IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received October 8, 2021, accepted October 31, 2021, date of publication November 17, 2021, date of current version December 10, 2021.

Digital Object Identifier 10.1109/ACCESS.2021.3129154

Hybrid RF/VLC Systems: A Comprehensive Survey on Network Topologies, Performance Analyses, Applications, and Future Directions

HISHAM ABUELLA[1], (Student Member, IEEE), MOHAMMED ELAMASSIE[2], (Senior Member, IEEE), MURAT UYSAL[2], (Fellow, IEEE), ZHENGYUAN XU[3], (Senior Member, IEEE), ERCHIN SERPEDIN[4], (Fellow, IEEE), KHALID A. QARAQE[5], (Senior Member, IEEE), AND SABIT EKIN[1], (Senior Member, IEEE)

[1]School of Electrical and Computer Engineering, Oklahoma State University (OSU), Stillwater, OK 74078, USA
[2]Department of Electrical and Electronics Engineering, Özyeğin University, 34794 Istanbul, Turkey
[3]CAS Key Laboratory of Wireless-Optical Communications, University of Science and Technology of China, Hefei 230052, China
[4]Department of Electrical and Computer Engineering, Texas A&M University, College Station, TX 77840, USA
[5]Department of Electrical and Computer Engineering, Texas A&M University at Qatar, Doha, Qatar

Corresponding author: Sabit Ekin (sabit.ekin@okstate.edu)

This work was supported by the Qatar National Research Fund (a member of the Qatar Foundation) under Grant NPRP 13S-0130-200200.

ABSTRACT Wireless communications refer to data transmissions in unguided propagation media through the use of wireless carriers such as radio frequency (RF) and visible light (VL) waves. The rising demand for high data rates, especially, in indoor scenarios, overloads conventional RF technologies. Therefore, technologies such as millimeter waves (mmWave) and cognitive radios have been adopted as possible solutions to overcome the spectrum scarcity and capacity limitations of the conventional RF systems. In parallel, visible light communication (VLC) has been proposed as an alternative solution, where a light source is used for both illumination and data transmission. In comparison to RF links, VLC links present a very high bandwidth that allows much higher data rates. VLC exhibits also immunity to interference from electromagnetic sources, has unlicensed channels, is a very low power consumption system, and has no health hazard. VLC is appealing for a wide range of applications including reliable communications with low latency such as vehicle safety communication. Despite the major advantages of VLC technology and a variety of its applications, its use has been hampered by its cons such as its dependence on a line of sight connectivity. Recently, hybrid RF/VLC systems were proposed to take advantage of the high capacity of VLC links and better connectivity of RF links. Thus, hybrid RF/VLC systems are envisioned as a key enabler to improve the user rates and mobility on one hand and to optimize the capacity, interference and power consumption of the overall network on the other hand. This paper seeks to provide a detailed survey of hybrid RF/VLC systems. This paper represents an overview of the current developments in the hybrid RF/VLC systems, their benefits and limitations for both newcomers and expert researchers.

INDEX TERMS Radio frequency (RF), visible light communication (VLC), hybrid RF/VLC, wireless fidelity (Wi-Fi), hybrid networks, hybrid RF/VLC environments.

I. INTRODUCTION

Wireless communication systems have undergone many changes and developments since their inception. This coincides with the discovery of electromagnetic waves (EM) and wireless telegraph to the present day as advanced technologies such as smartphones, connected vehicles and the Internet of Things (IoT) became widely available. All these new technologies rely on wireless communication to adapt to the common demand for high bandwidth and data rates. Over the past decades, mobile communications that started with first-generation (1G) and followed by second, third, fourth and fifth generations (2G, 3G, 4G, and 5G). In addition, the wireless fidelity (Wi-Fi) standards for short-range wireless

The associate editor coordinating the review of this manuscript and approving it for publication was Kai Li.

communication (IEEE 802.11) have evolved rapidly especially in terms of data rate, capacity, and medium access methods.

To cope with over-occupied low-frequency bands and provide higher data rates, the idea of millimeter-wave (mmWave) systems was lately introduced. Unfortunately, using radio frequency (RF) systems in the mmWave band has a lot of challenges in terms of channel modeling and transmission power. In addition, using mmWave band is faced with multiple challenges from propagation characteristics of mmWave band (atmospheric and rain attenuation) to beamforming and alignments issues which are discussed in more details in [1]. However, channel modeling and measurements for this band were reported by a lot of studies such as [2]. Despite these challenges, mmWave systems are seen as one of the strongest candidates for 5G systems and some IEEE standards for these systems were introduced as in [3] (IEEE 802.11ad for the 60 GHz band). Alternatives to traditional RF systems in terms of mmWave systems are discussed in [2], [4], [5].

As an alternative to communication systems that operates in the RF band (3 kHz to 300 GHz), the use of visible light (VL) band (400 THz to 800 THz) for wireless communications has been proposed. The idea of using light to transmit a signal has been proposed by Bell and Tainter in 1880 (photo-phone) as discussed in [6]. However, the idea of transmitting data using a light source was first introduced using a fluorescent lamp in [7]. Later, the idea of using the fast switching light-emitting diodes (LEDs) was discussed for the first time in [8]. As early as the 2000s in Japan, the white-LED was used for both illumination and communication by researchers at Keio University [9]. After this achievement, numerous studies have been published on how to make use of white-LEDs in communication systems. Based on visible light communication (VLC) technology, light fidelity (Li-Fi) was then proposed in [10], [11] to form a small-cell wireless access network where multiple light sources in an indoor environment are used as access points (APs). Furthermore, in 2011, the first IEEE standard related to VLC (802.15.7-2011) was published by IEEE 802.15 working group for Wireless Personal Area Networks. The details of this standard pertaining to data rates, modulation schemes, and dimming mechanisms are discussed in [12]. As a broadens of IEEE standard of STD 802.15.7-2011 to include much more Optical wireless communications (OWC) technologies, STD 802.15.7-2018 has been proposed with six PHY layers categories [13]. Particularly, this version describes the use of OWC for optical wireless personal area networks (OWPANs) and well-known as the first IEEE standard for Optical Camera Communication (OCC). Actually, OCC technology represents a promising approach to take advantage of the benefits of VLC in beyond-5G applications and is one of the key technologies for the IoT. It can also be considered as the best compatible with the available infrastructures and can be used in several scenarios/applications. For example, vehicles can exchange safety-related traffic information such as braking performance, accident notifications, speed's and direction's related information. In OCC, with typically low-frame-rate camera detectors, special modulation schemes are needed for non-flickering illumination [14]. OCC is also a mature technology that is clearly described within the IEEE 802.15.7-2018 standard [13]. Particularly, there are three physical layer (PHY) categories for OCC within the IEEE 802.15.7-2018 standard:

- **PHY IV:** For outdoor applications with mobility support. Therefore, it can be used for vehicular communication.
- **PHY V:** For commercial cameras with rolling shutter type such as the used cameras in smartphone. Therefore, it can be suitable for indoor applications with small distances.
- **PHY VI:** For screen signage services. Therefore, it can be used for applications such as TV, tablet, smartphone screens.

Since OCC is one of OWC systems that use cameras to receive data rather than photodetectors [15] and, recently, the use of advanced cameras in smart devices such as mobile phones has been increasing dramatically, the paths for OCC to address several challenges in different applications are opened [16]. The most common applications are vehicle-to-everything (V2X) communications [17], [18], positioning of smartphones and mobile robots (MRs) [19], [20], localized advertising, digital signage, and augmented reality (AR) [21]. While OCC can be considered as one of the good solutions for long-distance LOS communication links due to several characteristics such as low interference, high SNR, high security, and high stability with respect to non-fixed communication link distances, the data rate is very limited due to the fact that the sampling rate of commercially widely available cameras is not high. Particularly, it ranges from several bits per seconds (bps) to several kilobits per seconds (kbps) that can be achieved by using cameras of 30 frame per second (FPS) [22]–[24]. It is, however, possible to overcome this problem by using high-speed cameras of 1000 FPS [25].

While OCC received good attention, VLC has received much more attention. Particularly, a lot of studies and surveys which discussed the possible applications, advantages, and limitations of these systems were published, see e.g., [26], [27]. In [28], the authors presented the limitations and advantages of using VLC as a candidate for 5G systems. In [26], Pathak *et al.* discussed the details of VLC based systems and some of the possible applications like VLC sensing and indoor localization and even using of VLC in vehicle-to-vehicle (V2V) communication. In [29], Uysal *et al.* discussed the usage of VLC in V2V and the achieved data rate limitations when utilizing LED headlamp used by automotive industry in VLC. In [30], Chowdhury *et al.* provided an overview on optical wireless communication systems and their network architectures and applications.

As for the comparison of the RF and VLC systems, Fig. 1 summarizes the weaknesses and strengths of each of these systems as standalone networks. Based on these, there are several studies investigating how RF and VLC systems can

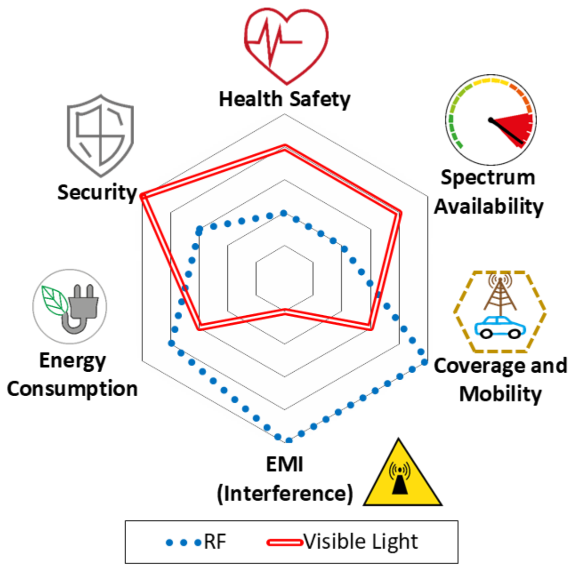


FIGURE 1. Comparing the pros and cons of VLC & RF standalone systems.

be used as a complementary technology to each other. Analogously, numerous studies have proposed hybrid RF/VLC systems to overcome the limitations of VLC by using RF technology in conjunction with the VLC systems.[1]

To our best knowledge, the only tutorial discussing hybrid RF/VLC systems was published in [31], [32]. Ayyash *et al.* in [31] discuss the coexistence opportunities of Wi-Fi and Li-Fi systems, the opportunities that these systems present for off-loading of Wi-Fi systems and the challenges faced by these wireless heterogeneous networks (HetNets) as a future solution in 5G systems. Chowdhury and Katz [32] discuss the possibility of using a hybrid RF and optical wireless network to meet the 5G requirements. They provide a brief overview of optical wireless networks and the possible hybrid network architectures and describe the possible research directions and improvements for hybrid RF/VLC networks. Moreover, multiple surveys discussing the improvements of VLC and Li-Fi networks have discussed the idea of hybrid RF/VLC networks as in [33]–[36]. In [33], Obeed *et al.* focus on the VLC networks and how to optimize them for downlink applications. The authors present the challenges facing VLC networks and proposed solutions by literature to maximize the benefit from VLC networks in terms of sum rate, fairness, energy efficiency, secrecy rate, and harvested energy. However, integration of VLC with current existing RF systems and how to utilize them together are not covered. In [35], Li *et al.* focus on the design of VLC networks system level from network centric to user centric (UC) design principle. Moreover, the survey focuses on a radically new UC design philosophy and discuss the visible light communication link structure and the unique characteristics. However, this study does not explain how RF and VLC can be used together in different network designs. It also does not discuss the performance analysis of different hybrid systems, their applications and environments. In [36], Feng *et al.* presented a magazine article which discusses the VLC networks and their main architecture. Moreover, the features of VLC networks make them a good candidate to play an important role in 5G networks. However, this article lacks important aspects of how hybrid systems are designed and used in different applications.

[1]The research carried out on hybrid RF/VLC are chronologically ordered and summarized in Table 9.

A survey was published on arXiv [37] which focuses more on optimizing the Li-Fi/ Wi-Fi network parameters (user behavior modeling, interference management, handover, and load balancing) but did not focus on the general RF/VLC systems.

In addition, a general overview of the optical wireless hybrid systems and current research trends and issues in network layer level is presented in [21]. In [21], authors focus on optical wireless hybrid systems, which include VLC and OWC. The authors have introduced the difference between different light-based technologies such as VLC, Li-Fi, OCC and free space optical (FSO) communications. Moreover, the authors presented different applications that cover hybrid systems. The author presented system models to show the different application where hybrid systems can be used. After the publication of [32], a large number of studies have been reported on the design and performance analyses of these systems as described in chronological order in Table 9.

In addition some studies discussed the use of hybrid RF/VLC in high level applications. Liu *et al.* in [38] presented an intelligent transportation hybrid system that utilizes the directionality of visible light to send a lane specific code for vehicles to decode a message sent by RF link which improves the effective communication area. Yang *et al.* in [39] discussed the idea of integrating visible light communication and positioning to assist in 5G networks for IoT devices where macrocell and picocell provide coverage and reliability in RF spectrum, and optical attocell provide the high-speed transmission and high-accuracy positioning services.

This survey focuses on achieving the following goals:

1) Highlighting the design aspects of VLC systems such as channel modeling, system performance, advantages, and limitations.
2) Highlighting the RF technologies that are used in hybrid systems and their corresponding channel models.
3) Offering readers a general understanding of hybrid RF/VLC systems, their history, and the desired goals intended to accomplish.
4) Pointing out the contributions of the major hybrid RF/VLC studies according to their network topology and performance analysis.
5) Outlining the challenges in the development of hybrid RF/VLC systems, future research directions, and possible promising applications.
6) Comparing all of the existing studies on hybrid RF/VLC systems in terms of the employed technologies, network topologies and main features.

7) Pinpointing research challenges, future research directions, and possible applications.

The rest of the paper is organized as follows. VLC and RF systems are presented in Section II. Hybrid RF/VLC systems, network topologies, performance analysis studies, system-level simulations, and implementations are discussed in Section III. Research directions and emerging applications of hybrid RF/VLC systems are presented in Section IV. This survey ends with concluding remarks on the potential of hybrid RF/VLC systems. Nomenclature and key symbols used in the paper are summarized at the end of the paper.

II. VLC AND RF TECHNOLOGIES

In this section, we provide an overview of the VLC and RF systems highlighting the used modulation techniques and channel properties. We further compare these two systems motivating the need for developing hybrid RF/VLC systems.

A. VLC SYSTEMS

The main requirement for a VL source to be used in a communication link is that the light intensity should be modulated at a rate higher than 200 Hz [12] to avoid any flickering effects to the human eyes. Despite this minor requirement, VLC research has shown that high data rates can be achieved (nearly 100 Mbps in IEEE 802.15.7 [12]).

In addition to academic/theoretical VLC research activities, industry interest in VLC has sparked related standardization activities in this emerging market. For example, the VLC consortium (VLCC) initiated the standardization activities and proposed two standards which are accepted by Japan Electronics and Information Technology Industries Association (JEITA). The two proposed standards by VLCC are VLC system standard (CP-1221) and visible light ID standard (CP-1222). The latter has been updated to visible light beacon system standard (CP-1223). CP-1223 describes the unidirectional VLC system for multimedia applications with supported wavelengths in the range of 380 - 780 nm and data rate around 4.8 kbps by the use of inverted 4 pulse position modulation (I-4PPM). Similarly, IEEE introduced IEEE Standard 802.15.7, which is defined for short-range communication. The sufficient data rates for supporting audio and video multimedia services are specified. This standard defines two layers which are physical layer (PHY) and medium access control layer (MAC). They have defined three types of PHY layers based on the supported frequency band, optical clock rate and data rate. The first PHY (PHY I) is defined for outdoor with low data rate applications. Particularly, it can support up to 266.6 kbps. The second PHY (PHY II) is defined for indoor with moderate data rate applications. Modulation schemes of on-off keying (OOK) and variable pulse position modulation (VPPM) up to 96 Mbps are supported. The third PHY (PHY III) is defined for application with multiple light sources/detector. Modulation scheme of color-shift keying (CSK) up to 96 Mbps is supported. On the other hand, the MAC layer handles accessing to PHY layer. The dedicate portions, also called guaranteed time slots (GTSs), are assigned by a coordinator device during contention free period [13], [40]–[42].

Despite the fact that the optical channel of visible light is in the order of THz, the bandwidth of commercial LEDs is limited. It has been shown that the LED's modulation bandwidth is in the order of MHz to hundreds of MHz [43]. This makes it a bottleneck for achieving high-rate transmission. Different efforts have been conducted to address this. The first optical transmitter that was adopted is phosphor-converted LED. The bandwidth of a phosphor-converted LED is limited because of its slow response. A post-equalization circuit which consists of one active equalizer and two passive equalizers was then proposed to extend the bandwidth up to 150 MHz [44]. Notice the fact that if higher bandwidth LEDs are employed, the bandwidth can be significantly increased. For example, 1 Gbps was reported by using micro LEDs as transmitters [45].

Different experiments have been conducted in the literature comparing line-of-sight(LOS) with non-LOS (NLOS) Links. In [46], they have carried out experimental studies where the measurements have been done in an empty room for different scenarios including LOS and NLOS cases. They have considered frequency sweeping technique in their measurements by using of vector network analyzer (VNA) in an effort to obtain channel impulse response (CIR). While the reflected rays can still be detected in NLOS scenarios, the channel gain severely dropped (see [46, Fig. 6]). Similar observations can be seen in [47] where a commercial optical and illumination design software is used for obtaining CIR. Moreover, uplink in VLC systems can be considered as one of the major challenges. Furthermore, the advancements in the LED industry are still hard to support the user equipment (UE)'s side with a VLC transmitter. Moreover, VLC is sensitive to interference caused by other light sources which can be clearer in daylight or outdoor scenarios. Also, the dimming mode for using VLC in low light scenarios can be an issue although an advanced modulation technique (enhanced unipolar orthogonal frequency division multiple access (eU-OFDM) [48]) has been proposed for Li-Fi systems to operate in the very low light intensity scenarios while keeping a reasonable data rate. An important design consideration for VLC networks is the LED connectivity to the internet source. Typically, VLC networks present a large number of APs of LED arrays which make internet connectivity challenging. Most of these limitations have been recognized in literature and solutions have been proposed to resolve them [49]. We will outline the main solutions later in this survey.

Next, we will focus on introducing the basic VLC system components, modulation techniques and channel properties that help in developing a robust hybrid RF/VLC system with respect to the limitations outlined above. Fig. 2 depicts the basic structure of the VLC system. We will later outline the main differences between the RF systems and VLC systems. It is clear that the base-band algorithms will not change a lot except for the fact that LEDs and photo-detectors (PDs)

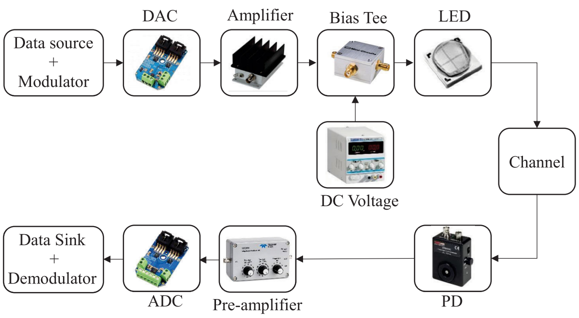


FIGURE 2. Block diagram of the basic structure of the VLC system.

operate in the non-negative voltage range, unlike the RF antennas. At the transmitter side, an LED is used instead of an antenna in the RF system. This LED needs two inputs: an analog signal and a direct current (DC) supply to drive the LED. Additionally, like in the RF-based systems, a digital to analog converter (DAC) is used to convert the digital signal into an analog signal after getting the modulated data from the base-band modulator. At the receiver side, a PD is used instead of a receiving antenna and the signal is amplified by using an electric amplifier, sometimes adding some optical lens and filters to improve the field of view (FOV) and gain of the receiver. After amplifying the signal, an analog to digital converter (ADC) is used to convert the analog signal into a digital signal that is to be processed by the base-band digital demodulator.

1) VLC FRONT-ENDS (TRANSMITTER/RECEIVER)

There are two major types of structures for colored/white LEDs used in general lighting. The first type consists of a blue-colored LED with a phosphor layer coated on top of it. When an electric current is applied to the LED, light is emitted from that LED and part of it is absorbed by the phosphor to generate the second color. The combination of these two colored lights results in colored/white light. Another type of LED is produced by mixing lights from three primary colored chips (RGB). Three chips emit each color simultaneously and at the output, the required colored/white light is produced. The phosphor white LED has the advantage of low cost. However, the nature of phosphor light conversion makes it unsuitable for high-speed data communication due to phosphorous response time. In other words, white phosphor LEDs (WPLEDs) exhibit a limited bandwidth of few MHz while RGB LEDs present a higher bandwidth with an order of magnitude higher than WPLEDs [40], [50]. Furthermore, RGB-LEDs are suitable for color shift keying (CSK) modulation technique. This will be discussed in more detail in the VLC modulation methods subsection.

On the receiver side, there are three types of receivers that can be used:

- **Photo-detector (photo-diode) (PD)**:
  It is a semiconductor device that converts the light energy to a voltage difference and it can support very high data rates.

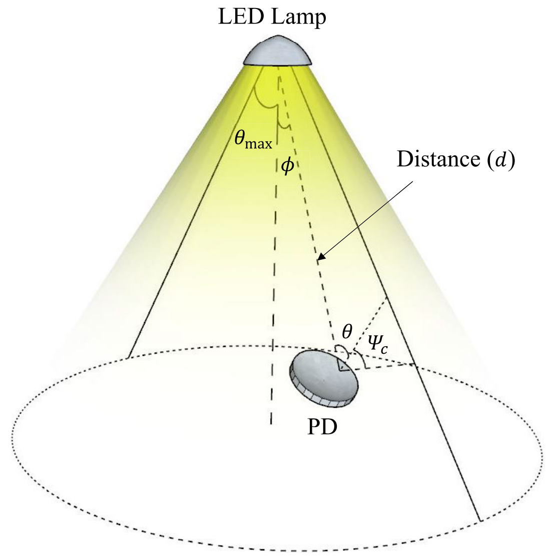


FIGURE 3. LED based LOS channel model [51], where a VLC transceiver system model illustrating the parameters of VLC channel models is presented.

- **Solar-cell**[2]:
  It is a larger version of a photo-detector used to collect as much light energy as possible.
- **Imaging-sensor**:
  It is an array of photo-detectors that can be used to improve the data rates.

Table 1 illustrates a comparison between the three methods for receiving the signal in VL-based systems in terms of cost, data rate, sensitivity, size, power consumption and availability in current UE.

In this survey, it is assumed that the VLC systems use normal blue LEDs with a phosphor transmitter and photo-detector receivers unless stated otherwise.

2) VLC PATH LOSS MODELS (CHANNEL MODELS)

Several works have been done on channel modeling and characterization for indoor optical link [52]–[59] and outdoor [60], [61] optical link. For example, assuming single reflections, Gfeller and Bapst in [52] have proposed the first propagation model. Assuming multiple reflections, Barry *et. al.* in [53] have proposed a recursive simulation model. While the previous models were proposed for IR, in 2011, Lee *et. al.* have extended the channel models of IR and produced the first indoor channel model for VLC systems [62].

For indoor VLC systems as shown in Fig. 3, the transmitter, which is based on LEDs, is generally modeled by a Lambertian pattern [52], [53], [63]. The channel gain based on LED with Lambertian pattern that considers LED beam solid angle, LED beam maximum half-angle, the angle between the source-receiver line and beam axis, and the angle between the

[2]Solar-cells, typically, detect light and other electromagnetic radiation near the visible range such as infrared.

TABLE 1. Comparison of different VLC receivers in terms of cost, data rate, sensitivity, size, power consumption and availability in current UE.

