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A study of modulation methods for light fidelity (Li-Fi)

Nitesh Arya[1], Dr. Yash Pal Singh[2]
[1] Research Scholar, OPJS University, Churu, Rajasthan, India
[2] Director SITM and Professor, OPJS University, Churu, Rajasthan, India

Abstract
Modulation techniques for light fidelity (Li-Fi) are reviewed in this paper. Li-Fi is the fully networked solution for multiple users that combines communication and illumination simultaneously. Light emitting diodes (LEDs) are used in Li-Fi as visible light transmitters, therefore, only intensity modulated direct detected modulation techniques can be achieved. Single carrier modulation techniques are straightforward to be used in Li-Fi, however, computationally complex equalization processes are required in frequency selective Li-Fi channels. On the other hand, multicarrier modulation techniques offer a viable solution for Li-Fi in terms of power, spectral and computational efficiency. In particular, orthogonal frequency division multiplexing (OFDM) based modulation techniques offer a practical solution for Li-Fi, especially when direct current (DC) wander, and adaptive bit and power loading techniques are considered. Li-Fi modulation techniques need to also satisfy illumination requirements. Flickering avoidance and dimming control are considered in the variant modulation techniques presented. This paper surveys the suitable modulation techniques for Li-Fi including those which explore time, frequency and colour domains. The term Li-Fi denotes “light fidelity” and it is a form of bidirectional, networked, mobile, and high-speed wireless communications closely equivalent to Wireless Fidelity (WiFi). Unlike WiFi, the technology uses visible light spectrum instead of the increasingly congested radio frequency (RF) spectrum. Similarly to WiFi, this technology allows connection of different web-enabled devices such as computers, smart TVs, smart phones, etc. to internet; provides the inter-connection of WiFi enabled things such as refrigerators, watches, cameras, etc. in Internet of Things (IoT); and makes off-loading from cellular networks possible, addressing this way capacity needs for mobile broadband connections. In addition, Li-Fi has a huge amount of visible light spectrum that is unregulated and does not require licenses. It has to be ensured, however, that Li-Fi systems do not present any health hazards and that they are properly installed so as not to create any electromagnetic interference.

Keywords: light fidelity (Li-Fi); optical wireless communications (OWC); visible light communication (VLC); intensity modulation and direct detection (IM/DD); orthogonal frequency division multiplexing (OFDM)

Introduction
Li-Fi technology is expected to reach the market value of 8,500 Million USD by 2020 [2]. Nowadays, there are several commercial products and a few product prototypes that seem to be in their final stages before appearing on the market. The technology seems promising and even National Aeronautics and Space Administration (NASA) recently announced plans to study Li-Fi’s potential uses in space travel [3]. Li-Fi technology offers numerous benefits, however, there are still important challenges that must be overcome before it becomes a ubiquitous part of everyday wireless communications.

In this report, we give an overview of the Li-Fi technology, discuss its benefits and challenges, and summarize research and standardization activities in the field, including commercially available products.

More than half a billion new communication devices were added to the network services in 2015. Globally, mobile data traffic is predicted to reach 30.6 exabytes per month by 2020 (the equivalent of 7641 million DVDs each month), up from 3.7 exabytes per month in 2015 [1]. The radio frequency bandwidth currently used is a very limited resource. The increasing dependency on cloud services for storage and processing means that new access technologies are necessary to allow this huge increase in network utilization. The visible light spectrum on the other hand offers a 10,000 times larger unlicensed frequency bandwidth that could accommodate this expansion of network capacity. Visible light communication (VLC) is the point-to-point high speed communication and illumination system. Light fidelity (Li‑Fi) is the complete wireless, bidirectional, multiuser network solution for visible light communications that would operate seamlessly alongside other Long Term Evolution (LTE) and wireless fidelity (Wi‑Fi) access technologies [2]. Li-Fi is a green communication method as it reuses the existing lightning infrastructure for communications. Information is transmitted by the rapid subtle changes of light intensity that is unnoticeable by the human eye. Recent studies have demonstrated data rates of 14 Gbps for Li - Fi using three off the shelf laser diodes (red, green and blue) [3]. It was also predict that a data rate of 100 Gbps is achievable for Li -Fi when the whole visible spectrum is utilized [3]. Li- Fi offers inherent security, and also it can be employed in areas where sensitive electronic devices are present, such as in hospitals. In addition, Li -Fi is a potential candidate for other applications such as underwater communications, intelligent transportation systems, indoor positioning, and the Internet of Things (IoT) [2].

