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ORIGINAL PAPER

Design and implementation of an integrated OWC and RF network slicing-based architecture over hybrid LiFi and 5G networks

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Abstract

Radio frequency (RF) systems tend to become congested and overused due to the increasing number of users, devices and the multiple technologies involved in their deployment. This leads to the downgrading of quality of service (QoS) further caused by interference with different signals. Optical Wireless communications (OWC) are emerging as a feasible alternative as they offer unlicensed, interference-free spectrum by using the frequency range located in the visible and invisible light spectrum. Its applications can be found in various fields such as healthcare, education, finance and industry 4.0. Moreover, it enhances the security and privacy of communications. Nevertheless, the limited spectrum in OWC also requires optimised resource allocation to support the QoS of different applications or users whilst lacking established infrastructure to manage this. To address these challenges, this paper proposes a novel 5G-LiFi framework able to ensure QoS requirements by introducing network slicing in Light Fidelity (LiFi) networks integrated with 5G infrastructure. This paper has developed and deployed a 5G-LiFi architecture capable of providing network slicing capabilities over the LiFi segment of the hybrid network. It allows a full control over the network traffic and tailored, improved QoS capabilities. The proposed solution has been empirically validated and evaluated in a realistic testbed employing real-world LiFi and 5G network equipment, and yielded promising results in terms of bandwidth, delay, jitter and packet loss. This work concludes that the use of heterogeneous networks integrating OWC with RF is a suitable solution and it can lead to a better use and exploitation of the different spectrums, improving the QoS offered to end-users.

Keywords LiFi · 5G · IoT · Network Slicing · OWC · RF · QoS

1 Introduction

In the era of rapid digital transformation and the growing demand for reliable, high-speed wireless communications, the need for these technologies to improve is remarkable. Moreover, the industrial sector is clamouring for the introduction of wireless technologies as they would reduce costs and enhance processes in several respects [1, 2]. Wireless systems provide benefits such as cost-efficiency, flexibility and comparable performance in terms of bandwidth and latency to wired technologies. Other important attributes are the mobility and scalability that make possible to increase the number of connected devices without having to carry out tedious tasks of cabling simplifying the installation process [3–5]. In addition, some new features and capabilities are introduced in the wireless networks such as network slicing. Network slicing refers to the creation of virtual networks from a physical infrastructure [6] allowing the isolation of the resources to achieve dedicated functionalities. A network slice can be introduced in different segments including radio networks, core networks or even in the transport segment [7]. This allows resources to be customised and optimised for a specific application providing a virtualised environment for end-users.

A precursor to this movement is the 5G. Its introduction as a solution for Industry 4.0 and 5.0 [8, 9] is noteworthy

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and outstanding. Its adaptability to different use cases in this area is due to its high speed and low latency features [10]. In addition, it also helps to drive research and application development in fields such as Internet of Things (IoT) [11, 12]. Other technologies such as Wi-Fi are also used as alternatives for different use cases. Wi-Fi can support applications requiring low-latency [13–15], making it a good choice to be implemented in some areas [16].

However, a problem with these wireless systems is that they employ radio frequency (RF) spectrum. This characteristic can compromise performance because of the susceptibility to interference from other electronic devices, neighbour networks or wireless devices [17–19]. In addition, there is a bandwidth limitation making it impossible to develop applications or services with absolute freedom, as there are many technologies competing for this resource.

To mitigate these concerns, other communications systems are being investigated. One solution provided is to exploit another range of the electromagnetic spectrum that is unused. Optical Wireless Communications (OWC) have emerged as an alternative for that purpose. OWC techniques utilise a different frequency range located in the visible and invisible spectrum of light. This change simply eliminates the problems related to interference. An example of such technology is Light Fidelity (LiFi).

LiFi can provide high speed and stable wireless communications [20] due to its signal characteristics. Immunity to RF interference makes it suitable for several use cases with different applications like healthcare environments. In these areas, RF signals often interfere with sensitive medical equipment; therefore, using OWC systems, transmissions are more secure for both patient and medical devices. Other applications that can take advantage of light-based wireless systems are related to privacy and security. Sectors where preventing information theft can be critical, such as finance and industry 4.0, can benefit from this technology. Nevertheless, LiFi also has some problems. Due to the spectrum used, signal propagation has a limited coverage as the light does not pass through walls. But this can be beneficial when it comes to privacy since data is kept within a secure area, reducing the risk of unauthorised access and achieving privacy-aware communications.

A lot of research is trying to find a solution for these systems to reach greater coverage distances. Others provide simpler solutions, such as coupling OWC systems to a RF network to create hybrid architectures [21]. OWC can be employed creating a local area network (LAN) to bring more privacy, security and stability to communications empowered by a RF network. An example can be found in [22] where a 5G macrocell with a LiFi system located in a home is presented.

Despite the great advantages of LiFi technology and its implementation in industrial environments, it has not yet been fully explored. To date, advanced capabilities offered by RF systems, such as network slicing, have not yet been introduced in OWC systems. It is in this context that the work presented in this paper comes into play. In this research work we present the first architecture that is able to monitor and control a LiFi network ensuring the quality of service offered to different users. To achieve this purpose, a framework has been developed in which several components are included to enable customisable control over LiFi by changing the bandwidth in both uplink and downlink in real time. Moreover, we deployed a hybrid testbed using both 5G and LiFi for IoT purposes. On one hand, 5G acted as the backhaul network offering connection to a Packet Data Network (PDN). It is noted that the network slicing over LiFi is managed from the 5G management layer, minimising the management overhead in LiFi. On the other hand, LiFi acted as a LAN for UEs.

According to these contributions, the following set of innovations are provided with respect to the state of the art:

1. A set of new architectural components to achieve the integration of LiFi technology with 5G networks.
2. A novel framework with network slicing capabilities suitable for LiFi networks to ensure QoS requirements for different users and services.
3. Empirical evaluation and validation of the proposed framework in a realistic testbed where a hybrid 5G and LiFi network architecture was deployed.

The rest of the manuscript is organised as follows. Section 2 reviews related work that create such hybrid wireless systems. Section 3 describes the proposed hybrid RF-OWC architecture comprising both a 5G segment and a LiFi segment. Section 4 explains how the LiFi system works and proposes network slicing into this LiFi system. Section 5 presents the different components designed and developed to achieve the proposed network slicing paradigm. Further on, section 6 describes the implementation with hardware and software of the proposed solution and explains the experiments for testing. Subsequently, section 7 shows the results obtained from the testing of the LiFi segment. Finally, section 8 concludes this paper.

2 Related work

In this section, various research work whose objective is similar to ours are presented. In addition, there is a discussion comparing the present research work with investigations by other authors. It is worth noting that creation of RF-OWC hybrid networks is not a common practice but is emerging as a solution to improve qualities of both type of systems. Moreover, introducing network slicing into OWC networks is a new concept. As a result, limited research work exploring this area have been found. To detail this section more clearly, it was divided in four subsections. Thus, subsection 2.1, stresses the importance and necessity of deploying an hybrid RF-OWC type network and how these can help to achieve a better quality of service for end-users. Subsection 2.2 explains some research where LiFi is used in combination with other wireless technology to create a hybrid environment. Then, in subsection 2.3 an introduction of network slicing in LiFi is presented. Finally, subsection 2.4 shows the importance of the contribution presented in this research work.

2.1 Importance of RF-OWC hybrid wireless systems

Hybrid networks involving optical and radio frequency systems are emerging due to the scarcity of space in the spectrum of RF systems. This is a result of the large number of technologies using this frequency range. Radio frequency spectrum is a finite resource shared by all wireless devices, from each user equipment to each deployed antenna. As the number of wireless technologies and devices increases, there are concerns about over-utilising or congesting this spectrum [23]. In addition, all the regulations on radio frequency spectrum have made it highly expensive for entities to deploy applications or services that use it, which leads to a situation that they have to rely on third party providers. However, reliance on third parties increases privacy and security concerns in addition to costs. On one hand, deploying a private 5G network requires a fairly high investment and the maintenance costs involved. On the other hand, using other RF alternatives such as Wi-Fi lowers these costs but brings other obstacles related to channel usage and the possibility of interference. The latter is present in all wireless technologies that use RF. The solution to this is to explore technologies that are inexpensive and provide security and stability while eliminating interference with other radio frequency systems. These networks can be those that use light spectrum. The deployment costs of these systems are much lower, and they do not cause any interference with other non-light technology. In addition, due to the short range, the possibility of two optical networks interfering with each other is minimal. Entities can deploy this type of network in specific areas where wireless communication is required without any problem as this spectrum is not regulated. In addition, these networks can extend services from other systems by creating heterogeneous networks of different technologies. One example of this is using OWC systems to support 5G networks is being proposed as a solution [24]. Hybrid architectures using both OWC and RF can be deployed to have different tiers depending on how many layers are presented in the architecture. It this research work, a two-tier RF-OWC architecture is considered using 5G and LiFi systems. Examples of hybrid architectures can be found in [25] where Perkovic et al propose an OWC-RF architecture for massive IoT where devices are able to connect to this OWC system and relay data via a backhaul RF network. Li et al in [26] introduce a relay architecture in which stationary devices are connected to OWC access points and, at the same time these devices are used as low power RF access points. With this, they demonstrated that the system adds capacity to the OWC link and offers flexibility to distribute it across different devices.