	Photo-detector	Solar-cell	Imaging-sensor
Cost	Moderate	Low	High
Data rate	High	Moderate	Moderate
Sensitivity	Sensitive	High Sensitivity	Low Sensitivity
Size	Small	Large	Moderate
Power consumption	Moderate	Low	High
Availability in current UE	No	Rare	Available with modification needed

source-receiver line and receiver normal is adopted by most papers that consider hybrid RF/VLC. VLC path loss models can be summarized as follow:

- **Lambertian model:**
  For indoor VLC, the channel gain of LOS is generally modeled by the Lambertian emission and given by [63]

$$H_v = \frac{(m+1)A_R}{2\pi d^2} T_s(\theta) g(\theta) \cos^m(\phi) \times \cos(\theta), \quad \forall \theta < \phi_{\max}, \tag{1}$$

  where A_R is the optical detector size, and d is the distance between the receiver and the transmitter. ϕ and θ stand for irradiance and incidence angles, respectively. In addition, $\phi_{\max}$ represents the semi-angle at half-power of the LED, m is the order of the Lambertian model and is given by $m = -\frac{\ln(2)}{\ln(\cos\phi_{\max})}$, $T_s(\theta)$ is the gain of the optical filter, and $g(\theta)$ is the concentrator gain, which is assumed to be a constant depending on the concentrator design.
- **Simple path loss model:**
  In the simple model (similar to the RF path loss model [2]), the power-distance relation is modeled as follows

$$H_v = K\,[d]^{-\varsigma}, \quad \forall\, d > 1, \tag{2}$$

  where H_v is the optical channel gain, K is a constant that represents all the gains and the transmitted power and ς denotes the channel path loss exponent which usually depends on the channel environment. This simple model assumes that the channel only has a path loss factor and a gain which is dependent on the system gains and interference from the environment. It is used by the studies where the VLC system is assumed static and only the distance of the LOS is changing without a change in the irradiance and incidence angles as in [64]–[66].

For outdoor, different VLC channel models are available in the open literature either via simulation software programs [60], [67], analytical means [61], [68], [69] or experimental methods [70]–[72]. In those models, either high beam headlamps [60], [67] or low-beam headlamps [61], [68]–[72] were considered as transmitting light sources. For instance, with a high beam headlight, a V2V channel model for perfect alignment case was proposed in [67] for distances up to 20 m using non-sequential ray tracing. This model was extended in [60] considering longer link distances and lateral displacements. While high beam has been widely considered since it allows further illumination and hence communication distances, there are several regulations [73] preventing the use of high beam headlights in several scenarios [74]. These limitations motivate researchers, recently, to use low-beam headlights for vehicular VLC connectivity [72]. While [61], [68], [69] considered Lambertian channel model, a model based on measurements of low-beam tungsten-halogen bulbs was introduced in [71]. Since patterns of the LED-based headlight are different from those of the traditional halogen headlight, the first experimental model for LED-Based headlight was proposed in [72].

3) VLC MODULATION METHODS (PHY)

The typical candidates for the front-end devices in VLC systems are incoherent LEDs and laser diodes (LD) because of their low costs. Due to their physical characteristics, information can be transmitted by modulating the intensity of the light. Therefore, the transmitted signal should be a unipolar non-negative real-valued signal. Such a VLC technique of modulation/demodulation is referred to as IM/DD (Intensity Modulation/ Direct Detection). For IM/DD, some techniques can be applied in, relatively, straightforward manner, e.g., pulse width modulation (PWM), pulse position modulation (PPM), on-off keying (OOK), and pulse amplitude modulation (PAM). As the data rate increases, these modulations begin to suffer from the effects of intersymbol interference (ISI) as a result of frequency selectivity. Therefore, a more suitable modulation technique is needed. A typical candidate is orthogonal frequency division multiplexing (OFDM). Not only OFDM has a flat fading channel for each subcarrier but also allows for an adaptive bit and power loading which leads to optimal utilization of available resources. Furthermore, OFDM includes simple equalization in the frequency domain with single-tap equalizers in addition to its ability to avoid frequency distortion due to flickering. It should be, however, noted that the typical OFDM signals are bipolar complex-valued. Therefore, the standard OFDM must be modified in order to make it suitable for IM/DD.

On the other hand, the use of light, simultaneously, for illumination and data communication purposes poses some challenges that require consideration in implementing the VLC system. The two main challenges are dimming support and flicker mitigation. Typically, the lighting fixture is equipped with dimming control that allows users to control the level of brightness they prefer, while flicker is observed by the human eye as a result of continuous switching between on and off during data transmission.

The main modulation schemes presented in the literature can be itemized as follows:

- *On-off keying*: OOK is the simplest form of modulation that represents data in VLC as, typically, the presence or absence of light. In this form, the presence of light represents a binary one, while the absence represents a binary zero. Some more sophisticated OOK schemes vary the duration of presence and absence [75]–[78].
- *Pulse modulation*: Pulse modulation is a simple modulation scheme where the transmitted signal is presented in form of pulses [79]–[82]. It is classified into three major types:
  - Pulse-width modulation/Pulse-duration modulation
  - Pulse-amplitude modulation
  - Pulse-position modulation
- *Orthogonal frequency division multiplexing*: OFDM is a multi-carrier technique, where the available frequency band is divided into many small bands by use of orthogonal sub-carriers [83]–[88].
- *Color shift keying*: CSK is a VLC modulation scheme, where the data is transmitted by the use of different colors with the same intensity [89]–[91].

4) VLC MULTIPLE ACCESS SCHEMES

In VLC, different multiple access methods that allow more than two users/nodes to be connected to the same transmission medium and transmitted over it have been proposed such as:

- *Carrier sense multiple access (CSMA)*: a user/node tries firstly to determine if another transmission is in progress before setting up its transmission by the use of carrier-sense mechanism (CSM). If CSM sensed a current transmission, user/node waits for the current transmission to be ended [92].
- *Orthogonal frequency division multiple access (OFDMA)*: OFDMA is a modified version of the OFDM where multiple access is achieved by assigning different subcarriers to different users/nodes. This allows simultaneous transmission from several users/nodes [93].
- *Code-division multiple access (CDMA)*: CDMA is a channel access scheme where several users/nodes can send data simultaneously over a single VLC channel. This allows several users/nodes to share the same band of frequencies without too much interference between them by the use of a special coding scheme where each user/node is assigned a special code [94].
- *Non-orthogonal multiple access (NOMA)*: in NOMA, users/nodes share the available time and frequency resources simultaneously, which leads to low latency and better spectral efficiency [95], [96]. NOMA systems can be accomplished in two domains, i.e., power or code domains. The most commonly used one is NOMA with a power domain where different power levels are assigned to different users/nodes. On the other hand, in the NOMA scheme with code-domain, multiplexing is accomplished by the use of spreading sequences similar to CDMA technology.

  The main differences between NOMA-VLC and NOMA-RF are the achievable capacity and the realization of successive interference cancellation (SIC). Since the classical Shannon's capacity does not work for optical systems, the exact capacity of a VLC system is still unknown. Alternatively, upper and lower bounds on optical capacity are derived in the literature [97]–[100]. It has been shown that the gap between the lower bound presented in [100] and the exact capacity can be neglected for high SNR. This simply requires scaling the SNR in Shanon's capacity by a constant of $\exp(1)/2\pi$. On the other hand, CSI is required at both the receiver and the transmitter sides for splitting the transmit power with suitable coefficients among users that allows the practical realization of SIC. This requires updating CSI at both transmitters and receiving nodes with a rate larger than the frequency of channel changes which is in RF more than VLC due to the fact that the VLC channel remains unchanged most of the time [101].

It should be further noted that the access method can be a part of multiple access protocol (MAP) and control mechanism (CM), which is known as medium access control (MAC). MAC deals with issues such as assigning channels to different users/nodes.

B. RF SYSTEMS

Since RF systems are old and well-established technology, researchers have used multiple standards and bands to improve their performance. Most of the proposed solutions employ Wi-Fi (microWave) technology. Conventional Wi-Fi operates in frequency ranges that are below 6 GHz.[3] In this frequency range, the data rate is in the range of several 100 Mbps. For achieving several Gbps, some studies explored the possibility of using mmWave systems instead of old microWave systems. The different RF systems used in RF/VLC systems studies can be classified in the following categories:

1) WI-FI

Wi-Fi is a wireless communication technology that refers to the IEEE communications standards for wireless local area networks (i.e., IEEE 802.11) and was created in 1997. This technology which is based on the direct sequence spread spectrum (DSSS) and frequency-hopping spread spectrum (FHSS) uses radio signals that allow accessing the internet while moving from one place to another via high-speed network connections. IEEE 802.11 supports up to 2Mbps

[3]There are several RF ranges for Wi-Fi communications: 900 MHz, 2.4 GHz, 3.6 GHz, 4.9 GHz, 5 GHz, 5.9 GHz, and 60 GHz bands. However, communication with 60 GHz is limited to a few meters and cannot pass through walls compared to conventional Wi-Fi frequencies.

data rates. Different versions of Wi-Fi (i.e., different standards) have been proposed: IEEE 802.11a which works on the 5 GHz band and yields a maximum of 54Mbps is based on OFDM and was created in 1997. IEEE 802.11b works on the 2.4 GHz band and offers a maximum of 11Mbps and was created in 1999. IEEE 802.11g works on the 2.4 GHz band, provides a maximum of 54Mbps and was created in 2003. IEEE 802.11n works on the 2.4 GHz and 5 GHz bands and was created in 2009. This standard supports multi-channel with a maximum of 150Mbps/channel. In addition, IEEE 802.11ac was invented in 2014, and this standard increases the data rate up to 1300 Mbps [102], [103].

2) mmWave

Most commercial radio communications including Wi-Fi work in a narrow band of the RF spectrum (i.e., 300 MHz-3 GHz). However, the part of the RF spectrum above 3 GHz is mostly unexploited for commercial applications. Recently, there is a huge interest in utilizing this range. For example, the range 3.1-10.6 GHz has been proposed for high data rate connectivity in personal area networks. The range 57-64 GHz is used to provide data rates at the order of Gbps for short-range local area networks. Furthermore, the range of 28-30 GHz has been proposed for local multipoint distribution services. Millimeter waves can support high data rates at the order of Gbps but are severely affected by the absorption caused by oxygen molecules and water vapors from the atmosphere. Since oxygen absorbs EM waves at around 60 GHz, the frequency range 57-64 GHz can experience huge attenuation on the order of 15 dB/km. On the other hand, the range 164-200 GHz is severely affected by the concentration of water vapors in the atmosphere and may be subject to attenuation on the order of tens of dB/km [104]–[106].

3) DEDICATED SHORT RANGE COMMUNICATIONS (DSRC)

DSRC is a wireless communication standard that is designed specifically for short and medium communication ranges. It is used mainly for vehicular communications, i.e., V2V, vehicle-to-infrastructure (V2I) and infrastructure-to-vehicle (I2V) communications. DSRC systems exploit microwaves in the ranges of 5.805-5.815 GHz and 5.795-5.805 GHz [107]. The first version of it has been proposed in 1999 [108]. In 2003, an improved version referred to as the American Society for Testing and Materials (ASTM)-DSRC standard has been proposed [108]. DSRC is not just for PHY and MAC layers, it is, actually, a complete communication protocol. The list of DSRC IEEE standards is given in [109], [110]:

- IEEE 802.11p-PHY Layer:
- IEEE P1609.1: Standard for Wireless Access in Vehicular Environments (WAVE) - Resource Manager.
- IEEE P1609.2-Security Layer: Standard for Security Services for Applications and Management Messages.
- IEEE P1609.3-Network and Transport Layers: Standard for Networking Services.
- IEEE P1609.4-MAC Layer: Standard for Multi-Channel Operation.
- IEEE P1609.11: Standard for WAVE– Over-the-Air Electronic Payment Data Exchange Protocol for Intelligent Transportation Systems (ITS)
- IEEE P1609.12: Standard for WAVE - Identifier Allocations

Table 2 shows how different hybrid RF/VLC systems studies employ different RF channel models based on the RF system assumed in each study.

TABLE 2. Utilized RF wireless technologies in hybrid RF/VLC systems.

RF Channel Model	References
Wi-Fi (2.4 GHz/5 GHz)	[32], [111]–[133]
WINNER II Channel Model (2-6 GHz)	[134]–[142]
mmWave (60 GHz)	[126], [143]–[146]
DSRC (5.9 GHz)	[147]

TABLE 3. Comparison of VLC and RF technologies that explains the main motivating factors behind hybrid RF/VLC networks.

	VLC	RF
Range	Low (Up to 100 m)	High (Up to 1km)
Environment dependency	Sensitive	Moderate
Ambient light	Sensitive	Not affected
EMI	No	Yes
Band license	Unlicensed	Licensed/Unlicensed
Cost	Low	High
Size	Small	Large
Power consumption	Low	High

C. COMPARISON OF RF AND VLC TECHNOLOGIES

In this section, the comparison of RF and VLC technologies (Table 3 [29], [31]) is presented.

As shown in Table 3, VLC offers more flexibility in terms of the angle of incidence and beam-width with the same high accuracy percentage. In terms of physical size, the VLC transceiver is expected to be much smaller as it only needs a PD, which can be very small in size similar to the PDs used in [148] and [149]. On the other hand, RF systems need to have the transceiver module and the antenna which depends on the frequency of operation. In addition, some limitations that need to be considered in the future work are the channel model estimation in real-time and the performance during different light and environment scenarios. Due to the fact that light wave has a higher frequency than RF wave used in RF systems, the operation (distance) range in VLC will be smaller than that in RF, as expected. However, VLC systems present immunity to EM interference (EMI), make use of unlicensed bands and present low power consumption (since VL is already used for illumination) [29], [150].

The motivating factors behind using VLC are summarized as follows:

- **RF spectrum scarcity problem:**
  The supporting band for the traditional RF communications is 300 KHz - 300 GHz. An application for wireless

spectrum resources requires in general a high license fee and a long waiting period. With the rapid development of wireless communications services, the global wireless spectrum resources are in short supply. VL presents a huge bandwidth of 400-790 THz. Thus, the visible spectrum range is 10,000 times larger than that of the entire RF wireless spectrum. Furthermore, no license is required for VLC [151].

- **Reduced capacity of RF-based systems:**
VLC technology assumes higher communication bandwidths by using higher frequency light waves to carry information. At the same time, due to the good directionality of the VL beam and weak diffraction, VLC can make use of diversity and multiplexing techniques to greatly expand the capacity of the communication system [152].
- **Minimum EM interference:**
VLC generates almost no EM radiation in space, which provides a good wireless communication solution for environments with EM interference sensitive devices or where radio silence is required [150].
- **Signal secrecy:**
Due to the long wavelength and antenna architecture, RF communication presents weak directionality and can be easily tracked by non-target receivers. In VLC, since the light wavelength is short, light is subject to directionality and attenuation effects and cannot penetrate walls when it propagates in space. Thus, light can only be received in a specific area and the confidentiality of transmitted information is ensured [153].
- **Energy efficiency:**
Compared to traditional light sources, LEDs present higher electro-optic conversion efficiency. If LEDs can be used to provide communication services while lighting, they will definitely save a lot of energy. Therefore, the concept of integrated lighting communication has also been proposed [154]. Furthermore, compared to RF femtocell networks, VLC systems could achieve a very large area spectral efficiency gain [155].
- **Health safety:**
Compared with infrared radiation (IR) communications, an improper application of IR can cause damage to the human body due to the high temperature since IR is a kind of heat radiation. For example, strong IR rays can cause skin burns or damage the retina of the fundus. Under normal lighting conditions, the use of VLC does not pose any safety problems for the human body [27].
- **Pervasive infrastructure (LEDs):**
Due to the gradual widespread adoption of LEDs as the fourth generation of lighting technology, lighting facilities represent a natural platform for VLC. Only communication modules need to be added to the existing lighting facilities to implement the VLC function, so the installation cost is very low [156]. Moreover, the current drives and controls the luminous intensity of LEDs, common VLC systems use the IM/DD scheme. When using LEDs for VLC, the interconnection of VL networks can be achieved through existing power line infrastructure [157]. Therefore, VLC is compatible with the smart power grid.
- **Coherence time:**
Since VLC is subject to significantly less multipath effects, the coherence time of the VLC channels is at least an order of magnitude larger than that of the RF channels. Thus, VLC requires less frequent channel estimation, a feature which is especially important for situations that require continuous and stable linking. In addition, higher coherence time means that VLC is a good fault-tolerant technology [150].

The key limiting factors of using VLC are summarized as follows:

- **Uplink hardware issues:** Uplink communication for VLC represents a challenge as it requires updating the user's hardware. The signal emitted from the LED to the photodiode on the mobile phone only solves the downlink communication problem, and the mobile phone needs to send a signal back to ensure the communication link is unblocked, but the design of the reverse communication link is difficult [158].[4] user's hardware).
- **Interference and noise from other light sources and inter-cell interference:**
Other unmodulated artificial light sources and natural light sources sometimes work in the same spectral band with the VLC systems. If the ambient light source is strong enough, it will increase the intensity of the shot noise or saturate the receiving end and the VLC systems cannot function properly [150].
- **Communication and lighting integration:**
As a communication and lighting integration technology, indoor VLC must balance the dual user requirements of lighting and communication. The transmission of information in VLC relies on changing the luminous intensity, and flickering may occur during communication, which is not allowed in daily lighting and can seriously affect the user's lighting experience. VLC needs to meet the corresponding lighting requirements in both lightings on and lighting off modes [160].
- **Terminal (user) mobility and handover overhead:**
If the receiver or transmitter is mobile, the received power on the detector array will fluctuate. The channel matrix will have to be updated over time. Soft handover mechanisms are especially important to extract these fluctuations and maintain a more stable connection when the light detection is handed over from one photodetector to another [161].

[4]Although the uplink in VLC is one of the main challenges, studies [159] have shown that hybrid VLC/IR (infrared) can be utilized to overcome this issue. Therefore, inherently a hybrid RF/VLC/IR system can be an ultimate solution for robust and high data rate indoor communication solution.

- **Signal coverage (the high attenuation rate of the signal):**
  In VLC, cell sizes are considerably smaller due to the high directivity of light and smaller transmission distances, thus the signal coverage area is limited. If the beam angle of the transmitter is increased, the detected signal intensity will be relatively reduced [162].
- **Shadowing, due to losing the LOS link:**
  As VL cannot penetrate obstacles, indoor VLC is built for the LOS link. Thus, the transmission is influenced by the blocking objects due to the random movement of people in a room. However, clear LOS is expected for the receivers of lighting systems at most time [163].
- **VLC network access to Internet:**
  The indoor VLC system must be connected to the base station to achieve the communication objective. The most practical problem is how to construct a VL wireless access network consisting of dozens or even hundreds of VL APs that are distributed over the ceiling since it is difficult to install new communication cables between different fixed networks and LED lights or among the LED lights [132].

Furthermore, more detailed discussion about the limitations of implementing VLC system is presented in section III-D.

III. HYBRID SYSTEMS

This section discusses the hybrid RF/VLC studies in more detail. It is divided into the following subsections: hybrid networks typologies, hybrid RF/VLC environments, optimization and smart technologies, performance analyses, hybrid network simulation and system implementation, and current applications of hybrid systems. Fig. 4 presents an overview of the main studies and it enables the readers to navigate easier through the topic of interest.

A. HYBRID NETWORKS TOPOLOGIES

The following three types of hybrid RF/VLC networks topologies were proposed in literature[5]:

1) DUAL-HOP HYBRID RF/VLC SYSTEM

In this type of hybrid system, the user access link is either VLC or RF. The network model where the user access link is RF can be observed in Fig. 5.[6]

The first component of the system is the communication between the VLC source (base station) and relaying nodes. The communication is carried out using VLC (LOS-link) in both uplink and downlink. Due to the fixed positions of the relay nodes and base-station, it is believed the maximum data rate can be achieved using the LOS VLC system.

[5]While "Heterogeneous" is commonly used for parallel hybrid RF/VLC networks, some references used it for dual-hop hybrid RF/VLC.

[6]Note that the VLC APs in Figs. 5, 6, and 7 are basically the ones that provides VLC links. Their placements would be application specific. These figures are provided for illustrative purposes. For example, the VLC APs are placed on the wall in Figure 6. Different scenarios would be possible as well.

The second component is the communication between the end-user and (plug-and-play) relay node (AP). The communication is accomplished using a low power directional RF system by dividing the area into cells using a concept similar to that of mobile base stations. Dividing large areas into small cells will provide the advantage of serving multiple users and saving power, simultaneously. Furthermore, RF communication schemes such as handover, multi-relaying, and beamforming (via directional antennas) can be applied to this system, if needed.

In [164], the secrecy performance of a hybrid RF/VLC system was investigated assuming that the relay node extracts the direct current component and collects energy from the optical signal and then uses the collected energy for retransmitting data. Exact and asymptotic expressions for secure outage probability and average secrecy capacity considering the effect of system parameters were also derived. In [165], the secrecy capacity of DF-based hybrid RF/VLC was compared with standalone RF and VLC systems and it was showed that the hybrid had better performance. This paper also analyzed the framework of non-adaptive power allocation where both the source and relay present the same amount of power and the case of cooperative power-saving where the total average power is shared between source and relay in a way that minimizes the total power while satisfying the required secrecy capacity. In [166], the effect of positions' randomness of both relay and destination on outage probability of cooperative hybrid RF/VLC wireless sensor networks was investigated. Decode & forward (DF) and amplify & forward (AF) relaying schemes were analyzed and approximate expressions for outage probability were derived. In [167], outage and BER performances of AF relay-assisted hybrid RF/VLC systems were investigated. Closed-form expressions for the outage probability were derived using probability density function (PDF) and moment generating function (MGF) approaches and by considering the effect of emission angle. The effect of timing errors on BER performance was also considered. In [168], taking into account the randomness of relay's and destination's locations, the outage and symbol error probabilities of a hybrid RF/VLC assuming DF and AF relaying schemes were derived.

In [169], a new multi-user hybrid RF/VLC was proposed. In this system, users are divided into pairs. The near user receives from source via VLC and forwards the information to its paired user through RF transmission. In [170], a learning algorithm-knowledge transfer context-aware hybrid RF/VLC system that takes into account the traffic type, location, and time was proposed. The presented simulation results illustrated that the proposed system could significantly improve the convergence speed and performance of reinforcement learning-based network algorithms. In [171], the secrecy performance of relay-jammer selection beamforming hybrid RF/VLC was investigated assuming the absence of a direct link between source and destination. The considered system presents multiple DF relays and the relay node is selected by minimizing the outage probability. The jamming node

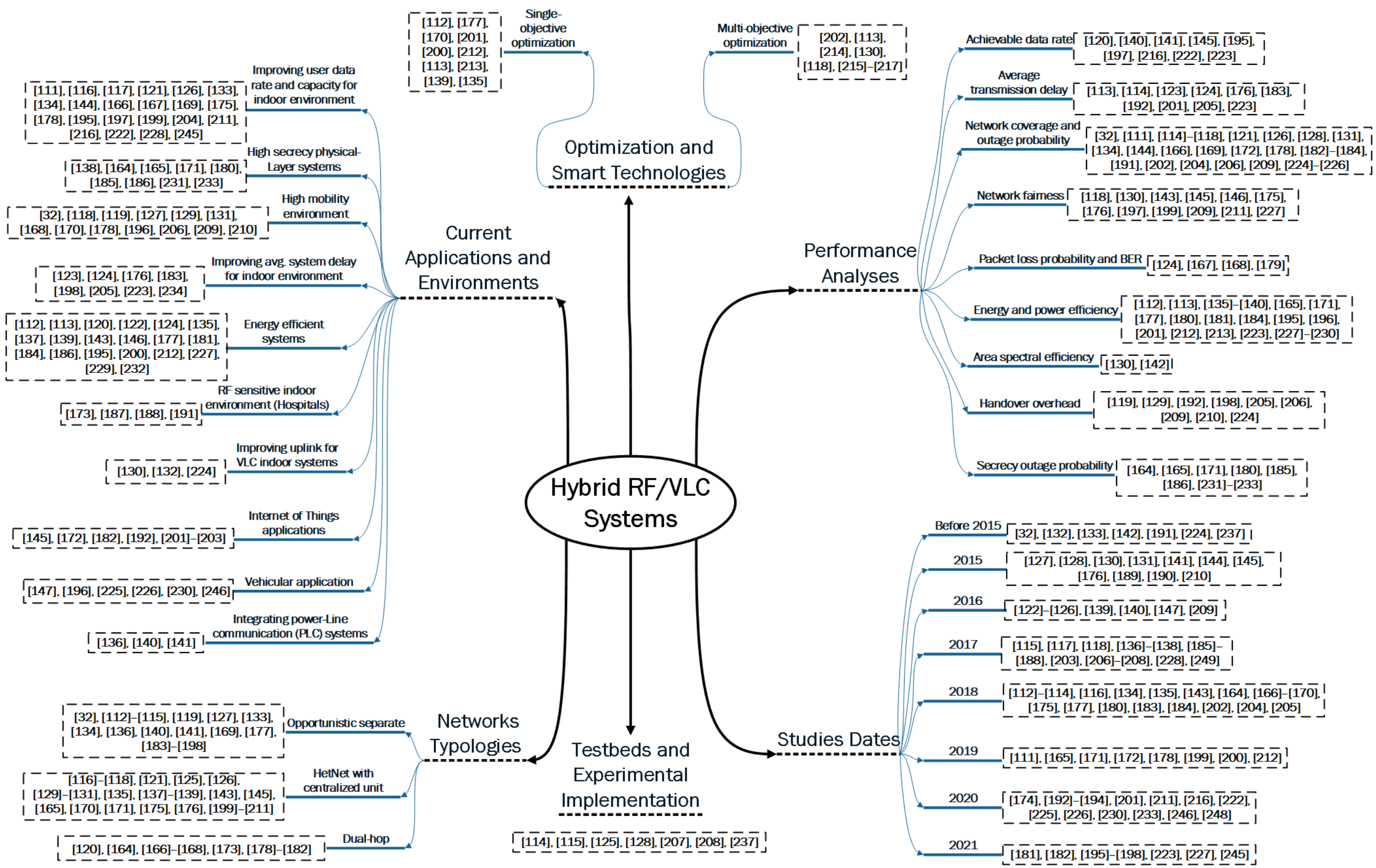


FIGURE 4. Classification of hybrid RF/VLC systems.

