Light Fidelity for Internet of Things: A Survey

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Abstract

Light-Fidelity (LiFi) is quickly emerging as the next-generation communication technology thanks to its unique benefits, such as available spectrum, high data rates, low implementation costs, and inherent beamforming capabilities. As a consequence, it is endorsed by the scientific literature as an appealing innovation for disclosing disruptive services. The wavefront of LiFi technology is very wide: in this manuscript, we focus our attention on the interplay with the Internet of Things. Essentially, LiFi can assist the IoT in interconnecting a massive number of heterogeneous devices by addressing the current Radio Frequency spectrum bottleneck. Moreover, by investigating LiFi and IoT individually, several surveys and review papers testify to the noteworthiness of both technologies. However, to the best of the authors' knowledge, a comprehensive investigation of contributions where both of them interplay is missing. To fill this gap, this survey provides a thorough investigation of all the research areas in which LiFi key features might enhance the upcoming IoT networks. The evaluation of existing literature on LiFi adopted in the IoT domain can be valuable in identifying missing gaps arising from the interaction of these two technologies, as well as proficiently pinpointing future research directions.

Keywords: LiFi, IoT, Survey

1. Introduction

Light Fidelity (LiFi) is a promising Optical Wireless Communication (OWC) technology which relies on Visible Light Communication (VLC) for wireless data transmission and has the potential to address the incumbent Radio Frequency (RF) spectrum scarcity. It has been introduced in [1] as a nm-wave communication system that uses VLC to enable a wireless networking system that offers bidirectional multi user and point-to-multi point communication. Furthermore, it is considered as the consequence of the continuous expansion of the electromagnetic spectrum employment to higher frequencies [2].

LiFi solutions provide several benefits over RF networks. In particular, they may ensure high-speed internet broadband services using Light-Emitting Diodes (LEDs) up to 10 Gbps [3, 4]. Additionally, the unlicensed bandwidth for LiFi transmission is several orders of magnitude greater than the whole RF spectrum. Indeed, visible light includes frequencies ranging from around 400 to 800 THz. As a consequence, its spectrum is 10,000 times broader than the total RF spectrum [5–8]. Furthermore, VLC transmits data utilizing LEDs and a photodiode at the receiving terminal. As a result, it could be applied efficiently in environments where RF transmission may be dangerous, such as aircraft cabins.

The fluctuation in light intensity directly pertains to the information contained in the transmitted message. In LiFi, there are several types of modulation, including single carrier, multiple carrier, and color modulation [9]. For example, the blinking of the LED (even at negligible frequencies for the human eye) can be used for the data transmission. In particular, if the LED is switched on it can be considered as a digital "1". On the contrary, if the LED is switched off, it is treated as a digital "0" [10]. Despite LiFi networks can be easily implemented as a bidirectional half-duplex system in VLC, some intriguing works make use of VLC for the DownLink (DL) and the infrared spectrum for the UpLink (UL) [11]. This is useful to avoid distracting human mobile users without affecting the lighting conditions of the room [12]. Moreover, it prevents interference between the UL and DL, by allowing simultaneous signal broadcasting [13, 14].

Since LEDs are already widely used in homes, factories, and streetlights, LiFi may take use of the existing lighting infrastructure by reducing the deployment fee. This holds true especially for massive Internet of Things (IoT) devices deployments, due to the capability of light-based communication to provide very large bandwidth and support high nodes density, which are important requirements for IoT environments [15]. Moreover, the adoption of LED lamps in LiFi can increase energy efficiency. In fact, as known, LED lamps are characterized by very long lifetimes and reduced energy consumption [16]. So, they can be effectively employed in LiFi systems by integrating data transfer and low-power illumination in a constrained scenario, such as IoT [15, 17, 18]. Even though it is clear that the amount of energy consumed depends on the various system components, the intrinsic low-power nature of

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LEDs, combined with additional techniques aiming to save energy (that will be discussed more in detail in Section 8), can greatly help to reduce the overall energy consumption in LiFi systems [16, 19–21].

The well-known IoT paradigm defines a network of smart interconnected objects that can sense real-world phenomena and transmit information over the Internet without the need for human interaction [22]. According to [23], in 2022 the IoT market reached around 15 billion active connections. In this context, wireless access is currently mostly accomplished with the aid of RF. However, radio technologies in access networks are already approaching their limit in terms of throughput and Quality of Service (QoS). Specifically, owing to the currently saturated RF spectrum, it is challenging to accommodate the ever-growing amount of devices to be handled in a IoT environment [24]. Furthermore, the application of the RF presents some relevant issues, including poor privacy due to radio waves freely penetrating walls, a huge amount of energy required for signal relaying and service equipment cooling, and limitations in its adoption in some environments like aircraft, hospitals, and specific factories. To cope with these issues, the implementation of LiFi may disclose disruptive services in the IoT domain.

Nevertheless, despite LiFi is still in its early stages and is not yet commonly accessible, numerous teams and researchers are working to create and deploy LiFi-based networking solutions [25]. Consequently, several review and survey papers is discussing the main functionalities of LiFi, but separately from the IoT environment. According to this, and to the best of the authors' knowledge, a thorough analysis of the state-of-the-art in LiFi technology integrated into IoT environments is still missing. To fill this gap, the primary goal of this work is to comprehensively examine all areas in which academics are focusing their efforts on the suitability and potential of the LiFi applied to a highly dynamic environment such as the IoT. Then, based on this analysis, the main challenges and open issues are illustrated, to provide guidelines for future research directions on this theme.

The remainder of the paper is organized as follows. Section 2 explains the rationale at the basis of the classification proposed in this survey. Section 3 illustrates the main topics covered by other similar surveys and review papers. Section 4 highlights the main differences and missing gaps filled by this work if compared to them. Sections 5-10 provide a detailed description of the contributions provided by all the surveyed papers, based on the classification scheme explained in Section 2. More in detail, Section 5 describes all papers proposing specific IoT application scenarios where LiFi is implemented. Papers analyzed in Section 6 describe different aspects of LiFi integration with other technologies. A physical layer analysis of LiFi for IoT is carried out in the papers analyzed in Section 7. Energy efficiency is the theme tackled in Section 8. Section 9 groups all the papers discussing communication schemes that include LiFi. Contributions proposing positioning algorithms for LiFi are discussed in Section 10.

Furthermore, in Section 11 the most relevant open issues are addressed, also providing some indications of the possible future research directions that the research work can follow in this field. Finally, Section 12 concludes this work.

2. The rationale of the proposed papers taxonomy on LiFi for IoT

The goal of this section is to explain the rationale at the basis of the classification of the papers that apply the multi-faceted aspects of the LiFi technology applied to the IoT environment. The classification approach proposed in this survey follows the taxonomy illustrated in Fig. 1. Specifically, papers are classified and discussed according to the following topics:

- **LiFi in IoT applications.** This section comprises all the works dealing with the implementation of the LiFi technology in a specific IoT application scenarios. There are some papers that provide only an overview of LiFi in different applications scenarios more suitable for the IoT market [26–28]. Other papers instead discuss a single IoT class of applications where LiFi can be fruitfully employed, like the e-health [29], telemedicine [30], mining environments [31], public transportation systems [32], smart factories [25], appliance automation [33], smart home [6], indoor positioning applications [34, 35], audio applications [36] and power grids [37].

- **Integration of heterogeneous communication technologies.** This section groups together all the papers that propose hybrid networks in which LiFi is integrated with other technologies like Wireless Fidelity (WiFi) [27, 38–44] or last-generation cellular networks [25, 45, 46]. Different aspects of the integration are faced, starting from a review of the integration in some application scenarios (often discussing the related advantages, limitations and challenges) [25–27, 45, 46] , to the implementation of QoS-aware strategies [40, 41, 44], proposals taking into account energy efficiency [38, 44], security aspects [39], or procedures at link layer [43].

- **Physical layer analysis.** Papers grouped in this section discuss several aspects related to the physical level of data transmission for LiFi systems in the IoT. Physical layer analysis is important to manage and improve several aspects of LiFi transmission, i.e., energy consumption [17, 18] and data rate [47] through Multiple-Input Multiple-Output (MIMO) techniques [18, 48] and modulation schemes [15, 26, 27, 42]. Also some security aspects related to LiFi can be analyzed at the physical layer [49].

- **Energy efficiency.** Papers belonging to this section analyze the energy consumption issue for the LiFi technology applied to IoT. The minimization of the energy consumption is achieved through different optimization strategies, ranging from the network design (i.e., the number of Access Points (APs)) [50], followed by the optimal selection of the LiFi AP that satisfies specific energy constraints [44], to the optimal allocation of the UL and/or DL transmission power [17, 44], the selection of the access scheme that minimizes energy consumption [15, 38], or exploiting MIMO transmission [18].

