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A guide to wireless networking by light

Harald Haas [a,*], Cheng Chen [a], Dominic O'Brien [b]

[a] *University of Edinburgh, King's Buildings, Edinburgh, EH9 3JL, UK*
[b] *University of Oxford, Parks Road, Oxford, OX1 3PJ, UK*

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ABSTRACT

The lack of wireless spectrum in the radio frequency bands has led to a rapid growth in research in wireless networking using light, known as LiFi (light fidelity). In this paper an overview of the subsystems, challenges and techniques required to achieve this is presented.

1. Introduction

Wireless data communication has become an essential utility in our private and business lives. There are more than 7 billion smartphones primarily used for personal communication. There is a sharp increase in the number of wearables such as smart watches, health trackers and digital glasses. The latter will drive new applications around virtual reality (VR), augmented reality (AR), high definition video streaming and Industry 4.0. In the future, there will also be 100 billion internet-of-things (IoT) devices that will underpin our smart homes and smart cities. Currently, all these digital wireless services use radio frequencies which are part of the wider electromagnetic spectrum. However, the lower frequency bands that are easy to use and have desirable propagation properties already have multiple uses. Consequently, there is very little spare resource to support the exponential growth in demand. The wireless community is working on multiple solutions to enhance wireless data transmission capabilities. For example, the new WiGig (wireless gigabit) systems, defined in IEEE 802.11ad and revised in 802.11ay, operate in the 60 GHz region and have access to around 14 GHz of bandwidth in the U.S.A. However, WiGig and other mmWave (millimeter-wave) radio frequency (RF) solutions (including the newest version of WiFi (wireless fidelity), 802.11ax) all exhibit similar challenges. For an RF link, the path loss is proportional to the square of the carrier frequency, and propagation becomes line-of-sight (LoS) or almost LoS. This means that moving wireless systems from the now 3 GHz region to the 60 GHz mmWave region will incur an additional path loss of 400, or 26 dB. Therefore, the high path loss along with the limited signal transmission power constraints require cells to be smaller, and beamsteering to direct energy from transmitter to receiver. In addition, the reliable coverage achieved with conventional cellular systems is much more difficult due to the LoS nature of the communications channel. There has been good technical progress to create the systems required to achieve this, with demonstrations at 30 GHz, and 60 GHz [1]. However, it is clear that these systems are complex. Furthermore, such high data capacity system does not easily provide the reliable, ubiquitous coverage that third generation (3G) and fourth generation (4G) cellular systems can deliver.

The optical spectrum offers a bandwidth which is many orders of magnitude greater than that the RF spectrum can offer. The visible and near infrared (IR) regions together are 2600 times larger than the 0–300 GHz RF spectrum. This spectrum is unlicensed and subject only to eye-safety regulations. Light emitting diode (LED) and laser sources are readily available across much of the spectrum, as are

* Corresponding author.
E-mail address: h.haas@ed.ac.uk (H. Haas).

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photodiodes to act as receiving elements. This makes optical wireless communication (OWC) systems, which includes the IR region, a potentially attractive medium for wireless communications [2].

Free-space point-to-point long distance optical wireless transmissions was the first OWC system to be considered, and this is known as free-space optical (FSO) communication [3]. A large body of work exists in this area, including commercial deployments, communications with mobile platforms [4], and increasingly communications in space [5]. Reference [6] provides a recent review of the field.

OWC technologies for short-range indoor applications were pioneered by the early work of Gfeller and Bapst, who demonstrated that a diffused IR radiation communication system could achieve data rates of around 100 kbps [7]. With the advancements of IR-based technology, the infrared data association (IrDA) formulated a set of protocols for wireless IR communications between electronic devices [8]. Such links were limited to several Mbps over ranges <1 m at wavelengths between 850 and 900 nm. More recently, work on very short distance IR links for cable replacement [9] has led to a 10 Gbit/s IR standard.

