Light Fidelity (LiFi)
The technology, the opportunities and the challenges

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Abstract

Wireless Communication is a hot topic nowadays and 5G Networks has become the wireless community buzzword. Although Electromagnetic Spectrum is long studied and used for the purpose of creating new devices and technologies especially for wired-free communications, only in recent years we observe a new wave of reborn interest towards "Visible Light." A new light-base technology called "Light Fidelity" or simply LiFi, promises to reach Gbps transmission data-rate using existing hardware and providing additional communication security. This developments has open a whole range of possibilities regarding wireless communications in many fields such as in-door communication and localization, under-water communications, vehicular communication, IoT, and many others.

Keywords: LiFi, Visible Light, Radio Frequencies, VLC, WiFi, EM Spectrum, Wireless Networks.

1 Electromagnetic Spectrum

In our everyday life we are bombarded with all sorts of Electromagnetic waves, some visible to the naked eye like the light some imperceptible to our senses like radio or infrared waves. The whole range of waves that we know are part of a spectrum, called the Electromagnetic Spectrum. More formally we are going to define the Electromagnetic Spectrum as the whole range of frequencies of the electromagnetic radiations and their specific wavelength and photon energy.

Although there are three essential factors that characterize each Electromagnetic wave, namely: Frequency ($\mathtt{f}$), Wavelength (λ) and Energy ($\mathtt{E}$), in the study of Wireless Communications we consider one more, the Phase (ϕ). From now on i am going to refer to Electromagnetic wave simply as wave and the Energy as Amplitude ($\mathtt{A}$) .

Usually when we study waves, we represent them as harmonic oscillations using sine functions where t represent the period (the time needed to complete e circle) and ω the angular frequency $\omega = 2\pi f$.

$$s(t) = A\sin(2\pi f t + \phi) = A\sin(\omega t + \phi) \tag{1}$$

Each sinusoidal function has a maximum value and a minimum value that in the case of waves are called respectively, the crest and the trough.

At this point we can use sine wave to formalize the concept of Frequency, Wavelength, Amplitude and Phase. Fig. 1 shows an example of sinusoidal.

We are going to define Frequency as the number of the times that the crest of a wave touch y-axes (Amplitude axes) in the time unit (seconds). Frequency is given by the formula $f = c/\lambda = 1/t$ and is measured in Hertz (Hz). Here c represents the speed of light.

Wavelength is inversely proportional to the Frequency and is given as the length between to continuous wave crests. Wavelength is measured in meters and is calculated using the formula: $\lambda = c/f$. In the context of radio waves λ is the most important factor in the decision of the size of Antennas. Amplitude or the quantity of the energy contained on the wave can be viewed as the high of the wave's crest. Higher amplitudes means longer the a wave can travel.

WSN (2020)

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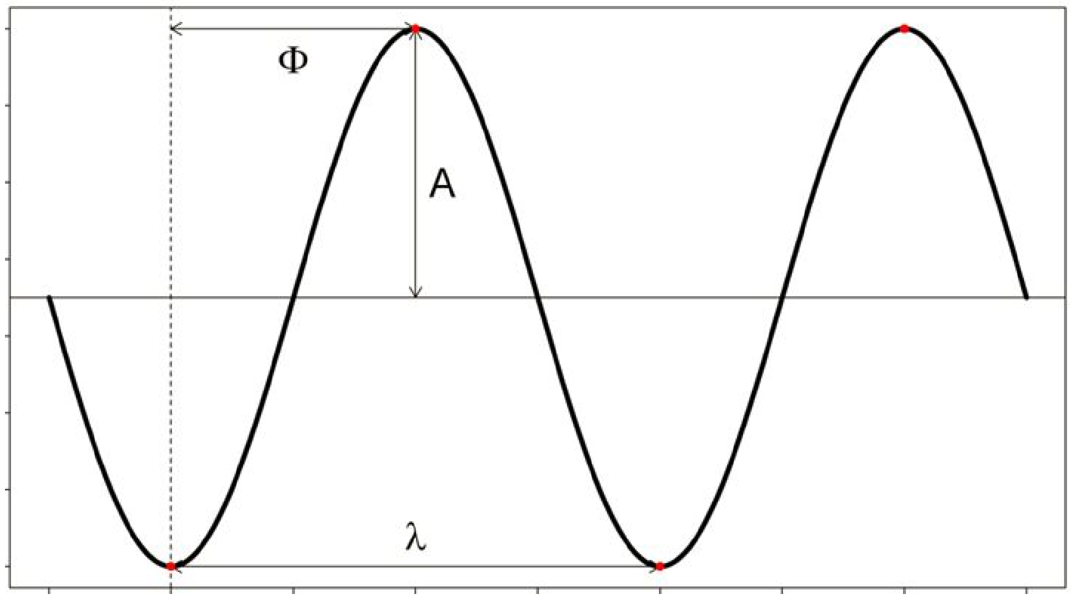


Figure 1. Sine Wave and it's characterizing elements, Wavelength, Amplitude, Phase and Frequency.

Phase is related with the position in time of a each point in the sine wave with respect to points in following waves.
Electromagnetic Spectrum covers an extended range of frequencies, spreading from a fraction of a Hz up to 10^{25} Hz. We divide the entire spectrum in seven major frequency bands: *Radio Waves*, *Microwaves*, *Infrared*, *Visible Light*, *Ultraviolet*, *X-rays*, *Gamma rays*.

Radio Waves are electromagnetic radiations with a frequency range spreading from 30 Hz up to 300 MHz, corresponding to wavelength from 1 mm up to 10'000 Km. They are generated when an electric field interact with a magnetic field and they are orthogonal to each other. The band of Radio waves is further divided in sub-bands that are used form many different purposes like radio and TV broadcasting, wireless communication, cellular communication and radars. Normally Radio Waves and Microwaves are considered together when we study wireless communications.

Microwaves are contained in the frequency range between 300 MHz up to 300 GHz. Their use varies from domestic heating devices like microwave ovens to cellular telephony, radar signaling, satellite and spacecraft communication, radio astronomy, GPS navigation and much more. One of the major characteristics of Microwave is that they travel only in Line-Of-Sight (LOS), meaning that in the presence of physical obstacles the signal cannot reach the receiver.

Infrared are electromagnetic radiation with a frequency range from 300 Ghz to 430 THz. This electromagnetic radiation is used extensively in the military for surveillance, target acquisition and night-vision. Non-military uses regards thermal analysis, wireless communication etc.

Visible Light is the main topic of this paper. Light is also a electromagnetic radiation that is perceived by the human eye. The frequency range of Visible Light is spread between 430 to 750 THz. We are going to study further in the next chapter Visible Light.

Ultraviolet is a electromagnetic radiation with a frequency range from 750 THz to 30 PHz. Is found in nature as part of the Sun radiation.

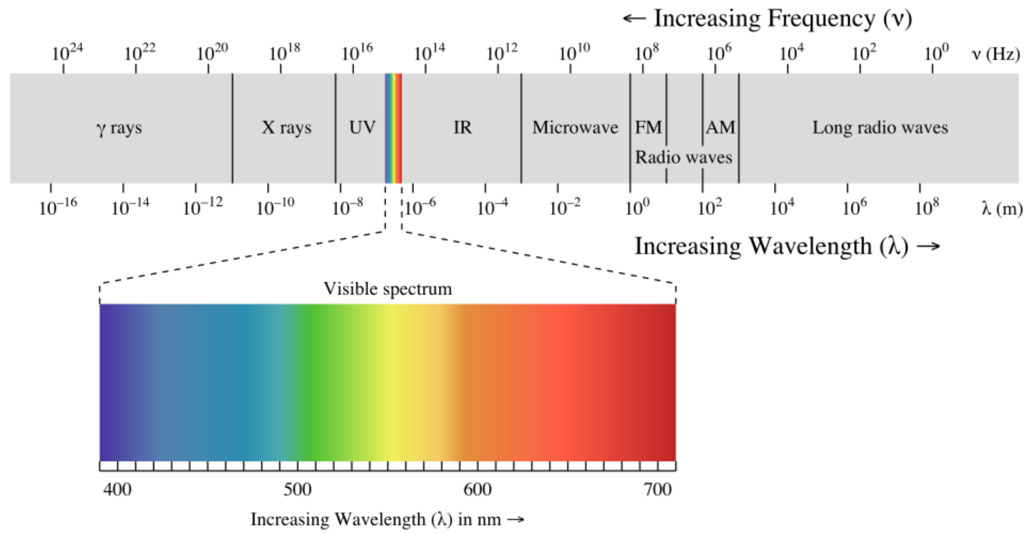


Figure 2. Electromagnetic Spectrum and its frequency bands. (Image courtesy of Wikipedia)

X-rays were discovered in 1895 by Rontgen and are contained in the frequency range between 30 PHz to 30 EHz. The main application of X-rays is in medicinal radiography.

Gamma rays are contained in the last band of the Electromagnetic Spectrum, from 10^{16} Hz to 10^{25} Hz. Gamma radiation find use in astronomy and in medicine. This extreme radiation was first discovered in 1900 by french scientist Villard.

2 State of the art of Wireless Communications

Wireless communication are ubiquitous in modern life. We find wireless networks everywhere, in our homes, in our offices, in the city squares, libraries, everywhere. They come in all different types of implementations and capabilities. State of the art wireless communication technologies use the frequency range between 100 KHz and 60 GHz (Radio and Microwave frequency bands). Just by looking the big picture that wireless systems present we can produce a first classification of such systems based on their implementation, standards and frequency band used.

- **Cellular data networks** are bidirectional wireless communication systems based on space division and frequency reuse. The idea is to map geographic areas into a honeycomb structures made of adjacent cells. To each cell is assigned a specific number of channel and is controlled by a central device called, base station. Today trend is to reduce the size of each cell while increasing the bandwidth and the number devices simultaneously connected to them. An extra benefit that comes with the reduced cell size is the low energy consumption. When the devices are close to each other the radiated effective energy is low. The benefit of small size cell comes with a price, and it regards the increase of the network complexity and newer and better ways to deal with the handover. Some of the well-known international standards for cellular data networks are: IS-54, IS-95, IS-136, GSM, EDGE, LTE, 4G and as we speak many countries are developing the new 5G standard. 5G is the most anticipated technology in cellular data networks for 2020. It utilize frequencies between 24 and 72 GHz and can reach speeds up to 2 Gbps. In order to successfully deploy this new standard new sophisticated hardware and software is needed. Big tech companies like Huawei and Ericsson, Cisco and others are the main players in this new tech adventure. Although many people are suspicious about 5G and its possible harmful effects in humans the trend of of adoption doesn't seem to stop any time soon. In this context Visible Light Communication can play an important role to empower 5G (Haas 2020) (Idris 2020). If we classify networks based on their geographical area coverage, cellular data networks (2G, 2.5G, 3G, 4G) are part of Wide Wireless Area Network (WWAN), with other technologies also such as: Nomadic (IEEE 802.16e), Mobile (IEEE 802.20), Handoff (IEEE 802.21) and WRAN (IEEE 802.22).