- **Design of communication schemes.** This section groups together all the contributions focused on the design and analysis of communication schemes and architectures that can be applied in the IoT context, and that implement the LiFi technology. In general, the architectural schemes discussed in this section describe the structure of the transmitter, the receiver, the components adopted to exchange data, and how they are interconnected. The architectural models related to the communication systems can be explicitly designed for specific application scenarios [15, 33, 37, 51], or to generic environments [34, 38, 52–55].

- **Positioning algorithms.** Papers that analyze this topic show how the LiFi technology can be effectively employed to estimate with high accuracy the position of IoT nodes in indoor environments. This task is accomplished through the proposal and implementation of algorithms that estimate the position of the IoT nodes by means of spatial coordinates [35] or time-based synchronization information [56, 57].

At the end of each section dedicated to a specific topic, a detailed analysis of the main findings is given, together with the related lessons learned.

Several papers analyze more than one topic among the ones described above. Thus, for ease of completeness, these papers have been analyzed in more sections of this survey, describing them from the point of view of the different topics they discuss.

3. Related survey and review articles

The key articles related to the subject of this survey are briefly analyzed in this section, along with their main differences concerning the present contribution.

There are two survey papers dealing with LiFi networks [39, 49]. The contribution [39] surveys the state-of-the-art related to authentication and handover protocols in hybrid LiFi/WiFi networks. Specifically, the main security issues and the related solutions are addressed in this analysis. Also handover protocols for hybrid LiFi/WiFi networks are discussed. Unfortunately, this survey is almost totally devoted to LiFi networks in general, without considering explicitly the IoT environment (it is only briefly mentioned in the Conclusions). The survey paper [49], instead, is mainly focused on the physical layer of VLC transmission. In this context, a security-related analysis is carried out, taking into account several factors like channel models, input distributions, network configurations, precoding/signaling strategies, secrecy capacity, and information rates. A discussion of possible research directions related to security for VLC is also carried out. The main drawback of this contribution is that the LiFi technology is only superficially covered as a particularization of VLC and only in a specific scenario of hybrid LiFi/WiFi networks. Furthermore, the IoT environment is not analyzed in detail. Rather, it is only mentioned in relation to the (high) number of connected devices.

Some contributions discuss several aspects of LiFi-based networks for the IoT [1, 6, 26, 27, 30, 45, 49, 58–60]. In all these

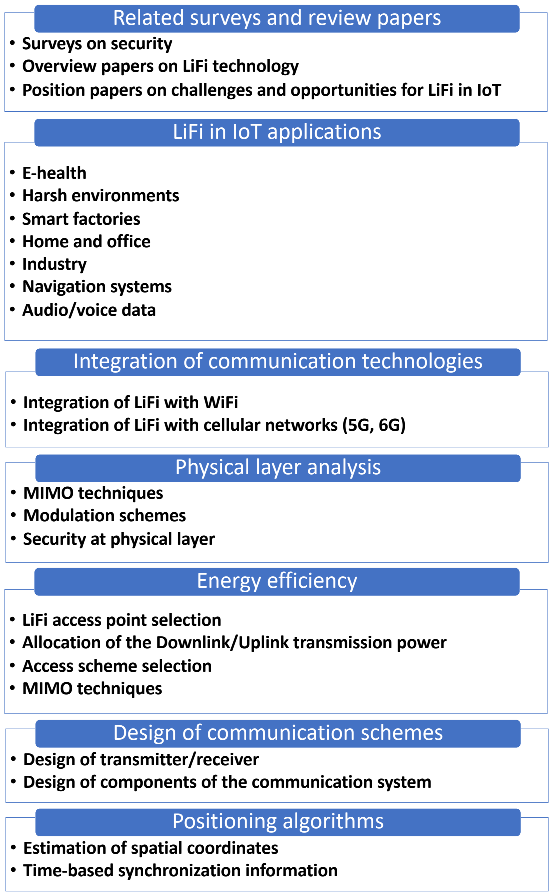

Figure 1: Paper taxonomy for LiFi in IoT environments

works, the review of the state-of-the-art literature on this theme is necessarily not thorough, being tailored to justify concepts and propose ideas, describe the implementation of ad-hoc systems, or clarify characteristics peculiar to LiFi. So, differently from the present contribution, they cannot be considered survey papers since the review work is partial and considers only some aspects of the integration of LiFi into IoT.

Papers [26, 27, 45] provide an overview of the LiFi technology, analyzing some technical aspects related to the physical layer (modulation techniques, channel capacity, adopted spectrum, etc.) and proposing application scenarios where LiFi can be employed. A discussion of the integration with other technologies like WiFi [26, 27, 61, 62] or Fifth Generation (5G) [45] is also carried out. In all these contributions, being LiFi the central topic of both these works IoT is only cited and its description neglected. Another intriguing paper is [1], that highlights the main differences between VLC and LiFi. According to this, the IoT environment is neglected, and the review work is focused on the research topics relevant to LiFi, with reference to modulation techniques, physical components, multiplexed access in the channel, network models, interferences and models of integrated LiFi/WiFi networks.

Papers [6, 58] are more related to the IoT world. They discuss the most relevant challenges and opportunities deriving from the integration of LiFi in IoT. In this context, the contribution [6] performs an exhaustive analysis of advantages and limitations of LiFi in IoT systems. A list of applications that support LiFi in IoT scenarios is also presented. Finally, an application example on smart home automation is designed, that integrates IoT and wireless communication. This paper exhaustively discusses the advantages and disadvantages of such integration, but it mainly presents the idea (as position paper), without analyzing the state-of-the-art literature in support of it. The same topic is tackled in [58], where some solutions are discussed on the adoption of LiFi in IoT scenarios. The goal of this contribution is to evaluate the integration of LiFi and IoT into real-world applications and scenarios. Different aspects are discussed, ranging from use cases to algorithms at different layers of the protocol stack, mobility, standardization activities, and prototypes. The solutions discussed in this paper are developed in the framework of an innovation action project on LiFi, whose focus is on challenges and solutions that allow concretizing the research work on this topic into real-world applications. Like the work [6], this paper does not survey all the state-of-the-art literature on LiFi for IoT.

The approach followed in [30, 59, 60] is to analyze some technological aspects of LiFi systems conceived for IoT applications. In [59], the main features needed to adapt LiFi systems to IoT applications are discussed, with a specific reference to the physical layer. In this layer, several features are analyzed, ranging from connectivity requirements (at different layers of the stack) to mobility support, implementation of integrated wireless/wired networks, and the management of interference. A broadband communication approach at the physical layer is also proposed, that integrates the LiFi technology with Plastic Optical Fiber (POF) links. The study is carried out in the framework of an EU H2020 project on the LiFi development for IoT.

The paper [60] analyzes the scientific contributions related to OWC technologies, including LiFi, devoted to IoT solutions. The review of the literature is more focused on OWC solutions than on LiFi, which is analyzed as part of the OWC environment. The review of the contributions is tailored specifically for 5G and IoT scenarios.

The most significant open issues for LiFi systems as related to the 5G technology are also reviewed in [30]. The review work conducted in this paper touches different aspects ranging from link design to system requirements, challenges and techniques to mitigate the impairments. A prototype of a LiFi system is identified, with a detailed analysis of the structure of the transmitter and receiver. An implementation example based on telemedicine is also considered.

Papers [34, 63] provide an overview of some concepts of LiFi networks. Also in this case, the literature review is aimed at clarifying some conceptual aspects of LiFi technology, without conducting a wide-ranging and detailed description of its integration in the IoT paradigm, which instead is the goal of the present contribution.

The work [34] proposes a system in which LiFi serves IoT nodes. Indoor application scenarios are considered in this work, with a description of the LiFi Access Point (AP) and IoT devices. The proposed system is designed explicitly for LiFi-for-IoT scenarios, describing all the system parts and system architecture and performing feasibility analysis, with particular reference to positioning and power delivery aspects. Specifically, it suggests viable solutions for IoT nodes that only need to deliver data intermittently, such as On-Off Keying (OOK), Pulse Position Modulation (PPM), spatial PPM, and random number modulation by exploiting off-the-shelf LEDs as an enabler for the IoT environment Finally, the main research directions of LiFi for IoT are discussed.

A more general review of LiFi networks is carried out in [63], without any discussion of the integration with the IoT environment, which is relegated mainly to the application area. In this work, the main concepts of LiFi technology are discussed. They encompass LiFi networks, state of the art in standardization activities, and applications. The main features of terahertz communications are also presented for the integration of LiFi into future 6G scenarios.

4. Contribution of this survey and main differences with other surveys and review papers

To the best of the authors' knowledge, the present contribution is the only one providing a wide-ranging and integrated discussion of all the relevant aspects concerning the integration of LiFi in the IoT environment. From the analysis of the most recent literature on this theme, the following topics have been analyzed in this work:

- Coexistence of LiFi and IoT in a specific application scenarios (e.g. e-health, hazardous environments, public transportation systems, home automation, etc.);
- Integration of LiFi and IoT with other communication technologies (like WiFi and optical fibers).
- Physical layer analysis, which extends the survey work made in [49] (that nonetheless mainly discusses security issues). The analysis at this level concerns mostly modulation and coding schema.
- Energy-efficient strategies, aiming to optimize the energy consumption of LiFi systems that can operate in the IoT context. In some contributions, energy efficiency is considered as a QoS requirement.
- Communication schemes, discussing in detail the system components and their interconnections for data transmission/reception in LiFi-based systems. In some works, this topic is related to the development of specific application scenarios.
- Positioning strategies based on LiFi, aiming to detect the position of IoT devices as precisely as possible, and in real-time.

