UNIVERSITATEA DIN PETROȘANI

DOCTORAL SCHOOL

DOCTORAL THESIS

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Contributions Regarding LiFi Technology's Industrial Application

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Abstract

During the last period, mobile data traffic has significantly increased worldwide. This phenomenon is due to several factors, such as: the increase of the number of smartphone users, the intensive use of mobile applications, the video and audio streaming, online games, social networks, the increase of the number of Internet of Things (IoT) devices, the increase of the number of people working remotely, online education, etc. In order to handle the growing demands for mobile data, telecommunication industry works hard to develop and get solutions and to improve the infrastructure of mobile networks. One such solution is relying on the LiFi technology (Light Fidelity), which was standardised for the first time on August 4th, 2023 (standard IEEE 802.15.13).

Concomitantly with the above facts, the industries manufacturing goods and services have been continually modernizing lately out of necessity and desire to increase their digital IQ. At present, a lot of manufacturing processes are out-dated and require various upgrades for matching the permanently increasing market demands. As part of this process of constant reinvention, the manufacturers of goods and services employ various automation devices that require, most of the time, long wires to operate; this restricts autonomy as well as the rapid reconfiguration of manufacturing lines. Nowadays, wireless telecommunication technologies for industrial domains have greatly improved the capacity of manufacturers to collect critical information, to analyse such information and to respond to such information. These innovating ideas represent the key factor for increasing productivity, profitability and for diminishing the drawbacks previously mentioned. At present, the wireless transmission of industrial data is carried out by means of techniques relying on radio frequencies (RF). They are included in the standard WLAN IEEE 802.11n, for transmissions displaying a data rate of up to 600 Mbps, or the standard 802.11ac for transmissions exhibiting a data rate of up to 1300 Mbps

At present, modern plants should appropriate the following concepts that define Industry 4.0: *interoperability* (plants should hire people and be equipped with machines, devices and sensors that are interconnected and are able to communicate with each other); *information transparency, technical assistance* (systems should be able to support the people in making decisions and solving problems as well as in providing assistance for tasks that exceed human capacities); *making decentralised decisions* (systems should be able to act autonomously and make simple decisions on their own). The main challenges Industry 4.0 has to face at present are as follows: *issues concerning data safety* (due to integrating new systems and to the permanently increasing need for accessing these systems); *integrity of the manufacturing process* (this process is hardly maintained with a small human monitoring team only); *technical issues* (reliability and stability of equipment for maintaining communication are difficultly achieved); *using radio frequencies for communication* (it faces latency dangers and issues turning these communication systems into unsafe systems).

Under such circumstances and considering the advantages and performance provided by the LiFi technology (high data transfer rates, data safety, reliability and connectivity in sensitive environments,

etc.), it is believed that its implementation in the industrial environment is going to greatly improve the capacity of producers to collect critical information, to analyse such information and to rapidly respond to such information; this represents the key factor for increasing productivity, profitability and for diminishing the drawbacks of the other technologies employed at present. Nowadays, the implementation of the LiFi technology in the industrial environment is in its pioneering stage.

Taking into account the context presented, the main objectives of the doctoral thesis are:

- Developing the user equipment (UEs) and access points (APs), used in LiFi technology;
- Getting the precise mathematical models of the LiFi communication channels (downlink and uplink channels);
- Developing efficient techniques for encoding/decoding and correcting errors with a view to enabling supplemental safety and the correct retrieving of the data transmitted through the LiFi communication channels;
- Experimental testing of a system of communication relying on LiFi technology;
- Exemplifying the manner of implementing LiFi technology in the industrial environment.

With a view to carry out the objectives presented, the doctoral thesis is structured in five chapters, seven appendixes and a bibliography, closely correlated to the topic approached.

In accordance, the *first chapter* displays a short history of LiFi technology as well as the main notions that regard: the structure of a LiFi communication system, LiFi networks and interferences management. The role of this chapter is to better understand LiFi technology, to find out the present stage of researches and to correctly identify research paths with a view to reach the objectives required.

Taking into account the importance of power electronics for the LiFi technology, in order to get more efficient lighting devices that are also used as access points (APs), the *second chapter* analyses, through numerical simulation in Matlab-Simulink, as well as experimentally, the main DC-DC convertors, which are employed as LED drivers in APs: DC-DC buck convertor, DC-DC boost convertor and buck-boost DC-DC convertor. On the other hand, at the end of this chapter, I analyse, through numerical simulation in Matlab-Simulink, the DC-DC resonant convertors.