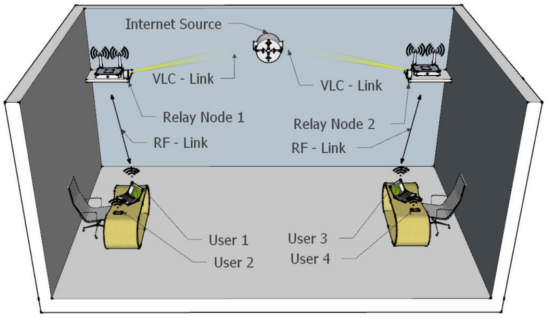


FIGURE 5. Hybrid RF/VLC Dual-hop systems.

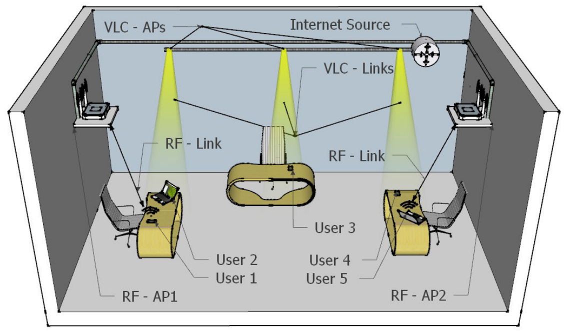


FIGURE 6. Hybrid RF/VLC systems: Opportunistic separate networks.

is then selected from the available relaying nodes based on the received signal-to-noise ratio (SNR) at the eavesdropper location. Furthermore, beamforming vectors for both RF and VLC subsystems were designed and exploited in minimizing the consumed power. In [172], the outage performance of the IoT hybrid RF/VLC system was investigated considering the randomness of the positions of devices. VLC was considered for the downlink from the source lamp to the IoT devices while RF with the NOMA scheme for the uplink. All IoT devices are equipped with PD for two purposes: data communication and energy harvesting from the light emitted by the source LED lamp. These devices are then using the harvested energy to transmit data to the RF receiver. Approximate expressions for the outage probability were also derived. In [173], a medical health care AF relaying RF/VLC system was proposed. In the proposed system, the RF link is for the outdoor link whereas the VLC is for the indoor link. The outage probability was also investigated assuming generalized K-fading in RF link.

2) OPPORTUNISTIC SEPARATE NETWORKS (RF/VLC)

Two separate VLC and RF networks with the user deciding on the which system needs to be used. This network model is presented in Fig. 6. In this network, the users are free to choose the best network depending on several parameters like SNR of the system, application requirements, mobility of the user, etc. This type of network is hard to control and optimize. Some of the studies adopted this model because of its low network overhead and its flexibility to the users. However, it is hard to control the users when there is a high number of users in the same place competing for the same resource without a control unit dividing the resources. Therefore, as the number of users increases, it is hard to adopt this model.

The coverage and rate analysis of opportunistic cellular RF/VLC and other network configurations were investigated and compared in [134]. Based on approximations of the complementary error function (erfc) and cumulative distribution function (CDF) of a Gamma random variable, an approximate expression for coverage was derived. It was shown that the opportunistic selection based on the maximum received signal power is more suitable for scenarios where the interference effects are not dominant. On the other hand, the opportunistic scheme deteriorates the performance for higher interference scenarios, due to wrongful connection to RF networks with higher interference instead of VLC networks. Hybrid cellular RF/VLC has also been considered in [174]. This paper presented both theory and implementation demonstrating the feasibility of heterogeneous RF/VLC network for IoT. Particularly, a hybrid cellular architecture that allows internet-operability between different technologies was proposed. They further discussed different applications such as localization, long-range communication, and monitoring.

In [175], a hybrid RF/VLC system was investigated with one RF AP and multiple VLC APs assuming that all APs perform NOMA. Considering the fact that grouping users in the NOMA system is challenging, this reference addressed the grouping of users using the coalitional game theory. In particular, a merge-and-split algorithm that determines the optimal user grouping is presented. A comparison of the proposed system with the conventional opportunistic scheme points out the effectiveness and robustness of the proposed scheme. Lastly, in opportunistic separate networks, all the nodes are competing on the resources. Therefore, the network optimization and control are challenging tasks, especially when there is no control unit handling the resource allocations between users.

3) HETEROGENEOUS NETWORKS (HetNet) WITH CENTRALIZED UNIT

As shown in Fig. 7, the heterogeneous system consists of RF and VLC networks with a central control unit. Based on the network conditions, the central unit assigns the resources to the user, and sometimes having the location of the user helps the network to optimize the resources and interference better. This type of network presents high network overhead data but it makes sure that all users are getting equal treatment (network fairness). Therefore, this network is needed when a high number of users are present in a small area network.

In [176], the optimal resource-allocation of mobile terminals in a heterogeneous wireless network under diverse quality of service (QoS) was considered. A decentralized algorithm was proposed to address the resource allocation problem. In [177], a heterogeneous cellular network that combines RF and VLC to maximize the energy efficiency of the

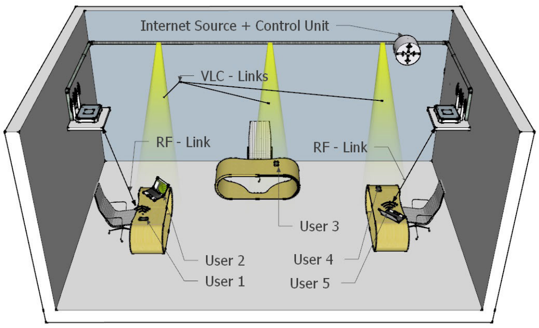


FIGURE 7. Hybrid RF/VLC systems: Heterogeneous networks with centralized unit.

TABLE 4. Hybrid RF/VLC studies: Network topologies.

Network topology	References
Dual-hop	[120], [164], [166]–[168], [173], [178]–[182]
Opportunistic separate	[32], [112]–[115], [119], [127], [133], [134], [136], [140], [141], [169], [177], [183]–[198]
HetNet with centralized unit	[116]–[118], [121], [125], [126], [129]–[131], [135], [137]–[139], [143], [145], [165], [170], [171], [175], [176], [199]–[211]

entire communication system under QoS requirements was considered. The optimization problem is not convex and it is addressed using successive convex approximations. In [127], a heterogeneous hybrid RF/VLC system where users can estimate their position based on the information broadcasted by VLC lamps was investigated. Based on the locations of users, the Wi-Fi unit allocates the resources of VLC enabled lamps. In [173], a medical health care AF relaying RF/VLC system was proposed. In the proposed system, the RF is assumed for the outdoor link whereas the VLC is considered for the indoor link.

Depending on system link-level topology of the system, the number of users and complexity of the system needed, different authors chose the network model that fits their study as shown in Table 4.

In terms of the utilization of the system resources, there are two categories that can describe a hybrid RF/VLC system:

- **Aggregated Technology:**
  Where users employ both VLC and RF technologies at the same time to improve their data rate and reliability of the connection.
- **Non-Aggregated Technology:**
  Where users employ only one of the two technologies to optimize the network conditions and manage the interference present in the network.

B. RESOURCE ALLOCATION

Different hybrid RF/VLC optimization problems spanning different topics such as resource allocation, transmit power minimization, load balancing and handover have been considered in the literature and are summarized in Table 5. These optimization problems can be divided generally into two categories:

1) SINGLE-OBJECTIVE OPTIMIZATION (SOO)

SOO is an optimization problem with a single objective function. The optimization problem of resource allocation where the heterogeneous Hybrid RF/VLC network has a single RF AP and multiple VLC APs was covered in [139], [212], with the objective of optimizing energy efficiency while meeting devices' QoSs. As a larger system with similar objective of energy efficient Hybrid VLC/RF optimization problem, several RF APs and VLC APs have been considered in [135]. In [112], authors consider an energy-efficient hybrid RF/VLC system. The objective of the optimization problem is to minimize the power consumption subject to satisfying the users' requests and maintaining an acceptable illumination level. In [170], they have considered the problem of selecting the network that provides the best long-term average performance where the network selection method is based on machine learning that assumes all participants have learning/cognitive abilities. Authors in [177] investigate a heterogeneous cellular network that combines RF and VLC in order to maximize the energy efficiency of the whole communication system under QoS requirements. In [201], a heterogeneous hybrid RF/VLC for wireless industrial networks is developed to support different QoS requirements such as high reliability, low latency and high data rates of IoT and industrial networks IoT (IIoT) devices. They have proposed a new deep post-decision state-based experience replay and transfer (PDS-ERT) learning algorithm in order to maximize the network energy efficiency. Particularly, they have considered an energy-efficient resource management problem by jointly considering network selection, channel allocation, and power management and formulated the decision-making problem as a Markov decision process (MDP). They have then proposed a new PDS-ERT learning algorithm to learn the optimal policy, which boost up the learning speed and enhance the learning efficiency. On the other hand, in [200] a collaborative RF with lightwave resource allocation scheme was proposed for enhancing the energy harvesting of the overall network which consists of one multi-antenna RF AP, multiple optical transmitters, and multiple terminal devices. Under an outage probability constraint, minimizing the area power consumption (APC) by optimizing the RF and VLC BSs intensities in [212]. Utilizing the knowledge of location information of user terminals, a location information-aided load balancing (LB) design for the hybrid RF/VLC networks was proposed in [111] to maximize the throughput under proportional fairness constraints. In [212], authors have designed energy efficient hybrid RF/VLC networks by considering a constraint on the outage probability. They have, particularly, proposed new strategies that optimize the intensities of macro cell BSs (MBSs), small cell BSs (SBSs) and VLC BSs (VLCBSs). They have left the energy consumption caused

TABLE 5. Hybrid RF/VLC studies: Objective optimization problems.

Single-objective optimization problem	
References	**Objective**
[112]	Minimizing the power consumption subject to satisfying the users' requests and maintaining an acceptable illumination level.
[177]	Maximizing energy efficiency of the whole communication system under QoS requirements.
[170]	Selecting the network using machine learning methods, the network that provides the best long term average performance assuming all participants have learning abilities.
[201]	Maximizing the network energy efficiency by jointly considering network selection, channel allocation, and power management and formulated the decision-making problem as a MDP.
[200]	Enhancing the energy harvesting of the overall network that consist of one multi-antenna RF AP, multiple optical transmitters, and multiple terminal devices.
[212]	Minimizing the area power consumption (APC) under an outage probability constraint.
[111]	Maximizing the throughput under proportional fairness constraints.
[213]	Allocation of available APs with the objective of increasing the overall throughput.
[139]	Optimize energy efficiency of heterogeneous RF/VLC network that has a single RF AP and multiple VLC APs.
[135]	Optimizing energy efficiency of heterogeneous RF/VLC network that has a multiple RF APs and multiple VLC APs while meeting devices' QoS.
Multi-objective optimization problem	
References	**Objective**
[202]	Outage reduction and system capacity improvement.
[113]	Reducing communications power consumption and minimizing the queue lengths.
[214]	Jointly optimizing user association and power control considering the required data rates and the maximum available transmit power for RF base stations (BSs) and the VLC in three-tier HetNet.
[130]	Providing a higher Mean Bandwidth Efficiency of VLC network and higher average throughput for the hybrid RF/VLC by employing Vectored Transmission Techniques.
[118]	Jointly and separately optimizing AP assignment and resource allocation considering the effect of users' mobility in an effort to increase the network's capacity.
[215]	Achieving better user satisfaction performance with low computational complexity by jointly dealing with AP assignment and resource allocation using Evolutionary Game Theory.
[216]	This is an extension of [215] where the orientation-based random waypoint mobility model has been considered with link selection and resource allocation optimization problem.
[217]	Adapting transmit power of both RF and VLC considering the tradeoff between power consumption and delay-limited connectivity where the topology control problem is modeled as a potential game.

by handover for future studies. In [213], a hybrid RF/VLC network that consists of more than one RF and VLC APs has been considered. Therefore, they have increased the degree of freedom for selecting the AP that the node should be connected to. Thus, an optimization problem for the allocation of these APs with the objective of increasing the overall throughput was proposed.

2) MULTI-OBJECTIVE OPTIMIZATION (MOO)

MOO is an optimization problem that considers more than one objective function simultaneously or sequentially (i.e., adopts multiple objective functions). Several studies have concentrated on load balancing optimization problem in heterogeneous RF/VLC networks in order to increase the network's capacity and improve devices fairness [118], [130]. In [118], a dynamic load balancing scheme for Hybrid RF/VLC networks is proposed considering the effect of users' mobility. They have considered both joint and separate optimization algorithms which are, respectively, jointly and separately optimize AP assignment and resource allocation. In [130], LB problem in the context of hybrid RF/VLC systems has been considered. They have employed vectored transmission (VT) techniques among all VLC APs. As a result, VLC network becomes capable of providing a higher Mean Bandwidth Efficiency (MBE) and the hybrid RF/VLC system become capable of providing a higher average throughput. When the link selection and resource allocation optimization problem in heterogeneous RF/VLC is classified as non-deterministic polynomial (NP), the coalitional game theory is used [215]–[217]. In [215], EGT based LB for an indoor hybrid RF/Li-Fi network has been considered. This system jointly deals with the AP assignment and resource allocation. They have demonstrated that their proposed EGT-based LB scheme is able to achieve a better user satisfaction performance with low computational complexity. They have then extended their work in [216]. In [216], The orientation-based random waypoint mobility model has been considered in a hybrid Li-Fi/WiFi network to support dynamic load balancing for mobile users. In [217], RF and VLC transmitting power of each vehicle in Hybrid RF/VLC vehicular ad-hoc network is adapted locally based on the vehicle's knowledge about the vehicular ad-hoc network topology considering the tradeoff between power consumption and delay-limited connectivity. In [202], multi-objective optimization problem for selecting either RF or VLC at each device-to-device pair in a multi-user communication network has been investigated. The proposed solution consists of a two-phase algorithm in which the change from RF to VLC depends on the interference caused to other devices and the interference received from other device-to-device pairs. The first phase of the algorithm is for outage probability reduction while the second phase is for system capacity improvement. It is shown that the performance of the proposed algorithm is close to the exhaustive search algorithm that minimizes outage and maximizes capacity but presents less computational complexity. Reference [113] investigates the optimization of network resources in hybrid RF/VLC networks to reduce energy consumption for the communication task while minimizing the queue lengths. In [214], they have considered three-tier HetNet by introducing VLC into a two-tier HetNet and investigated the performance in terms of system's throughput, energy efficiency (EE), and spectral efficiency (SE). The optimization problem has been formulated to jointly optimize user association and power control considering the required data rates and the maximum available transmit power for RF BSs and the VLC.

In optimizing hybrid RF/VLC communication systems, an important problem is establishing the constraint conditions. Since the hybrid communication systems include both RF and VLC transceivers, the constraints are divided into two categories: lighting and coupling constraints, respectively.

- **Lighting Constraints:**
  Since VLC needs to maintain illumination and communication requirements simultaneously, several constraints should be considered. Due to the requirement of intensity modulation in VLC, the transmit signal has to satisfy the non-negative constraint [218]. In order to avoid excessive nonlinear distortions, it is sufficient to consider the peak optical power or a peak-to-average-power ratio (PAPR), which in general are constrained to guarantee that the LED is working in the linear region [219]. The transmission of information in VLC relies on changing the luminous intensity. However, flickering may occur during communication, a condition that is not allowed in daily lighting and can seriously affect the user's lighting experience. For illumination purposes, dimming constraints are desirable features to consider [220]. For multi-color VLC, it is necessary to ensure that the illumination meets the white light constraint. Using MacAdam ellipse as a statistical measuring tool, the small chromaticity difference between two colors in the same luminance color map can be described. Due to the limitation of human eyes in color recognition, when two colors are on the same MacAdam ellipse, ordinary human observers cannot distinguish between the two colors [219].
- **Coupling Constraints:**
  In the dual-hop RF/VLC systems, the RF and VLC systems work in serial, the data rate of the mobile terminals are constrained by the system where the transmission speed is slower [122]. In heterogeneous RF/VLC systems, the RF and VLC systems work in parallel such that the mobile terminals aggregate the data from both networks. Hence, the data rate at the mobile terminals is constrained by the total data rate of the RF and VLC systems [140]. The optimization problem is constrained by the power budget for these two serial/parallel communication links such that $P_{\text{t-VLC}} + P_{\text{t-RF}} \leq P_{\text{t}}$, where P_{t} is the maximum allowable total power [141]. In [221], the channel correlation in VLC over broad spectra is analyzed. However, for hybrid RF/VLC systems, the coupling constraints of the RF and VLC channels have not been investigated yet and it represents an important problem for future studies.

C. PERFORMANCE ANALYSES

Most of the existing studies have conducted different performance analyses. In Table 6, the studies discussing the same investigations are grouped to enable researchers an easy comparison. Moreover, a list of the main studies carried out is presented next.

- **User throughput (achievable data rate) of RF/VLC networks:**
  The average achievable data rate is a critical performance metric in any wireless network used to estimate the average user throughput in the network given a certain bandwidth. The average data rate of a user (R_i) can be expressed as follows:
  $$R_i = E\left[B \log_2\left(1 + \gamma_i(t)\right)\right], \tag{3}$$
  where $E[\cdot]$ is the expected value operator with respect to time domain, $\gamma_i(t)$ is the signal to interference and noise ratio which changes over time (t) depending on the user location and technology used (VLC or RF) since each technology has different channel model and B is the user assigned bandwidth.
  In [126] and [117], an efficient AP selection scheme for hybrid RF/VLC networks is proposed. Based on the different channel characteristics, a tailor-made AP selection method for the hybrid network is formulated as a two-stage algorithm, which first determines the users that need service from Wi-Fi and then performs AP selection for the remaining users. The simulation results show that the proposed method achieves a near-optimal throughput.
  Reference [115] proposed an indoor VLC-Wi-Fi hybrid network experimental platform that integrates multiple links with multiple access, hybrid network protocol, user mobility management mechanisms, and cell handover. The proposed hybrid VLC-Wi-Fi network exhibits better coverage and greater network capacity.
  In [131], a dynamic load balancing scheme that considers handover overhead in a hybrid RF/VLC network is proposed. The throughput performance is analyzed across the service areas and the effects of the handover

TABLE 6. Hybrid RF/VLC studies: Performance analyses.

Analysis	References
Achievable data-rate	[120], [140], [141], [145], [195], [197], [216], [222], [223]
Average transmission delay	[113], [114], [123], [124], [176], [183], [192], [201], [205], [223]
Packet loss probability and BER	[124], [167], [168], [179]
Network coverage and outage probability	[32], [111], [114]–[118], [121], [126], [128], [131], [134], [144], [166], [169], [172], [178], [182]–[184], [191], [202], [204], [206], [209], [224]–[226]
Network fairness	[118], [130], [143], [145], [146], [175], [176], [197], [199], [209], [211], [227]
Handover overhead	[119], [129], [192], [198], [205], [206], [209], [210], [224]
Energy and power efficiency	[112], [113], [135]–[140], [165], [171], [177], [180], [181], [184], [195], [196], [201], [212], [213], [223], [227]–[230]
Area spectral efficiency	[130], [142]
Secrecy outage probability and secrecy rate	[164], [165], [171], [180], [185], [186], [231]–[233]

overhead on handover locations and user throughput are discussed.

- **Average transmission delay (end-to-end delay):** Average transmission delay is the average time needed to send a packet from source (transmitter) to the receiver in the network. This average time includes all the multi-hop retransmission time (T_{tr}^{i}) (time needed by middle nodes to process and retransmit the data), error retransmission time (T_{err}) (time needed when a new data packet is retransmitted due to an error). Moreover, this parameter includes the time delay added due to the handover process (T_{HO}). The average transmission delay (T_{avg}) can be expressed as follows:

$$T_{avg} = E\left[\begin{array}{c} \sum_{i=1}^{N}\left(T_{tr}^{i}(t)\right) + T_{err}(t)\,P_{err} \\ +T_{HO}(t)\,P_{HO} \end{array}\right], \quad (4)$$

where P_{HO} and P_{err} are, respectively, the probability that a handover process is needed and a transmission error occurred. In (4), N is the maximum number of hops in the system.
In [122] and [124], the relay between the two hops in a dual-hop RF/VLC transmission system is used to energy harvest from different artificial light sources and sunlight. The total time to transmit one data packet from the source to the receiver must satisfy a strict delay constraint. The statistical model for the harvested energy at the relay is further proposed to analyze the packet loss probability. In [123], [132], the delay analysis of unsaturated heterogeneous omnidirectional/directional small cell hybrid RF/VLC wireless networks was investigated. In the first case, the minimum average system delay of the aggregated scenario is always lower than that of the non-aggregated scenario. In the second case, the heterogeneous contention-based omnidirectional small cells - directional small cell (CBOSC-DSC) network is studied. Extensive simulation results illustrate that the non-aggregated scenario outperforms the aggregated scenario due to the overhead caused by contention. In [234], the handover delay which would occur when the transmitter moves from one link to the other was investigated. In addition, the non-asymptotic bounds on data buffering delay were derived as well.
- **Packet loss probability and bit error rate (BER):** BER is a ratio of the number of bit errors to the number of bits sent during a certain time interval. Since BER is a ratio of two numbers, it is a unitless parameter and sometimes expressed as a percentage. Moreover, packet loss probability can be expressed in terms of BER for a packet size of L bits packet error rate (PER) is $BER \times L$. Finally, the error rate depends heavily on channel conditions, signal-to-interference-plus-noise ratio (SINR), error coding rate, and modulation type.
In [124], the packet loss probability is analyzed using a statistical model for the harvested electrical power and the time dedicated for excess energy harvesting. The data packet retransmission rate presents an optimal value that minimizes the packet loss probability, is independent of the RF channel path loss, and is inversely dependent on the packet size. In [167], outage and BER performances of AF relay-assisted hybrid RF/VLC system have been investigated. Closed-form expressions for the outage probability are derived by considering the effect of emission angle. The effect of timing errors on BER performance has also been considered. In [168], considering the randomness of both relay's and destination's locations, the outage and symbol error probabilities of hybrid RF/VLC with DF and AF relaying schemes have been studied.
- **Network coverage and outage probability:** The signal coverage probability (P_c) for an average user is defined as the probability that the users' instantaneous SINR (γ_o) is higher than a target SINR threshold (γ_{th}) given as:

$$P_c = P\left[\gamma_o > \gamma_{th}\right]. \quad (5)$$

Usually, RF networks have better coverage than VLC networks due to the difference in the wave propagation in both technologies. On the other hand, the outage probability (P_{out}) is the probability that the users' data rate is less than a threshold minimum data rate which is effectively the inverse of P_c.