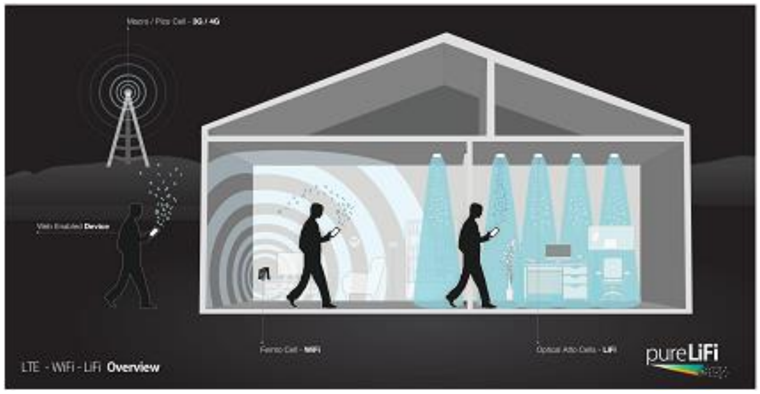

Fig 1: Li-Fi works in complement with existing and emerging wireless systems

Review of literature

Modulation techniques developed for intensity modulation and direct detection (IM/DD) optical wireless communication (OWC) systems are suitable for Li‑Fi communications systems. However, these modulation techniques may not be suitable for all lightning regimes. Li‑Fi transceivers are illumination devices enabled for data communications. Therefore adapting IM/ DD modulation technique should first satisfy certain illumination requirements before being Li-Fi enabled. For example, modulation techniques should support dimmable illumination so that communication would be still available when the illumination is not required. Li‑Fi uses off-the-shelf light emitting diodes (LEDs) and photodiodes (PDs) as channel front-end devices. This restricts signals propagating throughout the channel to strictly positive signals. Single carrier modulation (SCM) techniques are straight forward to implement in Li-Fi. Modulation techniques, such as on off keying (OOK), pulse position modulation (PPM), and *M* ‑ repulse ‑ amplitude modulation (*M* ‑ PAM), can be easily implemented. However, due to the dispersive nature of optical wireless channels, such schemes require complex equalizers at the receiver.

