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LiFi is a paradigm-shifting 5G technology

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ABSTRACT

In this paper we will first explain what Light-Fidelity (LiFi) is and argue that it is a 5th Generation (5G) technology. Peak transmission speeds of 8 Gbps from a single light source have been demonstrated, and complete cellular networks based on LiFi have been created. We will discuss numerous misconceptions and illustrate the potential impact this technology can have across a number of existing and emerging industries. We also discuss new applications which LiFi can unlock in the future.

Introduction

LiFi is a wireless communication technology that uses the infrared and visible light spectrum for high speed data communication. LiFi, first coined in [1] extends the concept of visible light communication (VLC) to achieve high speed, secure, bi-directional and fully networked wireless communications [2]. It is important to note that LiFi supports user mobility and multiuser access. The size of the infrared and visible light spectrum together is approximately 2600 times the size of the entire radio frequency spectrum of 300 GHz (see Fig. 1). It is shown in [3] that the compound annual growth rate (CAGR) of wireless traffic has been 60% during the last 10 years. If this growth is sustained for the next 20 years, which is a reasonable assumption due to the advent of Internet-of-Things (IoT) and machine type communication (MTC), this would mean a demand of 12,000 times the current bandwidth assuming the same spectrum efficiency. As an example, the industrial, scientific and medical (ISM) RF band in the 5.4 GHz region is about 500 MHz, and this is primarily used by wireless fidelity (WiFi). This bandwidth is already becoming saturated, which is one reason for the introduction of Wireless Gigabit Alliance (WiGig). WiGig uses the unlicensed spectrum between 57 GHz–66 GHz, i.e., a maximum bandwidth of 9 GHz. In 20 years from now, the bandwidth demand for future wireless systems would however, be 12,000 × 500 MHz which results in a demand for 6 THz of bandwidth. The entire RF spectrum is only 0.3 THz. This means a 20 times shortfall compared to the entire RF spectrum, and a 667 times shortfall compared to the currently allocated bandwidth for WiGig. In comparison, the 6 THz of bandwidth is only 0.8% of the entire IR and visible light spectrum. One could argue that a more aggressive spatial reuse of frequency resources could be adopted to overcome this looming spectrum crunch. This approach has been used very successfully in the past and has led to the ‘small cell concept’. In fact, it has been the major contributor towards the improvements of data rates as illustrated in Fig. 2. The cell sizes in cellular communication have dramatically shrunk. The cell radius in early 2 G systems was 35 km, in 3G systems 5 km, in 4G systems 100 m, and in 5G probably about 25 m in order to reuse the available RF spectrum more efficiently and to achieve higher data densities. However, further reductions in cell sizes are more difficult to achieve due to the high infrastructure cost for the backhaul and fronthaul data links which connect these distributed access points to the core network. Moreover, with a smaller cell size the likelihood of line-of-sight between an interfering base station and a user terminal increases. The resulting interference can significantly diminish data rates and may cause a major problem in cellular networks [4]. Therefore, WiFi access points have been mounted under the seats in stadia to use the human body as an attenuator for the RF signals and to avoid line-of-sight interference links. Clearly, this is not a viable solution for office and home deployments. For these reasons, it is conceivable

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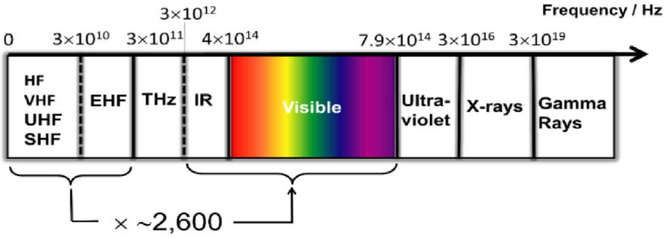


Fig. 1. The radio frequency (RF) spectrum is only a fraction of the entire electromagnetic spectrum. The visible light spectrum and the infrared (IR) spectrum are unregulated, and offer 780 THz of bandwidth.