In the *third chapter* I present three new topologies of DC-DC convertors, which do not include large electrolytic capacitors. They are minutely designed so that the output voltage fluctuations as well as the output current ripple do not affect the quality of lighting and the data transmitted and LED protection occurs optimally. The DC-DC convertors presented in this chapter are analysed through simulation in LTSpice. These topologies enable the size decrease of the access points (APs), and of the user equipment (UE) employed by LiFi technology, with energy efficiency and reliability that are higher than those of the classical DC-DC convertors, which include large electrolytic capacitors (convertors studied in the second chapter). In addition, the absence of large electrolytic capacitors in the APs and UEs enables the decrease of costs and of electromagnetic noise.

In the *fourth chapter* I set out the most relevant researches and results in the field of the mathematical modelling of the LiFi communication channels, assuming that both the AP and the UEs are fixed. The importance of this chapter relies on the fact that the most precise mathematical models of the LiFi communication channels enable performing designing as well as the most accurate testing of the LiFi communication systems. The mathematical models of the LiFi communication channels are classified in the fourth chapter in two large categories: non-parametric mathematical models and parametric mathematical models. Among the most important mathematical models displayed in this chapter we should mention the following ones:

- The non-parametric mathematical model relying both on the geometry of the room and on the diffuse reflexions of the objects and walls in the room. The relations that define this mathematical model enable the calculation of the impulse response of the LOS and NLOS communication channels in a LiFi communication system. In addition, I present, in detail, the simulation program in Matlab, which ensures the pinpointing of the impulse response of the LOS and NLOS communication channels as well as the highlighting of the SNR, in decibels, depending on the distance between the AP and the UE;
- The parametric model of the LiFi communication channel based on FLANN (Functional Link Artificial Neural Networks) neuronal networks, which employs the orthogonal Laguerre function and generalised Laguerre function. With a view to getting the input/output data used for training the FLANN neuronal network, I carried out an experiment with a photo resistor and a buck DC-DC convertor, without a large electrolytic capacitor. In accordance, the input signal is considered to be the current through the coil of the buck DC-DC convertor, while the output signal is defined by the voltage on the photo resistor. On the other hand, I present, in detail, Matlab program that enables the training of the FLANN network with a view to getting the mathematical model of the LiFi communication channel.

In addition, based on the study carried out in this chapter and corroborated with other researches conducted so far, I pinpoint two very important research paths that have not yet been sufficiently approached and that regard the mathematical modelling of the LiFi communication channels.

In the *fifth chapter* I display two methods for detecting and correcting the errors of the data received along the LiFi communication channels, affected by noise (enhanced Hadamard code and 3D Hadamard code). Both error detection and correction methods of the data transmitted are presented at length and are implemented in Matlab program. Based on these Matlab programs, the users might encode/decode as well as detect and correct the errors of the data received, relying on the enhanced Hadamard code and 3D Hadamard code. Meanwhile, with a view to pinpoint the usefulness and performance of the enhanced Hadamard code and 3D Hadamard code in detecting and correcting the errors of the data received along a LiFi communication channel, I design, also in this chapter, a LiFi communication system between an access point (AP) and a user equipment (UE), with two computers and two LiFi (IPMS 1GHS) hotspots, manufactured by Fraunhofer Institute for Photonic Microsystems (IPMS), in Germany. The final part of this chapter presents two practical applications of LiFi technology in the industrial environment. Both applications include the FX3U PLC, manufactured by Mitsubishi as well as LiFi (IPMS 1GHS) hotspots. The first application displays the control module of a series of electro valves while employing LiFi technology and RS485; the second application presents a system for monitoring the pressures and temperatures of a series of heat exchangers, where the interface between the automation panel and the computer (where the acquired data are saved) occurs through LiFi technology. With this in view, I employ two LiFi (IPMS 1GHS) hotspots, manufactured by IPMS. On the other hand, as part of the first application, I propose a new concept for decentralising the automation panel, through employing user equipment (UE) based on LiFi technology, which enables various functions, such as: data acquiring from various transmitters, UEs with 4/6/8 analogic inputs/outputs, UEs with 4/6/8 digital inputs/outputs, etc.

At the end of the doctoral thesis, I set out the main *conclusions and personal contributions* to LiFi technology as well as a series of research proposals that might be approached in the future.

All the chapters and the *bibliography and seven appendixes* at the end of the doctoral thesis represent a solid theoretic and practical support for the designers and researchers in the domain of LiFi technology.

