

LiFi and Hybrid WiFi/LiFi Indoor Networking: From Theory to Practice

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LiFi and Hybrid WiFi/LiFi Indoor Networking: From Theory to Practice

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Abstract

Today, researchers and manufacturers consider light fidelity (LiFi) technology as an essential solution for fast data transfer in networks. In addition, one of the essential solutions to meet the traffic restriction challenge caused by the growing demand of Internet users is the integration of various communication technologies. Combining LiFi and wireless fidelity (WiFi) technologies is an effective solution to overcome this challenge. Hybrid WiFi/LiFi network uses fast data transfer from LiFi and wide coverage from WiFi. Therefore, their integration can complement the shortcomings of each of these technologies and increases the network performance. In this work, while presenting theoretical concepts of LiFi and hybrid WiFi/LiFi networks, issues such as network structure, cell deployment, modulation techniques, multiple access schemes, and criteria for measuring network performance are discussed. We present practical concepts for implementing LiFi-based networks in detail.

Keywords: LiFi, hybrid WiFi/LiFi, optical communications, visible light communications

1. Introduction

Studies show that at the end of 2020, mobile data transmission accounted for 71% of Internet traffic, which more than 80% of this data transmission being in indoor areas, such as offices and homes. Due to the limited resources of the radio frequency (RF) spectrum and the dense establishment of WiFi hubs, radio systems will have difficulty meeting the growing demand for mobile Internet, especially in the fifth and higher generations of cellular networks. To deal with the shortage of RF spectrum, the use of LiFi technology is recommended [1].

Figure 1 shows an overview of an indoor LiFi network. In LiFi, using light as a carrier, a wide spectrum (around 300 THz) can be used. For example, LiFi with a light emitting diode (LED) can achieve data rates above 10 Gbps [2]. However, despite the high data transmission speed, LiFi networks also have problems such as coverage area limitation and light blockage.

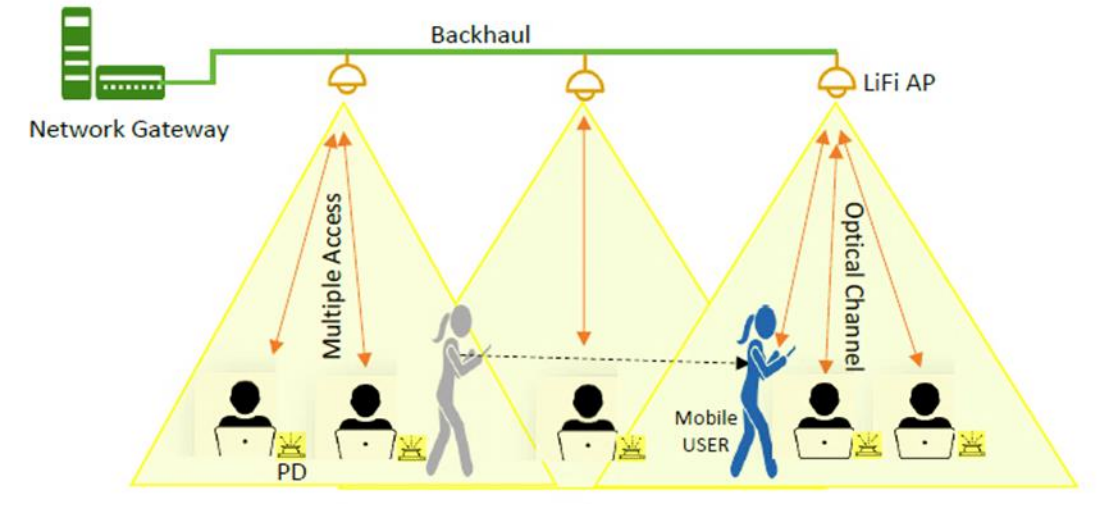


Fig. 1: A LiFi network structure

In return, WiFi networks have wider coverage, and the problem of the carrier route blockage is reduced greatly. Therefore, using hybrid WiFi/LiFi network is proposed. Combining LiFi and WiFi networks is a practical proposition for pure LiFi challenges. Hybrid WiFi/LiFi network uses fast data transfer from LiFi technology and wide coverage from WiFi. Therefore, WiFi/LiFi combination can complement the shortcomings of each of these technologies. Hybrid WiFi/LiFi can use the LiFi fast data transfer and WiFi wide coverage [3]. The hybrid WiFi/LiFi network performs better than either LiFi or WiFi systems separately [4]. Figure 2 shows the structure of a hybrid WiFi/LiFi indoor network .

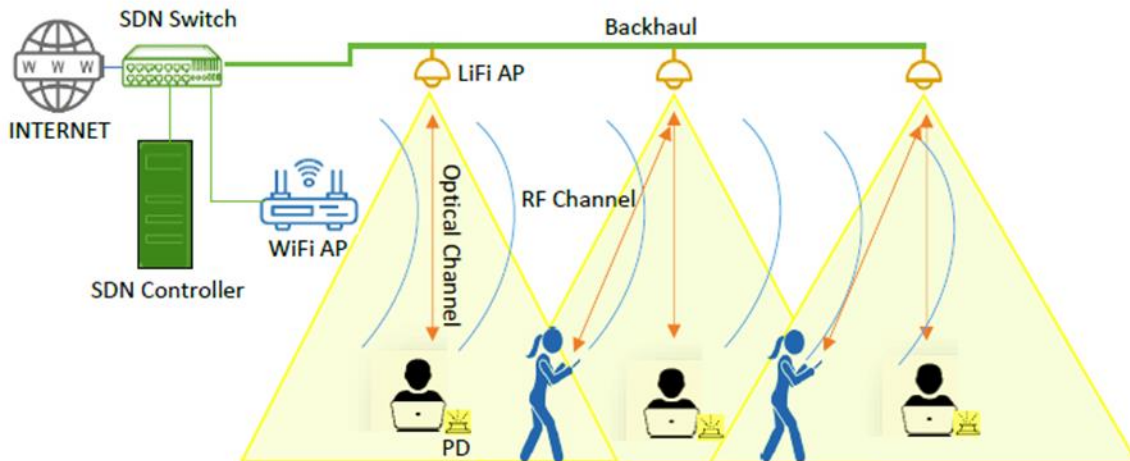


Fig. 2: A hybrid WiFi/LiFi indoor network

In this paper, we present the issues related to the implementation of LiFi and hybrid WiFi/LiFi networks for practical purposes. Matters include; 1) design of LiFi and hybrid WiFi/LiFi networks to determine the location of LiFi and WiFi access points (APs), 2) allocation of resources to balance the load on the network, 3) mobility and challenges such as user path, light path blockage, and handover, and 4) network performance improvement in terms of efficiency will be discussed in detail. In the following, we show how to implement a LiFi-based indoor network.

The rest of the article is as follows: The second section describes the topics related to LiFi and hybrid WiFi/LiFi networks. In the third section, the attributes of LiFi and hybrid WiFi/LiFi networks are presented. In the fourth section, the performance of the LiFi and hybrid WiFi/LiFi networks is evaluated. In the fifth section, we present how to implement a LiFi indoor network and finally, in the last section, we summarize and conclude the article .

2. Background and Related Works

In this section, we introduce LiFi and hybrid WiFi/LiFi networks and related topics. In general, any LiFi or hybrid WiFi/LiFi network consists of six main components including; 1) network structure, 2) cell deployment model, 3) multiple access method, 4) modulation technique, 5) illumination (if required), and 6) backhaul [5]. Each of these components includes subsets as shown in Figure 3.

2.1. Network Structure

According to the general structure of LiFi or hybrid WiFi/LiFi networks, as shown in Figs. 1 and 2, respectively, to achieve flexible communication and resource allocation for the users, it is necessary to manage users and network resources. In a hybrid network, as shown in Fig. 2, management is provided by software-defined networking (SDN) server.

2.2. Cell Deployment Model

LiFi networks can be designed as cellular networks. Cellular networks can be provided with different types of cell deployment models. Cell deployment can be deployed in one or two dimensions. In one-dimensional cell deployment, the transmitter/receiver (T/R) points are arranged in a linear array [6]. This cell deployment model is commonly used for LiFi outdoor network scenarios along a street, highway, or railroad [7]. In the indoor networks, it is preferable to develop the cells in two dimensions, because this model can provide a general form of coverage in the desired location. LED or infrared (IR) transmitters, used as LiFi transmitters, are usually mounted permanently on the ceiling of an indoor area. In the two-dimensional deployment, four models include; 1) Lattice, 2) Hexagonal, 3) Poisson point process (PPP), and 4) Hardcore point process (HCPP) are used [8]. Figure 4 shows the cell deployment models. The lattice model is the most practical and standard method used for LiFi and hybrid WiFi/LiFi networks due to the topological location of the optical T/Rs (LED or IR). This deployment model has been widely used in many studies of LiFi and hybrid WiFi/LiFi networks [9]. The hexagonal deployment model provides the best possible Signal-to-Interference & Noise Ratio (SINR) coverage in the LiFi network. In the PPP deployment model, instead of regular and definite cell deployment, cell deployment is performed randomly. This model is unusual and impractical. In addition, the PPP model offers the worst probability of SINR coverage among the three mentioned models [10]. The HCPP model is a pessimistic practical approximation model in which two light sources might be placed side by side. This condition can only occur in rare cases. To compensate the lack of cell deployment in the homogeneous PPP model, point processes such as the hardcore point process (HCPP), suggest a better approximation in the real world. Therefore, this model has recently been considered in the analysis of cellular systems .