2.2 Hybrid wireless systems

Wang and Haas in [27] proposed a dynamic load balancing scheme in a LiFi-Wi-Fi hybrid network, considering handover overhead. The study analyzes the service areas of LiFi Access Points (APs) and the throughput performance of the hybrid system. At the end of their study, they came to several conclusions. The first was that the coverage area of a LiFi APs is circular when there is no interference, but not when there is interference. The second conclusion is related to throughput. This metric increases if the Wi-Fi speed is improved. This parameter is related in this hybrid network even though they do not use the same spectrum. Finally, the handover overhead can lead to a handover location offset due to the transmission loss. For the study of the throughput performance they have considered analytical studies but for the handover process and user throughput they have considered simulation.

To enable widespread adoption of autonomous operations, the manuscript [28] presents a proof-of-concept for a hybrid architecture combining millimeter-Wave (mmWave) and LiFi technologies within a fifth generation (5G) framework. The focus is on the LiFi component, and promising results are reported. High received power and signal-to-noise ratios at low speeds were obtained. Practical prototype simulations also demonstrate positive results, with the ability to transmit at high data rates without the need for high-power processors. The proposed hybrid architecture offers advantages such as reconfigurable high bandwidth channels, simultaneous multimedia mmWave-LiFi connections, and ultra-low latency support.

Tota et al. in [29] focus on the potential of creating mesh networks using LiFi communication among telepresence robots, particularly in emergency situations where traditional telecommunications infrastructure may be unavailable. The study explores the use of both Wi-Fi and LiFi technologies for data communications in mobile telepresence robots. Additionally, the paper investigates the capability of medical telepresence robots to fulfill the technical equipment requirements in post-disaster medical emergencies. By leveraging LiFi-based mesh networks, this research aims to address the need for reliable communication solutions in large-scale disasters when conventional infrastructure is compromised.

Papanikolaou et al. in [30] investigate the coexistence of LiFi and Wi-Fi networks in a hybrid setup, where both systems are served by the same backhaul network. The researchers address the challenges of resource allocation and coordination in this multi-user scenario. They formulate and solve optimization problems to optimize power allocation, taking into account the limited capacity of the shared backhaul network and the distinct characteristics of each system. Through computer simulations, they demonstrate the effectiveness of their proposed techniques in achieving proportional fairness and fair distribution of available resources, showcasing the potential of LiFi networks in providing improved data rates and full coverage for indoor wireless applications in the near future.

Zeng et al. in [31] create a hybrid network using LiFi and Wi-Fi to improve performance in indoor environments. This solution provides a potential solution to wireless communications where LiFi augments Wi-Fi providing more speed of transmissions and low-latency communications. The authors propose a low-complexity orthogonal frequency-division multiple access (OFDMA) resource allocation scheme for LiFi systems and an efficient group-based transmission (EGT) scheme for load balancing (LB) that takes handover effects into account in heterogeneous LiFi-WiFi networks. For the experiments, simulated experiments were carried out. The results showed that in the LiFi system, the OFDMA-based resource allocation scheme outperforms the TDMA scheme And, the EGT-based LB scheme achieves better data rate and fairness performance compared to benchmark LB schemes.

Mohammad Reza Ghaderi in [32] proposes a hybrid network solution between LiFi and Wi-Fi to improve the performance of both. The former suffers from the short coverage distance it offers while the latter provides not-so-fast data transmission. Therefore, both technologies, combined, would achieve better performance and offer a better quality of service for the user. In his research work, he discusses the different studies that are currently being carried out in this field. Finally, the manuscript concludes by presenting insights on how a LiFi-based indoor network should be implemented.

Marcel et al. in [33] focused on utilizing LiFi as a non-3GPP access technology for offloading 5G radio network traffic at data hotspots in factories. They presented a multistage demonstrator set-up and network architecture to evaluate the enhancements of the 5G protocol stack, enabling seamless handover between LiFi and 5G. They also evaluated the end-to-end performance of user applications over LiFi and commercial off-the-shelf 5G SA NR links. The paper highlights that further performance evaluation and deployment in a factory environment are planned to analyze the system's performance under real-world conditions.

2.3 Network slicing using LiFi

Hamada and Haas in [34] propose a utility-based resource quota and scheduling policies that offers potential for multiple Mobile Virtual Network Operators (MVNOs) to dynamically provide 5G services on customized LiFi network slices. By employing sigmoidal utility functions with adjustable parameters, these policies can effectively characterize the performance of services running on different LiFi network slices. The derived utility functions serve as optimization objectives, allowing users to maximize network utility based on factors like throughput or Head-of-Line (HoL) delay.

Hamada et al. in [35] present a LiFi network architecture that incorporates DDS (Dynamic Spectrum Sharing) and SDN (Software-Defined Networking) capabilities to support diverse wireless applications with varying traffic patterns and QoS needs. The paper applies a matching game algorithm to efficiently allocate LiFi ADCB (Adaptive Dual Carrier Bandwidth) slices to MVNOs (Mobile Virtual Network Operators) based on their data rate requirements and traffic load. The study demonstrates that matching game theory establishes a stable relationship among different players, ensuring efficient sharing of the LiFi attocell AP (Access Point) downlink channel bandwidth. The research also highlights the revenue potential for the InP (Infrastructure Provider) by catering to MVNOs with higher data rate demands.

2.4 Related work discussion

Table 1 shows the characteristics of each of the studies presented compared to ours. Those fields containing an ✕ indicate which feature or metric has not been taken into account in that research work. Fields with a ✓ indicate that it has. In addition, an explanation of the different columns is attached in Table 2.

Many research work studied hybrid architectures with Wi-Fi and LiFi systems in which both networks are at the same level. In addition, to test them, most of the papers have carried out analytical or simulated experiments. Our distinction is that the OWC network is deployed in such a way that it creates a LAN with the resources of the RF network. Furthermore, to test this heterogeneous network, we deployed it using a 5G network and a real LiFi network. In this approach, the experiments performed were performed in the field to observe what results can be obtained. Our first objective was to check how a LiFi network works, what benefits it brings, what expectations are expected from it and what results it can yield. As a second objective we had to study how network slicing can be introduced on it by modifying the behaviour of the traffic flowing through the

Table 1 State of art comparison

	RF-OWC		Tier	Network slicing	Validation	Software	Hardware	Analysis				Protocol
Publication	1	2	3	4	5	6	7	8	9	10	11	12
[27]	Wi-Fi	LiFi	1	×	Analytical/Simulation	–		✓	×	×	×	×
[28]	5G	LiFi	1	×	Simulation	MOBATSim	Arduino	×	×	×	×	×
[29]	Wi-Fi	LiFi	1	×	Analytical	×	×	×	×	×	×	×
[30]	–	LiFi	1	×	Simulation	–	×	×	×	×	×	×
[31]	–	LiFi	1	×	Numerical Simulation	–	-	✓	×	×	×	×
[32]	–	LiFi	1	×	×	×	×	×	×	×	×	×
[33]	5G	LiFi	2	×	FieldWork	Open5GCore	–	×	×	×	×	×
[34]	×	LiFi	1	✓	Simulation	MATLAB	×	✓	×	×	×	×
[35]	5G	LiFi	1	✓	Simulation	MATLAB	×	✓	×	×	×	×
Our contribution	5G	LiFi	2	✓	Fieldwork	OpenAirInterface	OledComm	✓	✓	✓	✓	UDP

Table 2 Column description of table 1

Column name	Column number	Description
RF-OWC	1	Radio frequency technology used as backhaul
	2	Optical wireless communication used
Tier	3	How many layers of networks exist in the hybrid architecture
Network slicing	4	Is Network slicing introduced into the architecture?
Validation	5	The type of validation carried out to check the functioning of the system
Software	6	Software used to test the architecture
Hardware	7	Hardware used to deploy the architecture
Analysis	8	Throughput
	9	Latency
	10	Packet loss
	11	Jitter
Protocol	12	Protocol used for communication

network. For this purpose, an architecture was developed with different components that allow both the monitoring of the network and the control over its resources. The latter has not been investigated in any other work found and presented in this section.

3 Proposed hybrid RF-OWC architecture

This section shows a general overview of the proposed architecture presented to emulate. The proposal states how implementation and establishment of LiFi technology as an extension of a 5G network is done. Also an industry scenario to provide more security, privacy and enhance communication between devices is shown. As a result, a RF-OWC architecture is deployed. For this purpose, Fig. 1 shows the scenario where both technologies are being used. This environment is creating a stable communication without interference with the help of LiFi. The different segments are explained below.

