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Review of LiFi Technology and Its Future Applications

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Abstract: In order to respond to the increasing demand of capacity and bandwidth caused by the high number of wireless applications and users, LiFi technology was introduced. It uses the visible light spectrum instead of the radio spectrum to transmit data wirelessly through the illumination of LED lamps. The main advantage of this technology is to provide wireless communications with high data rates. Other advantages include efficiency, availability, security and safety. Also, this technology uses free unlicensed spectrum, and it is cost-effective. Additionally, unlike RF systems, no multipath fading and the transmitter and receiver circuits are not complex. However, LiFi has several issues, which include high path loss, sensitivity to blockages and Non-line-of-sight (NLOS) situations. Probably, the biggest issue of LiFi is the uplink communication which is difficult to implement due to practical and cost reasons. Several future applications of this technology include places where RF is restricted such as hospitals and airplanes. Also, it can be used for traffic management, underwater communication, and outdoor access to the Internet. Moreover, it can be combined with WiFi technology either in hybrid technique or aggregated technique. It is found that later technique gives better results. Another possible application is the optical attocells. It is found that the hexagonal cells model is the best for deterministic deployments of optical APs, whereas the hard-core point process (HCPP) model is the best for random deployments. Furthermore, LiFi can be used for multiuser access with high data rate by using non-orthogonal multiple access (NOMA) technique. Due to the great features of LiFi, more applications and everyday life devices will adopt this technology in the future. However, Because of its limitations, it may not totally replace RF technology, but they will work collaboratively to achieve a better performance.

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1 Introduction

Communication technology, specifically wireless communications, is one of the fastest growing technologies in history. In just a few decades, we moved from heavy large devices used only for voice communications, to small smart devices that are capable of doing multiple functions which include accessing the Internet and video streaming. The main difference between wireless mobile generations is the data rate. As we able to increase the data rate, wireless devices will be able to do more functions.

This advancement in wireless communications functions has accompanied by increasing the number of wireless devices. It is envisioned that the next generation of wireless communication, 5 G, will have a new era in wireless communications functions and technologies, as we expect such technologies: smart cars, e-health and smart grids, and so on. Furthermore, the integration of the physical and the digital word, which is known as the Internet of Things (IoT), will be realized. As a result, more wireless smart devices will be deployed in the future and high amount of wireless data will be exchanged. Therefore, Cisco forecasts that from 2017 to 2020, the global wireless data traffic will increase by more than 20 exabytes, which is equivalent to increase by 200 %, as illustrated in Figure 1. It is also expected that smart devices will cause 98 % of the wireless data communication in 2020, as shown in Figure 2.

These smart devices require wide bandwidths and high data rates. However, most of the radio frequency (RF) spectrum has been utilized or assigned for certain applications, and it becomes more difficult to accommodate more wireless devices. One of the proposed solutions that can tackle this issue and provides high data rate is the LiFi technology, which uses the visible light spectrum for wireless communications, instead of the radio spectrum. This is a recent technology introduced by Prof. Harald Hass in 2011, 6 years ago.

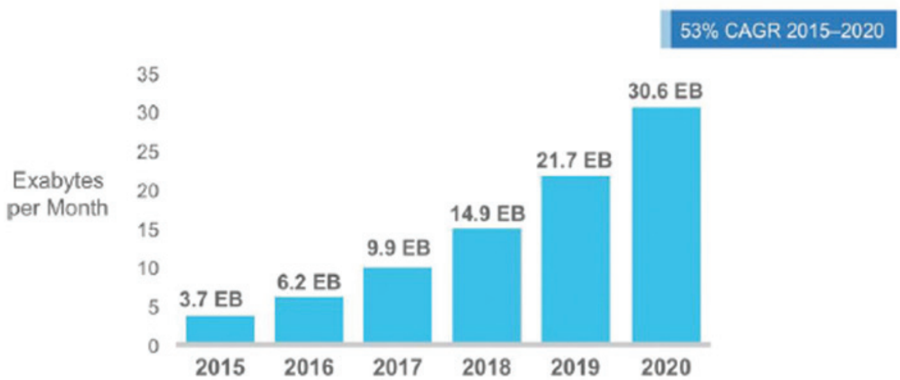

Figure 1: Global wireless data traffic forecast by Cisco [source: Cisco VNI Mobile, 2016].

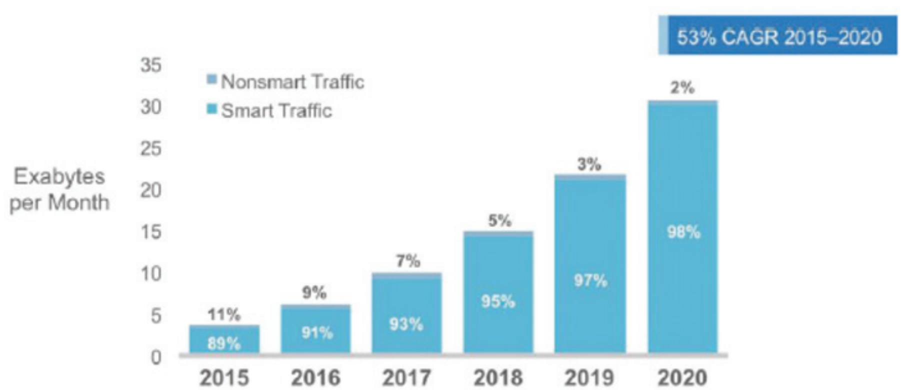

Figure 2: Effect of smart mobile devices and connections growth on traffic [source: Cisco VNI Mobile, 2016].