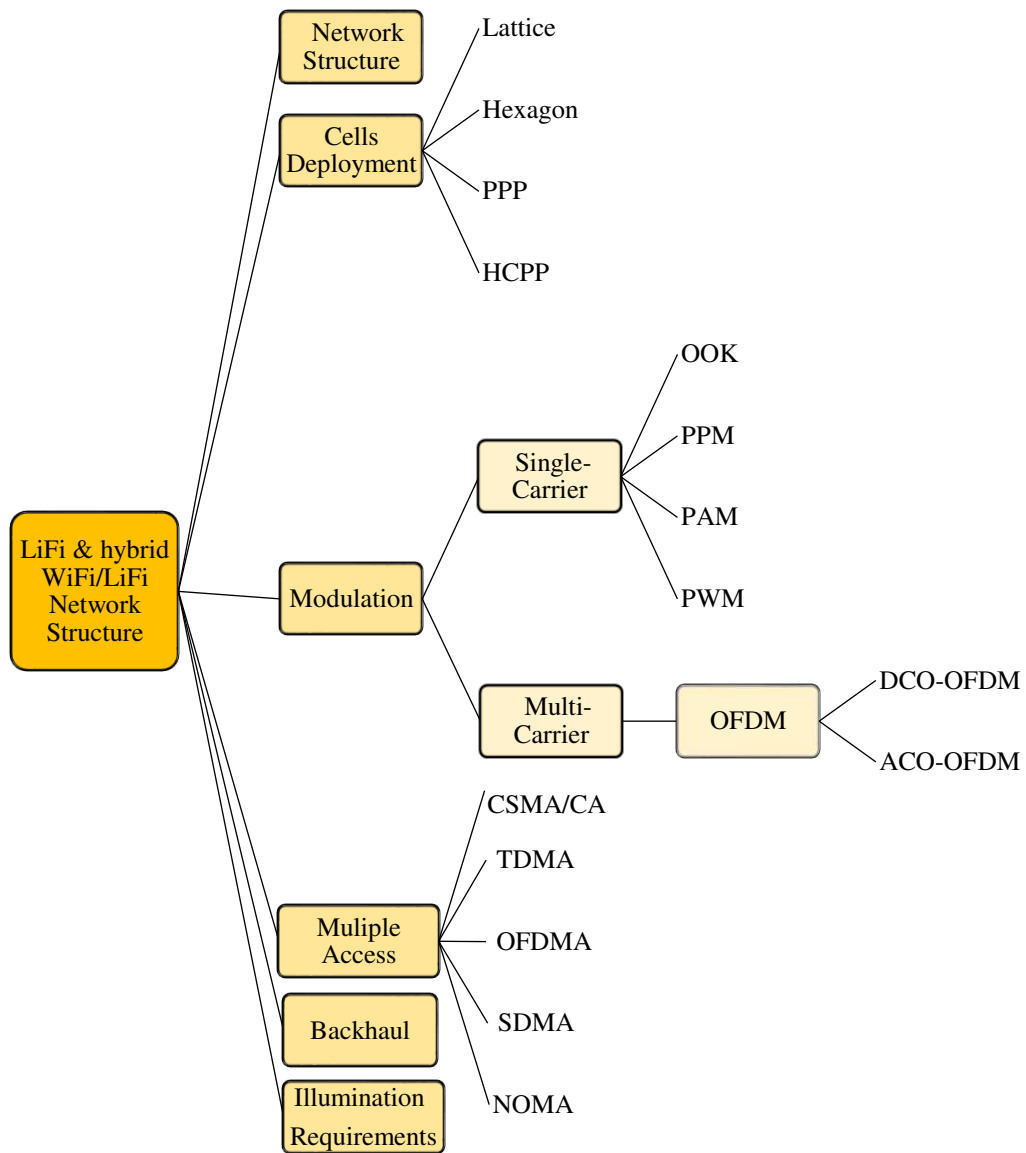


Fig. 3: Components of LiFi and hybrid WiFi/LiFi networks

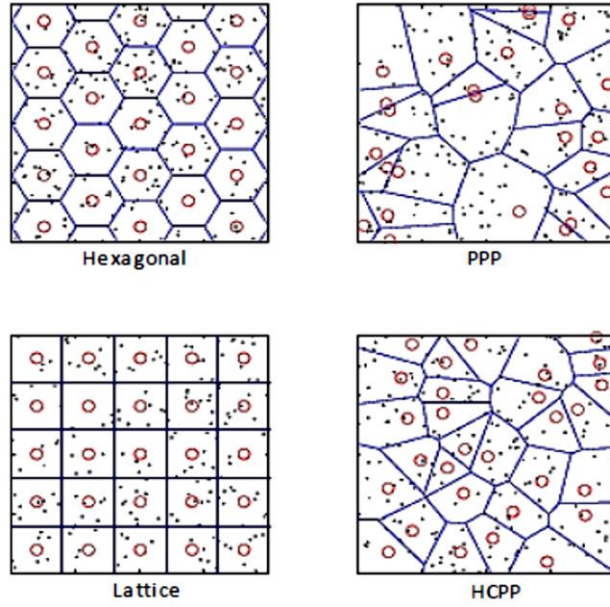


Fig. 4: Types of cellular deployment models [10]

A) Light sources allocation models

Light sources (LED or IR) allocation models include; 1) point-to-point, 2) point-to-multipoint, 3) multipoint-to-point, and 4) multipoint-to-multipoint as shown in Figure 5 [11].

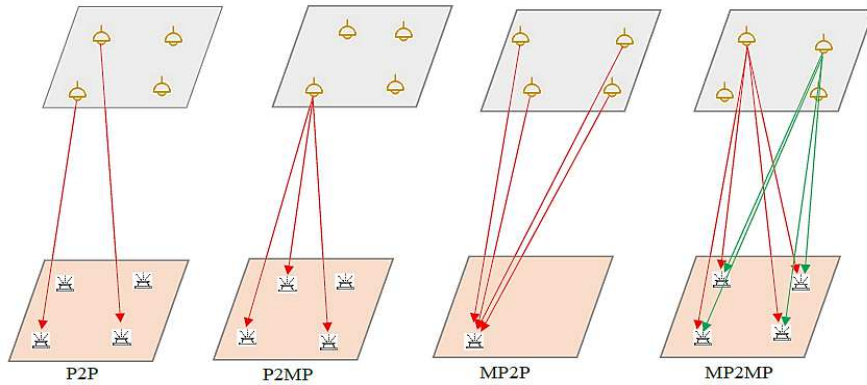


Fig.5: Light sources allocation models [11]

2.3. Modulation

In general, modulation techniques in LiFi systems can be classified into two categories; 1) single-carrier, and 2) multi-carrier.

A) Single-carrier modulation

On-off keying (OOK), pulse position modulation (PPM), unipolar pulse amplitude modulation (PAM), pulse width modulation (PWM), and "multi-ton discrete modulation" PAM are standard single-carrier modulation techniques. Single-carrier modulation methods are easier to implement and more suitable for low-rate applications. Among these modulation schemes, OOK modulation is more prevalent in medium-speed data transmission due to its less complexity. Using OOK, bit "1" is indicated by the presence of a light pulse, while a bit "0" is indicated by the absence of a light pulse. Return to zero (RZ), and non-return to zero (NRZ) schemes are different forms of the OOK method. In the NRZ, the "0" bit duration is the same as the pulse duration sent to indicate "1", while in the RZ scheme, durations are not equal. The low complexity of OOK has led to use it in commercial wireless optical systems such as fast IR links at the less than 4 Mbps applications. Single-carrier modulation schemes are prone to inter-symbol interference (ISI) [1]. Therefore, as the amount of data required increases, the implementing of these modulation techniques requires more sophisticated equalizers in the receiver to deal with ISI through the dispersive channel.

B) Multi-carrier modulation

Compared to single-carrier modulation schemes, multi-carrier modulation techniques are more spectrally practical and can provide higher data rates. Orthogonal frequency division multiplexing (OFDM) is one of the most common and widespread methods of multi-carrier modulation. OFDM is one of the effective solutions to deal with the impact of ISI in LiFi systems [12]. In LiFi systems, the ISI is limited due to the signal passing through a dispersive optical channel in high-speed data transmission mode [12]. In addition, in the LiFi systems that use LEDs as light carriers in the downlink, bandwidth is limited due to off-the-shelf LEDs. OFDM uses fast Fourier transform (FFT) and inverse FFT (IFFT) techniques. In LiFi systems, a modulated signal is used. Therefore, this signal must have a positive and real value. So, a typical OFDM modulator that generates complex and bipolar signals cannot be compatible with a direct Intensity Modulation/Direct Detection (IM/DD) scheme [13]. Optical OFDM (O-OFDM) is a unipolar solution that can be used based on IM/DD. Figure 6 shows an overview of an IM/DD short-range O-OFDM system. In the transmitter, the high-speed data is first to split into a large number of low-speed datasets by the serial-to-parallel converter. Serial to parallel conversion occurs before encoding in quadrature amplitude modulation (QAM) symbols. Then, it is applied to N sub-channels with equal distance. These symbols are converted to time signals through the inverse fast Fourier transform (IFFT). The n^{th} symbol in the IQ modulator (modulating with both in-phase (I) and quadrature (Q) inputs) is obtained from the following equation [14]:

$$x_n = \frac{1}{N} \sum_{k=0}^{N-1} (X_k^I + jX_k^Q) \exp(j \frac{2\pi}{N} kn) \quad (1)$$

where $(X_k^I + jX_k^Q)$ is the mixed value of the symbol modulated on the k^{th} subcarrier. Since the OFDM signal is the sum of a group of independent and uniformly distributed components, the number of subchannels or alphabetic size x_n , is approximately Gaussian due to the central limit theorem. The output of the OFDM modulator is converted to a digital data sequence via a parallel to serial converter. A digital-to-analog converter (DAC) is used to convert this sequence into an analog waveform, generally bipolar. A biasing and cutting process can then deliver this signal through the IM/DD unipolar system. If we consider the bias voltage as I_{DC} , the asymmetric cut samples in the time domain that represent the output distorted signal sequence are shown as follows :

$$S_n = \begin{cases} 0 & , x_n < I_{DC} \\ x_n + I_{DC} & , x_n > I_{DC} \end{cases} \quad (2)$$

This helps us avoid the complexity and high cost associated with the analog cutting module. Although the analog driver signal may still be below zero due to the DAC and filter, but the effect of this issue can be neglected. This unipolar signal will be used to launch a linear optical modulator. For simplicity, we assume that an ideal IM is used, where the optical power output is an instant copy of the corresponding electrical drive signal. The light output through the channel, which has been affected by various attenuations, is affected by scattering and different nonlinear effects before the distorted signal reaches the receiver. So, can be re-distroyed by electrical noise. A "cyclic prefix" can be added to each OFDM symbol so that both inter-symbol and inter-channel interference can be eliminated due to the propagation of modal scattering delay. For short-range applications, achievable rates are limited by achieving a combination of optical power and modal scatter. Although IM/DD in OFDM can only compensate for linear defects, it makes sense to start with a simple mode in which loss and scattering are fully compensated. The operation of the system is limited by the electronic noise of the receiver, so the optical channel is modeled as an additive white Gaussian noise channel (AWGN). Sometimes the optical noise is related to the optical power of the transmitter. Therefore, it has a great deal to do with the signal in the time domain. However, in OFDM systems, optical power dependence can be significantly reduced due to the parallel transmission in the frequency domain, where the noise power is propagated through the FFT deformation process of the spectrum [14].

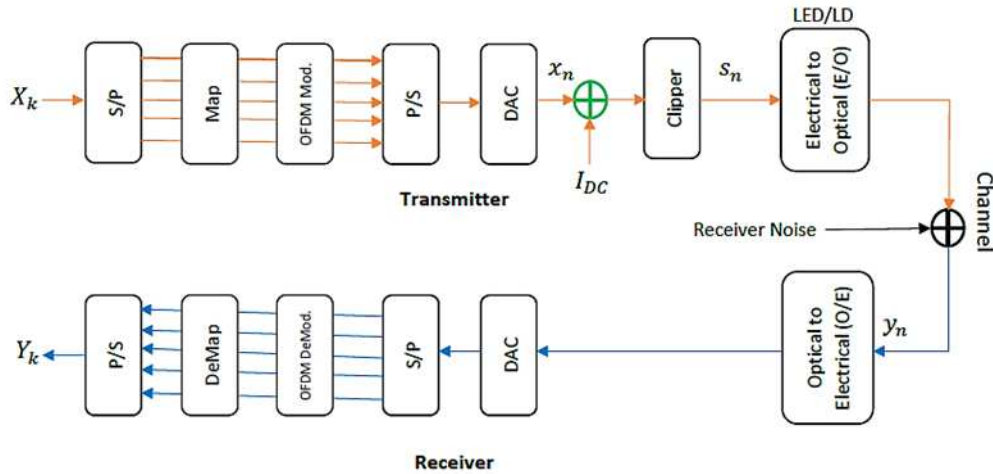


Fig. 6: An IM/DD short-range optical OFDM system

Several types of O-OFDM can produce real negative signals. Two well-known types of O-OFDM are; 1) DC-biased optical OFDM (DCO-OFDM), and 2) asymmetrically clipped optical OFDM (ACO-OFDM).

1) *DCO-OFDM*:

Figure 7 shows a complete DCO-OFDM transceiver system. The first bits of information are formed in quadrature amplitude modulation (QAM). Consecutive modulation symbols are grouped to form an OFDM frame. This frame is used as the input of the IFFT module. To generate signals with real-time values, a hermetic symmetry is applied to the OFDM frame. After passing the IFFT module, a cyclic prefix (CP) is added to the symbols to combat ISI due to the presence of a scattered wireless channel. After adding the CP, the symbols are applied to a DAC module. To ensure the polarity of the modulated signal, a DC bias is added to the analog waveform. A Positive limitation is essential for optical modulation systems for cutting off the noise [3].

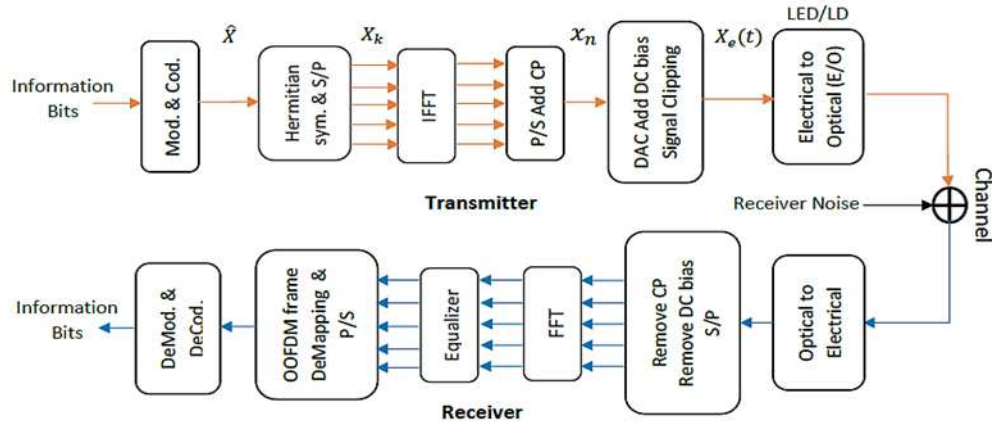


Fig. 7: A complete DCO-OFDM transceiver system

2) ACO-OFDM

ACO-OFDM is another type of O-OFDM in which there is no need to add DC bias to the signal. In ACO-OFDM, only individual sub-carriers are used to transmit information, which leads to a loss of spectral performance. Compared to DCO-OFDM, half of the spectrum is sacrificed by ACO-OFDM to polarize the signal in the time domain. Therefore, the signal generated after IFFT will be a real asymmetric value. The asymmetry property ensures that no data will be lost due to zero signal interruption. It is shown that the bit error rate (BER) in ACO-OFDM is half DCO-OFDM because data transfer occurs in only half of the sub-carriers. Comparison of these two schemes shows that the OFDM-DCO is better than the OFDM-ACO method in terms of spectral gain, energy gain, and data rate [5].