- **WiFi** is a group of wireless communication technologies described in IEEE 802.11 family of standards. Each of them has different implementations, characteristics and coverage. Based on the coverage we can classify wireless networks into 4 major groups: WWANs, WMANs, WLANs and WPANs. A myriad of devices and modulation schema are used to implement this networks. Obviously in everyday life we are more attached to WLANs (Wireless Local Area Network) and WPANs (Wireless Personal Area Network). Usually we use the term WiFi (Wireless Fidelity) as an alias for WLANs. "Fidelity" here underline the fact that all devices with the WiFi logo from any manufacture in the World are compatible with each-other and this fact is assured by WiFi Alliance, a non-profit organization charged with the responsibility of testing and assuring uniformity. How WiFi works?
  In an WLAN any client device, Mobile phone, PC, tablets etc. that want to access the Internet has previously to contact and pair with a device called WAP (Wireless Access Point). WAPs or as broadly known AP are layer 2 devices, just like switches that connect a wireless network to an wired network. The connected network are in the same broadcast domain, in the same LAN. Once client devices are connected to AP, they are enabled to access the Internet.
  IEEE 802.11 standards rely on many important features that have make WiFi a very attractive and broadly used technology.
  Firstly, transmission speed. Although not yet in the range of wired systems but still a very sever competitor. First IEEE 802.11 system in far 1997 had very low speed 1 to 2 Mbps, but this was only the start. Newer 802.11 protocol work on 11, 54, 108, 200 Mbps, up to several Gbps.
  Also all IEEE 802.11 standards support Ad-hoc and Infrastructure implementation of networks, providing effective solutions to P2P spontaneous networks created on the go also for administrative and corporate networks where the control is centralized.
  A third characteristic is the use of SST (Spread Spectrum Techniques), a technique that allow to spread the radio signal in the whole frequency domain. This technique, previously used by military has some very important advantages such as: Avoiding interference between radio signals, avoiding jamming and also avoiding interception of the signal. Regarding the frequency band, usually is used ISM (Industrial, Scientific and Medical) band.
  Further more WiFi standards provide support for time-critical traffic and power management. This characteristics allow QoS and the possibility that a device can go to "sleep mode" if inactive for certain time, reducing the power consumption.
  To conclude, all IEEE 802.11 standards describe the implementation of Physical Layer (PHY) and Media Access Control Layer (MAC). Standardization is a continuous process and new IEEE 802.11 standards are being develop periodically. Table 1 shows some of the most important 802.11 standards and their major characteristics.

- **WiMAX** or IEEE 802.16 is a wireless medium range, broadband communication technology classified as Wireless Metropolitan Area Network (MWAN). The development of the first standard started in 1999 and the first deployment become in 2009. 802.16e standard describes 2 layers, PHY and MAC.
  Frequency ranges are between 2 up to 66 GHz, that creates plenty of space for multi-channels (carriers). Usually WiMAX uses up to 2048 subcarriers. As for the modulation techniques, MiMAX

Table 1. The most important IEEE 802.11 standards until 2019

Standard	Year	Frequency Band	Speed	Modulation
802.11	1997	2.4 GHz	1-2 Mbps	DSSS-FHSS
802.11b	1999	2.4 GHz	11 Mbps	DSSS
802.11a	1999	5 GHz	54 Mbps	OFDM
802.11g	2003	2.4 GHz	54 Mbps	OFDM
802.11n	2009	2.4/5 GHz	65-600 Mbps	OFDM
802.11ac	2013	5 GHz	Up to 7 Gbps	MIMO-OFDM
802.11ax	2019	2.4/5/6 GHz	Up to 10 Gbps	MIMO-OFDM

used Orthogonal Frequency-Division Multiple Access (OFDMA), Quadrature Amplitude Modulation (QAM) and Quadrature Phase Shit Keying (QPSK). WiMAX implement also MIMO techniques increasing the transmission speed.

- **Bluetooth** or IEEE 802.15.1 is one of the most successful wireless technologies for short distance communication, usually under 10 meters. The technology was developed by Ericsson in the meed 90' and the first Bluetooth devices appeared in the markets in 1999. Bluetooth use frequency ranges in the segment between 2.402 and 2.480 GHz that is divided in 79, 1 MHz channels used to transmit Bluetooth packets. Different modulation techniques are used such us: Gaussian Frequency Shift Keying (GFSK), $\pi/4$-Differential Quadrature Phase Shift Keying ($\pi/4$-DQPFS), 8-Differential Phase Shift Keying (8-DPSK) etc. As mentioned previously, Bluetooth is a packet-based protocol developed using a master/slave architecture, where one master device can control as much as seven other active slave devices and as much as 255 parked devices, creating a so called "piconet".
  Technologies such as Bluetooth, ZigBee (IEEE 802.15.4) and IEEE 802.15.6 are classified as Wireless Personal Area Network (WPAN). WPAN networks lay certain challenges that Bluetooth has to solve such as: the device have to be battery powered, meaning that is required to maximize the life of the battery. The topology is dynamic, so short time connections have to be establish and cancel continuously. Also there is no need for an Infrastructure type organization, devices have to be able to create ad-hoc networks. WPAN devices have to avoid interference with other wireless technologies such as WiFi. The standard has to provide extreme interoperability, with billion of different type devices to connect to a network. Finally, the cost of this devices have to be very low. In fact a Bluetooth chip is of size 9 mm^2 and costs around 5$. Bluetooth has meet all this requirements successfully becoming one of the most used technologies of close range communication.
  Fig. 3 shows the classification of wireless networks based on their geographical coverage.

3 Optical Wireless Communications

CISCO's Annual Internet Report projections give some very important numbers regarding the technology trends for 2018-2023. The projection shows a 15% more of the World population will have access in the Internet, and also the number of network devices for person will increase from 2.4 to 3.6 in the next 5 years. This development puts an arduous challenge to producers and providers of communication technology. New standards and hardware need to be conceive and put in production. This new products should be able to provide a transmission speed around 92 Mbps for wireless devices. Taking into consideration the fact that today WiFi speed is around 30 Mbps, we will need a three-fold leap to reach this target, and that is not an easy task considering

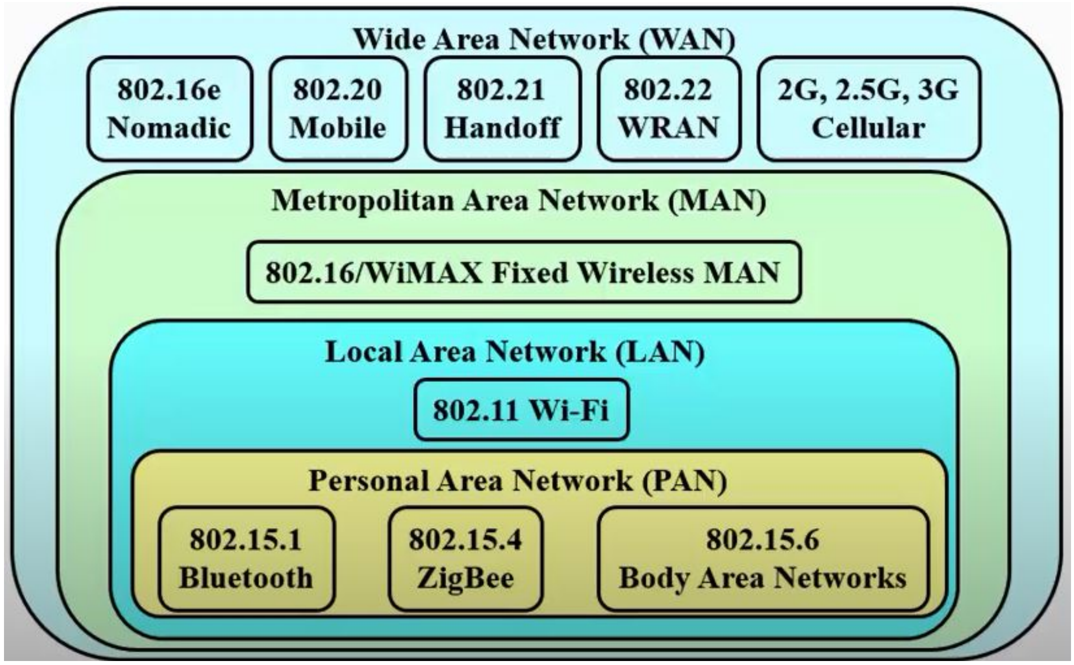


Figure 3. Classification of Wireless Networks based on geographical coverage

the availability of radio spectrum. Some new approaches have to be taken...
The need for alternative ways to replay to the users and application demand for larger bandwidth in the context of even higher radio frequency congestion has push the researchers to explore other parts of the Electromagnetic spectrum. We are talking about the large frequency ranges containing UV, visible light and IR. In this context we are going to define Optical Wireless Communication (OWC) as set of the methods and technologies that relay on optical signals in order to transmit data. The use of optical carriers has open new perspectives and attract many researchers in the whole World. Although not a new idea, OWC promises a new and bright era in the wireless communications.
The first attempt to create a optical wireless communication devices goes back to 1880 when Alexander Graham Bell invented the photophone, the first wireless device in the history. But only in the mid-twentieth century, with the discovery of laser beam and light-emitting diodes (LED) the research on optical technologies got a new speed. The modern era of wireless optical technologies started in 1962 when researchers from MIT used a GaAS LED device to transmit a TV signal through a 48 Km distance. It was a promising achievement, that was repeated a year later in 1963. This time they send acoustic signals using a He-Ne Laser covering 190 Km distance. The first commercial application of OWC saw the light only 1970 in Japan when NEC created the first inter-city link between Yokohama and Tamagawa covering a 14 Km distance. After this breakthrough the interest on developing optical carrier based system seemed to vanish due to the concentration on radio band. The benefits of OWC are huge, starting from the cost. OWC devices usually use "off the shelf" hardware, meaning that there is no need to develop new dedicated hardware. Furthermore OWC rely on a huge non allocated band, something that is not true for the radio frequency range (3 KHz - 300 GHz) that is almost all allocated by state organizations. Only this fact is enough to speed up the research on OWC. Another important feature of OWC technologies is the related with the security issues. While radio signal is able to get through walls and other obstacles, light is limited in the enclosed area, and this is the best assurance for communication security. Last but not least, OWC can be a great solution to use in the new growing applications such as Vehicular communication, Internet of Things (IoT) , inter-chip communication, WPAN devices and much more.
We can classify OWC technologies based on EM spectrum they use or the distance they cover.