A. Final conclusions

The final conclusions of the doctoral thesis rely on the conclusions pinpointed in each chapter.

In accordance, from **Chapter 1** the following conclusions come out:

- LiFi (Light Fidelity) technology has emerged from the need to supplement the radio spectrum used in wireless communication, which has lately been extremely congested due to the very high mobile data traffic;
- The term LiFi was first used in August 2011, by Professor Harald Haas, in a speech at TEDGlobal Conference, in Edinburgh, Scotland;
- LiFi technology was standardised on August 4th, 2023 by IEEE (standard IEEE 802.15.13), being an extension of VLC (Visible Light Communication) technology;
- LiFi is a wireless optical communication technology (OWC - Optical Wireless Communication), where data transmission occurs along short distances, relying on the electromagnetic waves in the visible, ultraviolet and infrared spectrum;
- The spectral resources of LiFi technology are about 10,000 times higher than those of the technologies relying on radiofrequency;
- The LiFi access point (AP) is an electronic device that enables the connection of one/several user equipment (UE);

- LiFi principle relies on the encoding and transmission of the data through modulating the amplitude of light sources, in accordance with a well-defined and standardised protocol; Communication between the devices in a LiFi network (communication between the access points and the user equipment) occurs bidirectionally (half – duplex/full – duplex), in multiuser mode (point-to-point, multipoint-to-point, point-to-multipoint, multipoint-to-multipoint). As a rule, for downlink, LiFi employs the electromagnetic waves in the visible spectrum, while for uplink it employs the electromagnetic waves in the infrared and/or ultraviolet (in order to eliminate the interferences between downlink and uplink and not to disturb mobile users' attention during uplink transmission). As far as the VLC technology is concerned, communication between two devices might occur unidirectionally (simplex) or bidirectionally (half – duplex/full – duplex), using, as a rule, the point-to-point communication mode, where both the downlink and the uplink use only the visible spectrum;
- The structure of a LiFi access point (AP) includes the following blocks associated with data transmission: *one or several LEDs* whose role is to light up the room and transmit the data through downlink; *one encoding block* owing to which a sequence of symbols gets a certain signification, with a series of semantic rules (by means of this operation, we are able to detect and correct possible errors in the data received and decoded), and *a modulator* (whose goal is to adapt the signal/message signals to the characteristics of the channel, to multiplexing signals, to efficiently transmit the signals and minimize the disturbing effects along the LiFi channel). The encoding block includes two subsets: the *source encoding block* ~ that transposes the message into the source alphabet, and the *channel encoding block* ~ that transposes the message into the alphabet of the communication channel. The *source encoder* converts the symbol sequence in a sequence of binary values (0 sau 1), while the *channel encoder* groups into *words* these binary symbols. On the other hand, the blocks associated with data reception in an AP are as follows*:* a *photodetector* (converting light into electric current), an *amplifier with transimpedance* (whose role is to convert the current at the output of the photodetector into voltage), an *ambient light filter* (used in the feedback loop of the transimpedance amplifier (TIA), (whose role is to decrease direct current at the output of the photodetector determined by the other lighting fixtures in the room), an *anti-aliasing filter* (which filters the voltage at the output of the TIA and adapts it to a certain field enabled by the demodulation circuit), a *demodulation block* (which extracts the original signal from the received modulated signal and also performs the demultiplexing function, whenever required), and a *decoding block* (which performs the same functions as the encoding block, but inversely). In addition, this block also memorizes a certain number of words/messages and also performs synchronising. Besides the previously mentioned blocks, the structure of an AP might also include the following blocks: analog-to-digital convertors (ADC),

digital-to-analog converters (DAC), clock and timing circuits, and equalising/adapting blocks. As a rule, the power supply of an AP is made by means of an external continuous voltage source.