2.4. Multiple Access

WiFi technology standards are the IEEE 802.11 series. In these standards, Carrier-Sense Multiple Access with Collision Avoidance (CSMA/CA) is provided. LiFi standardization is performed in three working groups include; IEEE P802.15.13, ITU G.vlc, and. IEEE 802.11bb [15]. Multiple access methods for LiFi include; CSMA/CA, TDMA, OFDMA, Space-Division Multiple Access (SDMA), and Non-Orthogonal Multiple Access (NOMA).

A) CSMA/CA

1) CSMA

The CSMA technique is proposed to reduce the probability of a collision when two or more stations start sending their signals through the data link layer. Multiple access based on the "carrier-sense" method requires each station to check the channel status before sending data. Persistence methods can assist the station during channel busy/idle .

2) CSMA/CD

In the Carrier Sense Multiple Access with Collision Detection (CSMA/CD) technique, a station monitors the environment after sending a frame to see if it will be successful. If the transmission is successful, the transmission process is completed by the station; otherwise, the frame will be resent .

3) CSMA/CA

CSMA/CA can benefit from the Request to Send (RTS) and the Clear to Send (CTS) methods between the transmitter and receiver [16]. When a node can access the channel, it can use the total bandwidth. CSMA/CA uses a scheme called slotted Binary Exponential Backoff (BEB) to reduce collisions caused by simultaneous sending in nodes. Hence, the nodes listen to the channel for a period known as Distributed Inter-Frame Space (DIFS) before sending. Then, if the channel is idle, the nodes generate random backups. The node with the least amount of backup is the first to send, and before the other nodes, it sends the RTS frame to the AP. If the RTS frame is successfully received in the AP, the AP responds with the CTS frame after a Short Interframe Space (SIFS). Once the node gets the CTS packet, it starts sending data after being specified by SIFS. Finally, an ACK packet is sent by the AP after SIFS to notify the successful receipt of the packet. Figure 8 shows the CSMA/CA scheme with a four-way handshaking RTS/CTS mechanism. CSMA/CA can be used on both WiFi and LiFi systems of a hybrid WiFi/LiFi network. However, if conventional CSMA/CA for LiFi is used in hybrid WiFi/LiFi networks, it can cause severe collisions [17]. This is due to the use of different transmission environments. In the downlink, LiFi uses visible or IR light, and the uplink uses IR light. Therefore, a modified CSMA/CA has been proposed to reduce the number of collisions used in the LiFi system of hybrid WiFi/LiFi networks [17]. In the modified version, a channel busy tone is sent to the AP from users to indicate that the channel has already been occupied. Using the modified CSMA, the probability of a collision can be reduced to less than 1% [2].

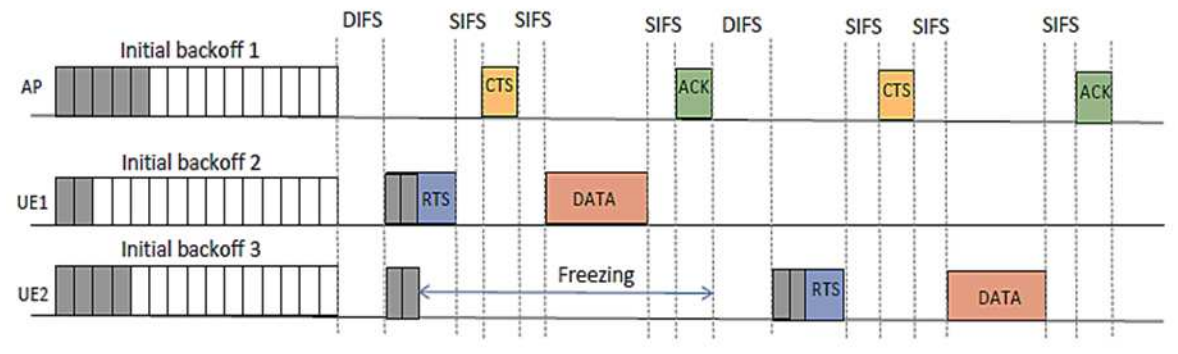


Fig . 8: A CSMA / CA scheme with RTS/CTS four-way handshaking mechanism [5]

B) TDMA

By assigning different time slots to each user, TDMA provides orthogonal access to all available modulation bandwidth for all users. Thus, users send data one after the other, while using each of their dedicated time slots. The TDMA technique is shown in Figure 9. This multiple access method can be used directly in the LiFi and hybrid WiFi/LiFi networks, especially in the downlink. However, because the need for synchronization in TDMA is an essential issue, this is very difficult at the uplink. The synchronization in the uplink is due to different signal propagation times in mobile user terminals that are randomly deployed. These random delays should be compensated with some methods such as timing advance to synchronize the transmission. In addition, due to inter-channel interference (ICI), reported in [1], TDMA performance is significantly degraded in LiFi and hybrid WiFi/LiFi networks. Therefore, interference reduction techniques are needed to reduce. ICI reduces the performance of the user at the edge of a cell.

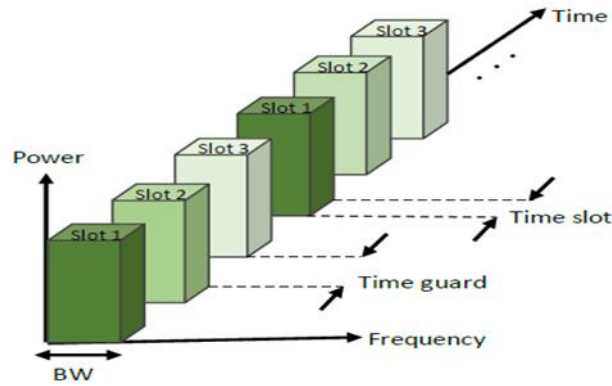


Fig. 9: TDMA technique

This multiple access mechanism enables users to use frequency resources under different carriers and widely used in the downlink in Long Term Evolution (LTE) systems.

By assigning different subsets of sub-carriers to the users, OFDMA can be achieved. The OFDMA technique is shown in Figure 10. Because of the quality of service (QoS) requirement, the available data rate can be controlled individually for each user. This can be achieved by assigning a different number of sub-carriers to other users. Therefore, OFDMA has recently been considered a promising and practical option for downlink. OFDMA can be used as a multiple access mechanism for WiFi connection. In several studies on LiFi and the hybrid WiFi/LiFi network, OFDMA has allocated frequency subcarriers between users [18, 19].

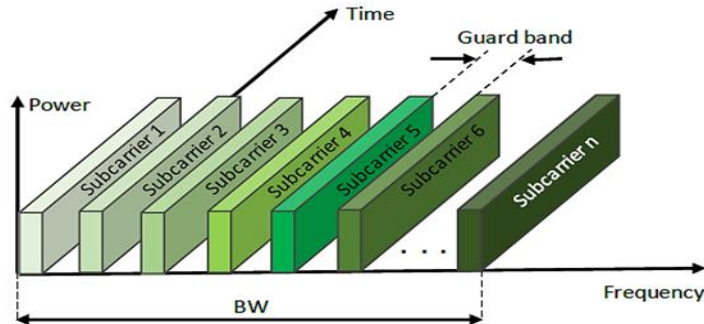


Fig. 10: OFDMA technique

C) SDMA

To increase system efficiency, one of the most effective ways is multiple users can use the channel simultaneously in one-time slot. However, the simultaneous using creates access interference between multiple active users. SDMA is a multiple access method that supports simultaneous transfer to spatially separated users. To avoid significant interference when accessing multiple users, the location transfer characteristics of transmitters and receivers should be controlled. Angular diversity transmitters are suitable for this purpose. SDMA for the first time implemented in RF systems. In SDMA, multiple active users are grouped in one-time slot, while in TDMA, only one active user occupies each time slot. For example, using TDMA, an optical AP requires four time-slots to provide services to four different users, while in SDMA, transmission to multiple users occur in a single time slot. However, grouping in SDMA has some disadvantages. Multi-element transmitters are required to support simultaneous and directional transmission. In additions, if users are grouped incorrectly, multi-user access interference will increase. To solve these problems, an angular diversity transmitter is used along with an "optimal spatial grouping" strategy in the SDMA system. The overall structure of the optimized SDMA is shown in Figure 11 for 10 users. In this case, the gain is defined as the return throughput in SDMA mode to the return throughput in TDMA mode ratio ($\text{Gain} = T_{\text{SDMA}}/T_{\text{TDMA}}$) [20].

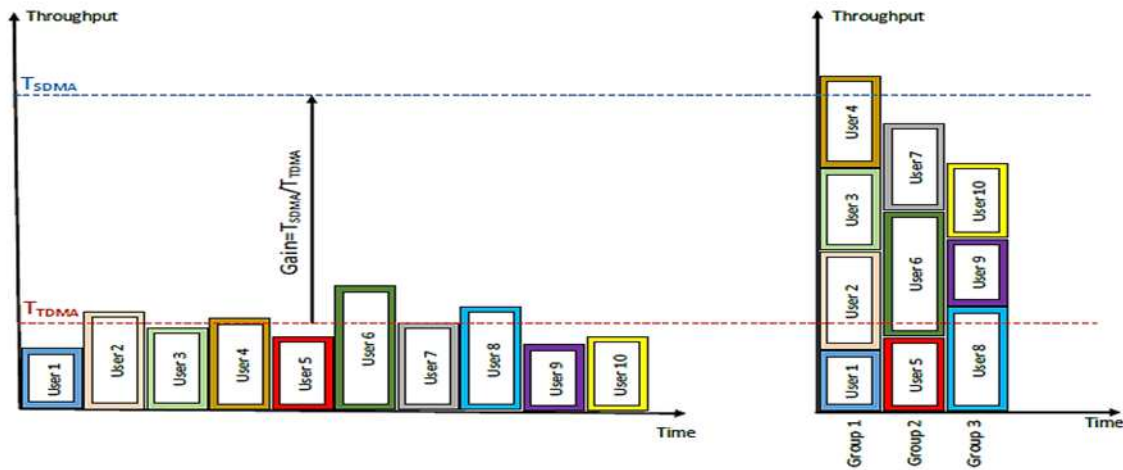


Fig. 11: SDMA technique

D) NOMA

Non-Orthogonal Multiple Access (NOMA), also known as multiple access in the power field, has recently emerged as a promising candidate for 5G wireless mobile networks. This is due to the increased spectral efficiency and the higher data rate in this technique compared to orthogonal multiple access techniques [21]. Unlike orthogonal multiple access methods such as TDMA and OFDMA, where time or frequency resources are allocated exclusively to users, in NOMA, all users use the same time and frequency resources. Users in the power domain are multiplexed by Superposition encoding and decoding the transmitted signals by using Successive Interference Cancellation (SIC) in the receiver. Hence, in this technique, Channel State Information (CSI) is required. In NOMA, users with good channel conditions are given less transmission power, while users with poor channel conditions are given higher transmission power. [22] NOMA-based hybrid WiFi/LiFi based on simultaneous data and wireless transmission is proposed. The nearby user receives the information and energy from the LED (or IR). It then uses the captured energy to transmit data via WiFi to users who cannot communicate directly with the LED (or infrared light source).

2.5. Backhaul

In mobile networks, the links that connect the light source points (LED or IR) to the central unit are called backhaul links. With the rapid growth of mobile users, backhaul links should also grow accordingly. Radio interfaces have long been a bottleneck for mobile networks due to their low performance. However, this bottleneck has shifted to backend networks in recent years, along with improved radio interfaces and demand for high-speed data service and data generation. Hybrid WiFi/LiFi networks should have separate or shared backhaul for LiFi and WiFi networks that can ensure availability, scalability, and visibility on hybrid networks. LiFi networks are made up of several small cells known as femtocells [23]. Using modern interference management techniques, the spectrum can be fully utilized in each LiFi cell [24]. Therefore, LiFi APs can provide data rates of several gigabits per second. Hence, backhaul links should transmit hundreds of gigabits per second over LiFi networks. Various technologies, including wireless optical technologies such as visible or infrared light, have been studied as possible solutions for connecting backhauls. The wired backhaul option is fiber optics that provide a wide bandwidth of several gigabits per second. Optical wireless communication is another possible solution that will be able to manage high-speed networks in backups for future networks. In [25], a wireless solution based on visible light communication is proposed for indoor auto cell LiFi networks. In [26], frequency reuse is provided for access and backhaul links. Both visible and infrared light bands are evaluated as backhaul solutions for LiFi networks. The effects of "between backhaul" and "backhaul-to-access" interference on the SINR have also been analyzed. To achieve re-realization with visible light, the authors evaluated both full reuse and in-bandwidth allocation methods. In hybrid networks where LiFi and WiFi systems are provided by the same backlink [27].