In [166], the effect of positions' randomness of both relay and destination nodes on the outage probability of cooperative hybrid RF/VLC wireless sensor networks was investigated. Both DF and AF relaying schemes were considered and approximate expressions for outage probability were proposed and verified via Monte Carlo simulations. In [172], the outage performance of an IoT hybrid RF/VLC system was investigated by considering the randomness of the positions of devices. VLC was considered for the downlink from the source lamp to the IoT devices and RF with NOMA scheme for the uplink. All IoT devices are equipped with PD for two purposes: data communication and energy harvesting from the light emitted by the source LED lamp. These devices are then using the harvested energy to transmit data to the RF receiver. Approximate expressions for the outage probability were also derived and validated via Monte Carlo simulations.

In [125], a hybrid RF/VLC based indoor wireless access network structure is proposed. In this paper, the relationship between the wireless signal quality and the distance in a typical family or small business indoor layout is analyzed to develop the handover scheme. Reference [128] assessed the throughput across various horizontal distances within the coverage of the VLC source and the results showed that the aggregating systems can achieve higher throughput. In [134], a unified framework is presented for the coverage and rate analysis of coexisting cellular RF/VLC networks under different network configurations.

- **Network fairness and users' satisfaction:**

CDF of users' satisfaction for various numbers of users is calculated and used to measure the fairness of the network among the users. Fairness parameter is used to determine if users are equally utilizing the network resources. There are multiple ways to measure the network fairness, one of the most famous metrics is Jain's fairness index (F) which is calculated as follows [143]:

$$F = \frac{(\sum_{i=1}^{N_{AP}} R_i)^2}{(N_{AP}) \sum_{i=1}^{N_{AP}} (R_i)^2}, \tag{6}$$

where N_{AP} is the number of APs connections for each AP in the network, R_i is the achievable data rate of the AP in a certain connection.

In [143], a new iterative joint power allocation and load balancing algorithm in a hybrid RF/VLC network for data rate maximization and system fairness improvement has been proposed. An iterative algorithm distributes users to APs and the powers of the APs to their users. In [176], optimal resource-allocation of mobile terminals in a heterogeneous wireless network under diverse QoS requirements has been considered. Decentralized algorithms were proposed for the resource-allocation problem. In [175], [199], a NOMA hybrid RF/VLC with multiple VLC APs and one RF AP system has been investigated. In the proposed system both VLC and RF perform NOMA, and coalitional game theory is adopted for grouping the users. In [130], the average throughput of users for different FOV and LOS blocking probabilities is analyzed first, and then the fairness from the perspective of systems and individual users is investigated to characterize the QoS experienced by users under different cell formation scenarios.

- **Handover overhead:**

Handover overhead is the control data sent over the network to coordinate the handover process between the control unit and users. This control signal is important to ensure that handover between RF and VLC APs is as smooth and fast as possible but it decreases the network efficiency and users' data rates. Therefore, it is critical to minimize the control data overhead. Handover overhead (L_{HO}) can be calculated as follows:

$$L_{HO} = \frac{R_{overhead}}{R_{data}}, \tag{7}$$

where $R_{overhead}$ is the average data rate in network for control signal and handover, and R_{data} is the average data rate for the users' actual data.

In [205], on-off based vertical handover for a hybrid RF/VLC system that decreases delay and hence decreases the quality of experience penalty has been proposed. The proposed vertical handover is compared with I-VHO and D-VHO schemes. The simulation results reveal that the proposed scheme presents around 87.6% drop in average handover delay cost and outperforms both I-VHO and D-VHO. In [210], a new vertical handover algorithm for a hybrid RF/VLC system is presented. Different network parameters such as average interruption duration and bit rate to assess the abilities of the proposed vertical handover algorithm to handle signal blockage/overload are considered.

In [224], a hybrid network model of VLC and OFDMA is proposed for VLC hotspots. Furthermore, a novel protocol is proposed combined with access, horizontal, and vertical handover mechanisms for the mobile terminal (MT) to resolve user mobility among different hotspots and OFDMA systems.

- **Energy and power efficiency:**

A lot of research in the wireless communication domain has studied techniques to reduce and minimize the networks' power consumption. However, it is important to relate the network's power consumption to average data rate and network outage and capacity. Therefore, calculating the power efficiency of the hybrid network is critical to compare it to standalone RF and VLC networks. Power efficiency (η_{power}) is calculated as the following [139]:

$$\eta_{power} = \frac{P_{avg}}{R_{avg}}, \tag{8}$$

where P_{avg} is the average power consumption of the network, and R_{avg} is the average data rate of the users in the network.

In [139], Energy efficiency was optimized in a heterogeneous RF/VLC network with multiple constraints on the minimum data rate for users and maximum power consumption per AP. It was shown how hybrid RF/VLC networks are more power-efficient than standalone RF networks. Moreover, the impact of multiple parameters such as LOS availability, the number of LEDs and the number of users in the network were taken into account while optimizing the power consumption. In [113], the network resource optimization problem for reducing communications power consumption while minimizing the queue lengths was investigated for hybrid RF/VLC networks. In [112], an energy-efficient hybrid RF/VLC system for wireless access networks was investigated. The optimization problem is formulated by minimizing the power consumption subject to satisfying the users' requests and maintaining an acceptable illumination level. In [177], a heterogeneous cellular network that combines RF and VLC to maximize the energy efficiency of the entire communication system under QoS requirements was considered.

- **Area spectral efficiency (ASE):**
Although VLC networks offer a larger free spectrum over RF networks, VLC cells cover a smaller area than RF cells. Therefore, to be fair, when comparing the performance of hybrid networks with standalone RF and VLC networks, measuring area spectral efficiency (ASE) is needed. ASE ($\eta_{spectrum}$) measures the spectral efficiency per network (cell) area and is calculated as follows:

$$\eta_{spectrum} = \frac{R_{avg}}{A_{cov}}, \tag{9}$$

where R_{avg} is the average data rate of the users in the network and A_{cov} is the area covered by the network with a certain minimum data rate.

In [142], a scheme for cell association based on the minimum distance to the closest AP is proposed, where the ASE of a three-tier (macro-, femto- and optical attocells) heterogeneous network is analyzed. It is shown that the average ASE of the hybrid RF/VLC the system can be increased by at least two orders of magnitude over the stand-alone RF network.

- **Secrecy outage probability (SOP) and achieved secrecy rate:**
Secrecy is another important parameter that measures how the network design protects users from eavesdropping from any intruder in the network. Usually, VLC networks offer better security performance than RF networks because of the nature of the signal and the capability of the RF signal to penetrate walls, unlike visible light. Therefore, it is important to calculate the secrecy of the network to be able to compare the performance of the hybrid RF/VLC networks with standalone networks. Considering a typical Wyner's three-node model, there is a source (S) transmitting a secret message to a destination (D), while an eavesdropper (E) is trying intercept the information sent from S to D. If a silent (realistic) eavesdropping scenario is considered then S does not have any channel state information for the link between S and E. S will be sending with a constant rate of confidential message (R_s). The secrecy outage probability (SOP) is defined as the probability that the secrecy capacity (C_s) is less than R_s [235], where $C_s = \max\{\log_2(1+\gamma_D) - \log_2(1+\gamma_E), 0\}$, and γ_D and γ_E are the instantaneous SNRs at D and E, respectively. Therefore, SOP (P_{SOP}) can be calculated as follows [236]:

$$P_{SOP} = P\left[\log_2(1+\gamma_D) - \log_2(1+\gamma_E) > R_s\right]. \tag{10}$$

In [180], [231], the achievable secrecy capacity of DF-based hybrid RF/VLC was investigated. This paper considers two stages for achieving the required secrecy capacity. In the first stage, the beamforming vectors for RF and VLC subsystems that maximize the achievable secrecy capacity are obtained. In the second stage, the power minimization algorithm that satisfies the required secrecy capacity is adopted. In [171], the secrecy performance of relay-jammer selection/beamforming hybrid RF/VLC has been investigated assuming the absence of a direct link between source and destination. The considered system presents multiple DF relays and the relay node is selected by minimizing the outage probability. Jamming node is then selected from the available relaying nodes based on the received SNR at the eavesdropper location. Finally, the beamforming vectors for both RF and VLC subsystems are derived and used in the formulation of a power minimization task.

In [164], the secrecy performance of a hybrid RF/VLC system has been investigated where the relay node extracts the DC component and collects energy from the optical signal and then uses the collected energy for retransmitting data. Exact and asymptotic expressions are derived for secure outage probability and average secrecy capacity considering the effect of system parameters. In [165], the secrecy capacity of DF-based hybrid RF/VLC has been compared with standalone RF and VLC systems and showed that the hybrid system exhibits better performance. The case of non-adaptive power allocation where both source and relay have the same amount of power and the case of cooperative power-saving where the total average power is shared between source and relay in a way that minimizes the total power while satisfying the required secrecy capacity were investigated.

D. HYBRID NETWORK EXPERIMENTAL IMPLEMENTATION

Even though the literature is full of simulation-based VLC systems, there is a very limited number of researches for VLC system that consider the implementation of real-time VLC. However, for paving the way to commercial VLC products and for simulation-based system verification, the implementation under real-life conditions is an important step. The early proof of hardware implementation was demonstrated in [87], [238], where the bandwidth of just 45 kHz was limited by the used digital signal processing (DSP) kit. The aim of the presented system was to investigate the performance of phase incoherent optical OFDM under different electrical SNRs. While in [87], the considered system was unidirectional OFDM-based real-time experiments. In [238], an array of nine white LEDs was used in an effort to enlarge the coverage area for OFDM experiments [238]. As a further improvement, a system achieving 100 Mbps has been implemented in [239], where the VLC- discrete multitone was considered. The bottleneck for VLC implementation includes the LEDs driving circuits. The bias-T is the common LEDs driver that has been widely used as VLC's modulator due to its on shelves availability and can transmit OFDM signal with high PAPR. The function of bias-T is to add a high-frequency data signal on the top of DC signal. The main limitation of bias-T is its cost. In other words, installing indoor VLC systems with a huge implementation of bias-T is not practically possible. Therefore, seven DIP Op-Amps LED driving circuits has been recently proposed in [240]. The other challenge is the widely used commercial white LED for indoor lighting fixtures. This type of lighting fixture generates light by exciting the yellow fluorescent powder by blue LED. While this lighting fixture has a long lifetime, it has a narrow bandwidth. Therefore, these have become the challenges of raising the VLC transmitting rate. Several methods have been used to improve the modulation bandwidth of the LED such as quantum dots (QDs) white LEDs, which were designed to improve the transmitting rate due to its high modulation bandwidths. One of the important aspects in VLC links is the received SNR which is affected by receiver's FOV and the LED's beam pattern. In an effort to improve the received SNR, the use of different lens combinations has been investigated in [241] where Planoconvex lenses were used at the transmitter side to collimate the light pattern, and plano-convex and biconvex lenses were used at the receiver side to reduce the photodetector FOV and consequently enhance the receive SNR.

Some studies have addressed experimental implementation of hybrid systems such as [114], [115], [125], [128], [207], [208], [237]. In [128], a proof of concept of coexistence of VLC and Wi-Fi networks was implemented. Two network implementations were proposed: the first uses the VLC channel as downlink and the Wi-Fi channel as an uplink, while the second aggregates Wi-Fi and VLC in parallel by using bonding technique in Linux OS. It turns out that the hybrid system improves the network throughput and decreases web page

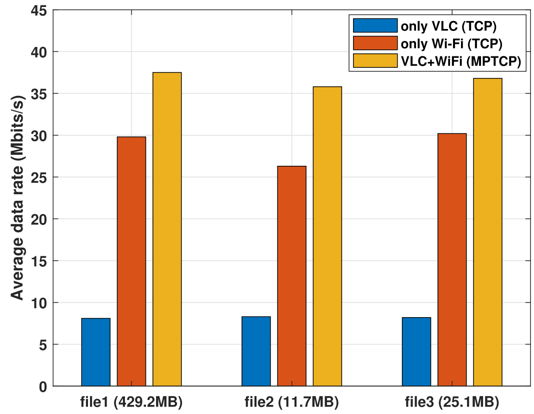


FIGURE 8. Performance results for multi-link parallel transmission (Figure regenerated from [115]).

loading time compared to normal Wi-Fi networks. In [115], a hybrid network experiment platform was implemented. This reference shows that a Wi-Fi/VLC hybrid network presents better performance than standalone VLC and Wi-Fi networks in terms of coverage and network capacity. In Fig. 8, authors present the transmission rate of three different files using three different links only Wi-Fi, only VLC and parallel Wi-Fi/VLC. As shown in figure the results show that the hybrid approach improves the capacity gain of the network.[7]

In [237], possible benefits of hybrid RF/VLC such as reliable improvements of connectivity, throughput, coverage, and energy efficiency have been discussed. In [207], [208], a hybrid RF/VLC network that is capable of switching with high speed between VLC and RF has been implemented. The proposed system was validated by capturing video streams with low latency. In [114], a practical simultaneous two-link system is presented. One of the links is a duplex RF link and the other one is an asymmetric duplex RF/VLC link. It turns out that the proposed system outperforms a standalone RF system as well as an asymmetric system. Studies of hybrid network simulation and system implementation are summarized in Table 7. While most of the studies used computer simulations, some other studies proposed using the ns3 network simulator as a reference, as discussed in [244].

E. CURRENT APPLICATIONS FOR HYBRID SYSTEMS

Hybrid RF/VLC can be classified based on the working environments. Hybrid RF/VLC is more feasible for the indoor environment due to the existence of both RF and VLC sub-systems. Therefore, most research works focus on indoor environments [234]. Hybrid RF/VLC can also be used in outdoor environments. For example, in [247], a hybrid RF/VLC

[7]The most important contribution of RF in a hybrid RF/VLC system is the stability. In VLC, weather including fog and rain can severely affect the link rate. Also, sun and its reflection can saturate the photodetectors [242]. Further, there can be cases that objects block the line-of-sight, hence reduce the data rate in VLC drastically. There are studies which aim to overcome these challenges by proposing omnidirectional coverage in VLC [243].

TABLE 7. Hybrid RF/VLC studies: Simulation and system implementation.

Dual hop Hybrid RF/VLC		Parallel Hybrid RF/VLC	
References	**Objective**	**References**	**Objective**
[115]	Performance comparison of Hybrid RF/VLC system with standalone VLC and Wi-Fi networks in terms of coverage and network capacity.	[207], [208]	Implemented a hybrid RF/VLC communication system where VLC is considered as a primary link. The system monitors the VLC link and switches to RF if the VLC link fails.
[237]	Based on the quality of first and second links, the system decides on the combination out of four possible combinations.	[128]	Proposed and implemented two heterogeneous RF/VLC systems. As a benchmark, first a duplex system is investigated with VLC and RF links for down- and up-link, respectively. The bonding technique is applied to use the VLC and RF links in parallel and compare it with the benchmarking system in terms of robustness, throughput and average system delay.
[114]	Two hybrid dual hop RF/VLC systems were investigated: 1) Uplink and downlink data are transferred from the user through the RF channel while the downlink data is transferred via the VLC channel from a relay to the user. 2) Two duplex links between the user and the AP have been implemented.	[125]	Implemented four different combinations: 1) VLC and RF are used for both up- and down-links, and RF is used if the VLC link drops. 2) VLC is used for both up- and down-links while RF is just for uplink. RF is used for uplink if the VLC link drops. 3) VLC is used for downlink and Wi-Fi is used for both up- and down-links. RF is used for downlink if the VLC link drops. 4) VLC and RF are used, respectively,for down- and up-links.

was proposed for a vehicular communication system. A security protocol (SP) for vehicular communication to ensure platoon stability and maneuver under data packet injection, jamming, channel overhearing, and maneuver attacks was proposed in [247].

Hybrid systems were used by many studies for different environments and applications which are summarized in Table 8.

Light energy-efficient systems represent an important application. Many studies used proposed RF/VLC systems for VL energy harvesting to improve the energy consumption of the hybrid system [112], [113], [120], [122], [124], [135], [137], [139], [143], [146], [177], [184], [186], [200], [212], [229], [232]. In [139], the energy efficiency of a heterogeneous network of VLC and RF systems was investigated and numerical results corroborate the improvement in energy consumption of the proposed hybrid system. In [184], the authors proposed a novel cooperative non-orthogonal division multiple access methods that allows the hybrid RF/VLC network to simultaneously transmit wireless information and power.

RF-sensitive indoor environments (e.g., hospitals) represent a critical application for VLC systems since the use of RF systems is limited due to the sensitivity of some RF-devices to RF-interference. In [173], [187], [188], [191], authors focused on using VLC network to decrease the usage of the RF network. In [191], VLC was used to provide a downlink connectivity in RF prone environment.

Improving user data rate and system capacity for the indoor environment is an important functionality of hybrid RF/VLC systems as shown in [111], [116], [117], [121], [126], [133], [134], [144], [166], [167], [169], [175], [178], [199], [204], [228]. This is due to the different characteristics of VLC and RF networks. Most of the studies optimize the resources of VLC and RF networks to maximize the users' data rate and average system capacity in an indoor environment. The same approach was used in [123], [124], [234] but to minimize the average system delay.

Since high mobility indoor environments can be challenging for standalone VLC networks, studies such as [32], [118], [119], [127], [129], [131], [168], [170], [178], [206], [209], [210] proposed using optimizing hybrid RF/VLC network handover protocols to maximize the user connectivity and the overall network throughput. In [209], authors introduced a mobility aware load balancing scheme by leveraging the location sensitivity feature of the VLC network to decrease the overhead needed for handover and to increase the network throughput.

Taking advantage of the small coverage of VLC networks and the low penetration features (high physical layer security feature), studies such as [138], [164], [165], [171], [180], [185], [186], [231] used a hybrid network of RF/VLC

TABLE 8. Application or environment used in the different hybrid studies.

Application or Environment need for Hybrid System	References
Energy efficient system	[112], [113], [120], [122], [124], [135], [137], [139], [143], [146], [177], [181], [184], [186], [195], [200], [212], [227], [229], [232]
RF sensitive indoor environment (hospitals)	[173], [187], [188], [191]
Improving user data rate and capacity for indoor environment	[111], [116], [117], [121], [126], [133], [134], [144], [166], [167], [169], [175], [178], [195], [197], [199], [204], [211], [216], [222], [228], [245]
Improving avg. system delay for indoor environment	[123], [124], [176], [183], [198], [205], [223], [234]
High mobility environment	[32], [118], [119], [127], [129], [131], [168], [170], [178], [196], [206], [209], [210]
High secrecy physical-layer system	[138], [164], [165], [171], [180], [185], [186], [231], [233]
Improving uplink for VLC indoor systems	[130], [132], [224]
IoT applications (high number of users and high data rate)	[145], [172], [182], [192], [201]–[203]
Vehicular application	[147], [196], [225], [226], [230], [246]
Integrating PLC systems	[136], [140], [141]
Demo testbeds (experimental implementation)	[114], [115], [125], [128], [207], [208], [237]

systems to increase the PHY security of the network. In [138], the average consumed power by the hybrid RF/VLC network was minimized given a certain required secrecy rate via power allocation and beamforming algorithms. Reference [165] compared the secrecy capacity of DF-based hybrid RF/VLC with standalone RF and VLC systems and showed that the hybrid system yields better performance. The case of non-adaptive power allocation where both source and relay present the same amount of power and the case of cooperative power-saving where the total average power is shared between source and relay in a way that minimizes the total power while satisfying the required secrecy capacity were both investigated.

Hybrid networks can be used to improve up-link for VLC indoor systems, a fact that was discussed in [130], [132], [224]. One of the early studies to present the idea of using both VLC and RF in the same network was [132]. An asymmetric RF/VLC combination was presented where VLC is used for downlink and RF is used for uplink to implement a full-duplex communication system.

IoT and device-to-device (D2D) communication applications were addressed in [145], [172], [192], [201]–[203]. In [145], authors introduced a new evolutionary game theory (EGT) algorithm that allows the users to adapt their needs to the hybrid RF and Li-Fi network.

Vehicular communications is a very promising application for hybrid systems because of its dynamic and changing features. In [147], the authors discussed the limitations of vehicular VL-only networks and the possibilities of utilizing them as a complementary technology with other RF wireless standards to improve the performance of conventional vehicular networks.

Since power lines can be an efficient way to connect the VLC with the internet, integrating power-line communication (PLC) systems with hybrid VLC and RF networks was discussed in [136], [140], [141]. In [140], the impact of OFDM-based PLC backhauling in a multi-user hybrid system was discussed. Optimal power and subcarrier allocation algorithms were utilized to maximize the users' data rates. The hybrid system performance was studied numerically as a function of several parameters including PLC transmission power, RF and VLC spectrum, and the number of mobile terminals and APs.

Finally, as seen in Table 9, most of the new studies focus on implementing hybrid systems while old studies focus more on performance analyses and simulations.

IV. RESEARCH DIRECTIONS AND FUTURE WORK

This section discusses the open research directions and future work for the hybrid RF/VLC studies.

A. CURRENT RESEARCH DIRECTIONS

- **Energy harvesting with dual-hop RF/VLC system under delay and data rate constraints:**
  Multiple studies have provided simulation analysis of a dual hop system consisting of VLC and RF links. While the idea of harvesting energy as well as transferring data between the user and APs is a new idea and it appears to be a power-efficient solution. The drawbacks of energy harvesting where delay is introduced have to

TABLE 9. Hybrid RF/VLC studies (chronologically ordered).

