Powering the Internet of Things through Light Communication

Ilker Demirkol, Senior Member, IEEE, Daniel Camps-Mur, J. Paradells, M. Combalia, W. Popoola, Senior Member, IEEE, H. Haas, Fellow, IEEE

Abstract: Novel solutions are required to connect billions of devices to the network as envisioned by the Internet of Things (IoT). In this paper we propose to use Light Fidelity (LiFi), which is based on off-the-shelf LEDs, as an enabler for the IoT in indoor environments. We present LiFi4IoT, a system which, in addition to communication, provides three main services that the Radio Frequency (RF) IoT networks struggle to offer: i) precise device positioning, ii) the possibility of delivering power, since energy can be harvested from light, and iii) an inherent security due to the propagation properties of visible light. We analyze the application space of IoT in indoor scenarios, and propose a LiFi4IoT Access Point (AP) that communicates simultaneously with IoT devices featuring different types of detectors, such as Complementary Metal Oxide Semiconductor (CMOS) camera sensors, Photo Diodes (PDs), and solar cells. Based on the capabilities of these technologies, we define three types of energy self-sufficient IoT "motes" and analyze their feasibility. Finally, we identify the main research directions to enable the LiFi4IoT vision and provide preliminary results for several of these.

I. INTRODUCTION

Embedding intelligence to everyday objects and providing Internet connectivity to these objects, also known as the Internet of Things (IoT) paradigm, is becoming a reality. However, along with the benefits it promises, this paradigm also brings significant challenges, especially related to communications. Pervasive IoT will require a very large number of connections per unit area, high aggregate bandwidth, ubiquitous coverage, sustainable energy resources, and a high level of security. A promising IoT communication solution that can address these challenges is Light Fidelity (LiFi), which consists of networked light communications using the visible and the infrared spectrum. In particular, a key advantage of leveraging the visible spectrum for IoT communications is the fact that a lighting infrastructure composed of LED luminaires is being adopted extensively [1] and will provide illumination to the indoor spaces where IoT communication is most needed. Densely deployed illumination points can be converted into IoT Access Points (APs) addressing the challenge of high density IoT nodes, enabling short range communication to achieve low energy consumption for power-constrained nodes. Moreover, as light is ubiquitous, it is an ideal source for energy harvesting compared to other sources such as temperature difference, movement, or Radio Frequency (RF), and its higher-efficiency energy harvester technology (i.e., solar cells) results in compact and lower-cost solutions [2].

LiFi brings several advantages over RF for indoor IoT communication. Apart from the energy-autonomous operation it enables at the receiver side [3], LiFi provides inherent security, since its signals do not penetrate walls. Such secrecy feature is an important requirement for IoT applications such as the ones for Industry 4.0. LiFi is also better suited to enable high-precision indoor localization [4], which is critical for IoT applications such as asset tracking. Although LiFi functions where light illumination is mostly available, such as warehouses, offices, hospitals, etc., studies show that several Mbps data rate is possible when the lights are off (i.e., perceived as off) [5]. Moreover, the already crowded RF spectrum is not expected to serve the projected several billions of IoT devices, for which LiFi spectrum will be a critical solution.

Table 1. IoT Application Space and the Corresponding Traffic Requirements

<table>
<thead>
<tr>
<th>IoT Application Type</th>
<th>UL rate</th>
<th>DL rate</th>
<th>UL Δt</th>
<th>DL Δt</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) Event driven monitoring: Report the event and periodic keep alive messages. Example: Report presence</td>
<td>bps-Mbps*</td>
<td>bps-kbps*</td>
<td>L</td>
<td>N/A</td>
</tr>
<tr>
<td>2) Continuous (periodical) low data-rate monitoring Example: Temperature data</td>
<td>bps-kbps*</td>
<td>bps-kbps*</td>
<td>M</td>
<td>L</td>
</tr>
<tr>
<td>3) Actuator: Remote control of actuators Example: Door opening</td>
<td>bps-kbps</td>
<td>kbps-Mbps</td>
<td>L</td>
<td>L</td>
</tr>
<tr>
<td>4) Rich monitoring: Sensors generating high data volume Example: Accelerometer</td>
<td>kbps-Mbps*</td>
<td>kbps-kbps*</td>
<td>L</td>
<td>L</td>
</tr>
<tr>
<td>5) Asset/object tracking: Periodic ID transmission Example: Warehouse tracking</td>
<td>bps-kbps</td>
<td>bps-kbps*</td>
<td>L/ M</td>
<td>—</td>
</tr>
<tr>
<td>6) Location-based end-user services Example: Localization in shopping malls</td>
<td>—</td>
<td>bps-kbps</td>
<td>—</td>
<td>VL</td>
</tr>
</tbody>
</table>

