limitations exist such as strong dependence on line-of-sight (LOS), small coverage area, sensitivity to sudden blockage of a connection, interference created by different light sources, performance degradation by the outdoor atmosphere, and limited transmitted power. Hence, overcoming these limitations is a challenging issue for a successful OWC deployment. The use of an RF band (3 kHz–300 GHz) is strictly regulated by different local and international authorities [30]. Moreover, interference is a serious issue in RF-based communications. However, wireless technologies based on RF support higher mobility and better performance in non-line-of-sight (NLOS) conditions. These special features of RF systems can overcome a few limitations of OWC systems.

To provide high QoS, the convergence of heterogeneous networks (HetNets) consisting of both RF and optical wireless-based networks will play an important role in integrating a diverse spectrum. The simultaneous operation of two or more different access technologies such as macrocell, microcell, femtocells, and attocell is termed as HetNets. In HetNets, different access technologies incorporate each other for traffic offloading as well as to overcome the QoS constraints. An additional tier in HetNets offers additional wireless capacity where it is needed. To overcome the constraints of both RF and optical wireless systems, researchers have proposed some hybrid RF/optical wireless systems [31]–[46]. The RF/optical wireless hybrid system consists both RF and optical based wireless technologies, where end users can benefit from the wide coverage area that RF systems ensure and the stable rates that optical wireless systems provide. Such networks are practically feasible as RF and OWC systems can coexist without causing interference for each other and can operate in the same environment, such as offices and rooms.

The hybrid approach integrates two or more different technologies [e.g., RF/optical, RF/FSO, wireless fidelity (WiFi)/LiFi, femtocell/VLC, power-line communication (PLC)/VLC, Bluetooth low energy (BLE)/OCC, VLC/FSO, LiFi/OCC, and acoustic/optical] and is capable of providing some benefits of both technologies [39], [47]–[63]. Hybrid networks can play an important role in load balancing,

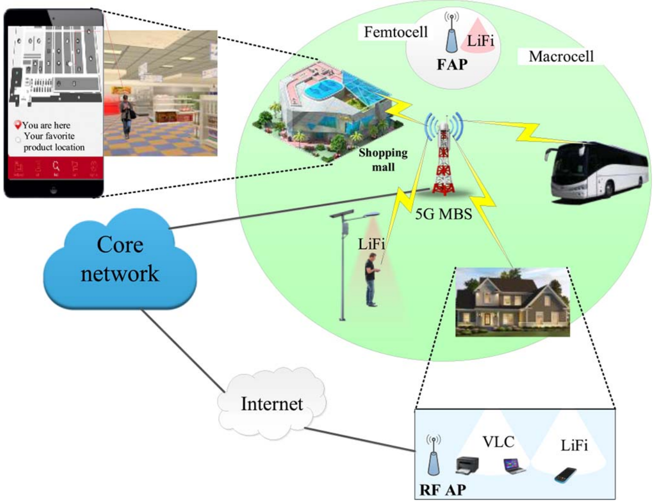


Fig. 1. Provision of multi-tier networks using optical wireless hybrid networks.

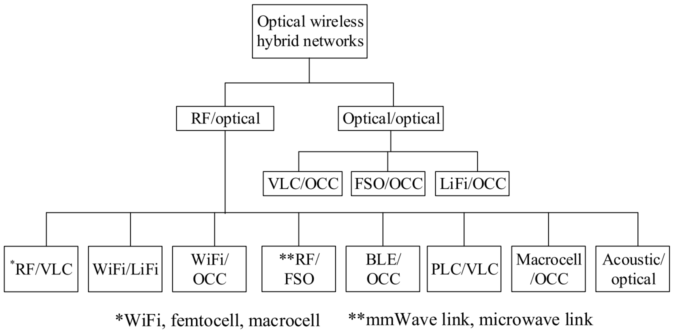


Fig. 2. Important optical wireless hybrid systems discussed in this paper.

link-reliability improvement, seamless movement, energy-efficiency enhancement, wireless connectivity availability in remote places (e.g., deep-space, deep-ocean, and deep-ground situations), security enhancement, and interference reduction. Therefore, such networks have attracted considerable research attention. In terrestrial, we can have both RF/optical and optical/optical wireless hybrid systems. For both these systems, there can be various combinations of hybrid systems. The optical/optical wireless system consists two or more types of OWC technologies.

Acoustic communication can be considered for an acoustic/optical wireless hybrid system in underwater communication (UWC). Various types of hybrid systems can be chosen for different communication environments as demanded. The possibility of building multi-tier networks is an important benefit of hybrid networks. In a multi-tier architecture, network coverage is overlaid by the coverage of one or several additional networks. Fig. 1 shows an example of the provision of multi-tier networks using optical wireless hybrid systems. This figure shows that a 5G macrocellular base station (MBS) provides a wider coverage area. Inside a home, the RF access point (AP), e.g., WiFi or femtocell AP (FAP), creates a small tier. The availability of VLC or LiFi attocells adds new tier, creating three-tier networks. A LiFi using street light also creates a two-tier network. Inside a shopping mall, users can use the OCC system to locate themselves as well as to discover product information, thus creating a two-tier network. Inside a bus, users can access macrocell, femtocell, or LiFi attocell networks, creating three-tier networks. A femtocell [64] is the RF small cell used to extend the cellular network connectivity within the premise of a targeted geographic area. A cellular LiFi network is referred to as the attocell network, whose cell size is smaller compared to a typical RF femtocell [65].

To the best of our knowledge, there is no review article in the literature on the optical wireless based hybrid system. In this paper, we present an article that comprehensively covers the area of optical wireless hybrid systems. Though, several works have been carried out on OWC and related technologies, but these survey articles focus only on different OWC technologies which is not sufficient. For better illustration, we present the related surveys/reviews of OWC and related technologies in Table I with a brief description on their main contributions. Our paper is one of the extensive surveys and it focuses on the optical wireless hybrid systems. It discusses different issues relating to various wireless hybrid systems comprising the OWC networks. This study discusses different issues pertaining to various wireless hybrid communication systems comprising OWC networks. We consider different OWC technologies such as VLC, OCC, LiFi, and FSO as well as RF technologies such as a femtocell, WiFi, macrocell, and microwave/millimeter-wave (mmWave) links for the possible combinations of hybrid solutions. In addition, acoustic communication is considered for a hybrid acoustic/optical system in UWC. Different important wireless hybrid systems discussed in this paper are shown in Fig. 2. The considered hybrid networks are RF/VLC, RF/LiFi, RF/OCC, WiFi/VLC, femtocell/VLC, WiFi/LiFi, femtocell/LiFi, RF/FSO, PLC/VLC, BLE/OCC, acoustic/optical, VLC/OCC, LiFi/OCC, and FSO/OCC. The contributions of this paper can be summarized as follows:

1) Possible wireless technologies that can be used for various hybrid systems are summarized.
2) The two categories of systems, namely, RF/optical and optical/optical wireless hybrid networks, are presented.
3) Various wireless hybrid systems in different application scenarios such as indoor, vehicle, localization, free-space, underwater, and electronic health (eHealth) are explained.
4) Recent works on RF/optical and optical/optical wireless hybrid networks are surveyed and the research trends are discussed.
5) The network selection, handover, resources sharing, packet scheduling, and load balancing issues for hybrid networks are discussed.
6) The challenging issues related to the hybrid system deployment are discussed.
7) Future research directions for hybrid systems are presented.

The rest of the paper is organized as follows. Section II provides a brief overview of the hybrid system development. The RF/optical wireless hybrid systems and their potentials, trends, and research directions are discussed in

TABLE I
RELATED SURVEYS/REVIEWS ON OWC AND ASSOCIATED TECHNOLOGIES

| **Year** | **Journal** | **Paper** | **Main contribution** | **Optical wireless system** |
|---|---|---|---|---|
| 1997 | Proceedings of the IEEE | J. M. Kahn *et al.* [20] | Detail presentaion of the physical characteristics of infrared channels using intensity modulation with direct detection | Infrared |
| 2008 | IEEE Communications Magazine | Z. Xu *et al.* [12] | Overview of UV communications and study on related issues such as link characterization, channel modeling, link capacity, transceiver design, link duplexing, multiple access, and networking | UV |
| 2011 | IEEE Communication Magazine | H. Elgala *et al.* [9] | Reviewing and summarization of the advancements in OWC with the main focus on indoor deployment scenarios | OWC |
| 2012 | EURASIP Journal on Wireless Communications and Networking | D. K. Borah *et al.* [16] | Overview of short range and long range OWC systems | OWC |
| 2013 | IEEE Communication Surveys & Tutorials | A. Sevince *et al.* [66] | Survey of advances in VLC and FSO, and exploring the potential for integration of these two as a single field of study | VLC, FSO |
| 2013 | IEEE Communication Magazine | L. Grobe *et al.* [23] | Presenting the achievements and trends in high-speed indoor VLC | VLC |
| 2014 | IEEE Communication Surveys & Tutorials | M. A. Khalighi *et al.* [67] | Survey of FSO communication systems incluing channel models, transmitter/receiver structures, modulation, channel coding, spatial/cooperative diversity techniques, adaptive transmission, and hybrid RF/FSO systems | FSO |
| 2015 | IEEE Journal on Selected Areas in Communications | Z. Ghassemlooy *et al.* [8] | Overview of the OWC systems focusing on VLC, FSO, transcutaneous OWC, UOWC, and optical scattering communications | OWC |
| 2015 | IEEE Communication Surveys & Tutorials | D. Karunatilaka *et al.* [28] | Comprehensive survey on VLC with an emphasis on challenges faced in indoor applications | VLC |
| 2015 | IEEE Communication Magazine | A. C. Boucouvalas *et al.* [14] | Review of standardization effort for the development of OWC systems | OWC |
| 2015 | IEEE Communications Surveys & Tutorials | P. H. Pathak *et al.* [68] | Survey of a systematic view of VLC research and identify important challenges | VLC |
| 2015 | IET Optoelectronics | N. Saha *et al.* [69] | Survey of OCC systems including OCC overview, implementation issues, modulations, challenges, and researcher directions | OCC |
| 2016 | IEEE Access | H. Kaushal *et al.* [70] | Overview of recent advances in UOWC along with channel characterization, modulation schemes, coding techniques, and various sources of noise | UOWC |
| 2016 | Digital Communications and Networks | L. U. Khan [71] | Survey of the potential applications, architecture, modulation techniques, standardization and research challenges in VLC | VLC |
| 2017 | IEEE Communications Surveys & Tutorials | A. Dimian *et al.* [72] | Addressing the issues related to the VLC usage in vehicular communication applications | VLC |
| 2017 | IEEE Communications Surveys & Tutorials | H. Kaushal *et al.* [73] | Survey of various challenges faced by FSO communication system for ground-to-satellite/satellite-to-ground and inter-satellite links | FSO |
| 2017 | IEEE Communications Surveys & Tutorials | Z. Zeng *et al.* [74] | Survey of UOWC research in three aspects such as channel characterization, modulation, coding techniques, together with the practical implementations | UOWC |
| 2017 | Digital Communications and Networks | I. K. Son *et al.* [75] | Classify of prospective global FSO networks into three subnetworks and detail explanation of them | FSO |
| 2018 | Journal of Lightwave Technology | T. Koonen *et al.* [10] | Overview of OWC and its supporting techniques for wide FOV receivers, device localization, bidirectional hybrid optical/radio networks, and bidirectional all-optical wireless networks | OWC |
| 2018 | IEEE Access | M. Z. Chowdhury *et al.* [30] | Overview of optical wireless technologies and clearly differentiate among these technologies | OWC |
| This paper | | | Being the first extensive survey dedicated to optical wireless hybrid systems, discusses different issues relating to various wireless hybrid systems comprising OWC networks | Hybrid RF/OWC OWC/OWC, and RF/UOWC |

Section III. Section IV discusses the optical/optical wireless hybrid network systems. Furthermore, some key challenging issues, future research directions, and lessons learned are provided in Section V. Finally, a conclusion of the review paper is presented in Section VI.

## II. SYSTEM OVERVIEW

Hybrid wireless systems facilitate the integration of two or more wireless technologies to achieve better features and overcome the limitations of individual technologies. The RF/optical wireless hybrid systems provide convergence or integration of RF and OWC networks, whereas optical/optical wireless hybrid systems provide the convergence or integration of two or more different OWC systems. The aim of hybrid wireless systems is quite similar to fixed-mobile convergence (FMC). FMC is the convergence of wired and wireless technologies into a single solution [76], [77]. It provides seamless connectivity between fixed and wireless networks

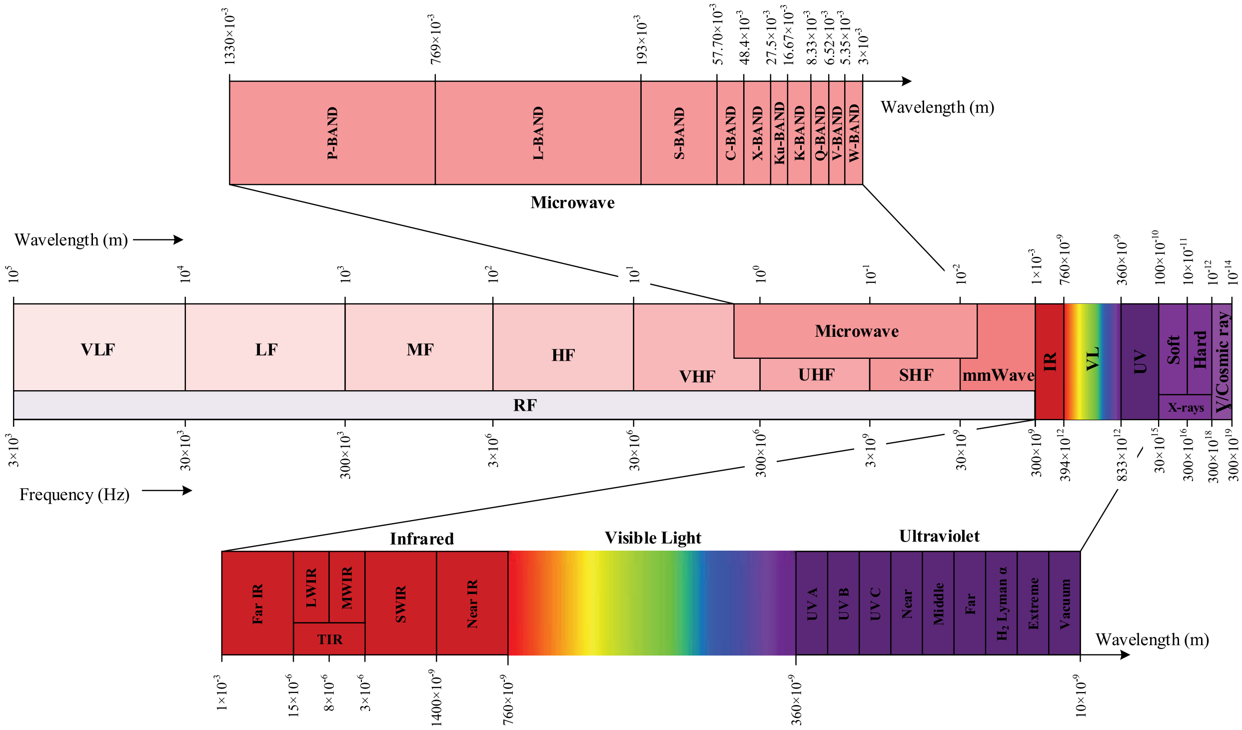


Fig. 3. Electromagnetic spectrum [30].

and can deliver services regardless of the fixed or mobile network.

### A. Brief Overview of Considered Networks for the Optical Wireless Hybrid Systems

In this study, different RF and OWC technologies, as well as underwater acoustic communication, are considered for hybrid systems. The electromagnetic spectrum employed for different RF and optical communications is presented in Fig. 3. The different categories of the electromagnetic spectrum have different names based on behavior in the transmission, emission, and absorption of the corresponding waves, and also based on their practical applications. A big portion of the electromagnetic spectrum is available for supporting the OWC systems. A brief description of OWC technologies is provided below:

*VLC* [28], [68], [71], [72], [78]–[88]: VLC uses LED luminaires or laser diodes (LDs) as transmitters and photodetectors (PDs) as receivers. It uses only VL as the communication medium and can provide communication, illumination, and localization. A 100 Gbps data rate has been achieved using VLC [24]. It can be either unidirectional or bidirectional as well as point-to-point or point-to-multipoint. Mobility and illumination supports are not mandatory in VLC. The performance of VLC is affected greatly by sunlight and ambient light sources, making it unsuitable for outdoor applications. Moreover, coverage holes are created at indoor VLC systems and the communication distance is small. A coverage hole depicts an area where the received signal strength is very low, such that communication between the transmitter and receiver is not possible.

*LiFi* [26], [65], [89]–[93]: LiFi technology is similar to WiFi. It provides high-speed wireless connectivity along with illumination. Similar to VLC, it uses LEDs or LDs as transmitters and PDs as receivers and also supports communication, illumination, and localization. In a LiFi system, transmitter and receiver are presented at both ends of the communication and thus it supports bidirectional communications. Moreover, it also supports point-to-multipoint communications. The support of mobility and illumination is mandatory in LiFi. The intensity modulation used in LiFi cannot be realized by the human eye, and therefore, communication is just as seamless as like other RF systems. The performance of LiFi is also affected greatly by sunlight and ambient light sources. In addition, coverage holes are created at indoor LiFi systems. Typically, the LiFi or VLC system can be used for the same hybrid architecture. The most important differences between LiFi and VLC system are that (i) LiFi provides point-to-multipoint communication, whereas it is not mandatory for VLC to provide point-to-multipoint communication, and (ii) VLC uses VL as the communication medium, whereas LiFi uses VL for the forward link and VL or IR for the reverse link [30].