2.6. Illumination Requirement

In LiFi or hybrid LiFi/WiFi systems that use visible light produced by LEDs as a downlink carrier, one of the most effective ways to improve energy efficiency is to properly design the placement or arrangement of the LEDs inside the building. By optimizing the location of the LEDs and controlling their output power level, the minimum energy consumption is achieved, and at the same time, a desirable lighting pattern is achieved. It is important to consider room lighting limits when designing a LiFi network that uses LEDs as a downlink carrier. the illumination requirement for an indoor environment should be in the range of 300 to 1500 Lux [28]. Typically, the light is low in the corners of the room while it is high in the center of the room. Therefore, careful design is required to ensure uniform brightness. The brightness level in each area can be obtained as follows :

$$I_{Lum}(x, y) = \sum_{i=1}^{N_{LED}} \frac{I_0}{d_i^2} \cos^m(\phi_i) \cos(\psi_i) \quad (3)$$

where I_0 is the central luminosity of the LEDs, which is assumed to be the same for all LEDs, and d_i is the Euclidean distance between the i -th LED and the desired location with coordinates (x, y) . The number of LEDs is indicated by N_{LED} . The radiance and incidence angles at the point (x, y) are denoted by ϕ_i and ψ_i , respectively. The Lambertian order, m , is obtained from the following equation in the half-intensity angle, $\Phi_{1/2}$ [29].

$$m = -1/\log_2(\cos(\Phi_{1/2})) \quad (4)$$

A) LiFi systems with IR

Some LiFi systems use IR transmitter/receiver instead of LED in up and downlinks. In this case, ambient illumination should be provided through other illuminating equipments (the IR transmitter/receiver only is used for sending and receiving data, and ambient illumination is not provided in this way).

3. Attributes of LiFi and Hybrid WiFi/LiFi Systems

A LiFi or hybrid WiFi/LiFi system has essential attributes include; 1) interference, 2) user behavior model, 3) handover, and 4) load balancing. Figure 12 shows the essential characteristics of LiFi and hybrid WiFi/LiFi systems.

3.1. Interference

Increasing the number of light sources (LED or IR) is one of the essential aspects of network density, which will be recognized as the primary mechanism of wireless evolution in the next decade. However, interference management is crucial. LiFi and WiFi do not interfere due to operating in different spectrums. In addition, CSMA/CA with WiFi can minimize co-channel interference (CCI). Hence, hybrid WiFi/LiFi networks focus more on LiFi interference management techniques. These techniques are listed in Figure 11[5].

A) Interference cancellation

Interference cancellation refers to techniques that decode the information and use this information along with channel estimation to cancel or reduce interference in the received signal [29]. These types of techniques are used at the end of the receiver, where receiving an interference signal. These techniques can be summarized as follows :

1) Precoding

Precoding techniques including zero forcing (ZF), block diagonalization (BD), and dirty paper coding (DPC), are widely used to eliminate interference signals in downlink. The basic principle in these techniques is to intelligently create orthogonal channels by breaking them down into individual units. Because optical signals are not negative, conventional Precoding techniques need to be modified by LiFi; for example adding DC bias is one of these methods [30]. Depending on the type of interference, Precoding techniques can be divided into two categories; multi-user detection (MUD) and coordinated multi-point transmission (CoMP). The purpose of the MUD is to eliminate interference between channels within the same APs. CoMP is designed to eliminate ICI by coordinating APs to exchange CSI knowledge. Encryption-based methods for override encoding require Channel State Information at the Transmitter (CSIT) for all subscriber channels. If no illumination is needed, WiFi typically uses IR and forms a Frequency Division Duplex (FDD) system. Therefore, implementing precoding techniques in LiFi is costly. CSI also disrupts precoding performance. This is more pronounced in LiFi because rapid device orientation create high-speed channels.

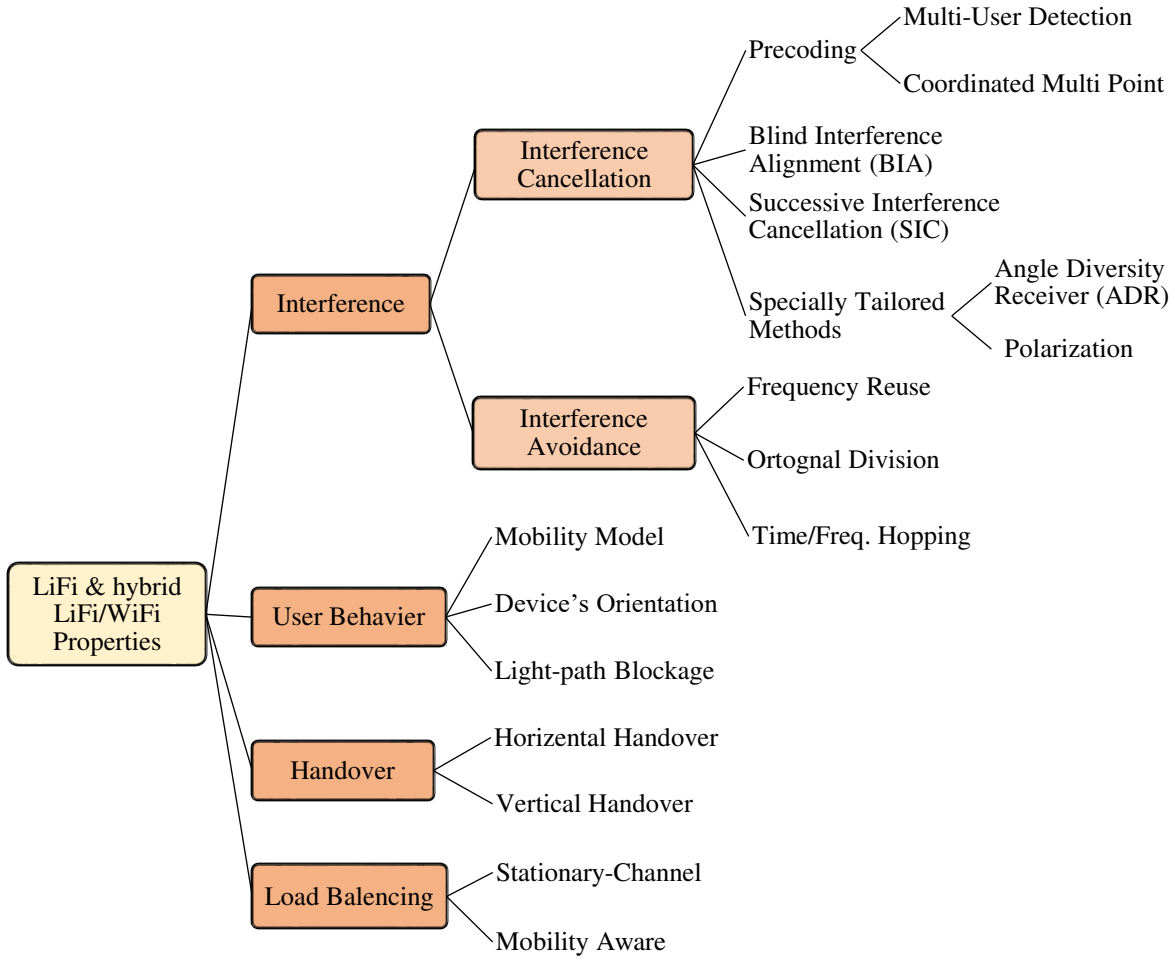


Fig. 12: Attributes of LiFi and hybrid WiFi/LiFi systems

2) Blind Interference Alignment (BLA)

When the CSI is not precisely known in the transmitter, the BIA can be obtained by pairing a "time-selective" user with a "frequency-selective" user [31]. The basic concept is to get the maximum freedom for shared channels by covering the transmitted signals based on channel coherence. Unlike pre-encryption, BIA can only partially reduce interference. The channel coherence condition for BIA may not always exist, so that channel manipulation will be required. In RF systems, adjustable antennas that enable the receiver to switch between antennas can achieve this issue [32]. In [33], BIA was applied to LiFi by equipping each user with a photodetector (PD) and several light beams. In [34], the BIA function for the hybrid network, where some users can switch to WiFi, is studied. However, BIA can only perform better than TDMA in the high optical power range, for example, above 50 dB, which is impractical for LEDs for lighting purposes [34].

3) Successive Interference Cancellation (SIC):

The SCI can detect signals arriving simultaneously by detecting different power levels of the received signals. Lighting requirements must also be met when power control is implemented in LiFi. Since only the AC component of the optical signal is converted into an effective electrical signal, the percentage of the AC component can be adjusted to maintain the same average optical transmission power. In [35], power control is checked when the user is served by multiple APs. Each user identifies a user at each stage, and therefore the channel will have complexity and latency in proportion to the number of users. Alternatively, Parallel Interference Cancellation (PIC), which detects all users simultaneously, can reduce latency by increasing complexity. In LiFi, SIC is preferable to PIC because each LiFi access point covers a relatively small area and probably serves only a small number of users. Using SIC to achieve multiple accesses evokes the concept of NOMA. SIC-based override methods rely on an appropriate pair of co-channel users who may not always be satisfied with very dense networks, as there are only a small number of users per cell.

4) Angle Diversity Receiver (ADR)

The ADR uses several narrow Photodetector-Field of Views (PD-FoVs) instead of one wide PD-FoV to reduce interference per PD. The performance of a combination of different signals for ADR was analyzed in the following ways: 1) selection of the best combination, 2) equal interest combination, 3) maximum ratio combination, and 4) optimal combination, in [24]. In [36], ZF decoding was combined with conventional ADR to reduce ISI and ICI. In [37], an optimized ADR with different PD numbers for different LED designs is presented. However, slim FoV PDs are prone to "device orientation changes". The performance of ADR techniques has not yet been verified in a real mobile environment.

5) Polarization

The light polarization feature can also be used for differential detection to eliminate interference. A polarization-based approach in which two different polarization filters are used to eliminate interference is proposed in [38]. A similar method is proposed in [39] for resistance to non-polarized light interference. This method requires a complete alignment for the polarization directions between the transmitter and receiver, which is possible in laboratory experiments. Still, it is complicated to implement in operation.

B) Interference avoidance

Interference avoidance refers to techniques that work at the end of the transmitter to prevent interference. These techniques include orthogonal division schemes including TDMA, OFDMA, and SDMA. Some studies, for example, in [40], cite power control as a method of preventing interference. However, this method can not work without SIC. It is therefore considered as SIC-based interference cancellation.

C) Frequency reuse

Frequency reuse (FR) is widely used to prevent ICI among neighboring cells, where frequencies are reused regularly. Various studies have been performed to apply FR in LiFi networks. In [41], experimental work was completed to demonstrate the application of FR in LiFi. The Soft Frequency Reuse (SFR) has been analyzed in [42]. In this study, in the first design, the cell region is divided into three equal parts, while in the second design, the cell structure of two layers is provided. Compared to accurate Fractional Frequency Reuse (FFR), SFR is visualizable and can achieve a higher frequency reuse ratio using the same ability to suppress interference. To adapt the different application, a dynamic SFR scheme in [43] with adjustable spectrum allocation is proposed. This design creates a more visible cell structure than SFR.

D) Frequency/time hopping

Frequency/time hopping methods, using a quasi-random sequence known to both transmitter and receiver, quickly move a carrier across many frequency channels or time slots. A time hopping method for LiFi was reported in [44], where the duty cycle of the optical carrier is different in a quasi-random manner. This method reduces the likelihood of two users occupying the time-frequency block but requires careful coordination between the AP and the user .

3.2. User Behavior

In LiFi cellular network and subsequently in hybrid WiFi/LiFi network, efficiency and Quality of Service (QoS) depends on various factors such as user mobility, random orientation of the user's device and link blocking. Many mobility models are presented in the articles [45]. The Random Waypoint (RWP) model is one of the simplest and most well-known models designed to simulate user mobility indoors or outdoors. Device orientation and link blocking are two other essential factors that affecting user performance on LiFi networks.