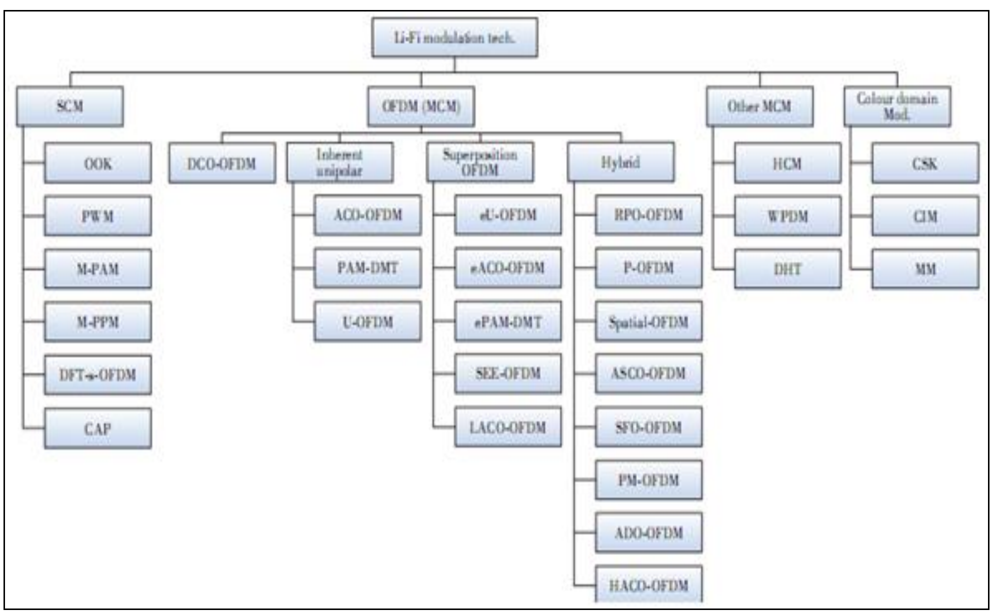

Fig 2: Li-Fi modulation techniques

Therefore, the performance of these schemes degrades as their spectral efficiency (SE) increases. On the other hand, multiple carrier modulation (MCM) techniques, such as the orthogonal frequency division multiplexing (OFDM), have been shown to be potential candidates for optical wireless channels since they only require single tap equalizer at the receiver. Adaptive bit and power loading can maximize the achievable data rates of OFDM‑ based Li-Fi systems by adapting the system loading to the channel frequency response. Moreover, the DC wander and low frequency interference can be easily avoided in OFDM by optimizing the adaptive bit/power loading to avoid the low frequency subcarriers. Colour modulation techniques are unique to Li-Fi communication systems as the information is modulated on the instantaneous colour changes. The colour dimension adds a new degree of freedom to Li‑Fi. The various modulation Li‑Fi modulation techniques discussed in this paper are shown in Fig. 2.

Li-Fi Technology

A typical indoor Li-Fi system link is illustrated in Fig. 3 [4]. It consists of a light source, line-of-sight (LOS) propagation medium, and a light detector. Information (streaming content), in the form of digital or analog signals, is input to electronic circuitry that modulates the light source. The source output passes through an optical system (to control the emitted radiation, e.g., to ensure that the transmitter is eye safe) into the free space. The received signal comes through an optical system (e.g., an optical filter that rejects optical noise, a lens system or concentrator that focuses light on the detector), passes through the photo diode (PD), and the resulting photo-current is ampLi-Fied before the signal processing electronics transforms it back to the received data stream.

For most indoor applications, light emitting diodes (LEDs) are the favored light sources due to the relaxed safety regulations, low cost, and energy efficiency. They are replacing incandescent bulbs as the primary source of illumination in residential and public environments and by as early as 2018, the majority of new energy-efficient lighting installations are expected to be LED-based. For higher speeds or longer distances, laser diodes appear to be a better choice.

The brightness of LEDs can be modulated at a high rate, which enables the combination of both illumination and wireless communication. LEDs emit incoherent light that has different wavelengths and phase (unlike the coherent light of laser diodes), hence, simple and low-cost Intensity Modulation (IM) is performed, where the transmitted signal is modulated into the instantaneous optical power of the LED. Since IM changes instantaneous power of the LED, Direct Detection (DD) is the only feasible demodulation method that converts the incident optical signal power into a proportional current. The setup is far simpler and less expensive than coherent detection chains used in RF, where a local oscillator is used to extract the base-band signal from the carrier. Modulation frequencies are kept high enough to avoid flicker in the emitted light, so that the modulation is imperceptible by human eye.

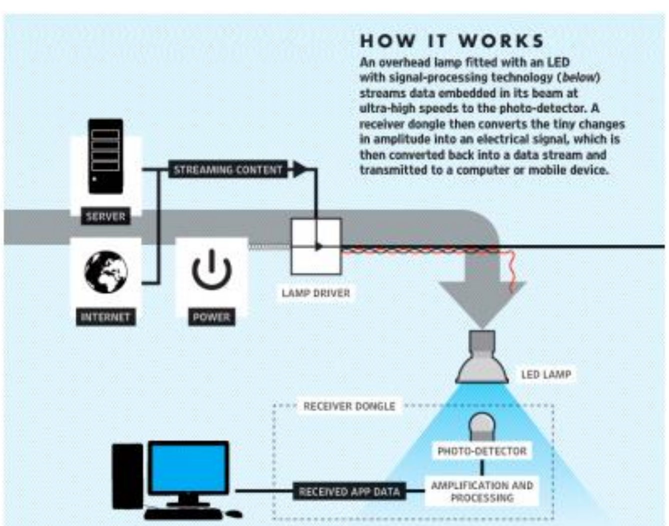

Fig 3: General Li-Fi link

There are generally two types of photo detectors that can be used in Li-Fi systems: PIN photo diodes and Avalanche photo diodes (APDs). Although the APD have a higher gain, the PIN PDs have been predominantly used due to high temperature tolerance, lower cost, performing better in scenarios where the receiver gets flooded with relatively high intensity light.