The objective of this paper is to describe this new emerging technology, main developments, its advantages and limitations, and its possible future applications. The organization of this paper is as follow: In Section 2, a detailed description of the LiFi function in terms of the system structure and modulation techniques will be presented. Section 3 provides a brief overview of the history of this technology and the main achievements. Section 4 was devoted to explaining the main advantages of this technology, whereas Section 5 presents the limitations of LiFi. The possible future applications of this technology will be described in Section 6. Section 6 H recaps the paper and highlights the main findings.

2 Technology description

The LiFi term is an abbreviation of light fidelity, which means transmitting wireless digital data through the illumination of light. The term was selected to represent the optical version of the WiFi technology. Instead of using the RF band to modulate the digital data and transmit it through an antenna, the data is modulated in the light frequency band and sent through the LED light. When the light is ON, digital 1 is sent, whereas digital 0 is sent if the light is OFF. The light seems as always ON because the variation between zeros and ones is done very quickly for the human eye to be detected. Instead of using single data stream, it is possible to use parallel transmission or use an array of LEDs to transmit thousands of data streams and thus we can achieve very high data rates.

2.1 Structure of the LiFi system

Figure 3 summarizes the mechanism of this technology. In the transmitter side, the digital streams data from the Internet will be fed to the lamp driver, which is responsible to transform the data in a form of light signal. The data will be sent through a LED lamp.

In the receiver side, a photodetector or photosensor detects the variations of the LED light and converts light photons into an electrical signal. The receiver device will receive the data after it is processed, amplified and converted back to its original format.

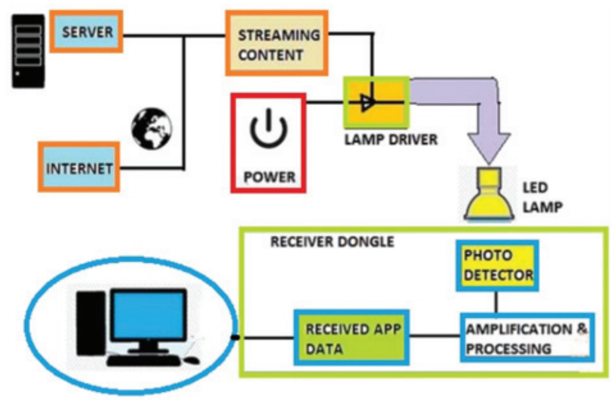

Figure 3: Architecture of the LiFi system.

2.2 LiFi modulation techniques

Generally, the typical modulation techniques used for RF communications (either single-carrier modulation or multi-carrier modulation) can be used for LiFi systems, since both light and RF waves are electromagnetic waves. However, due to the light signal features, LiFi capable of using some unique modulation techniques [1].

2.2.1 Single-carrier modulation (SCM)

Examples of SCM schemes include on-off keying (OOK) and pulse position modulation (PPM), which have been studied and compared in wireless infrared communication systems [2]. OOK is a simple modulation scheme, easy to implement and provides an acceptable performance. The PPM has more power efficiency, but it is less spectral-efficient.

A new modulation scheme called optical spatial modulation (OSM) is proposed in [3] and proved to be both power and bandwidth efficient for indoor optical wireless communications.

2.2.2 Multi-carrier modulation (MCM)

MCM is a method of transmitting the digital data with different carrier frequencies. The main advantage of this technique is to cope with severe channel conditions, such that fading, attenuation and interference. The MCM is robust against fading caused by transmission over more than one path at a time (multipath fading). It is also invulnerable against intersymbol interference (ISI), narrow-band co-channel interference and less sensitive than SCM to interference caused by impulse noise. In addition, MCM is more capable than SCM to cope with attenuation in high-frequency communications, such that in the visible light band. Moreover, MCM has higher spectral efficiency than double sideband modulation schemes, and it is less susceptible to time synchronization errors. Therefore, MCM is more bandwidth-efficient than SCM and it is preferable for high-speed optical wireless communications.

However, there are some disadvantages of MCM schemes. They are more sensitive to frequency synchronization problems and generally they are less energy-efficient than SCM schemes.

The most common technique in MCM used for LiFi communications is orthogonal frequency division multiplexing (OFDM) [4, 5]. By using this scheme, parallel data streams can be transmitted simultaneously through a collection of orthogonal subcarriers. An OFDM modulator is implemented by an inverse discrete Fourier transform block followed by a digital-to-analog converter (DAC). Thus, the OFDM generated signal is complex and bipolar. However, since the light intensity can't be negative, the LiFi signal should be unipolar. Also, there are some requirements for the intensity modulation (IM) or direct detection (DD) to be met with the available LEDs. Therefore, some modifications to the conventional OFDM techniques are required to be used in LiFi networks. Examples of these modulation techniques include DC biased optical OFDM (DCO-OFDM), asymmetrically clipped optical OFDM (ACO-OFDM) and asymmetrically clipped DC biased optical OFDM (ADO-OFDM). A detailed comparison between these three techniques in optical systems is presented in [6].