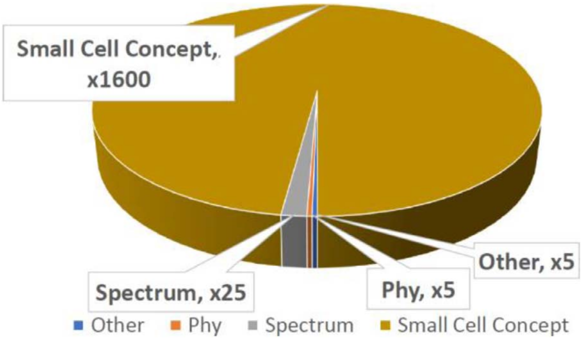


Fig. 2. The main contributors that led to the factor 1,000,000 improvement of data rates in cellular communications during the last decades. The key factor has been the small cell concept, followed by the allocation of new spectrum. Interestingly, new physical layer technologies have only contributed by an overall factor of 5.

that the contributions for the future mobile data traffic growth will stem from more spectrum rather than spatial reuse. In particular, the optical resources are very attractive as they are plentiful as shown in Fig. 1 and they are license-free.

These resources can be used for data communication which is successfully demonstrated for decades in fibre-optic communication using light amplification by stimulated emission of radiation (lasers). With the widespread adoption of high brightness light emitting diodes (LEDs) an opportunity has arisen to use the visible light spectrum for pervasive wireless networking.

Traditionally, a VLC system has been conceived as a single point-to-point wireless communication link between a LED light source and a receiver which is equipped with a photo detection device such as a photo detector (PD). The achievable data rate depends on the digital modulation technology used as well as the lighting technology. The available lighting technologies are summarised in Fig. 3.

Most commercial LEDs are composed of a blue high brightness LED with a phosphorous coating that converts blue light into yellow. When blue light and yellow light are combined, this turns into white light. This is the most cost-efficient way to produce white light today, but the phosphor color converting material slows down the frequency response, i.e., higher frequencies are heavily attenuated. Consequently, the bandwidth of this type of LED is merely in the region of 2 MHz. With a blue filter at the receiver to

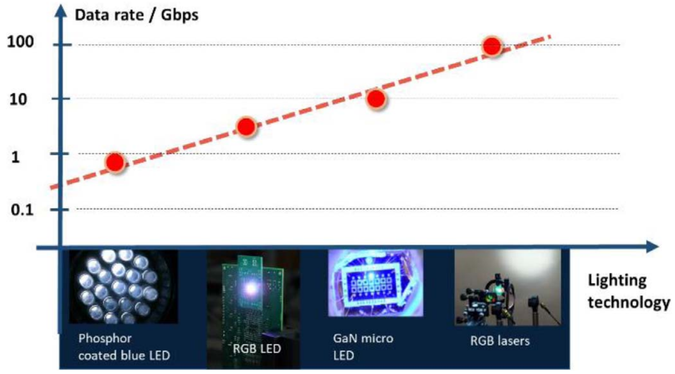


Fig. 3. The maximum achievable data rates in LiFi depend on the technology of the actual light sources. Here we consider single blue chip technology with phosphorous coating; red, green and blue (RGB) LEDs; Gallium Nitride (GaN) micro LEDs and laser-based lighting. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