3.1 5G segment architecture

The 5G segment is acting as the backbone of the network enabling communications from different locations. In the scenario presented, each site has its own edge allowing the usage of edge computing services. At the edge of the network is the Radio Access Network (RAN). This is one of the two most important segments of a 5G network and is composed of a Centralised Unit (CU) and a Distributed Unit (DU). These elements are responsible of the generation of the wireless medium access, with the help of an antenna, necessary to connect UEs to the network. The CU is in charge of the higher layers of the 5G protocol stack. It supports the Service Data Adaptation Protocol (SDAP), the Packet Data Convergence Protocol (PDCP) and the Radio Resource Control (RRC). Meanwhile, the DU is in charge of

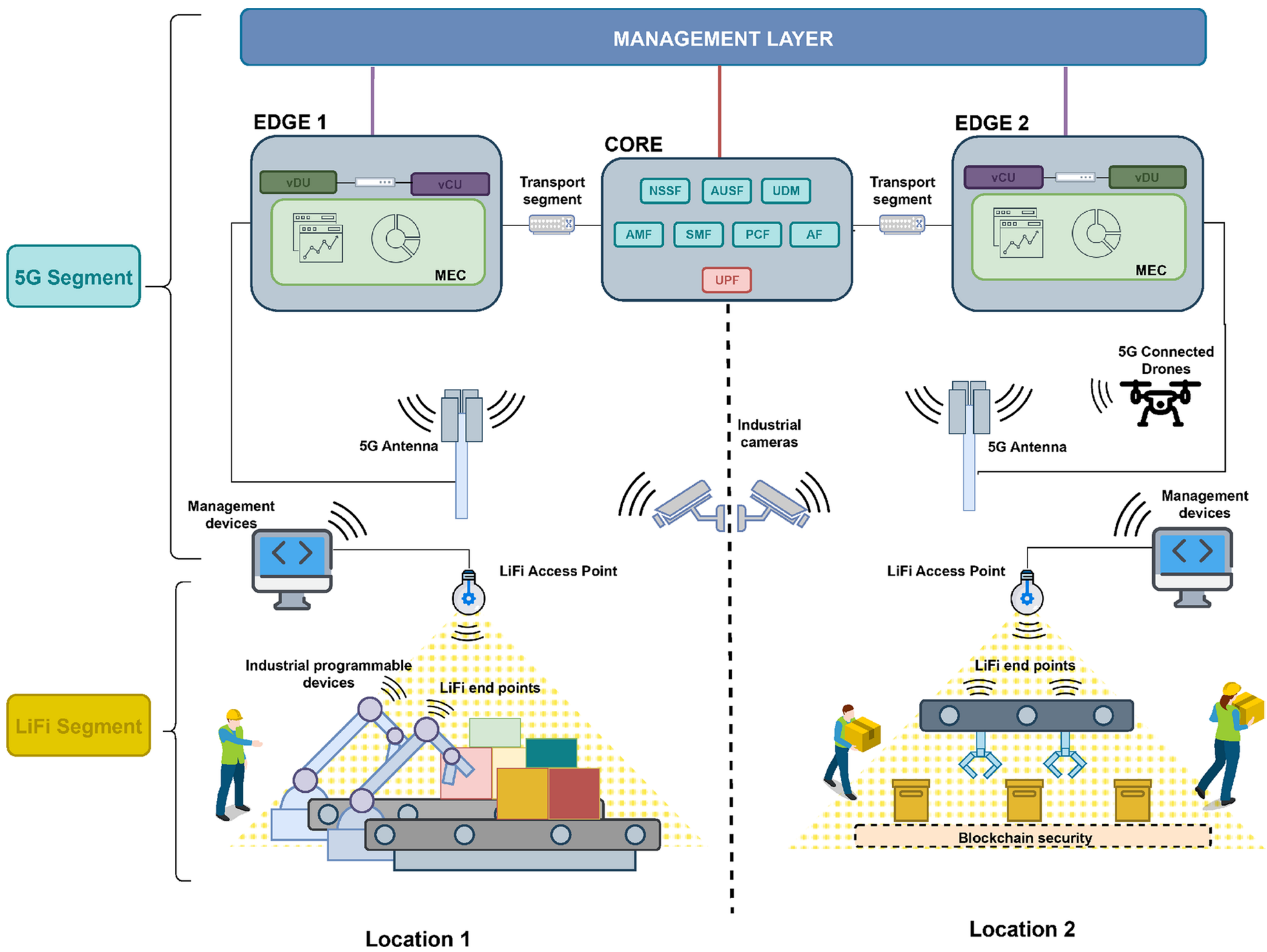


Fig. 1 Overview of the proposed integrated OWC-RF architecture for industrial applications

the lower layers such as the Radio Link Control (RLC), the Medium Access Control (MAC) and the physical layer. For each RAN there has to be at least one CU but there can be multiple DUs. These last ones are in charge of each Radio Units (RU) connected to the antennas. The edge comprises geo-distributed servers with virtualisation capabilities that provide information technology service environments and cloud computing capacities. Also, as shown in Fig. 1, there is one Multi-access edge computing (MEC) for each edge. This component makes it possible to bring services and applications closer to the end users, resulting in a decrease of the latency [36].

Both locations shown in Fig. 1 share the same 5G core of the network. Therefore, the whole traffic pass through the same path to exit from this environment. The core is composed by two planes. The first plane, called the control plane, is responsible of the user authentication, session control, slicing functionalities, etc. The components that integrate this plane are the Access and Mobility Management Function (AMF), the Authentication Server Function (AUSF), the Session Management Function (SMF), The Network Slice Selection Function (NSSF), the Unified Data Management (UDM), the Policy Control function (PCF) and the Application Function (AF). The second plane, called data plane, is in charge of the exchange of the traffic between the end device and the Internet. The component responsible of providing such functionality is the User Plane Function (UPF). So, once the user equipment (UE) is allowed in the network, it only communicates with this last element of the core.

Additionally, the usage of a 5G system allows network slicing as a capability. This concept, as discussed in [37], is a term that refers to the possibility of customising the service by assigning a specific resources of the network to a tenant in order to provide a higher quality of service to users. In other words, it consists of allocating specific network resources to each user in order to make the most efficient use of the network. With 5G, network slicing can be applied to both RAN and core. As for example in the RAN part, it is possible to provide different bandwidth to each user or service depending on the importance of this.

The network slicing configuration, the LiFi control and other 5G network functions take place in the management layer of Fig. 1. Both edge and core are connected to it in order to transmit information about the network status and receive network intents. The management layer is responsible of monitoring, controlling, optimizing and maintaining the network infrastructure. It improves operational efficiency of the network allowing network operators to better and more efficiently manage large-scale networks. Furthermore, this layer ensures the delivery of high-quality services by monitoring performance, optimizing resource allocation, and enforcing QoS policies. It is in the management layer that network slicing capabilities are configured for both 5G and LiFi.

3.2 LiFi segment architecture

The second segment reflected in Fig. 1 shows how LiFi was explored to connect the IoT devices to each other. The adoption of this technology is related to the stability it offers in communications thanks to the avoidance of interference with RF technologies, among other benefits such as increased security, as mentioned before.

As shown in Fig. 1, the LiFi architecture is formed by two components: an access point (AP), connected to the source of origin of the network and the LiFi receptors (dongles or end-points), connected to the IoT devices at the distributed locations. In the proposed architecture, a 5G-UE is acting as source of the LiFi network. The computer acts as the gateway for the LiFi end-points to the 5G network. Consequently, a 5G network extension is created using LiFi to bring more stability and security to the communication. In this architecture, LiFi acts as a local area network.

4 LiFi System

This section consists of two subsections that will help to better understand and present the devices used to deploy the LiFi network and how these devices are used to introduce network slicing to this segment.

4.1 LiFi devices

To deploy the LiFi segment for the RF-OWC architecture, the OledComm LiFiMAX solution was used. This is an indoor networking system that allows LiFi connections up to 100 Mbps [38] in both uplink and downlink. The system consists of 2 components: the AP and the end-points. Each end-point can be connected to an access point to have connectivity and move between different zones by switching between APs. This has the advantage of offering mobility to the devices throughout the infrastructure where the system is installed offering a significant advantage compared to wired technologies.

The coverage area of each AP is approximately 12 m^2 allowing connectivity to 16 devices at the same time. In order to comply with this specification, the AP has to be at a height of 2 ms [38]. In addition, there must also be a direct view between AP and end-points, with no obstacles in between.

The connections of this system differ depending on which component is being used. In the case of the AP, it is connected to a Power over Ethernet (PoE) interface that allows both power the component and transmit data. In the case of the end-points, these are connected to the devices using USB-C (or USB-A if an adapter is used). The advantage of this connection is that when the end-point is connected to a host, this last one recognizes it as a network interface. OledComm offers a solution called LiFiMAX controller by which they control both AP and end-point, thereby enabling the management and monitoring of the network. In the case of this research work, this controller is not used, but replaced by components that are placed in the management layer of the 5G network. This allows control over both 5G and LiFi segments to be managed from the same point.

4.2 Network slicing over LiFi

To understand how network slicing is introduced into the LiFi segment, it is necessary to explain the LiFi components design. Figure 2 shows the different layers available on the LiFi components and how the communication with the host is facilitated.

LiFi components are composed of two layers. Layer 1 (physical layer) and layer 2 (Medium Access Control). The

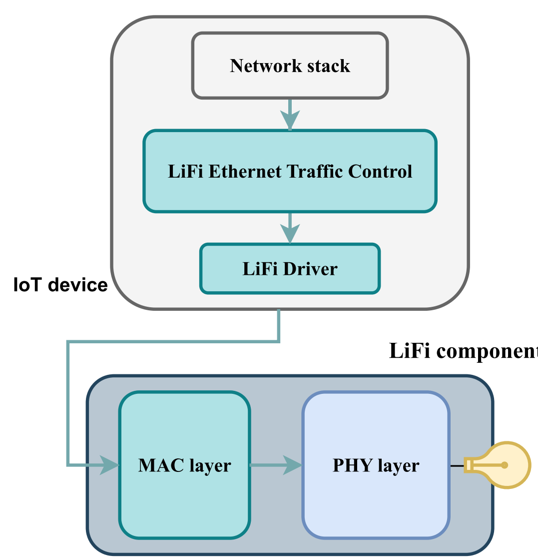


Fig. 2 LiFi protocol stack model

physical layer is related to the physical connections and is responsible for the data transmission itself. This layer provides an interface to the transmission medium. With LiFi systems, this transmission medium is light and uses LEDs. Layer 2 is responsible for controlling the hardware that interacts with the physical layer. As mentioned before, LiFi components act as a network interface with an associated MAC address. This helps to interact with the traffic flowing through the modules. Is in this layer where network slicing is introduced creating different queues and associating different traffic flows to them. This allows to control the traffic transmission by assigning different bandwidth or different latency to each traffic flow. Additionally, the host to which the LiFi device is connected, has the driver capable to interact with the LiFi component creating different slices. In short, by acting on layer 2 of the LiFi devices, different slices can be created to which traffic flows can be assigned. In Fig. 2, layer 2 of both the LiFi component and the host (IoT device) to which it is connected are shown in the same colour. With the information provided by the MAC layer of the LiFi component, the ID of the network interface and the metrics related to the traffic flow through it can be obtained. Once this data is obtained, configurations can be created from the host to modify the behaviour of this traffic by creating different slices.