Starting from this schematization followed in this contribution, and comparing the topics listed above with the survey and review papers described in Section 3, the following important differences arise:

- The two survey papers [39, 49] are the only ones that carry out a thorough review of the literature on LiFi technology. Nevertheless, this analysis is not explicitly referred to its integration with the IoT environment. Furthermore, the survey works are mainly dedicated to LiFi security aspects [39, 49] and protocols [39], and on the integration of LiFi with WiFi, neglecting several other relevant topics (i.e.: application scenarios, integration among different technologies, energy-efficient strategies, etc., as listed above).

- The contributions [1, 6, 26, 27, 30, 45, 58–60] cannot be properly considered as survey works, as specified above, since their review work is tailored to the investigation of specific aspects, or to better support the analysis and implementation of particularized schema, thus considers only some aspects of the integration of LiFi into IoT.

- Papers [34, 63] are even more general in their literature review, which is performed to overview some basic concepts of the LiFi technology and not always referred to its implementation in the IoT environment. Also in this case, the analysis of the state-of-the-art literature does not take into account, point by point, all the most important aspects of the application of LiFi to the IoT.

For ease of completeness, Table 1 shows the main differences between this survey work and the other survey and review papers on the adoption of LiFi for the IoT found in literature, highlighting the missing topics of the latter that are covered in this contribution.

5. LiFi in IoT applications

This section describes all the papers that focus on specific IoT applications where the LiFi technology can be effectively adopted. According to the state-of-the-art literature, the IoT applications scenarios chosen for the implementation of LiFi are mainly indoor (even if there are some exceptions to this, as shown in [26, 28, 32, 35]) and range from e-health [29, 30] to harsh environments [31], smart factories [25], home and office [6, 28], industry [28, 37], navigation systems [35] and transmission of audio/voice data [35, 36]. Many of these scenarios are briefly cited in the review paper [26, 27], which also mentions other interesting scenarios like underwater, aircraft, defense, disaster management and risky environments.

Several application scenarios are grouped, listed and briefly discussed in the review papers [26, 27]. The goal here is to better highlight the potential of the LiFi technology in practical application examples, in a more general framework of a technological overview of LiFi and the description of its potential in several scenarios of interest. Many LiFi applications are also suitable for IoT networks, even if this technology is not explicitly described in these works.

The contribution [28] focuses on the integration of LiFi use cases in the IoT environment. Starting from the assumption

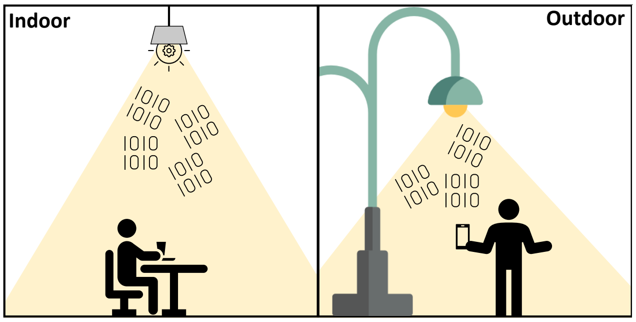

Figure 2: Figure on LiFi in indoor and outdoor environments.

that LiFi solutions are usually customized for their own ecosystem, the goal of this study is to propose and discuss a LiFi system concept and how it can satisfy the requirements imposed by IoT applications. The main LiFi use cases, with related requirements for IoT applications, are described pointing out the flexibility in the adoption and versatility of hardware and software components.

The integration of LiFi in IoT for the e-health scenario is analyzed in [29]. The integration between these two technologies is exploited for the enhancement of a health monitoring system, where a doctor can quickly update the health conditions of his/her patients in the cloud. The cloud is the IoT system while the LiFi network guarantees very fast and noninterfering connectivity. the doctor can thus analyze the patient's data and provide real-time feedback to the assisting person. The key-elements of the health monitoring system are precisely identified, and their interaction is described, also providing flow diagrams of the system.

LiFi is also used in mining environments, as described in [31]. This work focuses on critical environments where the management of emergency information is very difficult because of the poor coverage of WiFi technology. Specifically, LiFi is used to monitor the critical conditions detected through IoT sensors. A decision-making system is also developed to detect abnormal conditions in the presence of hazardous gas. Performance analysis of the proposed system is evaluated in a real testbed, describing the hardware components adopted.

The LiFi technology is exploited in [32] for local advertising in the public transportation scenario. This paper focuses on the outdoor scenario (as shown in Fig. 2), where LiFi is used to transmit the local advertisement to devices close to LED sources, but the proposed model is claimed to be suitable also for indoor IoT communications, increasing their data reliability and solving bandwidth bottlenecks. Both transmitter and receiver sections are analyzed in detail for LiFi communication, providing a hardware-based implementation model and testing its performance in terms of signal attenuation and bit error rate.

LiFi is employed to support smart factories in combination with the 5G network in [25]. The main requirements for this use case are analyzed, in terms of coverage, throughput, network infrastructure, data reliability and delay. A factory demonstra-

Table 1: Review of other surveys/review papers and comparison with this survey.

Covered topics	[49]	[39]	[27]	[26]	[45]	[1]	[6]	[58]	[59]	[60]	[30]	[34]	[63]	This work
Application scenarios			✓	✓			✓	✓			✓	✓	✓	✓
Energy-efficient strategies														✓
Integration of different technologies		✓	✓	✓	✓	✓							✓	✓
Physical layer analysis	✓		✓	✓	✓				✓	✓			✓	✓
Communication schemes						✓			✓	✓	✓	✓		✓
Positioning evaluation strategies														✓

tor that considers the factory environmental conditions and the integration between LiFi (in the access network) and 5G (in the core network) components and protocol stacks is then implemented. Its goal is to demonstrate reliable communication between end IoT devices and application servers.

In the work [33], the LiFi technology is adopted to build an appliance automation model in combination with the Message Queue Telemetry Transport (MQTT) protocol, which is an application layer protocol typical of IoT environments. The proposed model is implemented in a hierarchical hybrid star-tree IoT network, with three levels of hierarchy. The leaf nodes lying at the third level of the hierarchy (the most peripheral one) are provided with LiFi technology and transmit data to a centralized server by using MQTT. The amount of data collected by LiFi nodes is analyzed by means of Machine Learning (ML) algorithms, to predict their temporal behaviour.

The main goal of the contributions [6, 30, 34] is to discuss the main challenges, opportunities [6, 30] and possible research directions [34] arising when LiFi is adopted to enhance the connectivity of IoT nodes. Nevertheless, in all these papers application examples are also presented, to provide a more clear discussion of the covered topics. Specifically, a home automation system integrating LiFi and IoT is discussed in [6]. The focus here is on the design and implementation of a home controlling and monitoring system. The main system functions are described, and a block diagram of the system is proposed, where all the components are identified and described also in terms of network connectivity. An android-based app for appliance control is also proposed, for the practical implementation of the home control system. In the review paper [30], telemedicine is adopted as an application example to address the challenges to be faced when LiFi is adopted in IoT networks. To this end, a LiFi architecture is proposed as a possible implementation scenario within hospitals. The application consists of a circuit transmitting information (an audio signal, in the example) via LiFi. All the components of the prototype are chosen and connected, and the signal is transmitted through LEDs with high illumination capabilities. The main challenges observed in the prototype implementation are also discussed. A more general indoor application scenario is proposed in [34], where LiFi serves IoT nodes. The proposed application scenario is suitable to provide some kind of services such as precise positioning, energy harvesting and security [34]. The system is described in detail, together with all its components, also providing a feasibility analysis in terms of power, energy efficiency, response time and data rate. A comparison with the adoption of LiFi with RF transmission is also carried out, highlighting the main limitations and challenges brought by LiFi. Finally, the main research directions to enable the LiFi/IoT integration are addressed.

A prototype of a LiFi system transmitting an analog audio signal is also discussed in [36] for IoT applications. The audio signal comes from a mobile phone. It is modulated and converted into light emitted by blinking LEDs. A solar cell receives the light signal and forwards it to a speaker. The system is implemented with real HW components, testing its effectiveness and addressing the main advantages in the adoption of LiFi for applications in IoT.

Location-based applications are discussed in [35], that employ LiFi as integrated with WiFi for indoor scenarios where GPS-based systems obtain poor coverage performance. In addition, a voice-based input system is implemented, that generates voice alerts in presence of hurdles for visually impaired people.