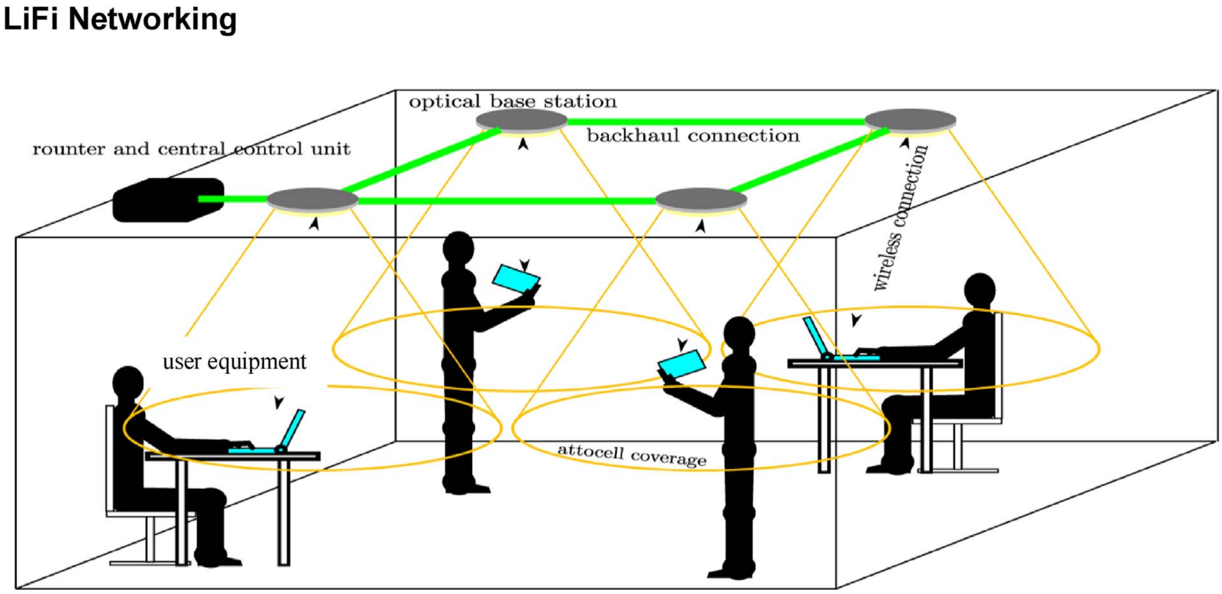


Fig. 4. The concept of LiFi attocell networks applied to indoor wireless networking.

remove the slow yellow components it, however, is possible to achieve data rates in the region of 1 Gbps with these devices. More advanced red, green and blue (RGB) LEDs enable data rates up to 5 Gbps as white light is produced by mixing the base colors instead of using a color converting chemical. Record transmission speeds with a single micro LED of 8 Gbps have been demonstrated [5], and it was shown that 100 Gbps are feasible with laser-based lighting [6].

The key advantages of a LiFi wireless networking layer are: (i) three orders of magnitude enhanced data densities [7]; (ii) unique properties to enhance physical layer security [8]; (iii) use in intrinsically safe environments such as petrochemical plants and oil platforms where RF is often banned; iv) with the advent of power-over-ethernet (PoE) and its use in lighting, there exists the opportunity to piggy-back on existing data network infrastructures for the required backhaul connections between the light sources with its integrated LiFi modem and the Internet.

LiFi networking

Fig. 4 illustrates the concept of a LiFi attocell network. The room is lit by several light fixtures, which provide illumination. Each light is driven by a LiFi modem or a LiFi chip and, therefore, also serves as an optical base station or access point (AP). The optical base stations are connected to the core network by high speed backhaul connections. The light fixtures also have an integrated infrared detector to receive signals from the terminals. The illuminating lights are modulated at high rates. The resulting high frequency flickers which are much higher than the refresh rate of a computer monitor are not visible to the occupants of the room. Power and data can be provided to each light fixture using a number of different techniques, including PoE and power-line communication (PLC) [9,10]. An optical uplink is implemented by using a transmitter on the user equipment (UE), often using an IR source (so it is invisible to the user). Each of these light fixtures, which at the same time act as wireless LiFi APs, create an extremely small cell, an optical attocell [11]. Because light is spatially confined, it is possible in LiFi to take the 'small cell concept' to a new level by creating ultra-small cells with radii less than 5 m while exploiting the huge additional unlicensed spectrum in the optical domain. The balance of light fixtures that contain APs and those that provide only illumination is determined by the requirement of the network, but potentially all light fixtures can contain APs. Compared to a single AP wireless hot-spot system, such cellular systems can cover a much larger area and allow multiple UEs to be connected simultaneously [12]. In cellular networks, dense spatial reuse of the wireless transmission resources is used to achieve very high data density - bits per second per square meter (bps/m^2). Consequently, the links using the same channel in adjacent cells interfere with each other, which is known as co-channel interference (CCI) [13]. Fig. 5 illustrates CCI in an optical attocell network.