5 Network slice control architecture design

In this section, the architecture used to achieve the extension of the network slicing capabilities on the LiFi segment is presented. Figure 3 specifies which components are used to accomplish this objective.

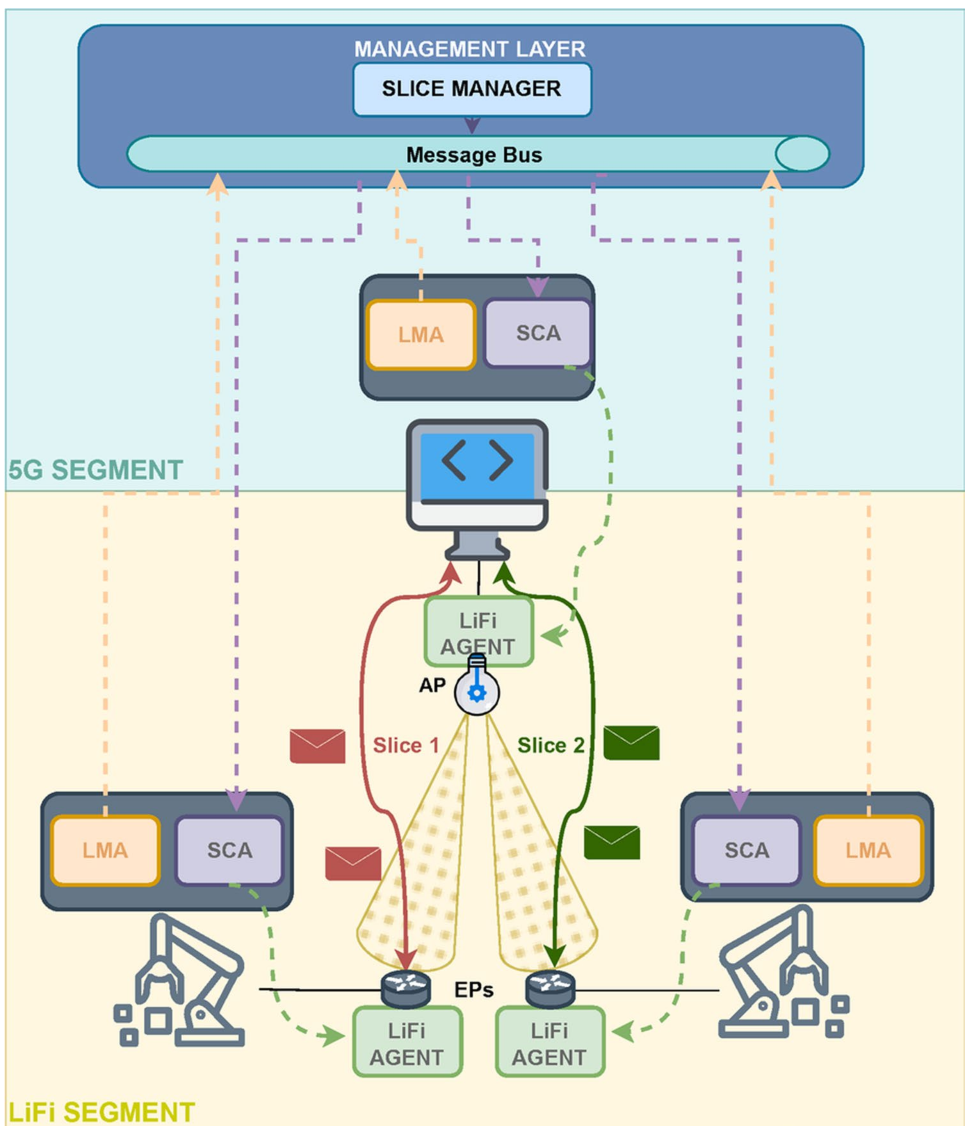


Fig. 3 Network slicing scenario over hybrid LiFi and 5G networks

The scenario presented in Fig. 3 is the same as the Fig. 1 but without the 5G components to simplify the explanation of the slice control architecture. Three important devices are shown in the scenario: one LiFi AP and two LiFi end-points. The LiFi access point is connected to the 5G user equipment. The LiFi end-points are connected to two IoT devices. The slice control components presented in the scenario are: the Slice Manager (SM) located in the management layer of the 5G architecture, the LiFi monitoring agent (LMA) and the Slice Control Agent (SCA). These last two components are situated in each network device. Such components and their interactions are detailed in Fig. 4. Their specific functionalities are also described below.

1. Slice Manager: the slice manager is situated in the management layer of the 5G architecture and is responsible of slice administration. It is in charge of requesting the creation or the cancellation of a slice. This request is based on intents that are transmitted to the SCA API. The decision to create a slice or not depends on the needs of the network and the importance of the traffic at that moment.
2. LiFi Monitoring Agent (LMA): a network component responsible for two differentiated functionalities. First, it is in charge of discovering topological network information in real-time. Such information comes from the network interfaces and the LiFi devices connected to them (whether APs or LiFi end-points). With this topological information, it is able to perform its second functionality, which is the monitoring of the LiFi devices. The LMA extracts metrics from the LiFi devices in real-time and publish them on the message bus. As it is shown in Fig. 4, the monitored metrics are configured by the metric engine.
3. Slice Control Agent (SCA): is responsible for the execution of the intent sent by the Slice Manager. Its functionality is to create or remove slices associated to a traffic flow. It consists of two layers. The first layer is

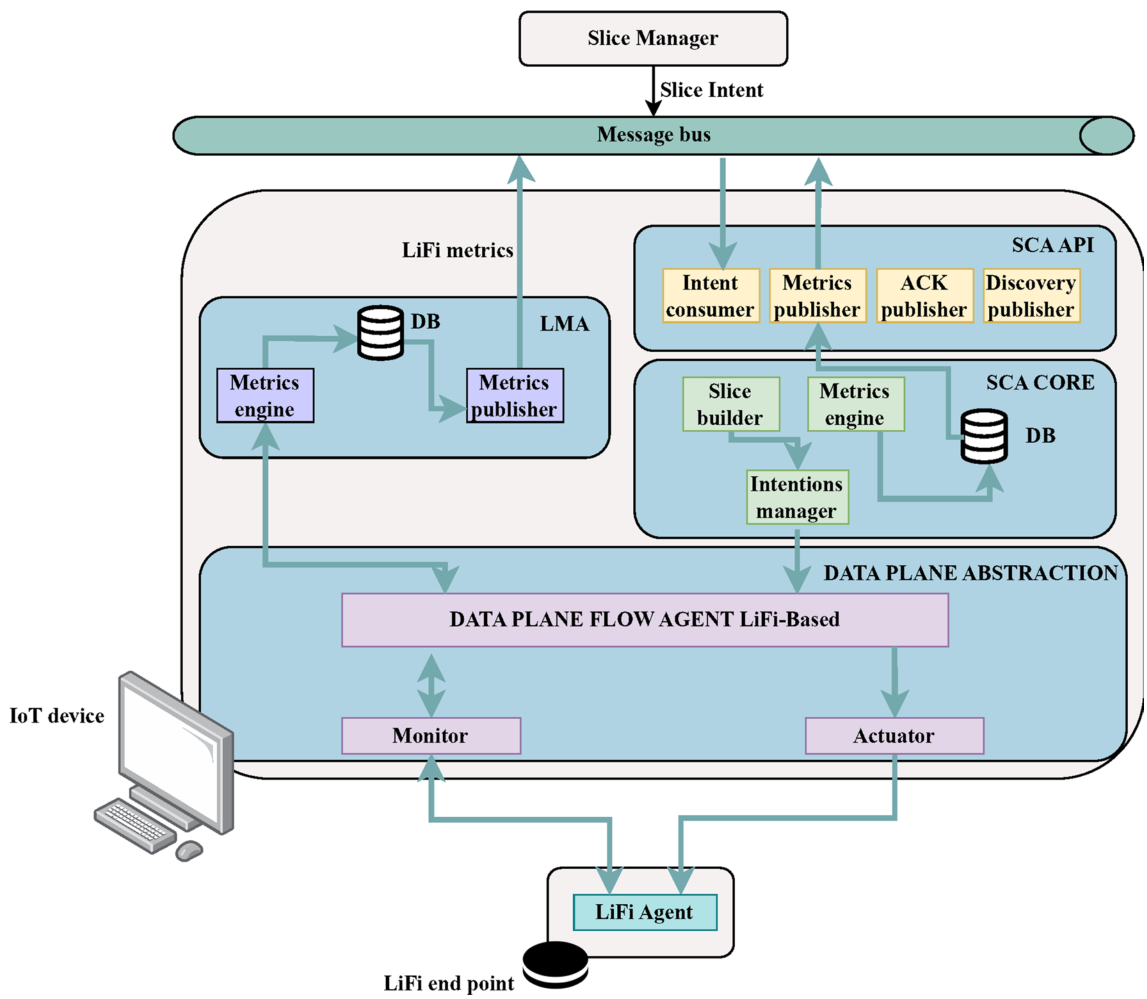


Fig. 4 Proposed functional architecture for network slicing over LiFi

an API with which the slice manager interacts by providing intents. This API also publishes metrics related to the state of the slices in the message bus so that the administrator can know the correct operation. The second part of the SCA is the SCA CORE. This division has two functionalities. The first one is in charge of the execution of the received intents. From the intent, a slice configuration is created with the specific parameters of bandwidth, latency or priority. Afterwards, the SCA CORE executes this slice on the agent or specific technology in order to modify the traffic sent through this agent. In the case of this research work, it acts on layer two of the LiFi device allowing the outgoing traffic to be queued and giving each flow the resources that were indicated in the intent sent by the slice manager. The second functionality of the SCA CORE is the collection of metrics related to the different slices that have been created. Once collected, these are stored in a database so that the SCA API can consume and publish them.