2.2.3 LiFi unique modulation

Unlike radio transmitters, LiFi transmitters have illumination function beside the communication function. Luminaires equipped with multicolor LEDs can provide various possibilities of other modulation techniques.

Color-Shift keying (CSK) scheme transmits data through the variation of the output light color [7]. There are two advantages for CSK compared to other IM schemes. First, it guarantees that the light illumination will not fluctuate, and the health issues of light flickering will be limited. Second, the LED driving current will be almost constant, since the illumination intensity is constant.

Metameric modulation (MM) is another specific light modulation scheme, which was developed based on CSK technique [8]. It is capable of providing higher energy efficiency and ability to control the color quality.

To satisfy color matching and dimming requirements in color space, and to maximize communication capacity, color intensity modulation (CIM) is introduced in [9], for orthogonal and non-orthogonal optical channels.

3 History of LiFi technology and developments

The general concept of "Li-Fi" was studied under the term visible light communication (VLC) since the 1880s, but "Li-Fi" term was coined by the professor Harald Hass at his TED Global Talk in August 2011 [10]. He is the Chairman of Mobile Communications at the University of Edinburgh and co-founder of PureLiFi. Later, he published some papers [1, 11] to describe this technology. In [1], he explained in details the differences between the old VLC term and the new LiFi term. VLC was envisioned as a point-to-point data communication technique, basically as a cable replacement. On the other hand, LiFi represents a complete wireless networking system, which includes bi-directional multiuser communication, i. e. multipoint-to-point and point-to-multipoint communication. Furthermore, LiFi involves multiple access points (APs), enables full user mobility and construct a new layer within the existing heterogeneous wireless networks.

In October 2011, after two months of Harald's TED talk, several companies and industries founded the "Li-Fi Consortium". It is a non-profit organization devoted to improve and introduce the optical wireless technology. The LiFi consortium's members are a leading group of international technology companies and research institutions in optical communication technology. The group is more interested in product development and real applications of LiFi technology than academic research. In 2012, the consortium outlined a roadmap for different types of optical communication such as gigabit-class communication and LiFi cloud [12].

In August 2013, PureVLC, which changed its name later to PureLiFi, demonstrated data rate up to 1.67 Gbps on a single color LED. They expected to achieve 2 Gbps on each of the green, red and blue channels by the end of the year [13].

In April 2014, the BeamCaster module developed by the Russian company "Stins Coman" provided data rate 1.25 Gbps, and it can be boosted to 5 Gbps. The core of the network is a router that is capable of transmitting data with a light beam up to 8 m, and the data can be delivered to eight devices [14]. In the same year, a huge improvement in LiFi data rate is achieved by the Mexican software development company Sisoft, which was able to transfer data at rate up to 10 Gbps using LED lamps [15].

In 2015, the LiFi center at Edinburgh University came up with a solution for long-distance optical communications by making the receivers more sensitive for weak signals. In the same year, Prof. Hass delivers a new TED talk, in which he demonstrated transmitting Internet data using LED light and solar cells.

The progress of this technology is every day growing. The main developments of this technology were highlighted. As we noticed, several industrial groups work to enhance this technology and promote LiFi products. This is because of the unique advantages of LiFi versus conventional wireless radio networks, as they will be discussed in the following section.

4 Advantages of LiFi technology

4.1 Capacity

The most important feature of the LiFi technology is, the ability to provide high data rate. The upper bound on the data rate in communication systems is called channel capacity. According to Shannon-Hartley theorem, the maximum data rate (R_{max}) is proportional to the available bandwidth as follow:

$$R_{\max} = B^{*}\log_2(1 + SNR) \tag{1}$$

Operating in the visible light band means higher operating frequency, which provides higher potential bandwidth (B), and yields eventually higher data rate. In fact, the visible light band is 10,000 times wider than the radio band, as demonstrated in Figure 4, light band in the range (10^{14}–10^{16}) Hz, while the range of the radio band is (10^{4}–10^{12}) Hz. Therefore, by utilizing this technology, we could achieve data rate in the gigahertz range or more.

4.2 Free spectrum

Due to the excessive amount of wireless applications and users, which causes large demand for the bandwidth, there is spectrum scarcity problem. Most of the spectrum

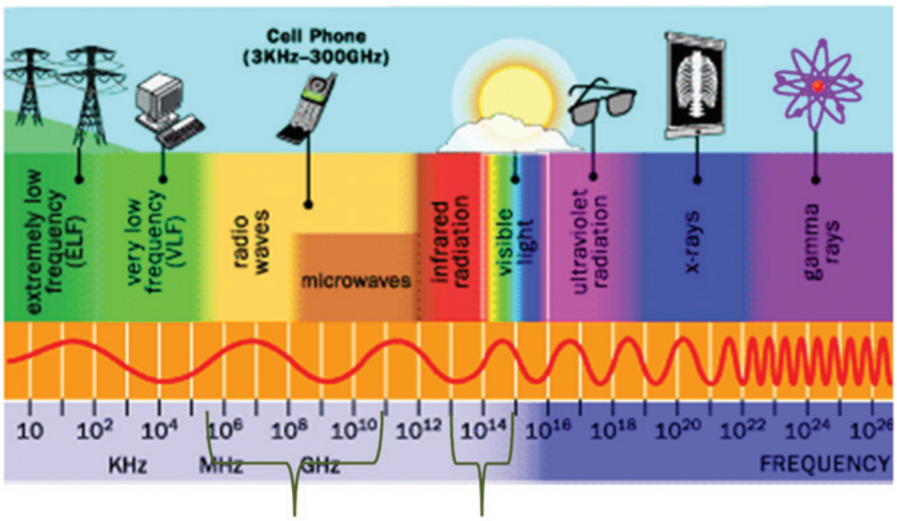

Figure 4: Frequency spectrum.

