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LiFi Opportunities and Challenges

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***Abstract*—This paper motivates the need for a new spectrum for current and future wireless networks. Furthermore, it argues that wireless networks based on light waves are at a very mature state. To this end, we introduce a taxonomy that defines the four major developments in this field: i) visible light communications (VLC), ii) optical camera communication (OCC), iii) free-space optical (FSO) communications, and iv) light-fidelity (LiFi) and discuss these technologies in the context of industrial private networks. Finally, key existing challenges are discussed in detail, and an outlook is provided.**

I. INTRODUCTION

The demand for wireless communications resources is growing at an unprecedented pace due to bandwidth consuming applications such as augmented reality (AR) and virtual reality (VR), xK-television (TV) where x stands for 4, 8, 16, *etc.*, mobile video streaming, mobile TV, etc. This growth is massively fuelled by new emerging trends such as machine-type communication (MTC) and the internet of things (IoT). Due to beneficial propagation conditions, mobile communications have traditionally relied on radio frequency (RF) bands below 6 GHz. However, due to increased bandwidth requirements, industry and academia have recently started to turn their attention to mm-wave and THz frequencies. A largely neglected part of the electromagnetic spectrum for wireless communications is the optical spectrum consisting of infrared (IR), visible light and ultra-violet light. These wavelengths constitute a huge amount of unregulated spectrum. In addition, a variant of optical wireless communications (OWC) systems named free-space optical (FSO) communications, can benefit from mature optical devices and components used in fiber optical communications.

Visible light communications (VLC) was introduced by Tanaka, *et al.* [1] and uses high brightness white light-emitting diodes (LEDs) for data communication. A limitation of LEDs is that the phase of the optical signal is not available for data encoding. Therefore, VLC is limited to intensity modulation (IM)/direct detection (DD). Historically, this has limited the attainable transmission speeds. However, high speed data transmission with LEDs at low computational complexity was enabled by modifying multilevel and multicarrier modulation techniques. To this end, basic orthogonal frequency division multiplexing (OFDM), as is used in RF communications, was modified to deal with strictly positive and real-valued signals imposed by IM/DD. The feasibility of modified OFDM for use in VLC was first practically demonstrated in [2]. This has led to a demonstration at TED Global 2011 [3] where the concept of 'light-fidelity (LiFi)' was first introduced.

LiFi is conceived as a secure, high-speed, bi-directional multiuser wireless networking technology which supports user mobility. Thus, it extends the concept of VLC. LiFi typically requires multiple access points (APs) forming dense optical attocellular networks [4]. The cell sizes can be ultra-small with radii in the metre region, since co-channel interference can be much better controlled than in RF communication systems. Therefore, LiFi not only benefits from a vast amount of free spectrum, but it also enables us to take the small-cell concept to new levels which are not easily possible in RF, leading to three orders of magnitude improvement in area spectrum efficiencies reaching tens of Gbps/m^2. The system supports random user locations within the LiFi coverage of a luminaire, which can be located indoors or outdoors. In addition, random orientations of the mobile device are supported and strict line of sight (LoS) is not required.

This paper is structured as follows: Section II provides a few rationales for the need for a new spectrum to make wireless communications future-proof. The existing OWC technologies are described in detail in Section III. The major challenges to unlock the full potential of the optical spectrum are presented in Section IV. Section V summarizes standardization activities on light-based communication systems. Section VI provides an outlook and concludes the paper.

II. WHY DO WE NEED NEW SPECTRUM?

Undeniably, there are multiple solutions that can provide an increase in the available spectrum and increased confinement of the RF signal. As an example, WiGig solutions, defined in IEEE 802.11ad and being revised in 802.11ay, that operate in the 60 GHz spectrum have access to around 14 GHz of bandwidth in the USA. However, WiGig and other mm-wave RF solutions (including the newest version of WiFi, 802.11ax) all exhibit similar challenges. Specifically, the path loss is proportional to the square of the carrier frequency. This means that moving wireless systems for the now 5 GHz region to the 60 GHz mm-wave region, will incur an additional path loss of 144, or 21.6 dB. This either means that (i) the transmit power has to be increased by a factor of 144, (ii) the cell size has to be decreased considerably, and/or (iii) the transmissions must be more focussed by means of antenna beamforming.