Year	References	Comments (contributions)
2021	[181]	A hybrid downlink system that proposes an optimization framework for VLC/RF information relaying and power transfer.
2021	[196]	Proposed an adaptive topology control scheme to achieve balance between connectivity and power consumption in VANET.
2021	[195]	Proposed an NOMA framework that is energy effiect for hybrid RF and VLC systems that take into account user mobility and imperfect channel state information.
2021	[227]	Improves sum-rate and fairness of the networks by utilizing a cooperative NOMA scheme for power allocation and link selection in a hybrid RF/VLC system.
2021	[182]	Proposed a dual hop system for optimized power and information transfer in IoT applications.
2021	[197]	Investigated the joint problem of AP assignment and power allocation in a hybrid RF/VLC system to maximize data rate and QoS under AP power constraint.
2021	[198]	Conducted an user mobility analysis for RF/VLC hybrid networks by evaluating handover rates based on a random UE movement distribution to maximize network load and minimize handover rates. s
2020	[192]	Optimized the AP assignment in HetNet RF/VLC network for IoT applications ensuring QoS and minimum outage and handover overhead.
2020	[193]	Improved fairness among all users and increase the overall network throughput by using reinforcement learning approach to improve network selection.
2020	[225], [248]	Studied outage Analysis of novel jamming-robust network for outdoor cognitive EV-enabled scenarios.
2020	[230]	Proposed a resource management algorithm for hybrid RF/VLC V2I wireless communication systems and demonstrated its energy efficiency enhancement.
2020	[233]	Investigated physical layer security analysis for an indoor heterogeneous VLC/RF network along with introducing a novel secure-link selection mechanism based on known and unknown CSI.
2020	[194]	Proposed a dynamic cell formation method jointly with a load balancing strategy for hybrid VLC/RF networks based on blind interference alignment.
2020	[211]	Proposed an optimization scheme of joint problem of MAC frame slots and power allocation in hybrid VLC/RF network.
2020	[222]	Proposed an optimal resource allocation for hybrid VLC/RF networks with common backhaul taking in consideration imperfect CSI.
2020	[216]	Proposed a new resource allocation and load balancing scheme for WiFi and OFDMA-Based Li-Fi indoor hybrid networks which improved the user average data rate.
2020	[174]	Implemented a a hybrid cellular architecture that allows inter-operability between different technologies (hybrid RF/VLC network) in the world of Internet of Things.
2020	[201]	Presented an energy-efficient resource management for a heterogeneous RF/VLC in industrial IoT networks supporting different QoS requirements.
2019	[172]	Studied the outage performance of a hybrid VLC-RF indoor IoT system with light energy harvesting.
2019	[212]	Achieved lower outage probability using more energy efficient base station intensities for hybrid RF/VLC networks.
2019	[200]	Proposed a collaborative resource allocation scheme for information and power transfer system in hybrid RF and VLC ultra cell networks.
2018,2019	[175], [199]	Proposed coalitional game approach for user grouping in hybrid RF/VLC networks With NOMA.
2019	[111]	Presented a location information-aided load balancing design for hybrid Li-Fi and Wi-Fi networks.
2019	[178]	Presented integrated RF/Optical wireless networks for improving QoS in indoor and transportation applications.

continued on the next page

TABLE 9. ***(Continued.)*** **Hybrid RF/VLC studies (chronologically ordered).**

continued from previous page

Year	References	Comments (Contributions)
2019	[165]	Studied the secrecy capacity of decode and forward based hybrid RF/VLC relaying systems.
2019	[171]	Investigated the secrecy performance of a design for a relaying hybrid RF/VLC system with minimized power.
2018, 2017	[202], [203]	Optimized selection between RF and VLC bands for device to device (D2D) communication in a multi user scenario to maximize spectral efficiency.
2018	[135]	Investigated the energy-efficient subchannel and power allocation of heterogeneous VLC and RF based networks relying on the software-defined systems.
2018	[134]	Investigated coverage and rate analysis for RF/VLC downlink cellular networks for RF/VLC only, opportunistic hybrid RF/VLC, and centralized hybrid RF/VLC.
2018	[143]	Proposed joint load balancing and power allocation for hybrid RF/VLC networks to improve system capacity and fairness.
2018	[168]	Investigated outage and symbol error probabilities of a hybrid RF/VLC under both DF and AF relaying schemes.
2018	[170]	Presented a context-aware solution for indoor network selection using reinforcement learning based network algorithms.
2018	[180]	Investigated beamforming design and secrecy capacity of hybrid RF/VLC DF relaying systems in the presence of the eavesdropper nodes.
2018	[183]	Studied effective capacity of a hybrid RF/VLC system subject to QoS constrains
2018	[167]	Investigated outage and BER performances of AF relay-assisted hybrid RF/VLC system.
2018	[166]	Investigated outage analysis of cooperative hybrid RF/VLC wireless sensor network (WSN) under DF and AF relay schemes.
2018	[112]	Proposed a new paradigm in designing and reducing the power consumption of wireless indoor access networks satisfying user requests and needed illumination level.
2018	[204]	Proposed a bandwidth aggregation protocol for hybrid RF/VLC networks and implemented a real-life prototype of the hybrid VLC and RF communication system to test the protocol.
2018	[164]	Studied the secure outage probability and average secrecy capacity of a dual-hop RF/VLC communication system.
2018	[184]	Investigated outage performance of a cooperative NOMA based RF/VLC system.
2018	[177]	Proposed coordinated beamforming design in a multiple input single output (MISO) downlink hybrid RF/VLC networks.
2018	[116]	Proposed learning aided network association for hybrid indoor Li-Fi and Wi-Fi Systems focusing on the LED AP selection strategies.
2017	[118]	Investigated optimization of load balancing in hybrid RF/Li-Fi Networks.
2017, 2016	[117], [126]	Proposed an AP selection method for VLC and RF networks to improve the throughput of the network.
2017	[136]	Analyzed the optimization problem of minimizing the total transmission power consumption for a hybrid power-line communication (PLC)/RF/VLC system.
2017	[185], [186]	Conducted secrecy outage analysis of hybrid RF/VLC system with light energy harvesting.
2017	[249]	Proposed a new OFDM design for hybrid RF/VLC baseband system consider both power and bandwidth allocation.
2017	[187], [188]	Studied modeling and outage analysis of hybrid RF/VLC system for real time health care applications outage probability.
2017	[115]	Developed an indoor hybrid VLC-Wi-Fi network network experiment platform to test coverage and network capacity.
2017	[207], [208]	Implemented a software defined hybrid RF/VL network that is capable of switching with high speed between VLC and RF.

continued on the next page

be minimized. Most of the studies have simulated the system and optimized it in terms of a single constraint like overall system delay, maximum user data rate, and system secrecy. Further analysis should consider multiple constraints and conduct more analysis for such systems. Moreover, a good handover scheme needs to

TABLE 9. ***(Continued.)*** **Hybrid RF/VLC studies (chronologically ordered).**

continued from previous page

Year	References	Comments (Contributions)
2016	[139]	Investigated and optimized power and bandwidth allocation for energy efficiency maximization of a heterogeneous RF/VLC network.
2016	[122], [124]	Optimized energy harvesting and data rate under delay constraint in daulhop hybrid RF/VLC system.
2016	[147]	Introduced the use of VLC as a complementary technology for the DSRC for connected vehicles (Future of heterogeneous vehicular network).
2016	[209]	Proposed a mobility aware load balancing in LTE/VLC networks to improve system throughput and handover overhead
2016	[123]	Investigated delay analysis of RF/VLC coexistence wireless networks for aggregated and non-aggregated scenarios.
2015	[130]	Investigated cooperative load balancing in hybrid VLC and Wi-Fi to improve high area spectral efficiency and optimize system throughput.
2015	[131]	Investigated dynamic load balancing with handover in hybrid Li-Fi and Wi-Fi networks taking into account user mobility and handover signaling overhead.
2015	[176]	Studied resource allocation under delay-guarantee constraints for heterogeneous visible-Light and RF femtocell.
2015	[128]	Conducted design and analysis of a VLC enhanced Wi-Fi system with and without aggregation.
2015	[189]	Investigated practical integration of VLC in 5G networks where motivation of using VLC and system component needed in deployment.
2015	[129]	Proposed an efficient vertical handover scheme for RF/VLC systems using a Markov decision process to obtain a trade-off between switching cost and delay requirement.
2014	[224]	Proposed a hybrid network of VLC and OFDMA system in which VLC is used only for downlink to improve the network capacity.
2014	[32]	Studied performance of cooperative data download indoor hybrid wireless local area networks (WLAN)-VLC and compared it with standalone WLAN-only and VLC-only networks.
2014	[191]	Proposed the use of hybrid RF/VLC systems in RF sensitive indoor environments.
2014	[237]	Implemented a Software defined hybrid RF/VLC system using off-the-shelf LEDs and photodetectors.
2011	[133]	Proposed an indoor hybrid system that integrates WiFi and VLC luminaries to improve throughput and delay for broadcasting.

be adopted to ensure system reliability. Finally, testing such system in a real hardware prototype would also be a possible future research direction.

- **Resource allocations and AP selection in RF/VLC networks:**
Multiple studies have discussed the AP selection in RF/VLC networks. Depending on whether the hybrid network design has a central control unit or not, the algorithm will vary. The main goal is to find an energy-efficient algorithm that will ensure the fairness of the network over the VLC and RF networks and maximize the throughput of the users in the network. Many studies can be conducted in the direction of utilizing machine learning to solve this non-convex optimization problem. Moreover, future work would be focusing on using the most efficient and low-cost optimization algorithm to ensure the best network throughput, and minimizing the control overhead, delay, and power transmitted. In addition, resource allocations such as bandwidth allocations and the number of APs would be critical network design problems that would depend on the requirement of the network, the availability of the resources, and mobility of the users. The metrics used to compare different algorithms are network fairness, user satisfaction, and outage probability.
- **Load balancing and handover between VLC and RF networks:**
It is evident from the current research that hybrid RF/VLC networks provide better performance in terms of bandwidth and user mobility. However, it is important to maximize the benefits of both networks by applying an efficient load balancing scheme and a fast handover algorithm to ensure network reliability in all times and locations. Researches are focusing on minimizing the handover latency and increasing the network overall throughput by using different techniques of load balancing schemes as mobility-aware and location-aware handover algorithms. The future direction for

this challenging issue in hybrid networks is having a dynamic load balancing scheme that updates the network resources whenever needed. Moreover, utilizing distributed users' shared information is another solution to decrease control overhead and power transmitted by the users. Finally, different solutions could be compared with respect to user maximum data rate, control overhead, network fairness, and outage probability.

- **Physical layer security of RF/VLC networks:** Secrecy is a growing network aspect and issue that is considered by multiple applications and users. Multiple studies have focused on increasing the security of the network and measuring the probability of the network's sustainability to eavesdropping. Since VLC networks are superior to RF networks in this particular aspect, the effect of using hybrid RF/VLC networks is studied and simulated by multiple researchers. Because the location of the eavesdropper is an important parameter that affects the secrecy of the network, more analysis would be needed to ensure that the network power consumption is minimized while ensuring a certain level of secrecy for the networks in different scenarios and network topologies.
- **Design and implementation of practical hybrid RF/VLC network (testbeds):** The most important step of proposing a new algorithm is to test it on real hardware. Therefore, designing and implementing testbeds for hybrid RF/VLC networks is critical for the development of any valid comparison between proposed handover and resource allocation algorithms. Moreover, these practical implementations will vary in cost and number of users that it can support. In the future, further optimization methods for the currently proposed testbeds would be needed to make it easier to implement on available hardware and give more flexibility to the researchers in terms of network design and the number of users supported. The development of lower-cost testbeds will allow more studies to be done on hybrid networks optimization algorithms from load balancing to AP selection. In addition, the availability of easy-to-setup hardware will make it more accessible for researchers to develop new applications and use cases for hybrid RF/VLC networks.
- **New modulation schemes and access methods (OFDM, NOMA) for Hybrid RF/VLC networks:** Numerous studies have been conducted on testing new modulation techniques and access methods. Devices that support hybrid RF/VLC would require its internal hardware RF front-end and baseband blocks (to be updated and optimized). For example, researchers in [249] proposed a new hybrid of radio optical OFDM (HRO-OFDM) scheme which combines both RF and VLC link in the physical layer. This new OFDM scheme design improves optimization and allocation of both power and bandwidth for both technologies which allows the network to achieve better performance. Moreover, multiple studies proposed using NOMA which appeared to be less sensitive to LOS availability compared to OFDMA [199], [250], [251]. In [250], a novel energy efficient NOMA hybrid RF/VLC system has been proposed. Particularly, authors have considered using downlink hybrid RF/VLC and deriving a closed-form expression for energy efficiency which is subsequently used for extensive energy efficiency analysis of their proposed scheme. Authors have further demonstrated that NOMA is less sensitive to LOS compared to its OFDMA-based counterpart. In [251], multiple access techniques were performed for maximizing the overall achievable data rate where they jointly decide on the power allocation coefficients, pairing index, and link selection. However, the non-cooperative nature of NOMA makes users competing on resources. Therefore, studies proposed using a coalitional game approach instead of standard opportunistic scheme [199]. In the future, it is expected that researchers would continue improving the modulation schemes and access methods utilized by hybrid RF/VLC networks to further improve the performance and optimize the utilized resources.
- **Environment adaptive RF/VLC networks (interference, data rate, coverage, number of users requirements) and application dependent networks:** As seen throughout the paper, hybrid RF/VLC networks were proposed to be utilized in different applications to make use of their advantages and flexibilities. However, depending on the application and its environment, either indoor or outdoor, the network parameters need to be adapted to fully utilize the benefits of a hybrid RF/VLC network. Moreover, it is expected that more applications would emerge for hybrid networks as more researchers get easy to use testbeds and realize the benefits and advantages of hybrid networks. This means new algorithms and network topologies would need to be introduced and studied to adapt networks to new environments and applications.
- **Backhauling of RF/VLC networks:** Backhauling is the connection of the APs of RF and VLC network to core network. Usually the AP side is the bottleneck of the network. However, with new modulation techniques and coding scheme the bottleneck of the network shifted to the connection between the AP and the core network as number of users and data rate demand increase. Some studies have discussed this issue and proposed solutions and analysis for the hybrid networks [140], [141], [222]. Another direction is the use of the dual hop network architecture as a solution where the VLC provides the backhaul for the RF APs instead of fiber cable which provides more flexibility to the network installation. More studies are needed to compare between the two solutions and provide more analysis on the costs and benefits.

B. EXPECTED FUTURE RESEARCH DIRECTIONS

After discussing the research work carried out in the area of hybrid RF/VLC networks, we present expected future directions in this section. From the trends we have seen in the VLC research, it is clear that more applications that are based on visible light technologies are going to be introduced in the future. More coexistence between RF networks and VLC based networks will be required to improve the user experience and reduce the networks delay and power consumption. Therefore, the following research directions could be investigated:

- Introducing new novel and efficient optimization techniques to improve the performance of hybrid RF/VLC networks.
- Improving implementations for the proposed network configurations using software defined radio systems (SDRs).
- Improving the energy efficiency of the network.
- Performing spectrum sensing and utilizing the best available RF or visible light spectrum by applying machine learning algorithms (e.g., cognitive radio).
- Finding new applications for hybrid systems (emerging applications for the hybrid RF/VLC systems).
  As discussed throughout the paper, hybrid RF/VLC technology is very important as it provides both advantages of RF and VLC standalone systems. Therefore, it will add diversity, increase coverage, decrease power consumption and interference. Potential applications are listed as follows:
  1) As a replacement for normal Wi-Fi systems, especially for indoor scenarios.
  2) In RF interference-free applications to decrease the RF power used, e.g., airports and hospitals.
  3) In vehicular communication technologies as V2X to make use of the built-in hardware (hybrid DSRC/VLC).
  4) Power efficient IoT applications and Machine-to-Machine (M2M) communication.
  5) In sensing applications as hybrid RF/VLS (VLS: Visible Light Sensing), e.g., occupancy estimation and positioning.

V. CONCLUSION

The idea of having a dynamic and reconfigurable network that can support both RF and VLC is being adopted by a lot of studies and researchers in recent years. This is due to the multiple advantages that these systems possess:

- Having a stable channel under different circumstances.
- Improving user mobility and security.
- Making the network less RF interfering.
- Improving network power consumption, delay, and capacity.
- Improving network reliability under a high number of users and data rates.
- Integrating it easily with multiple technologies and in different applications.

These types of networks present features such as smart cognitive networks that are capable of adapting to the surrounding environment and exploiting optimally the available resources. These networks offer flexibility and high performance, which greatly suits the new requirements of future networks such as 5G and beyond.

This paper summarized all the important aspects of these hybrid networks. First, we have shown how different network topologies can be used in these hybrid systems depending on the application considered. These topologies are currently being tested in the recent hardware implementations of these hybrid networks. Second, we discussed the different optimization techniques to maximize the performance of these networks. Third, we described different performance analysis tools for hybrid networks. These tools ranged from network metrics to user specific metrics. Moreover, we presented the applications and environments where these hybrid networks find applicability and outperform the normal standalone networks. These applications are going to expand more as more studies dedicated to these hybrid networks.

Finally, as a conclusion of the survey work, it is important to note that hybrid RF/VLC networks come in different network topologies, use variable handover and load balancing schemes, and utilize a wide range of modulations and access methods. The most important thing is to understand the nature of the intended application of each user-case for the network to adapt its specifications to the needs of the users and available resources. Future analyses and simulations for these hybrid networks are still needed for hybrid networks in terms of access methods and load balancing to take advantage of the idea of using two different technologies (operating frequencies) competing in the same network. Eventually, these networks would evolve into smarter cognitive networks that would maximize the performance of their users while maintaining efficient resource utilization.

NOMENCLATURE

ADC	Analog to Digital Converter
AF	Amplify and Forward
APs	Access Points
AR	Augmented Reality
ASTM	American Society for Testing and Materials
BER	Bit Error Rate
bps	Bits Per Seconds
BS	Base Station
BS	Base Station
CDMA	Code Division Multiple Access
CSK	Color Shift Keying
CSMA	Carrier Sense Multiple Access
D2D	Device to Device
DAC	Digital to Analog Converter
DC	Direct Current
DF	Decode and Forward
DSRC	Dedicated Short Range Communications
DSSS	Direct Sequence Spread Spectrum
D-VHO	Dwell Vertical Handover

EGT	Evolutionary Game Theory
EM	Electromagnetic
eU-OFDM	enhanced Unipolar Orthogonal Frequency Division Multiple Access
FHSS	Frequency-Hopping Spread Spectrum
FOV	Field Of View
FPS	frame per second
FSO	Free Space Optical
HetNet	Heterogeneous Network
I2V	Infrastructure-to-Vehicle
IM/DD	Intensity Modulation/Direct Detection
IIoT	Industrial Networks Internet of Thing
IoT	Internet of Thing
IR	Infrared Radiation
ITS	Intelligent Transportation Systems
I-VHO	Immediately executes Vertical Handover
kbps	Kilobits Per Seconds
LB	Load Balancing
LED	Light Emitting Diode
Li-Fi	Light Fidelity
LOS	Line of Sight
LTE	Long Term Evolution
M2M	Machine to Machine
MAC	Medium Access Control
MBE	Mean Bandwidth Efficiency
MBSs	Macro Cell BSs
MDP	Markov decision process
MGF	Moment Generating Function
MIMO	Multiple Input Multiple Output
MISO	Multiple Input Single Output
mmWave	millimeter Waves
MOO	Multi-Objective Optimization
MR	Mobile Robots
NOMA	Non-Orthogonal Multiple Access
NLOS	Non-LOS
NP	Nondeterministic Polynomial
OCC	Optical Camera Communication
OFDM	Orthogonal Frequency Division Modulation
OFDMA	Orthogonal Frequency Division Multiple Access
OWC	Optical Wireless Communications
PAPR	Peak-to-Average-Power Ratio
PD	Photo-Detector
PDF	Probability Density Function
PDS-ERT	Post-Decision State-Based Experience Replay and Transfer
PHY	Physical Layer
PLC	Power-Line Communication
QoS	Quality of Service
RF	Radio Frequency
SDR	Software Defined Radio
SNR	Signal-to-Noise Ratio
SOO	Single-Objective Optimization
SP	Security Protocol
SBSs	Small Cell BSs
UE	User Equipment
V2I	Vehicle-to-Infrastructure
V2V	Vehicle-to-Vehicle
VL	Visible Light
VLC	Visible Light Communication
VLCBSs	VLC BSs
VT	Vectored Transmission
V2X	Vehicle-to-Everything
WAVE	Wireless Access in Vehicular Environments
Wi-Fi	Wireless Fidelity
WLAN	Wireless Local Area Networks
WSN	Wireless Sensing Network

SYMBOLS

A_R	Optical detector size
d	Distance between the receiver and the transmitter
FOV	Field of view for VLC receiver
ς	Channel path loss exponent
$g(\theta)$	Concentrator gain
H_v	Optical channel gain
K	All the gains and the transmitted power
m	Order of the Lambertian model
ϕ	Irradiance angle
$\phi_{\max}$	Semi-angle at half-power of the LED
P_t	Maximum allowable total power
P_{t-RF}	Power transmitted for RF system
P_{t-VLC}	Power transmitted for VLC system
θ	Incidence angle
$T_s(\theta)$	Gain of the optical filter
R_i	Average data rate of user i
$E[\cdot]$	Expected value operator
$\gamma_i(t)$	SINR over time for user i
B	User assigned bandwidth
T_{tr}^i	Multi-hop retransmission time delay per hop i
T_{err}	Error retransmission time delay
T_{HO}	Handover time delay
T_{avg}	Average transmission delay
P_{HO}	Probability a handover process occurs
P_{err}	Probability a transmission error occurs
N	Maximum number of hops in the system
BER	Bit error rate
P_c	Signal coverage probability
γ_o	Users' instantaneous SINR
γ_{th}	Target SINR threshold
F	Jain's fairness index
N_{AP}	Number of connections for all APs in network
R_i	Achievable data rate of the AP per connection
L_{HO}	Handover overhead
$R_{overhead}$	Average data rate of control signal and handover
R_{data}	Average data rate for the users' actual data
η_{power}	Network power efficiency
P_{avg}	Average power consumption of the network
R_{avg}	Average data rate of all users
$\eta_{spectrum}$	Area spectral efficiency

A_{cov}	Area covered by the network with a minimum data rate
R_s	Source constant data rate of confidential message
P_{SOP}	Secrecy outage probability
C_s	Secrecy capacity
γ_D	Instantaneous SINR at the destination
γ_E	Instantaneous SINR at the eavesdropper

ACKNOWLEDGMENT

The authors would like to thank Dr. Qian Gao for his great support in the preparation of this study and his helpful suggestions and perspectives, and Md Zobaer Islam for his valuable comments and suggestions to improve this article. The statements made herein are solely the responsibility of the authors.