in the radio range has been fully utilized, and it is almost difficult to get wide bandwidth there. In addition, you have to have a license to access most of the bands in the RF range. However, the visible light band is free spectrum band that we use it normally to see things. Utilizing this band for wireless communication will mitigate the spectrum scarcity problem.

4.3 Efficiency

Conventional RF communication systems consume a lot of energy and most of this energy is used to cool base stations (BSs) or APs. However, LiFi communication systems are based on LED lamps which consume less energy and provide communication in addition to the illumination function. Thus, LiFi is more energy-efficient.

4.4 Availability

The wireless communications in the RF band have some restrictions for use in some places, such as hospitals and airplanes, whereas lamps are available everywhere and can be used in any place. Therefore, by replacing the typical fluorescent lamps with LED lamps, we will make the wireless communications available everywhere.

4.5 Security

Unlike the radio waves, light waves cannot penetrate through the walls. As a result, the data will be securely confined around the light source, and cannot be accessed by intruders for bad intentions.

4.6 Complexity

LiFi is a very simple technology in comparison with the radio technology. It is based on direct modulation and direct demodulation, and a light source in the transmission side, and a photodetector in the receiver side. However, any radio technology system, WiFi for example, requires a complex RF circuit for modulating the information and an antenna to transmit the data. Also, the radio receiver is more complex since it requires synchronous demodulation circuit with a receiver antenna [16].

4.7 No fading

One of the biggest issues for signals in the radio range is the channel fading caused by multipath propagation. The reflected signal may be in anti-phase with the transmitted signal, and thus they will cancel each other and cause signal fading. The light signal always adds and cannot cancel each other. Therefore, multipath fading is not an issue for light signals [16].

4.8 Safety

A large number of studies in the literature tried to examine the effects of the electromagnetic waves in the radio bands to the human body, and many of these studies concluded that the radio signals, such as WiFi and mobile signals, can negatively affect overall human body health, especially in children. Intense regular exposure to the radio mobile signals can change the brainwaves and behavior [17]. Also, it contributes to the development of insomnia, which yields struggles for sleeping at night, and this could be the beginning of larger health problems in the future [18]. Moreover, it is experimentally proved that the exposure to the radio radiations can affect the cell growth and disturb normal fetal development [19]. Furthermore, some researchers found that 4 G wireless radiations reduce the brain functionality [20]. In addition, several potential dangers include fertility problems [21], and cardiac stress [22].

However, the electromagnetic waves of the light signal are inherently safe from these aforementioned issues. The only possible health issue may happen when high-intensity light is directed to the human eye. Therefore, by relying on LiFi technology, especially in indoor environments, the health issues resulted from wireless communications can be mitigated.

4.9 Cost-effective

Besides all the previous benefits, the cost of a LiFi system is much less than a WiFi system or any radio comparable system. This is because the LED light bulbs and the required circuit components in a LiFi system are cheaper than the required components in a radio system. In fact, no need for special LEDs for a LiFi system. Any LED can be used for data transmission, but practically excellent results can be achieved by using COTS LED devices [16].

5 Limitations of LiFi technology

For every technology, besides knowing its advantages, we have carefully to realize its limitations in order to better suggest possible applications of this technology. In this section, a brief description of some challenges of LiFi technology compared to radio technology will be presented. Some possible solutions for these limitations will be introduced.

5.1 High path loss

The path loss of any communication system is proportional to the square of the operating frequency ($PL \,\alpha\, f^2$). The frequency of visible light waves is much higher than the frequency of radio electromagnetic waves. The maximum RF is in the range of gigahertz (10^9), whereas the light wave is in the range of terahertz (10^{12}). Therefore, typically the light signal is subjected to higher attenuation than the radio signals. As a result, the LiFi technology will be difficult to use for long distances. A possible solution for this issue is to increase the number of LED lamps to increase the coverage area.

5.2 Blockages

The light signal is more sensitive to blocks and obstacles than the radio signal. In indoor situations, unlike radio signals, light signals cannot pass through walls. This is coverage disadvantage, but security advantage at the same time. In outdoor communication environments, the quality degradation of data transmission will be severely affected by using light waves instead of radio waves.

5.3 NLOS issues

The LiFi system will be less reliable when there is no line-of-sight between transmitting source and receivers. Therefore, the number of transmitters should be increased in order to increase the possibility of LOS between transmitters and receivers.

