Uplink wireless transmission overview in bi-directional VLC Systems

Pablo Pérez-Nicoli and Fernando Silveira
Instituto de Ingeniería Eléctrica, Facultad de Ingeniería
Universidad de la República, Uruguay
Email: {pablop, silveira}@fing.edu.uy

Xun Zhang and Amara Amara
Institut Suprieur dElectronique de Paris, ISEP
Paris, France
Email: {xun.zhang, amara.amara}@isep.fr

***Abstract*—This paper introduces the concept of uplink wireless transmission technologies for visible light communication (VLC). An overview of the different uplink existing methods and its feasibility in various applications such us indoor positioning is presented. We also showed that, unlike existing technologies of wireless communication like, Bluetooth, WiFi and Zigbee, Wireless Power Transfer (WPT) can be not only used for uplink transmission but also provides energy for certain power hungry devices. Simulation results and analytical approximations show that around 450 *kbps* uplink throughput can be achieved in a system capable of delivering up to 1.3 *mW* to small indoor devices (94.6x56.8x3.65 *mm*).**

I. Introduction

In the last decade we have witnessed a dramatically increase in the number of mobile devices (MDs) used in the daily life. The same trend has occurred in the industry, where the fourth industrial revolution (Industry 4.0) is taking place [1]. It means there are more MDs wirelessly connected that are also able to take decentralized decisions. This revolution not only increases the automatization process but also introduces the possibility of self-optimization, self-configuration and self-diagnosis. This leads to high-end quality services or products with a more transparent commodity chain, increasing profit and reputation of the factories.

This general tendency, to increase the number of MDs, creates challenges that have to be addressed to make this revolution possible.

The first challenge that we have to face is the spectrum crisis [2], since some segments of the spectrum are already congested. As there are more devices connected in the same room, interference increases, and providing wireless connection with enough throughput is not trivial. Developing communications system using the less used spectrum segments (like visible light communications, VLC [3]) is essential to overcome this challenge.

VLC, in addition to provide an alternative communication link using a usually free segment of the spectrum, also allows high throughput links [3]. Moreover, visible light does not interact with the electronic components which makes this communication technology suitable for electromagnetic wave-sensitive environments.

Due to their low cost, low power consumption and long life time, LEDs are widely used for illumination. It allows the modulations of light at frequencies imperceptible for humans, making possible the integration of VLC in already installed illuminations systems in a cheap and easy way.

These are the reasons why VLC has become a rapidly growing technology and is nowadays being used in many different scenarios. In indoors applications for instance, VLC can be integrated in the illuminations system making possible a communication link from the building to MDs (downlink) with all the afore mentioned advantages. However, for the uplink (communications from the MD to the building) VLC may not be the best technology since considerable amount of power is required to generate the light and it will produce an undesired effect to users. What is more, the uplink light will suffer from interference with the reflected light used for the downlink communication. The wireless communication technology used for the uplink is not a trivial decision and depends on the application, it will be addressed later in this paper.

The second challenge is the power supply and power management issue. In many applications the amount of power storage in batteries is not enough for the device whole operation. In addition, since there are more MDs, the number of batteries that have to be recharged also increases. Energy harvesting is usually not able to provide enough power in many applications. What is more, running out of power in certain part of the production chain could not be acceptable for economics or even human safety reasons. In this case, having the capacity of transferring power wirelessly to MDs helps to beat this problem making the whole system more robust. This supports the growing interest in the development of wireless power transfer (WPT) systems.

In this paper we have carried out an overview study of the different RF technologies that can be used to implement the uplink in a VLC system. We have shown that in applications where high throughput is not required for the uplink, inductive coupling in addition to provide a suitable uplink communication link, also allows the possibility to transfer power wirelessly from the building to the MD. A preliminary design of a bidirectional communication system, using VLC for the downlink and inductive coupling for the uplink and WPT capability (Hybrid-Bidirectional link) is generally described in order to analyze the feasibility of the proposed link.

This paper is organized as follow. First Section II presents the uplink state of the art analysis. Then, the feasibility of use inductive coupling for uplink and WPT in the context of VLC system is addressed in Section III. In Section IV the final discussion and conclusions of this work are presented.

II. Uplink for VLC systems

Information can be sent unidirectionally from the buildings to MDs (downlink) without uplink communication at all. However, if we want to transmit information only if the device request it, control the data access through passwords, or simply receive acknowledges, we need an uplink.