In addition to these cm-range links, a number of IR demonstration networks and systems concepts have been reported. Kahn and co-workers demonstrated a limited system operating at 50 Mbit/s [10], as well as introducing angle diversity concepts [11]. Imaging [10] and holographic [12] receiver designs have also been developed. Demonstration networks, operating at rates of up to Gbps have also been reported [13]. Reference [14] provides a recent review of the field. Eye safety regulations have led to a constraint on the amount of maximum emission power of the IR transmitter. Consequently, this has resulted in a limited link budget for IR networks. Therefore, it is not possible to cover typical indoor spaces with a single access point (AP) and achieve high data rates. Such rates, combined with good coverage requires multiple transmitters and receivers, which leads to complex systems that do not scale well as data rate increases. Using a limited number of narrow beam optical links within a room, and beamsteering to direct these to terminals allows data rates to scale. Furthermore, using light from optical-fibre systems combined with beamsteering has led to the highest rate indoor wireless links (RF or optical) demonstrated thus far. Recent demonstrations, operating at up to several hundred Gbit/s are reported in Refs. [15–17].

With the emergence of energy-efficient white-LEDs, solid state lighting (SSL) is gaining great popularity in the lighting industry [18]. It is expected that LED-based lighting infrastructures will replace all conventional lighting infrastructure in the coming decades. This trend provides a unique opportunity to create novel combined lighting and wireless communication networks. The use of LEDs for wireless data transmission is known as visible light communication (VLC) [19] which was first introduced by Nakagawa [20]. The wireless networking using VLC is referred to as LiFi, first introduced in 2011 [21]. During the last 10 years, there have been significant advancements in this field. The link data rates have increased three orders of magnitude from 10 Mbps in 2006 to 10 Gbps in 2016 [22,23], and in 2011, the Institute of Electrical and Electronics Engineers (IEEE) published the first standard for short-range VLC applications [24]. In the last 5 years, there has been a significant shift from point-to-point, static VLC systems to complete LiFi cellular systems. As a result, now there is a LiFi ‘topic interest group’ in IEEE 802.11, and this has now progressed to an IEEE 802.11 Study Group.

While IR networking requires dedicated infrastructure, VLC requires modification of an existing lighting system, thus offering potential cost-savings. Crucially, as detailed later in the paper, the level of illumination required for human users leads to a link margin many orders of magnitude superior to that in IR systems, enabling high data-rates with good coverage using simple components. These advantages, and others detailed elsewhere in the paper, have led to the rapid growth in this area.

This paper introduces the elements required and the challenges faced in creating LiFi networks. This paper does not attempt to provide a comprehensive overview of the field of VLC and LiFi (for these, the reader is referred to recent review papers [25–28] and references therein).

2. LiFi attocell networks

Fig. 1 illustrates the concept of a LiFi attocell (LAC) network. The room is lit by a number of light fixtures, which provide illumination and an optical AP to users within the illumination pattern of the light. The illumination can be modulated at high rates, not visible to the occupants of the room, providing an optical downlink. Power and data can be provided to each light fixture using a number of different techniques, including power over ethernet (PoE) and power line communication (PLC) [29,30]. 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), and a receiver close to the light fixture. Each of these light fixtures, which at the same time act as wireless LiFi APs, create an extremely small cell (an attocell), which can provide high bandwidth density due to the highly confined illumination from an individual light source. 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 [31]. 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 [32]. Fig. 2 illustrates CCI in an optical attocell network.

Advanced CCI mitigation techniques often require that these multiple LiFi APs are operated by means of a centralised control mechanism [32] such as the ‘hypervisor’ within the server of a software defined network (SDN) [33]. The main tasks of the central controller are to adaptively allocate signal power, frequency, time and wavelength resources. Other functions of central controller include achieving multi-user, and the handover process from cell to cell when terminals move.

LAC networks have a number of 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, LAC networks can be implemented by