Table 2. OWC technologies based on their range

Type	Range	Technology	Application Areas
Ultra short range	millimeters	2.4 GHz	Inter-chip links
Short range	centimeters	2.4 GHz	WBAN, WPAN
Medium range	meters	5 GHz	WALN, under-water communication
Long range	kilometers	2.4 GHz	WMAN, backhauls
Ultra long range	> 10'000 Km	2.4/5 GHz	Satellite communication

Classification based on used band.

- **Free Space Optics (FSO)**: make use of IR spectrum, comprising wavelength between 750 to 1600 nm.
- **Visible Light Communications (VLC)**: lay on visible light spectrum. Wavelength is between 390 to 750 nm.
- **Ultraviolet Communication (UVC)**: uses the UV section of the EM spectrum spreading between 200 and 280 nm of wavelength.

Although in this paper we are going to elaborate on VLC and see in detail LiFi, is important to know all the other similar technologies because in some occasions they are combined together in hybrid settings in order to provide upstream and downstream data transmission (Liverman 2018).

Classification based on the covered range.

- **Ultra Short Range OWC**: is the use of optical signal at the single chip level. With the progression of the miniaturization techniques for chip construction has gone to the physical limits. At the contrary the need for higher speed in inter-chip communication is also increasing. One solution is to use optical carriers to transfer huge amount of data between chips. On this basis Free Space Optical Interconnects (FSOI) has been developed with important results.
- **Short Range OWC**: is the application of OWC in small distances. usually some few meters. Here the areas of application are WBAN (Wireless Body Area Network) and WPANs. In the case WBANs we are dealing with microprocessors that are in direct contact with the body and provide information about its conditions and health. Information such as, temperature, sweat, heart rate monitoring, levels of glucose in the blood and much more. WPAN work also in short distance and can be implemented using short range OWC.
- **Medium Range OWC**: concerns *in-door* and WLAN applications. The range is around 100 meters and LED lights are used for two purposes: illumination and data transmission. The fact that normal illumination devices are used even for communication make this technologies very much attractive and easy to deploy. VLC and LiFi implementations are the main developments in this area.
- **Long Range OWC**: are basically *out-door* point-two-point systems used to communicate in long distances, usually some kilometers. The technology used to construct this kind of channels is based on FSO systems. This links can achieve very high speed in the order of some Tbps. To summarize, Long Range OWC are the wireless alternative for the creation of MANs.
- **Ultra Long Range OWC**: is a FSO technology used to create communication links between satellites and Earth stations. The covered distance is around 10'000 Km and the speed more than 600 Mbits. In 2013 NASA used FSO technology to create a data communication link between Earth and Moon, a distance of 386'6000 Km and reaching a speed of 662 Mbits.
  Table 2. shows a summary of OWC technologies based on range.
  In the next chapter we are going to see VLC from a theoretical and application point of view.

4 Visible Light Communication

VLC is a short-range, optical communication technology that operates in the visible range of the EM spectrum, between 380 and 780 nm of wavelength. The first standard came out in 2011 and is called: "IEEE Standard for local and metropolitan are network-Part 15.7: Short-Range Wireless Optical Communication Using Visible Light". The latest version of the standard was published in 2018 and include the new developments in the technology. Before going into the details of how physical and Mac layer are described in the standard we have to consider the devices that make all this happen in the first place, and this are LED (Light Emitting Diode) and LD (Laser Diode). VLC transmits data by modulating the intensity of optical sources, such as LEDs and LDs, faster than the human eye can perceive. Although the use of visible light for communication is known for many decades only the last decade we see an renewed interest in this technology. This fact can be explained with the advances of the LED and LD technology and the widespread use of those devices as energy efficient alternative for in-door/out-door illumination. As we have seen previously the radio spectrum is running out of bandwidth very fast and high-speed communication is becoming a challenging issue. On the other hand visible light with a bandwidth around 300 THz promise to fill this gap. VLC can reach multi-gigabit-per-second ranges by using LED arrays and applying some sophisticated modulation techniques. There are also economic advantage by using LED instead of high-power consumption RF transmitters. In the next paragraph we are going to look LEDs, LDs and Photodiodes.

- **Light Emitting Diode (LED)**

  LEDs are electronically controlled solid state materials that can produce light when crossed by electric current. This physical effect called *electroluminescence* was first discovered in the beginning of the 20-th century and is the basis LED operation. First LED devices were characterized by a very poor efficiency , as low as 0,03%. The progress in the semiconductor technology eventually changed the situation dramatically. The discover of white light LED opened the prospective for mass adoption of the device for illumination and communication. In order to understand the operation of LED devices we have to understand the atomic structure of the materials. Is exactly this structure that divides materials into three categories, non-conductors, conductors and semi-conductors. Bohr model provides us the theoretical means to analyse electroluminescence effect. Electrons surround the nucleus of the atom and circle it into well specified energy level orbits. This orbits have different distance and energy level to different elements. Materials used for creating LEDs are chosen in such a way that last two outside orbits to be as close as possible to each other. In this case only a small change on the material temperature would be enough to excite the electrons and push them to the outside orbit. As we know, electrons in the outside orbit can radiate in the form of photons and produce light. This process is highly controllable and allow the construction of high speed intensity manipulation LEDs that we use to transmit data. The materials that are used to construct LEDs are: Germanium, Silicon, Carbon, Gallium etc. Fig. 4 shows the schema of a LED.

  The advantages of LEDs as source of illumination and data transmission are the following:

  1. **Efficiency**: LEDs emit more lumens per watt and it is not effected by the size of the device.
  2. **Color**: can be changed electronically, no filters needed.
  3. **Size**: the size can as small as 2mm and can feet into any chip.
  4. **Dimming**: can be controlled easily.
  5. **Lifetime**: can be very high.

- **Laser Diode (LD)**

  LDs are semiconductor devices able to convert electric current into light. Like LEDs, LDs are

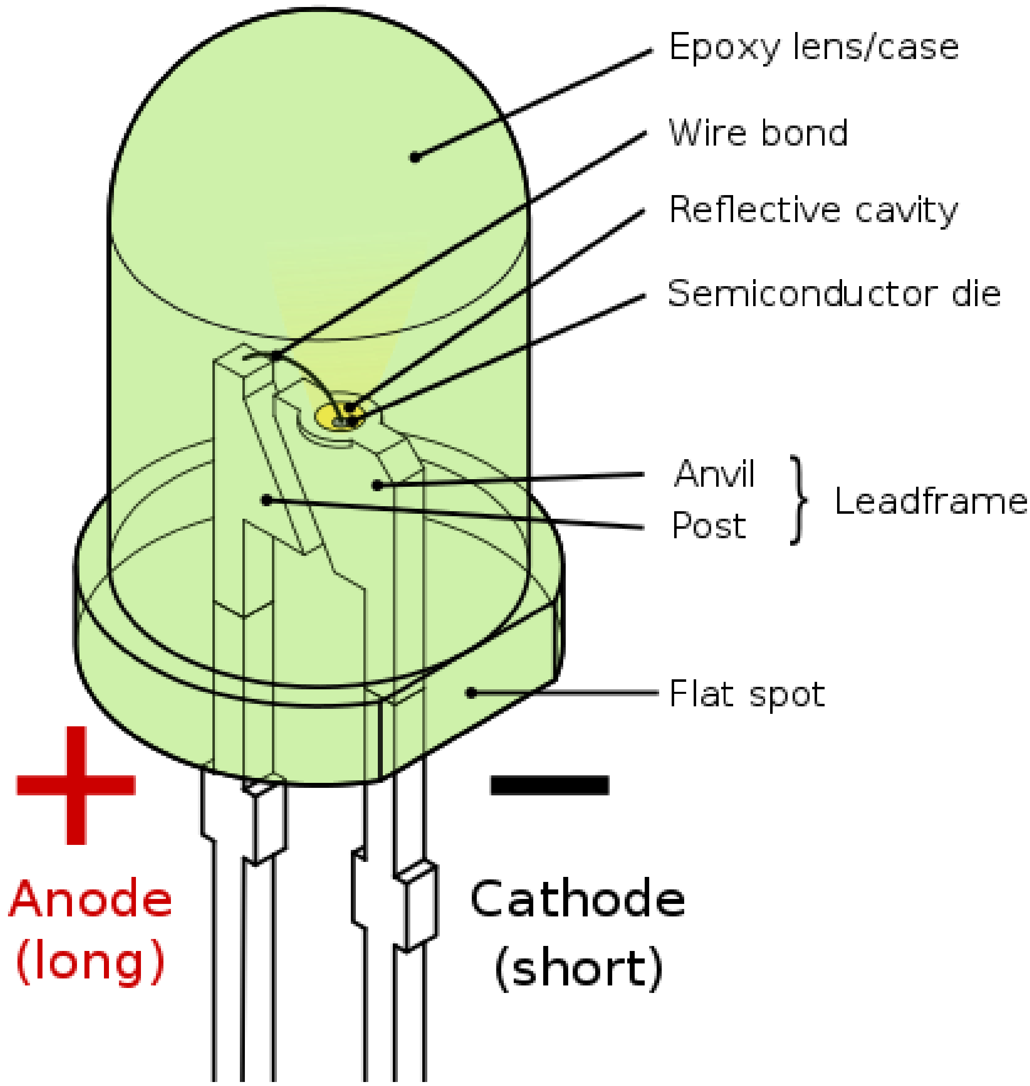


Figure 4. Light Emitting Diode. (Image courtesy of Wikipedia)

devices that emits light through a process of optical amplification based on stimulated emission of electromagnetic radiation. The device is constructed as a PIN diode, where the active region is is "i". LDs sometimes are prefer to LEDs because they have faster response time and also the radiation (light) can be focused much better even in to small diameter areas like $1\mu m$.
LDs are used in various devices such as: laser pointers, CD-players, bar-code scanners, and also as transmitters of data.