First, information and communications technology (ICT) has gone through a radical transformation driven by the 'green' agenda to reduce the carbon footprint. This transformation is still ongoing and, therefore, an increase of transmission powers of new wireless systems is not a viable solution for any fifth generation (5G), beyond 5G (B5G) or sixth generation (6G) solution. This rules out (i). Second, this means a further reduction of cells sizes is inevitable. The typical coverage of a 5G cell will be in the region of 10 m – 50 m. However, to cover realistic outdoor scenarios at manageable infrastructure cost, it is inevitable to implement (iii) beamforming. So, there will be a hybrid solution of small cells and antenna beamforming in 5G systems. The latter poses a few technical challenges: (i) beamforming requires multiple antennas and phase shifters which increase hardware complexity and cost, and (ii) while current beamforming works well in a downlink point-to-multipoint scenario, beamforming in the uplink, i.e., uncoordinated and random multipoint-to-point transmission where place and orientation of the mobile terminal can vary greatly, is still an unsolved problem. In this context, it is vital to remember that RF is only one part of the electromagnetic spectrum and that visible light and infrared have been, for the most part, underutilised. The visible light spectrum alone stretches from approximately 430 THz to 770 THz, which means that there is potentially more than 1000x the bandwidth of the entire RF spectrum of approx. 300 GHz. Moreover, both the visible light spectrum and the infrared spectrum are unlicensed.

III. Optical Wireless Communication Technologies

Although there is huge available unlicensed bandwidth in the optical spectrum, the signal transmission suffers from high path loss and this affects the link budget. In order to mitigate the high path loss and to achieve long distance communication, optical components are used both at the transmitter and at the receiver to collimate the light beam. Therefore, there are relative mature OWC systems that use laser diodes (LDs) and collimation optics to build static point-to-point links. This has led to the introduction of FSO systems, primarily for backhaul use cases. However, the landmark paper by Gfeller and Bapst [5] shows that diffused infrared light can be used to build indoor OWC networks. Kahn and Barry in their seminal work [6] laid new foundations for infrared OWC systems by providing a systematic characterisation of usage scenarios supported by detailed channel and communication system modelling work. With the advent of high brightness white LEDs, the focus went from infrared to visible light communication systems, and early works in this area [1], [7] proposed to convert LED lights into simultaneous illumination and data communication devices, but primarily for LoS scenarios. Motivated by these early works, methods were developed to substantially increase data rates from white LEDs and to enable connectivity in non-line of sight (NLoS) scenarios, which led to the introduction of LiFi [8].