- The structure of the user equipment (UE) is usually identic to that of the access points (APs), with the difference that a UE includes a *photo diode* (acting as a photo detector through downlink reception) and *infrared LEDs* (used for transmission of the data in the infrared spectrum to the APs through the uplink). The power supply of the UE is made by means of a battery/accumulator in order to enable the full mobility of the users;
- Several access points (APs) may be included in LiFi networks, which may connect according to various network topologies. Backhaul connections of the access points occur, as a rule, through optical fibre; nonetheless, other connections might be used, such as PoE (Power over Ethernet), EoP (Ethernet over Powerlines), etc.;
- Connecting LiFi networks with other communication networks is made through a network gateway. LiFi networks may be used in tandem with the wireless communication networks in radiofrequency (WiFi, Bluetooth, ZigBee, etc.);
- MultiCast communication may be carried out in LiFi networks (when the sender communicates with a part of the network devices – not with all of them) as well as BroadCast communication (when a sender in the network communicates with all the other devices in the network);
- LiFi networks as well as hybrid RF/VLC networks represent, nowadays, a viable solution for the spectrum crisis. This crisis consists in the lack of a wireless frequency spectrum that is broad enough to provide communication in most wireless devices;
- As a rule, through the uplink, mobile devices (UEs) transmit feedback information to the APs (confirmation of the reception of the data communicated through downlink, information on the condition of the communication channel (CSI), file loading, etc.);
- The most widely used handover techniques in complete LiFi networks are the following ones: horizontal handover (HHO) and vertical handover (VHO);
- In case of HHO, the user exchanges an access point with another access point that employs the same network technology;
- In the case of VHO, a user exchanges an access point with a certain network technology (for instance, an AP with LiFi technology) with another access point that employs a different network technology (for instance, an AP with RF/VLC technology);
- In LiFi networks, both the techniques that enable the handover between adjacent APs (neighbouring) and the techniques that enable the handover between non-adjacent APs (handover skipping) may be encountered;
- At present, decisional algorithms that allow choosing between HHO or VHO, at a certain moment, take into consideration one or several parameters that regard: the speed of the UE, the

condition of the communication channel (CSI), data rate, statistic information concerning the blockage of the communication channel, etc.;

- With a view to getting robust LiFi networks, the decisional algorithms employed in the handover techniques should provide the obtaining of rapid answers so that the transmitted data are not affected. These decisional algorithms should take into account the quality of the communication channel, available resources as well as the time according to which a certain UE is maintained connected with a certain AP (CDT - Cell Dwell Time);
- In order to get heterogeneous LiFi networks (HetNet networks), cell-centred architecture has been preferred lately (this is due to the small coverage radius of an AP);
- Within a cell-centred LiFi network, the control of UEs' mobility (within the coverage of a certain AP), signal processing, resource management, service providing, etc. are provided by the associated access point (AP);
- The most used architectures for bidimensional positioning of the LiFi APs are as follows: hexagonal architecture, square bars architecture, architecture relying on the process of homogeneous Poisson point and Hardcore point process architecture;
- With a view to avoiding the interferences among adjacent cells (CCI - Co-Channel Interference) as well as to minimizing the consumption of electrical energy, in the case when there is no UE within the coverage area of an access point, it is disabled (the communication functions of the associated AP are disabled). In such a case, the AP is only used for lighting the room;
- CCI interferences might also be attenuated by means of a series of resource management algorithms that are transmitted to the UEs in a LiFi network. The resources associated with these methods are divided into blocks that regard the domain of time, frequency, wave length, power, etc. The partitioning of these resources might be static or dynamic;
- Another method for decreasing CCI interferences relies on the angle diversity of the APs and/or UEs in LiFi networks (ADT - Angle Diversity Transmitter). This method for decreasing interferences is specific for the LiFi technology as it is not borrowed from radiofrequency cellular technologies;
- The LiFi networks containing APs and UEs with angle diversity are more performing than the LiFi networks that contain APs and UEs with a single element (CCI interferences are significantly softened; the APs and UEs display a better spectral efficiency; communication system is not significantly influenced by the space location of mobile UEs, etc.);
- The most important advantages of LiFi technology are as follows: *very high data transmission speed* (at present, the speed reached is 224 Gbits/s, in laboratory conditions); *no radio interferences*; *safety* (unlike WiFi, light does not go through walls, which accounts for a better safety of LiFi networks); *bandwidth* (the spectral resources of LiFi technology are about 10,000

times higher than those of WiFi technology); *use in sensitive environments* (hospitals, nuclear plants, underground mining units, airplanes, etc.); *fewer exploitation costs* than WiFi technology;

- The main drawbacks of LiFi technology are as follows: *limited range* (an AP is able to cover one room, at most); *requiring of a light source for functioning* (this limits the use of LiFi technology to the rooms which do not require light or where light should be decreased); *high initial costs* (the implementation of LiFi technology requires high initial investments; for instance, two LiFi, IPMS 1GHS hotspots, manufactured by IPMS, Germany, cost 3,600 Euro in 2022); *interferences produced by other light sources* (natural light as well as light coming from other light sources might interfere with LiFi signal, accordingly affecting reliability and performance); *issues regarding compatibility* (as this is a rather new technology, it is not compatible with a series of existing devices and equipment).