*OCC* [94]–[104]: OCC employs LEDs and a camera as the transmitters and receiver, respectively. The data transmitted from different light sources are easily captured and distinguished simultaneously using the image sensor of a camera [30]. Sunlight and other background noise sources are discarded by separating the pixels associated with them. Hence, the OCC system can provide interference-free communication even in outdoor conditions. Although OCC provides stable performance in outdoor environments, the achievable data rate is comparatively low. Consequently, the only

TABLE II
COMPARISON OF VARIOUS OWC TECHNOLOGIES [8], [24], [27], [30], [67], [94], [105]–[109]

| **Issue** | **VLC** | **LiFi** | **OCC** | **FSO** |
|---|---|---|---|---|
| Transmitter | LED/LD | LED/LD (combined LDs with optical diffuser) | LED | LD |
| Receiver | PD/camera | PD | Camera | PD |
| Communication distance | 20 m | 10 m | 60 m | More than 10,000 km |
| Mobility support | Not mandatory | Mandatory | Not mandatory | No |
| Interference level | Low | Low | Zero | Low |
| Communication topology | Unidirectional or bidirectional | Bidirectional | Unidirectional | Unidirectional or bidirectional |
| Data rate | 10 Gbps using LED and 100 Gbps using LD | 10 Gbps using LED and 100 Gbps using LD | 55 Mbps | 40 Gbps |
| Spectrum | VL | IR/VL/UV | IR/VL | IR/VL/UV |
| Spectrum regulation | No | No | No | No |
| Advantages | -Very high data rate<br>-Very wide available spectrum<br>-Wide range of applications<br>-Simultaneous use of illumination and communication<br>-High security | -Bidirectional communication<br>-Point-to-multipoint communication<br>-Low mobility support<br>-Very high data rate<br>-Very wide available spectrum<br>-Wide range of applications<br>-Simultaneous use of illumination and communication<br>-High security | -Good performance in outdoor conditions<br>- Simultaneous use of illumination and communication<br>-High security | -Very high data rate<br>-Very long rage communication<br>-High security<br>-Performance not significantly affected by rain |
| Limitations | -Mobility support not guaranteed<br>-Small coverage area<br>-Performance affected by environment condition<br>-Poor performance in outdoor applications<br>-May create coverage hole<br>-Very limited NLOS communication | -Small coverage area<br>- Performance affected by environment condition<br>-Poor performance in outdoor applications<br>- May create coverage hole<br>-Very limited NLOS communication | -Not for long range communications<br>-Only low-data-rate applications<br>-Only LOS communications | -Performance significantly affected by fog, snow, and dust<br>-Suffers from transmitted-receiver misalignment<br>-Only LOS communications |

applications supported by OCC are applications requiring low data rates.

*FSO* [73], [111]–[113]: FSO uses LD and PD as the transmitter and receiver, respectively. Laser lights produced from the LD transmitter of the FSO system are concentrated, and because of their coherent nature, they can travel long distances. Given this nature, LDs cause less interference and enable high-data-rate communication. This technology is normally operated using the IR as the communication medium. It provides an exceptionally long distance point-to-point communication with an excellent high data rate. The performance of FSO is affected by the conditions of the environment. Moreover, precise pointing is challenging especially when the transmitter or receiver or both are in mobility.

Table II presents the comparison of various OWC technologies in terms of some important features. Hybrid systems comprise not only OWC technologies, but may also include RF technologies. A brief description of some popular RF wireless technologies is provided below:

*RF small cell network* [64]: RF small cells, e.g., the femtocell network technology, are widely deployed in subscribers' homes to provide high QoS. The small cell base station (sBS), e.g., FAP, is a small-size cellular base-station deployed to serve 6–8 users. The sBSs are operated in the spectrum licensed for cellular service providers. Small cell networks allow service providers to extend cellular connectivity toward the cell edge, especially where the access is limited or unavailable. Existing broadband networks, e.g., Ethernet, cable TV (CATV), and PLC networks are used for backhauling the traffic of small cell networks. The RF frequency spectrum employed for small cells is very valuable and needs to be managed efficiently. Small cells technologies are excellent approaches to deliver the benefits of FMC.

*Macrocellular network:* This technology is most extensively deployed in outdoor to provide a higher coverage area and user mobility. However, the MBS cannot provide higher data rate connectivity, and its capacity is low for serving a large number of users, and hence its valuable spectrum should be managed very carefully.

*Microwave-link network* [114]: Microwave link communication systems use a beam of radio waves in the range of microwave frequency to transfer information between two points at a long distance with a high data rate. A 12.6 Gbps communication link is demonstrated in [114]. A microwave-link communication system provides a point-to-point communication and is a good alternative to optical fiber connectivity, especially for remote areas. It can provide a communication link for over 100 km distance. The performance of this communication is impacted by weather conditions, e.g., rain and solar storm.

*Bluetooth* [115], [116]: Bluetooth is a wireless technology standard for exchanging data up to 2 Mbps data rate over short

TABLE III
KEY ADVANTAGES AND LIMITATIONS OF VARIOUS RF TECHNOLOGIES [64], [70], [74], [114]–[120]

| Technology | Advantages | Limitations |
|---|---|---|
| WiFi | -High-data-rate communication<br>-Unlicensed free spectrum<br>-Medium coverage<br>-Moderate mobility support<br>-Low deployment cost<br>-LOS/NLOS communications | -No guaranteed QoS<br>-Low level of security<br>-Huge interference effect |
| Femtocell | -Guaranteed QoS<br>-Medium coverage<br>-Moderate mobility support<br>-LOS/NLOS communications | -Limited spectrum<br>-Limited capacity |
| Macrocell | -Guaranteed QoS<br>-Large coverage<br>-Full mobility support<br>-LOS/NLOS communications | -Limited spectrum<br>-Low data rate<br>-Expensive |
| Microwave/mmWave link | -Performance not significantly affected by snow, fog, and dust | -Performance significantly affected by rain<br>- Subject to electromagnetic and other interference |
| Bluetooth | -Unlicensed free spectrum<br>-LOS/NLOS communications | -Low level of security<br>-Large interference effect<br>-Limited operational range |
| Underwater acoustic communication | -Long range communication<br>-LOS/NLOS communications | -Very low data rate<br>-Long propagation delay<br>-Sensitive to the nature of water |

distances using short-wavelength radio waves in the 2.400–2.485 GHz band. Its power consumption is very low and its security level is also low.

*WiFi* [117], [118]: WiFi technology provides RF-based wireless local area networking of devices based on the IEEE 802.11 standard. IEEE 802.11ad can support up to approximately 8 Gbps data rate. There are security concerns in this technology even though several encryption systems are used.

*Underwater acoustic communication* [70], [74], [119], [120]: Underwater acoustic communication is a technology to exchange data below water, and it can provide up to 20 km UWC link range, which is the longest among all UWC technologies [121]. However, the data rate in this technology is in the kbps range only.

The key advantages and disadvantages of the mentioned RF technologies are summarized in Table III.

## *B. How Hybrid System Works?*

A hybrid system contains two or more networks [122]–[126]. These networks can be operated in different manners based on the application scenarios and type of available networks. If two networks are presented simultaneously, the following types of communication are possible.

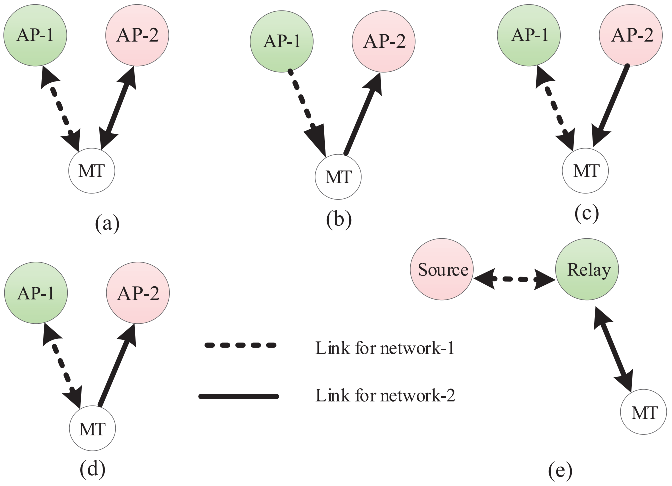


Fig. 4. Hybrid network topology: (a) both the networks for both uplink and downlink, (b) network-1 for downlink and network-2 for uplink, (c) network-1 for both uplink and downlink and network-2 for downlink, (d) network-1 for both uplink and downlink and network-2 for uplink, (e) network-1 for communication between source and relay, whereas network-2 for communication between relay and destination.

- Access both networks simultaneously: The receiver receives information from both the networks simultaneously, thereby improving the system's reliability.
- Access the best network from one of the available networks: The receiver assesses the best network from the available networks.
- Access one network for forward and another for return paths: In this hybrid system, one network is used for the forward path and another network for the return path.
- Access based on traffic type: Different applications require different levels of QoS, supported by a variety of networks. Hence, based on the application type, the available networks are classified to serve the specific purposes.
- Access top priority network and keep others as a backup network: In this system, one network is used for connectivity and another network is kept as a backup.

Fig. 4 shows the hybrid network topologies [31], [127]–[131]. Any of the available networks can serve as the uplink or downlink or both. Nevertheless, in relay type hybrid system also termed as mixed network, one network establishes communication between the source and relay, whereas another network establishes communication between the relay and destination. The figure shows that AP-1 and AP-2 of network-1 and network-2, respectively, serve for the mobile terminal (MT) in different manners. All possible combinations to communicate a MT is shown in this figure.

The important issues regarding a hybrid system include the sharing of resources, uplink/downlink sharing protocol, packet scheduling, mobility support, load balancing, network selection, and physical layer security. A joint resource allocation system iteratively optimizes the power and bandwidth allocated by the APs to their associated users in a hybrid wireless system. Several studies already addressed resource allocation issues in their work. The joint algorithm presented in [33] optimizes the power and bandwidth allocated by the RF and VLC APs to their associated users. It settles the non-concave optimization problem by solving a power allocation sub-problem and a bandwidth allocation sub-problem using alternating optimization. The bandwidth aggregation protocol in [132] distributes data packets to the VLC and RF communication links and subsequently merges these distributed packets in the same order at the destination. Because of the blockage of the communication link, some of the transmitted packets toward the VLC link can be lost. This presented protocol is appointed with a retransmission functionality to retransmit the lost packets through RF communication. This bandwidth aggregation protocol employs a throughput-optimal scheduler. This scheduling decision is vital to the overall system performance. The presented distributed channel allocation and rate control approach in [59] solves the cross-layer design problem in the FSO/RF hybrid system. It applies the carrier-sense multiple access with collision avoidance (CSMA/CA) protocol and determines the channel usages by measuring the channel demands of links. The link adaptation scheme in [52] jointly optimizes the overall mutual information of the communication system, which is maximized for RF/optical wireless hybrid systems. The total system power is jointly and optimally distributed to the individual channels. Wang *et al.* [133] presented an evolutionary game theory based load balancing for an indoor RF/LiFi hybrid network. This system jointly deals with the AP assignment and resource allocation rather than only focusing on the network selection. Moreover, the max-min fairness and proportional fairness schedulers are employed in the resource allocation. The medium access control protocol in [31] solves the multiple access problems for nodes in the RF/VLC hybrid network by combining the carrier-sense multiple access with the collision avoidance algorithm and the concept of parallel transmission. The dynamic resource optimization scheme for the RF/VLC hybrid system in [123] formulates a two-timescale stochastic network resource optimization problem by employing the Lyapunov optimization technique to adapt to the stochastic content arrival rates and dynamic channel conditions.

The uplink/downlink sharing approach depends on the application strategies and the type of wireless technologies used in the hybrid system. The LED-based receiver devices are not equipped with high-power. Examples of the LED-based receiver devices are the smartphones. Therefore, the LED-based OWC systems such as VLC and LiFi cannot perform well for uplink communication in a hybrid RF/optical wireless system [53], [134]. Therefore, RF system is normally used to manage and control the uplink communications in RF/optical wireless hybrid systems. The downlink communications can be managed by either optical or RF systems through different manners. Hence, the performance of the optical wireless system suitable for downlink communications depends on the nature of the optical wireless system. The OWC systems such as VLC and LiFi usually serve for high-data-rate connectivity. Meanwhile, the RF downlink acts as an accessory to support handover, to overcome the NLOS situations, and finally, to minimize the interference effect. According to Feng *et al.* [55], three possible ways were presented to provide downlink communications through RF/optical wireless hybrid system. We have the following related features for downlinks:

(i) Optical network for downlink: This is the simplest form of deployment. The downlink communication is performed by the OWC link independently. The technical hurdles in this scenario are due to LOS misalignment and blockage of light. The following usually affects the optical link: the shadowing, multipath, inter-symbol interference, multiple access interference, and phase-induced intensity noise [55].

(ii) RF as a backup of optical downlink: The RF link acts as the backup downlink in this strategy. This RF backup supports to attain higher reliability in data transmissions. Whenever a LOS misalignment or blockage occurs or the signal quality fades on the optical downlink, then the data transmission is moved to the backup RF networks. This helps to maintain uninterrupted communication. Moreover, when the optical signal quality is recovered, the transmission switches back to the optical downlink. This approach can be deployed in such environments where optical LOS blockage happens frequently.

(iii) Simultaneous optical and RF systems for downlink: In this strategy, both the optical and RF links are used simultaneously in the downlink in order to afford high-capacity transmission. This strategy maximizes the downlink data transmission rate. However, it facilitates the complex dynamic traffic management and algorithms for data stream splitting. This strategy fits very well for situations where large capacity is required. The performance of the optical link depends on the LOS blockage and user mobility. Therefore, the performance of the optical link reduces considerably due to the repeated LOS blockages and user mobility. However, these problems can be effectively managed using proper techniques such as channel coding, relay technology, and propagation protocols.

Among the problem encountered in hybrid wireless system, is the packet scheduling decision. An efficient scheduling decision adequately balances the traffic load between each of the individual systems. In a hybrid communication system, packets which arrive at the system are scheduled to be transmitted through one of the considered networks. An effective scheduling decision is very crucial to maximize the overall system performance. According to Pratama and Choi [132], they proposed a scheduling algorithm based on queue lengths for an RF/VLC hybrid system. This scheduling algorithm is also applicable to other optical wireless hybrid systems. The maximum throughput scheduling is a procedure for scheduling data packets in a packet-switched best-effort communications network, typically a wireless network with the aim of maximizing the total throughput of the network. Therefore, this scheduling algorithm maximizes the throughput of the network. A Lyapunov function was defined as a function of queue lengths. It attains the optimal scheduling strategy by minimizing the drift of the Lyapunov function. They also proposed a real-life prototype of the hybrid RF/VLC system. This packet scheduling bandwidth aggregation protocol is able to distribute data packets to the individual links in a hybrid system. It merges these scattered packets in order again at the receiver. Some of the packets assigned to an optical link can be lost due to the LOS misalignment. Some researchers [132] proposed a re-transmission technique. This approach retransmits the packets that were lost due to the optical NLOS through RF network. Their proposed approach has the ability to manage handover between optical and RF networks efficiently. This approach employs a throughput-optimal scheduler. The gateway of the hybrid RF/optical wireless system transmits all data packets into the optical and RF access networks. The packet scheduler is placed between the gateway and schedules individual packet to a subsequent optical or RF transmitter. The gateway is used for scheduling, retransmitting, and managing of all the arrived data packets at the gateway. Each packet is labeled with a sequence number. Hammouda *et al.* [135] provide data transmission to a desired network in a hybrid RF/VLC system. This approach is also applicable to other hybrid systems. It considers a multi-mechanism strategy for data transmission. The packet is sent through the link that can assure the desired QoS level. It employs ON–OFF data source to maximize the average data arrival rate and minimize the data buffering delay.

Vertical handover is a very common phenomenon in a hybrid wireless system. The greatest challenge of vertical handover is efficient management to maintain a better level of system performance. Several researchers already addressed this issue and they provided different approaches to handle this critical issue. Among several approaches are: Markov decision process, Fuzzy-logic, and Analytic Hierarchy Process (AHP). But together with the cooperative game (CG), are the most popular and effective approaches used to handle vertical handover issue in hybrid wireless systems. Wang *et al.* [18] propose and formulate an approach as a Markov decision process. They adopted a dynamic approach to achieve a trade-off between the delay requirement and the switching cost. Their scheme helps to decide whether to execute the vertical handover or not for a certain queue length and the wireless channel condition. The most common reason to perform vertical handover in an RF/optical wireless hybrid system is the LOS blockage of an optical link. However, this LOS blockage is temporary in most of the scenarios. Their approach is aimed at minimizing the ping-pong effects by predicting the interruption of the optical link. To have an efficient handover scheme, it is important to decide whether and when to perform a vertical handover once a LOS blocking occurs. Therefore, if LOS link is blocked, then the unnecessary switching is avoided. The optical link disruption mostly depends on user activities, which follow certain patterns. This is characterized by few factors such as location, time, and duration. Based on the record of these factors, the movement of a user can be predicted and thus, there is a need to model and predict the LOS interruption of optical link. Hence, the packet delivery process of a hybrid RF/optical wireless can be modeled using a Markov chain. Also, the vertical handover decision is formulated as a Markov decision process. The two basic vertical handover schemes such as immediate vertical handover (I-VHO) and dwell vertical handover (D-VHO) are applied in different vertical handover problems. Hou and O'Brien [48] proposed a fuzzy-logic based decision-making algorithm for vertical handover. This algorithm is adopted for different optical wireless hybrid systems. It shows the importance of both I-VHO and D-VHO to achieve outstanding handover decision. The fuzzy-logic addresses the uncertainty and contradiction involved in decision metrics. The predicting of handover probability is an approach to handle the vertical handover. Purwita *et al.* [136] provides a scheme for predicting of handover probability due to the random movement of a user in a WiFi/LiFi hybrid system. This approach considers RSS for developing handover algorithm. We adopt this approach for other types of optical wireless hybrid systems as well. Using the AHP with the CG can handle the multi-attribute decision-making process. The researchers in [38] provide such an approach to tackle the vertical handover in an RF/VLC hybrid system. Their AHP approach uses two decisions. These decisions are "perform vertical handover" and "not perform vertical handover" for the handover process. Their approach considers the decisions as cooperators and applies CG.

