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Article *in* Applied Sciences · July 2023

DOI: 10.3390/app13137906

4 authors, including:

Gerardo Hernandez-Oregon
Instituto Politécnico Nacional

Mario Eduardo Rivero-Angeles
Instituto Politécnico Nacional

Juan Carlos Chimal
Instituto Politécnico Nacional

applied sciences

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Performance Analysis of P2P Networks with Light Communication Links: The Static Managed Case

Gerardo Hernández-Oregón †,‡, Mario E. Rivero-Angeles *,†,‡, Juan C. Chimal-Eguía †,‡ and Jorge E. Coyac-Torres †,‡

Centro de Investigación en Computación, Instituto Politécnico Nacional, Av. Luis Enrique Erro S/N, Mexico City 07738, Mexico; ghernandezo1101@alumno.ipn.mx (G.H.-O.); jchimale@ipn.mx (J.C.C.-E.); jcoyact1900@alumno.ipn.mx (J.E.C.-T.)

* Correspondence: mriveroa@ipn.mx; Tel.: +52-55-57-29-60-00-56661

† Current address: Centro de Investigación en Computación, Nueva Industrial Vallejo, Av. Juan de Dios Bátiz S/N, Gustavo A. Madero, Ciudad de México 07738, Mexico.

‡ These authors contributed equally to this work.

Abstract: *Peer-to-Peer (P2P)* networks have emerged as potential solutions to issues that cause inefficient download times in networks because they can use the resources in the entire network, allowing nodes to act both as servers and clients simultaneously. Commonly, P2P networks use *radio frequency (RF)* to communicate among nodes; however, *light fidelity (LiFi)* has been developed as an alternative to *wireless fidelity (WiFi)* systems due to some advantages such as great speed (up to 1 Tbps), a high level of security, and less saturated channels in unlicensed bandwidth, making it ideal for RF-sensitive environments and networks with static nodes, since LiFi systems require a high node alignment level to enable efficient communication. In this article, we develop a mathematical model that captures the dynamics of LiFi- and WiFi-based P2P networks in static environments to allow for adequate LiFi links in managed conditions where the content is distributed from a single source node to the rest of the peers through different architectures. For the services considered in our work, we compare the performance of P2P networks using WiFi 7 and LiFi 2.0 technologies to provide clear quantitative numerical results that allow for adequate selection between these systems. Also, we validate our mathematical results through extensive simulations.

Keywords: P2P; LiFi; decentralized; teletraffic; CTMC; analysis

Citation: Hernández-Oregón, G.; Rivero-Angeles, M.E.; Chimal-Eguía, J.C.; Coyac-Torres, J.E. Performance Analysis of P2P Networks with Light Communication Links: The Static Managed Case. *Appl. Sci.* **2023**, *13*, 7906. https://doi.org/10.3390/app13137906

Academic Editor: Agostino Forestiero

Received: 8 May 2023
Revised: 3 July 2023
Accepted: 4 July 2023
Published: 5 July 2023

1. Introduction

The rapid growth in the number of devices connected to the Internet (between 41.6 billion [1] and 500 billion [2] by 2025), the high demand of hot spots of traffic in local networks, and the size and number of data transmitted mainly due to the video streaming services and video content in social networks in the last decade have prompted the creation of new technologies and architectures to provide an adequate service to users in these highly demanded scenarios. In view of this, the new generation of telecommunication systems must be able to handle high traffic demands, providing low latency and high download rates to users demanding very different services in different scenarios. Also, congestion in these systems can be aggravated by variables such as the number of nodes in a centralized structure, upload and download bandwidths, and storage and processing capabilities. As such, traditional client–server structures to share files rapidly deteriorate by the increase in the number of nodes in the network, and in the same way, P2P networks are useful due to the fact that they can offer scalability (generally, a greater number of peers constitutes a better performance). This is because a basic P2P network is constituted of nodes that act as both servers and clients; this means that nodes can download and upload information to each other at the same time. On the other hand, in many popular P2P networks such as *BitTorrent*, the data sent in the network are divided into smaller pieces called *chunks*, and peers are identified as either *leechers* or *seeds*. *Leechers* are peers that have not downloaded all the chunks (or even none); conversely, *seeds* possess all chunks, and they can share the complete file to any *leecher*. Furthermore, P2P networks have been extensively studied under radio frequency channel assumptions, but they have been largely overlooked for light channel scenarios. Currently, WiFi is one of the most widely used technologies worldwide, and it is in continuous improvement processes in the face of adversities and applications that come year after year. In this context, WiFi 7 has arisen through the need for new challenges presented by low-latency or real-time technologies in the *Internet of Things (IoT)* paradigm, such as multimedia, healthcare, *augmented reality/ virtual reality (AR/VR)*, and industrial and transportation applications [3]. WiFi 7 was developed from the IEEE 802.11be standard, and can reach throughput/speed peaks of up to 30 Gbps and incorporate solutions to WiFi ecosystems as multilink and multiaccess point operations, also reducing latency and jitter in these environments [4]. Consequently, due to the advantages that WiFi 7 presents, we consider this technology for the models and simulations of this article. Conversely, LiFi has emerged as a technology capable of transmitting data through light (visible or invisible), creating and complementing solutions to emerging technologies through *Internet of Everything (IoE)* and vehicular networks [5], as well as outdoor and indoor applications. Specifically, LiFi could substitute WiFi systems in hostile areas for existing technologies, in case of a shortage in the radio frequency spectrum or highly saturated channel environments, in high traffic demand, and high-node-density applications such as classrooms, museums, concerts, sporting events, and airplanes, among others. LiFi uses the ranges of visible light (VLC), infrared (IR), and ultraviolet (UV) as unlicensed bandwidth, also establishing itself as a green [6] (since LiFi works through light waves, which are not harmful for life, it also utilizes the current light infrastructure and reduces carbon footprint with respect to other technologies), secure (data cannot be received outside the walls of a certain room; hence, a potential malicious agent has to be in close proximity to the receiver, complicating their unauthorized access), fast (peaks of throughput of up to 1 Tbps in the case of LiFi 2.0 [7]) and low-cost (used with existing infrastructure) [8]. LiFi 2.0 works through the 802.11bb standard and concentrates energy to achieve high rates of transmission. However, LiFi systems require a relatively high alignment accuracy among nodes, effectively reducing the mobility of nodes. Since nodes are considered to have null mobility capabilities, otherwise the use of LiFi would not be possible or effective, nodes cannot arrive or leave the system as it occurs in conventional P2P networks. Hence, the population in the system is considered to be finite and closed. This is a major challenge, and required important modifications to the traditional models developed in previous P2P studies. Building on this, we consider managed networks where the download procedure is initiated and controlled by the system administrator. There are many systems with these characteristics, such as in education, where the teacher shares files with the rest of the class; museums, where people get close to a particular display (where they remain static during a certain period) and information is downloaded to the visitor's devices; in cultural and sporting events, where people are seated with no mobility, and the stadium or concert hall distributes information regarding the event or in future applications where augmented reality and virtual reality capabilities are downloaded to the attending audience. Note that in different scenarios, where high degrees of mobility are allowed, it would not be possible to provide a fair performance comparison between LiFi and WiFi systems, since the link quality is greatly degraded if the node alignment is lost in light-based transmissions. In such cases, it is clear that RF-based transmissions should be adopted. Based on this, for applications where nodes are without mobility, it is not clear or straightforward to choose among these technologies, i.e., choose between RF or light, as a communication technology. In this work, we provide a mathematical analysis, based on continuous-time Markov chains (CTMCs), of P2P networks using either RF or light transmissions to study and understand the limitations and advantages of each technology. To the best of our knowledge, this is the first work that considers and models a P2P network with LiFi capabilities. As such, we aim to supply clear guidelines for the implementation of these systems by providing quantitative performance results in terms of the average file download time for the different number of nodes and network architectures. Specifically, we model both WiFi and LiFi wireless technologies in their most recent versions (*WiFi 7* and *LiFi 2.0*), contemplating these technologies in *static* node scenarios (considering *line-of-sight (LOS)* and *non-line-of-sight (NLOS)* propagation modes for LiFi environments) for centralized and decentralized networks. The main contributions of the article are listed below:

- We develop a mathematical analysis of P2P-managed systems with no mobility capabilities that allow for the introduction of light-based transmissions.
- We provide a detailed performance comparison between LiFi 2.0 and WiFi 7 networks.
- Several scenarios are proposed in order to evaluate average download time and node variation in networks (P2P-WiFi, P2P-LiFi, centralized WiFi (C-WiFi) and centralized-LiFi (C-LiFi) networks).
- A P2P-LiFi concept is introduced based on the operation and characteristics of LOS and NLOS scenarios.
- We provide performance metrics in terms of the average download time for different file sizes across different network population sizes.
- In addition to a numerical solution for the continuous-time Markov chain (CTMC), discrete event simulations (DES) of each scenario are provided to validate the analytical model.

In the following, the organization of the paper is detailed: In Section 2, we present a short brief about some articles related to P2P, LiFi, and WiFi networks in a general way, since Sections 3 and 4 address these issues by detailing the features and models of P2P networks and the operating modes in which LiFi and WiFi networks will be used. In addition, Section 5 outlines the scenarios and values used in the experiments, while in Section 6, we develop the mathematical models through the CMTC of the system, as well as the equations and algorithms involved. Finally, in Sections 7 and 8, we present and validate the solutions proposed by means of relevant numerical and graphical results.