It is very easy to see that uplink is also needed in almost any application where VLC is used to provide services that are currently being provided by Wifi, like mail access, share files, voice over IP, etc.

Summarizing, uplink is needed in many applications. Thus, a question arises. which technology/standard (Wifi, Bluetooth, Infrared, Zigbee, etc.) should be used to implement the uplink?

To answer this question, we should know which are the requirements for the uplink in order to determine the best technology to be used. Then, the technology that fulfill the requirements with the best performance should be selected. Many different properties can be considered when evaluating a communication standard performance [4], even so, we consider that in our application the most important metrics are range distance, throughput and power consumption.

Some of the more typically used technologies for wireless communications are presented in Fig. 1. That figure only pretends to give an idea of the ranges and throughputs that can be achieved showing some standards as examples. For instance, we are presenting Bluetooth v1.2 class 2, nevertheless, larger distances can be achieved using class 1 (around $100\ m$) and higher throughputs using newer versions like 4.0 ($32\ Mbps$). The same happens with all the technologies, variations exists to reduce power consumption at the expense of lower throughput or range distance, or the other way round, increase throughput or range distance bearing higher power consumption.

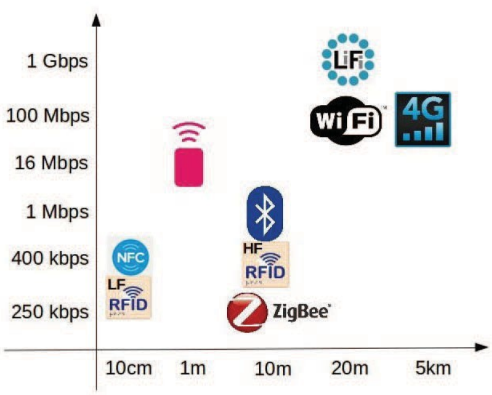

Fig. 1. Different technologies typically used for wireless communications. This plot was done considering the following standards: *Zigbee* IEEE 802.15.4, *Bluetooth* 1.2 class 2 IEEE 802.15.1, *4G* IEEE 802.16m for MDs, *Wifi* IEEE 802.11n, *Infrared* IrPHY VFIR standard range, *NFC* and *High-frequency RFID* 13.56MHz ISO/IEC 18000-3, *Low-frequency RFID* below 135kHz ISO/IEC 18000-2, *Lifi* (BeamCaster P2P solution).

The requirements for the uplink depends on the scenario of use. In terms of range distance, as we are focused on indoor ap- plications, short distance ($10\ m$) are enough. Therefore, from Fig. 1 we can see that ZigBee, Bluetooth, Wifi or inductive coupling (high frequency RFID) can be used, depending on the required uplink throughput.

Most of the published papers proposed hybrid systems using Wifi for uplink, [5] among many others, since it supports high throughput and is an extensively used technology.

Hybrid VLC-Zigbee systems are used in application where high throughput for uplink is not needed like assisted indoor location systems [6] and lighting control [7]. Thus, low power consumption is achieved.

Since Zigbee is not available in most of the MDs (phones, laptops), Bluetooth low energy is a better solution for massive commercially used applications [8].

RFID and Bluetooth are used together to assist an indoor self-positioning system in [9]. Although inductive coupling (Near field) is used in RFID, this technology has not been commonly used to implement uplink communication for VLC systems. In this work, we also explored the feasibility of using inductive coupling to implement the uplink and WPT capability together.

In order to estimate the power consumption for Zigbee, Bluetooth and Wifi, we have chosen 5 commercial modules and presents their power consumption at transmitting stage on Fig. 2. Of course these different chips have different features, but even the same chip can be configured to transmit with different power or throughput. Thus, we present the power con- sumption of Fig. 2 in a 3D plot where the transmitting power have slight approximations to be able to present all the chips in a comprehensible plot (e.g. RN4020 power consumption is presented at $5.8\ dBm \sim 5\ dBm$ transmitted power).