REFERENCES

[1] A. N. Uwaechia and N. M. Mahyuddin, "A comprehensive survey on millimeter wave communications for fifth-generation wireless networks: Feasibility and challenges," *IEEE Access*, vol. 8, pp. 62367–62414, 2020.
[2] T. Rappaport, R. Heath, R. Daniels, and J. Murdock, *Millimeter Wave Wireless Communications*. London, U.K.: Pearson, 2014.
[3] T. Nitsche, C. Cordeiro, A. B. Flores, E. W. Knightly, E. Perahia, and J. C. Widmer, "IEEE 802.11ad: Directional 60 GHz communication for multi-gigabit-per-second Wi-Fi [invited paper]," *IEEE Commun. Mag.*, vol. 52, no. 12, pp. 132–141, Dec. 2014.
[4] T. S. Rappaport, S. Sun, R. Mayzus, H. Zhao, Y. Azar, K. Wang, G. N. Wong, J. K. Schulz, M. Samimi, and F. Gutierrez, "Millimeter wave mobile communications for 5G cellular: It will work!" *IEEE Access*, vol. 1, pp. 335–349, 2013.
[5] S. A. Busari, K. M. S. Huq, S. Mumtaz, L. Dai, and J. Rodriguez, "Millimeter-wave massive MIMO communication for future wireless systems: A survey," *IEEE Commun. Surveys Tuts.*, vol. 20, no. 2, pp. 836–869, 2nd Quart., 2018.
[6] D. L. Hutt, K. J. Snell, K, and P. A. Belanger, "Alexander Graham Bell's photophone," *Optics Photon. News*, vol. 4, no. 6, pp. 20–25, Jun. 1993.
[7] D. K. Jackson, T. K. Buffaloe, and S. B. Leeb, "Fiat lux: A fluorescent lamp digital transceiver," *IEEE Trans. Ind. Appl.*, vol. 34, no. 3, pp. 625–630, May 1998.
[8] G. Pang, T. Kwan, C.-H. Chan, and H. Liu, "LED traffic light as a communications device," in *Proc. IEEE/IEEJ/JSAI Int. Conf. Intell. Transp. Syst.*, Oct. 1999, pp. 788–793.
[9] Y. Tanaka, S. Haruyama, and M. Nakagawa, "Wireless optical transmissions with white colored LED for wireless home links," in *Proc. 11th IEEE Int. Symp. Pers., Indoor Mobile Radio Commun.*, vol. 2, Sep. 2000, pp. 1325–1329.
[10] D. Tsonev, S. Videv, and H. Haas, "Light fidelity (Li-Fi): Towards all-optical networking," in *Proc. SPIE*, vol. 9007, Feb. 2014, Art. no. 900702.
[11] H. Haas, L. Yin, Y. Wang, and C. Chen, "What is LiFi?" *J. Lightw. Technol.*, vol. 34, no. 6, pp. 1533–1544, Mar. 15, 2016.
[12] S. Rajagopal, R. D. Roberts, and S.-K. Lim, "IEEE 802.15.7 visible light communication: Modulation schemes and dimming support," *IEEE Commun. Mag.*, vol. 50, no. 3, pp. 72–82, Mar. 2012.
[13] *IEEE Standard for Local and Metropolitan Area Networks—Part 15.7: Short-Range Optical Wireless Communications*, Standard 802.15.7-2018, Apr. 2019.
[14] P. Luo, M. Zhang, Z. Ghassemlooy, S. Zvanovec, S. Feng, and P. Zhang, "Undersampled-based modulation schemes for optical camera communications," *IEEE Commun. Mag.*, vol. 56, no. 2, pp. 204–212, Feb. 2018.
[15] V. P. Rachim and W.-Y. Chung, "Multilevel intensity-modulation for rolling shutter-based optical camera communication," *IEEE Photon. Technol. Lett*, vol. 30, no. 10, pp. 903–906, May 15, 2018.
[16] W. Huang and Z. Xu, "Characteristics and performance of image sensor communication," *IEEE Photon. J.*, vol. 9, no. 2, pp. 1–19, Apr. 2017.
[17] T. Yamazato, M. Kinoshita, S. Arai, E. Souke, T. Yendo, T. Fujii, K. Kamakura, and H. and Okada, "Vehicle motion and pixel illumination modeling for image sensor based visible light communication," *IEEE J. Sel. Areas Commun.*, vol. 33, no. 9, pp. 1793–1805, Sep. 2015.
[18] T.-H. Do and M. Yoo, "Multiple exposure coding for short and long dual transmission in vehicle optical camera communication," *IEEE Access*, vol. 7, pp. 35148–35161, 2019.
[19] L. Bai, Y. Yang, C. Guo, C. Feng, and X. Xu, "Camera assisted received signal strength ratio algorithm for indoor visible light positioning," *IEEE Commun. Lett.*, vol. 23, no. 11, pp. 2022–2025, Nov. 2019.
[20] B. Lin, Z. Ghassemlooy, C. Lin, X. Tang, Y. Li, and S. Zhang, "An indoor visible light positioning system based on optical camera communications," *IEEE Photon. Technol. Lett.*, vol. 29, no. 1, pp. 579–582, Apr. 1, 2017.
[21] M. Z. Chowdhury, M. K. Hasan, M. Shahjalal, M. T. Hossan, and Y. M. Jang, "Optical wireless hybrid networks: Trends, opportunities, challenges, and research directions," *IEEE Commun. Surveys Tuts.*, vol. 22, no. 2, pp. 930–966, 2020.
[22] P. Ji, H.-M. Tsai, C. Wang, and F. Liu, "Vehicular visible light communications with LED taillight and rolling shutter camera," in *Proc. IEEE 79th Veh. Technol. Conf. (VTC Spring)*, May 2014, pp. 1–6, doi: 10.1109/VTCSpring.2014.7023142.
[23] M. F. Ahmed, M. K. Hasan, M. Shahjalal, M. M. Alam, and Y. M. Jang, "Experimental demonstration of continuous sensor data monitoring using neural network-based optical camera communications," *IEEE Photon. J.*, vol. 12, no. 5, pp. 1–11, Oct. 2020, doi: 10.1109/JPHOT.2020.3017642.
[24] P. Hu, P. H. Pathak, X. Feng, H. Fu, and P. Mohapatra, "ColorBars: Increasing data rate of LED-to-camera communication using color shift keying," in *Proc. 11th ACM Conf. Emerg. Netw. Exp. Technol.*, New York, NY, USA, Dec. 2015, pp. 1–13.
[25] T. Yamazato, I. Takai, H. Okada, T. Fujii, T. Yendo, S. Arai, M. Andoh, T. Harada, K. Yasutomi, K. Kagawa, and S. Kawahito, "Image-sensor-based visible light communication for automotive applications," *IEEE Commun. Mag.*, vol. 52, no. 7, pp. 88–97, Jun. 2014.
[26] P. H. Pathak, X. Feng, P. Hu, and P. Mohapatra, "Visible light communication, networking, and sensing: A survey, potential and challenges," *IEEE Commun. Surveys Tuts.*, vol. 17, no. 4, pp. 2047–2077, 4th Quart., 2015.
[27] D. Karunatilaka, F. Zafar, V. Kalavally, and R. Parthiban, "LED based indoor visible light communications: State of the art," *IEEE Commun. Surveys Tuts.*, vol. 17, no. 3, pp. 1649–1678, Aug. 2015.
[28] S. Wu, H. Wang, and C. H. Youn, "Visible light communications for 5G wireless networking systems: From fixed to mobile communications," *IEEE Netw.*, vol. 28, no. 6, pp. 41–45, Nov. 2014.
[29] M. Uysal, Z. Ghassemlooy, A. Bekkali, A. Kadri, and H. Menouar, "Visible light communication for vehicular networking: Performance study of a V2V system using a measured headlamp beam pattern model," *IEEE Veh. Technol. Mag.*, vol. 10, no. 4, pp. 45–53, Dec. 2015.
[30] M. Z. Chowdhury, M. T. Hossan, A. Islam, and Y. M. Jang, "A comparative survey of optical wireless technologies: Architectures and applications," *IEEE Access*, vol. 6, pp. 9819–9840, 2018.
[31] M. Ayyash, H. Elgala, A. Khreishah, V. Jungnickel, T. Little, S. Shao, M. Rahaim, D. Schulz, J. Hilt, and R. Freund, "Coexistence of WiFi and LiFi toward 5G: Concepts, opportunities, and challenges," *IEEE Commun. Mag.*, vol. 54, no. 2, pp. 64–71, Feb. 2016.
[32] H. Chowdhury and M. Katz, "Cooperative data download on the move in indoor hybrid (radio-optical) WLAN-VLC hotspot coverage," *Trans. Emerg. Telecommun. Technol.*, vol. 25, no. 6, pp. 666–677, 2014.
[33] M. Obeed, A. M. Salhab, M.-S. Alouini, and S. A. Zummo, "On optimizing VLC networks for downlink multi-user transmission: A survey," *IEEE Commun. Surveys Tuts.*, vol. 21, no. 3, pp. 2947–2976, 3rd Quart., 2019.
[34] Y. Zhuang, L. Hua, L. Qi, J. Yang, P. Cao, Y. Cao, Y. Wu, J. Thompson, and H. Haas, "A survey of positioning systems using visible LED lights," *IEEE Commun. Surveys Tuts.*, vol. 20, no. 3, pp. 1963–1988, 3rd Quart., 2018.
[35] X. Li, R. Zhang, and L. Hanzo, "Optimization of visible-light optical wireless systems: Network-centric versus user-centric designs," *IEEE Commun. Surveys Tuts.*, vol. 20, no. 3, pp. 1878–1904, 3rd Quart., 2018.
[36] L. Feng, R. Q. Hu, J. Wang, P. Xu, and Y. Qian, "Applying VLC in 5G networks: Architectures and key technologies," *IEEE Netw.*, vol. 30, no. 6, pp. 77–83, Nov./Dec. 2016.
[37] X. Wu, M. D. Soltani, L. Zhou, M. Safari, and H. Haas, "Hybrid LiFi and WiFi networks: A survey," 2020, *arXiv:2001.04840*.
[38] J. Liu, P. W. C. Chan, D. W. K. Ng, E. S. Lo, and S. Shimamoto, "Hybrid visible light communications in intelligent transportation systems with position based services," in *Proc. IEEE Globecom Workshops*, Dec. 2012, pp. 1254–1259.

[39] H. Yang, W.-D. Zhong, C. Chen, and A. Alphones, "Integration of visible light communication and positioning within 5G networks for Internet of Things," *IEEE Netw.*, vol. 34, no. 5, pp. 134–140, Sep. 2020.
[40] Z. Ghassemlooy, L. N. Alves, S. Zvanovec, and M.-A. Khalighi, *Visible Light Communications: Theory and Applications*, 1st ed. Boca Raton, FL, USA: CRC Press, Jun. 2017, pp. 69–72.
[41] P. Nantivatana, K. Jaruwongrungsee, T. Srited, P. Kovintaveewat, and P. Kocharoen, "Visible light communication development kits complianted to CP1223 standard," *IEICE Proc. Ser.*, vol. 61, no. M1-4-4, pp. 69–72, 2016.
[42] Y. Su and T. Sato, "A key technology for standardizing outdoor optical wireless communications," *ICT Exp.*, vol. 3, no. 2, pp. 62–66, Jun. 2017.
[43] Z. Wang, Q. Wang, W. Huang, and Z. Xu, *Visible Light Communications: Modulation and Signal Processing*. Hoboken, NJ, USA: Wiley, 2017.
[44] H. Li, X. Chen, B. Huang, D. Tang, and H. Chen, "High bandwidth visible light communications based on a post-equalization circuit," *IEEE Photon. Technol. Lett.*, vol. 26, no. 2, pp. 119–122, Jan. 15, 2014.
[45] J. J. D. McKendry, R. P. Greeen, A. E. Kelly, Z. Gong, B. Guilhabert, D. Massoubre, E. Gu, and M. D. Dawson, "High-speed visible light communications using individual pixels in a micro light-emitting diode array," *IEEE Photon. Technol. Lett.*, vol. 22, pp. 1346–1348, Sep. 15, 2010.
[46] H. B. Eldeeb, M. Uysal, S. M. Manay, P. Hellwigy, J. Hilty, and V. Jungnickel, "Channel modelling for light communications: Validation of ray tracing by measurements," in *Proc. 12th IEEE/IET Int. Symp. Commun. Syst., Netw. Digit. Signal Process. (CSNDSP)*, Porto, Portugal, Jul. 2020, pp. 1–6.
[47] M. Uysal, F. Miramirkhani, T. Baykas, and K. Qaraqe. (Sep. 2018). *IEEE 802.11bb Reference Channel Models for Indoor Environments*. IEEE P802.11 Wireless LANs, doc.: IEEE 11-18-1582-02-00bb. Accessed: Jul. 2020. [Online]. Available: https://mentor.ieee.org/802.11
[48] D. Tsonev, S. Videv, and H. Haas, "Unlocking spectral efficiency in intensity modulation and direct detection systems," *IEEE J. Sel. Areas Commun.*, vol. 33, no. 9, pp. 1758–1770, Sep. 2015.
[49] H. Haas, "LiFi is a paradigm-shifting 5G technology," *Rev. Phys.*, vol. 3, pp. 26–31, Nov. 2018.
[50] Z. Ghassemlooy, W. Popoola, and S. Rajbhandari, *Optical Wireless Communications: System and Channel Modelling With MATLAB*, 2nd ed. Boca Raton, FL, USA: CRC Press, 2019.
[51] K. Cui, G. Chen, Z. Xu, and R. D. Roberts, "Line-of-sight visible light communication system design and demonstration," in *Proc. 7th Int. Symp. Commun. Syst., Netw. Digit. Signal Process.*, Jul. 2010, pp. 621–625.
[52] F. R. Gfeller and U. Bapst, "Wireless in-house data communication via diffuse infrared radiation," *Proc. IEEE*, vol. 67, no. 11, pp. 1474–1486, Nov. 1979.
[53] J. R. Barry, J. M. Kahn, W. J. Krause, E. A. Lee, and D. G. Messerschmitt, "Simulation of multipath impulse response for indoor wireless optical channels," *IEEE J. Sel. Areas Commun.*, vol. 11, no. 3, pp. 367–379, Apr. 1993.
[54] R. Perez-Jimenez, J. Berges, and M. J. Betancor, "Statistical model for the impulse response on infrared indoor diffuse channels," *Electron. Lett.*, vol. 33, no. 15, pp. 1298–1300, Jul. 1997.
[55] F. J. Lopez-Hernandez, R. Perez-Jimeniz, and A. Santamaria, "Monte Carlo calculation of impulse response on diffuse ir wireless indoor channels," *Electron. Lett.*, vol. 34, no. 12, pp. 1260–1262, Jun. 1998.
[56] B. C. Jeffrey and M. K. Joseph, "Modeling of nondirected wireless infrared channels," *IEEE Trans. Commun.*, vol. 45, no. 10, pp. 1260–1268, Oct. 1997.
[57] J. B. Carruthers and P. Kannan, "Iterative site-based modeling for wireless infrared channels," *IEEE Trans. Antennas Propag.*, vol. 50, no. 5, pp. 759–765, May 2002.
[58] N. Hayasaka and T. Ito, "Channel modeling of nondirected wireless infrared indoor diffuse link," *Electron. Commun. Jpn. I, Commun.*, vol. 90, no. 6, pp. 9–19, 2007.
[59] S. R. Pérez, R. P. Jiménez, F. J. L. Hernández, O. B. G. Hernández, and J. A. andA Alfonso, "Reflection model for calculation of the impulse response on IR-wireless indoor channels using ray-tracing algorithm," *Micro. Opt. Technol. Lett.*, vol. 32, no. 4, pp. 296–300, 2002.
[60] M. Karbalayghareh, F. Miramirkhani, H. B. Eldeeb, R. C. Kizilirmak, S. M. Sait, and M. Uysal, "Channel modelling and performance limits of vehicular visible light communication systems," *IEEE Trans. Veh. Technol.*, vol. 69, no. 7, pp. 6891–6901, Jul. 2020.
[61] A. Al-Kinani, C.-X. Wang, Q. Zhu, Y. Fu, E.-H. M. Aggoune, A. Talib, and N. A. Al-Hasaani, "A 3D non-stationary GBSM for vehicular visible light communication MISO channels," *IEEE Access*, vol. 8, pp. 140333–140347, 2020.
[62] K. Lee, H. Park, and J. R. Barry, "Indoor channel characteristics for visible light communications," *IEEE Commun. Lett.*, vol. 15, no. 2, pp. 217–219, Feb. 2011.
[63] J. M. Kahn and J. R. Barry, "Wireless infrared communications," *Proc. IEEE*, vol. 85, no. 2, pp. 265–298, Feb. 1997.
[64] H. B. Eldeeb, F. Miramirkhani, and M. Uysal, "A path loss model for vehicle-to-vehicle visible light communications," in *Proc. 15th Int. Conf. Telecommun. (ConTEL)*, Jul. 2019, pp. 1–5, doi: 10.1109/ConTEL.2019.8848562.
[65] H. Abuella, F. Miramirkhani, S. Ekin, M. Uysal, and S. Ahmed, "ViLDAR—Visible light sensing-based speed estimation using vehicle headlamps," *IEEE Trans. Veh. Technol.*, vol. 68, no. 11, pp. 10406–10417, Nov. 2019.
[66] W. Viriyasitavat, S.-H. Yu, and H.-M. Tsai, "Short paper: Channel model for visible light communications using off-the-shelf scooter taillight," in *Proc. IEEE Veh. Netw. Conf.*, Dec. 2013, pp. 170–173.
[67] M. Elamassie, M. Karbalayghareh, F. Miramirkhani, R. C. Kizilirmak, and M. Uysal, "Effect of fog and rain on the performance of vehicular visible light communications," in *Proc. IEEE 87th Veh. Technol. Conf. (VTC Spring)*, Jun. 2018, pp. 1–6, doi: 10.1109/VTCSpring.2018.8417738.
[68] A. Al-Kinani, J. Sun, C. Wang, W. Zhang, X. Ge, and H. Haas, "A 2-D non-stationary GBSM for vehicular visible light communication channels," *IEEE Trans. Wireless Commun.*, vol. 17, no. 12, pp. 7981–7992, Dec. 2018.
[69] Q. Chen, C.-X. Wang, J. Sun, W. Zhang, and Q. Zhu, "A non-stationary VVLC MIMO channel model for street corner scenarios," in *Proc. Int. Wireless Commun. Mobile Comput. (IWCMC)*, Jun. 2020, pp. 365–370, doi: 10.1109/IWCMC48107.2020.9148315.
[70] H.-Y. Tseng, Y.-L. Wei, A.-L. Chen, H.-P. Wu, H. Hsu, and H.-M. Tsai, "Characterizing link asymmetry in vehicle-to-vehicle visible light communications," in *Proc. IEEE Veh. Netw. Conf. (VNC)*, Dec. 2015, pp. 88–95.
[71] P. Luo, Z. Ghassemlooy, H. L. Minh, E. Bentley, A. Burton, and X. Tang, "Performance analysis of a car-to-car visible light communication system," *Appl. Opt.*, vol. 54, no. 7, pp. 1696–1706, Mar. 2015.
[72] B. Aly, M. Elamassie, and M. Uysal, "Vehicular VLC channel model for a low-beam headlight transmitter," in *Proc. 17th Int. Symp. Wireless Commun. Syst. (ISWCS)*, Berlin, Germany, Sep. 2021, pp. 1–5.
[73] *Driving Tests*. Accessed: Oct. 5, 2021. [Online]. Available: https://driving-tests.org/beginner-drivers/high-beam-headlights-use/
[74] *Driving Safely*. Accessed: Oct. 5, 2021. [Online]. Available: https://www.idrivesafely.com/defensive-driving/trending/high-beam-and-low-beam-headlights
[75] J. Grubor, S. C. J. Lee, K. D. Langer, T. Koonen, and J. W. Walewski, "Wireless high-speed data transmission with phosphorescent white-light LEDs," in *Proc. 33rd Eur. Conf. Exhib. Opt. Commun.*, Sep. 2007, pp. 1–2.
[76] H. L. Minh, D. O'Brien, G. Faulkner, L. Zeng, K. Lee, D. Jung, and Y. Oh, "High-speed visible light communications using multiple-resonant equalization," *IEEE Photon. Technol. Lett*, vol. 20, no. 14, pp. 1243–1245, Jul. 15, 2008.
[77] J. Vučić, C. Kottke, S. Nerreter, K. Habel, A. Buettner, K.-D. Langer, and J. W. Walewski, "230 Mbit/s via a wireless visible-light link based on OOK modulation of phosphorescent white LEDs," in *Proc. Conf. Opt. Fiber Commun. (OFC/NFOEC) Collocated Nat. Fiber Optic Eng. Conf.*, Mar. 2010, pp. 1–3.
[78] N. Fujimoto and H. Mochizuki, "477 Mbit/s visible light transmission based on OOK-NRZ modulation using a single commercially available visible LED and a practical LED driver with a pre-emphasis circuit," in *Proc. Opt. Fiber Commun. Conf. Expo. Nat. Fiber Optic Eng. Conf. (OFC/NFOEC)*, Mar. 2013, p. JTh2A-73, doi: 10.1364/NFOEC.2013.JTh2A.73.
[79] G. Ntogari, T. Kamalakis, J. Walewski, and T. Sphicopoulos, "Combining illumination dimming based on pulse-width modulation with visible-light communications based on discrete multitone," *J. Opt. Commun. Netw.*, vol. 3, no. 1, pp. 56–65, Jan. 2011.
[80] B. Bai, Z. Xu, and Y. Fan, "Joint LED dimming and high capacity visible light communication by overlapping PPM," in *Proc. 19th Annu. Wireless Opt. Commun. Conf. (WOCC)*, May 2010, pp. 1–5, doi: 10.1109/WOCC.2010.5510410.

[81] M. Noshad and M. Brandt-Pearce, "Application of expurgated PPM to indoor visible light communications—Part II: Access networks," *J. Lightw. Technol.*, vol. 32, no. 5, pp. 883–890, Mar. 1, 2014.

[82] M. Noshad and M. Brandt-Pearce, "Multilevel pulse-position modulation based on balanced incomplete block designs," in *Proc. Global Commun. Conf. (GLOBECOM)*, Dec. 2012, pp. 2930–2935.

[83] R. Mesleh, H. Elgala, and H. Haas, "On the performance of different OFDM based optical wireless communication systems," *IEEE/OSA J. Opt. Commun. Netw.*, vol. 3, no. 8, pp. 620–628, Aug. 2011.

[84] J. Armstrong, "OFDM for optical communications," *J. Lightw. Technol.*, vol. 27, no. 3, pp. 189–204, Feb. 1, 2009.

[85] M. Z. Afgani, H. Haas, H. Elgala, and D. Knipp, "Visible light communication using OFDM," in *Proc. 2nd Int. Conf. Testbeds Res. Infrastruct. Develop. Netw. Communities (TRIDENTCOM)*, Mar. 2006, pp.–134.

[86] J. Armstrong and A. J. Lowery, "Power efficient optical OFDM," *Electron. Lett.*, vol. 42, no. 6, pp. 370–372, Mar. 2006.

[87] H. Elgala, R. Mesleh, H. Haas, and B. Pricope, "OFDM visible light wireless communication based on white LEDs," in *Proc. IEEE Veh. Technol. Conf.*, Apr. 2007, pp. 2185–2189.

[88] D. Tsonev, H. Chun, S. Rajbhandari, J. J. D. McKendry, S. Videv, E. Gu, M. Haji, S. Watson, A. E. Kelly, G. Faulkner, M. D. Dawson, H. Haas, and D. O'Brien, "A 3-Gb/s single-LED OFDM-based wireless VLC Link using a gallium nitride μLED," *IEEE Photon. Technol. Lett*, vol. 26, no. 7, pp. 637–640, Apr. 1, 2014.

[89] R. J. Drost and B. M. Sadler, "Constellation design for color-shift keying using billiards algorithms," in *Proc. IEEE Globecom Workshops*, Dec. 2010, pp. 980–984.

[90] E. Monteiro and S. Hranilovic, "Design and implementation of color-shift keying for visible light communications," *J. Lightw. Technol.*, vol. 32, no. 10, pp. 2053–2060, May 15, 2014.

[91] E. Monteiro and S. Hranilovic, "Constellation design for color-shift keying using interior point methods," in *Proc. IEEE Globecom Workshops*, Dec. 2012, pp. 1224–1228.

[92] V. V. Mai, T. C. Thang, and A. T. Pham, "CSMA/CA-based uplink MAC protocol design and analysis for hybrid VLC/WiFi networks," in *Proc. IEEE Int. Conf. Commun. Workshops (ICC Workshops)*, May 2017, pp. 457–462.

[93] X. Ling, J. Wang, Z. Ding, C. Zhao, and X. Gao, "Efficient OFDMA for LiFi downlink," *J. Lightw. Technol.*, vol. 36, no. 10, pp. 1928–1943, May 15, 2018.

[94] Y. Qiu, S. Chen, H.-H. Chen, and W. Meng, "Visible light communications based on CDMA technology," *IEEE Wireless Commun.*, vol. 25, no. 2, pp. 178–185, Apr. 2018.

[95] Z. Ding, X. Lei, G. K. Karagiannidis, R. Schober, J. Yuan, and V. Bhargava, "A survey on non-orthogonal multiple access for 5G networks: Research challenges and future trends," *IEEE J. Sel. Areas Commun.*, vol. 35, no. 10, pp. 2181–2195, Oct. 2017.

[96] Z. Wei, L. Yang, D. W. K. Ng, J. Yuan, and L. Hanzo, "On the performance gain of NOMA over OMA in uplink communication systems," *IEEE Trans. Commun.*, vol. 68, no. 1, pp. 536–568, Jan. 2020.

[97] A. Lapidoth, S. M. Moser, and M. A. Wigger, "On the capacity of free-space optical intensity channels," *IEEE Trans. Inf. Theory*, vol. 55, no. 10, pp. 4449–4461, Oct. 2009.

[98] J.-B. Wang, Q.-S. Hu, J. Wang, M. Chen, and J.-Y. Wang, "Tight bounds on channel capacity for dimmable visible light communications," *J. Lightw. Technol.*, vol. 31, no. 23, pp. 3771–3779, Dec. 1, 2013.

[99] A. Chaaban, J.-M. Morvan, and M.-S. Alouini, "Free-space optical communications: Capacity bounds, approximations, and a new sphere-packing perspective," *IEEE Trans. Commun.*, vol. 64, no. 3, pp. 1176–1191, Mar. 2016.

[100] L. Yin and H. Haas, "Physical-layer security in multiuser visible light communication networks," *IEEE J. Sel. Areas Commun.*, vol. 36, no. 1, pp. 162–174, Jan. 2018.

[101] H. Marshoud, V. M. Kapinas, G. K. Karagiannidis, and S. Muhaidat, "Non-orthogonal multiple access for visible light communications," *IEEE Photon. Technol. Lett.*, vol. 28, no. 1, pp. 51–54, Jan. 1, 2016.

[102] M. Gast, *802.11ac: A Survival Guide: Wi-Fi at Gigabit and Beyond*. Newton, MA, USA: O'Reilly Media, Jul. 2013.

[103] X. Wang, L. Kong, F. Kong, F. Qiu, M. Xia, S. Arnon, and G. Chen, "Millimeter wave communication: A comprehensive survey," *IEEE Commun. Surveys Tuts.*, vol. 20, no. 3, pp. 1616–1653, 3rd Quart., 2018.

[104] A. Gupta and E. R. K. Jha, "A survey of 5G network: Architecture and emerging technologies," *IEEE Access*, vol. 3, pp. 1206–1232, 2015.

[105] Z. Pi and F. Khan, "An introduction to millimeter-wave mobile broadband systems," *IEEE Commun. Mag.*, vol. 49, no. 6, pp. 101–107, Jun. 2011.

[106] L. Wei, R. Q. Hu, Y. Qian, and G. Wu, "Key elements to enable millimeter wave communications for 5G wireless systems," *IEEE Wireless Commun.*, vol. 21, no. 6, pp. 136–143, Dec. 2014.

[107] A. Goel, *Fleet Telematics: Real-Time Management and Planning of Commercial Vehicle Operations*. New York, NY, USA: Springer, 2008.

[108] S. Bitam and A. Mellouk, *Bio-inspired Routing Protocols for Vehicular Ad-Hoc Networks*. Hoboken, NJ, USA: Wiley, 2017.

[109] T. M. Kurihara. *IEEE 1609.0-2019—IEEE Guide for Wireless Access in Vehicular Environments (WAVE) Architecture*. Accessed: Oct. 2020. [Online]. Available: https://standards.ieee.org/standard/1609_0-2019.html

[110] N. Vivek, P. Sowjanya, B. Sunny, and S. V. Srikanth, "Implementation of IEEE 1609 WAVE/DSRC stack in Linux," in *Proc. IEEE Region 10 Symp. (TENSYMP)*, Jul. 2017, pp. 1–5, doi: 10.1109/TENCONSpring.2017.8070033.