Integration of LiFi in power grids, which is a typical IoT application, is the topic of [37]. The paper discusses the so-called Optical Internet-of-things (OIoT), which is the IoT that adopts optical wireless connections. This concept is translated into power grid environments. This paper analyzes the optical theory on the basis of OIoT. It is then exploited to develop an analytical method for the OIoT performance evaluation, and design the block-based diagram of an optical wireless communication system for the power grid. Finally, different application scenarios in the power grid domain are described, where OIoT can be effectively exploited.

5.1. Lessons learned on application scenarios for LiFi in IoT

The papers analyzed in this section testify that the LiFi technology can be effectively adopted in a wide variety of application scenarios peculiar to the IoT world, where each application has its own traffic features [34]. In these contexts, LiFi can be very advantageous for different reasons: high energy efficiency [32], security [6, 30, 32], high precision in localization [34], huge available bandwidth [6, 29], low-cost components [29], robustness towards electromagnetic interference [6, 28, 30, 32] and capability to serve a huge amount of IoT nodes [32, 34]. Nevertheless, the abovementioned studies suggest that LiFi is still not mature to totally replace the WiFi connections currently adopted in IoT, at least in the short term. Instead, it should be integrated and harmonized with existing technologies [30]. In fact, LiFi suffers from some limitations that can be relevant in some IoT environments. Just to cite some of them: the necessity of a Line of Sight (LoS) and a very short distance between two LiFi nodes, a constant light source to access the network, the high difficulty in implementing LiFi connections in outdoor

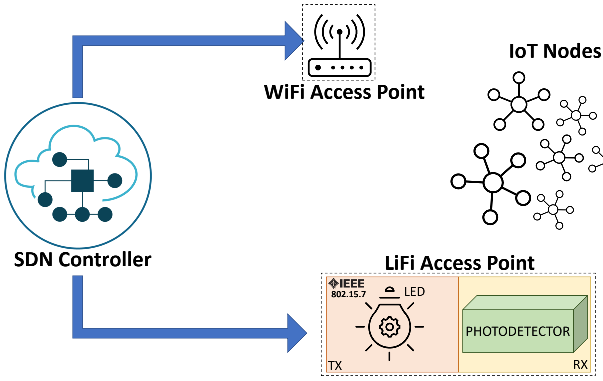

Figure 3: Example of Integration of heterogeneous communication technologies.

scenarios due to other interfering light sources (like the sun) and varying weather conditions, and the time and expensiveness needed to set-up and install LiFi infrastructures [6]. As a consequence, LiFi will be worth being adopted in all that IoT applications, especially indoor, that need to be optimized for high throughput, high reliability, or low latency, at the same time optimizing costs [28]. From the analysis carried out in these papers, it is also noteworthy that most probably LiFi will be the best candidate technology for the future IoT [28, 34].

6. Integration of heterogeneous communication technologies

This section describes the proposals for the integration of different communication technologies that include the adoption of LiFi in IoT environments, as shown in Fig. 3. In particular, relying solely on traditional networks to accommodate the explosive growth in bandwidth demand from the burgeoning number of IoT devices is no longer sufficient. In fact, LiFi systems have drawbacks due to the blockages of the light path that limit the received signal due to opaque objects and obstacles. Consequently, combining LiFi and RF can be an easier way to fulfill future IoT requirements. The most widely discussed kind of integration is between LiFi and WiFi communication technologies, as testified by several papers found on this topic [26, 27, 38–41, 43, 44].

The contribution [38] proposes a technique for energy harvesting, in a scenario that combines both WiFi and LiFi. The goal of the proposal is to achieve higher data rates by integrating both technologies rather than using them separately. The analysis is carried out by designing a model that accounts for the capability of the energy-harvesting sensor to transfer the harvested energy to the sensor node or storage charge and to manage the output of sensors. The performance comparison, in terms of data rate and Bit Error Ratio (BER), is conducted for LiFi only, WiFi only, and hybrid scenarios considering bidirectional communication.

Papers [26, 27, 39] discuss the integration between LiFi and WiFi. In these papers, an explicit description of the IoT environment is missing. Nevertheless, there are some aspects detailed that are suitable for IoT-related networks (e.g., some application scenarios, some system specifications, etc.). Specifically, the study [39] attempts to highlight potential security issues when employing LiFi solely and during the handover protocols between WiFi and LiFi technologies. It explores a wide range of LiFi and handover LiFi/WiFi protocols by disclosing security flaws that might lead to severe attacks. It describes some methodologies to increase security, like the adoption of beamforming methods that reduce the Signal-to-Noise Ratio (SNR) of unauthorized entities in VLC networks to zero, or channel matrices for precoded signals that are invertible only for authorized users. Channel security during the handover process is improved by avoiding the share of the same passwords.

Papers [26, 27] basically adopt the same approach to provide an overview of the main features, developments, advantages and challenges of LiFi. More in detail, the contribution [26] proposes an analysis of the LiFi technology, its main developments, its advantages and limitations. The combination of LiFi and WiFi is discussed, with a focus on the advantages of the resulting hybrid network, especially in terms of security, data rate, coverage and precise positioning in indoor environments. Different possibilities of combination are also presented. Another contribution that provides an overview of the implementation of LiFi over WiFi is found in [27]. Starting from the description of the evolution of the VLC technology into LiFi, a technical comparison between LiFi and WiFi is performed. Some specific aspects are mentioned, i.e., IEEE standardization, the implemented topologies of LiFi and WiFi networks, the operation bands, the coverage and the data rate. Also in this paper, these topics are summarized without going into deep detail.

Also the works [40, 41, 44] deal with hybrid LiFi/WiFi IoT networks. In this scenario, the contributions [40, 41] define the optimization problem of the selection of the most suitable AP based on client-specific QoS constraints in the indoor LiFi/WiFi environment. According to the QoS provisioning mechanism, the IoT nodes can select a LiFi or a WiFi AP, given specific QoS constraints. More specifically, the work in [40] presents an innovative access device selection strategy that attempts to optimize the channel quality (i.e., throughput, energy consumption, and delay) while allowing each IoT node to define its subset of QoS requirements. The goal is the reduction of the average delay experienced by each IoT node while satisfying all the QoS constraints. This methodology is implemented in a Mininet-based indoor hybrid LiFi/WiFi network.

The study carried out in [40] has then been extended in [41] by presenting an enhanced algorithm of access device selection that is solved with a game-theory approach. This paper analyses in-depth the LiFi channel while assessing its data rate capacity by varying the angle of inclination of the APs with regard to IoT nodes. It reduces the average delay and increases the average throughput of the network while meeting the QoS requirements of the IoT nodes. The performance of the proposed algorithm is evaluated by emulating a real-world scenario.

In the paper [44], the integration between LiFi and WiFi translates into modeling differently the LiFi and WiFi channels and integrating these two models for the formulation of the optimization algorithm that allows to select the most suitable AP that maximizes energy efficiency, thus respecting specific QoS guarantees. The proposed methodology is also compared with WiFi-only and LiFi-only scenarios.

The LiFi/WiFi combination is analyzed in [43] at the single interface level. This work considers a virtual interface, composed of the aggregation of two physical interfaces, one based on LiFi and the second on WiFi, obtained by means of a bonding driver at the data link layer. Some performance results are presented, focused on the evaluation of the connectivity downtime occurring during the switching from one physical interface to the other, due to different reasons (signal loss, interface failure, load balancing, etc.)

Other works present an overview of an hybrid LiFi/WiFi network able to overcome the shortcomings of both standalone technologies by combining the fast data transfer capabilities of LiFi with the wide coverage of WiFi, without focusing on the IoT domain. Specifically, [61] presents an overview of LiFi technology, practical concepts for implementing LiFi-based indoor networks, and criteria for measuring network performance. It also discusses how to design and set up a LiFi-based indoor network as standalone LiFi or hybrid LiFi/WiFi network. Furthermore, [62] presents network architectures, cell deployments, multiple access and modulation schemes, illumination requirements, and backhaul. Moreover, key performance metrics are then reviewed to demonstrate the superiority of hybrid LiFi/WiFi network against standalone networks. Then, the challenges are elaborated on key research topics including user behavior modeling, interference management, handover, and load balancing. It also examines the potential benefits of LiFi/WiFi network for application services, such as indoor positioning and physical layer security.

Another topic on this theme debated in the modern literature consist of the integration of LiFi with 3GPP-based last-generation cellular networks like 5G and beyond, which are suitable for IoT support. This aspect is emphasized in [25, 45, 46].

In this context, in [25] LiFi is integrated in the 5G network. The focus of this work is to exploit the LiFi technology in the access network while using the 5G technology in the core network. Since, differently from 5G, LiFi is a non-3GPP technology, the effort of this study is devoted to the integration of the LiFi and 5G components and the related protocol stacks. A demonstrator is also developed, that shows the reliability of the communication between IoT devices and application servers.

The integration between LiFi and 5G is discussed in [45]. Even though this paper does not propose any novel methodology, it carries out a comparison between the main LiFi performance parameters with the correspondent 5G ones, to evaluate the possibility of implementation of LiFi-based cellular networks. Accordingly, the main aspects of LiFi technology are discussed exhaustively, also briefly mentioning the integration of LiFi with WiFi.