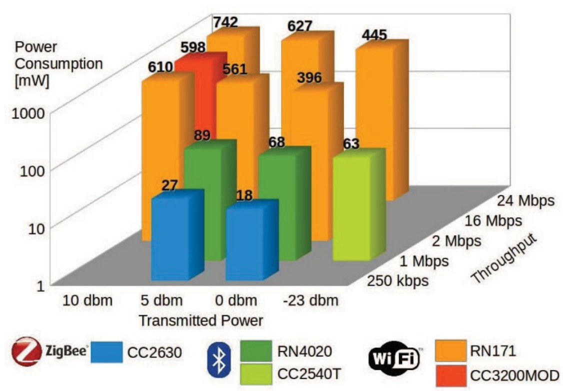

Fig. 2. Power consuption at transmitting stage of commercial modules for Zigbee, Bluetooth and Wifi.

It is worth mentioning that there are chips that implement ultra-low power Wifi with lower power consumption and bit rate as well as bluetooth modules with higher throughput. However, the idea here is to quantify the power consumption as it is not possible to include all the different technologies. The chip's price follows a similar behavior than the power consumption since higher throughput chips are usually more expensive.

To summarize, Zigbee Bluetooth and Wifi can be used depending on the requirement for the uplink and some works have been published using these technologies in a bidirectional hybrid communication link [5–7].

Nevertheless, in this work we show that inductive coupling can also be used to implement the uplink providing not only a communication link but also a mean to transfer power wirelessly to MD's. The results showed in the following section (Section III) evidence that the proposed method is competitive with the technologies presented in this section.

III. Analysis and Simulations of Inductive Coupling for VLC Systems

The scenario to analyze and simulate the use of inductive coupling for VLC uplink and WPT is a $6m$ x $6m$ x $3m$ room shown in Fig. 3. In order to achieve an average of $400\ lux$, enough for normal office work, show rooms or labora- tories, 6 lights from General Electric (ED35/DK24/835/10/SO, 46.6^{11} (L) x 22.5^{11} (W), $36W$) distributed as illustrated on Fig. 3 were used.

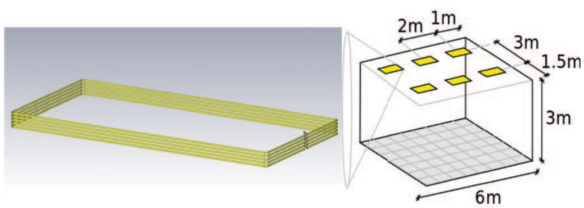

Fig. 3. Transmitter coil and scenario to simulate.

We will assume that the transmitter coil is a five turn cooper wire placed in the edge of each light box, the exact values of coils inductance and quality factor depends on the coil design which is out of the scope of this paper. Each MD will have the VLC receiver photo diode (downlink) and a coil to implement uplink and receive power. The size of the coil in the MD may varies depending on the available space.

The throughput that can be achieved by the inductive coupling is much lower than the one that can be achieved by VLC [3]. By using VLC for downlink we also has all the advantages mentioned in Section I. In addition, as the inductive coupling is used for WPT (and not for downlink) higher link efficiency can be achieved. This justify the joint use of VLC and inductive coupling.

Since maximum throughput and WPT efficiency are strongly related by the coils quality factor on an inductive coupling link [10], both characteristics are studied for the same system in the remainder of this section.

A. WPT in VLC context

The selected frequency for WPT is $13.56\ MHz$ since it is the same used in some RFID and NFC systems, and is available worldwide. Others previously proposed systems to transfer power for relative long distance ($2\ m$) have used this same frequency. In addition, this frequency is far from the GHz where most of the communication technologies work, preventing interference.

The maximum power that can be transmitted is limited by the safety levels with respect to human exposure to radio frequency electromagnetic field [11]. In our application, for inductive coupling, the maximum peak magnetic field strength $H_{peak} = 1.7\ A/m$ at $13.56\ MHz$ [11] must be taken into account. The simulation presented in Fig. 4 shows that for a current of $500\ mA_p$ in all the coils, the magnetic field fulfill the safety limit $30\ cm$ below the coils in the ceiling. Thus, $500\ mA_p$ is going to be considered the maximum permitted peak current in our system.

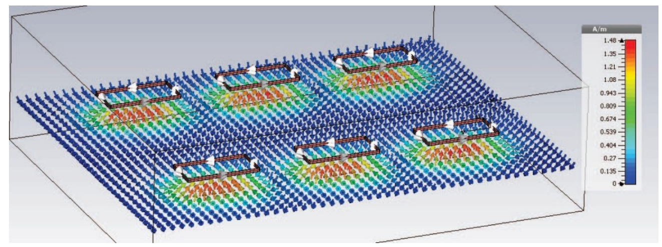

Fig. 4. Magnetic field peak strength (H) $30\ cm$ below the coils in the ceiling with $500\ mA_p$ excitation current. The maximum value of H is $H_{peak} = 1.5\ A/m$ (red arrows). CST Studio Suite simulation.