4. LiFi Agent: This component refers to layer 2 of LiFi devices. It is in charge of assigning priority to the different traffic flows. The SCA core acts on it to modify the behaviour of the traffic and in this way to be able to configure this behaviour in the way it is needed.

To better understand how a slice is created using these components, the diagram presented in Fig. 5 is used. As it is shown, the LMA obtains metrics of the LiFi network of each device and forwards them to the message bus. In this scenario, there are 3 devices, therefore, there are 3 LMAs, one for each LiFi device. Meanwhile, the Slice Manager reads the metrics from the manager bus and create a slice intent based on the ID of the device. The intent can be related to the bandwidth, latency or priority. Subsequently, this intent is sent to the SCA of the SCA and this last one is responsible for the creation of the slice, operating on the LiFi agent of the LiFi device.

6 Implementation details

This section explains details about the testbed infrastructure deployed to empirically evaluate and validate the RF-OWC architecture and the introduction of network slicing into the LiFi network. In addition, a description of the experiments carried out is presented.

6.1 Testbed infrastructure

To emulate the architecture presented in Fig. 1, several hardware components were used. On the one hand, for the 5G segment, three computers were located, one for the RAN, another for the 5G core and the last one for the management layer. All computers had the same capabilities. This were an Intel Xeon CPU E5-2630 v4 architecture with 10 cores operating at 2.20 GHz as the base frequency and a

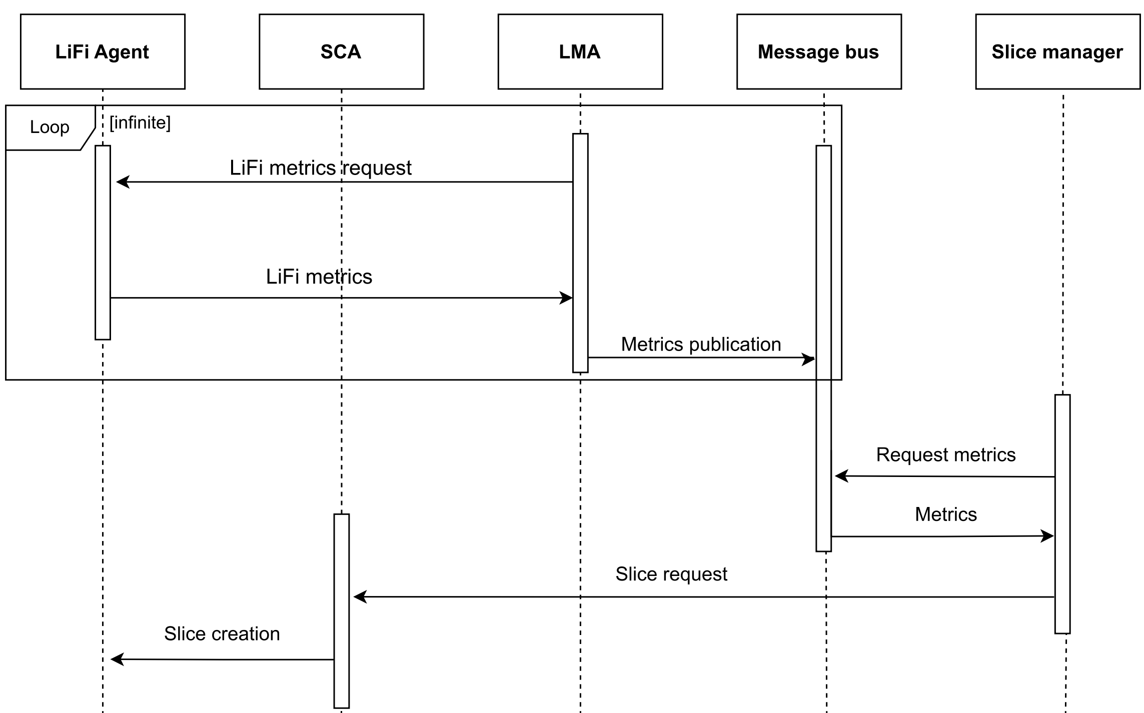


Fig. 5 Slice creation diagram

32 GB RAM memory. All computers had UBUNTU 20.04 as operating system running a Linux kernel with the 5.4.0 version. The software used for 5G network deployment was OpenAirInterface for both RAN and core.

On the other hand, for the LiFi segment, three computers were used to create the traffic flow. The first computer, called Controller, had two functionalities. First, it acted as gateway between the 5G segment and the LiFi network. Secondly, it was used as the access point for the LiFi end-points. For a better understanding, please refer to Fig. 3. The other two computers, were employed as user equipment emulating IoT devices.

Figure 6 shows how the testbed was deployed during the experiments of the LiFi segment. For the connection between the LiFi access-point and the Controller, RJ45 Ethernet cables were used. In the middle, a switch with PoE output was set up to give power to the LiFi access point. The LiFi end-points were connected to the other two computers via USB-C.

Both UEs had the same capabilities. An AMD Ryzen 5 3500U as processor operating at 2.10 GHz with for 4 cores and a RAM memory with a capacity of 8 GB. The kernel version and the Operating System installed were the same

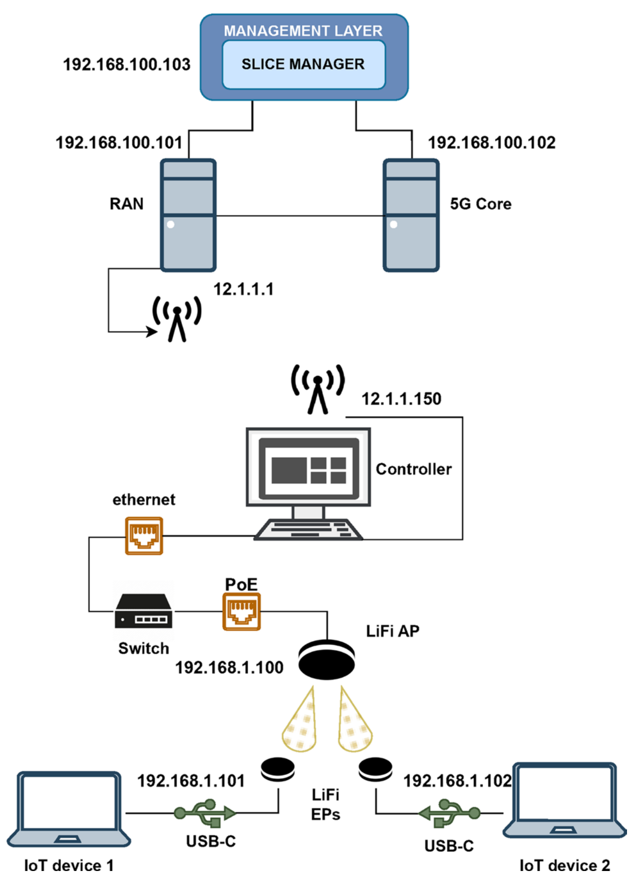


Fig. 6 Testbed used for the experiments

as the other computer. We had one access point and two end-points available for the experiments. This is the reason why all the results presented in section 7, contain these three components.

6.2 Experiments implementation

In order to test our architecture combining 5G and LiFi and the introduction of network slicing into an OWC system we developed two experiments phases. The first phase contained the study of the performance of the LiFi network itself. This is to test only the LiFi components we employed and to analyse the wireless network in this segment. For this purpose, different metrics were studied. The first metric was the throughput. With the analysis of this metric, we wanted to check whether the hardware provided by Oledcomm delivers what it promises. The specifications indicate that the LiFiMAX system offers a throughput of 100 Mbps on both uplink and downlink channels. Therefore, the question was whether the system can actually achieve these speeds. The second metric was the latency. With the analysis of this metric we wanted to know how long it takes for the packets to get from one LiFi component to another. Knowing the times that can be achieved, it is possible to know for which applications this technology is intended. The third metric was the jitter. This metric provides information about the variability of latency between different packets. This is whether the packets suffer the same conditions as they travel through the network from one point to another. Finally, the last metric studied was the percentage of packets lost during transmission. This metric provides information about the stability of the network and its reliability. The second phase of the experiments dealt with the analysis of the LiFi network under network slicing conditions. In order to do so, we tried to control the traffic flow through the LiFi network. This control would allow to manage the network resources depending on the service being provided. In this part, the architecture defined and explained in section 5 of the paper was introduced.