More tailored to the integration of LiFi into future 5G and beyond network is the work [46], which recommends the further integration of 6G in a LiFi/WiFi network to provide high coverage also on subways, aircraft, and trains. Specifically, 6G would ensure connectivity to the public network, LiFi would achieve a reasonable indoor data rate, and WiFi would compensate for LiFi shortcomings (e.g., penetrating walls).

6.1. Lessons learned on the integration of different communication technologies

The analysis of the literature on this topic suggests that the integration process of the LiFi technology with other existing and consolidated technologies like WiFi or 5G is a central topic in the framework of the LiFi technology. In fact, when a new promising technology (like LiFi is) arises, it needs a more or less long period of integration and coexistence with the other existing ones, that have already been implemented in existing network infrastructures. So, it is not surprising that there is a consistent amount of research work that tackles the integration between LiFi and WiFi, which is widely adopted in IoT scenarios. Also the integration with 5G and beyond systems is a promising line of research, since the last-generation cellular networks are standardized also taking into account the IoT environment. As a consequence of this, a relevant effort should be spent on the interoperability among the different standards, developed for architectures, devices, and protocols that characterize WiFi, 5G (and beyond) and LiFi systems.

In the context of this integration, efforts have been devoted to designing communication schemes satisfying specific QoS guarantees. The fulfillment of this goal for LiFi-based networks helps improve the LiFi network performance in terms of different metrics like energy consumption, data rate, and network throughput. On the contrary, this is not a trivial task. Indeed, strategies in this direction always translate into finding the solution to a constrained optimization problem, which is usually a complex and computationally intensive task, not suitable for IoT devices that usually are resource-constrained. The task becomes even more complex when the QoS guarantees are heterogeneous, depending on the features of the IoT nodes.

7. Physical layer analysis

In this section, the strategies related to the physical layer of LiFi transmission in IoT are discussed in detail.

Physical layer aspects can be found in the framework of energy efficiency strategies, as testified by [17, 18]. More specifically, in [17] the enhancement in energy efficiency performance in a LiFi environment for IoT is studied by modeling a Non-Orthogonal Multiple Access (NOMA) channel. This channel is modeled with an optimal power allocation method to achieve greater performance than a standard Orthogonal Multiple Access (OMA) channel while still meeting all of the QoS requirements of a IoT node. Also in paper [18], the energy efficiency of a VLC communication is boosted by leveraging an adaptive MIMO strategy. This paper investigates the effectiveness of various MIMO approaches by identifying the most energy-efficient method while fulfilling an acceptable error rate.

Related to MIMO techniques is also the work [48]. It proposes a MIMO technique for a OOK modulation suited for the VLC. Even though the strategy is presented for only one transmitter and one receiver (being not suitable for IoT scenarios with high numbers of nodes), the proposed methodology can improve the LiFi communication if compared to conventional schemes, in terms of data rate and communication range.

Many papers discuss modulation schemes for LiFi [15, 16, 26, 27, 42]. In [16], the main modulation schemes are grouped into two different categories, such as single carrier modulated transmission and multiple carriers modulated transmission. The former includes both Pulse-Based Modulation (PBM) (i.e., OOK, Pulse Amplitude Modulation (PAM), Pulse Width Modulation (PWM), PPM [64]) and Continuous Wave Modulation (CWM). In detail, a PBM imposes that the signal is composed of a periodic pulse (AC current) that is added to the illumination (DC current) by modulating the amplitude of the light. On the contrary, the CWM modulates the light intensity with a sinusoidal carrier signal. Herein, the information can be coded either by amplitude (ASK), phase (PSK) or frequency (FSK) shift keying. Finally, if the signal is modulated both in amplitude and phase is called Quadrature Amplitude Modulation (QAM) [9]. The latter uses many carriers to convey information. Specifically, the main method is the Orthogonal Frequency-Division Multiplexing (OFDM) which maps bits with a given modulation scheme (e.g., QAM) by exploiting orthogonal subcarriers. Then, the output is obtained using the Fourier transform [65]. Nevertheless, OFDM signals should be shaped for Li-Fi systems to allow for LED source intensity modulation. Hence, a positive limitation is essential for an optical modulation system to cut off noise and ensure the accuracy of the modulated signal. Indeed, to counteract the bipolar nature of the OFDM signal, the DC-biased optical OFDM (DCO-OFDM) is commonly employed. Alternatively, the asymmetrically clipped optical OFDM (ACO-OFDM) only transfers data on the odd subcarriers. The resulting bipolar signal at the output of the IFFT is clipped at zero to give a non-negative signal. However, it sacrifices some spectral performance to ensure that no data is lost. Finally, even though the DCO-OFDM attain higher spectral efficiency and data rates [61, 62], ACO-OFDM is employed in more energy-efficient applications [62, 66, 67].

Modulation schemes for LiFi are reviewed also in papers [27, 42]. Both these contributions describe the modulation techniques adopted for LiFi, subdividing them into two main groups: modulation schemes in common with radio wave communications, further classified into single carrier and multicarrier modulations, and modulations techniques that are exclusively adopted in LiFi transmission since they exploit features peculiar of light signals. In [15] the coexistence issues among low-power IoT nodes with low data rates and LiFi nodes that can easily manage high data rates and high reliability is faced at the physical layer. In fact, this work evaluates the suitable modulation techniques such as QAM, PAM, Color-Shift Keying (CSK), Discrete Hartley Transform (DHT), DCO-OFDM, interleaved subcarrier mapping, modified data sequence and multi-access techniques such as Wavelength Division Multiplexing (WDM) and Orthogonal Frequency-Division Multiple Access (OFDMA). In addition, the performance of each technique is evaluated in terms of Peak to Average Power Ratio (PAPR), delay and throughput. Also the contribution [26] evaluates the performance of alternative modulation schemes, including OFDM, Filter Bank Multi-Carrier (FBMC), and Universal Filtered Multi-Carrier (UFMC) in a LiFi environment using MATLAB simulations. More in detail, this work emphasizes the benefits of using UFMC with respect to OFDM in terms of BER, PAPR, spectral density, and spectral efficiency while at the same time guaranteeing a lower implementation complexity.

Different physical layer aspects are tackled in [49]. This contribution highlights the security challenges that might arise while using VLC communication technology by examining several configurations for data transmission such as Single-Input Single-Output (SISO), Multiple-Input Single-Output (MISO), MIMO, and hybrid LiFi/WiFi systems. To cope with this issue, this paper reviews different channel models, user mobility, and Key Performance Indicators (KPIs) capable of monitoring the safety of this technology. Moreover, security approaches at the physical layer are investigated for boosting VLC channel security, also analyzing the impact of factors like input signaling, the number of eavesdroppers, and Channel State Information (CSI) availability at transmitting nodes on the security performance of the system.

Another contribution is found in [47], that deals with the parallel transmission of data in a LiFi network. This work considers an area covered by several LiFi APs simultaneously connected to an IoT node. In this scenario, an optimal resource allocation algorithm is proposed, that aims to maximize the achievable data rate of the LiFi network. Several factors are taken into account in the resulting optimization problem: the channel model, the node mobility, and the light-path blockage modeled by analytical functions.

7.1. Lessons learned on physical layer strategies in LiFi transmission

This section explores papers that discuss the implementation of traditional RF modulation schemes in the optical domain, including the modifications and adaptations needed to make them suitable for use in a LiFi network (such as adding a DC-bias). However, it is not yet proven whether all of these approaches adopted for the RF domain can be effectively implemented in their current form also in LiFi networks, without introducing penalties like a reduction in spectral efficiency and data rate. Furthermore, a recurring theme in these works is the possibility to consider a LiFi/WiFi network, which still allows for the use of traditional RF approaches by trying to fit the well-known results into the optical domain. Unfortunately, none of the current state-of-the-art approaches precisely focuses on the IoT environment whenever addressing these considerations.

Papers dealing with this topic reveal that the almost totality of the physical layer aspects are well-known concepts, related to modulation schema and multi-antenna transmission techniques. The most relevant aspect is the description of features of the physical signal that are peculiar to LiFi transmission since they exploit the characteristics of the light signal. Results testify that some schemes can outperform the modulation schemes adopted in WiFi networks in some network configurations. Another issue is the coexistence at the physical layer between classical WiFi nodes, which typically are low-power and low-rate nodes, and LiFi nodes that can manage very high data rates. This is another aspect, strictly related to the LiFi/WiFi integration discussed in Section 6, that requires further research efforts.

There are also some security aspects discussed at the physical layer. The starting assumption is that the LiFi signal is, by its own nature, open and broadcast, and this surely poses important security issues also for LiFi networks. Security is faced from the point of view of the physical signal, involving aspects like beamforming, MIMO techniques, modulation and precoding schemes, and CSI.