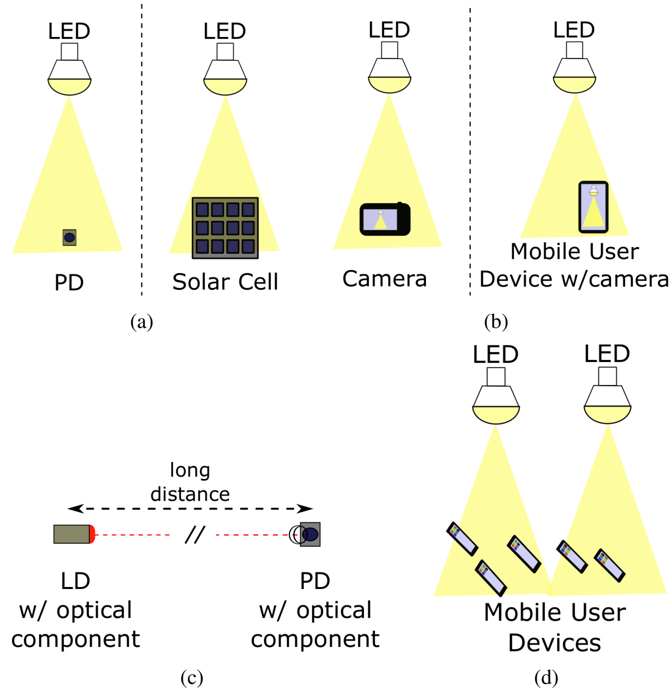


Fig. 1. Different OWC technologies. (a) VLC system with a PD (left) and a solar cell (right). (b) OCC system with a camera with a lens and image sensor (left) and a mobile user device with an embedded camera with a lens and image sensor (right). (c) FSO communication system with an LD and PD. (d) LiFi system with multiple LEDs and mobile user devices.

The different OWC technologies are optimally suited to different use cases. Like in RF communications where Bluetooth serves different use cases as, for example, Long Term Evolution (LTE), a similar taxonomy can be established for OWC. Fig. 1 summarises these four principal light communication technologies: (i) VLC, (ii) optical camera communication (OCC), (iii) LiFi, and (iv) FSO communication systems.

Light communication systems have unique features such as:

- they are not affected by interference from RF systems, and vice versa;
- they can be used in intrinsically safe environments where RF signals are not permitted;
- their spectrum is unregulated/unlicensed; and
- they exhibit better physical-layer security properties compared to RF systems.

The following subsections describe in more detail the different OWC systems and discuss use cases for industrial private networks.

A. Visible Light Communications - VLC

VLC makes use of LEDs for illumination and data transmission simultaneously. The switching rate of an LED is sufficiently fast so it cannot be detected by the human eye. VLC initially was standardized in 802.15.7 [9]. In the industrial and private networks vertical, VLC can be used for IoT and machine-to-machine (M2M) type communications. VLC based IoT and M2M can be used for communication between tools/machines/devices that are stationary in a factory and/or industrial site. VLC provides reliable communication links and reduces the air interface latency. This is termed ultra reliable low latency communication (URLLC) and is listed as one of the main objectives of 5G and B5G systems for Industry 4.0 applications.

B. Optical Camera Communications - OCC

OCC is a variant of VLC that uses an LED or display as the transmitter. However, different from VLC, OCC uses a camera image sensor as the receiver and can use infrared, visible or ultraviolet bands. Recent advancements in image sensor and camera technologies have enabled higher resolutions and frame rates. Moreover, the size of cameras have become small and are compact enough to be mounted on smartphones, where nowadays a smartphone can have several cameras both on the front and back sides. Therefore, OCC systems have become a promising optical wireless technology [10]–[12].

OCC systems are seen as a potential candidate for accurate indoor localization, vehicle-to-vehicle (V2V) and infrastructure-to-vehicle (I2V) communications [12]. For example, an autonomous vehicle that is used to deliver/carry goods such as a drone or a forklift should be informed on (i) the movement of other mobile vehicles around; (ii) the location/position of the goods; and/or (iii) the route. OCC can be used in order to provide the noted information to the vehicle and control the time-critical processes inside a factory/warehouse.

C. Free-Space Optical Communications - FSO

FSO is known as a point-to-point, long-range, high-speed, outdoor OWC system. Point-to-point optical link distances up to several kilometers can be achieved by FSO systems. Hence, FSO systems are mainly used to provide high-speed backhaul connections between the edge and core of a network [13]. In general, FSO links are widely deployed in between physical locations that are impractical/expensive for fiber-cable installations. Even for the fiber-cable practical environments such as city centers, FSO links are preferred due to the ease of mounting/demounting. Moreover, FSO systems can be used to provide ultra high-speed backhaul connections within a data center. Another reason to prefer FSO system deployment is security. As the optical link is aligned as a narrow beam from one point to another, it is hard to intercept. Unlike indoor VLC and OCC systems, outdoor FSO systems are vulnerable to beam misalignment and atmospheric effects such as rain, fog, etc. To overcome beam misalignment and atmospheric effects, several physical layer concepts such as channel coding, transmit diversity etc. are proposed [13].