2. Related Work

As stated before, P2P networks may provide a solution to the exponential growth of connected devices. Indeed, by 2030, we expect to have hundreds of millions of devices in indoor environments [9]. As such, P2P networks reduce—and in some cases avoid—bottlenecks at the servers, since each node connected to the system provides additional resources. P2P networks have been extensively studied before in works such as [10]. However, our work proposes a totally different mathematical analysis based on transitory CTMCs, while in these previous works, they use irreducible CTMCs. The reason for this is to model static P2P networks, where nodes have to maintain a certain degree of alignment to allow for the use of LiFi communications. Also, since nodes are not allowed to enter or leave the system in the considered applications, we model managed networks where the administrator controls the download procedure. As stated earlier, this is the first work that develops such models for P2P networks with LiFi capabilities. Although there are a large number of works related to performance analysis in LiFi networks, most of them focus on the study and modeling of sender–receiver orientations [11,12], as well as their radiation patterns, distances, and angles of incidences [13] to estimate metrics such as signal-to-noise ratio (SNR), signal-to-interference-and-noise ratio (SINR), and bit error ratio (BER). Therefore, another important contribution of our work is to present relevant data about the performance of a LiFi network through the estimation of its download times under certain environments and configurations.

By taking a look at alternatives to improve network performance, we find the use of decentralized networks such as those implemented in *decentralized federated learning (DFL)* models through *machine learning (ML)* as presented by Mengxuan Du et al. [14], which looks for the exchange of parameters between neighbors promoting *device-to-device communication (D2D)* to reduce communication costs in IoT environments and thereby improve data compression and collaboration efficiency. In the same way, Fitsum [15] presents the idea of a decentralized system through a decentralized deep reinforcement learning (DRL) for each user to dynamically learn the selection of bands that maximizes its download rate, improving resource utilization and predominance of *quality of service (QoS)* in the system and modeling the behavior of each *access point (AP)* as a Markov chain. The previous work shows the efforts being made in the field of decentralization structures in networks for the optimization of resources due to the way that nodes behave in the network and that they can be modeled by Markovian processes. However, important efforts also predominate in the types of technologies that are used, and in many cases, complement to give way to new technological alternatives. Despite the fact that most research considers total mobility in P2P networks, in the context of static managed networks, there are some interesting works, such as those presented by Charalambous [16], Vicino [17], and Tsoumakos [18], where semistatic P2P networks are studied using mathematical models and simulations, in which some of the nodes are maintained with some mobility over time and the rest remains static, obtaining network performance metrics such as success rate, messages per requests, successful delivery ratio, and latency, among others (unlike these works, we do not measure the impact of network mobility; on the contrary, we consider nodes with null mobility, according to the principles of operation of LiFi).

Interestingly, there is another range of work related to P2P networks in which a description is made of the advantages of using decentralized structures instead of classical ones through specific techniques and protocols such as Juxtapose (JXTA) [19,20], Context-Aware Recommendations (CARS) [21] or Coordinated Multi-RobotExploration Aquila Optimizer (CME-AO) [22] in the branches of genetic computing, networking, and automation. In addition, all these analyses can be potentially applied in static scenarios such as hospitals, robotized processes, and museums [23].

On the other hand, an important branch has emerged in the use of optical and radio frequency technologies; although there are currently no works related to the comparison of their performances in many metrics, major studies focus on the formation and development of hybrid networks between these technologies, as can be seen in works about LiFi and WiFi hybrid networks [24], which is based on the AP selection of the most convenient technology in energy consumption, taking into account the number of nodes in IoT networks and preferably looking for static APs. Likewise, the work presented by Sanusi [25] describes load-balancing processes in LiFi and WiFi channels for the handover process (processes approached with various techniques like self-adaptive medium access control (SA-MAC) protocols [26] or hidden Markov models (HMMs) [27]). In addition to focusing on LiFi and WiFi networks, some other works model and measure metrics such as permanence times (performing simulations with Monte Carlo, also capturing the mobility of users in the system [28]), throughput, delay (using the enhanced distributed channel access (EDCA) protocol for channel selection [29,30]), and packet drop rate (analyzing the MAC layer to improve throughput across the network and calculating collision probability and packet drop rate [31]), among others. In our work, since nodes are static, and the download procedure is fully controlled by the administrator, we do not consider mobility or packet drop rate. Conversely, we provide average file download times in different architectures and scenarios.

Finally, and keeping in mind that there are not many works about LiFi performance and use cases, this article proposes a novel comparison between pre-existing scenarios, such as those in which WiFi is used, and unprecedented scenarios, which use LiFi in P2P and centralized environments, describing the characteristics and considerations of each of these systems and providing guidance to enable the use of new alternatives for the exchange of large amounts of information. Consequently, new concepts of LiFi networks are added to the literature, supported by quantitative results.

3. Centralized and Decentralized Networks

In this section, we explain in detail the centralized and P2P networks studied and mathematically modeled in this work. As previously mentioned, another way to optimize the average download times in a network could be through the structure and organization (logical and physical) in which the system works. In general, architectures can be measured by standard parameters such as bandwidth, transmission rate, storage or processing capacity, the technologies used for their operation, topologies, and the way that nodes interact in the network. Due to this last parameter, two main architectures of great impact have been used in current networks, namely centralized architectures (client–server) and decentralized architectures (peer-to-peer (P2P)) [32]. Centralized networks, such as the one depicted in Figure 1, are mainly used for transferring data from single or multiple servers to every client. This occurs even if the information shared is the same in many nodes such as in social media and video streaming applications. Hence, every client requests resources from the server, which can cause bottlenecks in case the traffic load is high, demanding a higher download bandwidth than the available bandwidth at the servers.

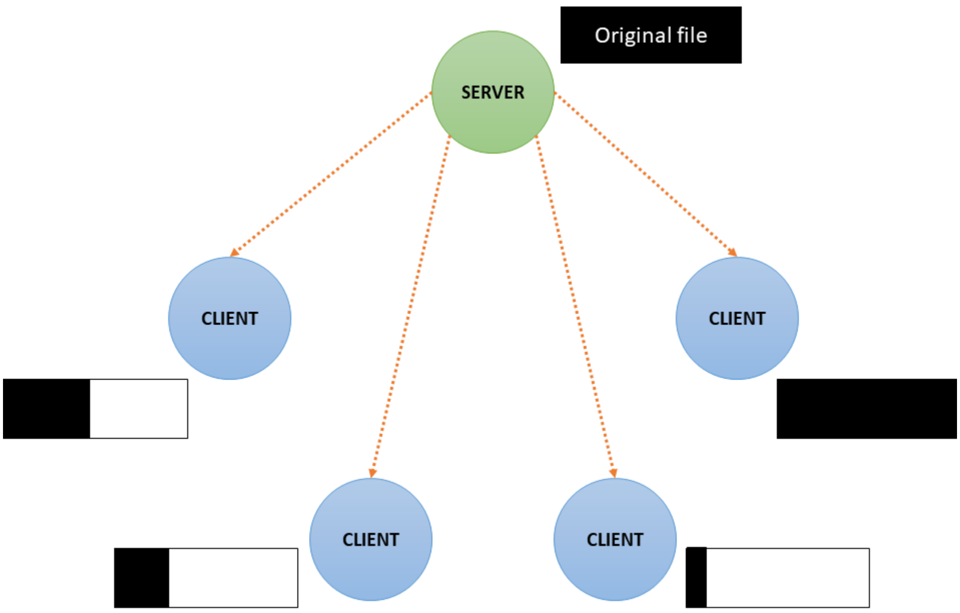

Figure 1. Client–server structure: download links from server to clients.

Conversely, P2P networks allow each node to behave as a client and server, downloading and uploading data, as illustrated in Figure 2. In addition, in P2P networks, the shared files are divided into small segments called *chunks*, so that the nodes can share their chunks with the rest of the peers in an efficient manner. Indeed, if chunks are too long, it would take much more time for a given node to download them and start sharing its resources. Then, the system has one or multiple servers that contain the complete file and starts downloading some chunks to arriving nodes. After a certain time, some nodes will complete the download process and they become *seeds*, i.e., nodes that have all the chunks, while nodes that do not contain the total *chunks* are referred to as *leechers*. Note that seeds can share all their resources with any other leecher, while some leechers, even if they have some chunks, cannot always share their resources, since they may have the same chunks. In this regard, the P2P system attempts to distribute different chunks to different peers, allowing for a more efficient data-sharing procedure.