8. Energy efficiency

This section analyzes all the research papers proposing solutions for energy efficiency suitable for LiFi in IoT scenarios [15, 17, 18, 38, 44, 50]. In all the analyzed papers, energy efficiency may be achieved by:

- selecting the optimal number of APs [50];
- electing the optimal LiFi AP [44];
- properly allocating transmission power in UL and/or DL directions [17, 44];
- choosing the most appropriate multiple access scheme [15, 38];
- designing antenna arrays in MIMO transmission techniques [18].

As testified in [15], at the physical layer an energy-efficient transmission in LiFi networks is influenced by the modulation scheme. Several modulation schemes can be adopted in LiFi systems, as highlighted in Section 7. Nevertheless, the choice of the modulation technique in IoT scenarios, where nodes are power- and resource-constrained, must be decided carefully. Indeed, multi-carrier modulation techniques like OFDM and its variants can provide higher spectral efficiency and throughput; nevertheless, they typically suffer from high computational complexity and energy consumption [34, 68, 69]. So, these techniques are not recommended for IoT nodes. From this point of view, single-carrier and pulse-based modulation techniques like OOK, PAM and CSK could be more effective. Such modulation schemes optimize the optical power utilization, also simplifying the design of the transmitter, where energy saving can be obtained by exploiting OOK. More specifically, higher energy efficiency can be reached if the OOK is implemented with switching transmitters where the power consumed is mainly due to the LED energy consumption [21]. In fact, by properly setting the amplitudes of the on and off states in the OOK-modulated signal, the dissipated energy in the optical transmitter can be made very negligible [21].

One of the main strengths of LiFi technology is its ability to provide both connectivity and illumination, indeed, [50] proposes a trade-off between the number of APs and energy consumption, using constraints that impose a threshold regarding the minimum level of illumination of the environment, by maximizing network performance in terms of the achieved data rate per user. More APs installed in the network mean a greater data rate experienced by each user (but the generated inter-AP interference will also increase). Conversely, the fewer the number of APs, the less energy is consumed (but the average level of illumination will also decrease). The decisive choice is made by the network designer, who selects the most essential metric from network performance and energy usage.

The contribution provided in [44] aims at decreasing the energy of IoT nodes in a hybrid LiFi/WiFi network. Specifically, it designs a Mixed-Integer Linear Programming (MILP) problem that finds the optimum AP while satisfying all QoS constraints, the maximum number of simultaneously connected IoT nodes to each AP, and taking into account the upper bound of each IoT node transmission power. More in detail, the goal is to maximize the energy efficiency of every IoT node, by setting the minimum transmission power able to meet the throughput constraints related to energy consumption. Performance results are compared with WiFi-only or LiFi-only network scenarios.

In the context of multiple access schemes, a promising technique is given by NOMA. Differently from orthogonal multiple access schemes (like OFDM previously discussed) where users are allocated into orthogonal time and frequency resources, in NOMA all the users share simultaneously the whole time and frequency resources, since they are multiplexed in the power domain and demultiplexed by means of Successive Interference Cancellation (SIC) techniques [17, 70]. Some works in literature have proven the effectiveness of this scheme in multi-user IoT scenarios for 5G systems [70–72]. The same contribution [70] also testifies the suitability of NOMA schemes also for VLC networks. It is noteworthy that the adoption of NOMA schemes overcomes the inherent limitations of techniques like the abovementioned OOK. Indeed, even if OOK is one of the simplest modulation techniques adopted in optical communications, it is not always suitable for high-rate transmission due to its low spectral efficiency. Conversely, also NOMA schemes can be made energy-efficient in LiFi systems by designing ad-hoc power allocation schemes that optimize the power allocated by users, at the same time improving the error performance of the system [70].

Given the considerations reported above, another low-complexity power adaptation strategy is proposed in [17] to improve the energy efficiency in a LiFi transmission for IoT environments. The proposal consists of a NOMA scheme that optimally adapts transmission power to maximize the energy efficiency in both DL and UL channels, achieving QoS guarantees for bidirectional communication. To this end, it proposes a closed-form solution with a low-complexity power allocation scheme suitable for LiFi bidirectional channel (i.e., visible light for the DL, infrared for the UL). The network energy efficiency is improved by reducing the likelihood of user outage while meeting all the QoS guarantees.

The lack of transmission methods capable of spatially multiplexing numerous devices without requiring a recurrent fee payment (e.g., NB-IoT) is critical in IoT scenarios. The contribution [15] addresses this issue by providing an innovative energy-efficient communication strategy based on optical OFDM in LiFi environment, that achieves interference-free communication. In the proposed system, LiFi users coexist with IoT devices under a common LiFi AP. This scheme is useful for taking the most appropriate decision on the combination of multiple access and modulation techniques in both the DL and UL channels, to save energy. Delay and throughput performance are also evaluated.

The work [38] provides a model based on the integration of an energy-harvesting wireless sensor network with hybrid LiFi/WiFi communication techniques. This study presents a model that allows for multiple channel accesses while reducing interference. It accounts for the capability of the energy harvesting sensor to transfer the harvested energy to the sensor node or storage charge and to manage the output of sensors. In this context, the single-carrier modulation schemes (e.g., PPM, OOK, PAM) are analyzed for LiFi, also addressing dimming performance for the OOK for visible light systems [38] or in hybrid visible light/infrared communication systems [20]. Multi-carrier modulation techniques, like OFDM, are also mentioned as more effective for high data-rate transmission, or in presence of signal distortion and frequency selectivity in the optical channel [38]. It is well known in fact that OFDM presents higher spectral efficiency and robustness against dispersion and varying channel conditions [21]. This contribution also analyzes the CSK as a LiFi-specific modulation. Finally, the simulation results show that a bidirectional multiaccess/multiuser hybrid LiFi/WiFi communication scheme can be effectively utilized due to its ability to provide interoperability for multiple devices/users at a high data throughput rate of 25 Mb/s.

As remarked in [73], MIMO can be effectively adopted in IoT environments due to its capability of serving simultaneously a large amount of IoT nodes, at the same time improving energy and spectral efficiency and increasing the overall system capacity. This holds true especially when a large number of antennas is deployed at the base station side [73]. Several other contributions also highlight the effectiveness of the MIMO adoption in different frequency bands, including millimeter wave (mmWave), terahertz (THz) and optical wireless bands, thus guaranteeing reliable and energy efficient communication in several IoT scenarios [74, 75].

Indeed, different MIMO transmission techniques are proposed in [18] for an indoor LiFi system based on VLC and employed in IoT scenarios. In detail, an adaptive method is proposed to enhance the energy efficiency of MIMO for VLC. Specifically, by varying the channel conditions, the desired spectral efficiency, and a target error rate, the MIMO technique is selected from three options: repetition coding, spatial multiplexing, and a modified version of spatial modulation. Finally, MIMO technique with the lowest energy requirement is chosen based on the user's location, thus reducing energy consumption, by also considering the desired spectral efficiency and target BER. This adaptive method can be particularly useful in IoT applications where energy consumption is a critical concern.

Since MIMO is based on spatial diversity for signal transmission, its performance is influenced by the position of the LiFi network elements (light sources and photo-detectors), and by the channel conditions [76]. The analysis carried out in this paper shows that this diversity factor impacts the main parameters

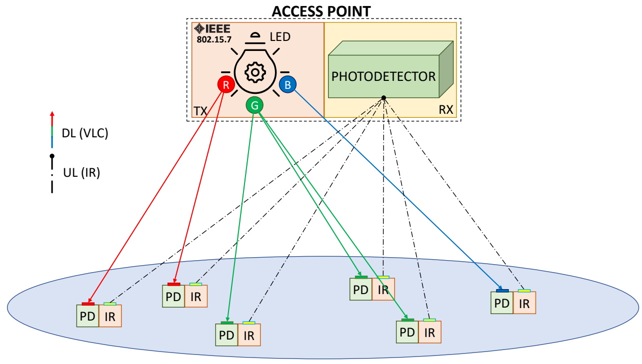

Figure 4: Example of design of communication scheme.

that contribute to energy consumption, i.e., the optical power needed to reach a target BER. So, the optimization of the energy consumption depends on the chosen MIMO technique as related to the specific IoT scenario (more details on this can be found in [18]).

8.1. Lessons learned on strategies for energy efficiency optimization

The works analyzed in this section suggest that the minimization of energy consumption is of paramount importance in LiFi networks serving IoT systems. Indeed, IoT nodes are usually battery-powered and batteries should last for a very long time. This issue is exacerbated for LiFi access networks, thought to achieve very high data rates that require a higher power consumption at the node side to meet this requirement. Efforts in this direction have been made mostly by analyzing data transmission at the physical layer, considering LiFi channel models, energy-efficient modulation schemes, the adoption of MIMO strategies and the optimization of the transmission power for the LiFi nodes.

9. Design of communication schemes

This section identifies and discusses the contributions that analyze communication schemes applicable to IoT environments adopting the LiFi technology, as shown in Fig. 4.