For the experiments, the same treatment of traffic was carried out in both phases. First, UDP packets with a specified length were generated and saved in PCAP files. The default UDP communication does not allow the location and identification of the packets, which makes it impossible to use it for the study of metrics such as latency. By not knowing which packet is which, it is not possible to know how long it has arrived at its destination. For this reason, it was necessary to manually create UDP packets modified in such a way that an identifier was located in their payload. With this, the different packets could be located at any time and in any part of the network. All this was using the Python language. By obtaining these packets and with the help of the Tcpreplay tool, it was possible to transmit these PCAP files at a constant bitrate. The Tcpreplay tool allows traffic to be sent at a manually assigned throughput. This made it possible to emulate traffic in the LiFi network. So, if we wanted to study how the network behaved with a transmission rate of 100 Mbps, we had the Tcpreplay tool send the PCAP file with the UDP packets generated at 100 Mbps and we measured at the destination to see if they were actually received at that rate. In addition, to test latency metric, traffic was sent from one LiFi component to another and forwarded back. By doing this, it was possible to measure the time a packet has spent sending and therefore to study the delay it had. The packet size chosen varies between 128 and 1500 bytes in 128-byte steps. Figure 7 shows the workflow carried out in the second phase of the experiments.

This phase was composed of 7 different steps. The first step was the design and definition of each of the scenarios to be studied. The different scenarios differed in the configuration of each of the slices to be applied to the devices. In total there were 3 scenarios. In the first scenario, no slice was introduced to study the behaviour of the network itself. It was analysed how the network managed the bandwidth resources when both end-users were receiving at their maximum capacity. For this phase of the experiments, packets with a length of 1500 bytes were used. The reason for this does not lie in any particular feature. As will be seen in the results section, as far as throughput is concerned, the network performs well with packets with that size. When we want to study the bandwidth behaviour with network slicing, it did not matter what packet size was chosen. In the second scenario, we limited the throughput transmitted to one of the LiFi components. We wanted to study the behaviour of network slicing in the downlink channel, as we wanted to prioritise the traffic sent to one of the end devices over the other. Finally, in scenario 3, the traffic sent by both end devices to the access point was modified.

The second step consisted of generating the UDP packets. This process was similar to the one explained above with the first phase of the experiments. The third step was to initialise the LMA component on each of the devices. This component would later allow us to monitor how the network behaves with each of the scenarios. This step was important as it was used to produce the graphs shown in the results section. Step 4 consisted of the transmission of the UDP packets. This was done once the LMA component was initialised in order to monitor the behaviour of these packets. When transmitting, each of the LiFi devices was assigned a specific source and destination port to transmit to. In this way it was possible to know which traffic was related to each of the devices. Once the traffic was constant, the process of introducing the slices was initialised. In step 5 a slice was requested to be applied and in step 6 this slice was assigned to the specified traffic. Finally, when the experiment was finished, step 7 analysed the results obtained.

All experiments had 1 min of duration. As mentioned before, it has only been possible to perform experiments with two devices. That is why experiments shown has only two LiFi end-points.

In relation to the results obtained, the different tests of the experiments have been carried out a total of 10 times. Therefore, graphs presented in the results section detail average analysis of each metric. In the case of the tests in which the network is checked, what is shown is the arithmetic mean of the metrics studied.

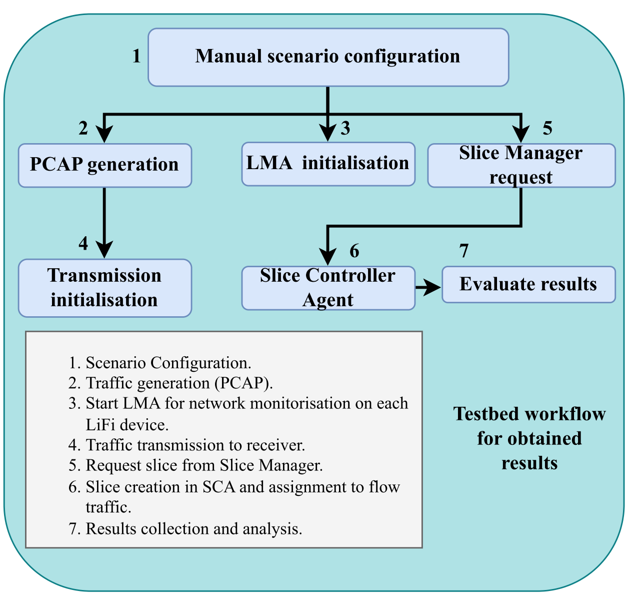


Fig. 7 Experiments Workflow

7 Results for empirical validation and evaluation

In this section, the empirical results obtained of the LiFi segment assessment are presented. As the number of phases in the experiments, this section is divided in two different subsections. First, there is a LiFi network analysis using one single LiFi end-point and one LiFi access point. Secondly, the outcomes of the introduction of network slicing into the LiFi segment is shown.

7.1 LiFi network performance

The aim of these experiments is to analyse how LiFi network performs and if it gives a real stable network to work with. Therefore, the metrics that have been studied have been chosen in such a way that it can be proved whether this is the case. The results obtained with each of the metrics are presented below.

7.1.1 Throughput

First metric studied was the throughput achieved using LiFi-MAX system. This parameter defines how much information can be send in a period of time. In networks, usually it is defined as the quantity of bytes sent in a second.

$$Throughput = \frac{Information(Bytes)}{Time(seconds)}$$

Figure 8 shows the results obtained. The figure shows a comparison between the theoretical bandwidth and the throughput achieved. The Y-axis (bandwidth) indicates the rate at which the packets were sent using the Tcpreplay tool from the sender. The Z-axis (throughput) indicates the rate at which these packets were received at the receiver. The maximum throughput achieved using these devices was close to 99 Mbps in both uplink and downlink. This is very close to what the manufacturer promise. However it can be seen that by using smaller packets (128 or 256 bytes), the practical bandwidth decreases compared to the theoretical.

To understand this behaviour, it is necessary to explain how the transmission system of the LiFi system works together with the Linux TC management system. When transmitting packets, the first step of this system is to put the packets into virtual queues. Depending on the existing policies on these queues, packets will be assigned one priority or another for transmission. Depending on the size of the packet and the speed at which it is transmitted, the queuing system will fill up more or less quickly. When using large packet sizes, e.g. 1500 bytes and sending them at a rate of 100 Mbps, the number of queued packets is lower than if a smaller packet size is used. In other words, using the same bandwidth, it takes more small packets than large packets to cover the same size of information. An example to understand this is that to cover 1 Mb (10^6 bytes) it takes 667 packets of 1500 bytes or 7812 packets of 128 bytes. Therefore, if small packets are used, the queues fill up faster and cause transmission delay or packets to be discarded altogether. Therefore, in Figure 8, when using small packets with a transmission rate of 100 Mbps, there is a decrease in the final throughput. There are a number of packets that are delayed during transmission, lowering the throughput achieved.

In any case, the conclusion reached regarding throughput is that the network is capable of operating adequately up to 90 Mbps. Beyond that, the network was often inconsistent in its performance and often presented problems. This will be discussed further in the following metrics.

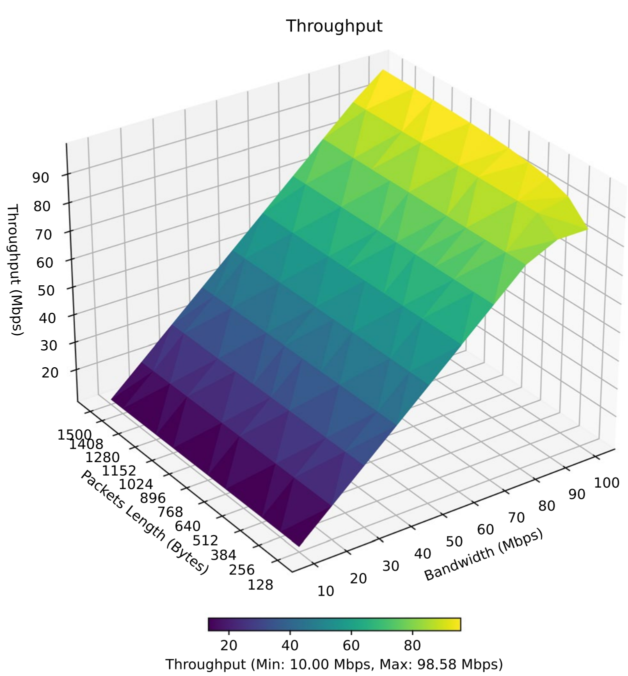


Fig. 8 Throughput obtained with the LiFi network

7.1.2 Latency

The second metric measured is latency. With this parameter we wanted to check if LiFi provides low latency as the 5G network promises and therefore does not affect the RF-OWC architecture. Since packets were modified to be tracked, by sending them to LiFi end-point and sending them back, the time they spend in transmission can be measured. Therefore, the equation used to derive this measure is as follows.

$$Latency = \frac{Round\ trip\ Time}{2}$$

Figure 9 shows packets delay time from the access point to the LiFi end-point. Again, the Y-axis indicates the theoretical bandwidth used using Tcpreplay, the X-axis indicates the packet size and the Z-axis indicates the latency obtained in one direction only.