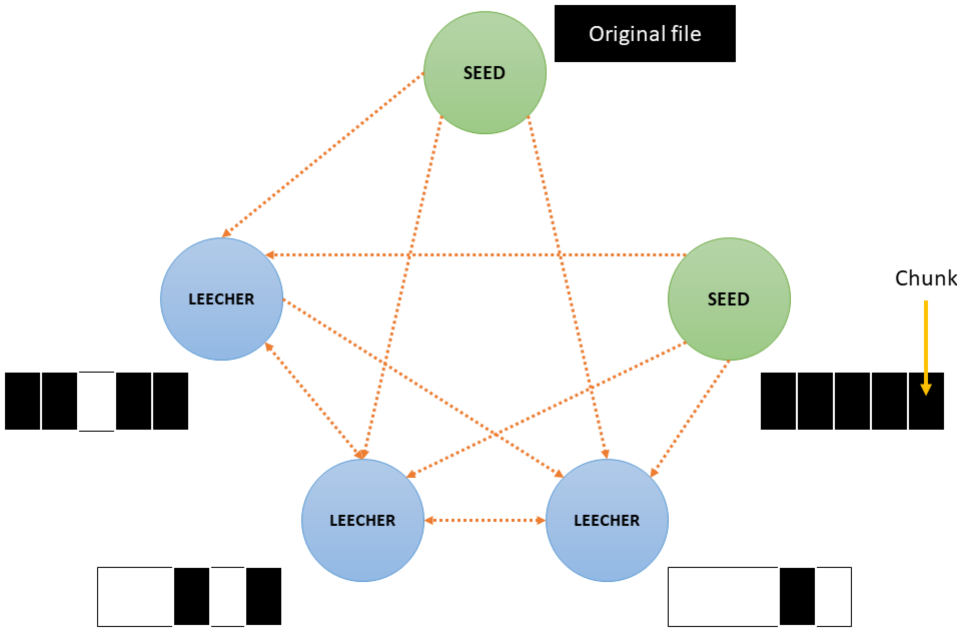

Figure 2. Peer-to-peer structure: download links and upload information between leechers and seeds.

Consequently, connections between nodes have the following characteristics:

- *Seeds* do not connect with other *seeds*, because they already have all the information available on the network.
- *Leechers* reach—and preferably try to connect with—a *seed*, since it can share all available chunks.
- *Leechers* also try to connect with other *leechers* that have different *chunks* between them.

In view of this, P2P networks are a viable option to reduce—and even avoid—bottlenecks at the servers, since all nodes share their bandwidth as they download chunks from the network. Let us assume that the nodes can download with a rate of c files per second and can upload information with a rate of μ files per second. Also, note that these rates are not constant, since servers and nodes have different transmission rates due to propagation losses, multipath fading, and even for hardware variations among nodes. Hence, it is common to assume that these rates are random variables with exponential distributions [33]. Also, in many cases, the download rate is higher than the upload rate, as it is shown in the relation in (1):

$$c \geq \mu \tag{1}$$

Also, the model assumes that nodes can enter the system with rate λ. Nodes that just enter the system have not downloaded any chunks. Then, they are considered leechers. And nodes can also leave the system: a leecher interrupts the download process with rate θ either for connection difficulties, for mobility reasons, or simply because the user has to leave the system. A seed can leave the system with rate γ; in this case, the nodes have finished the download procedure and the user is no longer required to remain in the system, but it can choose to dwell for longer times to provide its resources to downloading peers. (In some cases, the system administrator offers rewards for seeds to dwell for longer times and share their resources, entailing a better system performance.) In this regard, note that usually $\theta \neq \gamma$. From this description, the rate at which *leechers* are converted into *seeds*, τ, can be expressed as follows:

$$\tau = min(cx, \mu(\eta x + y)) \tag{2}$$

As Equation (2) describes, the total bandwidth in the system is the total number of peers, $x + y$, uploading at rate μ, and accounting for the fact that not all leechers can share the file, i.e., there is an efficiency parameter η added to the leechers. Then, in case all leechers, x, are downloading at the maximum rate, c, the total required bandwidth from the network is cx, and the rest of the bandwidth is not used. In case the leechers are not downloading at the maximum rate, the effective bandwidth used is $\mu(\eta x + y)$. Then, the parameters involved in the P2P system are:

$$\begin{aligned}
&\tau : conversion\ rate(\forall \tau \in \mathbb{R}, \tau > 0) \\
&c : the\ downloading\ bandwidth(\forall c \in \mathbb{R}, c > 0) \\
&\mu : the\ uploading\ bandwidth(\forall \mu \in \mathbb{R}, \mu > 0) \\
&\eta : sharing\ effectiveness(\forall \eta \in \mathbb{R}, 0 < \eta <= 1) \\
&x : number\ of\ leechers(\forall x \in \mathbb{N}, x >= 0) \\
&y : number\ of\ seeds(\forall y \in \mathbb{N}, y >= 1)
\end{aligned}$$

And the P2P system can be classified into two conditions: *penury* and *abundance*, whose relationship is described in Table 1.

Also, the P2P network can be expressed in a system of differential equations, as shown below in (3) and (4) [34]:

$$\frac{dx}{dt} = \lambda - \theta x - \tau \quad (3)$$

$$\frac{dy}{dt} = \tau - \gamma y \quad (4)$$

Table 1. P2P system conditions.

State	Condition	Description
Penury	$cx > \mu(\eta x + y)$	There is not enough bandwidth to download at the maximum rate
Abundance	$cx < \mu(\eta x + y)$	There is enough bandwidth for all peers to download at the maximum rate

It is important to highlight that in Equation (3) we see that the number of leechers increases by arrivals and decreases by early departures and leech conversions to seeds while Equation (4) clearly depicts that the number of seeds only changes by leechers conversions or seed departures. Once the Equations (3) and (4) have been solved under stable conditions, the state in which the system is going to be studied can be defined according to the value of the rate γ, according to the Table 2.

Table 2. Range of γ values for stable conditions.

State	τ	γ
Penury	$\tau = cx$	$\gamma < \frac{\mu c}{c - \mu\eta}$
Abundance	$\tau = \mu(\eta x + y)$	$\gamma > \frac{\mu c}{c - \mu\eta}$

These values of γ are very useful to provide rewards to peers to remain in the system for specific average times in order to achieve abundance conditions. However, these conventional models to describe the dynamics of the P2P system cannot apply in the case of static networks, such as the ones that can allow LiFi communications, due to the alignment requirements. Then, in our case, peers cannot enter or leave the system at any time, and the downloading procedure can only start when the administrator initiates the procedure. These differences require important modifications to the model, which will be explained in detail in further sections.

4. LiFi- and WiFi-Based Communication P2P Architectures

Having explained the potential of centralized and decentralized structures, this section describes the details and characteristics when these structures are analyzed with the parameters of LiFi 2.0 and WiFi 7, stressing that the use of LiFi applications is not usually straightforward nor the connections are usually direct as in the case of WiFi, considering node alignment, power and reflections of the signal, transmission and reception angles, and even electronic limitations. In this regard, this work makes an important contribution by proposing network architectures to allow the concept of P2P-LiFi to be really useful in the efficient distribution of information. Further, this research presents the visualization, practical approach, simulation, and implementation proposal of LiFi networks for static node environments (classrooms, museums, offices, control systems, and storage systems, among others) through a formal evaluation and quantitative values that allow for the comparison of LiFi-based technology with WiFi in centralized and distributed structures, to clearly define the cases in which one scenario is better than another.

In detail, LiFi prototypes in general behave like Lambertian sources with a determined *field of view (FOV)* and a *LOS* between the optical emitter and receiver, as described in Figure 3. However, there are scenarios in which due to phenomena such as reflections or scattering, LiFi can act as a non-Lambertian source (*NLOS* propagation mode), as depicted in Figure 4, where the light beams corresponding to the emitter and the receiver constitute an overlapping volume through their *FOVs* [35]. In this regard, LiFi 2.0 is a constantly growing technology that can coexist with current and future RF technologies, providing extra capacity to offload traffic and reducing latency for critical applications. Due to its features and utilities, LiFi 2.0 has been considered as a complement to radio frequency technologies in scenarios that can provide solutions in fields like IoT, artificial intelligence (AI), big data, or vehicle communications, where hundreds of nodes are placed in a small region, generating high traffic rates that may cause congestion and high packet loss probability under RF transmissions that are usually omnidirectional [36,37]. In contrast, LiFi communications comprise a much more restricted coverage area that allows for communication among a reduced number of nodes, which can improve the system's performance. However, there has not been an extensive study where both technologies are evaluated and analyzed. Indeed, we believe that LiFi cannot only complement WiFi networks but rather has certain characteristics that provide better performance than RF-based systems.

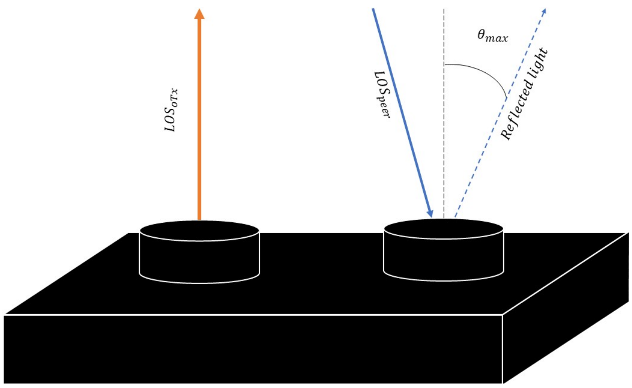

Figure 3. LiFi 2.0 prototype in LOS propagation mode used for VL and IR spectrum.