For industrial private networks, providing high-speed fiber-cable backhaul links is secure but expensive and/or impractical as most of the industrial sites are located in rural areas. Therefore, FSO is a promising solution for industrial private networks. FSO can be used to provide a high-speed (i) backhaul connection from a server that holds sensitive information about a manufacturing process/factory; and/or (ii) secure intranet link from one factory site to another. It can be said that FSO enables secure and high speed fiber-like connection wirelessly for private networks.

D. Light Fidelity - LiFi

LiFi describes a fully wireless network. It supports multi-user wireless communications and seamless handover between APs. VLC and OCC systems typically transmit data in one-direction only. LiFi supports bi-directional communication where the downlink uses visible light and the uplink typically uses infrared light. LiFi is conceived to utilise existing lighting infrastructure. The cells in LiFi are referred to as *attocells* [8]. The coverage of LiFi attocells is limited by the illumination area of an LED luminaire. Therefore, co-channel interference among LiFi attocells can effectively be managed and ultra-dense AP deployment can be achieved. LiFi can be considered as a complementary wireless networking technique, which not only provides additional unlicensed spectrum for *offloading* and dense AP deployment for *network densification*, but also contributes to enhancing the spectrum/area efficiency of existing WiFi networks. This means that the coexistence of hybrid LiFi and WiFi systems enables a higher system area capacity (area spectral efficiency). This in turn supports both URLLC and enhanced mobile broadband (eMBB) objectives of B5G systems. Hence, LiFi can enable the use of VR and AR applications in order to provide real-time information/updates to workers/engineers inside a factory.

In Fig. 2, the use cases of the indoor and OWC technologies are depicted for an industrial private network. The factory on the left-hand side depicts a manufacturing site, and the right-hand side depicts a warehouse. The inter-building connection of the two factory sites is provided by an FSO link. The densely deployed LED bulbs comprise a bi-directional, high-speed LiFi network, and provide both illumination and data communication simultaneously. On the one hand, LiFi APs communicate with devices/tools such as mobile handsets, surveillance cameras, manufacturing line robot arms, drones and forklifts. On the other hand, the noted devices/tools use VLC and/or OCC to connect with each other, i.e., achieving M2M and device-to-device (D2D) communications.

IV. Challenges and Outlook

A. Improving receiver sensitivity

One of the main issues in IM/DD light-based wireless communication systems is the receiver sensitivity due to the existing detector technology. The typical receiver sensitivity is in the region of -40 dBm to -45 dBm. This has an impact on the number of photons that need to be collected to achieve a certain signal-to-noise ratio (SNR). Unlike in fiber-optic communication where the light beam is very focused on a small detector, in FSO communications, usually there are significantly fewer photons hitting the detector. This is an issue that needs to be overcome. One solution would be to increase the detector size, this however, (i) reduces the field-of-view (FOV) according to étendue law, and (ii) decreases the bandwidth due to the higher capacitance. Therefore, larger