A) Mobility

Various models have been proposed to demonstrate indoor mobility. In [46], user mobility is considered in rectangular microcells in which users may either move at a constant speed or remain stationary during a call. In this model, users tend to move in straight lines to the point where they change direction, according to the Poisson process model. In [47] a mobility model based on a new rule is proposed inside a multi-room building in which users move in specific paths from one room to another. In [48] a mobility model is defined in which nodes move along the edges of the graph. The edges represent authentic paths inside the room. Each node randomly selects a destination chart from the vertex subset and moves along the edge. A 3D mobility model inside the building considering boundary conditions is presented in [49]. In this model, horizontal and vertical movement are modeled. In [50] the same idea is extended to a 3D mobility model in high-rise building environments where vertical movement is performed by elevator. A new and more realistic three-dimensional internal mobility model based on actual building data is presented in the reference [51]. To model the building, various factors such as walls, floor, and ceiling are considered, and then, a diagram-based model is introduced in which users move along the edges between nodes in valid paths. A simple and widely used mobility model is the RWP model. In recent studies, they have considered the RWP mobility model in their simulations. Therefore, this internal mobility model is usually used. The RWP mobility model was first proposed in [52] for random human modeling. Figure 13 shows the basic concept of the RWP mobility model in a room with dimensions $A \times B$. According to the RWP model, at each point along the way, the User Equipment (UE) should meet several characteristics to move from one point to the next. These characteristics include; i) the choice of destination or next point is random with a probability of $1/AB$, ii) the path is a straight line, and iii) the speed is constant while moving between two stations in a row .

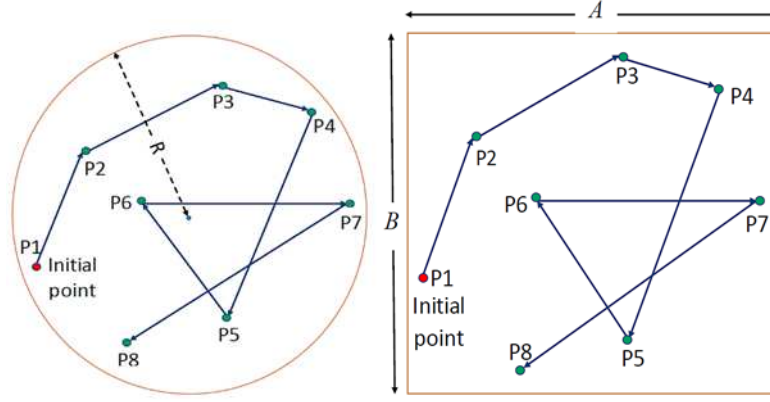


Fig. 13: Basic concept of RWP mobility model: a) A room with dimensions $A \times B$ b) An autocell with radius R [52]

B) Orientation

Orientation of the user device is another factor that can affect the LiFi network performance. The effect of device orientation on current WiFi systems is negligible, while this is very important in the LiFi systems due to the short wavelength of the light. Due to the lack of a suitable model for device orientation, in most studies related to LiFi, the effect of random device orientation is ignored. The receiver's direction is determined based on three angles α , β , and γ . Figure 13 shows the UE orientation model and its associated rotations on three axes in a Cartesian coordinate system. The rotation on the z-axis is between 0 and 360 degrees, while on the x-axis is between -180 and +180 degrees, and on the y-axis is between -90 and +90 degrees. Using Euler's rotation theorem, each rotation in the three-dimensional space (\mathbb{R}^3) is uniquely characterized by two characteristics: 1) the axis of rotation, which is a one-dimensional space (\mathbb{R}^1), and 2) the orthogonal plane with the axis of rotation, which is a two-dimensional space (\mathbb{R}^2) (see Figure 14).

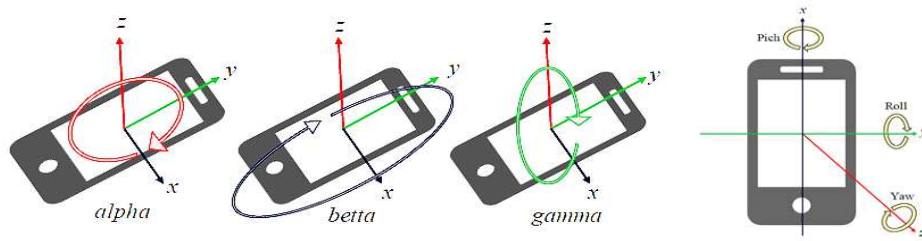


Fig. 14: Alpha, beta, and gamma angles

Assuming $n_{rx} = [n_1 \ n_2 \ n_3]^T$ and $n'_{rx} = [n'_1 \ n'_2 \ n'_3]^T$ are the normal angles of the user's receiver before and after rotation, respectively (T is the symbol of a transposed matrix) (see Figure 15), then the normal vector after the rotation will be obtained from the following equation :

$$\mathbf{n}'_{rx} = \begin{bmatrix} \sin\alpha \sin\beta \cos\gamma \\ \sin\alpha \sin\gamma - \cos\alpha \sin\beta \cos\gamma \\ \cos\beta \cos\gamma \end{bmatrix} \quad (5)$$

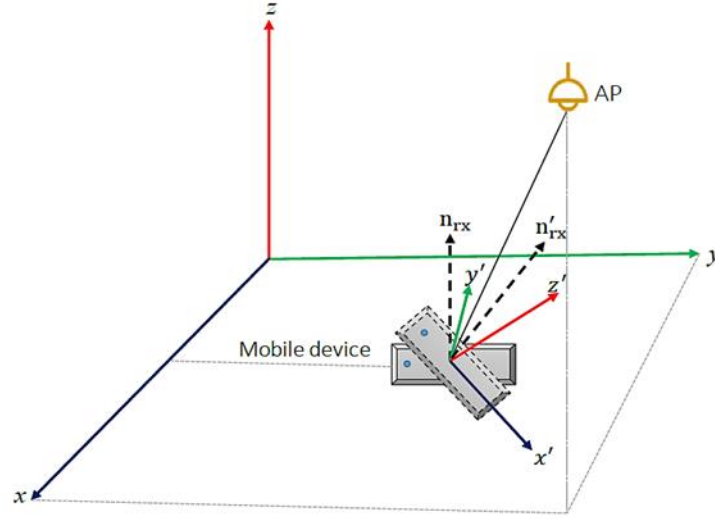


Fig. 15: Orientation model in a mobile receiver [53]

In [54], the effect of device random orientation on the load balance in the network is considered. Their proposed load balancing algorithm is used evolutionary game theory to efficiently allocate resources between UEs. In [55], the effect of device random orientation on the performance of Bit Error Rate (BER) is evaluated. A random process model for changes in the orientation of the device based on the real-world characteristics measurements are presented in [56], the temporal characteristics of the device are considered in the stochastic process model. It is modeled as a channel with slow change. The integration of the device's random orientation with the conventional mobile RWP model was investigated to provide a more realistic and accurate framework for analyzing the performance of mobile users. The performance of mobile users in LiFi networks has been evaluated using Orientation-based Random WayPoint (ORWP) model in [57]. These studies are from a Gaussian correlated model used to generate a polar angle while the user is moving. The ORWP mobility model has been proposed for the first time in the hybrid WiFi/LiFi network for the more accurate evaluation of system performance and support for dynamic load balance for mobile users [58].

C) Light Blockage

Another critical factor in a LiFi or WiFi/LiFi network is an accidental light blockage. It should be noted that in a hybrid WiFi/LiFi network, the LiFi system is more vulnerable to blockage. In contrast, the WiFi system is stronger than the LiFi. The effect of link blockage in WiFi is negligible. Due to the nature of the LiFi channel, the connection between a pair of transmitters/receivers can be blocked by a matte object such as a human body or other similar objects. In indoor networks, the main reason for link blocking is mobile users. Blockers can be modeled as rectangular [59] or cylindrical objects [60]. Figure 16 shows the obstruction models for the human body either in the form of a rectangle of size $H_b \times L_b \times W_b$ or a cylinder of height H_b and radius R_b . Note that when a communication link is blocked, the LiFi system error cannot be

compensated by adding power. Solutions to reduce the blockage effect are provided. For multidirectional receivers of multiple PDs on different sides of the smartphone, has been evaluated to solve the problem of accidental blockage of the device [57]. In [61], a directional receiver is provided in which PD is used all around the phone to be more robust against the obstruction. The excellent performance of this proposal compared to single PD and dual PD configurations are discussed. The Line of Sight (LoS) occlusion analysis is presented in [62]. When the LiFi link is blocked, the user connects to the WiFi access point because it can provide integrated coverage. In [63], a method is proposed in which the data rate is improved through a hybrid WiFi/LiFi network in the presence of blockers with different blocking densities in indoor network. In this research, the effect of link blocking about intercellular interference on user power in a hybrid WiFi/LiFi is evaluated. The authors propose a load balancing algorithm based on evolutionary game theory to allocate LiFi and WiFi resources among users effectively, where the shadow effect is considered in their proposed algorithm. A simple blockage-resistant hybrid WiFi/LiFi network is introduced in [64]. The impact of LoS blocking on LiFi performance in a hybrid WiFi/LiFi network is evaluated. In this study, it has been shown that by widening the LED half power angle, the blocking effect of the LoS link can be reduced. This is due to the broader coverage of the LiFi AutoCell, which leads to a lower chance of LoS blockage. When the LiFi link is blocked, the user connects to a WiFi access point to provide coverage. In this case, the average data rate in the link below is obtained from the following relation :

$$\bar{R} = P_b R_{\text{wifi}} + (1 - P_b) R_{\text{LiFi}} \quad (6)$$

In this regard, P_b is the probability of blockage, R_{LiFi} is the data rate in the LiFi system and R_{wifi} is the data rate in the WiFi system. In the absence of blockage, the regional data rate in the hybrid WiFi/LiFi network will be improved indoor networks .

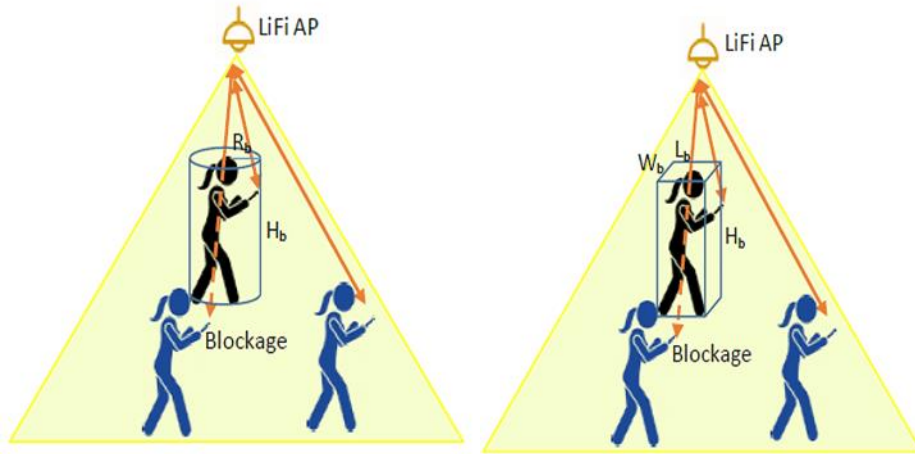


Fig. 16: Blockage modeling in LiFi network

3.3. Handover

In mobile communications, redirection occurs when a user is transferred from one AP to another with a given session without disconnection. Depending on the disconnection sequence, handovers are classified into two categories: hard handover and soft handover. With a hard switch, the user first disconnects their current link and then establishes a new connection to another AP known as the target AP. During the handover process, the target user and AP exchange signaling information through dedicated channels, and

no data transfer will be available. In the case of soft switching, a new connection is established before the user disconnects from the host AP. This allows data to be transferred in parallel with the handover process. Soft switching can typically be used when the host and target APs are operate at the same carrier frequency. Conversely a handover that requires a change in the carrier frequency is called a hard handover. Therefore, it is necessary to examine the effect of how the handover process on the performance of the hybrid network. In general, the transfer process in a hybrid network is divided into two categories include horizontal handover (HHO), and vertical handover (VHO). Horizontal handover occurs within a single wireless access technology, while VHO occurs between different accesses technologies. With VHO, the air interface changes, but the routing to the destination remains the same. In some studies, a third category called diagonal handover has been introduced, in which both the air interface and the destination change direction .