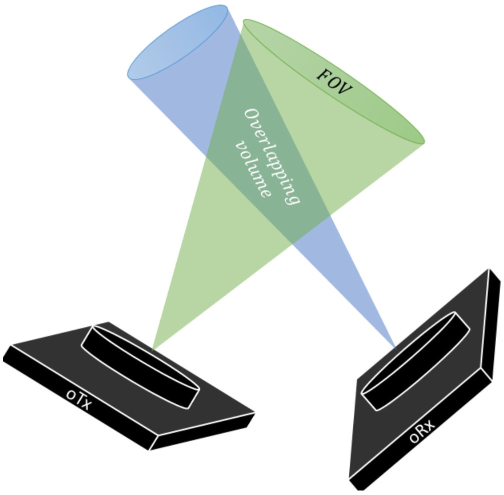

Figure 4. LiFi 2.0 prototype in NLOS propagation mode used for UV spectrum.

LiFi networks can use the whole spectrum of light, going through infrared, visible, and ultraviolet lengths. Generally, the first two ranges of spectra behave like Lambertian sources, then they require LOS propagation, opposite to the ultraviolet range, which is commonly used in NLOS propagation modes. In Figure 5, we show a P2P-LiFi LOS connectivity scenario, in which LOS propagation is needed to connect with the pairs of adjacent nodes that are in the north, south, east, and west positions (if it is applicable). Another architecture of P2P-LiFi with NLOS conditions is shown in Figure 6 where data are transmitted in one sense between adjacent levels, assuming that the first seed in the network (level 0) is in charge of distributing information through the nodes that it can reach, i.e., nodes in level 1, and so forth. Note that nodes in the same level can share chunks among them.

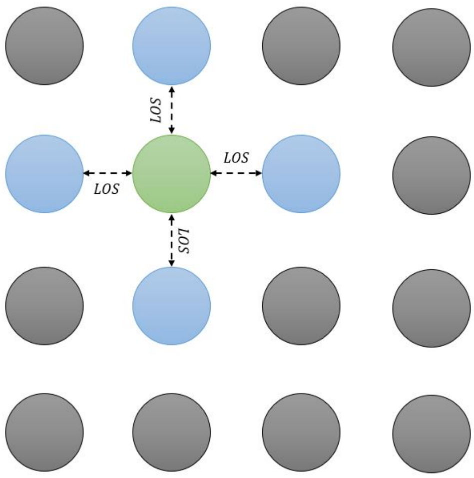

Figure 5. P2P-LiFi propagation scenario: a node (green) can download or upload information with its adjacent nodes (blue) in the cardinal points through their LOS and not with nodes that are out of range (gray).

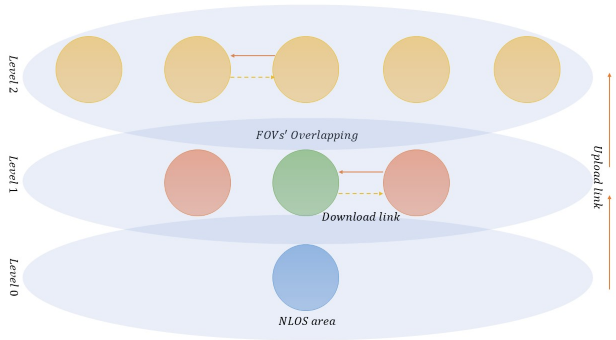

Figure 6. P2P-LiFi NLOS propagation scenario: nodes in level 1 (green nodes) can download information from upper nodes in level 0 (blue nodes) or upload information to immediate lower nodes in level 2 (yellow nodes) and upload data from the peers in the same level (red nodes).

For the case of WiFi-based networks, we could assume that all nodes inside the transmission range are reachable by a given peer in the network, i.e., nodes do not require a strict alignment, as in the case of LiFi-based transmissions. Nevertheless, sometimes nodes cannot reach all nodes in the network due to obstacles, power restriction, and propagation of the signals. In general, the transmission range is adjusted in such a way as to avoid interference among neighbor systems or clusters, and also to provide an adequate service in terms of bit error rate and data rate transmissions. This WiFi scenario is illustrated in Figure 7.

It is important to mention that in centralized networks, unlike P2P networks, all clients are reachable from the server whose capacity allows for connecting and sharing information with up to four nodes at the same time, allowing information to be propagated through the network directly from the server. Figures 7–9 outline scenarios for the proposed LiFi and WiFi networks, stressing that for centralized LiFi 2.0 and WiFi 7 networks, a single server is used.

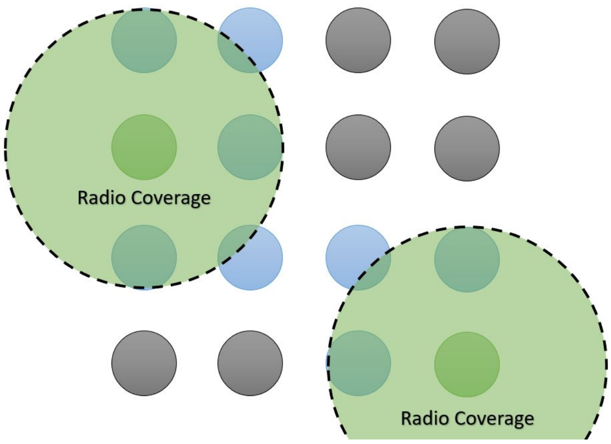

Figure 7. In the proposed P2P-WiFi scenarios, a node that acts as a server (green) can connect with the nodes that are within its coverage radius (blue) but not with nodes that are out of its range (gray nodes).

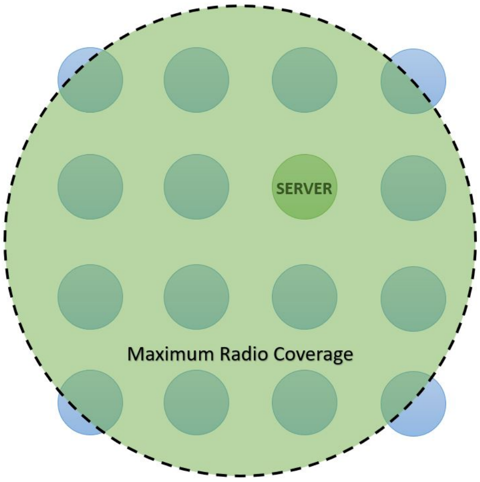

Figure 8. WiFi centralized case: maximum coverage range (green circle with dotted line) is strictly required for connections where a server (green node) reaches all the clients (blue nodes).

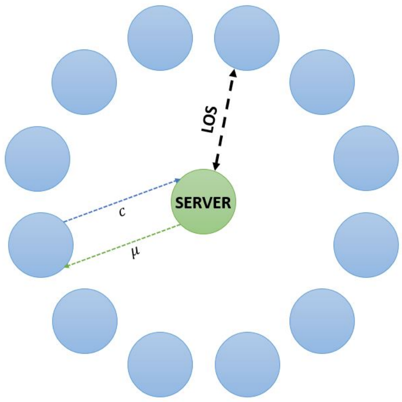

Figure 9. The centralized scenario proposed for LiFi environments requires that all the leechers (blue) have a LOS towards the server (green) channel, in which they will establish upload and download links.

It is important to mention that for the LiFi case, and in order to have an adequate comparison with WiFi-based networks, we consider a fixed number of nodes without mobility to provide the required alignment in light-based communications. In the literature, it is common to consider an infinite population model where nodes can enter and leave the system. Hence, we develop a new mathematical model considering these restricted mobility conditions where the system administrator initiates the file-sharing procedure in the fixed population network.

5. System Description

Now that the LiFi 2.0 and WiFi 7 scenarios and architectures have been explained, in this section, we describe the variables considered in the mathematical model and simulations developed in this work, namely the download and upload rates in the system, μ and c packets per second, respectively (as shown in Equations (5) and (6)), and the transmission rate $(Transmission_{rate})$ provided by each technology.

$$c : download\ bandwidth \left[\frac{Files}{s}\right] \tag{5}$$

$$\mu : the\ uploading\ bandwidth \left[\frac{Files}{s}\right] \tag{6}$$

we assume $c >= \mu$ (since it is usually the case in much practical hardware and equipment where the download of data is more frequent than the upload of data [38]). In our case, we consider in Equation (7) the relation of c and μ for our tests:

$$c = 5\mu \tag{7}$$

From this, we can calculate the average time required to download a file, which depends on the file size (bits), as we can see in Equation (8):

$$Download_{time} = \frac{size}{Transmission_{rate}}[s] \tag{8}$$

Applying (8) for the case of a LiFi system for a 8Tb file size at 1Tbps, we obtain:

$$Download_{time} = \frac{8Tb}{1Tbps} = 8[s] \tag{9}$$

Then, the download rate is calculated as:

$$c = \frac{1}{8[s]} = 0.125\left[\frac{files}{s}\right] \tag{10}$$

Finally, applying (7) we calculate μ:

$$\mu = \frac{c}{5} = 0.025\left[\frac{files}{s}\right] \tag{11}$$

For the WiFi system, we can calculate c and μ similarly, obtaining:

$$time = \frac{8Tb}{32Gbps} = 250[s] \tag{12}$$

$$c = \frac{1}{250} = 0.004\left[\frac{files}{s}\right] \tag{13}$$

$$\mu = \frac{c}{5} = 0.0008\left[\frac{files}{s}\right] \tag{14}$$

Table 3 shows the system parameter values used to obtain numerical and simulation results in the following sections.

Table 3. General parameters for the scenarios proposed.