In order to provide internet access, an uplink from the device to the network needs also to be ensured in addition to the downlink, which will allow the device to request, modify, and upload information. An example of bidirectional (duplex) Li-Fi communication system is shown in Fig. 4. LED-PD pairs need to be placed on both ends of the wireless communication link to provide this functionality.

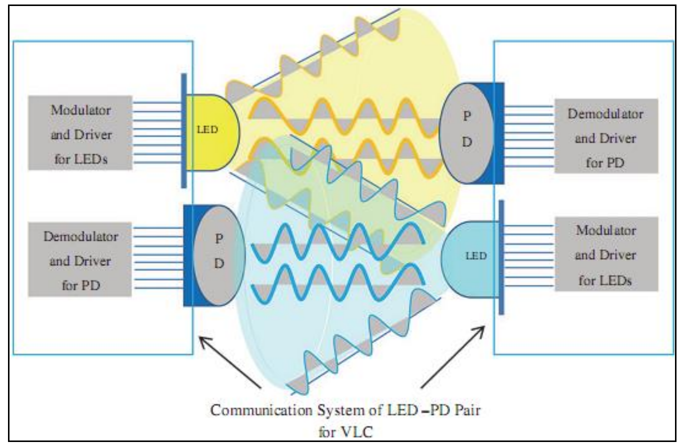

Fig 4: Basic concept of Li-Fi duplex communication

Due to the inherent directionality of light (as opposed to RF signals), any space that is to be illuminated needs several light fixtures to sufficiently cover the area. Since in a Li-Fi network, every light source is a wireless access point, it is essential for network operation that the communication link remains unbroken while a user is moving. Additionally, if a given area hosting several users/devices is illuminated by a single luminaire, Li-Fi will necessitate sharing of time and frequency resources by providing *multiple accesses*.

Benefits and Advantages of Li-Fi vs. RF Communications

Recently, communication by visible light has been gaining popularity as a complement to RF communications due to the following advantageous features (Table 1):

RF congestion and capacity crunch

The RF spectrum is a natural resource of the state and its usage is regulated to mitigate interference and pollution and to ensure its efficient usage. According to Cisco predictions, overall mobile data traffic is expected to grow to 49 Exabyte's per month by 2021, which amounts to a sevenfold increase over 2016 (Fig. 5). According to the same report, mobile off-load will increase from 60 percent (10.7 exabytes/month) in 2016 to 63 percent (83.6 exabytes/month) by 2021. The demand for broadband wireless data access is constantly increasing and the radio frequency spectrum, that is limited and for the most part licensed, is becoming progressively more congested.

On the other hand, the visible light spectrum is unlicensed and currently largely unused for communications. Moreover, potential bandwidth of visible light (~ 400 THz to ~ 780 THz) is thousand times wider than the conventional RF bandwidth

(~ 3 kHz to ~ 300 GHz). As a result, Li-Fi system have huge amount of available unregulated spectrum to complement short-range wireless transmission and to potentially alleviate the RF spectrum congestion that is especially apparent in the 2.4-GHz Industrial, Scientific, and Medical (ISM) band. With 12 billion light bulbs around the world with unlicensed, reusable bandwidth, there can be potentially as many Li-Fi transmitters and access points.

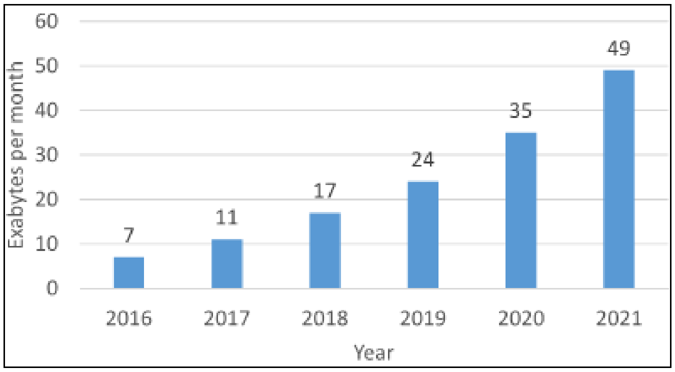

Fig 5: Cisco forecasts 49 exabytes per month of mobile data traffic by 2021

Spatial Reuse
Since visible light does not penetrate through building walls or other opaque materials and can be directed to the desired working area, Li-Fi can exhibit a high degree of spatial reuse. Li-Fi signals in adjacent areas, rooms, or apartment units would not interfere with each other, thereby potentially admitting a far higher spatial density of communication rates than it is achievable with RF.