Load balancing is one of the important reasons for performing hybrid wireless system. Load balancing in an efficient way is very crucial to maximize the overall system performance. Obeed *et al.* [7] propose an iterative algorithm to educate users on access networks of a hybrid RF/VLC system. Moreover, they formulated an optimization problem to allocate the power of RF AP and VLC AP to maximize the total achievable throughput. Their algorithm discovers optimal dual variables. Also, their algorithm provides faster convergence and better performance than the subgradient method. Using this approach, a lower data-rate user transfers from one access network to another only if it increases the summation of the achievable data rates as well as enhances the system fairness. Wang *et al.* [46] proposed a multi-armed bandit model for selecting optical access network. The "exponential weights for exploration and exploitation" algorithm are raised for updating the decision of the probability distribution. Also, the exponentially weighted with linear programming algorithm are raised for updating the decision of the probability distribution. Wang *et al.* [137] proposed a dynamic load balancing scheme considering the handover overhead in a hybrid wireless system. The proposed joint optimization jointly optimizes the AP assignment. Also, the separate optimization algorithm separately optimizes resource allocation.

It is important to provide physical layer security in optical wireless hybrid systems. Marzban *et al.* [138] use this approach for a hybrid RF/VLC system. This approach is also applicable to the optical wireless hybrid system. They formulated a minimization problem of the consumed power while satisfying the user's required secrecy rate. A zero-forcing beamforming approach and a minimum power allocation algorithm were provided to perform the physical layer security challenges. Therefore, this approach is adopted to solve the physical layer security issues in different optical wireless hybrid systems.

## III. RF/OPTICAL WIRELESS HYBRID NETWORKS

Different RF/optical wireless hybrid systems can be deployed through various combinations [37], [59], [160]–[168] as required. Table IV summarizes some applications of hybrid RF/optical systems. An RF/optical

TABLE IV
SUMMARY OF HYBRID SYSTEM APPLICATIONS

| Scenario | Application type | Reference | Description | Hybrid type |
|---|---|---|---|---|
| Indoor | Load balancing and high-data rate communication | [7], [31], [36], [40], [41], [49], [57], [132], [133], [137], [139]–[145] | The hybrid systems ensure high-data rate services by providing network-sharing facilities. A huge amount of traffic is diverted to the VLC or LiFi network from highly congested and low-capacity WiFi, femtocell, or macrocell network. | WiFi/VLC, WiFi/LiFi, macrocell/VLC, macrocell/LiFi, femtocell/VLC, and femtocell/LiFi |
| | Link reliability improvement | [132]–[134] | The link reliability is improved by the existence of two or more networks. | WiFi/VLC, WiFi/LiFi, macrocell/VLC, macrocell/LiFi, femtocell/VLC, and femtocell/LiFi. |
| | Backhaul connectivity | [55] | Traffic from an RF-based network is shifted to an FSO network for the backhaul connectivity. | Microwave-link/FSO |
| | eHealth | [60], [146] | For remote patient monitoring, hybrid OCC/Bluetooth networks are used to improve system performance. | OCC/Bluetooth |
| | Localization/ navigation/ positioning | [42], [103] | Indoor smartphone or mobile robot uses a hybrid system to increase accuracy. | macrocell/VLC, macrocell/OCC, and LiFi/OCC |
| Outdoor | V2X (vehicle-to-vehicle, vehicle-to-infrastructure, and infrastructure-to-vehicle) | [147] | For the V2X communications, hybrid systems consisting of optical OCC and/or FSO and RF networks improve the link reliability. | RF/OCC and RF/FSO |
| | Vehicle localization/ navigation/ positioning | [102], [148] | Hybrid RF/OCC systems are used to establish reliable V2X communications for vehicle localization/navigation/positioning. | RF/OCC |
| | Backhaul connectivity | [55], [58], [59], [110], [111], [147], [149]–[159] | Because of the existence of microwave/mmWave as well as FSO links, the link reliability is improved. A suitable network is chosen considering the atmospheric condition. | Microwave/FSO and mmWave/FSO |
| Underwater | High-data rate, link reliability improvement, and backhaul connectivity | [70], [74], [119], [120] | Considering the communication distance, water condition, and LOS/NLOS situation, a suitable network among RF, optical, and acoustics systems is selected for communication. | RF/FSO and acoustics/FSO |

wireless hybrid network seems to offer the best of both technologies. If a user requires higher throughput, then, generally, the switch to an optical wireless network can be made. If the user requires NLOS communication or higher mobility support, then the RF wireless system is chosen. The provision of RF/optical wireless hybrid systems can be applied for both indoor and outdoor applications, including vehicular and underwater communications. A few examples of such hybrid systems are discussed in this section. Although the application scenarios for the RF/optical wireless hybrid systems is similar to that for individual RF and optical systems, the hybrid systems enhance the network performance compared to the individual systems. This section presents various cases of RF/optical wireless hybrid systems.

### A. Indoor RF/Optical Wireless Hybrid Systems

Currently, RF-based technologies such as WiFi, femtocell, and Bluetooth as well as optical wireless technologies such as VLC, LiFi, and OCC systems are widely used for most of the indoor wireless applications. For most of the indoor cases, multi-tier HetNets utilize a combination of macrocells, which provides broader coverage and lower-data-rate services; RF femtocells and WiFi, which provide improved coverage; and optical attocells, which provide additional capacity through the use of the optical spectrum. LiFi and VLC enable traffic offloading from the capacity-stressed licensed macrocells and/or RF small cell/femtocells. Hence, RF/optical wireless hybrid systems overcome the limitations of each network and facilitate the advantages of different networks. Fig. 5 shows the basic connectivity of a few indoor RF/optical wireless hybrid systems [18], [38], [44], [47], [161]. For indoor cases, the term RF is used in general for WiFi, femtocell, and macrocell networks. Since the receiver devices such as smartphones cannot be equipped with high-power LEDs for uplink communication, VLC and LiFi cannot perform well for uplink communication [53], [134] even though both uplink and downlink communications are possible. Various combinations of connectivity using a femtocell, LiFi, and VLC are shown in this figure. The OCC performs only one directional communication, with the communication in other directions performed using LiFi, VLC, or RF networks. All possible combinations of an uplink, downlink, and uplink/downlink are realized through VLC and LiFi networks. The RF systems perform both uplink and downlink communications in all the presented scenarios. These wireless hybrid systems achieve several important goals of wireless communications, such as improved throughput by load balancing, reduced interference by co-deploying of opposite nature RF and OWC technologies, smooth handover between OWC systems by supporting wider RF coverage, and improved linked reliability by provisioning both LOS/NLOS communication systems.

*1) Hybrid Systems With RF-Based WiFi and Small Cells:* Various combinations are possible using hybrid systems by considering OWC technologies with RF-based WiFi and small cells. The hybrid WiFi/VLC, small cell/VLC, WiFi/LiFi, RF/OCC, and small cell/LiFi network systems improve the

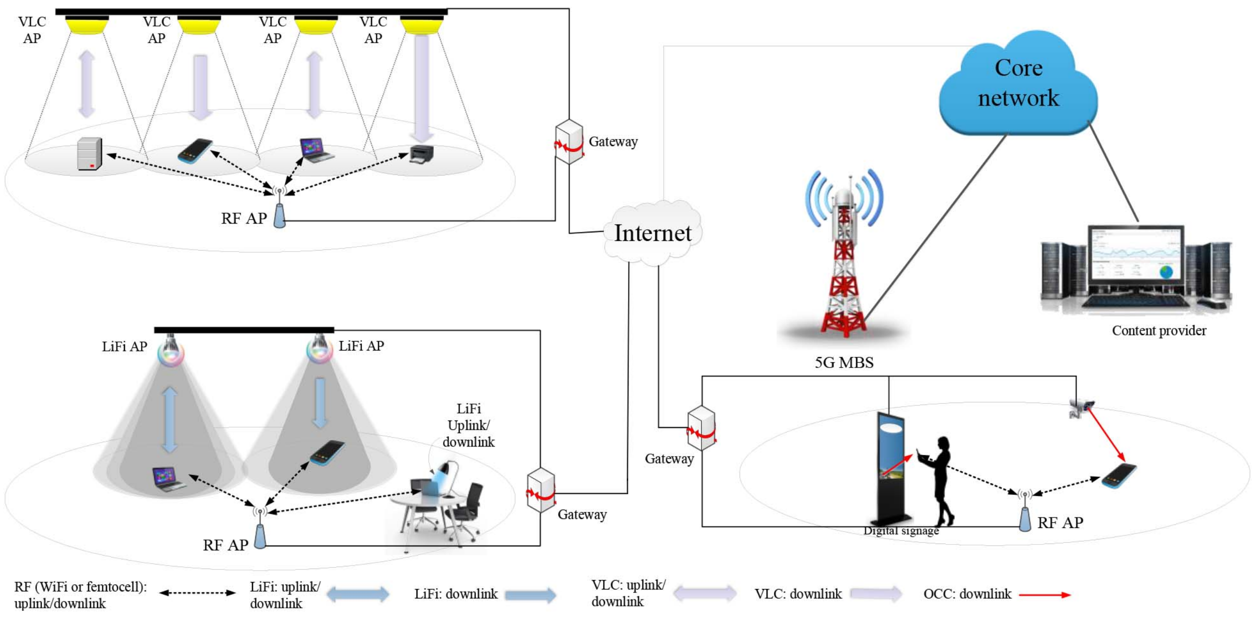


Fig. 5. Basic connectivity of indoor RF/optical system.

system performance. Both LiFi and VLC support high data rate, whereas WiFi and small cells provide comparatively wider coverage for better mobility support. If LED transmitters are situated closely, VLC and LiFi systems suffer from interference effects [148]. RF networks ensure coverage of the coverage holes created by LiFi and VLC networks, thus smoothening the handover process. Both the RF and optical APs are connected through the same gateway.

*2) Hybrid Systems With Macrocells:* WiFi or small cells are not always available in every indoor environment. For these indoor scenarios, the macrocell/VLC or macrocell/LiFi hybrid systems improve the QoS level. Background traffic that requires low mobility, high data rate, and comparatively lower QoS is served by LiFi or VLC network, whereas services that require higher mobility and comparatively higher QoS are connected to macrocell network in an indoor environment. Moreover, the macrocell network ensures coverage of the coverage holes created by LiFi and VLC networks, smoothening the handover process. Hence, similar to WiFi/VLC, small cell/VLC, WiFi/LiFi, and small cell/LiFi systems, macrocell/VLC and macrocell/LiFi hybrid systems also support traffic offloading to high-data-rate and less expensive VLC and LiFi networks, thereby improving spectral utilization, link reliability, seamless movement of optical wireless users, and security. VLC and LiFi offload the increasingly heavy traffic in the macrocellular network, thus improving the spectral and energy efficiency without introducing additional interferences [41]. This type of hybrid system is typically formed through different backhaul connectivity, as different access networks exist in the hybrid system. Optical APs are connected in homes through Ethernet, CATV, PLC, or other backhaul networks. Meanwhile, the outdoor MBS is connected through different optical fibers, FSO, or other backhaul networks. Traffic backhauling for a user through different backhaul connectivity may give rise to a synchronization problem.

*3) Network Selection in Indoor RF/Optical Wireless Hybrid Systems:* In RF/VLC and RF/LiFi hybrid systems, traffic is distributed between two networks such that better service levels are assured and resource utilization is maximized. A network in a hybrid system can be chosen on the basis of criteria such as traffic type, required level of security, required data rate, illumination requirement, mobility support, and uplink/downlink type services. Few common approaches used for network selection are fuzzy logic, queue model, and reinforcement learning. The following are details of the criteria for the selection of an appropriate network:

*Uplink/downlink transmission:* In an indoor environment, networks can be assigned based on uplink and downlink types. Normally, optical downlink provides more data volume compared to uplink. VLC and LiFi networks support higher-data-rate services compared to RF systems. Hence, VLC or LiFi networks can be used for downlink support and RF networks can be used to provide uplink support. Consequently, huge traffic can be offloaded from RF networks to optical networks and interference effect can be reduced significantly.

*Traffic type:* Few services such as real-time voice and banking require a low data rate with a high QoS level. In contrast, few traffic types such as video streaming require a high data rate, but a low QoS level is not their major concern. Hence, a network can be selected according to the traffic type as RF and OWC networks support different QoS levels.

*Required level of security:* Optical links are sensitive to obstacles. When a user uses an optical wireless network in a room, information cannot penetrate outside the room and it cannot be hacked by a person outside the room. Hence, the level of security is an important parameter for network selection for a specific service.

*LOS/NLOS:* Optical wireless systems do not provide a reliable communication link for NLOS conditions. However, RF systems can provide communication for NLOS situations. Hence, consideration of LOS or NLOS is another important parameter for network selection.

*Illumination requirement:* During certain times of a day, use LEDs may not be required for illumination purpose. For example, illumination is not required during holidays in an office, daylight, and midnight. Hence, few or all the wireless connectivity can be served by RF networks if they are able to provide services during these times.

*Mobility support:* The services that require mobility support can be served by RF networks, whereas the services that do not require significant mobility support can be served by optical networks.

*4) Opportunities for Indoor Hybrid Optical/RF Systems:* The indoor hybrid systems can bring many opportunities for wireless users. A few of them are briefly discussed below:

*Traffic offloading to optical wireless networks:* Offloading traffic to the VLC and LiFi networks can enhance the performance of RF-based unlicensed WiFi as well as licensed small cell and macrocell systems [143]. The performance is seriously degraded by high interference signals from neighboring WiFi APs and/or multiple active users sharing the limited bandwidth of a WiFi AP. Although small cell technology uses a licensed frequency band, it also causes interference. Services that require a high QoS, e.g., voice, and comparatively higher mobility can be supported by RF networks, whereas low mobility or static users with comparatively low-QoS-requirement services, e.g., background traffic, is supported by LiFi (or VLC). Hence, these hybrid systems offload huge traffic from RF networks to the LiFi (or VLC) network. The traffic offloading can be done by uplink/downlink or traffic type classification.

*Improvement of link reliability:* The existence of two or more networks surely increases the link reliability. VLC/WiFi, VLC/small cell, LiFi/WiFi, LiFi/small cell, VLC/macrocell, and LiFi/macrocell hybrid systems create two-tier networks that make reliable connectivity between transmitters and receivers.

*Enhancing seamless movement:* In addition to high-speed traffic offloading, all of the hybrid RF/VLC and RF/LiFi systems offer excellent seamless connectivity. The RF-based WiFi, small cells, and macrocells offer wider coverage area for indoor users. Hence, RF networks can support seamless movement between two optical networks by providing coverage within the coverage holes.

*Energy efficiency:* The energy consumption in an optical wireless system is low compared to that of an RF system. Moreover, LEDs are used for illumination purposes. Offloading of traffic from RF to optical networks reduces the overall power consumption. Hence, indoor RF/optical hybrid systems significantly reduce energy consumption.

*Security enhancement:* Optical wireless networks are very sensitive to obstacles. Consequently, the information cannot be hacked outside of the room. Therefore, all hybrid VLC/WiFi, VLC/small cell, LiFi/WiFi, LiFi/small cell, VLC/macrocell, RF/OCC, and LiFi/macrocell systems improve the security level.

*Interference reduction:* Interference levels in both optical and RF networks are significantly reduced in indoor RF/optical wireless hybrid networks. RF and optical signals do not interfere each other. Traffic offloading from the RF to optical wireless systems reduces the transmitted power level in a user equipment (UE) and RF APs. Using RF networks to support a coverage hole can reduce the transmitted power of LEDs. Moreover, the users severely affected by interference can be served by a less affected network in hybrid RF/optical wireless systems.

*Improvement of spectral utilization:* Provision of RF/optical wireless hybrid systems for indoor users improves the utilization of the valuable RF spectrum. High-data rate background traffic is offloaded to optical wireless networks, whereas the traffic that requires higher priority or higher mobility is supported by the RF system.

### *B. RF/Optical Wireless Hybrid in Vehicular Systems*

Due to safety issues, the link reliability is very crucial in V2X communications [72], [88], [101], [102], [169]. Although OWC has many advantages for V2X communications, its application is limited to LOS. Therefore, its combination with RF systems such as 5.9 GHz dedicated short-range communications (DSRC) improves link quality considerably. DSRC is a mature technology that can provide comparatively longer-distance communications. In contrast, except FSO, other OWC technologies cannot provide comparable communication distances, but they are considered to have a great potential in high traffic densities, whereas its large geographical distribution also signifies a great benefit [72].

VLC can support very short distance inter-vehicle LOS communications, whereas OCC can support 60 m distance and FSO can support even longer-distance point-to-point communication [109]. For comparatively longer-distance communications, the messages are transmitted in a multi-hop manner in VLC. Whenever we talk about high priority messages, multi-hop transmissions may lead to an increased end-to-end (E2E) delay. The use of RF/optical wireless hybrid systems can be applied for different V2X communications. Fig. 6 shows some application scenarios of RF/optical wireless hybrid systems in the vehicle and describes application scenarios for vehicle-to-vehicle and vehicle-to-infrastructure communications. Every vehicle on the road sends emergency information to a certain destination (i.e., other vehicles or traffic infrastructures) with the help of the nearest MBS. Using OCC, each camera mounted on the vehicle receives a signal from the forwarding vehicle, which moves inside the field-of-view (FOV) of that camera. In addition, this camera receives optical signals simultaneously from the traffic infrastructures. It is not possible to communicate with a car ahead of the front car using the OCC. Hence, DSRC is used to establish such communications. The wireless hybrid system in vehicular communication is particularly challenging due to the moving nature of transmitters and receivers, and the dynamic nature of the weather. Moreover, this scenario requires the

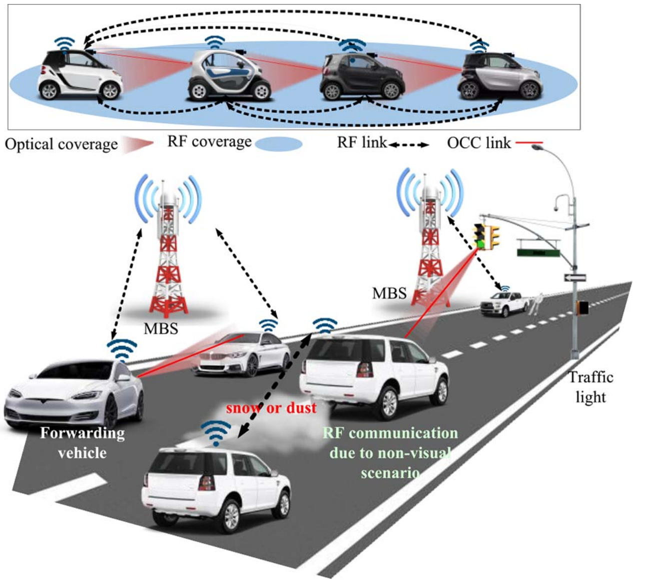


Fig. 6. Application scenarios for hybrid RF/optical networks in vehicular systems.

support of infrastructure, e.g., traffic lights and cellular connectivity.