5.4 Uplink issues

Most of the presented experiments and demonstrations of this technology are done for just the downlink direction. Due to practical reasons, the reverse communication direction, from wireless devices to the AP or the BS is not feasible. Although there are many publications that promote or review this technology, most of these studies ignore this issue from consideration. There are two possible alternatives for the uplink direction in LiFi system, either to use infrared waves or using high-frequency radio waves.

6 Applications of LiFi technology

Because the distinct features of LiFi technology, this new emerging technology will have useful real-life applications.

In this section, a brief description of some suggested applications will be introduced.

6.1 Places where using RF is limited or restricted

Because the light signal is safe and available everywhere, it can be used to provide wireless communication in places where the use of RF signals is limited due to the potential dangers. Examples of such places include hospitals, airplanes and sensitive plants.

6.1.1 Hospitals

Generally using the WiFi network or the mobile network in hospitals is restricted, especially beside medical monitoring devices. This is because the radio electromagnetic transmissions may interfere with medical devices and cause problems. By incorporating the LiFi technology in such places, wireless communications and accessing the Internet will be easy and safe for all people inside [23]. Furthermore, we could have access to the Internet even in operation rooms, since they are equipped with lamps. As a result, doctors and experts may be consulted online during critical operations, or maybe operations can be broadcasted online for educational and medical purposes.

6.1.2 Airplanes

Using cellphones or WiFi network to access the Internet is banned on airplanes, due to the fears of interference with sensitive airplane devices. In just few years ago, several airlines offered limited access to the Internet using WiFi with very high charges. However, LiFi can utilize each seat's reading light to provide access to the Internet with a very high data rate, and without any concerns of interference [24].

6.1.3 Sensitive plants

The RF communications are prohibited in sensitive plants, such as power plants, petrochemicals plants and nuclear plants, because of the ignition risks in these environments. However, since the light is safe in these places, the LiFi system can provide easy coverage and data transmission in such environments. Consequently, monitoring the plants or detecting faults can be done remotely [25].

6.2 Traffic management

If the cars' headlights and backlights are replaced by LED lamps, the LiFi network can be established between cars. Cars can communicate each other in order to reduce chances of car accidents [25] (Figure 5).

Also, the street lamps can be equipped with cameras to monitor the roads and detect any congestion or emergency cases, and then send the information directly through LiFi technology to the traffic management center to take quickly the possible action.

Figure 5: The communication between cars to reduce chances of accidents.

6.3 Underwater applications

For underwater remotely operated vehicles, radio communications such as WiFi fails completely. Such vehicles use long cables for communications. By using high powered lamps with LiFi technology, we can get rid of these cables and thus the vehicles can move easily to explore larger areas, and send the data wirelessly [26].

6.4 Outdoor access to the Internet

Nowadays, the only possible option for accessing the Internet outdoors is through the cellular network. WiFi is limited for indoor environments, and cannot be used outdoors in most practical situations. But, the LiFi technology will use the outdoor lamps to enable accessing the Internet easily. Therefore, if someone is walking on the street, sitting at the beach, or playing in the park, he could have easy access to the Internet as long as he has lamps around him.

It is shown in [27] that the achieved data rate of LiFi technology in outdoor environments is just slightly

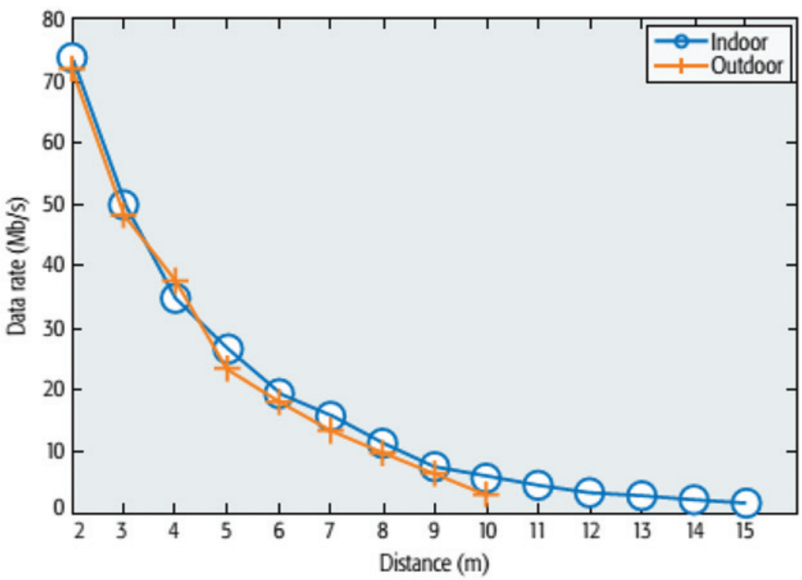

Figure 6: Comparison of LiFi technology between indoor and outdoor environments [27].

lower than in indoor environments. The resulted date rate for different distances between user devices (UDs) and the AP is shown in Figure 6. However, the considered outdoor environment here is in the most favorable situations, i. e. no rain or fog. But, if such conditions exist, the performance of outdoor LiFi system will degrade significantly.

6.5 Educational purposes

Since LiFi provides high data rate and has a very wide bandwidth, it may replace the WiFi systems in educational institutions in order to serve a large number of students, professors, and other institution staff with very high data rate [25, 28]. Thus, researching and accessing the information will be fast and easy. In addition, it will be quite simple and fast to download or upload lectures, or any high definition video streaming activity.