Relying on the experimental studies as well as on the numerical simulation in Matlab-Simulink carried out in **Chapter 2**, I am able to pinpoint the following conclusions:

- In LiFi technology, the emitter in an AP should carry out two functions: room lighting function and data communication function;
- At the moment, the designing of the control circuits of high luminosity LEDs (LED drivers) faces the following challenges: capability for implementing modulation, driver efficiency and providing the bit rate required for communication. The modulation of the intensity of the light emitted by the LED should be done so that the room lighting function is not affected. With this in view, the control of the current through the LED should be efficient and performing. In accordance, in order that lighting is not affected, modulated current should be according to a certain DC polarisation level;
- LED drivers associated with DC-DC convertors with a rapid output response are able to change the output voltage at rates of the order of MHz. These convertors generate, at the output, both the polarising current associated with the LED and the current associated with the information that is going to be transmitted;
- The main DC-DC convertors that are used as LED drivers in APs are the following ones: buck DC-DC convertors, boost DC-DC convertors, and buck-boost DC-DC convertors;
- Buck, boost, buck-boost DC-DC convertors are able to provide digital modulations (ASK, PSK, QAM, etc.);
- DC-DC convertors behave as radio frequency power amplifiers (RFPA), where the supply voltage applied to the power amplifier (RF) is continually regulated so that the amplifier operates with maximum efficiency (ET - Envelope Tracking technique; EER - Envelope Elimination/Restoration technique);

- The main problem of the buck, boost, buck-boost DC-DC convertors used as LED drivers reagards their dynamic performance under transitory regime of the output response of the DC-DC convertor. Overshooting is high at swithcing frequences of the order of tens of MHz. As a rule, in order to diminish this drawback, higher order filters are employed at the output of the DC-DC convertors (these filters employ large electrolytic capacitors). The output filter should behave as a band-pass filter that eliminates switching frequency. The designing of the filter should be done so that its chopping frequency is high enough to be able to cancel the superior components of switching harmonics. Besides, the switching frequencies of the transistors included in the DC-DC convertor should range within reasonable limits so that the efficiency of the convertor is not affected;
- Another strategy for increasing the transitory regime performance of LED drivers relies on the use of hybrid architectures, where, apart from the rapid response DC-DC convertor, a linear controller is also employed. At present, there are researches that pinpoint the fact that, in certain cases, the parallel hybrid architecture is more efficient than the series hybrid architecture;
- The experimental tests have shown that switching frequency influences the efficiency and thermal performance of the DC-DC convertors analysed (buck, boost and buck-bost) as well as the current-voltage feature of the LED (due to temperature). The higher the switching frequency the more efficient the DC-DC convertor. Nonetheless, a too high switching frequency might determine switching losses as well as the excessive warming of the components of the DC-DC convertor and LED. In accordance, I may assert that the output current and voltage of the DC-DC convertors studied change depending on the switching frequency of the transistor. In the case of the buck and boost convertors, the output voltage does not change, while the output current increases with the increase of the swithcing frequency. In addition, in the case of the buck-boost convertor, both the output voltage and the output current increase with the increase of the switching frequency. These effects enable the getting of various LED brightnesses. In accordance, when increasing the switching frequency of the transistor in the DC-DC convertor employed, LED brightness increases;
- Besides, experimental tests show that, in the case when the switching frequency of the transistor in the DC-DC convertor increases, the output voltage is much more stable, displaying smaller ripples. On the other hand, the increase of the switching frequency of the transistor in the DC-DC convertor enables the getting of a much smaller ripple of the output current;
- Another possibility for getting LED drivers relies on the use of DC-DC resonant convertors (a resonant convertor includes an invertor, a band-pass filter and a rectifier). The main advantages of the DC-DC resonant convertors regard the small switching losses as well as the decreased energy required for controlling the transistors. In addition, the use of the soft switching in DC-DC convertors (SSC - Soft-Switching Converters) decreases the noise in the system and

electromagnetic interferences are smaller, too. With a view to getting a desired wave form on the LED, the recovery block is built around a double-alternating diode single-phase rectifier, at the output of which a low-pass filter is attached (an RC filter);