For outdoor vehicular communication, this hybrid architecture can provide a better QoS for V2X communications [148]. The most important aspects that use the hybrid system are traffic offloading and link reliability. Offloading traffic to optical VLC network releases load from the congested RF-based systems such as DSRC, thus improving the performance of the RF system. Furthermore, the performance is seriously degraded by high interference signals from unplanned neighbor RF APs, which is also solved by offloading huge traffic to optical wireless networks. Link reliability is a very important issue in V2X communications. As a result of hybrid system, the probability of failure of a link is decreased for any situation such as the worst environment, NLOS positioning between the transmitter and receiver, and a high density of cars. Some criteria such as LOS/NLOS, required communication distance, and environment condition can be considered for network selection in such RF/optical wireless hybrid systems. The consideration of LOS/NLOS is an important parameter for network selection in RF/optical-based V2X communications. Optical FSO supports long distance communication with precise pointing between the transmitter and receiver. By contrast, OCC supports medium range communications, but VLC based on LED/PD supports only small distance communications. Existing RF systems support a medium range of V2X communications. Hence, a network can be selected on the basis of communication distance in an RF/optical wireless hybrid system. Optical systems are greatly affected by environmental conditions such as fog, dust, and surrounding lights. Therefore, environment condition is also an important criterion for selecting an appropriate network.

### C. RF/Optical Wireless Hybrid in Free-space

FSO becomes an attractive solution for wireless communication systems specially for the last mile connectivity problem because of its obvious advantages such as an extremely high available bandwidth, low-cost deployment, and license-free spectrum [170]–[181]. The FSO system provides a very high-data-rate outdoor point-to-point communication link. However, this system heavily suffers from atmospheric effect, especially in atmospheric turbulence and visibility limiting conditions such as fog, snow, and dust conditions. In particular, the FSO system relies on the availability of an LOS, which introduces critical limitations for mobile nodes [149]. The tight pointing of the transmitter toward the PD is another limitation of the FSO system. Thermal expansion, dynamic wind loads, and weak earthquakes cause vibration of the transmitter beam, thereby leading to a misalignment between the FSO transmitter and the receiver [73], [106], [113], [182]. The simultaneous use of RF systems such as microwave and mmWave [183] links can overcome these limitations. The RF links using mmWave or microwave suffer heavily in rainy condition. In addition, RF systems cannot provide very long-range and high-speed communication. Therefore, the FSO/RF hybrid system is a potential solution for ensuring the reliability of the link in different weather conditions. This is because links are affected differently depending on the weather conditions. An FSO system is used as the primary network, whereas an RF system acts as a secondary backup network in an FSO/RF hybrid system. This hybrid system can be used for even very long distance free-space communication systems such as airplane-to-airplane, inter-satellite, satellite-to-earth, earth-to-satellite, satellite-to-airplane, airplane-to-satellite, airplane-to-ground, ship-to-ship, and ship-to-infrastructure links with very high reliability.

Fig. 7 shows an overview of hybrid RF/FSO system deployments. The system model shows that one of the available networks is used for link connectivity. The hybrid systems containing two networks of RF and FSO links are used to make inter-networking with increased link reliability. The connectivity through the relay is an important feature of this hybrid system. This relay-based hybrid system is also termed as mixed RF/FSO network. Some examples of possible connectivity are also shown in this figure.

For free-space communications, this hybrid architecture ensures better link reliability for different environment conditions. The most important benefit of this hybrid system is the availability of a link at any worst environmental condition. It can work well in all the weather conditions. Due to dynamic changes in the weather conditions, appropriate network selection is important in hybrid RF/FSO connectivity. The most important parameters to be considered for network selection in hybrid RF/FSO systems are environment condition and required communication distance. The FSO link is greatly affected by fog, dust, and snow, whereas microwave and mmWave are greatly affected by rain. For normal weather conditions, the FSO system can be operated, while a link can be selected on the basis of the nature of the weather. However, FSO can provide even longer communication range compared to RF links. Hence, a network can be selected according to the required communication distance.

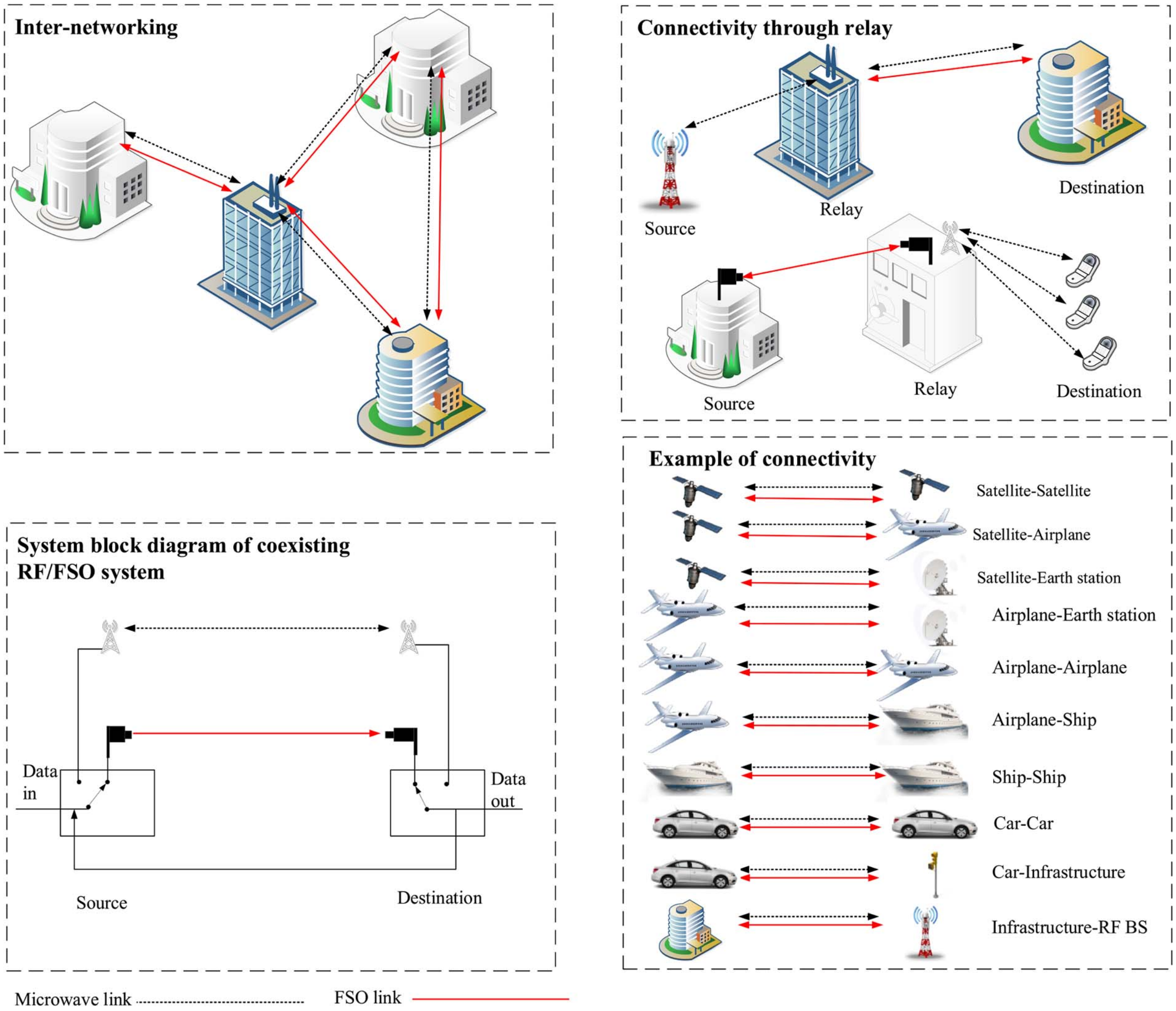


Fig. 7. An example of outdoor hybrid RF/FSO networks and their deployments.

### *D. RF/Optical and Acoustic/Optical Hybrid Networks in Underwater*

In recent years, underwater wireless optical communication (UWOC) has attracted much attention due to its consideration in various potential applications such as environmental monitoring, oil pipe investigation, and offshore investigation. Long-range and high-speed links are required for many applications of UWC. The possible means of realizing underwater communications are acoustics, RF, and optics [184]–[191]. Compared to RF-based terrestrial communications, underwater communications based on RF and acoustic waves cannot support high-data-rate communication link. Because acoustic communication provides up to 20 km underwater communication link range, which is the longest among all UWC technologies, it is widely employed method in the underwater wireless communication [121]. However, since the frequency range of operation of this system is between tens of hertz and hundreds of kilohertz, the data rate in this system is in the kbps range only [121]. Moreover, due to the slow propagation speeds, acoustic links are prone to serious communication delay. RF results in extremely poor performance for long distance underwater communications because of the severely affected factors such as multi-path propagation, time variations of the channel, and strong signal attenuation, especially over long ranges. Hence, the RF systems are limited by the associated short link range. Employment of 405-nm blue light LD is expected to be an important research issue for a long-range UWC. Communication using optical systems can provide Gbps level LOS data-rate link [70] within a 10–100 m distance. The excellent technical advantages of UWOC are the lowest link delay, highest communication security, highest transmission rate, and lowest implementation costs compared to other methods [121], [186], [187]. However, UWOC cannot perform well for NLOS scenarios and precise pointing between the transmitter and receiver is essential for LOS scenarios. Moreover, the performance of UWOC systems can be severely degraded by the absorption and scattering effects of seawater, channel turbulence, misalignment errors, and other impact factors [74], all of which can cause recurrent communication failure. Thus, the reliability of UWOC systems should be enhanced. Table V shows basic differences among three underwater communication technologies.

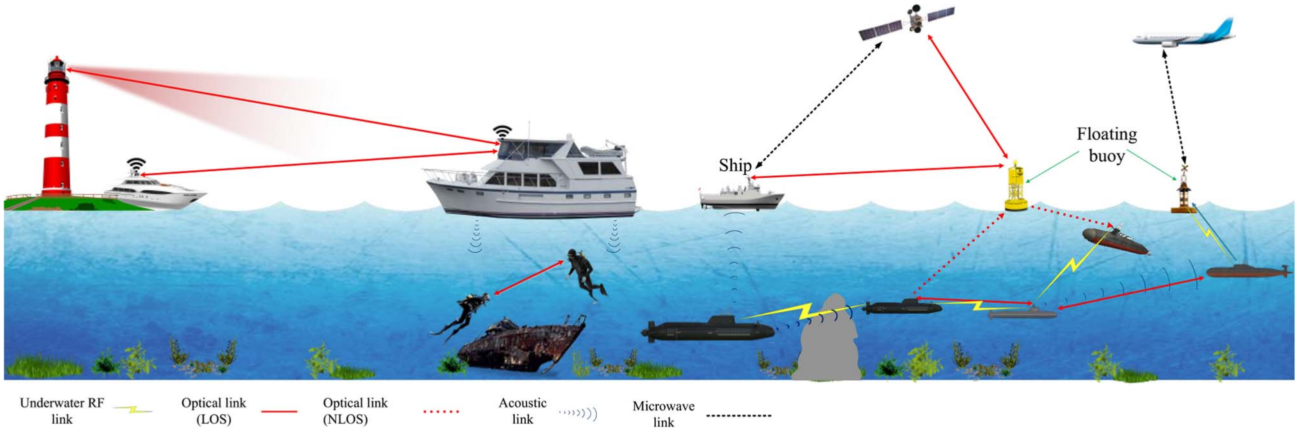


Fig. 8. Basic connectivity of a hybrid RF/optical system in underwater communications.

TABLE V
BASIC DIFFERENCES AMONG THREE UWC TECHNOLOGIES [70], [74], [119] [120], [185]–[191]

| Issue | RF | Acoustic | UWOC |
|---|---|---|---|
| Frequency | 30–300 Hz or MHz ranges | 10 Hz–100 kHz | $10^{12}$-$10^{15}$ Hz |
| Transmitted power | In the range of milliwatt to watts | Typically tens of watts | Few watts |
| Data rate | Mbps range | kbps range | Gbps |
| Communication distance | up to 10 m | up to 20 km | 10–100 m |
| Antenna size | 0.5 m | 0.1 m | 0.1 m |
| Performance parameter | Conductivity and permittivity | Temperature, salinity, and pressure | Absorption, scattering, turbidity, and organic matter |
| Propagation delay | Moderate | High | Low |
| Attenuation | 3.5–5 dB/m | 0.1–4 dB/km | 0.39 dB/m in the ocean and 11 dB/m in turbid |
| LOS/NLOS | Both | Both | LOS only |

Based on the discussion on the merits and demerits of each of the UWC technologies, it can be decided that the presence of more than one communication system, i.e., a hybrid system, can overcome the limitations. We can have RF/optical or acoustic/optical or even RF/acoustic/optical hybrid systems for UWC. Fig. 8 shows some basic connectivity for hybrid RF/optical, RF/acoustic, and acoustic/optical systems in underwater communications. Communication among different nodes inside the water as well as between a node inside water and that outside water is possible.

The hybrid systems can bring important advantages for UWC such as traffic offloading to optical wireless networks and improve link reliability. In a hybrid system, traffic offloading to an optical network increases the system capacity as RF and acoustic networks cannot offer a very-high-capacity link like optical wireless networks. In an RF/optical hybrid system, high-data-rate services for both long and short distance communications can be realized using the optical wireless system, whereas the RF system can serve short distance communication. Similarly, in an acoustic/optical hybrid system, high-data-rate LOS services are supported using the optical wireless system, whereas the acoustic system can serve in NLOS communications. Link reliability is lower in UWC compared to air communications. Hence, the existence of two or more communication systems definitely ensures higher link reliability. The RF or acoustic system can perform during lose pointing between the transmitter and receiver, thereby improving the link reliability. The most important criteria for suitable network selection in underwater communications are required communication distance, traffic type, and precise pointing of optical link. The acoustic system can be used for very long distance communication, while the RF system can be used only for very short distance communication. UWOC can be used for medium distances with support for high-data-rate communications, and it requires very high precise pointing between the transmitter and receiver. Hence, during precise pointing situations, the links can be supported by UWOC, and by RF or acoustic systems in other situations.

### *E. RF/Optical Wireless Hybrid in eHealth*

The provision of a good monitoring system is very important in healthcare systems. Currently, most of the countries are emphasizing on the improvement of human healthcare systems [146], [192]. For any potential eHealth solution to be viable, wearable sensors/patches-to-access network connectivity is necessary. This communication is currently performed using RF-based BLE technology. There are several disadvantages of using the existing RF technologies for eHealth solutions. RF for healthcare solutions causes serious electromagnetic interference effects and many medical devices are extremely sensitive to such electromagnetic interference, leading to device malfunctioning. However, BLE provides communication link in NLOS conditions. An OCC system is a complementary promising solution for wearable sensors/patches-to-access network connectivity. The main limitation of this is the non-availability of the link during NLOS conditions. Hence, in future eHealth systems, a hybrid system containing

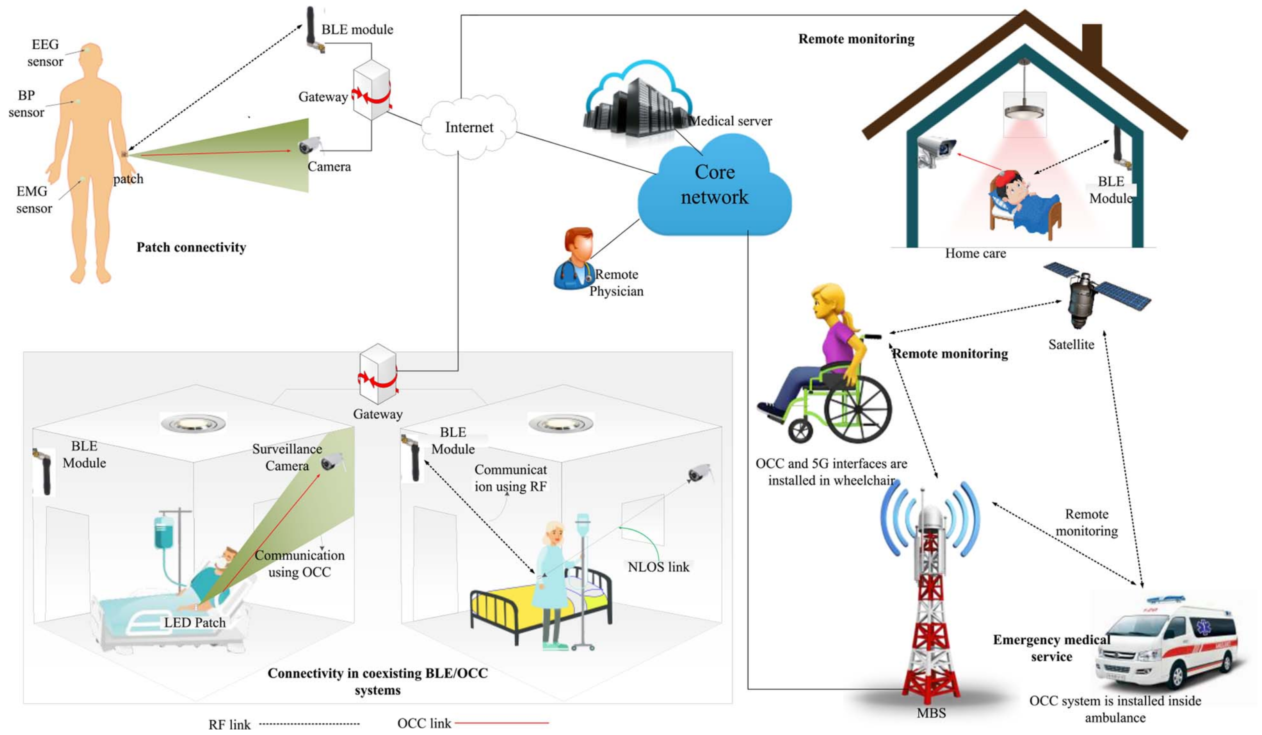


Fig. 9. Examples of connectivity of hybrid RF/optical systems in eHealth.