6.6 Combination of WiFi and LiFi technologies

Taking into consideration the advantages and disadvantages of LiFi technology, some proposed scenarios that combine the WiFi with the LiFi technology are introduced in several references, such as [29, 30] and [27]. The combined system has many new interesting features. These features include security enhancement, high data rate, wider coverage region and improved indoor positioning. The first three features come from the LiFi technology, whereas the coverage feature comes from the WiFi technology.

As depicted in Figure 7, stationary and quasi-stationary users will have wireless data connection through LiFi technology, whereas more mobile users will depend on the WiFi network. This approach of connection will mitigate the congestion in RF network and free up WiFi system capacity to accommodate any potential future demand growth.

In the literature, there are two approaches for combining the WiFi and LiFi. The first approach is hybrid technique [29] [30], whereas the second one is the aggregated technique [27].

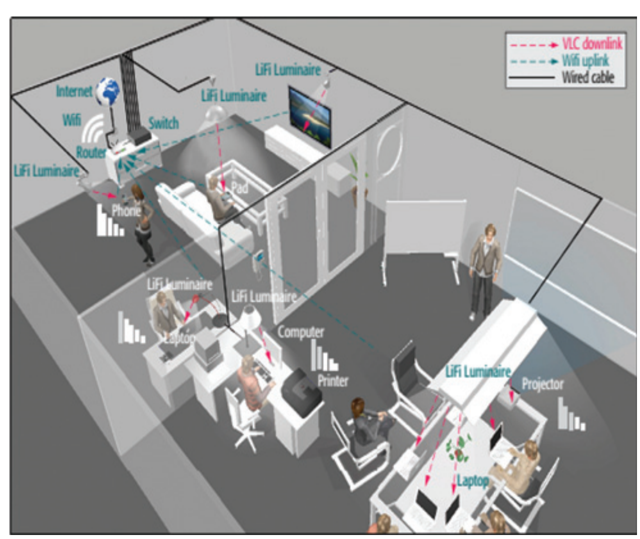

Figure 7: Combination of WiFi and LiFi technologies [27].

The hybrid technique uses WiFi for the uplink direction and the LiFi for the downlink direction, whereas the aggregated technique uses both WiFi and LiFi in parallel. In other words, unidirectional LiFi link is exploited in hybrid technique to support the traditional WiFi downlink. However, in the aggregated technique, both bi-directional LiFi and WiFi links are fully utilized. The difference between these two techniques is graphically demonstrated in Figure 8.

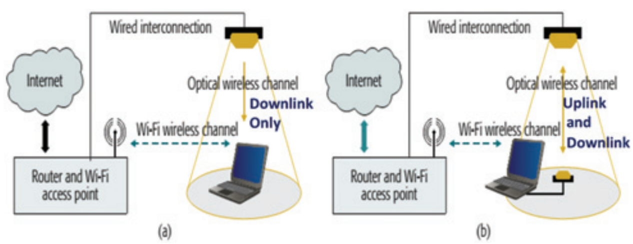

Figure 8: Configurations of the a) hybrid technique, and b) the aggregated technique. (Image reproduced from [27]).

The performance comparison of these two combination techniques is conducted in [27]. They compare between these two techniques and the case where only WiFi system is available. The comparison is done in terms of the average data rate measured at different distances between the AP and a UD. The obtained results are shown in Figure 9.

It is clear that using the combination of WiFi and LiFi gives higher data rate than using only WiFi technology, and the results show that the aggregated combination techniques are much better than the hybrid technique. However, as the distance between the AP and a UD increases, the data rate of the combined systems degrades significantly. This rate degradation is faster in hybrid technique than in aggregated technique. The average data rate of WiFi only system seems to be constant for this range of distance (8 m), and it will degrade substantially after the distance becomes more than 25 m. This is because the path loss of radio signals is much less than the optical signals, as explained previously.

6.7 The attocell

In wireless cellular networks, it is shown that reducing the cell size will increase the network spectral efficiency. By reducing the cell size, the coverage will enhance and the frequency reuse will increase, and consequently the data rate will increase. Therefore, small cells such as microcells, picocells and femtocells have been introduced.

This small cells concept can be easily extended to the LiFi technology. The optical BS or AP is referred to as an attocell [31]. The optical attocell does not interfere with the RF cellular networks, because it operates in the optical spectrum. Also, LiFi attocells allow for considerably dense bandwidth reuse, because of the properties of light waves. Therefore, by deploying attocells, we gain two benefits: improving indoor coverage and enhancing the capacity of the RF wireless networks [31].

However, due to the high path loss of light waves, the coverage of every single attocell is very limited, and at the same time, walls prevent the system from experiencing co-channel interference between rooms. This means we need multiple BS/AP to cover a certain area. Fortunately, the required infrastructure already exists, because of the indoor illumination requirements.