In this framework, a basic approach is proposed in [54]. In this work, the system is made up of a smartphone and a LED that implements a LiFi bidirectional channel. The former is outfitted with a flashlight as a transmitter and a camera that serves as a receiver. The initial stage in acquiring information is a picture captured by the camera, which extracts the brightness component of the image. The LED position is then detected. The signal is decoded after equalization and quantization. Finally, the information can be successfully collected following the error-checking procedure. Furthermore, the LED can act both as a transmitter and a receiver. Specifically, variations in incoming light intensity can be detected by charging a reversed biased LED and measuring its electric tension after a short time interval [54]. Specific efforts have been made in the design of communication schemes for outdoor scenarios, which are critical for LiFi networks [52, 53]. The authors in [52] propose use cases suitable for a disaster scenario by exploiting the VLC over a lighthouse to communicate with fishermen in an emergency situation. The outdoor LiFi communication scheme is implemented following the DMX512-A standard that enables the unidirectional data transmission for VLC. Specifically, the device block diagram includes a power supply, a serial interface linked directly to a laptop and a microcontroller that manages the light-based transmitter or receiver. Another contribution in [53] designs a Software-Defined Networking (SDN)-enabled LiFi attocellular network virtualization able to share the infrastructure over multiple Mobile Virtual Network Operators (MVNOs). This is possible thanks to a resource slicing application offered by the northbound of the SDN controller that is also able to handle the on-demand creation of a LiFi DL channel. Under heterogeneous bursty traffic conditions, the proposed approach aims to maximize the data rate and optimize the allocated resources of each MVNO infrastructure, while minimizing the fees incurred by the providers. To this end, a heuristic matching game method is exploited to properly address the resulting optimization strategy.

Differently from the previous works, communication schemes for indoor scenarios are proposed in [15, 33, 37, 51]. The authors of [15] propose a novel architecture for LiFi-based indoor networking for IoT users. In detail, the work designs a LiFi AP with a transmitter that can operate on three distinct wavelengths (i.e. red, blue, and green) to communicate with different receivers at the same time, and a receiver consisting of a photodetector capable of gathering IoT node signals. Furthermore, it proposes equipping IoT nodes with one element capable of sending in the infrared band and the other component capable of receiving by filtering the system's different wavelengths. Once the communication equipment has been described, the block diagram of the various forms of modulation employed in the DL channel is defined, beginning from modulation and moving through the DAC and ADC until the signal demodulation. The work in [33] envisions the deployment of a one-way LiFi hotspot that is engaged for DL communication only. It transmits the data stream to the end user by generating it via LED. First, the data stream is encoded by the transmitter, enabling an asynchronous communication based on MQTT and with frames as small as 11 bits (one start bit, two stop bits, and eight ASCII characters). Finally, the receiver may decode the broadcast signal into alphanumeric characters by analyzing the received frame with the help of a solar panel that detects tiny changes in light. The benefits of adopting LiFi in high interference conditions due to high voltage and strong magnetic fields are shown in [37]. First, this contribution introduces a novel concept called the Internet of Light, in which lights are assigned an IPV6 address and are considered network nodes. In detail, a sensor is inserted inside a High Voltage Direct Current converter to provide constant feedback on its functioning state. Finally, the voltage is detected by the sensor, which sends the signal created by a modulator to the light source, which is received by an optical antenna of the receiver and demodulated before passing to the signal processing phase. According to the authors of [51], a LiFi network is used to achieve device-to-device (D2D) communication in an ultra-dense Industrial Internet of Things (IIoT) environment, by adopting a scenario drawn from the IEEE 802.11bb standard for VLC communication.

The choice of such a standard is particularly suitable for the analysis of realistic IIoT scenarios, like the one described in detail in [77], especially for what concerns the channel model. Furthermore, as remarked in [78], if compared to the other optical wireless communications standards like IEEE 802.15.7, IEEE 802.15.13, or the ITU-T G.9991, IEEE 802.11bb introduces only slight modifications to the MAC layer of the IEEE 802.11 standard adopted by for WiFi, thus easing the LiFi/WiFi coexistence which is an important aspect in an IoT environment [38, 44, 62].

In this scenario, the network is split into clusters identifiable by a given LiFi AP, and each of these AP covers a variable number of mobile devices that act as relying upon the AP for the gathered data from the IIoT nodes. Specifically, the IIoT nodes use the measured received optical intensity to choose the optimal mobile device suitable for the D2D. Finally, the network performance is quantified by evaluating different mobile device speeds, transmitter heights from the ground, and room sizes.

Unlike the previous contributions, papers [34, 38] focus on energy harvesting strategies. The work in [34] introduces IoT nodes that are self-sustaining in terms of energy and conducts a feasibility analysis using the existing technology. It specifically provides three alternative setups that employ an AP outfitted with a LED for transmission, a photodetector, and a CMOS camera for data reception. In the first configuration, an IoT node is equipped with a solar panel that can perform both energy harvesting and data reception in DL, while for transmission a liquid crystal shutter is employed, which can perform both backscattering and UL communication in VLC. The second configuration employs a solar panel that is also responsible for waking up the IoT node to allow communication in the UL channel exploiting the infrared technology. The third configuration presents a hybrid node that uses both LiFi and RF, with the DL channel acting as a control channel to efficiently employ the RF, interrupting the sleep state. This study also illustrates three potential autonomous setups from the standpoint of energy, which is a crucial requirement for the IoT.

Another contribution analyzes a typical indoor IoT environment for smart housing and smart industries using a hybrid LiFi/WiFi network [38]. The proposed system includes an EH-sensor node that can manage energy harvesting and communicates utilizing the frame structure defined in the 802.15.7 standard. When smart devices want to connect with EH-sensor, they transmit data to the frame creator block. Then, the output is sent to the encoder block. Once encoded, the data frame is sent from the modulation block to the LED driver, which produces blue light to interact with the EH-sensor. Indeed, it has an optical color filter to filter the blue-colored LED light and receive the data frame with the help of the photodetector. Furthermore, it keeps the received data in the buffer after demodulating and decoding the data frames. When EH-sensors wish to connect with smart devices opposite approach is taken utilizing a green LED

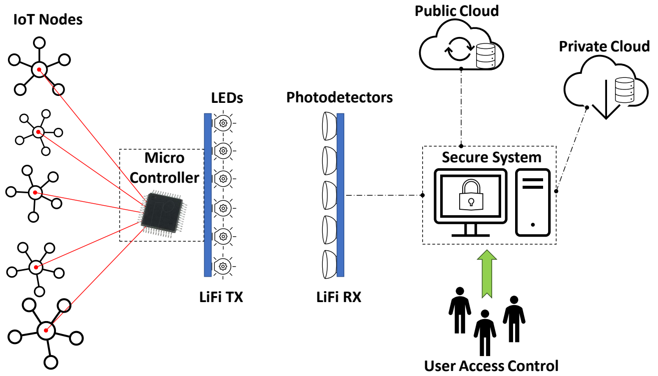

Figure 5: Example of a security system.

light to avoid interference.

Finally, the contribution [55] proposes a solution for data storage in a secure LiFi environment for the IoT. Specifically, it describes a LiFi-IoT environment in which the sensors are coupled to a microcontroller capable of driving an array of LiFi transmitters, as shown in Fig. 5. Consequently, another array of photodetectors serves as an AP through the proposed system, which also includes a Advanced Encryption Standard (AES) algorithm adopting 128-bit symmetric keys and a Role-Based Access Control (RBAC) authentication and authorization mechanism. As a result, a method to securely store the sensed data is implemented.

9.1. Lessons learned on the design of communication schemes

The communication schemes proposed in the analyzed works often investigate in depth the components of the communication systems and relate them to specific use case scenarios. An important aspect covered in these contributions is the proposal of communication schemes for outdoor scenarios, that are more critical for LiFi-based communication. In this context, the optimal selection of available resources to maximize the network data rate seems to be an interesting topic, bringing encouraging performance results. Unfortunately, finding the solution to this kind of optimization problem is time- and resource-consuming, making it difficult to meet the real-time requirements that are instead important in some IoT scenarios. Also, some standardization aspects and the coexistence among different modulation schemes at the physical layer are discussed, thus making the proposed schemes suitable for implementation into real testbeds.

It can be noted anyway that the proposed schemes are quite simple, in most cases being made of a single transmitter and a single receiver. More complex, multi-node scenarios, that are much closer to the IoT reality, are almost totally neglected or are evaluated theoretically, or their performance analysis is carried out through simulations. Also, a compliance analysis of the different standards adopted, wherever implemented simultaneously in the proposal, would be beneficial for practical implementations and performance evaluation in real-world scenarios, especially when LiFi is integrated with WiFi technology. Another important lesson learned is that almost all the proposed communication schemes are described at the physical layer. To strengthen the analysis and provide a more exhaustive description of the schemes, an analysis of the schemes at higher layers (e.g., network layer, application layer, etc.) with the related standardized protocols adopted, would be beneficial.