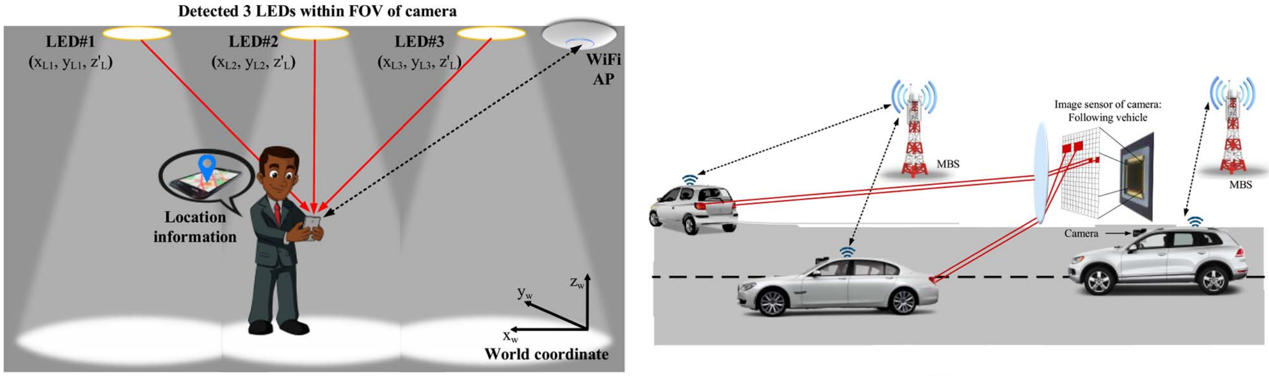
OCC and BLE could be an attractive solution for real-time health monitoring using patch connectivity. Fig. 9 shows some basic connectivity in hybrid RF/optical wireless systems. Body sensors, e.g., electroencephalogram (EEG), blood pressure (BP), and electromyography (EMG) sensors, collect data from different parts of the body. The sensors are connected to a skin patch [60], [148], which has an integrated module of OCC and BLE. This patch can be connected to a camera and the BLE module for OCC and RF connectivity, respectively. The OCC cannot perform in NLOS conditions. As shown in the figure, the patient is connected to the OCC system during the LOS condition and to BLE for the camera NLOS condition. The hybrid system is also used for remote patient monitoring [30], [60], [146], [148]. The patient's conditions are measured at home through different body sensors. The information is collected through a BLE/OCC hybrid system, which allows the physician to monitor the patient's condition remotely. A wheelchair-bound person is monitored through a hybrid RF/OCC system. The OCC system collects information regarding the person's health condition through a skin patch. The information is sent through a macrocellular network or satellite network that is to be connected to the core network. Another example of application of hybrid RF/OCC is the provision of emergency medical service in an ambulance [148]. The patient information is collected through a BLE/OCC hybrid system installed inside the ambulance. The 5G macrocellular or satellite network connects the ambulance to a core network for remote monitoring.

It is very important to provide an extremely high-reliable link for real-time patient monitoring with the lowest level of interference. Link reliability is lower in OCC when it is operated in NLOS, whereas BLE produces significant interference. Hence, the existence of two communication systems surely improves the link reliability. Moreover, the BLE/OCC hybrid system also improves the security of patient data as the data cannot be hacked in an OCC system from outside the network. Thus, the main factors to be considered for network selection in a hybrid BLE/OCC system are the LOS/NLOS situations.

### *F. RF/Optical Wireless Hybrid in Localization/Positioning/ Navigation*

Both optical and RF systems are used for localization, positioning, and navigation purposes [68], [97], [102], [103], [193]. The localization accuracy in VLC, LiFi, and OCC is better compared to the WiFi system in the LOS condition [68].

However, the WiFi system provides better accuracy in NLOS conditions. Compared to RF-based technologies, directional optical networks improve indoor positioning in a centimeter range [103]. However, in an optical-based system in NLOS scenarios, the performance is severely degraded. The performance of optical systems is also poor in outdoor scenarios for different weather conditions. The coexistence of omnidirectional RF technologies with directional optical wireless technologies thus improves the overall performances in indoor and outdoor localization/positioning/navigation. Fig. 10 shows two examples of hybrid systems for the purpose of localization. The hybrid RF/optical wireless signals enhance the localization process from a remote location. In an indoor environment, a smartphone can be localized with the help of LEDs. As shown in Fig. 10 (a), an RF/optical wireless hybrid system improves the localization performance. While using OCC, the



(a) (b)

Fig. 10. Examples of hybrid RF/optical connectivity for localization. (a) Indoor localization. (b) Outdoor vehicle localization.

camera of the smartphone receives signals from more than two LEDs, which are within the FOV of the camera. The received signals contain much information such as the physical size of LEDs and its coordinate data (i.e., x-, y-, and z-coordinates), which help to determine the distance between the camera and the LEDs using photogrammetry [102]. The position of the smartphone is always changing; therefore, every estimated position information is sent to the lighting server using the WiFi AP. The lighting server removes the localization estimation error by estimating the next possible position of the smartphone. As shown in Fig. 10 (b), RF/optical wireless hybrid networks can be applied in vehicle localization scenarios. Each camera mounted on the vehicle receives LED data and measures its location information, which can be shared with the vehicles that are situated at long distances. The MBSs deliver this location information to the core network. Hybrid RF/optical systems enhance the localization process from a remote location.

The RF/optical wireless hybrid system provides a very highly reliable communication link. Due to the existence of two systems, the localization accuracy is also increased. LOS/NLOS and environmental considerations are important factors for an effective network selection in an RF/optical wireless hybrid system in localization/positioning/navigation purposes.

### *G. RF/Optical Wireless Hybrid Systems for Backhaul Network Connectivity*

Providing a high-capacity backhaul infrastructure that can support a huge node density and carry a large amount of aggregated data in 5G and beyond communication systems is a challenging issue. With the expected large data requirements of 5G and massive connectivity of IoT, the fundamental problems of backhaul architecture optimization are provided in [112], [194]. Currently used backhaul links can be classified broadly into four types, namely copper wire, radio links (e.g., mmWave, and microwaves), optical fiber, and FSO links. Despite the importance of wired backhaul solutions (like fiber optical) in 5G and beyond communication systems, they are not great relevant to this article. Traditionally, copper lines are the most widely used technology for the backhaul network [194]. However, the provided data rates of T1 and E1 copper lines are low (1.544 Mb/s for T1 and 2.048 Mb/s for E1) [194]. Multiple parallel connections are required, which results in prices growing linearly with the provided capacity. Therefore, for high data rates in 5G and beyond communication systems, copper technology becomes very expensive and is no longer a feasible solution. Optical fiber is a high-data-rate solution that can support more than 10 Gbps communication links over long distances. The installation of optical fiber based backhaul connectivity is sometimes limited due to the high deployment cost, especially in ultra-dense environments, and it may be even impossible in some restricted areas and applications because of the remote connectivity and limitation on cable installation [48], [155]. Optical fiber or other wired backhaul connectivity is not possible in locations where deploying wired connections is not feasible. Wireless technologies are a realistic alternative to copper and optical fiber links for backhaul connectivity, especially in locations where the deployment of wired connections is challenging. An FSO system is a good alternative to the optical fiber connectivity being utilized for backhaul links, since it can provide high-data-rate backhaul connectivity. Moreover, the use of similar optical transmitters and detectors for FSO and fiber optics realizes similar achievable bandwidth capabilities [182]. The capacity of FSO backhaul is comparable with that of the optical fiber, but the deployment cost is significantly lower [195], [196]. Other benefits of FSO backhaul include easy deployment, non-interfering nature, rapid setup time, and low maintenance cost [112], [156], [197]. However, the performance of the FSO system is adversely affected by the atmospheric turbulence and atmospheric loss due to unfavorable weather conditions, e.g., fog, snow, and dust [112], [198]. It requires a clear LOS path and hence, it suffers from a transmitter–receiver misalignment problem. Conversely, the RF-based mmWave and microwave links are not seriously affected by fog, snow, and dust, however, they suffer heavily in rainy conditions. Hence, the best solution to improve link reliability of the FSO backhaul system is to integrate it with an RF system and form a FSO/RF hybrid backhaul system. The RF/FSO hybrid system can be used for high-data-rate backhaul connectivity with improved link reliability. The FSO system can act as the primary backhaul network and

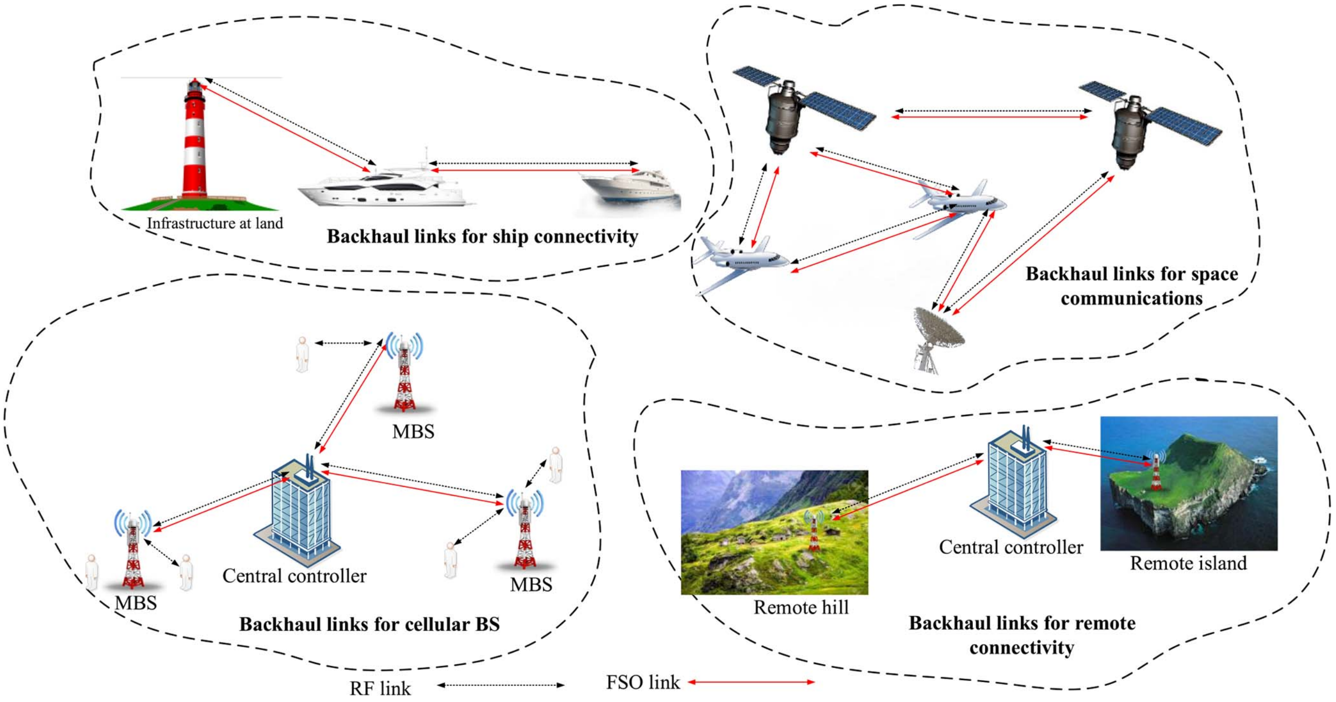


Fig. 11. Application scenarios for RF/FSO backhaul connectivity.

the RF system as a secondary backup. Fig. 11 shows some application scenarios for RF/FSO hybrid networks in backhaul connectivity. As shown in this figure, hybrid systems provide high-capacity backhaul links for cellular BSs, ship connectivity, space communication, and remote connectivity. This hybrid system can provide services for any sophisticated and remote area as a replacement of optical fiber networks. The existence of two networks in the RF/FSO hybrid system increases the backhaul capacity and reliability.

In contrast to the RF/FSO hybrid system, the optical-wireless integration (OWI) deals with the merging of optical fiber and wireless networks [199]–[202]. Combining the high capacity of optical fiber networks with the ubiquity and mobility of wireless networks, OWI forms a platform to support high-data-rate wireless applications. In an OWI system, wireless access technologies provide ubiquitous mobility support, whereas the optical fiber network supports backhauling the large volume of traffic. As mentioned earlier, an optical fiber connection is not always possible, and FSO is a good alternative of the optical fiber. Hence, the FSO system can play a similar role as optical fiber network to perform the objectives of OWI. The addition of RF systems (microwave and mmWave links) to FSO, i.e., RF/FSO hybrid backhaul connectivity, ensures the reliability of the backhaul links.

### *H. Literatures Surveys on RF/Optical Wireless Hybrid Networks*

Tables VI and VII summarize the key research on VLC-based hybrid systems. These hybrid systems consist of VLC networks with RF-based WiFi or small cell/femtocell and macrocell. Many researchers use the term RF instead of specific WiFi or small cell/femtocell or macrocell networks. Hence, we also use the term RF as generalized RF systems. For these generalized RF systems, any of the mentioned RF-based networks can be considered as a part of a hybrid system. The research on VLC-based hybrid systems mainly focused on capacity enhancement, mobility support, network selection, and reliability issues.

As we mentioned earlier, there exist some differences between VLC and LiFi systems. The related hybrid network research activities based on LiFi systems are shown in Table VIII. These hybrid systems consist of LiFi networks with RF-based WiFi or small cell/femtocell or macrocell networks. Similar to VLC, these works on LiFi-based hybrid systems also focused mainly on capacity enhancement, mobility support, network selection, and reliability issues.

The research interest on the mixed RF/FSO networks have recently increased due to its ability to provide high data-rate last-mile connectivity. On the other hand, the co-existing RF and FSO links enhance the link reliability. A number of researchers proposed and studied different algorithms for these hybrid RF/FSO systems. Varshney and Jagannatham [154] proposed a decode-and-forward based mixed MIMO RF/FSO cooperative relay system for cognitive radio strategy. This work analyzes the E2E performance with decode-and-forward based cooperation. Multiple antennas are employed at the cognitive source and relay which improve the reliability of communication. Djordjevic *et al.* [196] proposed a model for FSO atmospheric turbulence using the Gamma–Gamma distribution. Petkovic *et al.* [197] analyzed dual-hop amplify-and-forward mixed RF/FSO system based on outdated channel state information. The FSO link is modeled by Gamma–Gamma distribution. Subcarrier intensity modulation is applied for electrical-to-optical signal conversion at the relay. Wu *et al.* [216] studied data transmission schemes

TABLE VI
SUMMARY OF CURRENT RESEARCH TRENDS ON VLC-BASED HYBRID SYSTEMS

| Hybrid type | Reference | Aim | Focus of the work | Contribution and Research Direction |
|---|---|---|---|---|
| RF/VLC | [7] | Increasing the system's capacity and fairness | Load balancing and power allocation | A power allocation algorithm, load balancing technique, and a suboptimal approach based on interference are presented. |
| | [18] | Improving handover performance | Investigation of vertical handover | Analysis of signaling cost, switching latency, and queuing length as well as the development of cost function using Markov formula are presented. |
| | [31] | Solving multiple access problems | Designing parallel transmission MAC protocol | A channel reservation model is constructed and the theory for analyzing throughput is provided. |
| | [32] | Enhancing energy efficiency | Development of energy harvesting model | Probability density function (PDF) and cumulative distribution function (CDF) of signal-to-interference-plus-noise ratio (SINR), a light energy harvesting model, and the expression for secrecy outage probability are developed. |
| | [33] | Maximizing the power efficiency | Optimizing power and bandwidth allocation | Joint power and bandwidth allocation algorithms are developed. |
| | [34] | Seamless vertical handover | Implementation of a hybrid RF/VLC system that supports seamless handover | Linux kernel bonding driver for switching between two links is studied. |
| | [35] | Intelligent network selection | Reinforcement learning solution for indoor network selection | Fine-grained network selection model considering the diverse traffic requirements and network performance of uplink and downlink is developed. |
| | [38] | Efficient vertical handover (VHO) | Analytic hierarchy process in two-person cooperative game model for VHO algorithm | A VHO algorithm considering multiple attributes, including dynamic network parameters and actual traffic preferences is provided. |
| | [47] | Creating a multi-layer network | Developing a new ns3-based module | A VLC module is developed considering channel and modulation models. |
| | [48] | Efficient VHO | Using fuzzy logic to reduce packet transfer delay | VHO algorithms are investigated and new fuzzy logic-based algorithm is proposed. |
| | [49] | Improving coverage | Investigation of the power and spectrum requirement | Design and development methods of the hybrid system are investigated by analyzing the key system parameters. |
| | [50] | Reliable communication | Developing a dual-hop multiple relayed hybrid system model | Improved connectivity is provided using dual-hop parallel relayed hybrid model. The best relay is also selected based on the E2E signal-to-noise ratio (SNR) from source to destination. |
| | [53] | High-data-rate communication | Designing hybrid networks by using power line networking | A hybrid WiFi/VLC network architecture through the use of power line communication is designed. |
| | [54] | Handover delay reduction | Investigation of energy consumption, switching latency, and queuing length of a waiting packet. | The Markov decision process is formulated to obtain the solution to achieve the optimal trade-off between energy consumption and delay requirement. |
| | [127] | Extending the VLC coverage | Designing a dual-hop RF/VLC heterogeneous system with harvesting energy | Analysis of the DC bias imposed on the electrical signal of a light source is conducted and two methods to design the optimal DC bias are provided. |
| | [132] | Throughput optimization | Bandwidth aggregation and scheduling algorithm | Scheduling based on queue analysis as well as Lyapunov theory, new packet transmission protocol, frame structure analysis, and optimal throughput analysis are provided. |
| | [135] | Maximizing the QoS | Link selection | The performance of the system is analyzed based on QoS as well as three strategies of link selection are proposed. |
| | [138] | Improving security | Formulating the minimization problem and zero-forcing beamforming strategy | Minimization problem of the consumed electrical power through beamforming is studied. Power allocation algorithms are also formulated to satisfy the user's secrecy requirements. |
| | [139] | Optimum resource utilization | Theoretical analysis based on FOV, intensity, and BS height | Theoretical derivations of coverage and rate in different RF/VLC scenarios are provided. |
| | [140] | Maximizing the energy efficiency | Formulating the problem of power allocation | The power and resource allocation for HetNets are analyzed to maximize energy efficiency. |
| | [141] | Solving the load-balancing problem | Increasing throughput without sacrificing fairness | Cooperative load balancing achieving proportional fairness is implemented by using both centralized and distributed resource-allocation algorithms. |
| | [142] | Maximizing the throughput | Providing VLC as a downlink and WiFi as uplink | Implementation of a hybrid solution in which the uplink challenge is resolved by using an asymmetric RF/VLC combination. |

for hybrid RF/FSO system employing link selection, power allocation, and reliability guarantees. The RF and FSO transmitters in the hybrid system make decisions under an explicit long-term average reliability requirement, about which links should be selected. It also determines how much power needed for the corresponding link. They consider the power