The move from point to point links to full wireless networks based on light poses several challenges. Within each cell, there can be several users and therefore multiple access schemes are required. The provision of an uplink can also require a different approach from the downlink. This is because low energy consumption is required in the portable device, and an uplink visible light source on the device is likely to be distracting to the user. Therefore, the use of the infrared spectrum seems most appropriate for the uplink. In addition, modulation techniques for a high-speed uplink have to be spectrum efficient and power efficient at the same time. Two recently developed modulation techniques that achieve this are enhanced unipolar OFDM (eU OFDM) [14], or spectral and energy efficient (SEE OFDM) [15]. Advanced CCI mitigation techniques [16] often require that these multiple LiFi APs are operated by means of a centralized control mechanism such as 'resource schedulers' within the controller of a software defined network (SDN)

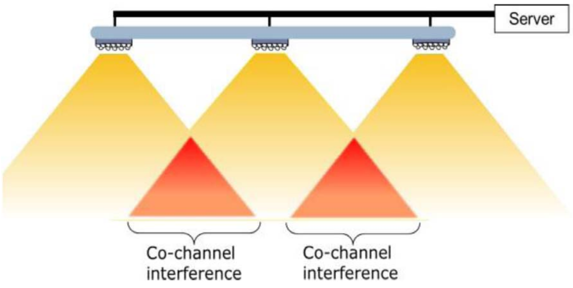


Fig. 5. CCI occurs in the region where the same light spectrum of neighboring APs overlaps, and when these APs use the same modulation bandwidth for data encoding.

[17]. The main tasks of the 'resource scheduler' are to adaptively allocate signal power, frequency, time and wavelength resources. Typically, there are trade-offs between signaling overhead, computational complexity, user data rates, aggregate data rates and user fairness, and the optimum selection of respective CCI mitigation and resource scheduling techniques depend on actual use cases and system constraints [18,19]. Other functions of the central controller include achieving multi-user access, and the process of handover from cell to cell when terminals move. Handover plays an important role in LiFi networks. For example, the handover controller has to ensure that connectivity is maintained when users leave a room, or the premises. Therefore, there might be situations when there is no LiFi coverage. In these scenarios to avoid loss of connectivity we utilize the fact that LiFi is complementary to RF networks. To this end, there have been studies on hybrid LiFi/RF networks, and the three key findings are: (i) LiFi networks will significantly improve services quality to mobile users, (ii) service delivery can be uninterrupted, and (iii) WiFi networks significantly benefit from LiFi networks. The latter is because well-designed load balancing will ensure that WiFi networks suffer less from inefficient traffic overheads caused by constant re-transmissions which happen when two or multiple terminals are in contention [20].

LiFi attocell networks have many advantages over incumbent technologies. Firstly, unlike omnidirectional RF antennas radiating signals in all directions, a LED light source typically radiates optical power directionally because of the way it is constructed. Therefore, the radiation of the visible light signals is naturally confined within a limited region. In contrast, RF mm-wave systems require complicated and expensive antenna beamforming techniques to achieve the same objective. Secondly, LiFi attocell networks can be implemented by modifying existing lighting systems. Any LiFi attocell network can provide extra wireless capacity without interference to RF networks that may already exist. LiFi attocell networks, therefore, have the potential to augment 5G cellular systems in a cost-effective manner [21].

A unique feature of LiFi is that it combines illumination and data communication by using the same device to transmit data and to provide lighting. Fig. 6(a) depicts a simple room scenario with two lights. Fig. 6(b) shows the resulting illuminance at desk level of 0.75 m. In the particular example, the lights are placed such that within the plane at desk height, 90% of the area achieves an illuminance of 400 lx based on a given illumination requirement. Fig. 6(c) depicts the resulting signal-to-interference-plus-noise ratio (SINR). The region where the light cones overlap is subject to strong CCI, and the SINR drops significantly. It is interesting to note that the SINR can vary by about 30 dB within a few centimeters. This example also highlights that the peak SINR can be in region of 50 dB which is two to three orders of magnitude higher than the peak SINR in RF based wireless systems. The achievable data rate strongly depends on the location of the receiver and also on the field of view (FoV) of the receiver [22].

Interference mitigation techniques are required to ensure that within the region of strong CCI, a mobile station can also achieve high SINR, and this is a non-trivial problem which involves signal processing such as successive interference cancellation [23].