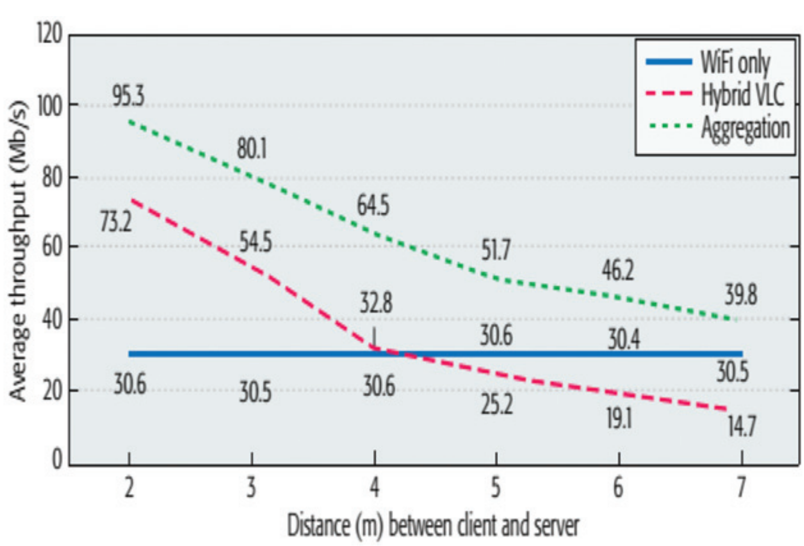

Figure 9: Average data rate versus distance between AP transmitter and UD receiver [27].

The deployment of multiple LiFi attocells in a room provides wide data coverage and at the same time provides uniform illumination. However, the placement of the optical APs can affect the system performance. In other words, the lighting design in a room affects the LiFi attocells network. In [11] and [1], four different deployments of the optical APs in a room of size 20 m*20 m are considered. They include hexagonal cells model, square cells model, homogenous Poisson point process (PPP) model and Matern type I hard-core point process (HCPP) model, as illustrated in Figure 10.

The hexagonal and square models are deterministic models suitable for regular and uniform lighting. However, in most real-life situations, the lighting will not be uniform, due to random positions of celling luminaries, desktop lamps and even LED screens. Therefore, some random models are proposed to provide more accurate performance results. The PPP model assumes the number of APs follows the Poisson distribution and the APs are geographically independent of each other. As a result, two APs can be arbitrary close to each other in PPP model, which is not realistic. Therefore, HCPP model is introduced, which has an additional parameter ***c*** that controls the minimum separation between any two APs.

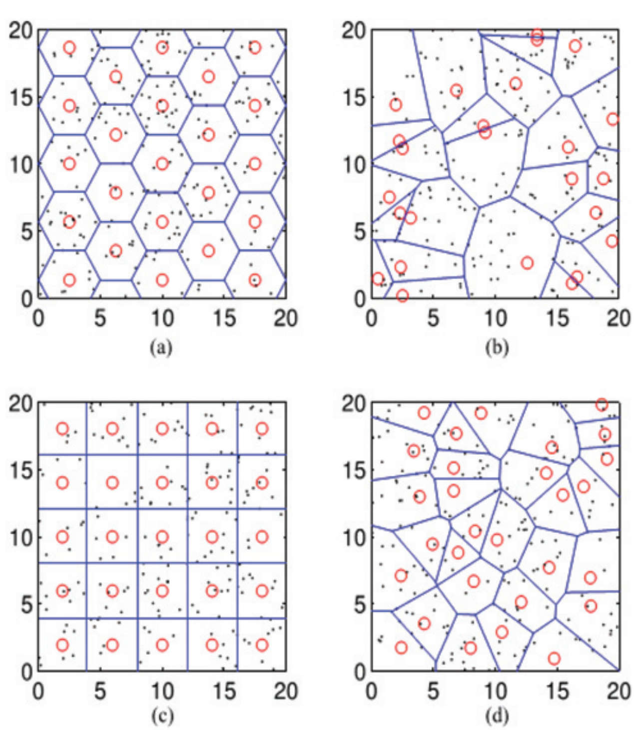

Figure 10: Different deployments of the optical APs in a room of size 20 m × 20 m. The red circles refer to the positions of the APs, which are also the room lights, whereas the black dots symbolize the user devices, such as smartphones. (a) Hexagonal cells model. (b) PPP model. (c) square cells model. (d) HCPP model [11].

Experimental performance comparison between these four deployments is conducted in [1]. In all these deployments, the optical output power of the LiFi AP is set so that the average illuminance in the room is at least 500 Lx. The rest of the experiment parameters are listed in Table 1.

Table 1: Experiment parameters.

Parameters	values
AP density	0.0353 [APs/m^2]
Photodiode responsivity	0.6 [A/W]
Photodiode physical area	1 [cm^2]
Vertical separation	2.25 [m]
Receiver field of view	90^o
Receiver noise PSD	10^{-19} [A^2/Hz]

The comparison results of these four deployments in terms of the cumulative density function (CDF) of the SINR are shown in Figure 11. It is clear that the hexagonal cells model gives the best performance, followed by the square cells model, whereas the PPP gives the worst performance. In HCPP model, the shown results are for three different minimum separation distances between any two APs 1, 2 and 3 m. The SINR performance is enhanced as the minimum separation distance increases. The results indicate that the performance of a LiFi optical attocell can vary notably. For example, with minimum SINR of 3 dB for data transmission at certain acceptable BER, the probability that this can be achieved varies between 50 % and 75 % [1].