Parameter	P2P-LiFi	C-LiFi	P2P-LiFi	C-WiFi
c	[0.125, 0.0625, 0.0416, 0.0312, 0.025]		[0.004, 0.002, 0.0013, 0.001, 0.0008]	
μ	[0.025, 0.0125, 0.0083, 0.00624, 0.005]		[0.0008, 0.0004, 0.00026, 0.0002, 0.00016]	
File size	[8 Tb, 16 Tb, 24 Tb, 32 Tb, 40 Tb]			
Nodes	[4, 8, 12, 16, 20, 24, 28, 32, 36]			
Max. upload	4 per node	4 per server	4 per node	4 per server
Max. download	1 per node	Not applicable	1 per node	Not applicable
Radio Coverage	Variable	Max.	Variable	Max.
Noises	Not considered			

6. Mathematical Analysis

Classical P2P and centralized networks can be modeled by aperiodic and irreducible CTMCs with recurring positive states when an infinite population model is considered, due to the intrinsic nature of the system, where nodes enter and leave the network, causing that the file can be continuously shared. These models generally focus on obtaining the average number of nodes in the queue and waiting/service times in the system. However, when the nodes have restricted mobility (in order to guarantee a certain level of alignment required in light communications), the arrivals and departures are no longer possible, and the node population becomes finite. As such, the file is no longer shared according to the variable population of nodes, but rather, file sharing ends when the last node has downloaded the complete file. Hence, the model developed in this article aims to obtain the average download time in P2P-LiFi and P2P-WiFi, by means of a transitory CTMC, as shown in Figure 10.

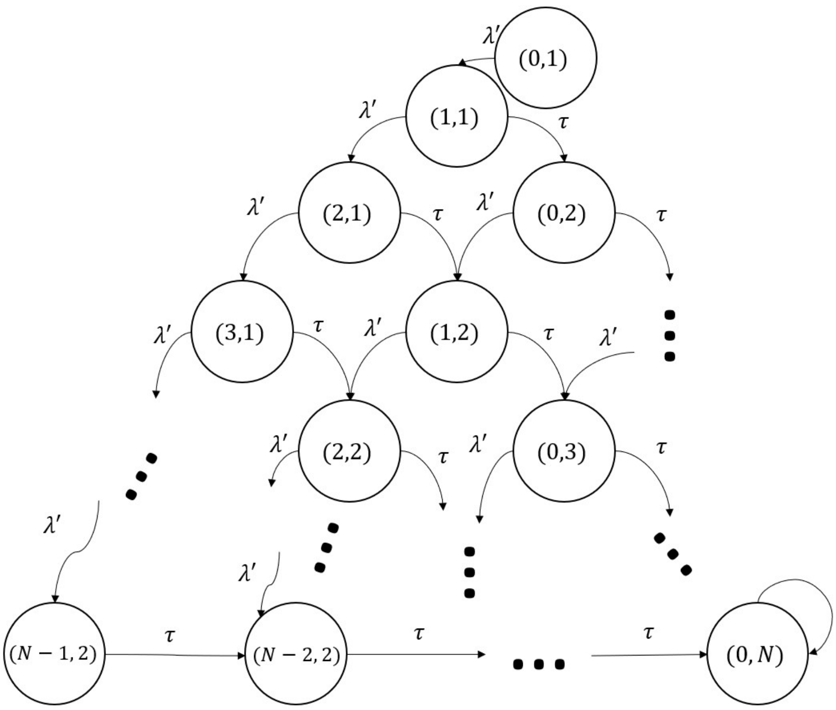

Figure 10. Mathematical modeling: CTMC of the P2P systems proposed in this work.

The aforementioned Markov chain is composed of two states, namely the number of leechers (x) and the number of seeds (y) for an arbitrary state (x, y) that has as a valid state space $\{\Omega_{x,y}\ 0 \leq x, y \leq N\}$, where N is the number of nodes in the system. The chain starts when the file is shared by the initial seed, i.e., the node that has the complete file, which is represented by state (0, 1). From this state, the system evolves to state (1, 1) when the first leecher starts the download of the file. After that, either a new leecher starts the download of the file (transiting to state (2, 1)), by using the bandwidth provided by the seed and the leecher, or the leecher ends its download of the file, also becoming a seed (transiting to state (0, 2), and so on and so forth, until the last node downloads the complete file, which occurs at the absorbent state (0, N). From this description, the valid transitions of the chain when the system is in the state (x, y) are the following:

- To state $(x + 1, y)$ with rate λ', when a new peer (with no chunks of the file) requests and starts the file download procedure in the system, and it becomes a leecher. Note that for the LiFi case, this highly depends on the position of the node with respect to the seeds and other leechers. Indeed, in light communications, it is not possible to reach all nodes directly, as opposed to a broadcast using RF. Here, it is relevant to consider the specific architecture of the network, as explained in previous sections.
- To state $(x - 1, y + 1)$ with rate τ, when a leecher acquires all the available data in the network and it becomes a seed.

The CTMC presented is an aperiodic and transitory chain, where all valid states are transient states, except for the absorbing state $(0, N)$ (where there are no *leechers* asking for information because all peers in the network became *seeds*). Using this model, we can obtain the average file download time in the system.

Note that if the coverage area of each node is the maximum, i.e., all nodes can directly reach any other node in the network (which can only occur in the RF system), then any peer can cooperate with each other, otherwise the nodes furthest away from the initial seed will have to wait until the neighbor nodes download the file to start their own download procedure. This can be seen as nodes placed at different levels, as depicted in Figure 5, such that nodes in level 1 have to download the file in order to provide connections to the nodes at level 2, and so on.

Another important detail in the model is the conversion rate (τ), which represents the rate that leechers become seeds, i.e., the download rate of the complete file. Note that this rate depends on the available bandwidth in the system, which is given by the number of seeds and leechers that can share their file, i.e., in the communication range of the downloading peer. As Equation (15) shows, if the number of sharing peers is sufficiently high such that the bandwidth available is higher than cx, i.e., the total download rate in the system, then $\tau = cx$ and the rest of the bandwidth is unused. Conversely, when the total available bandwidth is lower, there are not enough resources to allow for the download of the file at the maximum capacity. Then, the transition rate can be expressed as:

$$\tau = min(cx, \mu(\eta x + y)) \tag{15}$$

where η is an efficiency parameter, given that not all leechers can share their chunks to each other, since other peers may already have those chunks. Note that seeds are not affected by this parameter. Finally, the rate λ', represents the rate at which neighbor leechers, i.e., nodes inside the coverage area of other leechers and seeds, request information for the first time in the system. Indeed, not all nodes start the download procedure simultaneously, but rather, it depends on hardware restrictions. Specifically, we assume that the time at which a node can start the file-sharing procedure will directly depend on the communication bandwidth, $c + \mu$, and a system control variable (ξ) particular to the system's hardware and software, as described in (16).

$$\lambda' = \xi(c + \mu) \tag{16}$$

Figure 11 is a generalization of the proposed chain shown in Figure 10, because at a given state (x, y) there can only occur two possible events: either a new peer starts the file download, with rate λ'; or a leecher becomes a seed, with rate τ. This *compact* representation of the Markov chain becomes very useful to numerically solve the chain, as described in Algorithm 1. The analytical results obtained from the proposed Markov chain are validated through discrete event simulation (DES) of the system described in Algorithm 2, in both cases having as a main objective the calculation of the time in which the information is fully propagated through the network (both algorithms are detailed in the Appendix A).

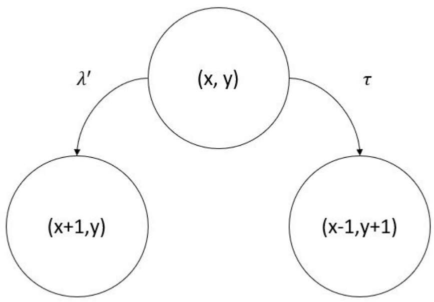

Figure 11. Generalization of the proposed CTMC, starting from a base state (x, y) and its possible transitions.

Algorithm 1: P2P-LiFi/P2P-WiFi/centralized numerical solution algorithm.

Data: $iterations, \mu, c, nodes, coverage, \xi$
Result: $tsharing$
$tsharing \leftarrow 0$;
while $i <= iterations$ **do**
  $y \leftarrow 1$;
  $x \leftarrow 0$;
  $tsim \leftarrow 0$;
  while $y < coverage$ **do**
    $tmin, index \leftarrow min(x, y, \xi, c, \mu)$;
    $tsim \leftarrow tsim + tmin$;
    if $index == 0$ **then**
      $x \leftarrow x + 1$;
    else
      $x \leftarrow x - 1$;
      $y \leftarrow y + 1$;
    if $y == nodes$ **then**
      $tsharing \leftarrow tsharing + tsim$;
$tsharing \leftarrow (\frac{nodes}{coverage})(\frac{tsharing}{iterations})$;

Algorithm 2: P2P-LiFi/P2P-WiFi/centralized DES solution algorithm.