* Measurement details data, †for ACK, #if ACK or paging is used, Δt: Latency, L: Low, M: Medium, VL: Very Low (to achieve tens of location estimates per second).

The use of LiFi for IoT has been a recent research topic, with most of the early studies focusing on the energy-harvesting aspect of LiFi for IoT nodes or the hybrid operation of LiFi with
RF, e.g., [3], [6]. This article presents a comprehensive analysis of LiFi for IoT communication, describing how LiFi is suited to satisfy the diverse IoT requirements. In fact, the wide IoT application space exhibits diverse traffic characteristics as listed in Table 1. As seen in the table, the requirements from the IoT communication network vary based on the application category. We advocate that the LiFi4IoT system described in this article can address all these requirements. The details of the LiFi4IoT system, which is composed of an AP and energy self-sufficient LiFi4IoT motes, are provided in Section II. We present a general architecture design for LiFi4IoT, and provide the design and feasibility analysis of three types of LiFi4IoT motes that cover the application space for indoor IoT provided in Table 1. We then list the research challenges that need to be solved to enable the vision of LiFi4IoT in Section III, and provide preliminary results for solutions targeting several of these challenges. Finally, we conclude the article with Section IV.

## II. LiFi4IoT SYSTEM VISION

### A. LiFi4IoT Communication Technologies and System Architecture

Although there is an extensive research effort towards high speed LiFi communication, the potential LiFi communication technologies that can address the low-rate IoT requirements listed in Table 1 are limited. Several key technology candidates to be employed in LiFi4IoT devices, and the IoT application space they can address, are analyzed in Table 2. Combinations of these technologies can be used to define LiFi4IoT device transceivers, or motes, for different applications. For example, an energy-autonomous mote solution would call for a solar panel as the downlink receptor for energy harvesting purposes. Consequently, and based on the application space analysis of Table 1, we define four types of motes shown in the conceptual architecture of the LiFi4IoT system in Figure 1. The mote technologies and the corresponding designs are detailed in Section II.B.

The vision of LiFi4IoT is to realize an integrated AP solution that is able to communicate with LiFi4IoT devices with different communication technologies. Figure 1 proposes such an AP solution, composed of a modulator, controlling the light intensity of an off-the-shelf LED through a driver, and optional receiver modules depending on the considered uplink technologies. By varying the light intensity, the AP performs downlink communication towards the LiFi4IoT devices. In addition, a LiFi Controller coordinates communication between APs. The LiFi Controller may interface with the IP network and with the Radio Access networks (RAN), the latter being necessary for hybrid motes that combine the RF and LiFi technologies.

Receiver technologies supporting the low power requirements of LiFi4IoT devices are needed at the AP. CMOS camera is a receiver option that allows simultaneous low bit rate transfers (limited by the camera frame rate) from multiple devices, while enabling spatial multiplexing. This is an attractive solution to enable real-time tracking of numerous low power LiFi tags. Another option is to use high sensitivity detectors as PD, such as Single Photon Avalanche Diode (SPAD), or arrays thereof [7]. A SPAD device is capable of higher bit rates (tens of Mbps) and can be used to receive data from all devices in the AP coverage area.