A) Horizontal handover (HHO)

The concept of horizontal handover in a LiFi network is shown in Figure 17. The hybrid network with LiFi APs has a coverage range of 2 to 3 meters in diameter [65]. The ultra-small cell allows the hybrid network to experience significant consecutive alterations, even if the user moves at a medium speed. In addition, it should be noted that the LiFi channel is related to the direction of receiving PD. A change in the direction of PD reception can occur very quickly and abruptly, leading to frequent and unexpected migrations. For the above reasons, metamorphosis overhead becomes an important and influential factor in network efficiency. Considering alterations, the separation distance between light sources affects the network performance in two ways. On the one hand, a minor separation can provide spectral efficiency in the higher range, and a major separation can reduce the handover rate. For this purpose, the optimal location of LiFi access points was studied in [66]. It is concluded that the area covered by the optimal coverage of LiFi access points is up to eight square meters depending on user density and handover overhead. Given that the areas covered by different access points often overlap, the authors examined the algorithm for non-overlapping coverage in [67]. This study proposes a soft handover for the non-overlap coating and a hard handover for the overlap coating. However, the above two articles only cover user mobility and do not consider the rotation of mobile devices. In [68], the degree of handover in the LiFi network with the movement and rotation of user equipment was investigated. It was found that when the user's equipment is tilted between 60 and 80 degrees, the amount of alteration is maximized. Although the optimal placement of light sources on the ceiling can partially eliminate the disadvantage of alteration, the reduction in efficiency is still prominent for high-speed users. Handover Skipping (HS) was introduced in [69], which enables the user to move between adjacent access points. In this research, a topology-aware HS scheme is proposed that if the cell chord length is less than a specified threshold, the user can exceed the coverage range of some light sources. A similar method has been used in [70] to research several light sources. However, the equivalent of a LiFi network topology is dynamic and user-dependent due to its PD reception effect. In addition, to gain knowledge of the user's movement path, positioning and transfer techniques are required at the link above to apply to access points. To circumvent the above precise requirements, the RSS-based HS approach is proposed in [71]. This method uses the rate of change in the RSS feed to indicate whether the user moves to a specific light source. The weighted average of the RSS and its rate of change are evaluated to determine the target light source for the handover. Because RSS is commonly used in current handover designs, no additional feedback is required. Notably, the HS method does not rely on knowledge of network topology .

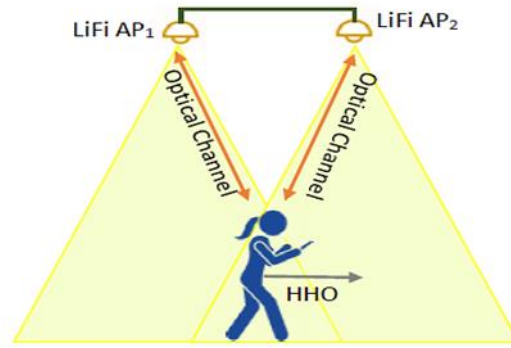


Fig . 17: Horizontal handover in LiFi

B) Vertical handover (VHO)

In hybrid networks, the users usually need a vertical switch from LiFi to WiFi when they lose their LiFi connection. The concept of vertical outsourcing in a hybrid network is shown in Figure 18. Loss of LiFi connectivity can occur for two reasons:

- 1) The light path is blocked by opaque objects such as the human body and furniture.
- 2) It is generally diverted from the LoS path to receiving PD.

In [72], the probability of VHO for a user with random rotations in a hybrid network is analyzed. In [73], a VHO scheme is proposed based on Markov's decision-making process. This method determines the VHO based on the queue length for WiFi and the status of the LiFi channel . Due to the change of air interfaces, VHO usually requires much more processing than HHO. In addition, the WiFi system has less system capacity than LiFi, and an excessive number of WiFi users significantly reduces system efficiency. So choosing between HHO and VHO is critical for a hybrid network. Users experience transient blockages in the light path. Apart from this, user speed is also an essential factor in deciding whether to serving the user with LiFi or WiFi. High-mobility users generally prefer WiFi because they experience frequent horizontal shifts in LiFi .

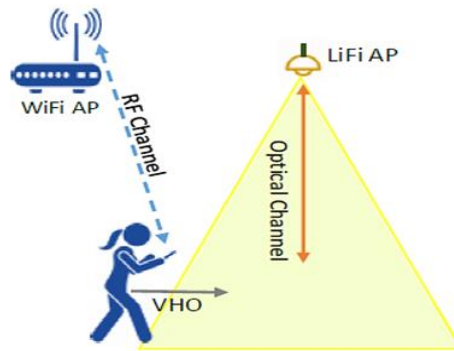


Fig . 18: VHO in a hybrid LiFi/WiFi network

3.4. Load Balancing

Wireless networks, load balancing (LB) refers to techniques that distribute user sessions among APs with overlapping areas. The goals of LB techniques are to optimize resource utilization, maximize operational

efficiency, minimize response time, and reduce network congestion. In homogeneous networks, coverage overlap is limited to minimize ICI among access points. As a result, LB only applies to cell edge users who enter unusual loads at different access points. In other words, LB is not needed when users' requests for data rates are evenly distributed over an area. In [67], the authors reviewed the LB techniques related to WiFi and classified these techniques into two categories: user-centric and based on the coverage area of the light source. Using user-based methods, each user according to their interest, with optimal network performance is difficult to achieve. In contrast, light source coverage area-based methods are implemented at the network level but require a central unit to coordinate applications. Unlike homogeneous networks, LB becomes necessary and challenging in combined WiFi/LiFi networks. This is because the areas covered by LiFi and WiFi overlap entirely. WiFi hotspots also have more coverage but less system capacity than LiFi hotspots. This makes WiFi prone to over-transmission, even if user demand for data rates is evenly distributed geographically. The proposed LB algorithms for LiFi and WiFi/LiFi hybrid networks can be classified into two categories: 1) static channel and 2) mobility awareness.

A) Stationary channel

An LB method in the form of centralized and distributed resource allocation algorithms for achieving Proportional Fairness (PF) among users is presented in [62]. To improve service quality (QoS), the LB problem is considered a problem that combines the correct value and formulated nonlinear programming that addresses different data needs among users. The above methods both create NP-hard problems, in which case the problem solving is faced with a computational complexity that increases exponentially with the number of access points. To reduce the processing power required, an iterative algorithm based on evolutionary game theory is reported in [54], in which multiple justice functions (MFF) are considered. In this research, the obstruction of the light path, the desired orientation of the receiver and the need for data speed to model a practical communication scenario are identified. The authors in [19] introduced an iterative algorithm but focused on force allocation. The algorithm consists of two modes: i) finding the optimal energy allocation of each AP to maximize its output power, and ii) searching for another access point for the user with the lowest data rate to increase overall efficiency and increase system equity. The above iterative algorithms, which require several iterations to achieve a steady-state, can be considered autonomous optimization. As mentioned, general optimization and autonomous optimization have their limitations, thus leading to a significant amount of processing time being spent. In LiFi and WiFi/LiFi hybrid networks, CSI can change quickly for mobile users, even at medium speeds. This limits processing time and therefore challenges the practicality of the above methods. Alternatively, direct decision methods are implemented that significantly reduce processing time. In other words, it first identifies the users who should be served by WiFi and then determines the other users as a standalone LiFi network. This method, based on fuzzy logic, relying on statistical knowledge of data rate needs and CSI, can have optimal performance in terms of power consumption and fairness and reduces processing time by more than ten times.

B) Movement awareness

The methods mentioned in the previous section have this feature in common, in all of which there is CSI awareness. Given that the CSI value changes due to user movements or environmental changes, in such cases, these methods must recalculate their solutions. The impact of alterations should also be considered when new solutions change the way users interact (which may change very quickly in LiFi and WiFi/LiFi hybrid networks). For example, users at the edges of LiFi access point cells prefer WiFi, and users at the center of LiFi access points prefer LiFi. Using fixed channel load balancing methods, users are frequently switched between LiFi and WiFi as they move across LiFi access points. To solve the above problem, user

mobility must be considered along with LB. This idea is referred to as the balance of motion-aware load [74]. Such an approach was proposed as a model of university admission. In this method, the achievable data rate and the user's direction are used to measure the user preference for route selection. The total user data rate in this case is used to calculate AP preferences. These two preferences are then calculated iteratively to arrive at a fixed solution. A dynamic LB scheme is proposed in [75], which also uses an iterative algorithm. In each iteration, resources are allocated to improve the effective data rate that does not include additional metamorphosis costs. In [76], a similar method is developed but with a joint implementation to allocate light sources and their budget. The results show that a joint implementation can be 50% more efficient than a separate implementation, with higher computational complexity costs. In all the proposed methods in this field, it is always tried to compromise between the instantaneous data rate and the conversion rate to maximize the average data rate .

4. LiFi and Hybrid WiFi/LiFi Network Performance Criteria

To evaluate the efficiency of LiFi and hybrid WiFi/LiFi network, various criteria such as coverage probability, spectral efficiency, area spectral efficiency, network efficiency, fairness, and service quality have been studied in multiple researches. These criteria can be categorized as Figure 19.

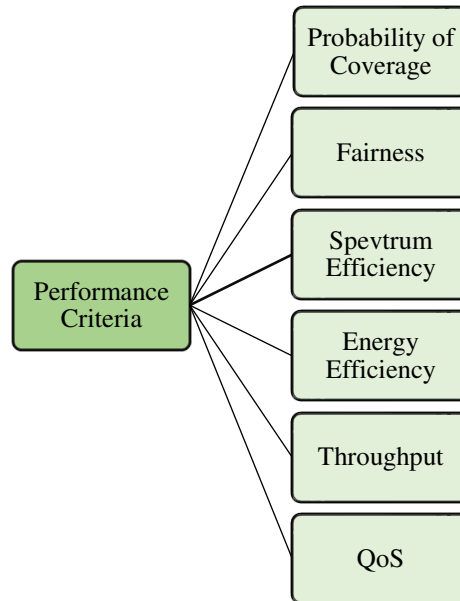


Fig . 19: Performance criteria for LiFi and hybrid WiFi/LiFi networks

4.1. Coverage Probability

The coverage probability is defined as the probability that the SINR is higher than a certain threshold used in the mobile networks. In LiFi and hybrid WiFi/LiFi network, especially in LiFi systems, the probability of coverage depends not only on the location of the UE but also on its orientation. Orientation can be

uniquely determined by three angles (α, β, γ). Therefore, the probability of coverage for the orientation of a particular device can be mathematically defined as follows [77].

$$P_c = P_r\{S > S_t | (\alpha, \beta, \gamma)\} \quad (7)$$

where, S is the SINR value of the received signal at UE and S_t is the threshold for SINR. Therefore, the probability of coverage for device orientation can be interpreted in three ways; 1) the probability that the SINR of a randomly selected user is higher than the threshold of S_t , 2) the average number of users whose SINR is greater than the threshold of S_t at any time more, and 3) the part of the cell region where the SINR is greater than the S_t threshold [53]. It can be concluded that the probability of coverage is equal to the cumulative distribution function of SINR.

4.2. Fairness

Fairness is a measure of how fairly the resources are distributed among users. When it comes to resource allocation, this criterion is considered to assess the equitable allocation of available resources. There are several definitions of fairness, such as "Jain's Fairness index", "max-min fairness", "fairness with quality of experience", and "fairness at worst". Researchers make extensive use of the Jain's Fairness Index. This criterion is defined as follows [78].

$$I = \frac{(\sum_{i=1}^N x_i)^2}{N \sum_{i=1}^N x_i^2} \quad (8)$$

where, x_i represents the average data rate of each user and N represents the total number of users. I is a value bounded between $1/N$ and 1. The total fairness of the user is equal to 1, while the value of $1/N$ corresponds to the situation where all available resources are allocated to only one user (completely unfair). A hybrid RF/LiFi network can dramatically increase the fairness index among users [79]. The combined LiFi and RF system can improve the fairness index among mobile users by using a dynamic load-balancing algorithm. In [19], the authors propose a combined "power allocation and load balancing" scheme for a combined LiFi/RF network consisting of one RF access point and several LiFi access points, showing that the combined system can transmit users. Increase fairness with weak QoS from overloaded light sources to lower-level light sources. The Grade of Fairness (GoF) for a combined LiFi/WiFi network is defined as follows [62]:

$$I_{GoF, LiFi} = \left| 1 - \frac{\epsilon_{T, LiFi}}{\epsilon_{N, LiFi}} \right| \quad (9)$$

$$I_{GoF, WiFi} = \left| 1 - \frac{\epsilon_{T, WiFi}}{\epsilon_{N, WiFi}} \right| \quad (10)$$

where, $\epsilon_{T, LiFi}$ and $\epsilon_{T, WiFi}$ are the efficiency of LiFi, and WiFi networks relative to the total efficiency of the combined network, respectively. In addition, $\epsilon_{T, LiFi}$ and $\epsilon_{T, WiFi}$ are the number of LiFi, and WiFi users about the total network users, respectively. GoF is commonly used to assess the "average fairness" of a

network. A hybrid network can generate a higher GoF, especially when the distance between the percentage of LiFi (WiFi) efficiency and the fraction of users connected to LiFi (WiFi) is small .