The size of the receiver will depend on the size of the MD. If the receiver is a portable device, the commercial W7002 wire loop Antenna from Larsen-Antennas can be used (94.6x56.8x3.65 mm, $L = 650\ nH$ and $Q = 57@13.56\ MHz$). For this antenna, placed concentric with the transmitter and $1.5\ m$ far from the ceiling, the maximum received power is $1.3\ mW$ (with $500\ mA_p$ at the transmitter). In this calculations we are not considering the losses in the circuits at the receiver (matching network, rectifier etc.) since it depends on the circuits used. This is useful to give an idea of the received power that can be achieved.

As can be seen, the transmitted power is low, compared with the power consumptions presented in Fig. 1 for example. However, this power is enough for many low-power circuits. If the transmitter coil has Q=60 the WPT efficiency will be $6.5\ m\%$. To improve it, the use of additional resonant coils can be considered as it was done in [10]. Anyway, as no high link efficiency will be achieved, we consider that the WPT capability is a feature to be used exceptionally. For instance, if a MD has run out of power and its function is essential, WPT can be used to maintain vital tasks until the device's battery is recharged by other mean or substituted. It can be also useful to have a communication link when the MD is totally powered OFF, and this link can be even used to turn it ON.

It is worth to mention that if our receiver is a robot, for instance, it could be possible to use a larger receiver coil increasing the power transfered and the link efficiency. Doing the same approximations, for a 46.6^{11}x22.5^{11} receiver (equal to the transmitter), 1.5 meters far from the ceiling up to $1.3\ W$ can be transmitted with a 5.8% efficiency.

Variation of received power and efficiency for different distance and orientations inside the room are out of the scope since it demands a deeper discussion. For example, the light distribution should be designed not only to generate a homogeneous illumination level but also to generate a good magnetic field strength. In addition, phase shift can be added to the coils' current to control field direction and allow different device orientations. The study with multiple receivers is also interesting, since the link efficiency increases if there are more than one device receiving power from the same transmitter. This topics can be included in the future on an extended version of the paper.

B. Inductive coupling for Uplink communication

The typical RFID high frequency ($13.56\ MHz$) follows the ISO/IEC 18000-3 international standard. It specifies that the reader works in full-duplex way while the tag replies to the interrogator by amplitude modulation of a subcarrier (between $969\ kHz$ and $3013\ kHz$). We consider that this standard does not fit our application. First, as it was shown in Sub-Section III-A, power will not be delivered all the time. Therefore, a full-duplex behavior (using the uplink while power is being received) is not necessary. Then, inductive coupling achieves higher performance if the working frequency is equal to the resonance frequency of the coils. By using a half-duplex link (power and data uplink are used at different times), thus we are able to use the same frequency for WPT and uplink. If we also implement the uplink using amplitude shift keying (ASK, instead frequency shift keying for example), we can be at resonance all the time, achieving high performance.

To validate the uplink implementation we consider the case where a sequence of high and low bits are transmitted from the W7002 coil $1.5\ m$ far from the ceiling using amplitude modulation at $13.56\ MHz$. The received signal by the coil in the ceiling is $10\ mV$ which is enough for bit decoding [10], when $3.8\ mW$ ($5.8\ dBm$) are transmitted from the MD. It should be noticed that this power was obtained only considering the power dissipated in the W7002 coil, the total power consumption will depend on the circuit implementation which is out of the scope.

In order to estimate the maximum throughput that can be achieved we follow the same approximations done in [10]. The limitation in throughput is imposed by the transient response of the system that may generate intersymbol interference between consecutive bits. Each bit takes Q/π cycles until decaying in value to 37% of its initial value on an isolated coil with quality factor Q. Thus, assuming a coil quality factor of 60, each bit should be transmitted for at least 30 cycles in order to be sure that the previous bit has reduced its amplitude below 37% for the last 10 cycles. Working at $13.56\ MHz$, it means that around $450\ kbps$ can be achieved. Of course it depends on the circuits used, the simplifications presented here are done to estimate the limitation imposed by the inductive coupling link.