- **Photodiode**
  Photodiodes are semiconductor devices that have the inverse role of LEDs and LDs. In other words Photodiodes convert light into electrical current. This current is generated when the electrons emitted by the light source hit the surface of the Photodiode. In optical communication, Photodiodes are used as receivers of the data. The only drawback of Photodiodes is their response time that is much inferior than those of LEDs and LDs. In order to define the photo-detection capabilities of a Photodiode we need to know the material it is constructed. Each material is

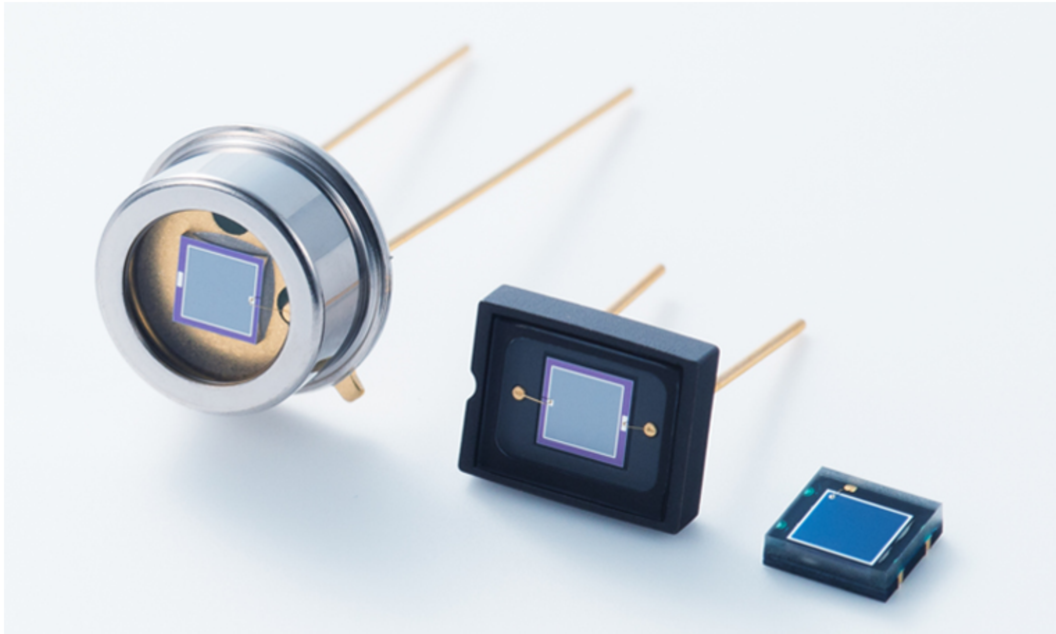


Figure 5. Photodiodes. (Image courtesy of Hamamatsu)

different in this aspect. Usually is used Silicon for wavelength between 190 to 1100 nm, Germanium for wavelenth between 400 to 1700 nm, graphene and other electron absorption materials. Other than for communication, Photodiodes are used also in many areas such as in solar cells, photodetectors, photoconductors etc. Fig. 5 show some different types of Photodiodes.

After studying the end physical devices used for the transmission and reception of the light we are going to focus now on the architecture of a VLC system and how it is described by the standard. VLC system support three types of network topologies: peer-to-peer, star and broadcast. Each device is identified by an unique 64-bit address. In the case of star topology there is a master device called a coordinator. Standard IEEE 802.15.7 classify the VLC devices into 3 categories: Infrastructure (coordinated), Mobile and Vehicle. Each category has different characteristics regarding power supply, form factor, light source, range and data rates. Fig. 6 shows the three types of topological arrangements.

One of the main concerns of VLC is the maintain communication even in the case of light dimming and to mitigate flickering. This two are major issues that we are going to discus further later on.
Fig. 7 shows the architecture of an VLC system. IEEE 802.15.7 standard describes two layers for each VLC system, physical (PHY) that contain the light transceiver and its control mechanisms and also MAC sublayer that provides access to the physical channel. The other layers that are shown are not part of the standard and are defined based on external criteria. Every OWPAN (Optical Wireless Personal Area Network) device comprises a PHY, which contains the light transceiver along with its low-level control mechanism, and a MAC sublayer that provides access to the physical channel for all types of transfers. The upper layers shown in the figure comprise the Network layer, which is responsible for network configuration, manipulation and message routing, and also the Application layer that defines the purpose of use of the device. The architecture support also a separate component called DME (Device Management Entity) that interface MAC and PHY layer with

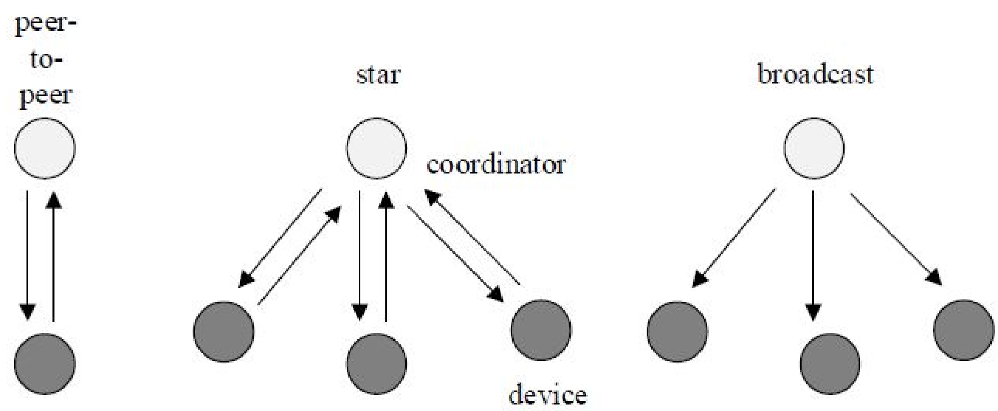


Figure 6. MAC Topologies. (Image courtesy of IEEE)

an external device called Dimmer and is used to change the luminosity of the device.

- **PHY**

  Physical layer is the interface between the superior MAC sublayer and the inferior physical channels that contains the light sources. Inside PHY exists an unit called PLME (Physical Layer Management Entity) that provide the interface for calling all the functionalities of PHY layer. PLME contain also a small database, PIB that stores all the objects that are in relation with PHY. Layer PHY offer two main services that are accessible from two access points called SAP (Service Access Point).

  1. PHY management service: uses PLME-SAP component for the management of the layer. Communicate with the uper layer through MLME (MAC Layer Management Entity).
  2. PHY data service: use the component PD-SAP in order to transport MPDUs (MAC Protocol Data Unit) from MAC layer to PHY layer.

  PHY layer is the fundamental layer of IEEE 802.15.7 and has the following responsibilities:

  1. Activation and deactivation of the VLC transceiver.
  2. WQI for received frames. The WQI (Wavelength quality indicator) measurement is a characterization of the strength and/or quality of a received frame.
  3. Channel selection.
  4. Data transmission and reception.
  5. Error correction.
  6. Synchronization

  The data that arrives to PHY layer are in the data format of MAC layer MPDU. This data after processing by PHY layer are transform into PSDU (PHY Service Data Unit). As we know, on each layer that data travel in the ISO/OSI stack modification are made and each layer add its specifications to the data. Some of the manipulations that PHY layer make to MPDUs are: channel coding, line coding etc. The product of all this modifications is the PHY frame called PPDU (Physical Protocol Data Unit). Fig. 8 show PPDU format.

  The *preamble* is used for the optical synchronisation between transmitter and receiver. Preamble has also an internal structure where in the first part is defined FLP (Fast Locking Pattern). FLP is an alternate sequence of 64 to 16'384, "0" and "1" bits. The second part of preamble consist of one or more TDP (Topology Dependent Patters) that are used in order to specify the network topology and are created by MAC layer. Preamble is transmitted using OOK modulation and is unique for the fist three of six types of PHYs defined by the standard. Fig. 9 show the format of

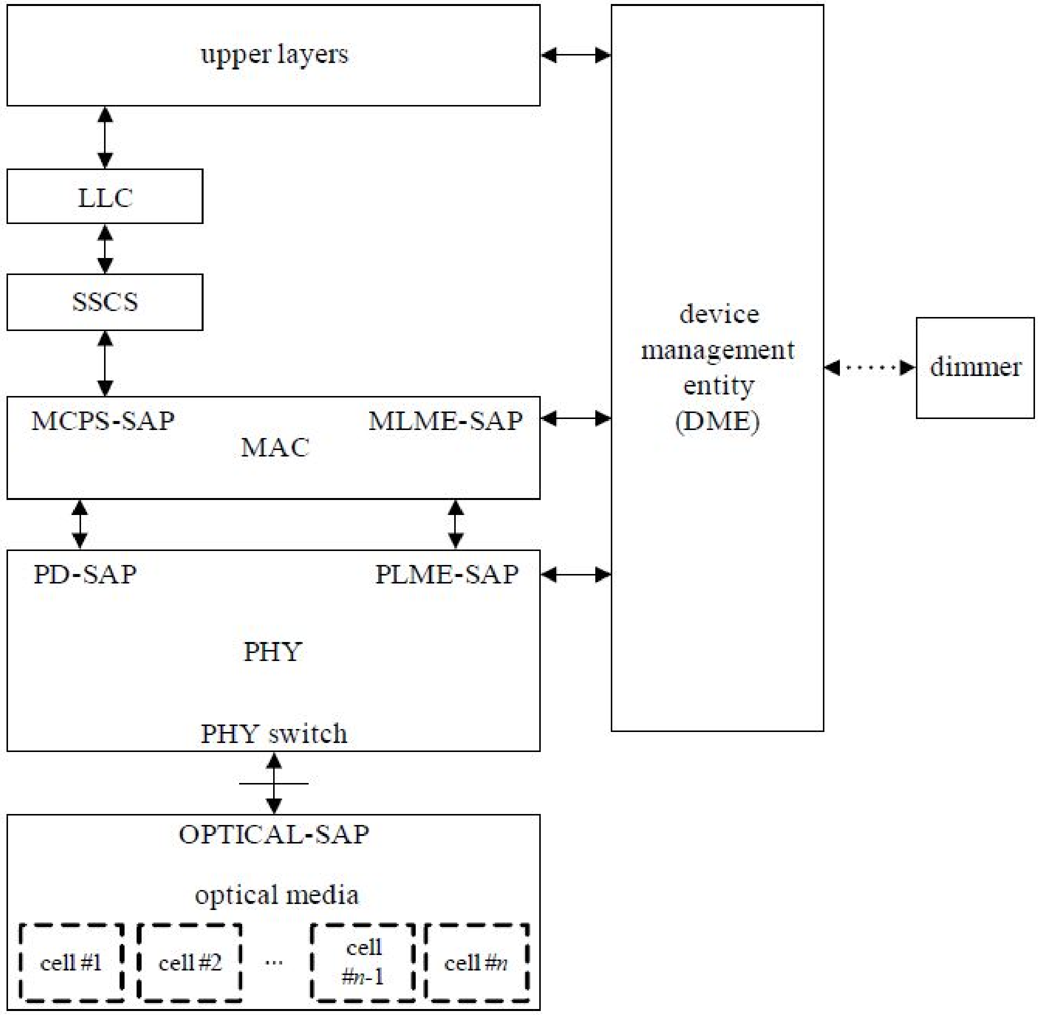


Figure 7. Architecture of a VLC system. (Image courtesy of IEEE)

preamble.
The *header* has 6 fields and contain important information for the transmission, like the number of channel, the size of PSDU etc. Header is transmitted with the lowest transmission speed in order to be captured even by discrete receivers. OOK modulation schema is used to transmit it.
HCS (Header Check Sequence) is a 16 bit security sequence, calculated using CRC-16.
Optional Fields are optional bits used in case of specific situations.
PSDU contains the real data of PHY layer and has also a variable size.
IEEE 802.15.7 specify also the wavelength range that VLC systems has to operate and the error limits. In order to avoid inter-frame interference a space called IFS (Inter-Frame Spacing) is added between consecutive frames. Based on the topology there 3 possible values of IFS, LIFS, SIFS and RIFS.
PHY supports 4 data transmission modes: single mode, packed mode, burst mode and dimmed OOK.