4.3. Spectral Efficiency

Spectral efficiency is one of the most common criteria for measuring the effectiveness of a link. Many studies on hybrid RF/ Visible light communication (VLC) networks have repeatedly confirmed that the spectral gain of a hybrid network is much higher than that of stand-alone RF or VLC networks. Some research through Monte Carlo simulations has shown that the hybrid RF/VLC system can provide higher spectral performance and data speed compared to a pure RF network. In [79], a hybrid internal network is proposed that solves the problem of dynamic load balance for mobile phone users. The idea was developed by optimizing AP allocation and resource allocation in a combined LiFi/RF network, which shows that the spectral effect is doubled compared to the conventional signal strength strategy. Because the AP in a LiFi network covers a specific area known as the autocell, the bandwidth source can be widely used in space. To compare the throughput in a hybrid network with a standalone LiFi or WiFi network, Area Spectrum Efficiency (ASE) studies have been considered in several studies on LiFi/WiFi hybrid networks. The ASE represents the user spectral performance for a given density [80]. Mathematically, the ASE can be expressed as follows :

$$\zeta = \frac{R}{A_r} \quad (11)$$

where, R is the data rate, and A_r is the internal area. LiFi networks can offer higher ASE compared to standalone RF cellular networks. It has been shown that a LiFi network, due to the reuse of bandwidth, can achieve ASE several hundred times that of a femtocell. Therefore, the integration of LiFi and RF networks can ensure comprehensive coverage and higher ASE. The authors in [80] proposed a combined RF system with LiFi and Femtocell, which increases the average ASE by at least twice as much as an independent RF network. In [62], a load balancing mechanism is proposed that can achieve proportional fairness and higher ASE compared to a stand-alone LiFi network. Both distributed and centralized resource allocation schemes have been developed and shown that a higher ASE can be achieved through the hybrid RF/LiFi system .

4.4. Energy Efficiency

Energy demand is also proliferating as requests for high-data-rate communications proliferate. In wireless communication, energy gain is defined as the ratio of data transfer rate to power consumption in terms of bits per joule [81]:

$$\eta = \frac{R}{P} \quad (12)$$

where, R is the available data rate in bit per second and P is the total power sent in watts. Research shows that hybrid RF/VLC networks have significantly more energy gain than stand-alone RF or VLC networks. In [81], energy in integrated VLC systems with RF networks has been studied. The authors formulated the problem of bandwidth optimization and power allocation to maximize the energy efficiency of the RF/VLC hybrid network. The effect of various parameters such as the number of users, direct emission (LoS), and number of LEDs on energy efficiency has been investigated. This study demonstrates the superior performance of an RF/VLC hybrid network compared to an RF system. In [19], a combined optimization of power allocation and load balancing for VLC/RF hybrid networks is proposed. The authors have proposed an iterative algorithm for power distribution among users. By submitting an optimization problem, their proposed design can guarantee the maximum amount of data available and thus the energy reliability of the VLC/RF hybrid network. It has been shown that the new algorithm converges quickly and can provide

better performance compared to conventional methods. In [82], with optimal energy allocation, the overall energy efficiency of the RF/VLC hybrid network is improved. It has been shown that the energy efficiency of a three-bit hybrid grid is higher than that of an independent RF system .

4.5. Network Throughput

One of the main goals of hybrid networks is to improve the efficiency of users and the network. Almost all studies on a hybrid WiFi/LiFi network compared to a pure LiFi or WiFi network have confirmed the potential. In [18], a simple RF deployment is introduced to increase data interrupt rate performance per user of standalone LiFi systems and improve overall network efficiency. It has been shown that the probability of disconnection via a combined LiFi/RF network is halved compared to a standalone LiFi system for an operating efficiency of 30 Mbps. The effect of Field of View (FoV) on the average user rate in a hybrid LiFi/RF is evaluated and compared with an independent LiFi and RF system. It turns out that a hybrid network can improve user performance of more than 30 Mbps and more than 40 Mbps, respectively, compared to a pure LiFi and RF network. In [62], a typical load balance scheme for hybrid WiFi/LiFi networks is proposed. The hybrid system is able to increase the average user efficiency for both conventional and integrated cell structures. In [76], the authors propose a dynamic load balancing mechanism by considering metamorphosis for LiFi and WiFi hybrid networks. The beneficial performance of the load balancing algorithm in this proposal also believes the system efficiency. It shows that the hybrid network can significantly serve the user power by serving mobile users via WiFi access points and semi-static users through LiFi access points. Improve. The combined RF and LiFi network can to solve better the problem of link blocking and increase system efficiency compared to the independent LiFi network [54], [63].

4.6. Quality of Service (QoS)

Another essential metric is QoS, which can be used in hybrid RF and VLC networks. In essence, QoS measures the service performance met by users on a network. To evaluate, and quantify the network QoS, various criteria such as bit rate, transmission delay, operational efficiency and link availability can be used. In addition, given the growing demand for latency-sensitive applications, including video streaming and games, it will be necessary to consider other QoS evaluations in the data link layer. Mainly when QoS constraints are needed, many researchers perform layer-by-layer assessments related to physical layers and data links. Hybrid WiFi/LiFi systems serve as a promising potential for meeting QoS constraints and needs in the future. Are considered. Using numerical results, the LiFi system has been shown to improve latency in hybrid LiFi/RF networks .

5. Scenario-Based Architecture

5.1. Implementing A LiFi-based Indoor Network

Step 1) Coverage and cell deployment model

A) Coverage

The first essential issue in implementing a LiFi-based network is providing the complete coverage of the desired area. For achieving complete coverage, the position of the light sources (LEDs or IRs) on the ceiling with respect to the position of UEs (such as computers or laptops) should be considered. Figure 20 shows the coverage area on the surface of the user's desk and on the floor. In figure 20, (H) is the vertical distance from the the light source on the ceiling to the user's desk, (r) and (R) indicate the diameter of coverage areas on the desk and on the floor, respectively.

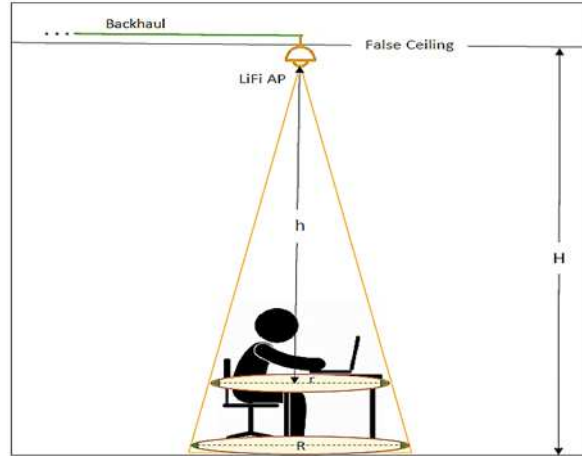


Fig. 20: Coverage area for a fixed user

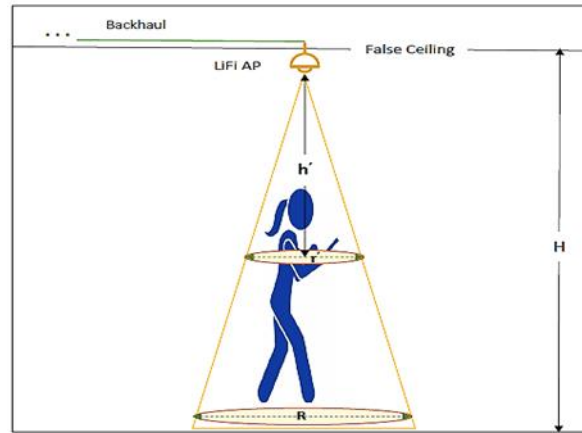


Fig. 21: Coverage area for a mobile user

The coverage area is slightly different for mobile users. The light coverage area for mobile users is a smaller area for each light source installed on the ceiling (see Figure 21). In this Figure, the vertical distance of the optical AP to the mobile user's equipment is h' . The coverage area diameter for this user is r' . Therefore, in the LiFi network, according to the technical specifications of light sources, the optical coverage areas of the network should be considered in such a way that both fixed and mobile users are always in the coverage area. So, in areas where there is a possibility of the presence of mobile users, the diameter of light coverage is deemed to be r' according to the Figure 21. In this case, to cover the whole area, more APs will be needed so that all fixed and mobile users will always be covered by the light. It should be noted that two parameter affect the data rate: 1) radial distance of the user to the center of the coverage beam, and 2) Euclidean distance between the UE to the light source (LED/IR). Figure 22 shows the optical beam of an IR transmitter. Figure 23 shows the effect of radial distance of the UE to the center of the coverage beam on the data rate in the up and downlinks.

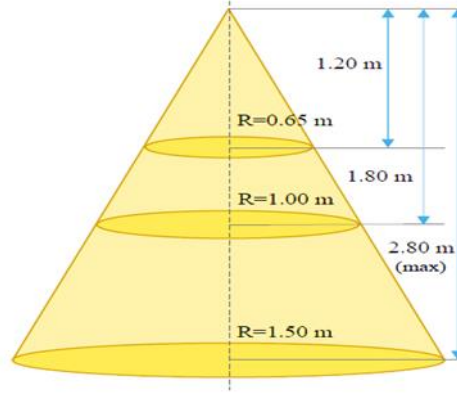


Fig . 22: Optical coverage beam of a typical IR transmitter (Product of Signify Co., trulifi-6002 model)

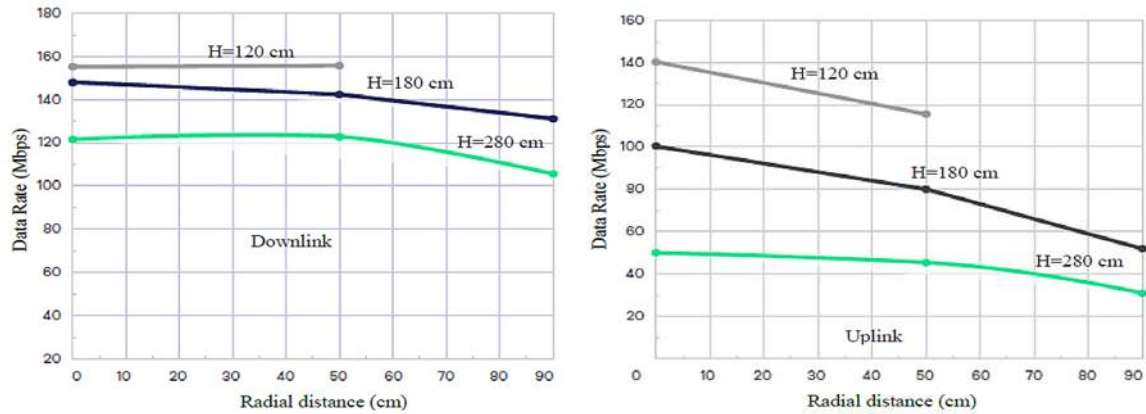


Fig . 23: Graph of data rate per radius of optical beam, radial distance to the center of the beam, and distance to the light source in uplink and downlink (Product of Signify Co., trulifi-6002 model)

B) Cellular model

Cellular model selection depends on the dimensions of the indoor area, equipment and their layout, surfaces, windows, ceiling height and other environmental considerations. For this purpose, a plan of the area, including the exact dimensions and arrangement of equipments include; desks, office furniture, devices and official equipments should be prepared. Figure 24 shows an example of a W×L-sized plan for implementing an indoor LiFi-based network