Some security aspects are also tackled in the context of communication schemes. Nevertheless, security protocols for LiFi is still a work in progress that requires more investigation. Actually, the solutions proposed focus mainly on cryptographic mechanisms. Nevertheless, they must be chosen accurately, to meet the resource-constrained nature of IoT nodes, at the same time being fully compliant with the ongoing standardization efforts in the LiFi environment.

10. Positioning algorithms

This section describes the positioning algorithms proposed in LiFi networks for IoT applications. The proposed algorithms allow the localization of IoT nodes, also in hybrid indoor and outdoor environments, as shown in Fig. 6.

The work [35] provides an integration of the outdoor navigation system (e.g., Global Positioning System) with an indoor navigation system (e.g., LiFi technology). It designs a technique for indoor localization, which is primarily used to store a series of points that represent the latitude and longitude while it proposes a triangulation method for outdoor locating systems.

According to [56, 57], the implementation of LiFi positioning algorithms is a promising solution for indoor applications [56] and industrial environments [57]. In both these contributions, an indoor standard-compliant positioning system based on the so-called time-of-flight approach is implemented. It makes use of the frame structure of LiFi transmission, as stated in the International Telecommunication Union (ITU) Telecommunications Sector G.9991 recommendation [79]. Based on the information contained in the LiFi frame, two kinds of time information are derived: coarse time information (obtained by using the frame synchronization preamble) and fine time information (derived from the channel estimation preamble), to estimate the relative distance between each LiFi AP and the IoT node with high precision.

Real-world tests have been used to validate the proposed system.

10.1. Lessons learned on positioning algorithms and localization techniques

Positioning algorithms can be useful to estimate the position of IoT nodes with high accuracy, thus being of great importance in some industrial environments or indoor scenarios where the position of an IoT node must be derived precisely. The main drawback of such techniques resides in the complexity of the LiFi network, which must be composed of a high number of APs to combine the information on the node position coming from the different APs, and the short coverage range of the LiFi signal that is negatively influenced by attenuations and obstacles. Another issue is that the positioning algorithms proposed in the state-of-the-art literature could be energy-consuming, especially in scenarios with high mobility of IoT nodes, since

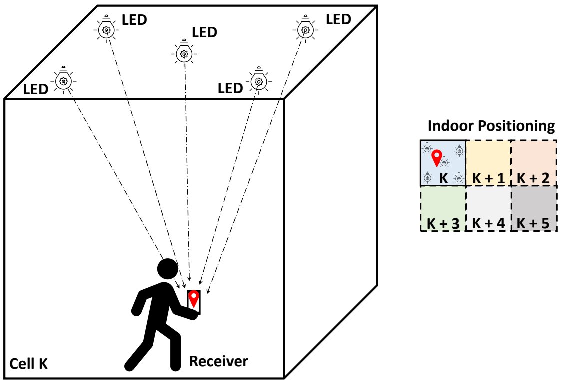

Figure 6: Example of indoor positioning approach.

their position needs to be continuously updated as they move in the reference area. So, their implementation should be carefully evaluated in such scenarios, when energy saving becomes a relevant issue.

11. Challenges and future research directions

This section aims at addressing the main challenges of LiFi adoption in IoT scenarios as derived from the analysis of the current literature, to find the related missing gaps. Based on this, possible research directions can be drawn to suggest what kind of themes deserve to be further investigated by future research work.

According to the analysis of the current literature, LiFi technology can fulfill the majority of the requirements of future systems put forward in the IoT field, including 5G, 6G, and others. Sharing LiFi and IoT technologies can be a highly effective solution to many of the challenges that take place in WiFi access networks, particularly in terms of data rates, energy consumption, and scalability. This validates the potential of LiFi in a wide variety of IoT scenarios. However, it should be noted that most of the LiFi-based technology is still under investigation. Therefore, in the authors' opinion, it is necessary to pay attention to the obligation to examine crucial theoretical issues.

The first issue is that building LiFi networks to serve IoT systems requires the use of a small cell architecture, which leads to a dense deployment of LEDs. As highlighted in the analyzed papers, this raises the problem of managing inter-cell optical interference, in the framework of light transmission which is different from RF signal transmission. Additional research is needed in this direction. In this case, it is desirable to conduct full-scale experiments using models of real network sections. This aspect is another interesting research direction that can be further explored to provide innovative and effective theoretical models for the LiFi part of the network in IoT scenarios. Another problem that needs further research efforts is the management of the handover of IoT nodes in indoor scenarios with multiple APs and mobile devices. This aspect is important, especially in dense scenarios with real-time data exchange, to minimize service interruptions and maximize system efficiency.

The second issue is related to the thorough evaluation of the throughput performance of IoT systems when using strategies of interference management like MIMO. Some works coping with this issue propose the adoption of MIMO techniques to increase the system throughput and energy efficiency. Nevertheless, the effectiveness of such adoption is considered as for RF systems. Also in this case, a thorough evaluation of the real performance of MIMO together with its effectiveness in terms of throughput and quality of service would be beneficial in future research works, especially in real testbeds.

Another interesting research field is related to the challenging issue of the proposal and adoption of analytical models for LiFi explicitly tailored for the IoT domain. In fact, many papers in the scientific literature focus on the analytical models for the LiFi network ([11, 80–85]). Nevertheless, all the models proposed in the abovementioned papers refer only to LiFi systems, totally neglecting their integration with the IoT environment. Furthermore, there is still a lack of a reliable channel model for these systems [12]. For instance, unrealistic assumptions are made about the receiver's placement, such as presuming that the LiFi receiver is vertically upward or randomly located within the communication range of the transmitter [12].

Consequently, it is challenging to adapt these models to an environment full of constraints such as the IoT is. Indeed, there is a need to comprehend, design and validate the models produced for LiFi networks in the IoT context. At the same time, mathematical expressions and formulas taken from monographs are used, which do not fully take into account the parameters of modern transmitters and receivers of light signals in the IoT domain. Thus, it would be interesting to create a layout of the minimum configuration of the LiFi system, take measurements and validate the model as accurately as possible by comparing the measurement results with the outputs of the analytical model. This aspect has currently not been properly addressed by the current literature and requires a relevant effort, to properly align analytical results with experimental ones in integrated LiFi/IoT scenarios, and iteratively refine the proposed models accordingly, to solve LiFi network design problems in the IoT domain.

As a result of the conducted survey work, it is evident that much effort in the field of LiFi technology has been devoted to the analysis of the physical layer of light signal propagation between the transmitter (LED) and the photodetector. There are no exhaustive studies of LiFi systems that would analyze the processes of information from the source to the recipient at all levels: physical, channel, network, and above, even by adopting cross-layer approaches. The key challenge is that each level has its own methods and procedures of data flow management, and there are opportunities to improve the efficiency of the system by analyzing the way(s) data is packetized and packets are managed at the different layers of the stack. In this context, also security assumes relevancy. More specifically, the management of authentication and authorization procedures is actually a challenge and needs further research to find the best trade-off among conflicting requirements, such as the implementation of lightweight security procedures to save the computational resources of IoT nodes, the layer(s) of the stack at which these procedures should e implemented, and the maintenance of the security guarantees when handover among different APs occurs. From this point of view, centralized or distributed security procedures could be implemented; nevertheless, they should take into account the specific IoT application scenario and the system architecture. In any case, by using recent achievements in solving the problems of information transfer at each level, it is feasible to identify new potential directions for the development of even more efficient LiFi systems.

12. Conclusions

This work aims at providing a thorough overview of the research activities on the LiFi technology applied to the IoT scenario. To this end, the available scientific literature has been investigated in detail and classified, to identify the covered topics and the current research trends. After a detailed description of the novel aspects of this work and the main differences from the other surveys and review papers, the surveyed papers have been classified based on the different topics, that range from the adoption of LiFi in IoT applications to integrated communication technologies, the solution to optimization problems, QoS provisioning, energy efficiency, physical layer analysis, positioning strategies, security and proposals of communication schemes. Finally, considerations on the main challenges and possible future research directions have been discussed, to provide some precise guidelines that can drive future efforts in this research field.

From the analysis of the surveyed literature, some important conclusions can be drawn. First, there are some topics that attract much interest, like the adoption of LiFi technology in different application scenarios and the integration or coexistence of LiFi with other technologies like WiFi or cellular networks. This is testified by the number of works on these topics. Second, the QoS provisioning is mostly related to the solution to optimization problems, that sometimes is hard to find due to the complexity of the problem itself and not always suitable for IoT devices, which usually have reduced computational resources. Third, the energy saving issue is crucial in IoT environments, where nodes are battery-powered. Nevertheless, for the sake of feasibility in IoT environments, the proposed strategies must keep a low complexity and a high transmission efficiency. Fourth, it is very important to focus the research efforts on the coexistence of LiFi with other communication technologies (WiFi or cellular networks), preventing communication systems and network architectures to be designed from scratch. The main difficulty related to this topic is the integration and interaction among different protocols, developed by different standardization bodies, and at different layers of the stack. Additional efforts have thus to be spent in this direction.

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