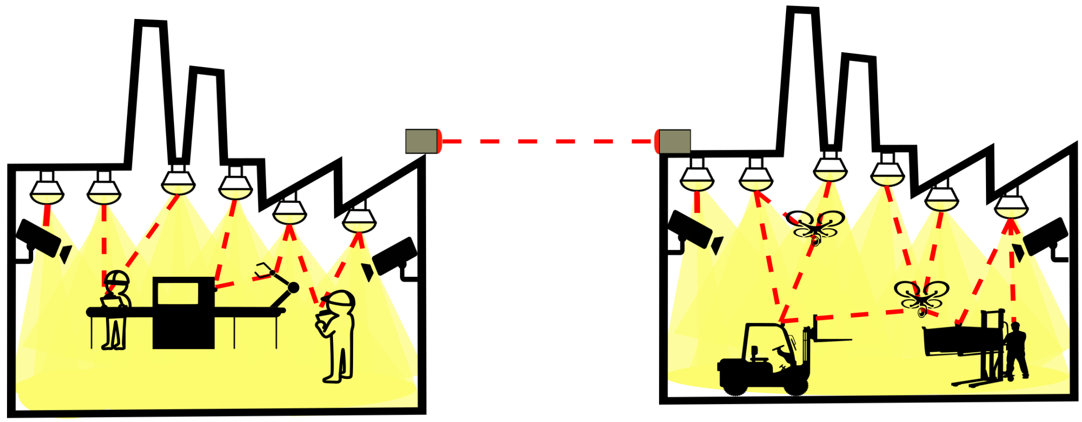


Fig. 2. Illustration of the indoor and outdoor OWC technologies for an industrial private network. The optical links are shown by red dashed lines.

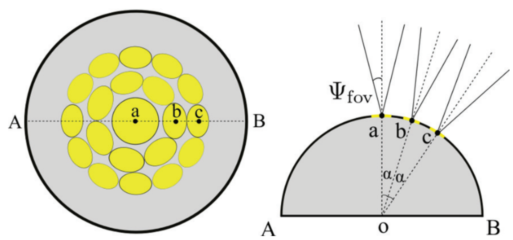
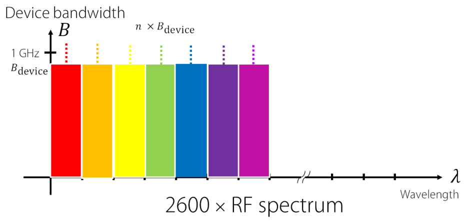


Fig. 3. An angular diversity receiver is constructed by assembling multiple small photo-detectors on a semi-spherical base.

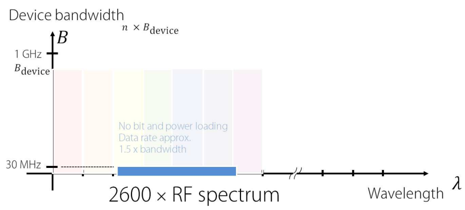
detectors are not a viable option. This has led to the introduction of segmented (fly-eye) receivers [14], or angular diversity receivers [15] as illustrated in Fig. 3. A receiver with a large field of view can be constructed to enable the collection of signal carrying light intensities from all possible directions. This is important to support user mobility. Signal combining techniques can be used to mitigate thermal and shot noise. Assume that there are N detectors. These N detectors receive s_1, s_2, ..., s_N. Each received signal is corrupted by additive thermal noise and shot noise modelled by n_1, n_2, ..., n_N. If the combiner is a simple summation followed by averaging, and assuming that all detectors receive the same signal, s_1=$s_2 = s_3 = \ldots = s_N = s$, then the total received signal is: $R = (s_1 + n_1 + s_2 + n_2 + \ldots + s_N + n_N)/N = s\,N/N + (n_1 + n_2 + \ldots n_N)/N = s + (n_1 + n_2 + \ldots n_N)/N$. For large N the second term approaches the expected value of the random variable of noise due to the law of large numbers, and if the expected value is known, it can be subtracted, which would lead to $R = s$ in the ideal case which essentially means that noise is removed. For example, in the case of additive white Gaussian noise, the expected value is zero, and in this case the second term tends to zero which means noise is intrinsically cancelled. This is comparable to the 'channel hardening' concept introduced for massive multiple input multiple output (MIMO) systems [16]. On the one hand, note that the received signal is only s while we may wish to receive $s\,N$ in low light conditions. On the other hand, this technique should be able to reduce the effect of shot noise when there is strong ambient light. However, more advanced and adaptive signal combining techniques such as maximum ratio combining (MRC) could be used to optimise the overall signal-to-noise-plus-interference ratio (SINR) [17] in the presence of co-channel interference.