[111] W. Ma, L. Zhang, and Z. Wu, "Location information-aided load balancing design for hybrid LiFi and WiFi networks," in *Proc. Int. Conf. Comput., Netw. Commun. (ICNC)*, Feb. 2019, pp. 413–417.

[112] A. Khreishah, S. Shao, A. Gharaibeh, M. Ayyash, H. Elgala, and N. Ansari, "A hybrid RF-VLC system for energy efficient wireless access," *IEEE Trans. Green Commun. Netw.*, vol. 2, no. 4, pp. 932–944, Jun. 2018.

[113] W. Wu, F. Zhou, and Q. Yang, "Adaptive network resource optimization for heterogeneous VLC/RF wireless networks," *IEEE Trans. Commun.*, vol. 66, no. 11, pp. 5568–5581, Nov. 2018.

[114] Z. Li, S. Shao, A. Khreishah, M. Ayyash, I. Abdalla, H. Elgala, M. Rahaim, and T. Little, "Design and implementation of a hybrid RF-VLC system with bandwidth aggregation," in *Proc. 14th Int. Wireless Commun. Mobile Comput. Conf. (IWCMC)*, Jun. 2018, pp. 194–200.

[115] W. Zhang, L. Chen, X. Chen, Z. Yu, Z. Li, and W. Wang, "Design and realization of indoor VLC-Wi-Fi hybrid network," *J. Commun. Inf. Netw.*, vol. 2, no. 4, pp. 75–87, Dec. 2017.

[116] J. Wang, C. Jiang, H. Zhang, X. Zhang, V. C. M. Leung, and L. Hanzo, "Learning-aided network association for hybrid indoor LiFi-WiFi systems," *IEEE Trans. Veh. Technol.*, vol. 67, no. 4, pp. 3561–3574, Apr. 2018.

[117] X. Wu, M. Safari, and H. Haas, "Access point selection for hybrid Li-Fi and Wi-Fi networks," *IEEE Trans. Commun.*, vol. 65, no. 12, pp. 5375–5385, Dec. 2017.

[118] Y. Wang, D. A. Basnayaka, X. Wu, and H. Haas, "Optimization of load balancing in hybrid LiFi/RF networks," *IEEE Trans. Commun.*, vol. 65, no. 4, pp. 1708–1720, Apr. 2017.

[119] X. Bao, J. Dai, and X. Zhu, "Visible light communications heterogeneous network (VLC-HetNet): New model and protocols for mobile scenario," *Wireless Netw.*, vol. 23, no. 1, pp. 299–309, Jan. 2017.

[120] M. R. Zenaidi, Z. Rezki, M. Abdallah, K. A. Qaraqe, and M.-S. Alouini, "Achievable rate-region of VLC/RF communications with an energy harvesting relay," in *Proc. IEEE Global Commun. Conf. (GLOBECOM)*, Dec. 2017, pp. 1–7, doi: 10.1109/GLOCOM.2017.8254192.

[121] X. Wu and H. Haas, "Access point assignment in hybrid LiFi and WiFi networks in consideration of LiFi channel blockage," in *Proc. IEEE 18th Int. Workshop Signal Process. Adv. Wireless Commun. (SPAWC)*, Jul. 2017, pp. 1–5, doi: 10.1109/SPAWC.2017.8227704.

[122] T. Rakia, H.-C. Yang, F. Gebali, and M.-S. Alouini, "Optimal design of dual-hop VLC/RF communication system with energy harvesting," *IEEE Commun. Lett.*, vol. 20, no. 10, pp. 1979–1982, Oct. 2016.

[123] S. Shao and A. Khreishah, "Delay analysis of unsaturated heterogeneous omnidirectional-directional small cell wireless networks: The case of RF-VLC coexistence," *IEEE Trans. Wireless Commun.*, vol. 15, no. 12, pp. 8406–8421, Dec. 2016.

[124] T. Rakia, H.-C. Yang, F. Gebali, and M.-S. Alouini, "Dual-hop VLC/RF transmission system with energy harvesting relay under delay constraint," in *Proc. IEEE Globecom Workshops (GC Wkshps)*, Dec. 2016, pp. 1–6, doi: 10.1109/GLOCOMW.2016.7848882.

[125] C. Yan, Y. Xu, J. Shen, and J. Chen, "A combination of VLC and WiFi based indoor wireless access network and its handover strategy," in *Proc. IEEE Int. Conf. Ubiquitous Wireless Broadband (ICUWB)*, Oct. 2016, pp. 1–4, doi: 10.1109/ICUWB.2016.7790528.

[126] X. Wu, D. Basnayaka, M. Safari, and H. Haas, "Two-stage access point selection for hybrid VLC and RF networks," in *Proc. IEEE 27th Annu. Int. Symp. Pers., Indoor, Mobile Radio Commun. (PIMRC)*, Sep. 2016, pp. 1–6, doi: 10.1109/PIMRC.2016.7794887.

[127] F. Duvnjak, J. Ozegovic, and A. Kristic, "Heterogeneous Wi-Fi and VLC (RF-optical) wireless access architecture," in *Proc. 23rd Int. Conf. Softw., Telecommun. Comput. Netw. (SoftCOM)*, Sep. 2015, pp. 310–314.

[128] S. Shao, A. Khreishah, M. Ayyash, M. B. Rahaim, H. Elgala, V. Jungnickel, D. Schulz, T. D. C. Little, J. Hilt, and R. Freund, "Design and analysis of a visible-light-communication enhanced WiFi system," *J. Opt. Commun. Netw.*, vol. 7, no. 10, pp. 960–973, Oct. 2015.

[129] F. Wang, Z. Wang, C. Qian, L. Dai, and Z. Yang, "Efficient vertical handover scheme for heterogeneous VLC-RF systems," *J. Opt. Commun. Netw.*, vol. 7, no. 12, pp. 1172–1180, Dec. 2015.

[130] X. Li, R. Zhang, and L. Hanzo, "Cooperative load balancing in hybrid visible light communications and WiFi," *IEEE Trans. Commun.*, vol. 63, no. 4, pp. 1319–1329, Apr. 2015.

[131] Y. Wang and H. Haas, "Dynamic load balancing with handover in hybrid Li-Fi and Wi-Fi networks," *J. Lightw. Technol.*, vol. 33, no. 22, pp. 4671–4682, Nov. 15, 2015.

[132] S. Shao, A. Khreishah, M. B. Rahaim, H. Elgala, M. Ayyash, T. D. C. Little, and J. Wu, "An indoor hybrid WiFi-VLC internet access system," in *Proc. IEEE 11th Int. Conf. Mobile Ad Hoc Sensor Syst.*, Oct. 2014, pp. 569–574.

[133] M. B. Rahaim, A. M. Vegni, and T. D. C. Little, "A hybrid radio frequency and broadcast visible light communication system," in *Proc. IEEE GLOBECOM Workshops (GC Wkshps)*, Dec. 2011, pp. 792–796.

[134] H. Tabassum and E. Hossain, "Coverage and rate analysis for co-existing RF/VLC downlink cellular networks," *IEEE Trans. Wireless Commun.*, vol. 17, no. 4, pp. 2588–2601, Apr. 2018.

[135] H. Zhang, N. Liu, K. Long, J. Cheng, V. C. M. Leung, and L. Hanzo, "Energy efficient subchannel and power allocation for software-defined heterogeneous VLC and RF networks," *IEEE J. Sel. Areas Commun.*, vol. 36, no. 3, pp. 658–670, Mar. 2018.

[136] M. Kashef, M. Abdallah, and N. Al-Dhahir, "Transmit power optimization for a hybrid PLC/VLC/RF communication system," *IEEE Trans. Green Commun. Netw.*, vol. 2, no. 1, pp. 234–245, Mar. 2018.

[137] M. Kafafy, Y. Fahmy, M. Abdallah, and M. Khairy, "Power efficient downlink resource allocation for hybrid RF/VLC wireless networks," in *Proc. IEEE Wireless Commun. Netw. Conf. (WCNC)*, Mar. 2017, pp. 1–6, doi: 10.1109/WCNC.2017.7925892.

[138] M. F. Marzban, M. Kashef, M. Abdallah, and M. Khairy, "Beamforming and power allocation for physical-layer security in hybrid RF/VLC wireless networks," in *Proc. IWCMC*, Jun. 2017, pp. 258–263.

[139] M. Kashef, M. Ismail, M. Abdallah, K. A. Qaraqe, and E. Serpedin, "Energy efficient resource allocation for mixed RF/VLC heterogeneous wireless networks," *IEEE J. Sel. Areas Commun.*, vol. 34, no. 4, pp. 883–893, Apr. 2016.

[140] M. Kashef, M. Abdallah, N. Al-Dhahir, and K. Qaraqe, "On the impact of PLC backhauling in multi-user hybrid VLC/RF communication systems," in *Proc. IEEE Global Commun. Conf. (GLOBECOM)*, Dec. 2016, pp. 1–6, doi: 10.1109/GLOCOM.2016.7842055.

[141] M. Kashef, A. Torky, M. Abdallah, N. Al-Dhahir, and K. Qaraqe, "On the achievable rate of a hybrid PLC/VLC/RF communication system," in *Proc. IEEE Global Commun. Conf. (GLOBECOM)*, Dec. 201, pp. 1–6, doi: 10.1109/GLOCOM.2015.7417378.

[142] I. Stefan and H. Haas, "Hybrid visible light and radio frequency communication systems," in *Proc. IEEE 80th Veh. Technol. Conf. (VTC-Fall)*, Sep. 2014, pp. 1–5, doi: 10.1109/VTCFall.2014.6965999.

[143] M. Obeed, A. M. Salhab, S. A. Zummo, and M.-S. Alouini, "Joint optimization of power allocation and load balancing for hybrid VLC/RF networks," *J. Opt. Commun. Netw.*, vol. 10, no. 5, pp. 553–562, May 2018.

[144] D. A. Basnayaka and H. Haas, "Hybrid RF and VLC systems: Improving user data rate performance of VLC systems," in *Proc. IEEE 81st Veh. Technol. Conf. (VTC Spring)*, May 2015, pp. 1–5, doi: 10.1109/VTCSpring.2015.7145863.

[145] Y. Wang, X. Wu, and H. Haas, "Distributed load balancing for Internet of Things by using li-fi and RF hybrid network," in *Proc. IEEE 26th Annu. Int. Symp. Pers., Indoor, Mobile Radio Commun. (PIMRC)*, Aug. 2015, pp. 1289–1294.

[146] M. Obeed, A. M. Salhab, S. A. Zummo, and M.-S. Alouini, "Joint load balancing and power allocation for hybrid VLC/RF networks," in *Proc. IEEE Global Commun. Conf. (GLOBECOM)*, Singapore, Dec. 2017, pp. 1–6, doi: 10.1109/GLOCOM.2017.8254783.

[147] A. Bazzi, B. M. Masini, A. Zanella, and A. Calisti, "Visible light communications as a complementary technology for the Internet of Vehicles," *Comput. Commun.*, vol. 93, pp. 39–51, Nov. 2016.

[148] B. Turan, O. Narmanlioglu, S. C. Ergen, and M. Uysal, "Physical layer implementation of standard compliant vehicular VLC," in *Proc. IEEE 84th Veh. Technol. Conf. (VTC-Fall)*, Sep. 2016, pp. 1–5, doi: 10.1109/VTCFall.2016.7881165.

[149] C.-H. Yeh, Y.-L. Liu, and C.-W. Chow, "Real-time white-light phosphor-LED visible light communication (VLC) with compact size," *Opt. Exp.*, vol. 21, no. 22, pp. 26192–26197, 2013.

[150] L. Cheng, W. Viriyasitavat, M. Boban, and H.-M. Tsai, "Comparison of radio frequency and visible light propagation channels for vehicular communications," *IEEE Access*, vol. 6, pp. 2634–2644, 2018.

[151] A. Perrig, J. Stankovic, and D. Wagner, "Security in wireless sensor networks," *Commun. ACM*, vol. 47, no. 6, pp. 53–57, Jun. 2004.

[152] J. Jun. and M. L. Sichitiu, "The nominal capacity of wireless mesh networks," *IEEE Wireless Commun.*, vol. 10, no. 5, pp. 8–14, Oct. 2003.

[153] A. Mostafa and L. Lampe, "Physical-layer security for indoor visible light communications," in *Proc. IEEE Int. Conf. Commun. (ICC)*, Jun. 2014, pp. 3342–3347.

[154] I. Din and H. Kim, "Energy-efficient brightness control and data transmission for visible light communication," *IEEE Photon. Technol. Lett.*, vol. 26, no. 8, pp. 781–784, Apr. 15, 2014.

[155] I. Stefan, H. Burchardt, and H. Haas, "Area spectral efficiency performance comparison between VLC and RF femtocell networks," in *Proc. IEEE Int. Conf. Commun. (ICC)*, Jun. 2013, pp. 3825–3829.

[156] S. Fuada, A. P. Putra, Y. Aska, and T. Adiono, "A first approach to design mobility function and noise filter in VLC system utilizing low-cost analog circuits," *Int. J. Recent Contrib. Eng., Sci.*, vol. 5, no. 2, pp. 14–30, 2017.

[157] S. Ayub, S. Kariyawasam, M. Honary, and B. Honary, "A practical approach of VLC architecture for smart city," in *Proc. Loughborough Antennas Propag. Conf. (LAPC)*, Nov. 2013, pp. 106–111.

[158] M. T. Alresheedi, A. T. Hussein, and J. M. H. Elmirghani, "Uplink design in VLC systems with IR sources and beam steering," *IET Commun.*, vol. 11, no. 3, pp. 311–317, Feb. 2017.

[159] O. R. Banda-Sayco, G. R. Laura-Choquehuanca, M. A. Zea-Vargas, S. A. Javier-Quispe, and P. L. Pari-Pinto, "Development of an indoor hybrid PLC/VLC/IR communication system based on TCP/IP model," in *Proc. IEEE Congreso Bienal de Argentina (ARGENCON)*, Dec. 2020, pp. 1–7, doi: 10.1109/ARGENCON49523.2020.9505441.

[160] S. Lou, C. Gong, N. Wu, and Z. Xu, "Joint dimming and communication design for visible light communication," *IEEE Commun. Lett.*, vol. 21, no. 5, pp. 1043–1046, May 2017.

[161] A. M. Vegni and T. D. C. Little, "Handover in VLC systems with cooperating mobile devices," in *Proc. Int. Conf. Comput., Netw. Commun. (ICNC)*, Jan. 2012, pp. 126–130.

[162] A. Vavoulas, H. G. Sandalidis, T. A. Tsiftsis, and N. Vaiopoulos, "Coverage aspects of indoor VLC networks," *J. Lightw. Technol.*, vol. 33, no. 23, pp. 4915–4921, Dec.1, 2015.

[163] Y. Xiang, M. Zhang, M. Kavehrad, C. Sakib, M. Liu, J. Wu, and X. Tang, "Human shadowing effect on indoor visible light communications channel characteristics," *Opt. Eng.*, vol. 53, Aug. 2014, Art. no. 086113.

[164] Z. Liao, L. Yang, J. Chen, H.-C. Yang, and M.-S. Alouini, "Physical layer security for dual-hop VLC/RF communication systems," *IEEE Commun. Lett.*, vol. 22, no. 12, pp. 2603–2606, Oct. 2018.

[165] J. Al-Khori, G. Nauryzbayev, M. M. Abdallah, and M. Hamdi, "Secrecy performance of decode-and-forward based hybrid RF/VLC relaying systems," *IEEE Access*, vol. 7, pp. 10844–10856, 2019.

[166] C. Zhang, J. Ye, J. Shi, G. Pan, Z. Li, and Z. Ding, "Cooperative hybrid VLC-RF systems for WSNs," in *Proc. Asia–Pacific Signal Inf. Process. Assoc. Annu. Summit Conf. (APSIPA ASC)*, Nov. 2018, pp. 436–441.

[167] M. Namdar, A. Basgumus, T. Tsiftsis, and A. Altuncu, "Outage and BER performances of indoor relay-assisted hybrid RF/VLC systems," *IET Commun.*, vol. 12, no. 17, pp. 2104–2109, Oct. 2018.

[168] C. Zhang, J. Ye, G. Pan, and Z. Ding, "Cooperative hybrid VLC-RF systems with spatially random terminals," *IEEE Trans. Commun.*, vol. 66, no. 12, pp. 6396–6408, Dec. 2018.

[169] Y. Han, X. Zhou, L. Yang, and S. Li, "A bipartite matching based user pairing scheme for hybrid VLC-RF noma systems," in *Proc. Int. Conf. Comput., Netw. Commun. (ICNC)*, Mar. 2018, pp. 480–485.

[170] Z. Du, C. Wang, Y. Sun, and G. Wu, "Context-aware indoor VLC/RF heterogeneous network selection: Reinforcement learning with knowledge transfer," *IEEE Access*, vol. 6, pp. 33275–33284, 2018.

[171] J. Al-Khori, G. Nauryzbayev, M. M. Abdallah, and M. Hamdi, "Joint beamforming design and power minimization for friendly jamming relaying hybrid RF/VLC systems," *IEEE Photon. J.*, vol. 11, no. 2, pp. 1–18, Apr. 2019, doi: 10.1109/JPHOT.2019.2905896.
[172] G. Pan, H. Lei, Z. Ding, and Q. Ni, "3-D hybrid VLC-RF indoor IoT systems with light energy harvesting," *IEEE Trans. Green Commun. Netw.*, vol. 3, no. 3, pp. 853–865, Sep. 2019.
[173] A. Vats, M. Aggarwal, and S. Ahuja, "Outage analysis of AF relayed hybrid VLC-RF communication system for E-health applications," in *Proc. Int. Conf. Comput. Commun. Autom. (ICCCA)*, May 2017, pp. 1401–1405.
[174] F. Delgado-Rajo, A. Melian-Segura, V. Guerra, R. Perez-Jimenez, and D. Sanchez-Rodriguez, "Hybrid RF/VLC network architecture for the Internet of Things," *Sensors*, vol. 20, no. 2, p. 478, Jan. 2020, doi: 10.3390/s20020478.
[175] V. K. Papanikolaou, P. D. Diamantoulakis, Z. Ding, S. Muhaidat, and G. K. Karagiannidis, "Hybrid VLC/RF networks with non-orthogonal multiple access," in *Proc. IEEE Global Commun. Conf. (GLOBECOM)*, Dec. 2018, pp. 1–6, doi: 10.1109/GLOCOM.2018.8647397.
[176] F. Jin, R. Zhang, and L. Hanzo, "Resource allocation under delay-guarantee constraints for heterogeneous visible-light and RF femtocell," *IEEE Trans. Wireless Commun.*, vol. 14, no. 2, pp. 1020–1034, Feb. 2015.
[177] Y. C. Hsiao, C. M. Chen, and C. Lin, "Energy efficiency maximization in multi-user miso mixed RF/VLC heterogeneous cellular networks," in *Proc. 15th Annu. IEEE Int. Conf. Sens., Commun., Netw. (SECON)*, Jun. 2018, pp. 1–9, doi: 10.1109/SAHCN.2018.8397105.
[178] M. Z. Chowdhury, M. T. Hossan, M. K. Hasan, and Y. M. Jang, "Integrated RF/optical wireless networks for improving QoS in indoor and transportation applications," *Wireless Pers. Commun.*, vol. 107, no. 3, pp. 1401–1430, Aug. 2019.
[179] M. I. Petkovic, M. Narandzic, D. Vukobratovic, and A. Cvetkovic, "Mixed RF-VLC relaying system with radio-access diversity," in *Proc. 28th Wireless Opt. Commun. Conf. (WOCC)*, May 2019, pp. 1–5, doi: 10.1109/WOCC.2019.8770633.
[180] J. Al-khori, G. Nauryzbayev, M. Abdallah, and M. Hamdi, "Physical layer security for hybrid RF/VLC DF relaying systems," in *Proc. IEEE 88th Veh. Technol. Conf. (VTC-Fall)*, Aug. 2018, pp. 1–6, doi: 10.1109/VTCFall.2018.8690700.
[181] Y. Xiao, P. D. Diamantoulakis, Z. Fang, L. Hao, Z. Ma, and G. K. Karagiannidis, "Cooperative hybrid VLC/RF systems with SLIPT," *IEEE Trans. Commun.*, vol. 69, no. 4, pp. 2532–2545, Apr. 2021.
[182] H. Peng, Q. Li, A. Pandharipande, X. Ge, and J. Zhang, "End-to-end performance optimization of a dual-hop hybrid VLC/RF IoT system based on SLIPT," *IEEE Internet Things J.*, early access, May 14, 2021, doi: 10.1109/JIOT.2021.3080518.
[183] M. Hammouda, S. Akln, A. M. Vegni, H. Haas, and J. Peissig, "Hybrid RF/LC systems under QoS constraints," in *Proc. 25th Int. Conf. Telecommun. (ICT)*, Jun. 2018, pp. 312–318.
[184] X. Zhou, S. Li, H. Zhang, Y. Wen, Y. Han, and D. Yuan, "Cooperative NOMA based VLC/RF system with simultaneous wireless information and power transfer," in *Proc. IEEE/CIC Int. Conf. Commun. China (ICCC)*, Aug. 2018, pp. 100–105.
[185] G. Pan, J. Ye, and Z. Ding, "Secrecy outage analysis of hybrid VLC-RF systems with light energy harvesting," in *Proc. IEEE 18th Int. Workshop Signal Process. Adv. Wireless Commun. (SPAWC)*, Jul. 2017, pp. 1–5, doi: 10.1109/SPAWC.2017.8227715.
[186] G. Pan, J. Ye, and Z. Ding, "Secure hybrid VLC-RF systems with light energy harvesting," *IEEE Trans. Commun.*, vol. 65, no. 10, pp. 4348–4359, Oct. 2017.
[187] A. Vats, M. Aggarwal, S. Ahuja, and S. Vashisth, "Hybrid VLC-RF system for real time health care applications," in *Advances in Optical Science and Engineering*, I. Bhattacharya, S. Chakrabarti, H. S. Reehal, and V. Lakshminarayanan, Eds. Singapore: Springer, 2017, pp. 347–353.
[188] A. Vats, M. Aggarwal, and S. Ahuja, "Modeling and outage analysis of multiple relayed hybrid VLC-RF system," in *Proc. Int. Conf. Comput., Commun. Electron. (Comptelix)*, Jul. 2017, pp. 254–259.
[189] M. B. Rahaim and T. D. C. Little, "Toward practical integration of dual-use VLC within 5G networks," *IEEE Wireless Commun.*, vol. 22, no. 4, pp. 97–103, Aug. 2015.
[190] T. D. C. Little and M. Rahaim, "Network topologies for mixed RF-VLC HetNets," in *Proc. IEEE Summer Topicals Meeting Ser. (SUM)*, Jul. 2015, pp. 163–164.
[191] S. I. Hussain, M. M. Abdallah, and K. A. Qaraqe, "Hybrid radio-visible light downlink performance in RF sensitive indoor environments," in *Proc. 6th Int. Symp. Commun., Control Signal Process. (ISCCSP)*, May 2014, pp. 81–84.
[192] Z.-Y. Wu, M. Ismail, E. Serpedin, and J. Wang, "Data-driven link assignment with QoS guarantee in mobile RF-optical HetNet of things," *IEEE Internet Things J.*, vol. 7, no. 6, pp. 5088–5102, Jun. 2020.
[193] A. M. Alenezi and K. A. Hamdi, "Reinforcement learning approach for hybrid WiFi-VLC networks," in *Proc. IEEE 91st Veh. Technol. Conf. (VTC-Spring)*, May 2020, pp. 1–5, doi: 10.1109/VTC2020-Spring48590.2020.9128892.
[194] A. Adnan-Qidan, M. Morales-Cespedes, and A. G. Armada, "Load balancing in hybrid VLC and RF networks based on blind interference alignment," *IEEE Access*, vol. 8, pp. 72512–72527, 2020.
[195] A. Al Hammadi, P. C. Sofotasios, S. Muhaidat, M. Al-Qutayri, and H. Elgala, "Non-orthogonal multiple access for hybrid VLC-RF networks with imperfect channel state information," *IEEE Trans. Veh. Technol.*, vol. 70, no. 1, pp. 398–411, Jan. 2021.
[196] J. Chen and Z. Wang, "Coordination game theory-based adaptive topology control for hybrid VLC/RF VANET," *IEEE Trans. Commun.*, vol. 69, no. 8, pp. 5312–5324, Aug. 2021, doi: 10.1109/TCOMM.2021.3077950.
[197] S. Aboagye, T. M. N. Ngatched, O. A. Dobre, and A. Ibrahim, "Joint access point assignment and power allocation in multi-tier hybrid RF/VLC HetNets," *IEEE Trans. Wireless Commun.*, vol. 20, no. 10, pp. 6329–6342, Oct. 2021, doi: 10.1109/TWC.2021.3073424.
[198] R. Arshad and L. Lampe, "Stochastic geometry analysis of user mobility in RF/VLC hybrid networks," *IEEE Trans. Wireless Commun.*, vol. 20, no. 11, pp. 7404–7419, Nov. 2021, doi: 10.1109/TWC.2021.3083604.
[199] V. K. Papanikolaou, P. D. Diamantoulakis, and G. K. Karagiannidis, "User grouping for hybrid VLC/RF networks with NOMA: A coalitional game approach," *IEEE Access*, vol. 7, pp. 103299–103309, 2019.
[200] H. Tran, G. Kaddoum, P. D. Diamantoulakis, C. Abou-Rjeily, and G. K. Karagiannidis, "Ultra-small cell networks with collaborative RF and lightwave power transfer," *IEEE Trans. Commun.*, vol. 67, no. 9, pp. 6243–6255, Sep. 2019.
[201] H. Yang, A. Alphones, W. Zhong, C. Chen, and X. Xie, "Learning-based energy-efficient resource management by heterogeneous RF/VLC for ultra-reliable low-latency industrial IoT networks," *IEEE Trans. Ind. Informat.*, vol. 16, no. 8, pp. 5565–5576, Aug. 2020.
[202] Z. Becvar, M. Najla, and P. Mach, "Selection between radio frequency and visible light communication bands for D2D," in *Proc. IEEE 87th Veh. Technol. Conf. (VTC Spring)*, Jun. 2018, pp. 1–7, doi: 10.1109/VTCSpring.2018.8417703.
[203] P. Mach, Z. Becvar, M. Najla, and S. Zvanovec, "Combination of visible light and radio frequency bands for device-to-device communication," in *Proc. IEEE 28th Annu. Int. Symp. Pers., Indoor, Mobile Radio Commun. (PIMRC)*, Oct. 2017, pp. 1–7, doi: 10.1109/PIMRC.2017.8292746.
[204] Y. S. M. Pratama and K. W. Choi, "Bandwidth aggregation protocol and throughput-optimal scheduler for hybrid RF and visible light communication systems," *IEEE Access*, vol. 6, pp. 32173–32187, 2018.
[205] X. Bao, W. Adjardjah, A. Okine, W. Zhang, and N. Bao, "Vertical handover scheme for enhancing the QoE in VLC heterogeneous networks," in *Proc. IEEE/CIC Int. Conf. Commun. China (ICCC)*, Aug. 2018, pp. 437–442.
[206] X. Wu, M. Safari, and H. Haas, "Joint optimisation of load balancing and handover for hybrid LiFi and WiFi networks," in *Proc. IEEE Wireless Commun. Netw. Conf. (WCNC)*, Mar. 2017, pp. 1–5, doi: 10.1109/WCNC.2017.7925839.
[207] M. S. Saud, H. Chowdhury, and M. Katz, "Heterogeneous software-defined networks: Implementation of a hybrid radio-optical wireless network," in *Proc. IEEE Wireless Commun. Netw. Conf. (WCNC)*, Mar. 2017, pp. 1–6, doi: 10.1109/WCNC.2017.7925873.
[208] M. S. Saud and M. Katz, "Implementation of a hybrid optical-RF wireless network with fast network handover," in *Proc. 23th Eur. Wireless Conf.*, May 2017, pp. 1–6, doi: 10.1109/WCNC.2017.7925873.
[209] L. Li, Y. Zhang, B. Fan, and H. Tian, "Mobility-aware load balancing scheme in hybrid VLC-LTE networks," *IEEE Commun. Lett.*, vol. 20, no. 11, pp. 2276–2279, Nov. 2016.
[210] S. Liang, H. Tian, B. Fan, and R. Bai, "A novel vertical handover algorithm in a hybrid visible light communication and LTE system," in *Proc. IEEE 82nd Veh. Technol. Conf. (VTC-Fall)*, Sep. 2015, pp. 1–5, doi: 10.1109/VTCFall.2015.7390808.