Data: $iterations, \mu, c, nodes, coverage$
Result: $tsharing$
$tsharing \leftarrow 0$;
while $i <= iterations$ **do**
  $y \leftarrow 1$;
  $x \leftarrow 0$;
  $Add(Seed(ID, status, connections, chunks))$;
  $y \leftarrow y + 1$;
  $tsim \leftarrow 0$;
  for $k \leftarrow 0; k < coverage - 1; k = k + 1$ **do**
    $List.add(Leecher(t, ID, chunks, state, connections))$;
    $x \leftarrow x + 1$;
  while $seeds < coverage$ **do**
    $conversions = updateChunks(tsim, seeds, leechers)$;
    $y \leftarrow y + conversions$;
    $x \leftarrow x - conversions$;
    $tsim \leftarrow tsim + List.timeFirst()$;
    if $y == coverage$ **then**
      $tsharing \leftarrow tsharing + tsim$;
      $clearList(List)$;
$tsharing \leftarrow (\frac{nodes}{coverage})(\frac{tsharing}{iterations})$;

7. Numerical Results

This section presents the main results derived from the mathematical model derived for static nodes in P2P systems using both LiFi and WiFi communications. We also compare the analytical results derived from the Markov chain to simulation results to validate our model. Finally, we present a comparison between LiFi 2.0 and WiFi 7 technologies in centralized and P2P systems.

7.1. Validation of the Analytical Model

To validate the analytical results derived from the proposed Markov chain, we developed a discrete event simulator of P2P-LiFi (LOS and NLOS modes), P2P-WiFi , C-LiFi and C-WiFi (with maximum and reduced radio coverage) systems to compare both results in different settings. The simulation results are obtained based on Algorithm 2, while the analytical results are obtained using Algorithm 1.

Figure 12 shows the system performance in terms of the average download times in a P2P network with LiFi communication capabilities in LOS conditions for different values of the upload rate (μ) and download rate (c). From these results, we can clearly see a good fit between the analytical and simulation results, which validates the mathematical model. Also, we can observe that the download rate has a major impact on the system's performance according to the abundance state, in which all leechers can download at the maximum rate, and the conversion rate is described as $\tau = cx$. The upload rate also has an impact, but is not as significant as the download rate. This is a very important result, since it can provide concrete guidelines to develop specific hardware that focuses on maximizing the download rate. Similarly, in Figures 13 and 14, we can see a very good fit between the simulation and analytical results. We can see from the results in Figure 13 that in a centralized network, the download rate also has a higher impact than the upload rate. However, the upload rate in a P2P network is much more important than in a centralized system, since in the P2P system, the upload rate is used to share the file among nodes, while in the centralized system, the server is the only node uploading the file. As such, the average file download time is lower in a P2P network, compared to the centralized system.

For the P2P network with WiFi capabilities, we show in Figure 14 the case where the coverage area is reduced in such a way as to form clusters of nodes, reducing the interference with other systems, as shown in Figure 7. In this case, the nodes outside the coverage area of the servers have to wait for the nodes closest to the servers to download the file to connect to them and start their own download. This entails higher download times, as shown in these results. The rationale for reducing the coverage area is to also reduce interference with other systems, since the WiFi channels are usually very congested due to the high number of mobile nodes connected to public sites. However, since the available bandwidth in WiFi systems is much lower than in LiFi systems, this WiFi clustering architecture proves to be very inefficient compared to LiFi communications.

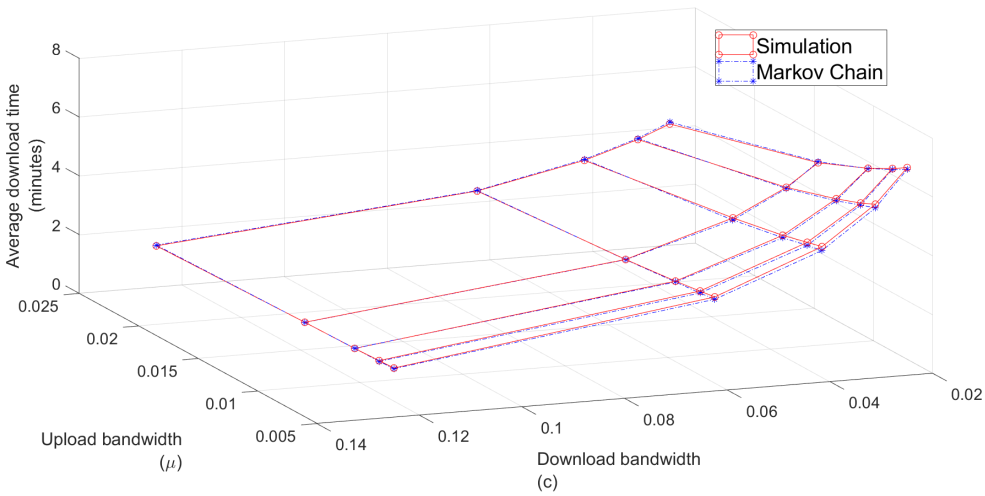

Figure 12. Average file download time for P2P-LiFi (LOS propagation mode) for different values of the upload and download bandwidths, c and μ, for 24 nodes in the system.

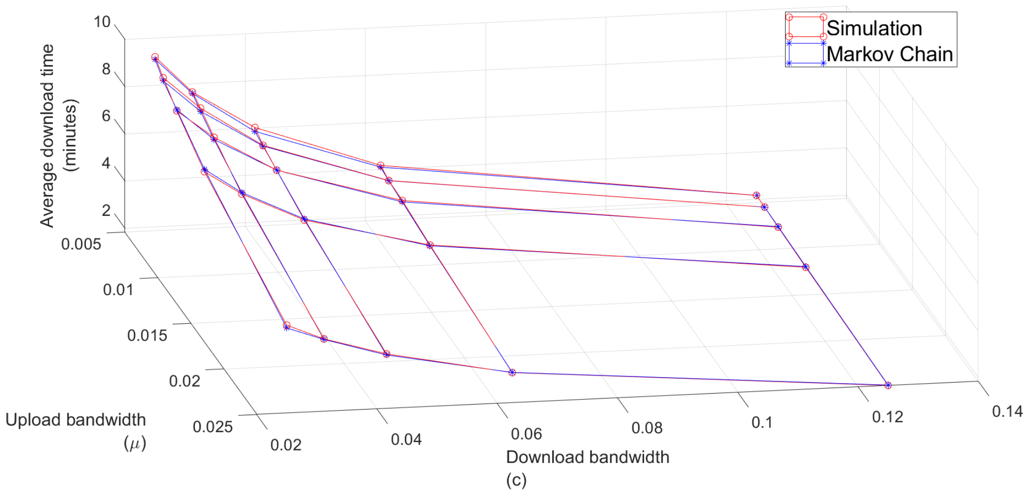

Figure 13. Average file download times in a centralized 32-node LiFi network for different values of the upload and download bandwidths, c and μ.

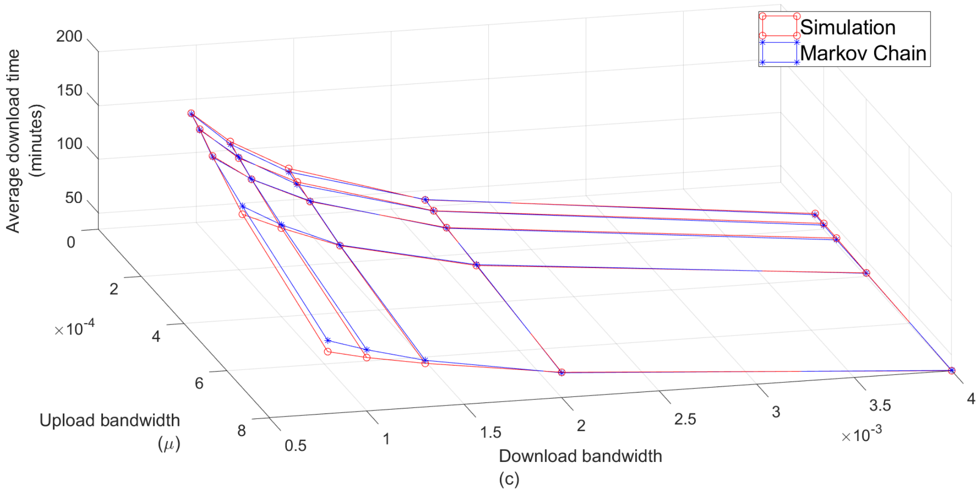

Figure 14. Average file download times for a P2P-WiFi network with 4 clusters of 7 nodes with reduced coverage area.

Now that the mathematical model has been validated, in the following figures, we will only use analytical results to analyze the system performance in different environments for illustration purposes.

7.2. Impact of the Number of Nodes in the System

Centralized networks, where servers attend all the client nodes directly, show a clear performance degradation when the demand of the file increases, as shown in Figure 15, in which the time gaps do not decrease in the surface between each increment in the number of nodes through the network. It can be seen that to provide a low download time for a high number of nodes, a high download rate has to be used, which entails higher costs for the system deployment.

Conversely, in P2P networks with the same amount of nodes, the average download time is reduced, since all nodes provide communication bandwidth and not only the servers, which entails a cost reduction and increased performance of the network, as shown in Figure 16.

Figures 15 and 16 confirm that contrary to centralized networks, P2P networks with adequate bandwidth can be applied in environments with a large number of nodes, which can be easily observable in our work by the distances in the surfaces plotted (the higher the number of nodes, the less distance between the previous and current surface).