The results show what was expected from the network and are related to the explanations of how the queuing system of the devices works. Up to the 80 Mbps bandwidth, the latency obtained for different configurations of packet size and bandwidth is minimal. From that point onwards, in the smaller size ranges, packets start to be queued, causing the latency to increase. In the larger packet size ranges, the latency remains minimal until 1500 bytes are reached. At that packet size, the latency starts to increase as well. From 90 Mbps onwards, the behaviour of the network, as mentioned in the previous metric, becomes unpredictable as this approaches the maximum bandwidth in the system as designed. It remains true that for smaller sizes, the latency increases as with the maximum size. However, undesirable behaviours occur that may be related to how the queuing

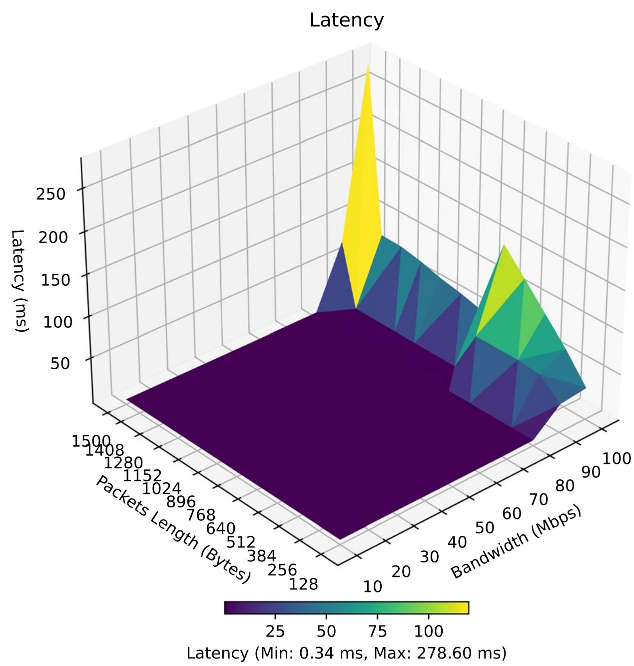


Fig. 9 Latency obtained with the LiFi network

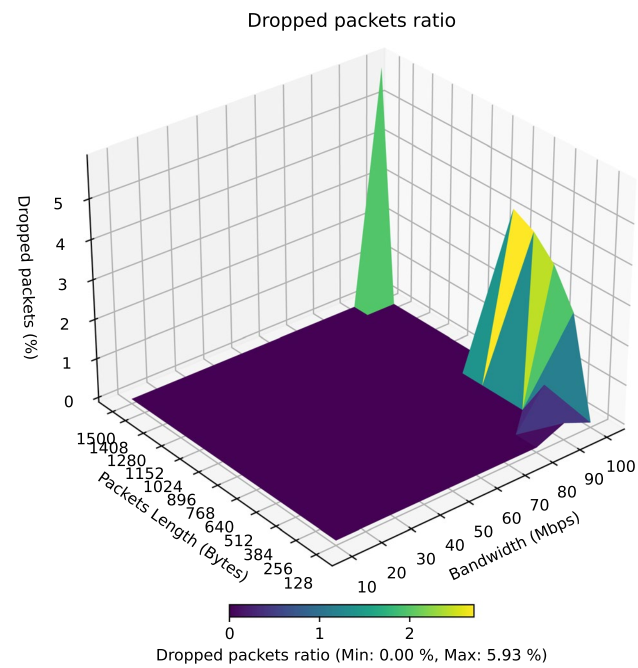


Fig. 10 Dropped packets ratio obtained with the LiFi network

system, the Linux kernel or the LiFi devices themselves work. This is the reason why we have mentioned that even if the system manages to reach 98 Mbps on some occasions, the optimal performance has been considered to be up to 90 Mbps. The minimum latency achieved is about 0.34 ms while the maximum latency is up to 278 ms.

7.1.3 Packet loss

The metric that provides the most clarity in understanding the performance of the LiFi network is the quantity of packets lost. With this metric it is possible to analyse what percentage of packets have been lost during transmission and therefore have not reached their destination. In a stable and perfect network, the percentage should be zero. In our scenario, the results obtained can be seen in Fig. 10.

Figure 10 shows that as the bandwidth exceeds 90 Mbps, the percentage of lost packets increases considerably. The behaviour of this metric resembles the behaviour of latency. With small packet sizes and the maximum (1500 bytes), at higher speeds more packets are discarded. Between the 80 Mbps and 90 Mbps range, 128 Mbps packets are discarded the most. The scenario where more packets are queued. From 90 Mbps onwards the behaviour of the network starts to be unpredictable within the same logic. However, the number of packages that have been lost is minimal. In the worst case, using 1500 bytes at 100 Mbps, a total of 5.93% is lost. In scenarios where conditions are more controlled, the percentage is 0%.

7.1.4 Jitter

Finally, the last parameter analysed was the jitter. This metric indicates the variance in the delay of packets arriving at their destination. Ideally, the value of this parameter would be 0 indicating that the system provides equal latency for all packets. Therefore, with this parameter is possible to know if the packets arrive at the destination in order or not. An example of how the jitter between 2 packets would be calculated would be the division between the latency of packet A and packet B as can be seen with the following equation.

$$Jitter = \left| \frac{Rx_A - Tx_A}{Rx_B - Tx_B} \right|$$

Figure 11 presents the results obtained. The results indicate a very low transmission jitter. The analysis shows values of less than half a millisecond indicating that LiFi provides or achieves packet transmission with the same latency regardless of packet size and bandwidth. Figure 11 shows results with a lot of variances. As the values are very small, the chaotic behaviour of this metric may be related to other aspects not related to the network, such as the devices themselves. The conclusions drawn indicate that these differences are not significant but jitter is very controlled in the LiFiMAX system achieving a very stable communication.

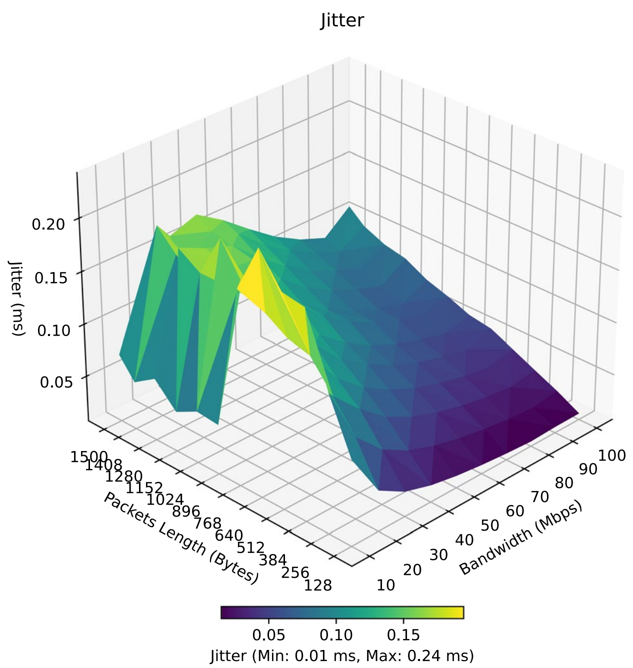


Fig. 11 Jitter obtained with the LiFi network

7.2 LiFi network performance discussion

From the results obtained from the analysis of the different metrics, several points can be concluded. The first is that the network is able to work optimally up to 90 Mbps. Above this throughput it becomes more unstable and more packets start to be lost and latency increases. The second point is that packet size matters. Smaller packets cause the queuing system to congest and therefore start discarding packets and take longer to transmit them. This is also true for the largest packet size (1500 bytes). This size coincides with the MTU size and can therefore also influence the transmission time. Regarding jitter, it remains small in all scenarios indicating that the network behaves the same for all packets sent.

7.3 LiFi network slicing

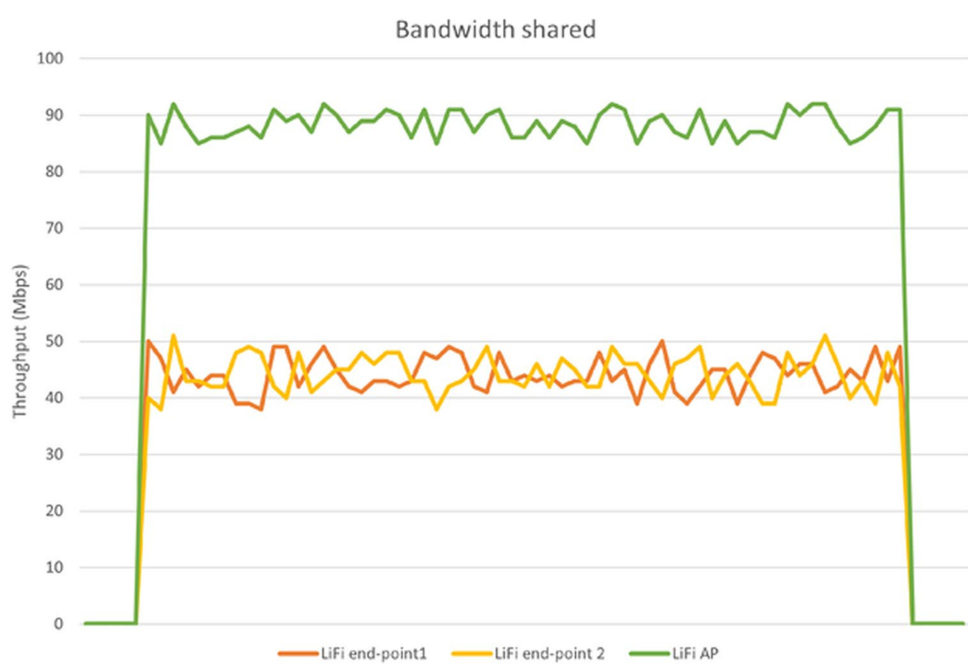
This subsection explains results obtained from the second phase of experiments The objective is to configure the bandwidth given to the different LiFi devices. With the proposed architecture, the slices created can be in both uplink and downlink channels as the necessary components (please refer to Fig. 4) are similar and exist in the different LiFi devices. Bandwidth used for this round of experiments was 90 Mbps instead of 100 Mbps because with this throughput, the network seems to be more stable resulting in less packet loss as was proven in the first round of experiments.