TABLE VII
SUMMARY OF CURRENT RESEARCH TRENDS ON VLC-BASED HYBRID SYSTEMS (CONTINUED)

| Hybrid type | Reference | Aim | Focus of the work | Contribution and Research Direction |
|---|---|---|---|---|
|  | [160] | Outage and symbol error performance enhancement | Development of approximated analytical and asymptotic expressions for outage probability. | The coverage of the VLC system is extended considering the decode-forward and amplify-forward schemes. Moreover, outage probability and average symbol error rate (ASER) are calculated considering the randomness of the positions of relay and receiver. |
|  | [203] | Maximizing the energy efficiency | Determining the benefits of energy efficiency | Analyses of power and bandwidth allocation and their impact on energy efficiency are conducted. |
|  | [204] | Designing software-defined-network-based architecture | Designing a multi-element hemispherical bulb to transmit data streams over LED modules | Bulb structure modeling and simulation-based evaluation of VLC architecture with the partitioning algorithm and coverage model are presented. |
|  | [205] | Maximizing the user QoS | Integration of RF and VLC systems by considering multiuser mobility scenarios and downlink/uplink | New VLC frame, multi-user access mechanism, and horizontal/vertical handover protocols are presented to support the VLC HetNet model, especially for solving the problems in multi-user mobility scenario. |
|  | [206] | Maximizing spectral efficiency | Investigation of the gains obtained in area spectral efficiency (ASE) by VLC systems | The ASE for both the RF and VLC systems is analyzed on the basis of Monte Carlo simulations. |
|  | [207] | Fast handover | Presenting the implementation details of a hybrid communication system | A fast handover mechanism using decision-making and link-monitoring scheme in between network and data-link layers of the communication protocol stack is presented. |
| Femtocell/VLC | [39] | Efficient resource allocation | Providing optimization solution of resource allocation problem of MTs | Decentralized algorithms are proposed for solving resource allocation problem. |
|  | [40] | Coverage extension | Dynamic beam and luminaire control of VLC system | The use of multiple sources tracking device orientation and position is provided to mitigate the off-angle performance degradation by increasing redundancy in the number of available connections. |
|  | [134] | Intelligent network selection | Dynamic environments and complicated service-requirement analysis for indoor network selection | The contextual information about the asymmetric downlink/uplink features of network performance is used to design a fine-grained utility model. Moreover, a context-aware learning algorithm that is sensitive to traffic type-location-time information is also provided. |
|  | [162] | Delay analysis | Delay analysis considering several cases | The potential gain in terms of the minimum average system delay through aggregating the bandwidth of omnidirectional small cells and directional small cell is evaluated. Furthermore, the proposed queuing model can represent aggregated as well as non-aggregated system models for HetNets. |
|  | [208] | Effective load balancing | Cell association based on the minimum distance to the closest AP | Downlink minimum distance user association is analyzed to improve the spectral efficiency and to provide efficient load balancing. |
| Macrocell/VLC | [41] | Maximizing the system utility | Developing a scalable load balancing scheme | A mobility-aware load balancing scheme is proposed, which allocates the mobile devices to their corresponding APs dynamically. Applying matching theory, the original allocation problem is formulated as a college admission problem. |
|  | [42] | Enhancement of localization performance | Positioning in triple-tier VLC/WLAN/Cellular networks | Probabilistic localization approach for increasing localization accuracy in multi-tier HetNet systems is studied. |
|  | [51] | Low-cost cellular infrastructure | Classification of links | The proposed system classifies the links by providing hybrid TV RF broadcast/VLC for downlink while telescopes, camera receivers, and LED arrays for the uplink. |
|  | [55] | System performance improvement | New heterogeneous cellular architecture considering 5G /mmWave/VLC networks | Networks are classified by coverage size and spectra. An overview of VLC downlink communication technologies is provided. |

consumption cost minimization, guaranteeing packet success-probability requirements, peak, and average power constraints for their scheme, and it is formulated as a stochastic problem. They develop a closed-form power allocation approach for link selection using the Lyapunov optimization techniques. Some recent research works related to RF/FSO hybrid systems are summarized in Tables IX and X. The RF-based networks in these hybrid systems include microwave and mmWave links. These hybrid systems provide alternative long-range point-to-point communication links as well as very high-data-rate backhaul links. Most of the works related to these hybrid systems focus on the communication link in space. However, few researchers focus on communication links in underwater. The coexistence of two networks overcome the environmental effects and improves reliability. These research works focus mainly on the system reliability improvement issues.

TABLE VIII
SUMMARY OF CURRENT RESEARCH TRENDS ON WIFI/LIFI HYBRID SYSTEMS

| Reference | Aim | Focus of the Work | Contribution and Research Direction |
|---|---|---|---|
| [44] | Enhancing the throughput | AP selection | Access point assignment method for hybrid LiFi and WiFi networks in consideration of LiFi channel blockage is proposed. |
| [45] | Power efficiency and green for IoT | Energy harvesting in indoor communications | For both transmission and support, a multiple access technique with minimal interference is developed. The proposed model used orthogonal Walsh codes technique and the color beams of the red/green/blue LEDs. |
| [46] | AP selection | LED source access control relying on multi-armed bandit theory | Exponential weights for exploration and exploitation (EXP3) as well as the exponentially weighted algorithm with linear programming learning techniques are proposed for updating the AP assignment decision probability distribution. |
| [57] | Load balancing | Load balancing considering user mobility and handover signaling overheads | Dynamic load balancing scheme is proposed, where the utility function considers system throughput and fairness. The presented load balancing scheme can mitigate frequent handover between LiFi attocells so that quasi-static users are served by Li-Fi attocells, whereas moving users are served by a WiFi AP. |
| [133] | Maximizing the throughput | Load balancing based on evolutionary game theory | Load balancing algorithm based on evolutionary game theory considering channel blockages, LiFi receiving orientation angle, and user data rate requirement is provided for efficient use of communication resources and enhancing QoS. |
| [136] | Determination of handover probability | Handover probability model analysis | The handover probability is modeled using a Markov chain. |
| [137] | Users' QoS level improvement | Dynamic load balancing considering the handover overhead | Joint optimization algorithm and separate optimization algorithm are presented to jointly and separately optimize the AP assignment and resource allocation, respectively. |
| [143] | Enhancing the throughput | Load-balancing between WiFi and LiFi networks | A practical framework of the hybrid system is demonstrated. |
| [144] | Interference management | Multi-user and the inter-cell interference | Blind interference alignment is presented to avoid multi-user and inter-cell interference. |
| [209] | Energy efficient wireless indoor access networks | A methodology of the LiFi and WiFi networks usage based on illumination requirement | The problem of minimizing the power consumption of the indoor systems is formulated while satisfying the users' requests and maintaining an acceptable illumination level. |
| [210] | Effective resource management | Position information of the users | Improved mobility management systems are developed using the location information provided by LiFi and WiFi APs. |
| [211] | Reduction of handover overhead | Appropriately assigning users to either the WiFi or the LiFi AP | Fuzzy logic-based dynamic handover scheme is developed using not only the channel state information but also the user speed and desired data rate to determine whether a handover needs to be prompted. |
| [212] | Enhancing user QoS | Selection criteria for the hybrid network system | A cross-layer approach of a hybrid system that operates under statistical QoS constraints is provided and they are inflicted as limits on the buffer overflow and delay violation probabilities. |
| [213] | Throughput analysis | Optical interference and the blockages of LOS optical channels | The effect of optical interference from neighboring LiFi APs and the blockages of LOS optical channels on the system throughput are investigated. The load balancing is also formulated as an optimization problem. |
| [214] | Increasing number of users | Load balancing considering the throughput loss due to handover | Mobility management issue of a hybrid LiFi/WiFi network is formulated as a joint optimization problem of load balancing and handover. |
| [215] | AP selection | Network selection algorithms | The fuzzy logic system is developed to determine the users that should be connected to Wi-Fi. The differences between homogeneous and HetNets regarding APS are discussed, and a two-stage AP selection method is proposed for hybrid LiFi/WiFi networks. |

Due to the ubiquity and the infrastructure availability of power-line networks, PLC technology is employed in OWC networks for data transfer between OWC sources. A very few research works related to PLC-based hybrid system has been done. Table XI summarizes the research works on PLC-based hybrid networks. These works mainly focus on the power and interference management issues.

To show the effectiveness of any proposed system, performance measurement is very vital. The performance can be measured through different ways such as through simulation, numerical analysis, and experimental validation. Different researchers have shown their research outcomes using different performance parameters. Table XII summarizes the performance metric used by different researchers for their research. System capacity is the main goal for the RF/VLC and RF/LiFi hybrid systems. However, for the RF/FSO system, link reliability is the most important concern. Each of the mentioned parameters is performed in different ways, e.g., average throughput and CDF of throughput in case of throughput analysis.

As mentioned earlier, the presence of two or more networks in the hybrid systems can be achieved in various ways. Hence, the selection of a network is a very important element in hybrid network systems to minimize the cost and ensure high level of user QoE. We survey several research works and summarize the network selection approaches in Table XIII.

TABLE IX
SUMMARY OF CURRENT RESEARCH TRENDS ON RF/FSO HYBRID SYSTEMS

| Area | Reference | Aim | Focus of the Work | Contribution and Research Direction |
|---|---|---|---|---|
| Space | [59] | Throughput maximization | Vehicular ad-hoc networks | Algorithms for distributed channel allocation and rate control are developed. Using alternating detection method of multipliers, throughput and capacity satisfaction are also ensured. |
| | [108] | Finding the optimal transmission power | Impact of RF co-channel interference on the hybrid networks | To obtain a solution to optimal power allocation, closed-form expressions of performance parameters are derived. |
| | [112] | Achieving reliable link connection | Investigation of RF fading and FSO fading in terms of atmospheric turbulence with Rayleigh and gamma-gamma statistics | To prevent needless switching, only one FSO link is considered at first as a hybrid system is developed for adverse weather conditions. The mathematical analyses are carried out for different system performance metrics. |
| | [149] | Enhancing the E2E performance | Designing of a cascaded system considering small cells and macrocells | Different link-allocation policies are proposed and throughput is analyzed for different delay requirements and signaling overheads. |
| | [150] | Performance analysis | Investigating ASER performance | Moment generating function (MGF) of SNR and ASER of different modulation schemes are obtained. |
| | [151] | System performance optimization | Performance analysis with transmitting opportunistic scheduling | Closed-form expressions of different performance metrics are derived considering pointing-error effects and SNR regime. |
| | [152] | Cost minimization and scalability improvement | Performance analysis considering the effect of pointing errors due to the misalignment | The mmWave RF and FSO fading channels are modeled by the Rician and the generalized Malaga distributions, respectively. Moreover, the effect of pointing errors due to the misalignment between the transmitter and the receiver in the FSO link is included. |
| | [153] | Throughput maximization | Orthogonal frequency-division multiple access (OFDMA)-based framework | A resource allocation scheme considering a multiuser framework and an OFDMA scheme, which includes power and subcarrier allocation, is proposed. |
| | [154] | To enhance reliability | Decode and forward based multiple-input and multiple-output (MIMO) hybrid system | Closed-form expressions of outage probability are derived assuming Nakagami-m fading for RF links and different optical channel impairments for FSO links. |
| | [156] | Effects of multipath fading and atmospheric turbulence mitigation | Dual-hop hybrid system considering a variable gain relay | Analytical expression of CDF and different performance metrics are developed considering the effects of multipath fading and atmospheric turbulence on the systems with multiple transmitters and multiple antennas. |
| | [157] | Throughput optimization | Network control algorithms based on different communication channel conditions | The widely used protocol model is analyzed with respect to a complex physical model for link allocation. Moreover, the mixed-integer linear program is analyzed for throughput maximization. |
| | [194] | Cost-effective backhaul solution | Combining the individual advantages offered by each network | The problem of cost minimization is studied when the BSs are connected with each other via optical fiber or hybrid RF/FSO links. |
| | [195] | E2E outage performance analysis | Dual-hop hybrid system considering channel models | Closed-form expressions for the outage probability are derived by considering Rayleigh fading RF and M-distributed fading FSO channel models of each link. |
| | [196] | Improving outage performance | Performance analysis considering outdated channel state information and misalignment between the FSO transmitter and receiver | Analytical expressions of outage probability and average BER are developed considering the effect of system parameters that are further utilized for optimization of beam waist at the transmitter output. |
| | [197] | Reliability improvement | Outdated channel-state information based on relay selection | Assuming partial amplify-and-forward relay, closed-form expressions of different performance metrics are derived. |
| | [198] | Ensuring constant SNR at receiver | Power adaption based on truncated channel inversion | Mathematical expressions of outage probability are developed considering two power adoption strategies. |
| | [217] | Increasing reliability | Analyzing a hybrid transmission system on the basis of an adaptive combination | A novel analytical expression of CDF is developed, using which the outage probability is derived. |

Among several approaches used, fuzzy logic approaches are the most widely used for the network selection. Different types of technologies in a hybrid system exhibit different characteristics. Moreover, the end users also demand varieties of service requirements. Hence, selecting the best access network is always a challenging task. Various studies have employed a variety of approaches for the network selection. A reinforcement learning approach in [35] considered a dynamic environment, taking into account both the uplink and downlink performance requirements of traffic for network selection in RF/VLC hybrid systems. The context-aware reinforcement learning solution for the RF/VLC hybrid network selection in [134] was able to tackle the challenges associated with dynamic environments and complicated service requirements. The contextual information about the asymmetric downlink and uplink features of network performance is considered to design a fine-grained utility model for this system. The fuzzy logic approach has the ability to solve the uncertainty and contradiction embedded within a problem. The fuzzy logic based decision-making algorithm for VHO in [48] is capable

TABLE X
SUMMARY OF CURRENT RESEARCH TRENDS ON RF/FSO HYBRID SYSTEMS (CONTINUED)

| Area | Reference | Aim | Focus of the Work | Contribution and Research Direction |
|---|---|---|---|---|
| Space | [216] | Reliability enhancement | Algorithms for link selection and power allocation | Various mathematical expressions and algorithm are developed considering power allocation for different link selection modes. |
| | [218] | Achieving optimal power allocation and enhancing secrecy performance | Investigating the performance of the hybrid network in multi-user single-input multiple-output scenarios | The closed-formed analytical expressions of outage probability, symbol error probability, and the channel capacity are presented and secrecy performance is investigated for the hybrid system. |
| | [219] | QoS enhancement | Controlling the topology in hybrid mesh networks. | To improve E2E delay and throughput, a new scheme based on adaptive adjustments of both transmission power of RF and FSO transmitters as well as the optical beam-width of FSO transmitters at individual nodes is proposed. |
| | [220] | Throughput and outage performance improvement | Performance analysis considering perfect channel state information | Closed-form expressions of message decoding probabilities, throughput, and outage probability are derived. |
| | [221] | Efficient link-quality scheduling | Multiuser diversity over the hybrid system | A hybrid FSO/RF considering point-to-multipoint, hybrid AP, multiple FSO users, and multiple RF users is presented. Moreover, a scheduling algorithm is proposed with a theoretical analysis of SNR, outage probability, and average bit error rate (BER). |
| | [222] | Effects of atmospheric and pointing error realization | Asymptotic hybrid links with pointing errors | Closed-form expressions of CDF, PDF, MGF, and the moments of the hybrid system are derived with analytical formulations of different performance metrics considering Meijer's G function. |
| | [223] | E2E performance improvement | Decoding of user-transmitted data streams | Analytical expressions of different performance metrics were derived considering Meijer's G functions. |
| | [224] | Performance investigation | Double generalized gamma turbulence with pointing error and Nakagami-*m* fading | The exact and approximate expressions for different performance metrics are evaluated for the hybrid system. |
| | [225] | Capacity improvement | Fixed-gain dual-hop hybrid system based on fixed-gain amplify-and-forward | CDF, PDF, and MGF of SNR are derived on the basis of finite power series that are utilized further to derive expressions for different performance metrics. |
| | [226] | Optimization of throughput | Modeling the system as two independent parallel channels | A link-adaption algorithm is proposed for maximizing throughput with and without bandwidth constraint. |
| | [227] | Overcoming the weaknesses of FSO links | Outage probability considering the effects of turbulence and pointing errors | Mathematical expressions of BER and outage probability are developed considering different channel conditions. |
| | [228] | Optimal relay selection | Maximization of throughput in a parallel hybrid system. | The optimal selection methods for relays are derived for different buffer-aided conditions. |
| | [229] | Throughput optimization | Throughput maximization algorithm for all weather conditions | Performance of the developed algorithm is presented for different low-density-parity check coding mechanisms. |
| | [230] | Capacity enhancement | Hardware impairments | Effects of hardware impairments are demonstrated for different SNR values. Mathematical expressions for various performance parameters are derived and the system gains are analyzed. |
| Underwater | [184] | Understanding the hardware and software architecture | Optical and acoustic networking protocols | Considering ultrasonic and optical communication systems, an underwater sensor network system is presented. |
| | [186] | Energy harvesting | Localization technique for energy harvesting hybrid acoustic-optical underwater wireless sensor networks | A hybrid received signal strength (RSS)-based localization technique is proposed to localize the nodes. It combines the noisy RSS-based measurements from acoustic communication and optical communication and estimates the final locations of acoustic/optical sensor nodes. |
| | [187] | Range extension and data-rate improvement | Hybrid acoustic/optical communications system architecture | A hybrid acoustic/optical underwater communication system that offers high data rates, low latency, and robustness is developed. |
| | [189] | Establishing communication in a harsh environment | Combining the acoustic/optical approach | Communication channels are elaborately presented. |
| | [190] | Link design | Link design using a hybrid acoustic/optical system | The limiting performance factors for the acoustic and optical aspects are found through respective channel modeling and SNRs. |
| | [191] | Overcome the bandwidth limitation of the acoustic channel | Signal attenuation in underwater | A hybrid acoustic/optical solution is provided to overcome the bandwidth limitation of the acoustic channel by enabling optical communication with the help of acoustic-assisted alignment between optical transmitters and receivers. |

of combining the merits of both RF and optical wireless systems. It considers network and traffic conditions for the decision. The two-stage AP selection in the RF/VLC hybrid system [215] is based on the fuzzy logic approach. In the first stage, a fuzzy logic system is developed to determine the users that should be connected to RF network. In the second stage,