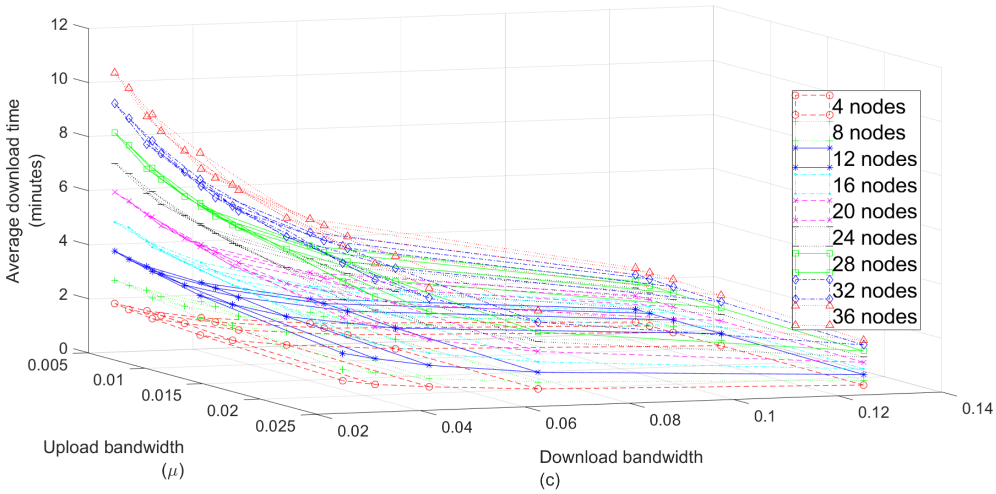

Figure 15. Impact of the nodes variation in data sharing through a centralized LiFi network.

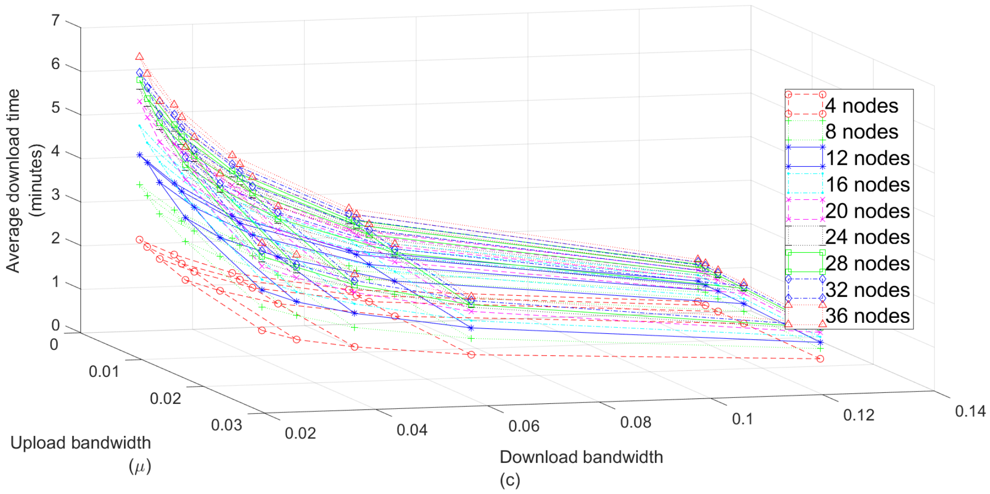

Figure 16. Impact of the nodes' variation in data sharing through a P2P-LiFi network in NLOS propagation mode.

7.3. WiFi vs LiFi Performance Comparison

In Figures 17 and 18, we present a clear comparison of the LiFi and WiFi technologies used for a fixed number of nodes (16 and 36, respectively). Once the required alignment is assured for the LiFi system, the main differences between these technologies are the upload and download bandwidth. From these results, we see a clear advantage of the higher available bandwidth provided by LiFi communications compared to RF transmissions, highly reducing the average download times.

Finally, note that centralized networks can show a better or similar performance than P2P (usually in a very low number of nodes); thus, Figure 17 and Table 4 (diagonal values from surface obtained in Figure 17) show the case of 16 nodes where the P2P-WiFi network shares information faster compared to the C-WiFi network. Nevertheless, we can also see that the P2P-LiFi$_{NLOS}$ network only presents some low sharing times for some values of c and μ with respect to the times presented by the C-LiFi network for the same number of nodes.

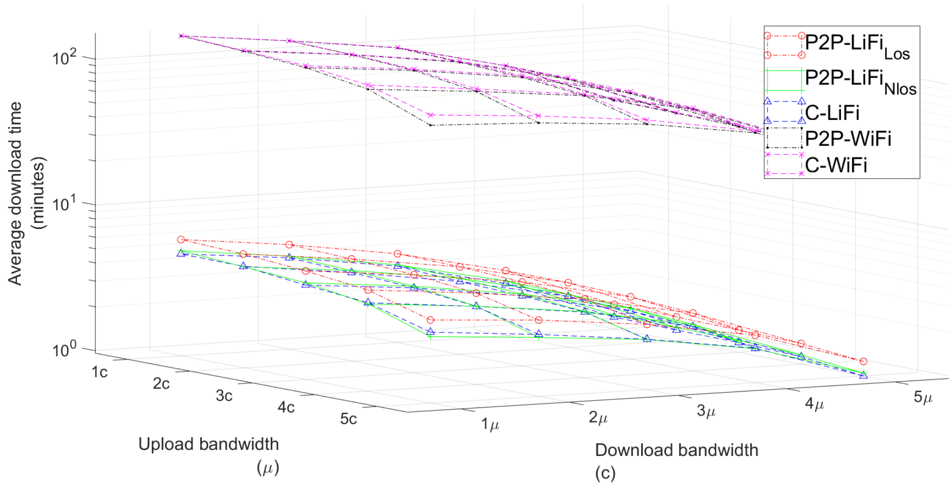

Figure 17. Comparison of average download times in the proposed networks through the interpretation of their respective bandwidths (16-node network).

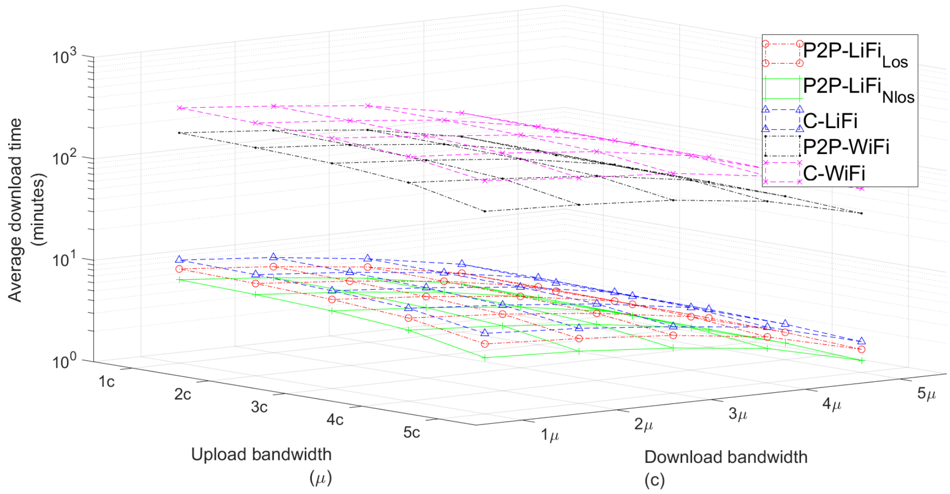

Figure 18. Comparison of average download times in the proposed networks through the interpretation of their respective bandwidths (36-node network).

Table 4. Average download time comparison between centralized and decentralized wireless technologies (16 nodes).

Bandwidth		**Average Download Time (min)**				
Down	***Up***	***P2P $LiFi_{LOS}$***	***P2P $LiFi_{NLOS}$***	***C-LiFi***	***P2P WiFi***	***C-WiFi***
1c	1 μ	1.20	1.00	0.95	29.84	30.37
2c	2 μ	2.39	1.99	1.93	59.96	60.97
3c	3 μ	3.61	2.97	2.90	91.45	93.70
4c	4 μ	4.79	3.99	3.87	120.70	121.22
5c	5 μ	6.02	5.04	4.80	150.13	150.57

On the other hand, Figure 18 and Table 5 (diagonal values from Figure 18) present lower average download times in all the proposed P2P networks compared to the centralized ones, as a consequence of the 36 nodes in the network, which confirms the scalability property of P2P networks; this means that the greater the number of nodes, the smaller the average download time in decentralized networks.

Table 5. Average download time comparison between centralized and decentralized wireless technologies (36 nodes).

Bandwidth		Average Download Time (min)				
Down	*Up*	*P2P-* $LiFi_{LOS}$	*P2P-* $LiFi_{NLOS}$	*C-LiFi*	*P2P-WiFi*	*C-WiFi*
1c	1 μ	1.69	1.31	2.01	37.02	64.75
2c	2 μ	3.36	2.62	4.14	74.56	129.66
3c	3 μ	5.05	3.98	6.24	114.02	196.12
4c	4 μ	6.76	5.28	8.26	148.54	257.31
5c	5 μ	8.44	6.61	10.32	184.76	325.89

For the tests performed, we can observe that depending of the applications or scenarios, we can obtain different average download times depending of the technology used (advantages and limitations), number of nodes, bandwidth availability, and network structures.