IV. Final Discussion

There are existing uplink transmission technologies in VLC, such as Bluetooth, WiFi, and Zigbee. We explained the benefits to combine WPT (Near field, inductive coupling) with VLC for applications like indoor positioning over current RF solutions including ability, power support and safety. Their benefits enable a new and wider range of indoor positioning system. Additionally, WPT can charge receiver terminal with a limited power which could be enough to maintain vital tasks until the device's battery is recharged by other mean or substituted.

If the system described in Section III is placed in Fig. 1 it will be near RFID high frequency as the operating principle is almost the same. Regarding transmitted power and throughput on Fig. 2 the inductive coupling described in Section III has similar features than the chip CC2630 (Zigbee) transmitting at $5\ dBm$.

The proposed joint use of VLC and WPT has similar characteristics than the system presented in [12], where a solar panel was used not only to receive the data from the light but also to harvest energy. In that case $8\ kbps$ downlink throughput was achieved and it was limited by the solar panel that acts as a low-pass filter. The power received by the solar panel $50\ cm$ far from the light was $125\ mW$. The proposed system has same advantages like the receiver coil could be lighter and cheaper than a solar panel (Receiver coil W7002 unitary price is around $USD\ 7$), it provides an uplink mechanism (which is not provided by the solar panel) and power can be transmitted even in the dark (light turned OFF). The main disadvantage is the low efficiency which can not be overcome with the geometry of the system (long distance and small receiver).

References

[1] K. Zhou, T. Liu, and L. Zhou, "Industry 4.0: Towards Future Industrial Opportunities and Challenges," in *FSKD 2015*, Aug 2015, pp. 2147–2152.

[2] C. Baylis, M. Fellows, L. Cohen, and R. M. II, "Solving the Spectrum Crisis: Intelligent, Reconfigurable Microwave Transmitter Amplifiers for Cognitive Radar," *IEEE Microwave Magazine*, vol. 15, no. 5, pp. 94–107, July 2014.

[3] O. Ergul, E. Dinc, and O. B. Akan, "Communicate to Illuminate: State-of-the-art and Research Challenges for Visible Light Communications," *Physical Communication*, vol. 17, pp. 72 – 85, 2015.

[4] J. Lee, Y. W. Su, and C. C. Shen, "A Comparative Study of Wireless Protocols: Bluetooth, UWB, ZigBee, and Wi-Fi," in *IECON 2007*, Nov 2007, pp. 46–51.

[5] X. Li, R. Zhang, and L. Hanzo, "Cooperative Load Balancing in Hybrid Visible Light Communications and WiFi," *IEEE Transactions on Communications*, vol. 63, no. 4, pp. 1319–1329, April 2015.

[6] Y. U. Lee and M. Kavehrad, "Long-range Indoor Hybrid Localization System Design with Visible Light Communications and Wireless Network," in *IEEE Photonics Society Summer Topical Meeting Series*, July 2012, pp. 82–83.

[7] M. S. Kim, I. S. Jang, S. K. Lim, and T. K. Kang, "Implementation of ZigBee-VLC System to Support Light Control Network Configuration," in *ICACT 2016*, Jan 2016, pp. 153–156.

[8] C. Seredy and K. Austin, "Companies to Showcase First Indoor Location Solution to Communicate with Shoppers' Smart Devices Using Both Visible Light Communication and Bluetooth Low Energy," June 2014. [Online]. Available: www.gelighting.com

[9] X. Liu, H. Makino, S. Kobayashi, and Y. Maeda, "Design of an Indoor Self-Positioning System for the Visually Impaired - Simulation with RFID and Bluetooth in a Visible Light Communication System," in *EMBC 2007*, Aug 2007, pp. 1655–1658.

[10] P. Pe´rez-Nicoli, A. Rodr´ıguez-Esteva, and F. Silveira, "Bidi- rectional Analysis and Design of RFID Using an Additional Resonant Coil to Enhance Read Range," *IEEE Transactions on Microwave Theory and Techniques*, vol. 64, no. 7, pp. 2357– 2367, July 2016.

[11] "IEEE Standard for Safety Levels with Respect to Human Exposure to Radio Frequency Electromagnetic Fields, 3 kHz to 300 GHz," *IEEE Std C95.1-2005 (Revision of IEEE Std C95.1-1991)*, pp. 1–238, April 2006.

[12] B. Malik and X. Zhang, "Solar Panel Receiver System Implementation for Visible Light Communication," in *ICECS 2015*, Dec 2015, pp. 502–503.