The standard defines six types for PHY, each one with specific characteristics.

1. PHY I: is defined for out-door applications and has low data rates (hundreds of kbps). Modulation techniques are ON-OFF keying (OOK) and Variable Pulse Position Modulation (VPPM).

Preamble (see 8.6.1)	PHY header (see 8.6.2)	HCS (see 8.6.3)	Optional fields (see 8.6.4)	PSDU (see 8.6.5)
SHR	PHR			PHY payload

Figure 8. PHY frames format (PPDU). (Image courtesy of IEEE)

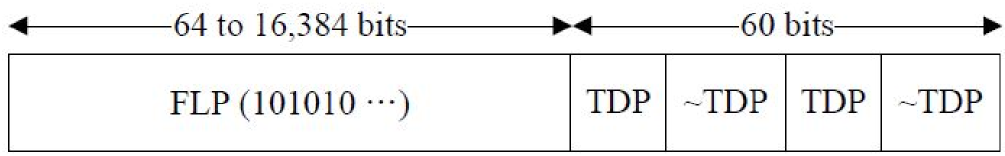


Figure 9. Preamble of PPDU. (Image courtesy of IEEE)

2. PHY II: is defined for in-door application, and reach data rates of tens of Mbps. Modulation techniques used are: OOK and VPPM.
3. PHY III: is defined defined for application that have multiple light sources and detectors. The data rate is in the order of tens of Mbps.
4. PHY IV: is defined for discrete light sources and has data rates on the range up to 22 kbps.
5. PHY V: provide low data rates, up to 5,71 kbps.
6. PHY VI: is intended for use with video displays.

This PHY types can coexist in a system but do not interoperate because the different implementation.

- **MAC**

  MAC is the sublayer of Data Link layer that stands over PHY layer. It provide the communication interface between 3 components, SSCS, DME and PHY. Fig. 10 shows the interaction between this entities. The most important component in the MAC layer is MLME (MAC Layer Management Entity) that manages all the layer.

  MAC layer handle all the access to physical layer and is responsible for the following tasks:

  1. Generating network beacons if the device is a coordinator.
  2. Synchronizing to network beacons.
  3. Supporting OWPAN association and disassociation.
  4. Supporting color function.
  5. Supporting visibility.
  6. Supporting dimming.
  7. Flicker-mitigation scheme.
  8. Supporting visual indication of device status and channel quality.
  9. Supporting device security.
  10. Providing a reliable link between two peer MAC entities.
  11. Supporting mobility.

  The data produced by MAC are conserved in the MAC frame called MPDU (MAC Protocol Data Unit). Each MAC frame has 3 components:

  MHR is the header of the MAC layer. Inside the header are specified other fields such as *Frame*

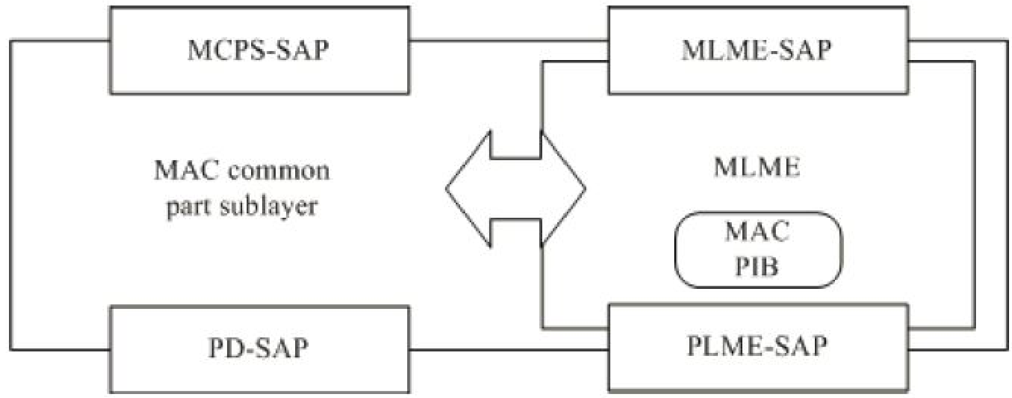


Figure 10. MAC layer diagram. (Image courtesy of IEEE)

Control, Sequence Number, Address Information and *Security Related Information*.
MSDU contains the valid data, also called the *payload*. The size of this field is variable.
MFR is used for error correction.
The standard defines 5 types of MAC frame formats. The type of each frame is written on the Frame Type portion of Frame Control field. Based on the type of frame changes the content of MHR and MSDU.
MAC level is responsible for the creation of a wireless network. It handle all the actions needed for this purpose. In order to be able to create a VPAN network, the devices have to be able to scan all the optical channel in the area they cover. There are 2 ways to scan the channels: the first one is called an active scan and is used by normal devices in order to identify coordinators that transmit beacons. This scanning method is used in peer-to-peer topology. The second type of scan is called passive scan and is used in broadcast topology.
MAC layer is responsible for the generation of the beacons and the discovery of the devices present in the VPAN. The detailed process is described in the standard. The coordinator devices should be able to detect and resolve possible conflicts. Another important issue is that MAC has to store the sequence number of each transmitted frame independent of the type of frame, beacon or data.
The fundamental characteristic of VLC is to combine illumination and data communication. Knowing this fact is necessary that MAC layer provide dimming support. Another important aspect of MAC is data security. MAC offer three types of protection: *Data Confidentiality, Data Authentication* and *Replay Protection*.

- **Modulation**
  Is the process of imposing a data signal wave onto a carrier wave. In other words modulation is the process of changing some property, such as Amplitude, Frequency or Phase of a carrier wave with data signal wave as an input. Sophisticated modulation schemes lead to better signal transmission and also higher bandwidth. There are hundreds of modulation techniques used in the wireless communications. Here we are going to see those used by VLC and later on those used by LiFi.
  As we have argued previously, IEEE 802.15.7 specifies 6 types of physical layer implementations. Each of this types has its characteristics.
  PHY I applications require low data rates, between 11.67 kbps and 266.6 kbps based on the modulation used. The standard defines two modulation techniques for this type: *OOK (ON-OFF Keying)* and *VPPM (Variable Pulse-Position Modulation)*.

OOK is the simplest form of Amplitude modulation scheme. The presence of a carrier for a certain duration represent the bit 1 and the absence of the carrier for a certain time duration represent the bit 0. PHY I used OOK with an optical clock rate of 200 kHz to reach data rates between 11.67 to 100 kbps.

VPPM is the second type of modulation used in PHY I. It is a variant of *PPM (Pulse-Position Modulation)* in which M data bits are encoded in a single pulse and the pulse width is variable in correspondence of the illumination intensity (dimming is taken into consideration). VPPM operates in 400 kHz optical clock rate and achieve data rates in the region between 35.56 to 266.6 kbps.

PHY II is similar with PHY I in the sense that it used the same modulation but changes the optical clock rate and as a consequence the data transmission rates. PHY II application can reach speed up to 96 Mbps.

PHY III slightly changes from the previous two physical types. It uses *CSK (Color Shift Keying)* encoding the bits as using different colors. PHY III can reach data transmission rates up to 96 Mbps.

The new version of IEEE 802.15.7-2018 has included three new PHY types (PHY IV, PHY V, PHY VI) that are different from those defined in the previous version of the standard IEEE 802.15.7-2011. The new types implement new and sophisticated modulation schemes.

PHY IV implement 5 new modulation schemes: *UFSOOK, Twinkle VPPM, S2-PSK, HS-PSK, Offset-VPWM* providing data transmission ranges between 10 bps to 22 kbps.

PHY V implement 4 modulation schemes: *RS-FSK, C-OOK, CM-FSK, MPM* reaching up to 400 bps.

PHY VI implements 6 modulation schemes: *A-QL, HA-QL, VTASC, SS2DC, IDE-MPFSKBlend, IDE-Watermark* and can reach up to 256 kbps.

VLC support also MIMO transmission where we use multiple channels to transmit and receive the data (Tavakkolnia 2019). In this case even more sophisticated modulation schemes are used, such as O-OFDM (Optical-Orthogonal Frequency Detection Modulation), DCO-OFMD (Direct-Current-Biased OFDM) (**haas**) (Islam 2019) etc. Fig. 11 shows a classification of all the possible modulations schemes in use for optical systems.

All the modulation schemes support dimming and also try mitigate flickering. Let's have a better look on this two concepts.

Dimming defined as controlling the perceived brightness of the light source according to the user's requirement and is a cross layer function between the PHY and MAC. In other words even when the user decrease the light intensity the device should be able to transmit data. Also in the case that when MAC is idle or RX is idle the PHY layer should be able to transmit an idle pattern. This is important since it is desired to maintain visibility and flicker-free operation during idle or RX periods at the infrastructure. There are three methods used to achieve dimming:

1. Adding compensation symbols is used in the case of OOK and MPM (Mirror Pulse Modulation) where the data are sent using constant brightness within a symbol. In this situation a compensation is needed to be inserted into the frames in order to adjust the average intensity of the perceived light.
2. Controlling pulse width is used on VPPM and FSK modulation. In this modulation schemes the pulse Amplitude remains always constant but we can use the pulse width to control dimming.
3. Controlling the Amplitude of the signal and keeping constant the other pulse parameters.