Security
RF waves pass through walls and are susceptible to eavesdropping. An intruder or hacker outside a building can tap into the WiFi data communications of computers inside the building. With the confinement property of visible light, on the other hand, there are well defined coverage zones that enhance communication security by preventing eavesdropping from outside of a room, apartment, or building. Although, some recent research has shown the feasibility of eavesdropping using the light signals leaked through the gap between floor and door, keyhole and even partially covered windows.

Electromagnetic Interference (EMI)
Radio waves create EMI that can impair normal operation of electrical instruments and equipment in airplanes and hospitals, and is especially dangerous in hazardous industrial zones, such as power/nuclear generation or oil and gas drilling. Li-Fi uses light instead of radio waves, which is intrinsically safe and does not create EMI. It is important to note, however, that recent measurements by European Broadcasting Union (EBU) have shown EMI coming from incorrectly installed LED lamps. Original transformers will no more comply with electromagnetic compatibility limits if full-load halogen lamps are simply replaced by low-load LED lamps as harmonics of the switching frequency of the transformer under low-load conditions can occur across the entire RF spectrum. Therefore, frequency limits of the lighting emissions standard CISPR 15 may need to be extended to beyond the present 300 MHz.

Safety
In illumination conditions, in principle, there are no health hazards of visible light. Studies have shown some health concerns relating to flicker that may induce biological human response (photosensitive epilepsy). Moreover, glare of certain blue-rich LED designs is thought to have psychological effects such as disrupting people's sleep patterns and harming nocturnal animals.

Multipath
At frequencies of the visible light, constructive and destructive interference occur on a micron scale and get averaged by the receiver that is thousand times greater in size. Therefore, Li-Fi exhibits no fading caused by multipath propagation or Doppler shift.

Complexity
Due to the fact that Li-Fi is a non-coherent mode of communication, the front-end components of both transmitters and receivers are relatively simple and cheap devices that operate in the baseband and do not require frequency mixers or sophisticated algorithms for the correction of RF impairments such as phase noise and IQ imbalance.

Existing Infrastructure
Li-Fi can be implemented into existing lighting infrastructure with the addition of a few relatively simple and low-cost front-end components operating in baseband.

Energy Efficiency
Li-Fi is combined with LED illumination. Since LEDs are energy efficient and highly controllable light sources, Li-Fi belongs to eco-friendly green communication technology.

Accurate indoor positioning
RF based positioning schemes cannot provide sub-meter accuracy. The Li-Fi provides a promising way to perform accurate (centimeter-level) indoor positioning of mobile devices due to the high directivity of visible light.

Table 1: Comparison of Li-Fi and RF Communication

Parameter	RF	LiFi
Spectrum	~ 300 GHz (licensed)	~ 400 THz (unlicensed)
Security	Limited	High
EMI	Yes	No
Safety	Intensity regulated	Unregulated
Coverage	Wide	Limited
Multipath	Yes	No
Complexity	High	Low
Infrastructure	Access point	Illumination
Power consumption	Medium	Low (combined with LED illumination)

Challenges and Limitations of Li-Fi
Despite having inherent advantages compared to RF communication systems, Li-Fi still faces numerous challenges and limitations that need to be addressed so that it can be

deployed in practice as a high-speed mobile networking technology. A non-exhaustive list of these shortcomings is given in what follows.