[211] M. Amjad, H. K. Qureshi, S. A. Hassan, A. Ahmad, and S. Jangsher, "Optimization of MAC frame slots and power in hybrid VLC/RF networks," *IEEE Access*, vol. 8, pp. 21653–21664, 2020.

[212] J. Kong, M. Ismail, E. Serpedin, and K. A. Qaraqe, "Energy efficient optimization of base station intensities for hybrid RF/VLC networks," *IEEE Trans. Wireless Commun.*, vol. 18, no. 8, pp. 4171–4183, Aug. 2019.

[213] M. Amjad, H. K. Qureshi, and S. Jangsher, "Optimization of slot allocation in hybrid VLC/RF networks for throughput maximization," in *Proc. Wireless Days (WD)*, Apr. 2019, pp. 1–4, doi: 10.1109/WD.2019.8734271.

[214] S. Aboagye, A. Ibrahim, T. M. N. Ngatched, and O. A. Dobre, "VLC in future heterogeneous networks: Energy– and spectral–efficiency optimization," in *Proc. IEEE Int. Conf. Commun. (ICC)*, Jun. 2020, pp. 1–7, doi: 10.1109/ICC40277.2020.9148909.

[215] Y. Wang, X. Wu, and H. Haas, "Load balancing game with shadowing effect for indoor hybrid LiFi/RF networks," *IEEE Trans. Wireless Commun.*, vol. 16, no. 4, pp. 2366–2378, Apr. 2017.

[216] Z. Zeng, M. D. Soltani, Y. Wang, X. Wu, and H. Haas, "Realistic indoor hybrid WiFi and OFDMA-based LiFi networks," *IEEE Trans. Commun.*, vol. 68, no. 5, pp. 2978–2991, May 2020.

[217] J. Chen and Z. Wang, "Topology control in hybrid VLC/RF vehicular ad-hoc network," *IEEE Trans. Wireless Commun.*, vol. 19, no. 3, pp. 1965–1976, Mar. 2020.

[218] Q. Gao, S. Hu, C. Gong, and Z. Xu, "Modulation designs for visible light communications with signal-dependent noise," *J. Lightw. Technol.*, vol. 34, no. 23, pp. 5516–5525, Dec. 1, 2016.

[219] C. Gong, S. Li, Q. Gao, and Z. Xu, "Power and rate optimization for visible light communication system with lighting constraints," *IEEE Trans. Signal Process.*, vol. 63, no. 16, pp. 4245–4256, Aug. 2015.

[220] J. Gancarz, H. Elgala, and T. D. C. Little, "Impact of lighting requirements on VLC systems," *IEEE Commun. Mag.*, vol. 51, no. 12, pp. 34–41, Dec. 2013.

[221] B. Liu, C. Gong, and Z. Xu, "Correlation analysis and path loss prediction for optical wireless scattering communication over broad spectra," in *Proc. IEEE Int. Conf. Commun. (ICC)*, May 2018, pp. 1–6, doi: 10.1109/ICC.2018.8422554.

[222] V. K. Papanikolaou, P. D. Diamantoulakis, P. C. Sofotasios, S. Muhaidat, and G. K. Karagiannidis, "On optimal resource allocation for hybrid VLC/RF networks with common backhaul," *IEEE Trans. Cognit. Commun. Netw.*, vol. 6, no. 1, pp. 352–365, Mar. 2020.

[223] K. Küçük, D. L. Msongaleli, O. Akbulut, A. Kavak, and C. Bayılmış, "Self-adaptive medium access control protocol for aggregated VLC–RF wireless networks," *Opt. Commun.*, vol. 488, Jun. 2021, Art. no. 126837, doi: 10.1016/j.optcom.2021.126837.

[224] X. Bao, X. Zhu, T. Song, and Y. Ou, "Protocol design and capacity analysis in hybrid network of visible light communication and OFDMA systems," *IEEE Trans. Veh. Technol.*, vol. 63, no. 4, pp. 1770–1778, May 2014.

[225] G. Nauryzbayev, M. Abdallah, I. S. Ansari, N. Al-Dhahir, and K. Qaraqe, "Outage of cognitive electric vehicle networks over mixed RF/VLC channels with signal-dependent noise and imperfect CSI," *IEEE Trans. Veh. Technol.*, vol. 69, no. 6, pp. 6828–6832, Jun. 2020.

[226] E. M. H. Abouzohri and M. M. Abdallah, "Performance of hybrid cognitive RF/VLC systems in Vehicle-to-Vehicle communications," in *Proc. IEEE Int. Conf. Informat., IoT, Enabling Technol. (ICIoT)*, Feb. 2020, pp. 429–434.

[227] M. Obeed, H. Dahrouj, A. M. Salhab, A. Chaaban, S. A. Zummo, and M.-S. Alouini, "Power allocation and link selection for multicell cooperative NOMA hybrid VLC/RF systems," *IEEE Commun. Lett.*, vol. 25, no. 2, pp. 560–564, Feb. 2021.

[228] A. Ashimbayeva, N. Kalikulov, and R. C. Kizilirmak, "Hard and soft switching for indoor hybrid VLC/RF systems," in *Proc. IEEE 11th Int. Conf. Appl. Inf. Commun. Technol. (AICT)*, Sep. 2017, pp. 1–5, doi: 10.1109/ICAICT.2017.8687098.

[229] W. Wu, F. Zhou, and Q. Yang, "Dynamic network resource optimization in hybrid VLC and radio frequency networks," in *Proc. Int. Conf. Sel. Topics Mobile Wireless Netw. (MoWNeT)*, May 2017, pp. 1–7, doi: 10.1109/MoWNet.2017.8045951.

[230] J. Chen, Z. Wang, and T. Mao, "Resource management for hybrid RF/VLC V2I wireless communication system," *IEEE Commun. Lett.*, vol. 24, no. 4, pp. 868–871, Apr. 2020.

[231] J. Al-khori, G. Nauryzbayev, M. Abdallah, and M. Hamdi, "Secrecy capacity of hybrid RF/VLC DF relaying networks with jamming," in *Proc. Int. Conf. Comput., Netw. Commun. (ICNC)*, Feb. 2019, pp. 67–72.

[232] G. Pan, H. Lei, Z. Ding, and Q. Ni, "On 3-D hybrid VLC-RF systems with light energy harvesting and OMA scheme over RF links," in *Proc. IEEE Global Commun. Conf. (GLOBECOM)*, Dec. 2017, pp. 1–6, doi: 10.1109/GLOCOM.2017.8254799.

[233] A. Kumar, P. Garg, and A. Gupta, "PLS analysis in an indoor heterogeneous VLC/RF network based on known and unknown CSI," *IEEE Syst. J.*, vol. 15, no. 1, pp. 68–76, Mar. 2021.

[234] M. Hammouda, S. Akin, A. M. Vegni, H. Haas, and J. Peissig, "Link selection in hybrid RF/VLC systems under statistical queueing constraints," *IEEE Trans. Wireless Commun.*, vol. 17, no. 4, pp. 2738–2754, Apr. 2018.

[235] H. Zhao, Y. Liu, A. Sultan-Salem, and M.-S. Alouini, "A simple evaluation for the secrecy outage probability over generalized-K fading channels," *IEEE Commun. Lett.*, vol. 23, no. 9, pp. 1479–1483, Sep. 2019.

[236] M. Bloch, J. Barros, M. R. D. Rodrigues, and S. W. McLaughlin, "Wireless information-theoretic security," *IEEE Trans. Inf. Theory*, vol. 54, no. 6, pp. 2515–2534, Jun. 2008.

[237] A. McBride, B. Derveni, J. Proko, P. Kamsula, H. Chowdhury, T. Hanninen, J. Mäkelä, and M. Katz, "Transitioning to hybrid radio/optical networks: Development of a flexible visible light communication testbed," in *Proc. 1st Int. Conf. 5G Ubiquitous Connectivity*, Nov. 2014, pp. 222–228.

[238] H. Elgala, R. Mesleh, and H. Haas, "Indoor broadcasting via white LEDs and OFDM," *IEEE Trans. Consum. Electron.*, vol. 55, no. 3, pp. 1127–1134, Aug. 2009.

[239] J. Vučić, L. Fernández, C. Kottke, K. Habel, and K. Langer, "Implementation of a real-time DMT-based 100 Mbit/s visible-light link," in *Proc. 36th Eur. Conf. Exhibit. Opt. Commun.*, Sep. 2010, pp. 1–5, doi: 10.1109/ECOC.2010.5621171.

[240] S. Fuada, T. Adiono, A. P. Putra, and Y. Aska, "LED driver design for indoor lighting and low-rate data transmission purpose," *Optik*, vol. 156, pp. 847–856, Mar. 2018.

[241] B. Aly, M. Elamassie, H. B. Eldeeb, and M. Uysal, "Experimental investigation of lens combinations on the performance of vehicular VLC," in *Proc. 12th Int. Symp. Commun. Syst., Netw. Digit. Signal Process. (CSNDSP)*, Jul. 2020, pp. 1–5, doi: 10.1109/CSNDSP49049.2020.9249597.

[242] B. Aly, M. Elamassie, and M. Uysal, "Experimental characterization of multi-hop vehicular VLC systems," in *Proc. IEEE 32nd Annu. Int. Symp. Pers., Indoor Mobile Radio Commun. (PIMRC)*, Helsinki, Finland, Sep. 2021, pp. 1–6.

[243] H. B. Eldeeb, S. M. Sait, and M. Uysal, "Visible light communication for connected vehicles: How to achieve the omnidirectional coverage?" *IEEE Access*, vol. 9, pp. 103885–103905, 2021.

[244] A. Aldalbahi, M. Rahaim, A. Khreishah, M. Ayyash, and T. D. C. Little, "Visible light communication module: An open source extension to the ns3 network simulator with real system validation," *IEEE Access*, vol. 5, pp. 22144–22158, 2017.

[245] C. Liu, C. Guo, Y. Yang, M. Chen, H. V. Poor, and S. Cui, "Optimization of user selection and bandwidth allocation for federated learning in VLC/RF systems," in *Proc. IEEE Wireless Commun. Netw. Conf. (WCNC)*, Mar. 2021, pp. 1–6, doi: 10.1109/WCNC49053.2021.9417407.

[246] E. Zadobrischi, "System prototype proposed for vehicle communications based on VLC-RF technologies adaptable on infrastructure," in *Proc. Int. Conf. Develop. Appl. Syst. (DAS)*, May 2020, pp. 78–83.

[247] S. Ucar, S. C. Ergen, and O. Ozkasap, "IEEE 802.11p and visible light hybrid communication based secure autonomous platoon," *IEEE Trans. Veh. Technol.*, vol. 67, no. 9, pp. 8667–8681, Sep. 2018.

[248] G. Nauryzbayev, M. Abdallah, and N. Al-Dhahir, "Outage analysis of cognitive electric vehicular networks over mixed RF/VLC channels," *IEEE Trans. Cognit. Commun. Netw.*, vol. 6, no. 3, pp. 1096–1107, Sep. 2020.

[249] F. Wu, L. Chen, and W. Wang, "HRO-OFDM scheme design and optimization for a hybrid RF/VLC baseband system," *IEEE Photon. J.*, vol. 9, no. 5, pp. 1–13, Oct. 2017.

[250] A. Al Hammadi, S. Muhaidat, P. C. Sofotasios, and M. al Qutayri, "A robust and energy efficient NOMA-enabled hybrid VLC/RF wireless network," in *Proc. IEEE Wireless Commun. Netw. Conf. (WCNC)*, Apr. 2019, pp. 1–6, doi: 10.1109/WCNC.2019.8885577.

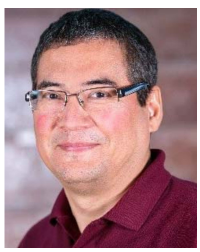
[251] M. Obeed, H. Dahrouj, A. M. Salhab, S. A. Zummo, and M.-S. Alouini, "User pairing, link selection and power allocation for cooperative NOMA hybrid VLC/RF systems," 2019, *arXiv:1908.10803*.

HISHAM ABUELLA (Student Member, IEEE) received the B.Sc. degree in communications and electronics engineering from Ain Shams University, Cairo, Egypt, in 2013. In Fall 2014, he joined Istanbul Sehir University as a Research Assistant for his M.Sc. degree in electronics and computer engineering at Istanbul, Turkey. He joined Oklahoma State University as a Graduate Research Assistant to pursue his Ph.D. study with the School of Electrical and Computer Engineering, in Spring 2017, and worked with Dr. Sabit Ekin at the Wireless Communications Research Laboratory (WCRL). Finally, he defended his Ph.D. dissertation and graduated in May 2021. He worked as a Digital System Design Engineer at Varkon Semiconductor Company, Cairo, for one year. He has recently joined Qualcomm Inc., as a Senior Modem Systems Engineer. His research interests include visible light communication, wireless communication systems design using SDRs, visible light sensing applications, DSP and machine learning for wireless communication, and hybrid RF/VLC systems performance analyses.

MOHAMMED ELAMASSIE (Senior Member, IEEE) received the B.Sc. and M.Sc. degrees in electrical engineering from the Islamic University of Gaza, Gaza Strip, Palestine, in 2006 and 2011, respectively, and the Ph.D. degree in electrical and electronics engineering from Özyeğin University, Istanbul, Turkey, in June 2020. Subsequently employed by Özyeğin University as a Research Associate. His current research interests include visible light communications, optical turbulence, underwater acoustic communication, diversity techniques for fading channels, performance analysis over fading channels and time-varying channels, channel estimation and equalization, and multi-input multi-output (MIMO) communications. On these topics, he has authored more than 28 Publications (journals and conferences) and received more than 300 Google Scholar Citations, with an H-index of 10. His major achievements include Best Paper Award in IEEE International Black Sea Conference on Communications and Networking, Sochi, Russia, in 2019. He also received the 2020 IEEE Turkey Doctoral Thesis Award. He is a Review Editor on the Editorial Board of Non-Conventional Communications and Networks (specialty section of *Frontiers in Communications and Networks*). He is also a Review Editor on the Editorial Board of Wireless Communications (specialty section of *Frontiers in Communications and Networks*). He as well has served as a reviewer for the Institute of Electrical and Electronics Engineers (IEEE) and the Optical Society of America (OSA) journals and conferences.

MURAT UYSAL (Fellow, IEEE) received the B.Sc. and M.Sc. degrees in electronics and communication engineering from Istanbul Technical University, in 1995 and 1998, respectively, and the Ph.D. degree in electrical engineering from Texas A&M University, in 2001. He is currently a Full Professor and the Chair of the Department of Electrical and Electronics Engineering, Özyeğin University, Istanbul, Turkey. He also serves as the Founding Director for the Center of Excellence in Optical Wireless Communication Technologies (OKATEM). Prior to joining Özyeğin University, he was a Tenured Associate Professor at the University of Waterloo, Canada. His research interests include the broad areas of communication theory and signal processing with a particular emphasis on the physical layer aspects of wireless communication systems in radio and optical frequency bands. He has authored some 400 journal articles and conference papers on these topics and received more than 16.000 citations with an H-index of 59. His major distinctions include the Marsland Faculty Fellowship, in 2004, the NSERC Discovery Accelerator Award, in 2008, the University of Waterloo Engineering Research Excellence Award, in 2010, the Turkish Academy of Sciences Distinguished Young Scientist Award, in 2011, the Özyeğin University Best Researcher Award, in 2014, the National Instruments Engineering Impact Award, in 2017, the Elginkan Foundation Technology Award, in 2018, and the IEEE Communications Society Best Survey Paper Award, in 2019, among others. He is the Former Chair of the IEEE Turkey Section. He serves as an Area Editor for IEEE Transactions on Communications. In the past, he served as an Editor for IEEE Transactions on Wireless Communications, IEEE Transactions on Communications, IEEE Transactions on Vehicular Technology, and IEEE Communications Letters.

ZHENGYUAN XU (Senior Member, IEEE) received the B.S. and M.S. degrees from Tsinghua University, China, and the Ph.D. degree from the Stevens Institute of Technology, USA. He was a Tenured Full Professor with the University of California at Riverside and Tsinghua University before he joined the University of Science and Technology of China. He was the Founding Director of the Multicampus Center for Ubiquitous Communication by Light, University of California, and the Founding Director of the Wireless-Optical Communications Key Laboratory, Chinese Academy of Sciences. He has published over 400 international journal articles and conference papers, and has coauthored a book entitled *Visible Light Communications: Modulation and Signal Processing* (Wiley-IEEE Press). His research interests include petahertz communication, optical wireless communications, mobile networking, artificial intelligence, wireless big data, sensing, ranging, and localization. He was a Distinguished Expert and the Chief Scientist of the National Key Basic Research Program of China. He has been on the Elsevier annual list of Most Cited Chinese Researchers, since 2014. He was the Founding Chair of IEEE Workshop on Optical Wireless Communications, in 2010. He has served as an associate editor for different IEEE/OSA journals.



ERCHIN SERPEDIN (Fellow, IEEE) received the Specialization degree in transmission and processing of information from the Ecole Superieure D'Electricite (SUPELEC), Paris, in 1992, the M.Sc. degree from the Georgia Institute of Technology, in 1992, and the Ph.D. degree from the University of Virginia, in 1999. He is currently a Professor with the Department of Electrical and Computer Engineering, Texas A&M University, College Station, TX, USA. He has authored two research monographs, one textbook, 17 book chapters, 160 journal articles, and 250 conference papers. His current research interests include signal processing, machine learning, cybersecurity, smart grids, bioinformatics, and wireless communications. He served as the technical chair for six major conferences. He served as an Associate Editor for over 12 journals, including journals, such as the IEEE Transactions on Information Theory, the IEEE Transactions on Signal Processing, the IEEE Transactions on Communications, the IEEE Signal Processing Letters, the IEEE Communications Letters, the IEEE Transactions on Wireless Communications, the *IEEE Signal Processing Magazine*, *Signal Processing* (Elsevier), *Physical Communication* (Elsevier), and the *EURASIP Journal on Advances in Signal Processing*.

KHALID A. QARAQE (Senior Member, IEEE) was born in Bethlehem. He received the B.S. degree (Hons.) in electrical engineering (EE) from the University of Technology, Bagdad, Iraq, in 1986, the M.S. degree in EE from the University of Jordan, Jordan, Amman, Jordan, in 1989, and the Ph.D. degree in EE from Texas A&M University, College Station, TX, USA, in 1997. From 1989 to 2004, he has held a variety of positions in many companies, and he has over 12 years of experience in the telecommunication industry. He has worked on numerous projects and has experience in product development, design, deployments, testing, and integration. He joined the Department of Electrical and Computer Engineering, Texas A&M University at Qatar, Qatar, in July 2004, where he is currently a Professor. His research interests include communication theory and its application to design and performance analysis of wireless communication systems. His main research interests include mobile networks, broadband wireless access, cooperative networks, cognitive radio, diversity techniques, index modulation, reconfigurable intelligent surfaces (RISs), mmWave, visible light communication, FSO, and telehealth applications.

SABIT EKIN (Senior Member, IEEE) received the B.Sc. degree in electrical and electronics engineering from Eskişehir Osmangazi University, Turkey, in 2006, the M.Sc. degree in electrical engineering from New Mexico Tech, Socorro, NM, USA, in 2008, and the Ph.D. degree in electrical and computer engineering from Texas A&M University, College Station, TX, USA, in 2012. He has four years of industrial experience as a Senior Modem Systems Engineer at Qualcomm Inc., where he has received numerous Qualstar awards for his achievements/contributions on cellular modem receiver design. He is currently a Jack H. Graham Endowed Fellow and an Assistant Professor of electrical and computer engineering at Oklahoma State University (OSU). He is also the Founding Director of the OSU Wireless Laboratory (OWL), OSU. His research interests include the design and analysis of wireless systems, including mmWave and terahertz communications in both theoretical and practical point of views, visible light sensing, communications and applications, non-contact health monitoring, and the Internet of Things applications.