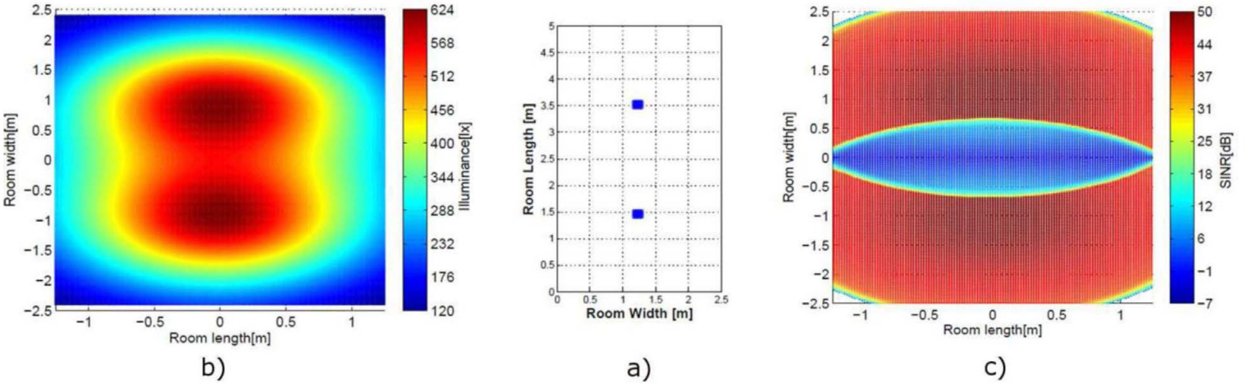


Fig. 6. A room of size 2.5 m × 5 m is equipped with two LiFi luminaires installed at 3 m height pointing vertically downwards. The LiFi luminaires are illustrated by two blue squares in subplot (a). Both luminaires use the same visible light spectrum to transmit independent information. Vertically upwards pointing receivers at 0.75 m desk height are assumed. The illuminance at desk height is illustrated in subplot (b). The resulting SINR assuming a receiver FoV of 45° is depicted in subplot (c). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Fig. 7. This illustration shows the operation of a LiFi link under strict non-line-of-sight (LoS) conditions (courtesy pureLiFi).

LiFi misconceptions

There are many misconceptions in relation to LiFi:

LiFi is a LoS technology: This perhaps is the greatest misconception. By using an orthogonal frequency division multiplexing (OFDM)-type intensity modulation (IM)/direct detection (DD) modulation scheme [24], the data rate scales with the achieved signal-to-noise-ratio (SNR). In a typical office room environment where the minimum level of illumination for reading purposes is 500 lx, the SNR at table height is between 40 dB and 60 dB [25]. This means higher order digital modulation schemes can be used in conjunction with OFDM to harness the available channel capacity. By using adaptive modulation and coding (AMC) it is possible to transmit data at SNRs as low as −6 dB. Fig. 7 illustrates a video transmission to the laptop in the front over a distance of about 3 m where the LED light fixture is pointing against a white wall in the opposite direction to the location of the receiver. Therefore, there is no direct LoS component reaching the receiver at the front, but the video is successfully received. Obviously, if the wall would be dark, more light would be absorbed which would compromise the SNR at the receiver. If the SNR drops below the −6 dB threshold, an error-free communication link would not be possible. However, in low-light conditions single photon avalanche diodes may be used at the receiver which enhance the receiver sensitivity by at least an order of magnitude [26].

LiFi does not work in sunlight conditions: Sunlight constitutes a constant interfering signal outside the bandwidth used for data modulation. LiFi operates at frequencies typically greater than 1 MHz. Therefore, constant sunlight can be removed using electrical filters. An additional effect of sunlight is enhanced shot noise, which cannot easily be eliminated by optical filters. In a study [27] the impact of shot noise was investigated qualitatively, and it was found that data rate is compromised by 1.5% and 4.5% assuming a 0.19 mm^2 detector, and 2 mm^2 detector respectively. Saturation can be avoided by using automatic gain control algorithms in combination with optical filters. In fact, we argue that sunlight is hugely beneficial as it enables solar cell based LiFi receivers where the solar cell acts as data receiver device, and at the same time harvests sunlight as energy [28].