Flickering is the temporal modulation of the light in frequencies higher than the human eye can perceive. In poor words, flicker is the a perceivable brightness fluctuation. There are two flickering types: Intraframe flicker and interframe flicker. Interframe flicker is defined as the perceivable brightness fluctuation between adjacent frame transmissions and Intraframe flicker is defined as

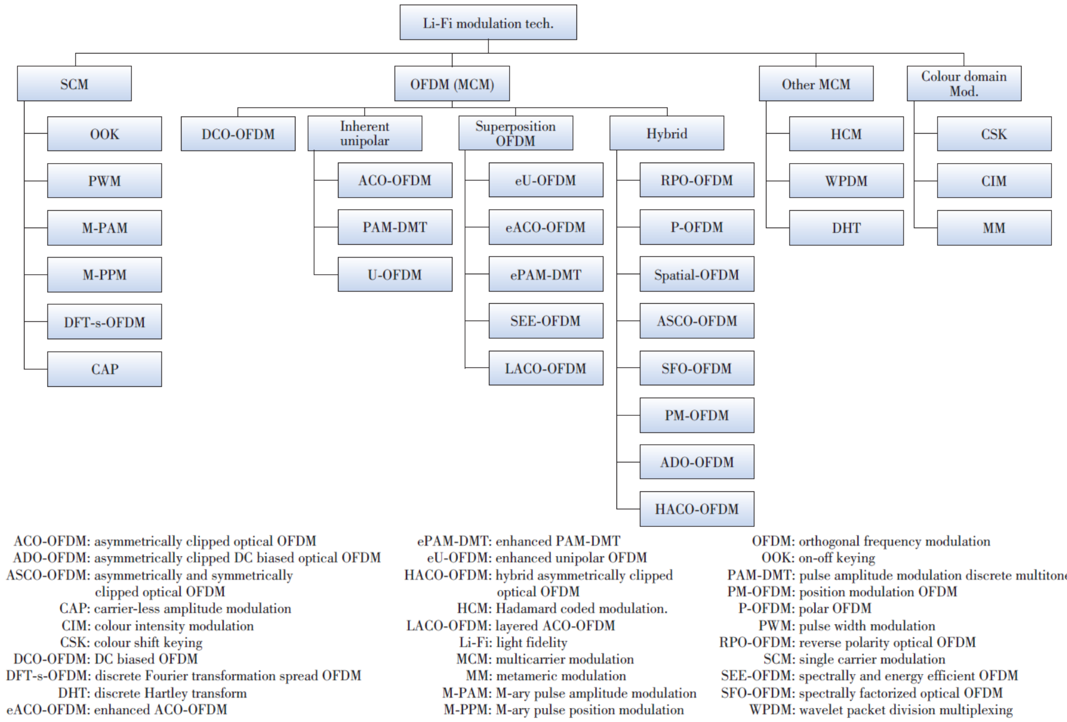


Figure 11. Classification of Modulation Schemes used in OWC (https://www.lifi.eng.ed.ac.uk/)

perceivable brightness fluctuation within a single frame. Intraframe flickering can be mitigated in two ways, by using modulation or by using Run-Length Limited coding (RLL) or both. The second type of flickering, Interframe flickering can be mitigated by the use of an idle pattern between consecutive frames that has the same brightness as the data frames.

- **Data transfer model**

  IEEE 802.15.7 defines three types of data transfer models:

  1. Data transfer towards a coordinator from a client device (used in a star and broadcast topology). Is used when a client device want to transmit data to a coordinator device, when there is a beacon-enabled OWPAN. The first thing the client device do is to listen for beacons. When it receives a beacon, synchronizes with the structure of the coordinator superframe. The device transmit the data frame in a specified time period called contention access period, (CAP) using a slotted random access method. After that the coordinator can choose to acknowledge or not the transmission.

     In the presence of an OWPAN that has no enable beacons the client device just transmit its data frame whenever likes using unslotted random access. The coordinator has to acknowledge any received data frame to the client device.
  2. Data transfer from a coordinator towards a client device (used in a star and broadcast topology). In this case is the coordinator that modify the beacon in such a way to indicate a pending data frame. The devices that periodically listen for beacons, examine the beacon and send to the coordinator a MAC command requesting the pending data frame. The coordinator receives the MAC command and acknowledge it to the client device. After that the coordinator transmit the data frame toward the client device. The data are transmitted using slotted random access. When the message is receive from the desired device, the message is removed from the beacon. At this point the transmission is concluded.

In a non-enable beacon OWPAN the coordinator just stores the data frames and just wait until the desired client device contact it. When the device is connected, it uses a specified MAC command to request the data using the unslotted random access method. The coordinator transmit back the data frame and the transaction finish.

3. Data transfer between two peer device (used only in a peer-to-peer topology). The standard indicates that each peer device can communicate with other device that are in its coverage area. This devices in order to be able to communicate should be able to periodically exchange synchronization information between them. In this situation unslotted random access method is used.

Before going into the details of how this 3 models work we have to introduce the *superframe structure* defined on the standard. The superframe is a limited period of time that is defined by the *coordinator* and contains three portions: beacon period (BP), contention access period (CAP), optional contention-free-period (CFP). BP is the first part of a superframe and is used for the following reasons: synchronize the attached devices, identify the OWPAN, describe the superfame structure to the other devices. Every device competes with each other in order to be able to communicate in the CAP period. The standard defines four types of random access methods:

1. Unslotted random access. Is used in the OWPAN that has not enabled the beacons.
2. Slotted random access. Is used by the OWPAN that have enable beacons.
3. Unslotted carrier sense multiple access with collision avoidance (CSMA/CA).
4. Slotted carrier sense multiple access with collision avoidance (CSMA/CA).

Superframe is not the only type of frame defined by the IEEE 802.15.7 standard. There are five type of frame formats defined:

1. Beacon frame, used for synchronization purpose by the coordinator.
2. Data frame contain the actual data the the application of the higher layers want to transmit.
3. Acknowledge frame, (ACK) used to indicate successful reception of data.
4. MAC command, used to handle MAC level activities.
5. Color Visibility Dimming (CVD) frame used for dimming and other purposes.

5 Light Fidelity

Light Fidelity or shortly *LiFi* is the evolution of VLC. The term gain popularity in 2013 after a TedX speech of professor Harald Haas from the University of Edinburgh. In that speech Haas publicly demonstrated the technology, by performing a image transmission using a LED based transmitter. Fig. 12 show professor Haas in he's studio. From then on the technology has arouse grate interest and many research is going on with extraordinary result over the years. Many new companies have been founded with the scope to develop the technology and the devices needed to produce a commercial product. Haas itself has founded a start-up called *pureLiFi* and also researcher in the university of Boston have founded a start-up called *ByteLight*. One can thing of LiFi as the WiFi, but instead of using RF it uses light. In 2011 a group of companies formed Light Fidelity consortium with the scope to develop and promote LiFi and promising to achieve more than 10 Gbps data transmission speed. The last decade the technology has improved dramatically and the transmission speed achieved is exceptional. Here we provide some of the main achievements:

Actually the success of LiFi based on the wide spread of LED bulbs as lighting source both in-door and out-door. In 2008 Minh et al. demonstrated a system based on white-light LED array capable of transmitting 40 Mbits using a NRZ-OOK modulation (Minh 2008). Vucic et al. using a Discrete Multitone (DMT) modulation achieved speed rates of 513 Mbits (Vucic 2010). Later on Khalid et al. used a rate-adaptive DMT and a phosphorescent white-light LED achieved 1 Gbits transmission speed (Khalid 2012). In 2013 Wu et al. realized a system capable of 3.22 Gbps using CAP and QAM-OFDM modulation combined with RGB-LEDs (Wu 2013). Bamiedakis et al. used PAM modulation and GaN micro-LEDs to achieve 2 Gbits transmission in 2016 (Bamiedakis 2016). Ferreira et al. using

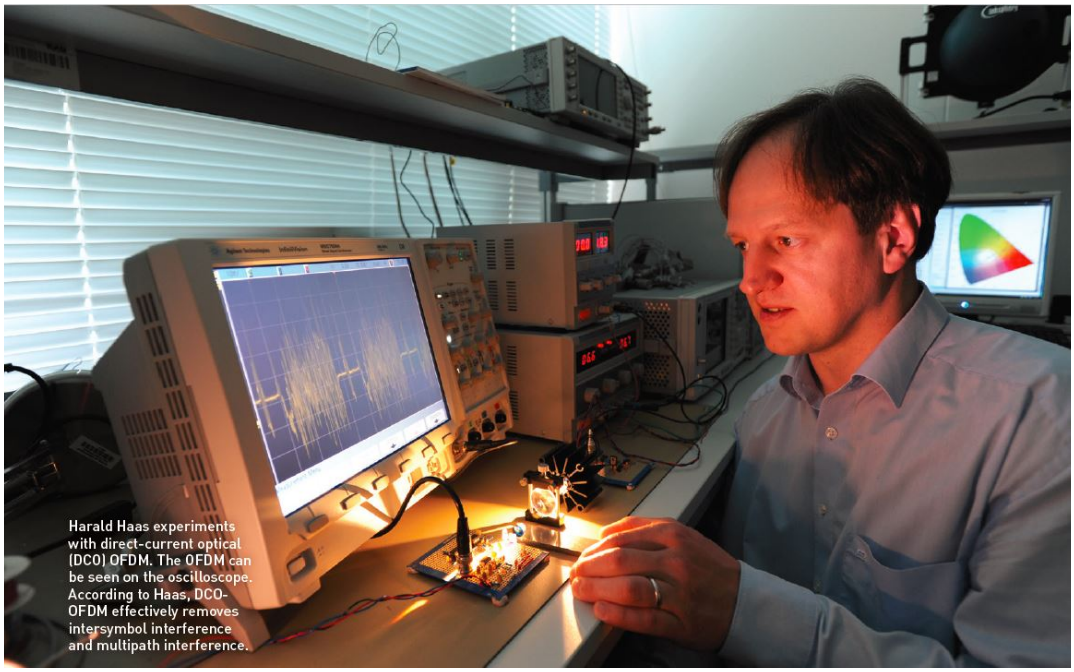


Figure 12. Professor Harald Haas.

using same technology and a bandwidth modulation over 800 MHz was capable to achieve 5 Gbits transmission (Ferreira 2016). Recently Islim et al. has employed DMT and violet micro-LEDs has demonstrated a transmission speed of 10 Gbps (Islim 2017). Except for the LED bulbs modern LiFi systems utilize LDs to achieve even greater speed due to the aforementioned physical characteristics of those devices. The earlier demonstration of this setup was made by Watson et al. in 2013. Watson achieved 2.5 Gbps speed by using off the shelf GaN blue LDs and OOK modulation (Watson 2013). Later on Chen et al. has demonstrated a bidirectional link using 16-QAM OFDM modulation capable of reaching 2.5 Gbps over 15 m distance (Chen 2013). The same year Chi et al. achieved 9 Gbps transmission speed using 64-QAM OFDM on a distance of 5 m (Chi 2013) with a free space P2P link based on LDs. Tsonev et al. was able to achieve 100 Gpbs transmission speed with RGB mixed LDs and QAM-OFDM (Tsonev 2015).
All this achievement has shown the future potential of the technology. It is estimated that the LiFi market for the year 2024 will reach 101.30 Billion $. This new green wireless technology can be the backbone of new 5G networks, avoiding radio frequency pollution. Also LiFi can be employed in areas where the use of WiFi is prohibitive and harmful, like in Hospitals intensive care, Planes etc.