B. Unlocking the full optical bandwidth

In order to fully harness the available bandwidth in the optical domain using IM/DD the relationship between the electrical device bandwidth and optical emission spectrum of the devices is important. Assume an emission spectrum, $\Delta\lambda = \lambda_1 - \lambda_2$, where λ_1 is highest emitted wavelength and λ_2 is the lowest emitted wavelength. The required electrical bandwidth of the device would the be: $B_{\text{device}} = \Delta\lambda\ c/(\lambda_1\ \lambda_2)$, where c is the speed-of-light. Assume $\lambda_1 = 1500.4$ nm, and $\lambda_2 = 1500$ nm, this would result in a required device bandwidth of 53 GHz. Current fiber-optic systems indeed operate at a channel spacing of 50 GHz. Now, assume $\lambda_1 = 501$ nm and $\lambda_2 = 500$ nm, i.e., a blue light source with an emission spectrum of 1 nm, this would result in a required device bandwidth of 1.2 THz, and even an emission spectrum of 0.4 nm would require an electrical bandwidth of 479.6 GHz. This means that further research is required to enhance the bandwidth of lighting devices while limiting the emission spectrum. Achieving the required colour rendering index (CRI) to fulfil the lighting requirements can be achieved by putting n devices of different narrow emission spectra into a light source. A comparison of the achievable bandwidths of off-the-shelf white LEDs and devices with combined n different spectral emission profiles is shown in Fig. 4. As it can be seen, the off-the-shelf white LEDs have a device bandwidth of 30 MHz and use a broad spectrum. However, the combined device has a substantially wider bandwidth due to its large spectral emission profile, and it can effectively utilize the available bandwidth using wavelength division multiplexing (WDM) and bit-and-power loading techniques. Such a device will most likely require lasers. Laser-based lighting would, therefore, constitute a great enabler for LiFi. This at the same time will unlock the full potential of LiFi. However, even if



(a)



(b)

Fig. 4. The potential of the combined infrared spectrum and visible light spectrum: (a) Device bandwidth has to be large to correspond to the spectral emission profile of the devices, and with WDM it would be possible to leverage the potential of the huge optical spectrum; (b) off-the-shelf white LEDs typically are single devices emitting a broad spectrum using phosphor based colour converting materials. This limits device bandwidth and prevents the significant WDM gains. Therefore, those systems completely rely on techniques that most effectively utilize the available bandwidth such as bit-and-power loading.

only 1% of the optical spectrum is exploited, this is still 26 times the full RF bandwidth.

V. Standardization

Several standardization activities as well as system demonstrations have been carried out to show that the light-based technologies are feasible and promising. Standardization efforts on low data rate applications of VLC and OCC are addressed in IEEE 802.15.7. Whereas, in IEEE 802.15.13, high data rate applications of VLC and FSO are addressed for special use cases such as private industrial networks. However, none of the noted standards have considered a comprehensive ecosystem of partners that enables mass market adoption of OWC technologies. Recently, light-based systems have been considered within in a IEEE 802.11 Task Group with the reference 802.11bb. The goal of IEEE 802.11bb is to use high-layer specifications and a unique ecosystem for chipset vendors, network infrastructure, device integrators and operators of IEEE 802.11. This will allow not only the co-existence and cooperation of LiFi with the rest of the WiFi standards, but also benefiting from the well established commercialisation phases of IEEE 802.11 for mass market adoption.

VI. Conclusions

Light-based technologies are considered as promising solutions to continue the trend towards higher frequencies in the electromagnetic spectrum. Given that the need for higher transmission speeds and more reliable wireless communication systems, we argue that light-based wireless communications systems are inevitable, meaning it is not a question if we will witness a mass-market deployment of these system, it is only a question of 'when' will see the mass market uptake. The existing standardization activities within IEEE 802.11bb primarily hold the answer to the latter question. In conclusion, VLC, OCC, FSO and LiFi are of the utmost importance to accomplish spectrally efficient, robust, reliable, high-speed and secure wireless connectivity requirement of the fourth industrial revolution.

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