6.8 Multiuser access

LiFi technology can provide multiple users with simultaneous network access. It is shown that by using optical space division multiple access (SDMA) technique, the achieved network throughput is ten times more than the conventional time division multiple access techniques (TDMA) [1]. But, SDMA technique is a complex to design and time-consuming. OFDM access technique provides an easy solution for multiuser access, where users are served and separated by a number of orthogonal subcarriers.

Because LiFi systems do not have fast fading like in RF systems, and the indoor optical wireless channel has similar characteristics to the frequency response of a low-pass filter, OFDM requires appropriate user-scheduling techniques to maintain fairness in the allocation of resources (subcarriers).

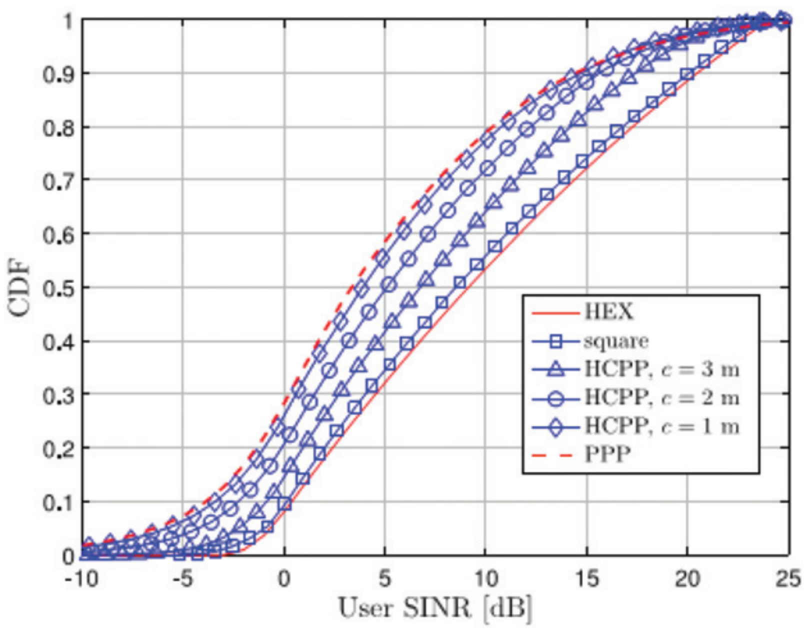

Figure 11: Cumulative density function (CDF) comparison of the SINR for different cell deployments [1].

To increase the data rate of cell edge users, non-orthogonal multiple access (NOMA) technique was introduced for RF communication systems in [32]. By using this technique and utilizing the broadcasting nature of LEDs, the performance of a LiFi system can be enhanced significantly, as illustrated in [33]. NOMA technique can serve an increased number of users via non-orthogonal resource allocation (RA).

7 Conclusion

LiFi is a recent technology that uses LED lambs for wireless communications. It uses the visible light band instead of the radio spectrum. Unlike RF systems, where antennas are used for transmission and receivers, LiFi systems use LED lamps for transmission and photodetectors in the receivers. In addition to the conventional modulation schemes used in RF, LiFi has its unique modulation techniques, such as CSK and MM.

Since the visible light band is 10,000 times wider than the radio band, LiFi can provide very high data rate. Also, the visible light band is unlicensed and free to use. Besides these two benefits of LiFi technology, it is an energy efficient system based on lighting, which is available everywhere. Also, it has a simple circuit with naturally a security feature, since light cannot pass through walls. Furthermore, unlike RF systems, LiFi does not suffer from multipath fading problem. In addition, the LiFi systems are safer and more cost-effective than RF systems.

However, there are some challenges for this technology. It is difficult to use for long distances because it has high path loss. Also, the LiFi system performance is very sensitive to any obstacles whether they are indoor or outdoor. Further, the communication quality will degrade significantly if there is no LOS between the transmitter and the receiver. In addition, the uplink communication could be the biggest issue for LiFi systems, since it is practically difficult to transmit light signals from UDs to the AP. It is suggested to use either infrared or normal RF signals for uplink communication.

Several applications for LiFi technology are presented. It can be used in places where RF communications are restricted, such as hospitals, airplanes and sensitive plants. Also, LiFi can be used for traffic management purposes and reduce accidents. Moreover, it can be utilized to provide communications for underwater vehicles. More interestingly, LiFi can provide easy outdoor access to the Internet as long as we are close to LED lamps. Additionally, LiFi can be efficient in educational institutions, where the very high data rate is needed for many users. Another possible application that was discussed is the combination of WiFi and LiFi systems, which integrates the benefits of both systems. There two types of such combination, hybrid and aggregation, and it is shown that the aggregated combination technique gives the best results. Further, the concept of small cells in RF communications can be extended in LiFi technology to the optical attocells. It is found that hexagonal cells model gives the best performance for deterministic deployments, whereas the HCPP gives the best performance for random deployments of the optical APs. The last discussed application is the multiuser access in LiFi. NOMA technique can be used to serve many users with high data rates.

This technology stills in her early ages, and more real applications will emerge in the future. However, due to its limitations, it will not replace conventional radio systems, but they will cooperate together to satisfy the large demand for high data rates caused by the increasing number of wireless devices.

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