- **The architecture of a LiFi network**

  We consider LiFi as a complete optical wireless communication system that enrich VLC with the possibility of bidirectional communication. Unlike VLC, LiFi combine different parts of the spectrum (visible and non visible light) to achieve high full connectivity in both upstream and downstream. Furthermore LiFi technologies use a huge type of LEDs and LDs in different configurations to achieve parallel data transmission. One of this is the use of an array of parallel LEDs allowing multiple fluxes of data in the same time. Another method is the use of RGB color LEDs with each frequency encoding a different data channel. This configurations result on multiple streams of fast data rates. Although the theoretical basis of the technology is IEEE 802.15.7 alias VLC it adds more features and capabilities to the system. In other word LiFi works on the principles of VLC, meanwhile increasing its possibilities and application fields.

  One of the main characteristics of LiFi is its adaptability for the creation of cellular like networks.

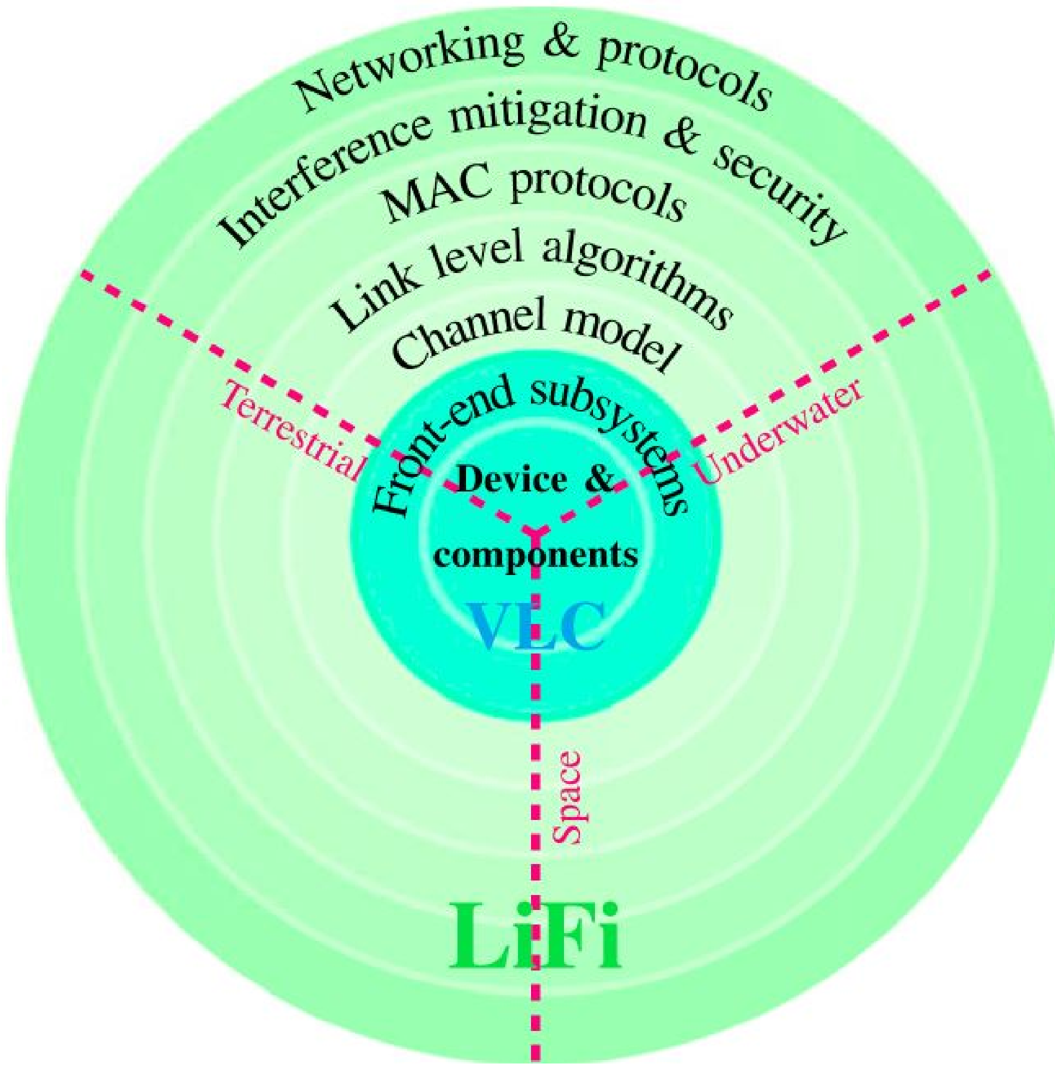


Figure 13. Light Fidelity technologies.

This type of networks are based on the concept of *attocell* (Videv 2013). In comparison with WiF's *femtocells*, attocells are smaller but in the same time provide better spectral and energy efficiency. In order to be able to construct a LiFi based network we should be able to resolve problems regarding the multiple access, bidirectional communication, full-duplex communication and interference-free channel between different users. The multiple access problem is solved by now with the use of efficient modulation and error correction schemes. Fig. 13 shows a schematic view of LiFi technology.

Full-duplex systems need to have an up-link and a down-link both realized with same technology and similar characteristics. In the previous chapters we have seen the modulation schemes used the down-link, for up-link side two main modulation schemes are used: Time Division Duplexing (TDD) and Frequency Division Duplexing (FDD). Usually FDD is the preferred option because allow the transmitter and receiver to operate in different wavelength. The third option used to implement up-links consist on the use of systems that operate in the Infrared portion of EM spectrum.
The interference problem is solved by using separate frequency for each user and the employment of RGB LEDs. In this case, the receiver utilizes color sensors in order to be able to filter the colors,

alias frequencies (users).
The cellular-like network has to implement techniques and strategies for user localization and allocation but also load balancing. The large average proximity between attocells requires new mechanisms to control the Access Point (AP) selection and load balancing process between different AP. Access Points are very important part of any network. In a LiFi network each optical transmitter can act as an Access Point and we can formalize it as an attocell in our high level view of the network. Of course the physical positioning of the attocells play a very important role in the throughput of the network. Many models have been used for this purpose. Fig. 14 shows some possible attocell models. Models 4a and 4c offer the best performance and are easy to implement and describe, but on the other side have one big drawback; they show show a poor representation of reality. Models 4b and 4d are more pragmatic models because are based on statistical distributions. Model 4b is based on Poisson process (PPP), while 4d is based on Matern process. Analysis of this models evidence the extraordinary potential of LiFi networks with respect to WiFi networks. Based on simulations attocell networks can reach transmission speed between 12 to 48 Gbps.

From the point of view of the infrastructure needed we can argue that each LiFi system need the following system components: A lamp driver, one or more LEDs or LDs for the light source and photodiodes as receiver. All this devices are easy to manufacture and to modify on purpose. Fig. 15 shows the chips used as transmitter and receiver.

- **Advantages of LiFi**

  Light Fidelity has many advantages that can be used in combination with existing technologies or as a substitution of them (Verma 2015).

  1. Light Fidelity uses light rather than radio frequency as signal carriers allowing greater available spectrum.
  2. LiFi can be used safely in contexts where radio frequency is prohibitive due to the sensibility of other instruments like in hospital intensive care compartments, airplane cabins etc.
  3. Underwater communication where WiFi is useless.
  4. Wide spread of LED bulbs that can easily transform into AP.
  5. LiFi provide better security because light cannot travel through walls and other obstacles (Blinowski 2019).
  6. LiFi can be used to empower Vehicular communication and IoT (Chowdhury 2019).
  7. LiFi provides higher transmission speeds and data density.
  8. The devices that empower LiFi are much more energy efficient than RF devices due to their double purpose.
  9. LiFi is a much more safer technology than RF, because utilize harmless portion of EM spectrum.
  10. Lif is easy to combine with with WiFi networks in order to create a hybrid network.
  11. Solar cells can be used as possible receiver in a LoS data network providing two services, solar energy harvesting and data communication. Experiments have shown that can be achieved 50 Mbps transmission rate (Lorrière 2020).
  12. Last but not least, LiFi use existing infrastructure, meaning that there is not need to develop specific hardware.