Uplink

Providing an efficient uplink scheme for Li-Fi (from photo diode to LED luminaire) has been challenging, as Li-Fi with illumination has predominantly broadcast characteristics. A visible light uplink would be inefficient for portable devices which run on low power and may also be considered inconvenient or unpleasant. To address this challenge, use of other types of communication has been proposed and investigated, where RF or infrared can be used for transmitting uplink data. Utilizing different technologies for uplink and downlink, however, gives rise to HetNets that impose additional practical challenges such as complex network management and reliable data recovery.

LED modulation bandwidth

The data rate of the Li-Fi link is limited by the modulation bandwidth of high brightness LEDs used in light fixtures and lamps. Due to the power-bandwidth trade-off of LEDs and the various parasitic impedances in the LED packaging, signals modulated at high frequencies are strongly attenuated. If the entire white spectrum is used at detection, the modulation bandwidth is limited to ~ 2.5 MHz. Blue filtering enhances the modulation bandwidth up to ~ 20 MHz. High data rates over such a limited bandwidth can only be achieved by exploiting high Signal-to-Noise Ratios (SNRs) with high-order modulation techniques; using arrays of smaller, less powerful LEDs (with lower internal parasitic impedances); or using Wavelength Division Multiplex (WDM) to transmit independent data streams on differently colored LEDs that combine to make white light. Ultimately, off-the-shelf laser diodes (LDs) may be used.

Coverage/shadowing/mobility

The transmission distance of visible light sources is limited and requires LOS for best SNR conditions to achieve high data rates. With an object or human blocking the LOS, the observed optical power degrades resulting in severe data rate reductions. User mobility thus introduces novel issues for Li-Fi as the SNR varies dramatically when the user moves within the cell. This effect may be minimized by distributing lighting sources so that high SNR is maintained throughout the cell.

Light Interference

Other artificial and natural light sources create interference and act as unmodulated sources at the receiver. This interference increases shot noise and if high enough can cause receiver saturation. Filtering can be used as a mitigation technique here to remove a significant portion of the shot noise.

Lights off mode

Li-Fi applications based on LED lighting are more attractive in environments where the lights are always switched on, for instance, in industrial settings, public transport, or medical areas. Some low data rate transmission can be achieved by making the light emitted to be low enough so that human eyes perceive it as being switched off. Integration of infrared LED chips into future LED luminaires would allow for continuous data flows when the lights are switched off.

Backhaul Integration

LEDs need to be connected to internet and their deployment is very dense. Therefore, the cost of implementing wired infrastructure (such as Ethernet, fiber, etc.) as backhaul can be very high. Given that LED fixtures and lamps are connected to the alternating current (AC) power line, a natural choice for the backhaul technology is power line communication (PLC). Even though the cost of cable deployment is alleviated in this case, the use of PLCs incurs cost overheads of using Ethernet-to-power modem and power-to Li-Fi modems. In addition, the implemented backhaul technology needs to provide high data rates especially in the cases in which multiple mobile devices are to be served by the same Li-Fi network.

Commercialization

There are certain business challenges facing widespread adoption of Li-Fi in the consumer market. For integrating downlink, for example, two different industries need to work together. One is the lighting manufacturers who need to make appropriate modifications to their lamp and fixture designs. The other are mobile device manufacturers who need to install high-speed photo-diode receivers in their devices. From the lighting manufacturers' perspective, the extremely high lifetime of LEDs may initially cause high revenue in LED sales but later on lead to 'socket saturation.' On the other hand, integrating a new hardware into the existing devices may lead to unnecessary increase in cost and change in robustness of design for mobile device manufacturers.

Conclusion

The modulation techniques suitable for Li‑Fi are presented in this paper. These techniques should satisfy illumination and communication requirements. Single carrier modulation techniques offer a simple solution for frequency ‑ flat Li-Fi channels. Low ‑ to ‑ medium data rates can be achieved using single carrier modulation techniques. Multicarrier modulation techniques offer high data rates solution that can adapt the system performance to the channel frequency response. Many variants of optical OFDM modulation techniques have been proposed in published research to satisfy certain illumination and/or communication requirements. The colour dimension offers unique modulation formats for Li-Fi and adds to the degrees of freedom of Li - Fi systems. Time, frequency, space, colour dimensions, and the combinations of them can be used for Li-Fi modulation. Li-Fi modulation techniques should offer a high speed communication and be suitable for most illumination regimes.

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