### Table 2. Features of Downlink and Uplink Technology Candidates for LiFi4IoT Devices (motes)

<table>
<thead>
<tr>
<th>Direction (Reception)</th>
<th>Technology</th>
<th>Bit rate</th>
<th>Cost</th>
<th>Power Consumption</th>
<th>Deployment complexity</th>
<th>Additional functionality</th>
<th>Matching App. Type (Table 1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Downlink</td>
<td>Photo Diode</td>
<td>Few Mbps</td>
<td>L</td>
<td>L</td>
<td>L</td>
<td></td>
<td>1, 3, 4</td>
</tr>
<tr>
<td>Solar Panel</td>
<td>(Infrared) LED</td>
<td>Tens of Mbps</td>
<td>L</td>
<td>M</td>
<td>M*</td>
<td>Can support CMOS or SPAD receiver at the AP</td>
<td>3, 4</td>
</tr>
<tr>
<td>OCC</td>
<td>Retroreflector</td>
<td>Hundreds of bps</td>
<td>M</td>
<td>M</td>
<td>M*</td>
<td>Requires the usage of CMOS receiver at the AP</td>
<td>2, 5</td>
</tr>
<tr>
<td>Uplink (Transmission)</td>
<td>Radio Frequency</td>
<td>Hundreds of kbps</td>
<td>M</td>
<td>H</td>
<td>L*</td>
<td></td>
<td>1, 4</td>
</tr>
</tbody>
</table>

To enable high-precision (i.e., cm level) indoor position information of a LiFi4IoT device, a CMOS camera is needed, either at the AP or at the device [4]. The former allows a lower cost system and requires less power. In case of a high bit rate uplink requirement in addition to the location service, the latter alternative can be considered. This however would limit the achievable downlink bit rate and increase the power consumption, albeit offering an easy implementation for existing smartphones.

B. LiFi4IoT Mote types and feasibility analysis

Based on the application requirements of Table 1 and the available technologies of Table 2, we derive four types of IoT devices a LiFi4IoT AP should be able to communicate with. These devices include three energy self-sufficient motes (Figure 2), which cover the most promising low-complexity, low-power and low form-factor solutions suited for the IoT. The fourth device is an Optical Camera Communication (OCC) device that is already available today, for example through smartphones [4]. In the following, we detail prospective mote designs, along with their feasibility analysis in terms of energy and bit-rate performances.

1) LiFi4IoT Retroreflector Mote: A liquid crystal shutter on top of a retroreflector at the mote enables the use of light backscattering as an uplink technology. Since the liquid crystal shutters are very low-cost and consume low-power, this technology is expected to be employed for many use cases in the future. For such mote technology, a CMOS image sensor is employed at the AP side. This will allow for simultaneous uplink communication with numerous motes, in addition to the added functionality of localization of the motes through the image sensor (reflected light excited) pixel location.

Feasibility Analysis: Modern low-power microcontroller units (MCUs) come with options to reduce the MCU frequency or to reduce the clock speeds. Since the maximum modulation frequency of the state-of-the-art LCD shutters vary between 100 Hz and 1000 Hz, the use of low-power run mode of, for example, STM32L1 MCU working at 32 kHz clock would be enough for the operation of the LiFi4IoT Retroreflector mote. In low-power run mode with the LCD driver enabled, the consumption of the CPU is 23.9 µW. State-of-the-art LCD shutters [8] consume less than 0.2 µW at 200 Hz. Hence, the Retroreflector mote is expected to consume ~24 µW in its active mode, with a bit rate of 200 bps using On-Off Keying (OOK). This complies with the results of [8], achieved with a range of 5 meters and using a retroreflector of a 20 mm radius. The harvested power is given as $P = I \times A \times \text{Eff}_{\text{solar}}$, where $I$ denotes the illumination intensity in units of mW/cm², $A$ represents the solar cell area, and $\text{Eff}_{\text{solar}}$ represents the solar cell efficiency factor. According to a recent indoor solar cell technology characterization, $\text{Eff}_{\text{solar}} = 15\%$ for $I = 0.1$ mW/cm², and $\text{Eff}_{\text{solar}} = 20\%$ for $I = 10$mW/cm² [9]. Then, for the lower illumination intensity of 0.1 mW/cm², the solar cell area should be at least $A > P/I/\text{Eff}_{\text{solar}} = 1.6$ cm². As a result, a target size greater than 1.6 cm² would provide enough energy from indoor light harvesting for an energy-autonomous functioning.

With the standard 30 fps frame rate image sensors, the achievable per mote data rate is limited to 15 bps (sampling at Nyquist frequency) for an OOK uplink modulation. Given the aforementioned energy budget calculation, these motes can always be on, working at a constant data rate, and represent a good candidate to address application types 2 and 5 in Table 1.