- **Applications of LiFi**

  In this section we are going to talk about the many fields LiFi can be use to improve ore even

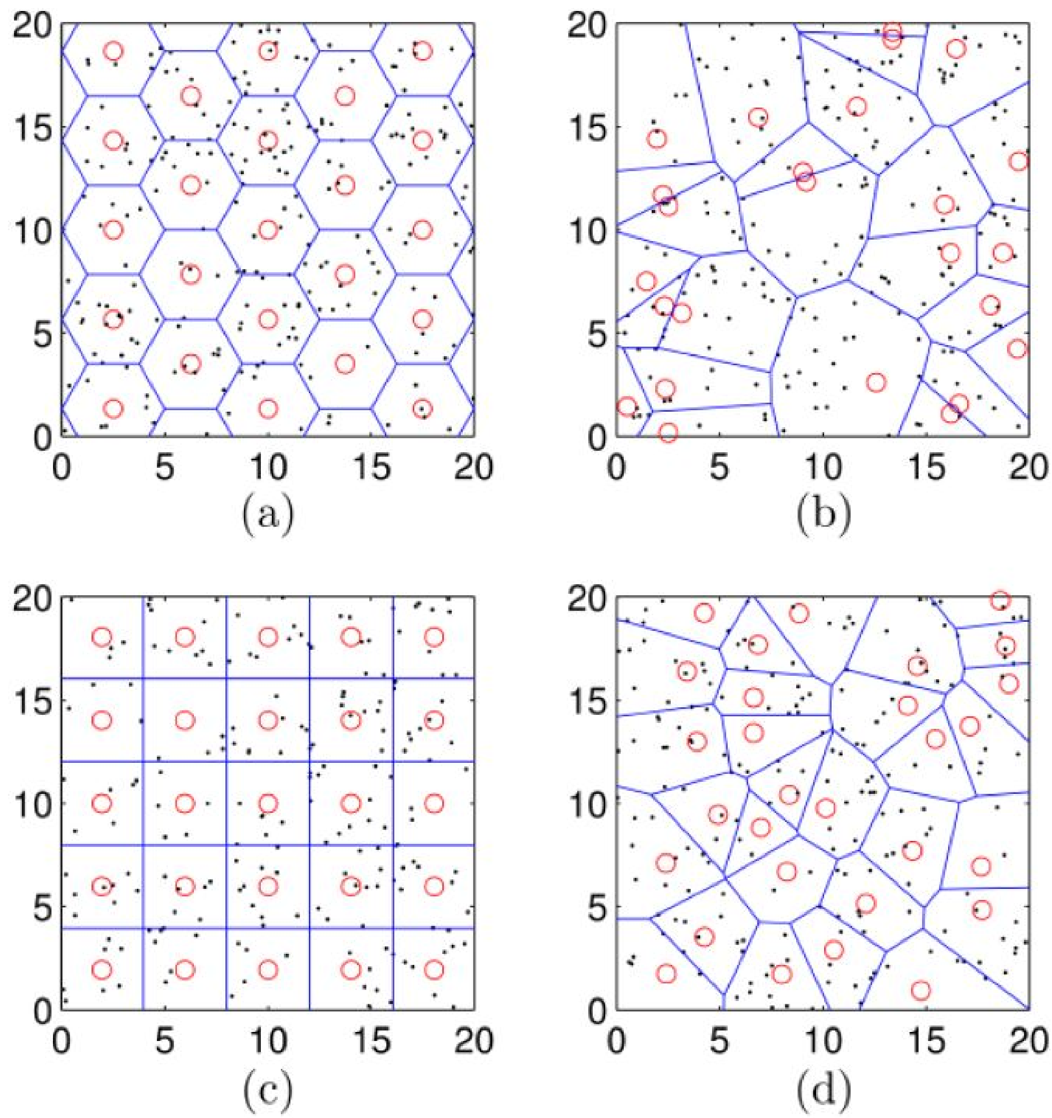


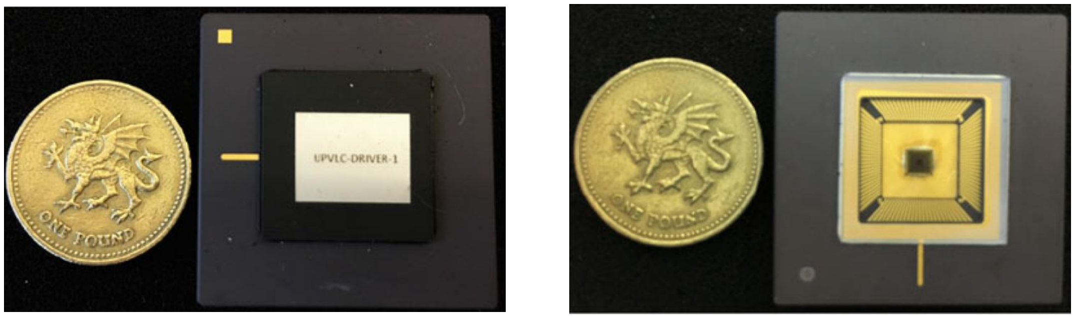
Figure 14. Attocell network models.

replace current solutions. Public illumination lamps, using LED light source can be turned into APs allowing unlimited internet access to the public. This could be an economic and safe solution that can be adopted with litter or almost no effort. Museums and event centers can also profit from this dual use of LEDs.

Another application of LiFi is in the automobile sector and especially in the Vehicular communication and self-driving cars (George 2019). In this scenario the vehicles can communicate with each other using their front and rear light in order to control driving and road parameters, keeping the driver safe and aware of the surroundings. There is a lot of research that is going on in this field, and the result are mostly encouraging.

Moreover, LiFi can be extensively used in areas where radio signals cannot be used due to their harmful effects. Examples of this areas are hospitals and airplanes.

Industrial applications and robotics is another important area where LiFi networks can be implemented. Machines and robotic arms usually produce and consume information transmitted using radio frequency. Radio signals can interference each other, adding noise or cancel the signal. This kind of situation is not accepted in a production environment. To avoid such problems light



(a) A Transmitter chip

(b) A Receiver chip

Figure 15. Components of a LiFi system

based technology such as LiFi can be deployed. Light is immune against EM radiation. Light can be used in power plants and other areas exposed to explosion or EM contamination. LiFi technology can have a big impact in the so-called Industry 4.0 and Logistics 4.0 (Mukku 2019). OWC systems can be used to implement communication between all kind of sensors in IoT devices (Demirkol 2019). ZigBee Light Link (ZLL) is one those applications.
Underwater communication between autonomous underwater vehicles is another potential application. Light is much better data carrier than radio frequency underwater.
Virtual and augmented reality is another important sector that attract more and more interest and can be implemented using wireless optical means.

Commercial products that empower LiFi are available in the market for many years now. Here are some of the companies that produce LiFi products: Firefly LiFi (www.fireflylifi.com), Oleodcomm (www.oledcomm.com), PureLiFi (www.purelifi.com), Signify (www.signify.com), Velmenni (www.velmenni.com), VLNcomm (www.vlncomm.com) etc. This companies produce both in-door and out-door LiFi devices with different characteristics and abilities. Fig. 16 shows different LiFi systems.

- **Challenges of LiFi**

  Like almost every new technology LiFi has its challenges and problems to overcome. The following are some real challenges of LiFi:

  1. *Improving receiver sensitivity*: This is considered one of the biggest problems of today receiver construction technology. Usually the photodiode sensitivity is between -40 and -45 dBm that in comparison with light beams in fibre-optic is very low. In fibre-optic the light beam is smaller and very focused, facilitating the job of the detector, on the other hand the photodetector in a VLC system are much less focused and the area of illumination is much larger. This inconvenient can be resolved by decreasing the field of view (FOV).
  2. *Unlocking the full optical available bandwidth*: This factor is related with the bandwidth of the lighting devices. The higher the bandwidth the more data can be transmitted.

In conclusion we can say that LiFi is a new and promising technology that can play a very important role in many sectors of wireless communication. It can easily adapt with existing systems or even substitute them, achieving same of better performance. Moreover LiFi can empower new communication networks such as 5G and also RF prohibitive contexts. Keeping in mind the potential bandwidth range of visible spectrum, we can argue that LiFi can be the backbone of the

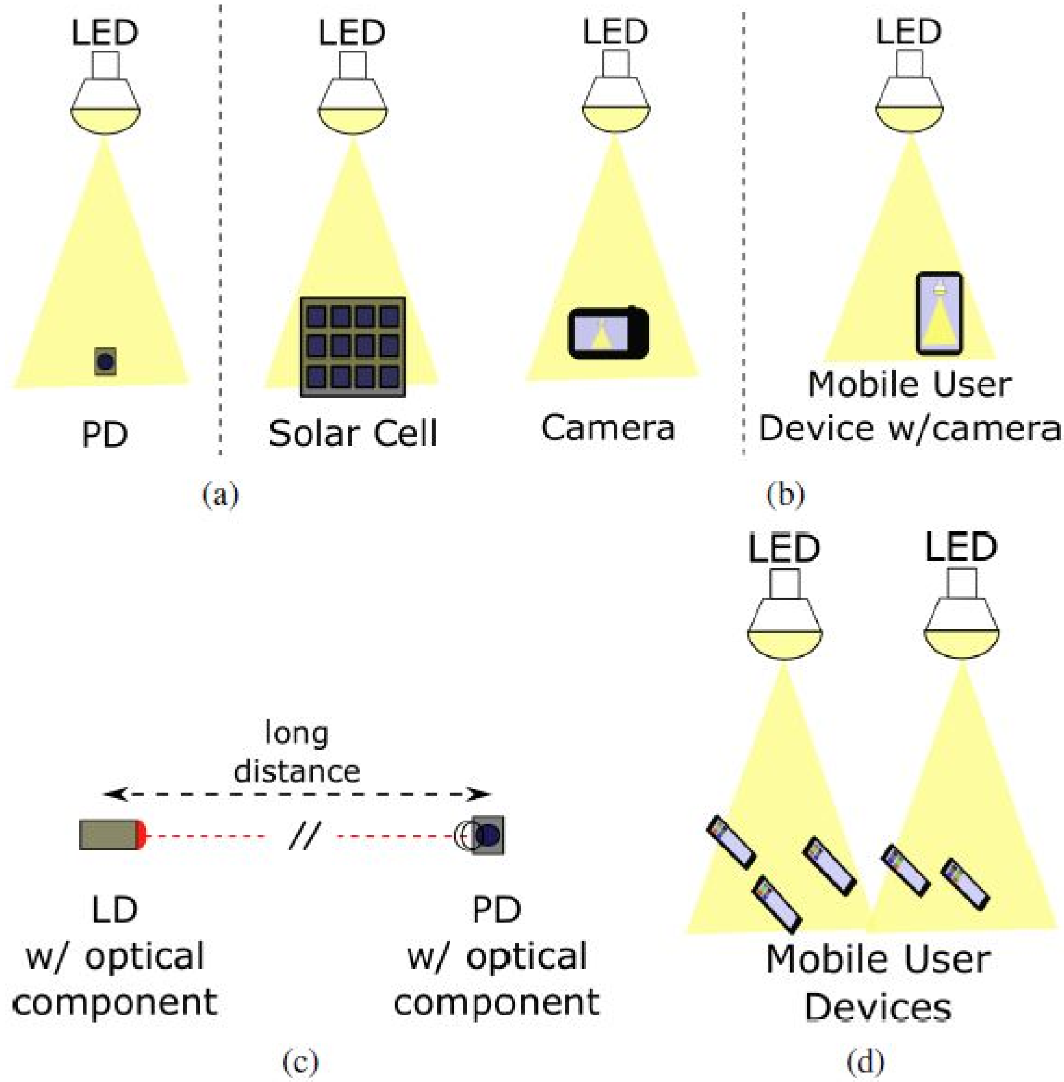


Figure 16. LiFi technologies

future revolution in wireless communications.

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