TABLE XI
SUMMARY OF CURRENT RESEARCH TRENDS ON PLC BASED HYBRID SYSTEMS

| Reference | Aim | Focus of the Work | Contribution and Research Direction |
|---|---|---|---|
| [43] | Minimization of power consumption | Power allocation problem of PLC/VLC hybrid systems in parallel to an RF wireless link | A single RF link in parallel with PLC/VLC link is analyzed, and the transmission power minimization problem is formulated. |
| [56] | BER improvement | Improving the modulation technique | An approach for modifying the modulation technique in accordance with the channel requirements of a hybrid PLC/VLC-based 5G communication system is presented. |
| [163] | PLC/VLC channel analysis | Channel frequency measurement of a hybrid cascaded PLC/VLC channel | An overall characterization, modeling, and spectral analysis for hybrid PLC/VLC channels are provided. |
| [231] | Interference mitigation | Developing the analytical framework for the VLC/PLC hybrid system | Different approaches to signal transition between PLC/VLC systems are investigated. Moreover, different subcarrier allocation schemes are proposed to exploit frequency selectivity, OFDMA, and OFDM-time-division-multiple access. |
| [232] | Overcoming the transmit power constrained | Resource allocation for multi-user OFDMA in the PLC system | To maximize the throughput of the PLC system, a resource allocation scheme is proposed with respect to joint consideration of the subcarrier and power constraint. |
| [233] | Better mobility support | Exploiting the statistical properties of PLC and VLC channels | The performance of a cascaded indoor PLC/VLC system is investigated with the presence of an amplify-and-forward relay. |
| [234] | BER improvement | Investigating the inherent clipping feature of OFDM to combat impulsive noise found in the PLC channel | The Hermitian symmetry is exploited to design a hybrid system that combines PLC and VLC technologies using OFDM. |
| [235] | BER improvement | Investigating a mixed cooperative PLC/VLC system | The closed-form expressions of the CDF and PDF of the equivalent E2E SNR are presented. |

remaining users are connected to the LiFi network. The link selection approach in [135] considers the desired QoS guarantee in the RF/VLC hybrid system. Considering the ON–OFF data source and physical/data-link cross layers, it employs the maximum average data arrival rate at the transmitter buffer and the non-asymptotic bounds. The link selection approach under statistical queueing constraints in [135] considers the desired QoS guarantee in the RF/VLC hybrid system. Considering the ON–OFF data source and physical/data-link cross layers, it employs the maximum average data arrival rate at the transmitter buffer and the non-asymptotic bounds.

Implementation or experimental demonstration is one of the best ways to measure the performance of a system. However, very few studies have tested hybrid RF/optical systems by the implementation or experimental demonstration. We survey around 250 research works on different optical wireless hybrid systems, and Table XIV shows a brief overview of the implementation or experimental demonstration found in literature.

If the hybrid system contains two networks, then it is possible to have four links such as uplink/downlink of network-1 and uplink/downlink of network-2. Hence, the links of the presented network-1 and network-2 can be used in various manner. Table XV provides a summary of network sharing policies in different research works for RF/optical wireless hybrid systems. Many researchers did not mention this network sharing issue as it was not the scope of their paper. RF performs well for both uplink and downlink communications. Since the receiver devices such as smartphones and wearables are not equipped with a high-power LED, OWC systems such as VLC and LiFi cannot perform well for uplink communications [53], [134]. However, uplink communication is possible using VLC or LiFi systems.

## IV. OPTICAL/OPTICAL WIRELESS HYBRID NETWORKS

Different optical wireless technologies show different characteristics. Hence, the optical/optical wireless hybrid systems are planned to increase the link reliability and to satisfy user QoS level. To the best of our knowledge, there is no significant research work yet on optical/optical wireless hybrid systems. Few possible examples of such hybrid systems are briefly discussed in this section.

Hybrid LiFi/OCC and VLC/OCC are possible optical/optical wireless hybrid solutions for indoor users. VLC and LiFi provide comparatively high data rate but are less immune to the interference effect compared to the OCC system [30]. Therefore, these are effective approaches for optical wireless deployment to avoid the interference effect on VLC or LiFi as well as to compensate for the low data rate of the OCC system. Hybrid LiFi/OCC, VLC/OCC, and FSO/OCC are possible optical/optical-type hybrid solutions for V2X communications to overcome the limitations of individual technology. OCC can provide comparatively longer communication distance with a stable communication link against increasing distance in V2X communications. FSO can perform well for very long distance V2X communications. However, it is considerably affected by outdoor atmospheric conditions and requires precise pointing of the transmitter and receiver. VLC and LiFi systems are being widely used for indoor and outdoor localization, positioning, or navigation. The localization resolution for OCC is better than PD-based VLC and

TABLE XII
SUMMARY OF PERFORMANCE METRICS USED FOR HYBRID SYSTEMS

| **Type** | **Metrics** | **Reference** | **Hybrid Type** |
|---|---|---|---|
| System capacity | Throughput | [7], [31], [34] | RF/VLC |
| | | [39] | femtocell /VLC |
| | | [44], [46], [137], [143], [213], [214] | WiFi/LiFi |
| | | [41] | macrocell/VLC |
| | | [59], [149], [152], [153], [156], [157], [198], [220], [226], [228] | RF/FSO |
| | User data rate | [36], [49], [127] | RF/VLC |
| | | [141], [142] | WiFi/VLC |
| | | [231] | PLC/VLC |
| | | [45], [57], [143], [144], [212], [215] | WiFi/LiFi |
| | | [211] | RF/LiFi |
| | Number of users | [135] | RF/VLC |
| | Ergodic capacity | [112], [151], [218], [222], [224], [230] | RF/FSO |
| Reliability | BER | [37] | WiFi/VLC |
| | | [45] | WiFi/LiFi |
| | | [110], [112], [152], [156], [197], [221], [222], [224], [225], [228] | RF/FSO |
| | SER | [47], [160] | RF/VLC |
| | | [150], [151], [222], [223], [230] | RF/FSO |
| | Packet loss | [18], [47], [207] | RF/VLC, |
| | Localization error | [42] | VLC/WLAN/cellular, |
| | Outage probability | [32], [36], [50], [160], [236] | RF/VLC |
| | | [108], [110]–[112], [151], [152], [154], [156], [195], [197], [198], [216], [217], [220]–[225], [227], [230] | RF/FSO |
| | Packet delay | [18], [48] | RF/VLC |
| | | [212] | WiFi/LiFi |
| | Link-blocking probability | [141] | WiFi/VLC |
| | | [151], [219] | RF/FSO |
| Signal quality | RSS | [53] | WiFi/VLC |
| | | [40] | Femtocell/VLC |
| | | [229] | RF/FSO |
| | SINR | [47], [139], [204] | RF/VLC, |
| | | [156], [198], [225]–[227], [230] | RF/FSO, |
| | Coverage probability | [139] | RF/VLC |
| Handover performance | Handover delay | [41] | Macrocell/VLC, |
| | Number of handovers | [160] | RF/VLC, |
| | | [214] | WiFi/LiFi |
| | Handover probability | [136] | WiFi/LiFi |
| Power management | Power consumption | [7], [135] , [138] | RF/VLC |
| | | [209] | WiFi/LiFi |
| | | [43] | PLC/VLC/RF |
| | | [108], [216], [218], [220], [228], [229] | RF/FSO |
| | Power/energy efficiency | [33], [140], [203] | RF/VLC, |
| Resource allocation | Fairness | [141] | WiFi/VLC, |
| | | [44] | WiFi/LiFi |
| | | [41] | macrocell/VLC |
| | Spectral efficiency | [206] | RF/VLC, |
| | | [208] | femtocell /VLC |
| | Payoff ratio | [46] | WiFi/LiFi, |
| Others | Communication distance | [127] | RF/VLC, |
| | Average reward | [134] | WiFi/VLC |
| | Queuing length | [18] | RF/VLC |
| | Secrecy | [138] | RF/VLC |
| | Backhaul cost | [194] | RF/FSO |

LiFi [103]. Therefore, the hybrid LiFi/OCC system can be a potential approach to improve localization performance as well.

Fig. 12 shows application scenarios of FSO/VLC, FSO/OCC, and LiFi/OCC hybrid systems [61]–[63], [179], [237], [239], [240]. In this figure, the FSO/VLC hybrid system

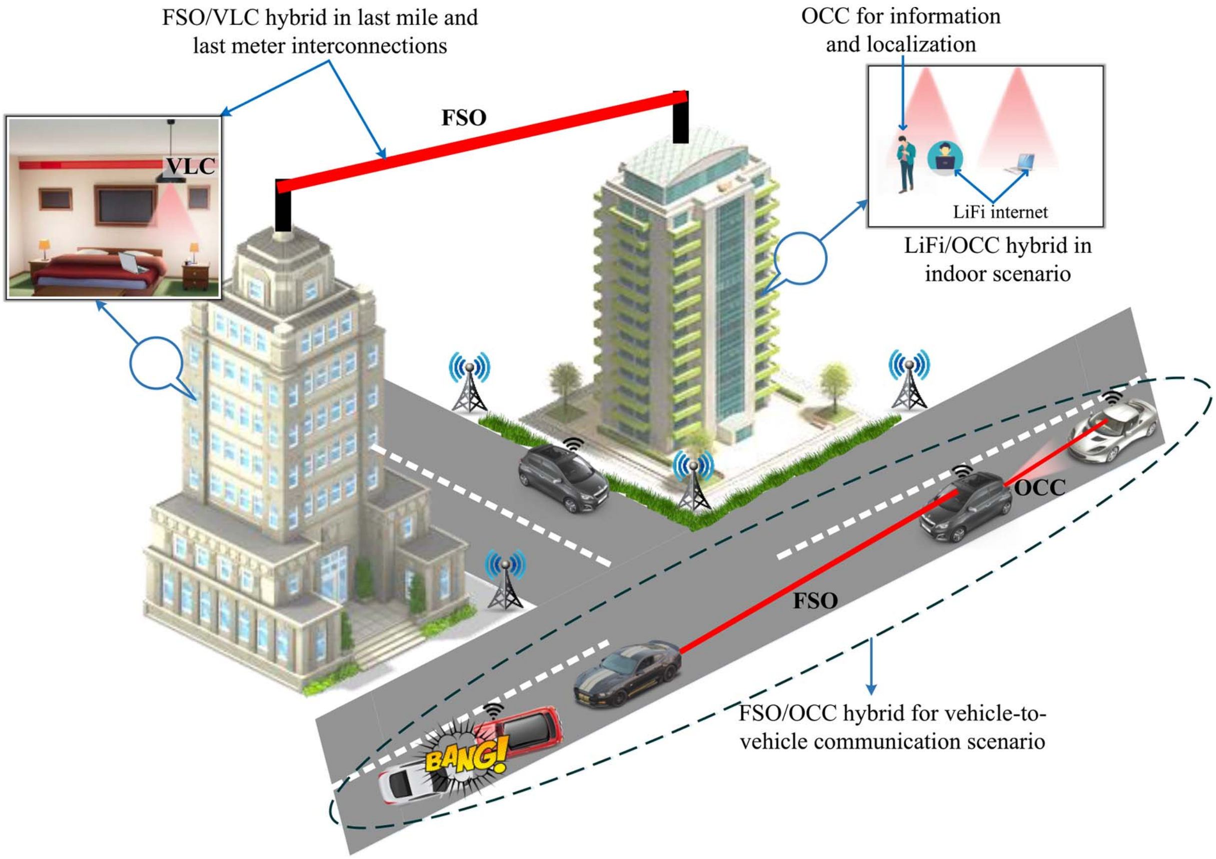


Fig. 12. Scenarios of hybrid FSO/VLC, LiFi/OCC, and FSO/OCC systems.

TABLE XIII
SUMMARY OF NETWORK SELECTION APPROACHES IN HYBRID SYSTEMS

| Hybrid type | Approach | Reference |
|---|---|---|
| RF/VLC | Queue analysis | [132], [135] |
| | Base station intensity, transmit power, and FOV | [139] |
| | Fuzzy logic | [48] |
| | Channel condition. | [49] |
| | Reinforcement learning | [35], [148] |
| | Markov chain state | [42] |
| | Effective capacity | [212] |
| WiFi/LiFi | Exponentially weighted algorithm | [46] |
| | Fuzzy logic | [215] |
| RF/FSO | Weather condition | [112] |
| | SINR calculation | [217] |
| | Channel state information of RF and FSO links | [149] |
| | Graph theory | [194] |
| | Physical interference model of RF | [157] |

provides the last mile and last meter wireless connectivity. The FSO system serves as backhaul connectivity, whereas the VLC network is used for connecting the users. The example of the LiFi/OCC hybrid system explains how a single LED transmitter is used for both the OCC and LiFi systems. An FSO/OCC hybrid system is shown for the V2V communication case. OCC provides communication between two cars whenever the distance is comparatively small. However, the FSO system is used for comparatively long-distance communication. Hence, the hybrid systems fulfill the user's requirement as well as increase the reliability.

The most important benefit generated by hybrid optical/optical systems is the improved link reliability. The hybrid LiFi/OCC, VLC/OCC, and FSO/OCC significantly improve the link reliability. The existence of two networks helps to provide services with less interference effect in LiFi/VLC and low data rate in OCC. Link reliability is a crucial issue in V2X communications that is surely improved by hybrid optical/optical systems. Several parameters such as interference effect, data-rate requirement, communication distance, and traffic type can be considered for the link selection in hybrid optical/optical networks. Moreover, the precise pointing of the transmitter and receiver optical links in FSO is an important consideration in FSO-based wireless hybrid systems for V2X communications. Table XVI shows some related works on hybrid optical/optical systems.

## V. CHALLENGES AHEAD AND LESSONS LEARNED

### A. *Challenges and Open Research Issues*

A number of issues must be solved efficiently for the successful deployment of different hybrid systems. Some important challenging issues and future directions for optical wireless hybrid systems are briefly discussed below.

TABLE XIV
BRIEF OVERVIEW OF IMPLEMENTED OR EXPERIMENTALLY DEMONSTRATED HYBRID SYSTEMS

| Reference | Hybrid type | Summary of implementation | Impact |
|---|---|---|---|
| [34] | RF/VLC | A link monitoring protocol is implemented for VLC link state and it is passed continuously to bonding driver for decision. | Handover performance is demonstrated successfully |
| [53] | WiFi/ VLC | This work implements a testbed for combining WiFi and VLC through the use of power lines. | The implemented testbed can be used for further extension of the work on a hybrid system. |
| [132] | RF/VLC | It presents numerical results of experiments conducted on their VLC/RF hybrid prototype testbed, according to three experiment scenarios, namely, scenario-1: RF with one VLC transmitter and one node, scenario-2: RF with two VLC transmitters and one node, and scenario-3: RF with two VLC transmitters and two nodes. | Overall throughput and link reliability are significantly improved. |
| [142] | RF/VLC | This paper implements an integrated hybrid link that enables wireless Internet access via VLC downlink and WiFi uplink. | Being complementary to WiFi, the downlink hotspots of VLC effectively alleviate contention and interference on the RF channel. |
| [143] | WiFi/ LiFi | A practical architecture of the hybrid system and different channel aggregation techniques are implemented. | Offloading opportunities for WiFi increase as the static users are served by LiFi. Overall throughput is also increased. |
| [207] | RF/VLC | The packet transmission for user datagram protocol in the hybrid system is implemented with the analysis of the packet drop rate and handover from VLC to RF. | The implemented VHO mechanism is fast and the implemented testbed can be further used to verify any proof of concept regarding the hybrid system. |

TABLE XV
SUMMARY OF NETWORK SHARING APPROACHES

| Hybrid type | Uplink | Downlink | User Datagram Protocol |
|---|---|---|---|
| RF/VLC | RF | VLC | [142], [208], [237], [238] |
| WiFi/VLC | WiFi | VLC | [32], [47], [53], [55], [205], [206], [210], [231] |
| WiFi/LiFi | WiFi | LiFi | [46], [143], [238] |
| RF/VLC | RF | Both RF and VLC | [31], [132], [212] |
| Small cell/LiFi | Small cell | LiFi | [208] |
| RF/OCC | RF | Both RF and OCC | [51] |
| RF/VLC, RF/LiFi | No difference for both up and down-links | | [18], [39], [41], [42], [57], [111], [137], [140], [141] |

*Network selection:* An effective network selection technique is essential for the hybrid system. While a hybrid wireless network improves system performance, it also challenges the process of access network selection due to the mixture of heterogeneous wireless technologies. This issue in a heterogeneous network is always more complicated than in a homogeneous network. In homogeneous networks, a straightforward network selection method is selecting the network providing the strongest signal to the user [215]. However, optical wireless hybrid systems comprise two or more heterogeneous technologies, and moreover these technologies may differ in terms of RF and optical wireless technologies. Thus, the complexity of the involvement of many factors makes the network selection challenging. The optimal network selection choice varies with the environment, and to ensure high user QoE, fine-grained intelligent network selection methods are required [134]. The network selection criteria differ for different optical wireless networks as well as differ considerably compared to those of existing RF-based networks. Different heterogeneous parameters should be considered for network selection in hybrid systems. This is a challenging task of network selection in a dynamic and unknown environment for real implementation of hybrid systems. Careful selection of such parameters as well as efficient selection policy is vital to harness the benefits of hybrid networks. Moreover, computation time should be considered to minimize the delay. Although several researchers addressed this issue on their theoretical works, successful deployment of hybrid RF/optical and optical/optical network systems is still a challenging issue.