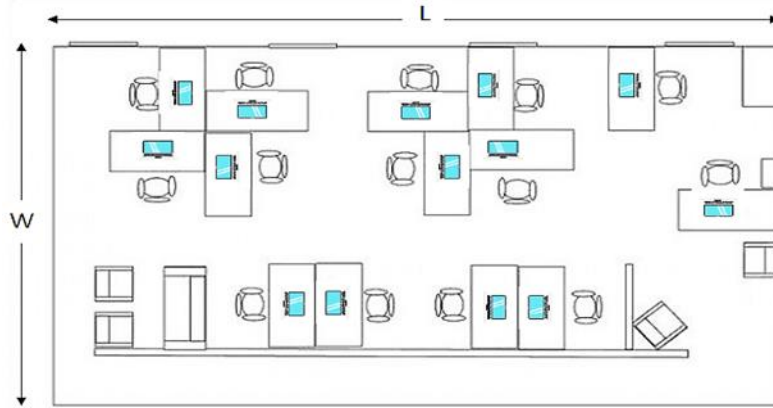


Fig. 24: An example of a plan for implementing a network

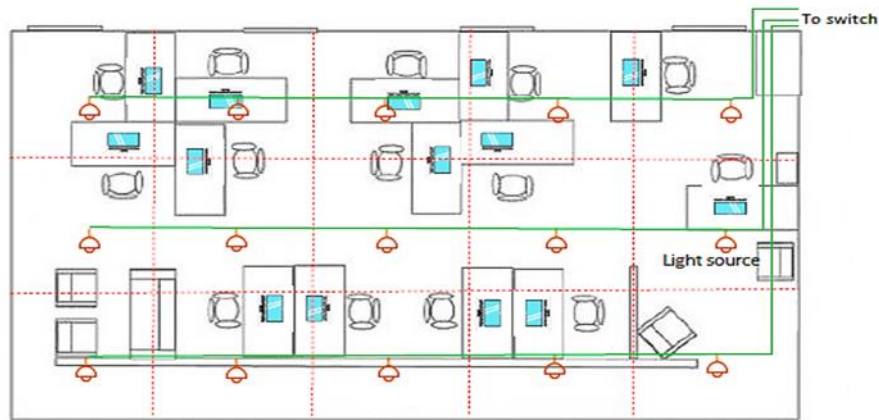


Fig. 25: An example of a lattice cellular model

The cell deployment model is determined based on the site plan. The most common cell deployment scheme is the lattice model. Of course, the choice of cellular deployment model depends on parameters such as site plan and users distributions. In this case, according to the technical specifications of the optical transmitter installed on the ceiling of the area, the coverage radius (r') is determined. The number and dimensions of cells will be determined based on the radius of the light beam and the site's dimensions. The light sources in the ceiling are distributed in the centers of the cells based on the lattice cell establishment model. (See Figure 25).

Step 2) Installation of LiFi equipments

A) UE dongle

The UE dongle acts as a transceiver that connects to the user's device. Dongles can be connected to PCs, laptops, or tablets via the USB port. The dongle is equipped with a PD to receive light in the downlink and an optical transmitter to send light in the uplink. In equipment that transmits visible light through a LED, a PD built into the dongle is used to detect the visible light. If the LiFi network has a downlink in the IR light band, then the dongle detector acts in IR band. Figure 26 shows both types of LED/IR and IR/IR dongles.

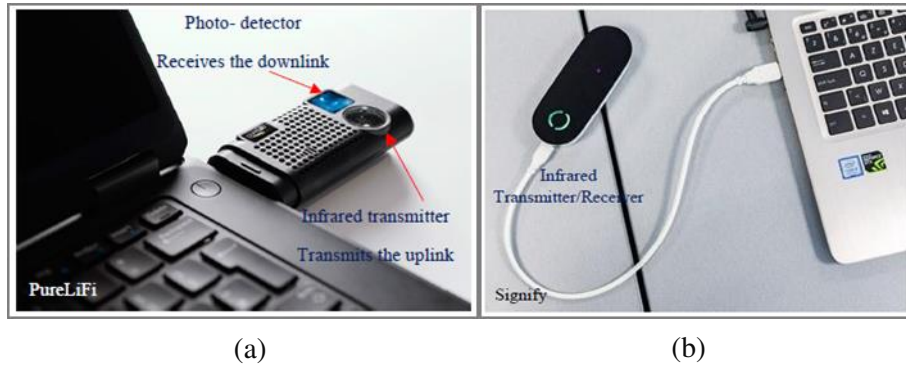


Fig . 26: UE dongle; a) Dongle with visible light detector in the downlink and the IR transmitter in the uplink, (product of PureLiFi Co.), b) Dongle with IR/IR transmitter/receiver (product by Signify Co.)

B) AP

The type of Aps are selected based on the type of light used for the downlink. In LiFi systems both visible or IR light are used for downlink. Figure 27 shows two types of APs, one in which the visible light provided by the LED is used for the downlink, and the other use IR for the downlink .

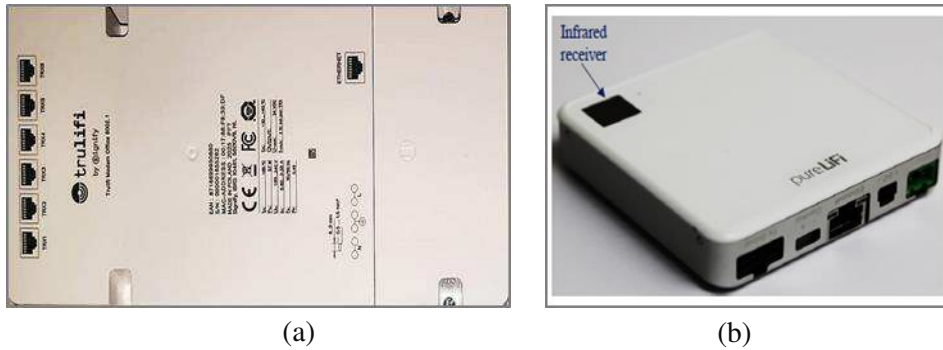


Fig . 27: An AP, a) AP including an IR receiver in the uplink and visible light by LED in downlink, produced by PureLiFi Co., LiFi-XC model, b) AP with cable connection to the IR transceiver in both up and downlinks, produced by Signify Co., trulifi-6002 model

C) LED

In LiFi systems, where visible light is used for downlink, the source of the light is LED. Figure 28 shows a LED used in LiFi systems . In addition, ambient illumination is provided by LED .



Fig . 28: A LED used in LiFi systems

D) IR/IR transceiver

Some LiFi systems use IR at both up and down links. Figure 29 shows an example of an IR/IR transceiver. In these systems, ambient illumination is provided separately .

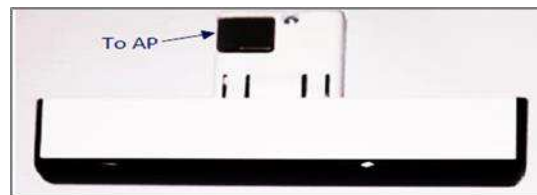


Fig . 29: An example of an IR/IR transceiver used in the LiFi system (produced by Signify Co., trulifi-6002 model)

Step 3) Backhaul

The backhaul network connects the APs installed on the ceiling to the switch. Figure 30 shows an example of creating a backhaul for a hybrid LiFi/WiFi network .

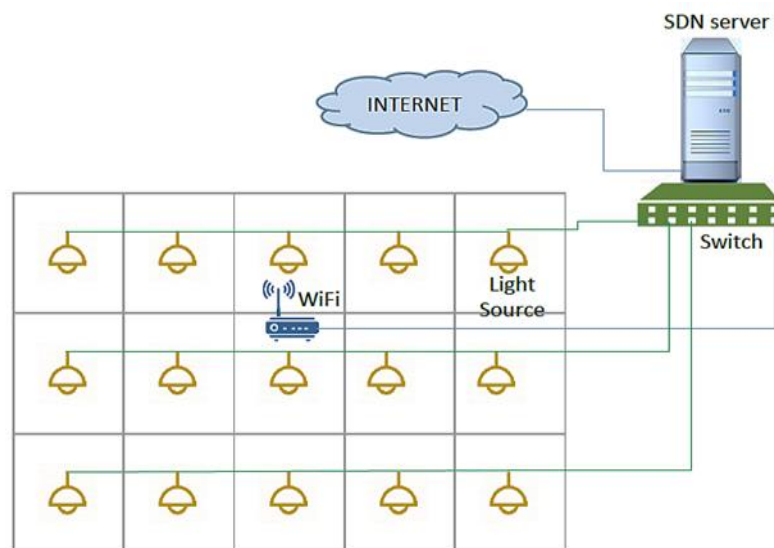


Fig. 30: An example of a backhaul in a hybrid LiFi/WiFi network

5.2. A Practical Example of Implementing A LiFi-based Network

In this section, we will pay attention to the introduction of Signify LiFi equipment, which is produced under the name of the Trulifi-6002 model. This model includes the following equipment: 1) access point with the ability to connect six transmitters/infrared optical receivers, 2) infrared transmitter receiver with mounting frame on the ceiling, and 3) transmitter/infrared transceiver dongle with port USB to connect to the user equipment. It should be noted that in this example, due to the use of infrared light sources, the light of the place should be provided through light bulbs. In this model, the desired product is also offered as a local light supply, in which the infrared transmitter can be installed. Figure 31 shows this feature .



Fig. 31: Illumination lamps with IR/IR transceiver (produced by Signify Co., trulifi-6002 model)

Figure 31 shows how to implement and communicate between optical equipment in order to implement a LiFi network with Signify, Trulifi-6002 model. Each access point in this model can support six infrared transceiver. Figure 32 shows how to connect IR/IR transceivers to APs. Each AP in this model has an Ethernet port connected to a LAN or Internet network through network switch ports. users can be connected to the network by connecting their IR/IR transceiver dongles to their devices via USB ports .

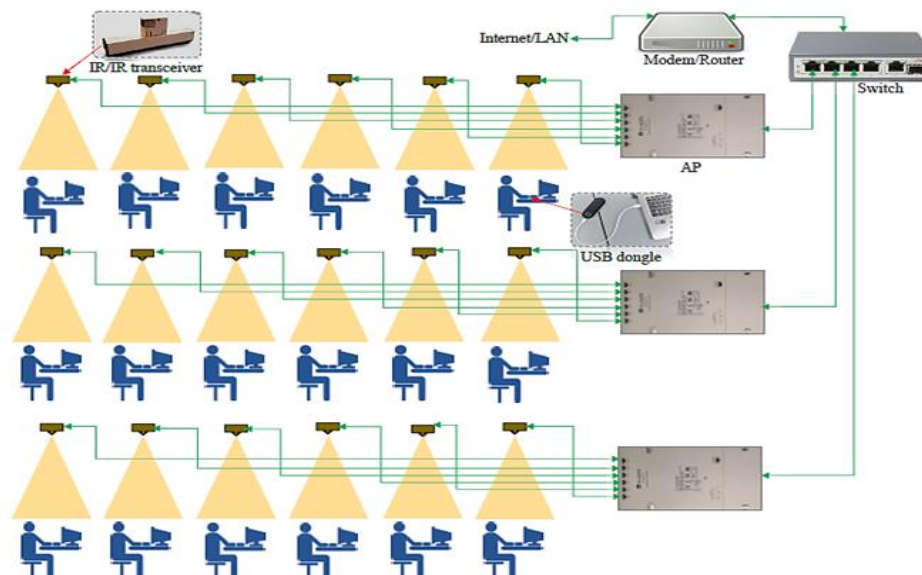


Fig. 32: A LiFi network implementation (produced by Signify Co., trulifi-6002 model)

6. Conclusion

Due to the limited resources of the RF spectrum, radio systems such as WiFi will have difficulty meeting the growing demand for mobile Internet, especially in the fifth and higher generations of cellular networks. LiFi technology is an essential solution for fast data transfer and RF spectrum limitations. However, LiFi networks also have problems such as coverage area limitation and light blockage. Therefore, integration of WiFi and LiFi can complement the shortcomings of each of these technologies and increases the network performance. Hybrid WiFi/LiFi networks uses fast data transfer from LiFi and wide coverage from WiFi. In this work, while presenting theoretical concepts of LiFi and hybrid WiFi/LiFi networks, issues such as network structure, cell deployment, modulation techniques, multiple access schemes, and criteria for measuring network performance are discussed. Some essential topics in LiFi and hybrid WiFi networks include; network structure, cell deployment, modulation techniques, and multiple access schemes are discussed. We also discussed about the main criteria for measuring the performance of LiFi and hybrid WiFi/LiFi networks. In the following, we presented practical concepts include LiFi equipments and steps of implementating a LiFi-based network .

Data Availability:

All data generated or analysed during this study are included in this published article.

Declarations: • The authors have no relevant financial or non-financial interests to disclose.

- The authors have no conflicts of interest to declare that are relevant to the content of this article.
- All authors certify that they have no affiliations with or involvement in any organization or entity with any financial interest or non-financial interest in the subject matter or materials discussed in this manuscript.
- The authors have no financial or proprietary interests in any material discussed in this article

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