2) LiFi4IoT PD+LED Mote: This mote solution defines two operational states. In the sleep state, the solar cell harvests energy from the ambient light, which can be stored to power the IoT mote when in active mode. To wake up the IoT mote, a ‘wake-up’ optical signal is broadcast from the AP. Solar cell is used to double as the ‘wake-up’ signal receiver through an addressable, ultra-low-power wake-up circuitry [3] that decodes the wake-up signal and turns on the IoT mote with the correct address. In the active state, the IoT mote communicates with the AP using the LEDs (possibly infrared) for uplink data transfer.
Feasibility Analysis: A total harvestable power in the order of 2 mW/cm² is feasible from a typical indoor lighting [9]. For a mote with a moderate 10 cm² solar panel, which is reasonable in industrial scenarios, the total harvestable power is 20 mW. By sharing the harvested power equally among sensing, processing and communication functions, a peak electrical power of about 6.6 mW is available for each function. If uplink transmitter is a typical LED, e.g. the L909 LED from Hamamatsu, which radiates 10 mW optical power when operated continuously at a drive current of 50 mA and forward voltage of 1.4 V, then the LED power consumption is 70 mW. As the mote is not expected to be active at all times, the dissipated electrical power will be less than this value. With a duty cycle of 1/100, the electrical power consumed by the LED transmitter will be 0.7 mW. Thus, the total estimated power dissipated during data transfer is 1.4 μW. Compared to RF, there are several limitations and challenges brought by LiFi. An important challenge is that LiFi signals are significantly attenuated when the LOS link is blocked. This will lead to a large drop in the link data rate, and in the worst case this could lead to outage. Therefore, its system design requires powerful link adaptation techniques, and a sufficient degree of diversity. As a result, concepts such as joint transmission and coordinated multipoint (CoMP) are required.

Another challenge stems from the fact that LiFi uses intensity modulation/direct detection (IM/DD). As a result, information cannot be encoded in the phase of the light signal. Consequently, tailored techniques are required to ensure high spectrum efficiency while the energy efficiency is not compromised either.

LEDs are natural beamformers, due to their narrow field of view (FoV) property. This has the advantage that light can be tightly focused to improve the link budget. However, unlike in RF beamforming, the beams cannot be changed dynamically. This means that angular diversity structures including multiple LEDs have to be considered in the system design.

III. LiFi4IoT Research Directions

In this section, we present the key research directions that will enable the LiFi4IoT vision. We also assess the ongoing studies in these research lines and present respective preliminary results, where possible.

A. Mitigating the Limitations of LiFi in Comparison to RF

Compared to RF, there are several limitations and challenges brought by LiFi. An important challenge is that LiFi signals are significantly attenuated when the LOS link is blocked. This will lead to a large drop in the link data rate, and in the worst case this could lead to outage. Therefore, its system design requires powerful link adaptation techniques, and a sufficient degree of diversity. As a result, concepts such as joint transmission and coordinated multipoint (CoMP) are required.

Another challenge stems from the fact that LiFi uses intensity modulation/direct detection (IM/DD). As a result, information cannot be encoded in the phase of the light signal. Consequently, tailored techniques are required to ensure high spectrum efficiency while the energy efficiency is not compromised either.

LEDs are natural beamformers, due to their narrow field of view (FoV) property. This has the advantage that light can be tightly focused to improve the link budget. However, unlike in RF beamforming, the beams cannot be changed dynamically. This means that angular diversity structures including multiple LEDs have to be considered in the system design.
B. Energy efficient multi-device LiFi modulations and Multiple Access schemes

While significant progress is being made in VLC/LiFi research [10], these efforts are not particularly directed at resource constrained devices. Compelling electrical and computing power limitations of the IoT nodes will inform the design of energy efficient modulation and multiple access techniques.