7.3.1 Two LiFi end-points without network slicing

The first case discussed is where both users are connected to the network sharing the same bandwidth. In Fig. 12, results of the throughput associated to each of the devices can be found. The green colour symbolises the traffic sent by the AP to the different users while the yellow and orange colour symbolises the traffic received by each one of the end devices.

In the absence of any slice that allows a specific bandwidth to be associated with each user, the access point is forced to share the resource between both EPs. In this case,

Fig. 12 Bandwidth equally shared by both devices



there is no directive on which the AP select how much bandwidth has to assign to each EP resulting in packet loss. In this scenario, AP is trying to transmit at 90 Mbps to each EP. Because of no slice to guarantee the BWP, AP transmits everything it can, resulting in sending only the half of the traffic for each EP and discarding the rest. Consequently, QoS is quite degraded. Figure 12 shows how at different times, one user receives more traffic, and in other cases it is the other way round.

7.3.2 One LiFi end-point limited

The second case addressed in these experiments is when a specific bandwidth is allocated to an end-user. Figure 13 shows the results obtained. As in the previous case, the colour scheme is the same and the direction of transmission is also the same.

In this scenario, LiFi end-point 2 is allocated a specific bandwidth of 20 Mbps to allow the other device to use the rest of the bandwidth. As can be seen, as in the previous case, at the beginning of the transmission, the AP is sending traffic at a specific rate for both EPs, which is 90 Mbps. AP divides the traffic flow between both end users. Consequently, there are packet loss during the process. Both EPs are receiving close to 40 Mbps of traffic. To improve this situation, a network slice is created for EP-2. Figure 13 shows that once the slice is created, EP-2 traffic becomes constant using only 20 Mbps throughput during the transmission, leaving more bandwidth resources to EP-1. The AP is still sending the same traffic, although EP-2 only receives 20 Mbps. Here we demonstrate how the proposed network slicing solution can control the traffic sent by the AP. This scenario may facilitate the timely delivery of critical information to a designated end user, such as EP-2, necessitating urgent processing. This improves the QoS provided to the second EP since the packet loss rate has decreased.

7.3.3 Network slicing in uplink

As mentioned above, the proposed solution also allows the creation of slices in the uplink channel. In this case, it is the LiFi EPs that are transmitting to the AP. Figure 14 shows the results obtained. The traffic sent by both EPs is shown in orange and yellow. In green, we can see the traffic received by the AP.

During these experiments, both EPs send at 90 Mbps during the entire transmission. However, it can be seen that the access point is not able to tolerate all the incoming traffic and is forced to discard packets at the entrance of the system. This happens for the same reason as explained above, and that is that the devices have specific specifications. To solve this problem of congestion in the AP, 2 slices are introduced. The first one limits the outgoing traffic from EP-1 to 10 Mbps and the second one limits the outgoing traffic from EP-2 to 50 Mbps. As a consequence, the AP will receive only 60 Mbps, eliminating all congestion and making it not discard any packets. Note that the rate at which traffic is being sent on the EPs has not been changed. The process that is in charge of sending the traffic is still sending at 90 Mbps. What has been limited by the slice is the useful bandwidth

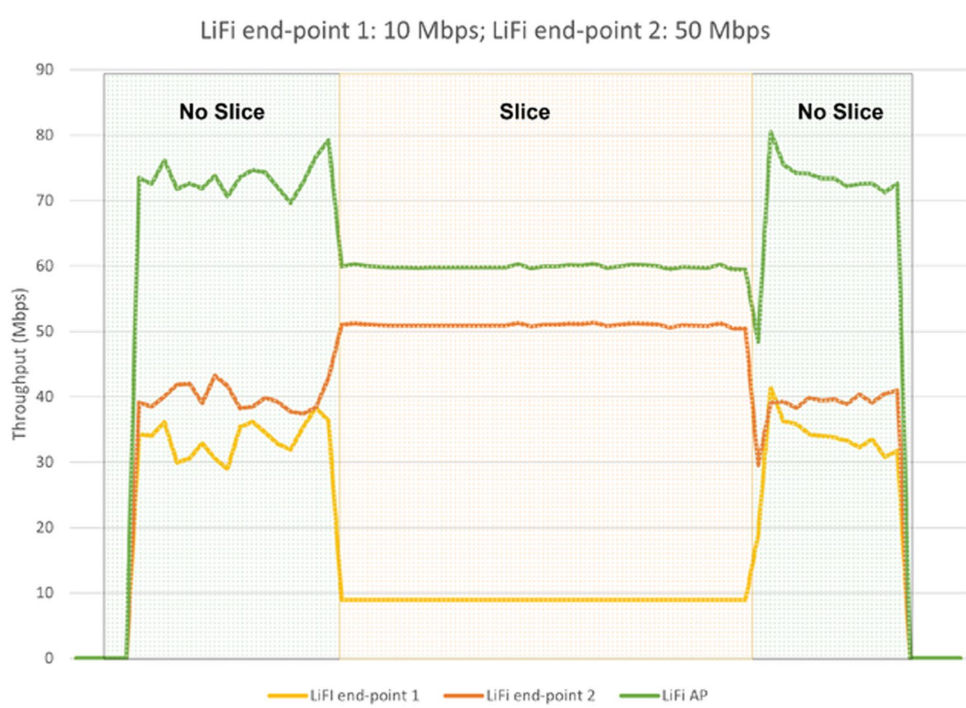


Fig. 13 One LiFi end-point limited

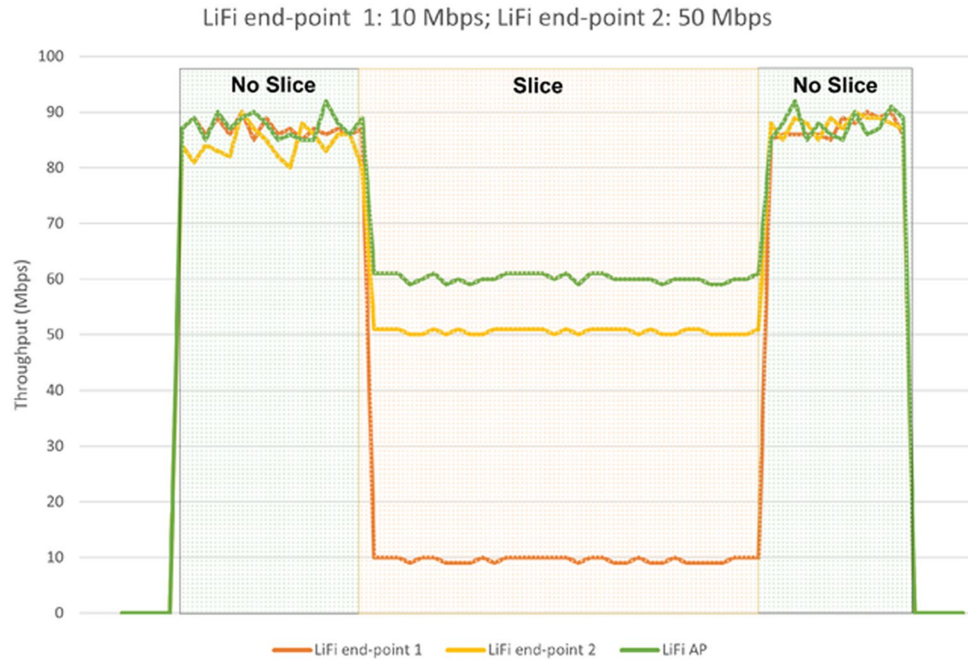


Fig. 14 Network slicing in uplink

used by the LiFi system for transmission. With this, the traffic that was causing congestion on the AP has been limited and brought under control.

8 Conclusion

In this paper we have presented the novel introduction of network slicing capability for the first time to a LiFi network. With this new feature it has been possible to control the traffic flow through the network by allocating the necessary network resources to each of the users. The empirical results have shown how the bandwidth has been modified as planned in real time, improving the quality of service of the prioritised UE whilst limiting the resources of the other. To carry out this work, both a 5G network and a LiFi network have been deployed to perform the field experiments. With both, a heterogeneous network has been achieved in which the 5G network acts as a backbone network and the LiFi acts as a local area network. In addition, in order to introduce network slicing over the LiFi network, a framework with different components has been created to monitor and control the network traffic. This framework is present in the LiFi network and is managed from the management layer of the 5G network, minimising the management overhead. To the best knowledge of the authors, this is the first time that network slicing has been achieved in an OWC system. However, some limitations have been found during the study of the LiFi network. The first one is to be able to study the network with several UEs. The LiFiMAX system used in this paper only had two UEs and one AP, and thus it was only possible to work with a maximum of two UEs. Even so, it has been possible to demonstrate how the traffic of the two UEs behaves when network slicing is introduced. The second limitation has to do with the mobility of the users. As there is only one AP, mechanisms such as handover could not be tested. Finally, the bandwidth limitation was also an important point. The LiFi system used was a prototype that can only offer a maximum bandwidth of 100 Mbps. This is why experiments with higher throughput were not possible. All these limitations will be considered for future work, including the improvement of the developed framework.

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