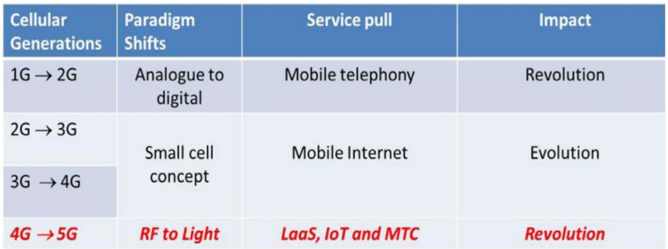
Lights cannot be dimmed: There are advanced modulation techniques such as eU-OFDM [14] which enable the operation of LiFi close to the turn-on voltage (ToV) of the LED which means that the lights can be operated at very low light output levels while maintaining high data rates.

The lights flicker: The lowest frequency at which the lights are modulated is in the region of 1 MHz. The refresh rate of a computer screen is about 100 Hz. This means the flicker-rate of a LiFi light bulb is 10,000 higher than that of a computer screen. Therefore, there is no perceived flicker.

This is for downlink only: A key advantage is that LiFi can be combined with LED illumination. This, however, does not mean that both functions always have to be used together. Both functions can easily be separated (see the comment on dimming). As a result, LiFi can also be very effectively used for uplink communication where lighting is not required. The infrared spectrum, therefore, lends itself perfectly for the uplink. We have conducted an experiment where we sent data at a speed of 1.1 Gbps over a distance of 10 m with an LED of only 4.5 mW optical output power.

Market disruption potential

LiFi is a disruptive technology that is poised to impact many industries. LiFi is a fundamental 5G technology. It can unlock the IoT, drive Industry 4.0 applications, light-as-a-service (LaaS) in the lighting industry, enable new intelligent transport systems, enhance road safety when there are more and more driverless cars, create new cybersecure wireless networks, enable new ways of health monitoring of aging societies, offer new solutions to close the digital divide, and enable very high-speed wireless connectivity in future datacenters. LiFi will have a catalytic effect for the merger of two major industries: i) the wireless communications industry and ii) the lighting industry. In 25 years from now, we argue that the LED lightbulb will serve thousands of applications and will be an integral part of the emerging smart cities, smart homes and the IoT. LaaS will be a dominating theme in the lighting industry, which will drive the required new business models when LED lamps last 20 years or more. LaaS in combination with LiFi will, therefore, provide a business model driven ‘pull’ for the lighting industry to enter what has traditionally been a wireless communications market. In the wireless industry, LiFi has the potential to create a paradigm shift by moving from cm-wave communication to nm-wave communication – see Fig. 8. It is, therefore, conceivable that the wireless industry and the lighting industry will merge into one.



Cellular Generations	Paradigm Shifts	Service pull	Impact
1G → 2G	Analogue to digital	Mobile telephony	Revolution
2G → 3G	Small cell concept	Mobile Internet	Evolution
3G → 4G			
4G → 5G	*RF to Light*	*LaaS, IoT and MTC*	*Revolution*

Fig. 8. The transition from cm-wave to mm-wave is already happening in 5G. LiFi will take this paradigm shift to a radically new level.

An important prerequisite for the large-scale adoption of LiFi technology is the availability of standards. In this context, efforts have started in IEEE 802.15.7, IEEE 802.11 as well as ITU-R to standardize LiFi technology.

Conclusion

In this paper we have shown that there has been a clear trend in wireless communications to use ever higher frequencies. This is a consequence of the limited availability of RF spectrum in the lower frequency bands of an exponential growth in wireless data traffic that we have been witnessing at the same time during the last decade. This growth will continue. It is, therefore, inevitable that other spectrum than the RF spectrum must be used for future wireless communication systems. We, therefore, forecast a paradigm shift in wireless communications when moving from mm-wave communication to nm-wave communication which consequently involves light – i.e., LiFi. There has been significant research in physical layer technologies for LiFi during the past 15 years and data rates have increased from a few Mbps in around 2002 to 8 Gbps from a single LED in 2016. In the last five years there has been increasing research in LiFi networking techniques such as multiuser access, interference mitigation and mobility support, and in parallel LiFi products have entered the market which have enabled wireless networking with light. Therefore, LiFi has become a reality and this technology is here to stay for a long time.

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