High spectral efficiency modulation techniques such as the discrete multi-tone modulation are undesirable for resource constraint IoT nodes due to its computational needs and high peak-to-average power ratio. Instead, solutions based on pulse based modulation techniques such as the OOK, pulse position modulation (PPM), and PPM variants including spatial PPM (SPPM) [11] are more appropriate. Another energy efficient modulation is the energy efficient random number modulation (RNM) technique proposed in [12]. To achieve the energy efficient operation, RNM transmits $B$ bits during a single effective channel-use (i.e. time slot), while a conventional continuous transmission system with $M$-level modulation technique transmits $\log_2 M$ during every symbol duration. RNM thus approaches conventional modulation techniques as $B \rightarrow \log_2 M$. RNM does not allow for continuous data transmission, hence the link must be tolerant to delays. This technique is therefore attractive for IoT and sensor nodes that only need to send data intermittently.

For the LiFi4IoT AP to communicate effectively with IoT nodes having different kinds of receivers (PD, solar cells and camera) a suitable multiple access technique is required. Designing such a low power multiple access technique with little or no cross-channel interference is a major challenge. The non-orthogonal multiple access technique (NOMA) recently proposed for LiFi is unlikely to be suitable for LiFi4IoT due to its high computational complexity.

Finally, the development of a common LiFi solution to communicate with both high-speed (e.g., consumer multimedia) and low-speed (e.g., IoT) devices is also a challenge to be addressed. To overlay a low-speed signal on a high-speed signal as done in LTE and NB-IoT would enable a single system solution to address applications with different requirements.

C. LiFi for CMOS receivers

OCC modulations can be divided into those based on the rolling shutter (RS) effect, which allows a CMOS receiver to demodulate multiple bits from a single image capture, and modulations that transmit at most one bit per frame (non-RS). Consequently, we identify the following two challenges for OCC based data communications: i) increasing the achievable data-rates to enable new applications, and ii) designing modulations that can be used to communicate simultaneously with RS and non-RS receivers.

OCC data communication solutions proposed in the state of the art achieve data rates around 1 kbps for RS receivers [13]. We envision several ways to increase these data-rates. First, using RGB LEDs instead of white LEDs would allow to encode independently each color component, while maintaining an acceptable color temperature. Second, while current solutions are mostly based on OOK [14], the use of multi-level amplitude modulation should also be studied. Third, a critical aspect that determines the data-rate in OCC is the amount of screen area illuminated by the modulated LED. Consequently, demodulating ambient light received across the whole CMOS sensor is the most efficient way to increase data-rate. This approach however, requires more complex image processing to recover the encoded signal from the image background. Finally, interference mitigation techniques are required to increase capacity when various APs in the same room transmit different information. Data rates in the order of tens or hundreds of kbps is feasible through the previous techniques but only if the receiver is at a reduced distance from the AP (e.g. $<4$ meters [14]). Receivers at longer distances should still be able to receive information, if they give up RS operation, i.e. communication is achieved by detecting the state of the LED source across different frames captured consecutively. Ideal OCC modulations should be able to address both receiver types, i.e. encode a low data-rate signal in non-RS mode for far-away receivers, and allow faster data-rates through the RS effect for closer receivers.

In the field of indoor positioning for OCC, recent solutions based on image processing have achieved cm-level precisions in 3D spaces. For example, Figure 3 depicts the results of an experiment we performed within Mobile World Congress 2016, where a smartphone positions and orientates itself in 3D space, based on codes decoded from LED fixtures. Further research is required to devise new schemes that can provide 3D cm-level precision in the presence of less than four luminaires, which are often not available in practice.

Mechanisms to minimize the impact of the camera sensor on battery life are also critical in OCC. For example, in the case of positioning, one should attempt to maintain accuracy while capturing the minimum number of images. This can be achieved by having algorithms that require a single frame to decode a position, and using inertial sensors to interpolate position data between captured camera frames. For data communication, blank frames can be considered where the camera can be turned off, trading off data-rate with battery duration.
Data rates are crucial. For example, the per-mote data rate can be increased using higher frame rate image sensors and/or multiple synchronized image sensors at the AP. In addition, the use of a CMOS sensor at the AP allows much higher aggregate uplink data rate through the use of spatial-division multiple access (SDMA).

F. High sensitivity receivers for LiFi4IoT APs

A fundamental challenge for SPAD receivers is ambient light rejection. Previous research has demonstrated SPAD receivers attaining data rates of 60-100 Mbits/s at BER of $10^{-3}$ and sensitivity of -41 dBm albeit in idealized environments. These data rates can be reduced to below 1 Mbits/s in favor of energy efficient pulsed LED drive schemes at the IoT transmitter, as well as greater ambient rejection. The SPAD sensitivity combined with modulation schemes inspired by lock-in techniques are essential to detect the very low power optical signals in the nW region within a given ambient noise floor, expected from energy limited LiFi4IoT devices.