*Access Protocol:* The support of user mobility is vital for future wireless systems. The user moves in an indoor as well as outdoor environment, which makes localizing the mobile receiver and the coordination mechanism between the LED transmitter and RF-BS key challenges in the access protocol [205]. The CSMA/CA protocol has been presented separately for single-network scenarios in several existing works, rather than RF/optical wireless hybrid networks [241]. Therefore, further research for designing the CSMA/CA protocol of different wireless hybrid systems is required. Further, there is a wide scope of possible contributions to the design of medium access control protocols for uplinks in RF/optical and optical/optical wireless hybrid networks.

*Heterogeneous receiver type:* Supporting of heterogeneous type of receivers is particularly important in hybrid network systems. Both the receivers for two different networks of the hybrid system should be active simultaneously. The characteristics of the RF-based receiver and the optical-based receiver are different. Hence, to combine RF and optical systems together as a hybrid network as well as to transmit the same data through different systems simultaneously is a crucial issue.

TABLE XVI
SUMMARY OF CURRENT RESEARCH TRENDS ON OPTICAL/OPTICAL BASED HYBRID SYSTEMS

| Hybrid type | Reference | Focus of the work | Contribution and Research Direction |
|---|---|---|---|
| VLC/OCC | [61] | Using the same LED transmitter for VLC and OCC systems | A system that can transmit to PDs and cameras of VLC and OCC systems, respectively, simultaneously at different data rates through the same physical transmission channel is proposed. |
| LiFi/OCC | [62] | Network assignment and link switching | Fuzzy-logic-based network assignment mechanism is developed for the hybrid system. Moreover, a dynamic link-switching technique for efficient handover management between networks is proposed. |
| FSO/VLC | [179] | System development and demonstration of a hybrid FSO/VLC system | This paper evaluates the system performance of a multiband carrier-less amplitude and phase (*m*-CAP) modulation scheme for a range of FSO/VLC link lengths and *m*-CAP parameters in terms of data rate. |
| | [237] | A hybrid optical wireless network based on FSO/VLC heterogeneous interconnection for space-air-ground-ocean-integrated communication architecture, especially in the RF sensitive or security-required environments | A hybrid network coordinator is defined, along with the implementation and deployment details. Moreover, three fundamental network-layer mechanisms are designed in the coordinator including user identification and localization, user mobility and handoff control, and routing and traffic management. Experimental FSO/VLC heterogeneous interconnection is also presented. |
| | [239] | System architecture and network selection in hybrid OCC/Li-Fi system | Fuzzy-logic approach is applied to select the best network when the same LED transmitter is used for LiFi and OCC systems. |
| VLC/FSO/VLC | [240] | Performance analysis of three hop hybrid VLC/FSO/VLC | The performance of the three hop hybrid system is derived in terms of the closed-form expression for the outage probability. Moreover, an expression for the asymptotic outage probability of the system is derived to investigate the behavior of the system. |

*Handover:* Handover is an important factor of a hybrid system. Although efficient VHO schemes have been extensively studied in RF communications, the property of an optical channel due to the random movement of users makes the VHO between RF and optical wireless networks more complex than that in all-radio environment. The properties and mechanisms of physical and data-link layers differ among such heterogeneous optical and RF-based wireless networks, which pose a great challenge to the mobility management of hybrid systems [48]. Appropriate handover decision criteria and algorithm remain relevant research questions for optical wireless hybrid networks. The challenges include user mobility and its effect on channel estimation and handover. Optical wireless systems are vulnerable to channel blockage due to obstacles, adding an important factor for targeting the network during the handover. The handover should be of short duration to satisfy the specification of the 5G requirement. During a handover, the time it takes for exchanging the signaling information between users and a central unit varies from ∼30 ms to 3000 ms, depending on the algorithms used [39], [141] in RF/VLC and RF/LiFi hybrid systems and the transmission losses occurring during this period. Moreover, the small coverage of LiFi and VLC in indoor applications creates a large number of handovers. Avoiding unnecessary handover is also an important issue.

*Load balancing:* Effective load balancing for hybrid networks is a technical concern. The first challenging issue in optical hybrid networks is how to allocate the users among the available access networks belonging to different access technologies. Finding optimal user association leads to solving a joint association and a resource allocation problem [208]. The load balancing mechanism must be performed periodically during a call session. During user movement, users may need to be switched to different better-serving APs and a handover may be prompted [211]. Therefore, considering the mentioned facts, optimum load balancing in a hybrid network is a challenging issue.

*High-capacity backhaul network:* A huge amount of overall data throughput in the access network is produced due to supporting of high-data-rate applications and massive connectivity by hybrid networks. To support this data throughput, an extremely high-capacity backhaul is still an open challenging research issue.

*Seamless steering of transmitted data:* There are multiple transmitters in a hybrid system. The data transmission to the desired receiver also varies due to several reasons such as a change in a communication environment, data type, and movement of a user. Moreover, the AP assignment and seamless steering of transmitted data become prominent challenging issues in hybrid networks. The major concerns regarding this issue are data loss minimization, optimal transmitter selection, and delay minimization.

*Different backhaul network connectivity and synchronization:* In a hybrid system, the involved networks may use same or different systems for backhauling the traffic, e.g., indoor femtocell and LiFi can use the same Ethernet or CATV networks for backhauling their traffic in a femtocell/LiFi hybrid system. In contrast, indoor LiFi can use Ethernet and the outdoor macrocellular network can use optical fiber networks for backhauling their traffic in a macrocell/LiFi hybrid system. Traffic backhauling for a user in a hybrid system through different backhaul networks requires precise synchronization. Moreover, switching between backhaul networks requires a smooth handover.

The backhauling for moving networks needs to continuously change the pointing of the backhaul connectivity, which may be challenging. To date, there are no studies addressing these issues. Hence, future research should focus on this important technical problem.

*Software-defined networking control for hybrid systems:* The control and management of different optical wireless hybrid systems in an efficient way is a major concern for dense network deployment. To this end, software-defined networking (SDN) can provide effective solutions, as it controls the networks centrally by the SDN controller [242]. Generally, the SDN system comprises three layers, namely the application layer, control layer, and infrastructure layer [243], [244]. Several hybrid OWC application strategies depending on the network demand, such as traffic controlling, security management, and network flow management, can be defined in the application layer. The northbound application programming interface (API) makes a communication link between the application and control layers. The necessary control and management protocols, such as updating the flow protocol, network selection mechanism for hybrid system, function generation, and programming the interfaces, can be performed in the control layer of the SDN system. Hybrid OWC network devices, such as routers and switches, are contained in the infrastructure layer. These devices can obtain the packet forwarding commands from the control layer through southbound API. SDN technologies can be implemented for the purpose of energy consumption reduction by controlling data traffic. With the development of recent hybrid OWC applications, real-time tasks and communication with multiple users is required. Consequently, the approach based on SDN will draw an essential part to understand the concept of the virtualizing network function for optical wireless hybrid systems.

*Cross-layer design:* RF/optical wireless hybrid systems proposed to date mostly from the perspective of physical layer [135]. They rarely focus on data-link layer metrics. Due to the dramatic increase in demand for reliable delay-sensitive services in recent years, we need to consider the QoS metrics of the physical layer as well as data-link layer. Hence, the cross-layer performance analysis tool between the physical and data-link layers features is crucial. Numerous studies concerning the cross-layer analysis between physical and data-link layers can be found in many different RF scenarios. However, there are only a few studies regarding the cross-layer performance levels investigation in OWC systems, and they are not sufficient to solve the issues of RF/optical wireless hybrid systems.

*Limited uplink communication using optical system:* According to the hybrid system topology, the forward and return communication paths may be different or the same, based on the application scenario and hybrid type. However, communication through optical wireless hybrid systems is to date not practically suitable for the uplink. The reasons are as follows: (i) mobile devices, e.g., smartphones and laptops are energy constrained, and equipping these mobile devices with a light source for communications requires use of large amounts of power; (ii) the uplink VLC with a narrow beam requires the transmission beam to be oriented to a fixed direction [128]. Minor movement of the mobile device could significantly affect the link performance and cause unsuitability is communication; (iii) uplink visible signals affect indoor illumination and cause discomfort to human eyes. Taking these inconveniences into consideration, VLC is ideally suited as a complementary downlink-only technology within an RF/optical wireless hybrid system. Hence, the support of uplink transmission using OWC systems is challenging in the real implementation of RF/VLC and RF/LiFi hybrid systems.

*Modulation techniques in optical/optical wireless hybrid systems:* The modulation techniques for OCC are different for LiFi and VLC systems. This is because OCC cannot support high-speed modulation due to the limited frame rate of conventional cameras. This brings difficulties to the use of the same light source as the transmitter for two different OWC systems, such as OCC and LiFi. Hence, the implementation of different modulation schemes for optical/optical wireless hybrid systems is a challenging task.

*Performance enhancement in mixed RF/FSO relay systems:* Atmospheric turbulence and pointing error may lead to significant degradation of the end-to-end performance due to a poor link between the RF and FSO, e.g., a high error floor or a limited end-to-end capacity in a dual-hop mixed RF/FSO system [149]. Additional transmission power can be forced to overcome the effects of such system impairments. Nevertheless, such increase in transmission power might affect the secrecy performance. Hence, efficient power allocation in a mixed RF/FSO relay system is an important concern for the mixed RF/FSO relay systems.

*Underwater communication:* The research on developing hybrid systems for UWC is still in its infancy and needs proper analysis. In addition, the adaptive switching between an acoustic and optical mode for various operations need extra attention in underwater hybrid optical/RF and optical/acoustic networks [185].

*Hybrid transmission:* Currently, LED transmitters are used for LiFi/OCC or VLC/OCC hybrid systems. The use of LEDs for different systems increases the system identification complexity and cost apart from making the system bulky. As the OCC and LiFi (or VLC) systems operate in different modulation bandwidths, it is also not easy to transmit data for both systems through the same LED transmitter. Only a few researchers have addressed this issue in their works, and the development phase of this issue is still in the primary stage. Therefore, investigation on this issue is important for the future development of indoor optical/optical hybrid systems.

### *B. Summary and Lessons Learned*

Different wireless access technologies have different attractive features as well as limitations. Optical and RF signals do not interfere with each other. Moreover, the RF and optical wireless technologies normally exhibit opposite performance characteristics. Besides, some optical wireless technologies, e.g., LiFi and OCC also exhibit opposite characteristics in terms of some performance metrics. These important facts motivate the need for OWC based hybrid wireless systems to overcome the limitations of a single technology and meet the growing demands of 5G and beyond communication systems. The main advantages of RF wireless systems are better mobility support through a wide coverage area, flexibility, and communication support both in LOS/NLOS conditions; whereas the scarcity of bandwidth and lower throughput are their key limitations. In contrast, wide available bandwidth and higher throughput are the main attractive features of most OWC systems. Common limitations of the OWC technologies are the limited or no support of NLOS communication, very low or no mobility support, and atmospheric effect. The hybrid wireless system consisting of both RF and optical wireless technologies can significantly overcome the limitations and gain attractive features of the individual wireless system. Hybrid wireless systems are effective in a wide variety of applications including indoor, outdoor, and underwater scenarios to improve various performance metrics such as throughput, reliability, security, and energy efficiency.

A hybrid wireless system can contain different combinations of various networks and function in different manners based on need. Both networks can be operated simultaneously, or one can be acted as a backup of the other network. The system can be applied for either single-hop or multi-hop communication. Two individual networks in a hybrid wireless system can either share the uplink and downlink of a user separately or serve totally different users. Table XV summarizes some uplink/downlink sharing approaches for different RF/optical wireless hybrid systems. A network in a hybrid wireless system is selected based on any of the criteria, such as traffic type, link type (i.e., uplink/downlink), required communication distance, scenario of LOS/NLOS, required level of security, and required mobility support. An efficient mechanism considering appropriate criteria is crucial to properly share the load among networks.

Data rate enhancement through traffic offloading, seamless movement support, and interference reduction are the main reasons for using hybrid wireless systems indoors. In contrast, link reliability improvement and overcoming the atmospheric effects are important reasons due to which outdoor hybrid wireless systems are deployed. The simultaneous use of the microwave/mmWave link and FSO technologies in RF/FSO hybrid backhaul connectivity has the ability to overcome atmospheric effects such as rain, snow, dust, and fog. RF/optical wireless hybrid systems significantly reduce the interference effects while improving other performance metrics. However, optical/optical wireless hybrid systems do not perform to reduce the interference effect. The improving of link reliability is the primary goal for using different kinds of optical/optical wireless hybrid systems. Table XII discusses the research outcomes on different RF/optical wireless hybrid systems in terms of various performance metrics.

Among various application scenarios, deployment of hybrid wireless systems in moving networks is more challenging, as both the access and backhaul networks are in movement, and outdoor atmospheric conditions need to be likewise considered. Moreover, for other networks, it is challenging if the data of a user needs to be sent through different type of backhaul networks due to the use of separate networks for the uplink and downlink.

The goals and issues of different hybrid wireless systems are different, and several approaches have been proposed to address them. Throughput enhancement is the main goal for the deployment of RF/VLC and RF/LiFi hybrid wireless systems depicted in [7], [31], [34], [39], [44], [46], [53], [137], [142], [143], [213], [214]. For the successful deployment of these hybrid systems, some issues have been considered as important research topics, including handover performance improvement [18], [34], [38], [48], [54], [207], enhancing the energy efficiency [32], [33], [140], [203], intelligent network selection [35], [134], coverage extension [40], [49], [127], outage probability reduction [160], error rate reduction [160], efficient load-balancing technique [140], [208], spectral efficiency maximizing [206], security enhancement [138], efficient resource allocation [39], and cost minimization [51]. To date, no significant research has been performed on OCC based wireless hybrid systems. Our previous studies [102], [148] explain the two use cases of RF/OCC hybrid systems. However, extensive studies on network selection, handover performance improvement, and security enhancement are required for RF/OCC hybrid systems. RF/FSO hybrid systems enhance the throughput and improve reliability by minimizing the atmospheric effects as presented in [55], [58], [59], [110], [111], [147], [149]–[159]. A wide scope of related studies has also been performed on different issues such as the optimal transmission power [108], reliability enhancement [154], [217], atmospheric turbulence mitigation [156], [222], outage probability reduction [195], [196], and optimal relay selection [228], with the aim to support RF/FSO hybrid systems. These RF/FSO hybrid studies indicate that considering the atmospheric conditions for the optimal solution in selecting the appropriate network seems like the most important factor. The research on the optical/optical wireless hybrid system is in primary stage. The use of the same light source as a transmitter for two different OWC technologies simultaneously seems to be a promising research step. Most studies related to hybrid wireless systems are not experimentally demonstrated, and only involve theoretical analysis. Optical wireless hybrid systems cover a wide range of areas. Several studies have already been performed to resolve numerous technical issues, however, many issues remain.

## VI. CONCLUSION

Recently, because RF systems cannot fulfill various growing demands of 5G and beyond communication systems, different OWC technologies have become a prominent part of the wireless communication system. OWC's excellent features make it is a promising complementary option to RF-based wireless communication systems. The co-deployment of two or more networks having different characteristics can overcome the limitations of a single network. Therefore, the hybrid systems comprising an optical wireless system with RF or another optical system can overcome many limitations of either RF or optical wireless based single networks. Studies on the remaining challenges related to the application of different hybrid wireless networks are underway.

This review paper addresses key research issues for optical wireless hybrid networks. The hybrid architecture scenarios and their opportunities are also discussed. This paper provides a summary of existing ongoing research works on RF/optical, optical/optical, and acoustic/optical wireless hybrid network systems. For different combinations of hybrid systems, RF-based macrocells, small cells, WiFi, and BLE as well as optical-based VLC, LiFi, OCC, and FSO communication technologies are considered. The opportunities created by these hybrid systems as well as network architecture, network selection, and application scenarios are discussed. A variety of application scenarios such as indoor, vehicle, space, eHealth, and underwater are considered in this paper. Furthermore, the key research directions of different hybrid network systems are discussed. The important challenges that need to be addressed for a successful deployment of hybrid network systems for 5G and beyond and IoT paradigms are also briefly pointed out.

Finally, this article is concluded by emphasizing the fact that the performances of optical wireless hybrid systems could be further improved by aiming at tight integration among counterpart networks and investigating innovative research trends that are not fully solved. This review paper will help in understanding the research contributions in different optical wireless hybrid systems and is expected to prompt further efforts for the successful deployment of OWC systems as a promising complementary to RF-based technologies in future 5GB communication systems.

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