8. Conclusions

This work proposes a Markovian analysis that models WiFi 7 and LiFi 2.0 technologies in centralized and decentralized environments based on the average download times in different scenarios and system variables, including different transmission rates, numbers of nodes, and different architectures. A mathematical model was developed to capture the main dynamics of these systems using transitory continuous-time Markov chains. The analytical results were validated through system simulations.

The numerical results prove that P2P networks with LiFi capabilities can drastically reduce the average download times of files in the order of terabits, sharing the file in a matter of minutes, which proves to be a viable solution for IoT environments, video streaming, real-time applications, social distancing environments, or event venues such as museums, movie theaters, sporting and cultural events, etc., considering applications where a certain degree of alignment is required to allow for light communications.

In future work, we intend to introduce quantum-based communications, considering that photons are used as the basis of the information-sharing procedure, which facilitates the use of particles in different quantum states, possibly increasing the system bandwidth and security level. We believe that light-based communications may facilitate the use of these quantum technologies compared to communications based on RF technologies.

Author Contributions: The activities of this article were accomplished as follows: Conceptualization, G.H.-O. and M.E.R.-A.; methodology, G.H.-O. and M.E.R.-A.; software, G.H.-O.; validation, M.E.R.-A., J.C.C.-E. and J.E.C.-T.; formal analysis, M.E.R.-A.; investigation, G.H.-O.; resources, M.E.R.-A. and J.C.C.-E.; data curation, G.H.-O.; writing—original draft preparation, G.H.-O.; writing—review and editing, G.H.-O., M.E.R.-A., J.C.C.-E. and J.E.C.-T.; visualization, G.H.-O. and M.E.R.-A.; supervision, M.E.R.-A. and J.C.C.-E.; project administration, G.H.-O. and M.E.R.-A.; funding acquisition, M.E.R.-A. and J.C.C.-E. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Instituto Politécnico Nacional grant number SIP 20231239.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: All experiments and data used in this work are available if required.

Acknowledgments: This work has been supported by Instituto Politécnico Nacional and Consejo Nacional de Ciencia y Tecnología (CONACYT).

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

AI	Artificial Intelligence
AP	Access Point
AR	Augmented Reality
BER	Bit Error Ratio
C-LiFi	Centralized LiFi
CTMC	Continuous-Time Markov Chain
C-WiFi	Centralized WiFi
D2D	Device-to-Device Communication
DES	Discrete Event Simulations
DFL	Decentralized Federated Learning
EDCA	Enhanced Distributed Channel Access
FOV	Field of View
HMM	Hidden Markov Model
IoE	Internet of Everything
IoT	Internet of Things
IR	Infrared
LiFi	Light Fidelity
LOS	Line of Sight
ML	Machine Learning
NLOS	Non-Line of Sight
P2P	Peer-to-Peer
QoS	Quality of Service
RF	Radio Frequency
SA-MAC	Self-Adaptive Medium Access Control
SINR	Signal-to-Interference-and-Noise Ratio
SNR	Signal-to-Noise Ratio
UV	Ultraviolet
VL	Visible Light
VR	Virtual Reality
WiFi	Wireless Fidelity

Appendix A. Markov Chain's Numerical Solution Algorithm

Algorithm 1 considers the dynamics of the Markov chain by generating random dwelling times with exponential distribution for the output rates of the system, looking for the minimum time (which represents the following transition) and taking advantage of the memoryless property of IID variables with exponential distribution used in the process (the algorithm is reposted and detailed below):

1. The process begins with the input data of the bandwidths (c and μ) and the control variable (ξ); those variables will allow fpr the calculation of the system rates (λ', τ), in addition, the number of iterations (*iterations*) is defined, as well as the number of nodes in the scenario (*nodes*) and the size of the clusters (*coverage*) into which the number of nodes will be divided (the greater coverage, the more peers that one node can reach in the networks; on the other hand, a very small coverage could provide enough information about average download times in the network). These input variables will allow for the calculation of the time in which the information is shared (*tsharing*) in the proposed networks.
2. Once the input data have been entered into the algorithm, the process will be repeated in the indicated number of iterations (until the chain obtains a steady state in the long term); therefore, for each iteration, it initializes the values of the simulation time (*tsim*) and the counters of leechers (x) and seeds (y), taking into account that for the studied networks, there must be at least one server in the system at all times.
3. The system starts at state $(0, 1)$, which corresponds to the case where the system is in initial conditions (in other words, there is just one seed in the system and the other

peers are not asking for information yet); the calculation of the time in which the next transition will take place is equivalent to obtaining the minimum number (*tmin*) of the times T_1 and T_2 calculated with rates λ' and τ, respectively (T_1 and T_2 are the random times that correspond to an event of conversion from a leecher to seed or an event of a request of information from one peer, and they are modeled as random variables exponentially distributed), as well as the position (*index*) of this calculated time.

4. The following step indicates the addition of the calculated minimum time to the simulation time, and then there are two possible conditions:
    - If the minimum time corresponds to the one created by the λ rate, it indicates that a node has requested information for the first time in the system, indicating the presence of a leecher in the system $(x+1, y)$.
    - Instead, if the smallest time corresponds to that created by τ rate, it indicates that a node has obtained all the circulating chunks, indicating that a conversion from a leecher to a seed has occurred $(x-1, y+1)$.
5. The process continues until all the nodes present in the cluster of the network have become seeds (recalling that the dimension of the clusters can be equal to or less than the number of nodes); it is at this specific moment when the simulation time is added to the sharing time. Finally (at the end of the repetitions), the sharing time is normalized by the number of iterations and the relationship between nodes and clusters.

Algorithm A1: P2P-LiFi/P2P-WiFi/centralized numerical solution algorithm

```
Data: iterations, μ, c, nodes, coverage, ξ
Result: tsharing
tsharing ← 0;
while i <= iterations do
    y ← 1;
    x ← 0;
    tsim ← 0;
    while y < coverage do
        tmin, index ← min(x, y, ξ, c, μ);
        tsim ← tsim + tmin;
        if index == 0 then
            x ← x + 1;
        else
            x ← x − 1;
            y ← y + 1;
        if y == nodes then
            tsharing ← tsharing + tsim;
tsharing ← (nodes/coverage)(tsharing/iterations) ;
```

Appendix B. DES Algorithm

As previously mentioned, we developed a discrete event simulator that captures the dynamics of the system in order to validate the analytical results of the Markov chain. This method allows for analysis of the proposed networks from a different approach to the previous numerical solution (Algorithm 1); therefore, the particularities of the Algorithm 2 (reposted) that describe this process are detailed below:

1. As an initial step, input variables for bandwidths (μ, c), iterations (*iterations*), nodes (*nodes*), and cluster dimensions (*coverage*) are entered. It is important to highlight that at the end of this process, the average time in which a file of a certain size is shared in all the nodes of the network (*tsharing*) will be obtained.
2. Subsequently, the process will be repeated according to the number of iterations, so the following step is to initialize the simulation time (*tsim*), the counter concerned

with the nodes that contain full chunks (y), and the counter concerned with nodes that do not contain all the information available in the system (x).

3. In the succeeding stage, a seed (state $(0, 1)$) is added to the queue with its respective initial parameters such as occurrence time, ID, chunk list, upload status, and connection list (depending on the range of coverage and the nature of the technology). Afterward, this process is repeated for all the leechers that are in the scenario ($coverage - 1$), remembering there are additional parameters in these kinds of nodes with respect to the seeds (downloading connection status, list of downloading connections, etc.).
4. Once all nodes have been initialized and added to the queue, the below subroutine is initialized until the number of seeds is equal to the nodes present in the cluster:
   - Total conversions from leechers to seeds ($conversions$) are calculated between the time the last event occurred to the time at which simulation is located (generally time among events). Above is an important point in the system simulation, because the number of conversions is found through all the nodes present in the network by the chunk-updating function ($updateChunks$).
   - Chunk updating is conducted by inspecting each node in the queue, and includes the processes of search and link between nodes; these connections depend on the occupancy states, the limit of uploading and downloading connections, the coverage lists, and even the transmission efficiency (nodes that can transmit a greater number of chunks between them are more likely to connect).
   - Next, conversions are added to the number of seeds, and those same conversions are subtracted from the number of leechers, obtaining the new state: $(x - conversions, y + conversions)$. Subsequently, the time of the following state in the queue is taken, and the subroutine is repeated.
5. When the previous point is completed, the simulation time is added to the total sharing time and a new iteration of the process begins. At the end of the iterations, the sharing time is normalized.

Algorithm A2: P2P-LiFi/P2P-WiFi/centralized DES solution algorithm

```
Data: iterations, μ, c, nodes, coverage
Result: tsharing
tsharing ← 0;
while i <= iterations do
    y ← 1;
    x ← 0;
    Add(Seed(ID, status, connections, chunks));
    y ← y + 1;
    tsim ← 0;
    for k ← 0; k < coverage − 1; k = k + 1 do
        List.add(Leecher(t, ID, chunks, state, connections));
        x ← x + 1;
    while seeds < coverage do
        conversions = updateChunks(tsim, seeds, leechers);
        y ← y + conversions;
        x ← x − conversions;
        tsim ← tsim + List.timeFirst();
        if y == coverage then
            tsharing ← tsharing + tsim;
            clearList(List);
```

$$tsharing \leftarrow \left(\frac{nodes}{coverage}\right)\left(\frac{tsharing}{iterations}\right);$$

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