G. LiFi4IoT integration with the 5G/IP network

Integration of LiFi4IoT network and other networks, such as 5G, can be performed at the IP layer. Essentially, the main challenge is to enable and optimize IPv6 support over the LiFi4IoT communications interface (i.e. physical and link layer). This can be achieved by defining an adaptation layer between IPv6 and the LiFi4IoT link layer, which should comprise header compression, optimized neighbor discovery, and fragmentation.

Header compression techniques are required to minimize the packet size when an IPv6 packet is communicated via a LiFi4IoT link. 6LoWPAN header compression is the reference mechanism for constrained devices and should be extended to enable LiFi4IoT [15]. 6LoWPAN Neighbor Discovery (ND) adapts the IPv6 ND protocol for devices that need to use sleep periods to save energy, thus it is a candidate solution for LiFi4IoT. Finally, if the LiFi4IoT link layer requires a frame format with a maximum payload size below 1280 bytes, then fragmentation is needed to support the IPv6 maximum transmission unit (MTU) requirement.

IV. CONCLUSIONS

In this article, we presented the LiFi4IoT system built on off-the-shelf LEDs as an enabler for the IoT in indoor environments. We described the indoor IoT application space by considering three types of energy self-sufficient motes. The energy-autonomy of these motes is validated feasibility analyses. These motes employ different LiFi receiver technologies such as CMOS camera sensor, PD, and solar cell, along with low-power LiFi transmitter technologies such as LCD-modulated retroreflector. The choice of the technology depends on the IoT application characteristics. The main research directions that would pave way to the LiFi4IoT vision are highlighted, in addition to some preliminary results in these directions. The presented LiFi4IoT motes are shown to cover a significant portion of the application types, while promising energy-autonomy - a crucial requirement for many IoT applications.
V. REFERENCES


VI. BIOGRAPHIES

Ilker Demirkol (ilker.demirkol@upc.edu), IEEE Senior Member, is a Ramon y Cajal Research Professor in Department of Mining, Industrial and ICT Engineering at the Universitat Politècnica de Catalunya, where he works on wireless networks, covering topics such as cellular systems, IoT, communication protocol development and performance evaluation.

Daniel Camps-Mur (daniel.camps@i2cat.net) is currently leading the Mobile and Wireless Internet group at I2CAT in Barcelona. Previously, he was a senior researcher at NEC Network Laboratories in Heidelberg, Germany. His research interests include mobile networks, Internet of Things, and Software Defined Networking.

Dr. Josep Paradells (josep.paradells@entel.upc.edu) is full professor in the Network Engineering Department of the Universitat Politècnica de Catalunya (UPC). He is the head of the Wireless Network Group and director of the Ubiquitous Internet Technologies Unit at the Fundació i2Cat. His research interests are on the wireless systems and Internet access technologies, in particular, on the evaluation of mobile network protocols.

Marc Combalia (marc.combalia@i2cat.net) is currently working on Visible Light Positioning systems in the Mobile and Wireless Internet group in i2CAT in Barcelona. Marc holds a BSc Degree in Sciences and Technologies of Telecommunications from the UPC.

Wasui O. Popoola (w.popoola@ed.ac.uk), IEEE Senior Member, has MSc in optoelectronic and communication systems and a PhD degree in free-space optical communications. He currently holds a chancellor’s fellowship at the Institute for Digital Communications, University of Edinburgh. Popoola has over ten years research experience in optical wireless communications.

Harald Haas (h.haas@ed.ac.uk) received the PhD degree from the University of Edinburgh in 2001. He currently holds the Chair of Mobile Communications at the University of Edinburgh, and is the initiator, co-founder and Chief Scientific Officer of pureLiFi Ltd as well as the Director of the LiFi Research and Development Center at the University of Edinburgh. His main research interests are in optical wireless communications, hybrid optical wireless and RF communications, spatial modulation, and interference coordination in wireless networks.