- In order to get a maximal power transfer, the DC-DC convertors should operate at a switching frequency close to the resonance frequency of the band-pass filter. The band-pass filter is designed around a LC resonant circuit (series, parallel or mixed);
- Another advantage of SSC convertors regards the possibility to use a small ferrite core (convertor), attached at the output of the band-pass filter, which enables its functioning within a wider range of continuous input voltages. Such a fact provides SSC convertors a better efficiency compared to the classic convertors (buck, boost, and buck-boost);
- Although, in DC-DC resonant convertors, the control of the current and voltage is more difficult than in the case of the DC-DC classic convertors, through an accurate planning of the control circuit and a proper designing, they might be employed for modulating the amplitude of light sources, with significant benefits for LiFi technology;
- Besides, nowadays researches show that the use of the DC-DC convertors with several phases (multi-phase convertors) in LiFi communication allows the increase of the bit rate as well as the better implementation of digital modulations. The main drawback is that the efficiency of multi-phase convertors is lower than the efficiency of classic convertors.

Chapter 3 sets forth the following conclusions:

- The DC-DC convertors that do not include large electrolytic capacitors enable the size decrease of the access points (APs) and of the user equipment (UE) in LiFi technology; they display a higher energy efficiency and reliability than the classic DC-DC convertors (which include large electrolytic capacitors);
- The absence of the large electrolytic capacitors from the APs and UEs enable the decrease of costs (DC-DC convertors are cheaper) and of electromagnetic noise (capacitors might determine electromagnetic noise);
- During the transitory starting regime of the DC-DC convertors without large electrolytic capacitors, the current through coils does not display override, in the case when the power supply of the convertors comes from a stable voltage source;
- The control systems of the DC-DC convertors that do not include large electrolytic capacitors are simple and robust in all cases of operation, when non-linear controllers with hysteresis are employed;
- In the case of the DC-DC convertors that do not include large electrolytic capacitors, the dimming effect might be easily controlled;

- Through using various LEDs (that radiate red, green and blue light) within the load of the DC-DC convertors that do not include large electrolytic capacitors, chrominance might be easily controlled and the data might be transmitted along three different channels towards the receiving system. Chrominance might be adjusted through changing the on-time of the LED rows (row of blue, red and green LEDs);
- In the case when the LEDs in the load of the DC-DC convertor without a large electrolytic capacitor are connected through wires that display a certain parasitic inductance, a snubber is placed in parallel with each transistor in order to eliminate overvoltage occurring on the transistor/transistors included in the convertor;
- When the voltage source is connected to the input of the DC-DC convertor that do not include a large electrolytic capacitor through wires that display a certain parasitic inductance, a small capacitor is installed at the output of the voltage source in order to eliminate the overvoltage on the main transistor;
- The DC-DC convertors without electrolytic capacitor might be easily extended for multi-phase systems.

From **Chapter 4**, the following conclusions may be set forth:

- The most appropriate mathematical models of the LiFi communication channels enable the analysis, testing and performant designing of the LiFi communication systems;
- The mathematical models of the LiFi communication channels may be classified into two large categories: non-parametric mathematical models and parametric mathematical models;
- The most used strategies for getting the non-parametric mathematical models of the LiFi communication channels are the following ones: experimental determination of the response of the communication channel at an impulse input; identification of the communication channel while employing sinusoidal sample signals (using frequency analysis); identification of the communication channel while using correlation analysis; identification of the communication channel through using spectral analysis, and analytical determination of the response of the LOS and NLOS communication channel, considering the geometry of the room and the diffuse reflexions of the objects and walls in the room;
- The most used strategies for getting the parametric mathematical models of the LiFi communication channels are the following ones: getting the impulse response of the communication channel based on Monte Carlo method/Monte Carlo adjusted method (relying on the monitoring of the beams that are randomly transmitted by a certain AP; the parameters determined are as follows: the number of beams received by a certain UE, the optic power of each of the beams received as well as the propagation time of each beam); polynomial identification (based on ARX, OE, etc. models, where the parameters might be determined by

means of an off-line or on-line algorithm), and the identification relying on neural networks (MLP - Multilayer Perceptrons neural networks, FLANN - Functional Link Artificial Neural Networks, etc.);

- With a view to determining the impulse response of the LiFi communication channel, specialised simulation programs might also be used, enabling the accurate description of the interaction of the beams in a room displaying a specific size. These programs are able to calculate the power and propagation duration for each beam transmitted by the AP, while considering the reflexion characteristics of the objects/surfaces in the room under analysis.

Relying on the analysis in **Chapter 5**, the following conclusions might be set forth:

- Through using the error detection and correction enhanced Hadamard code/3D Hadamard code, the need for re-transmitting the data decreases, while saving, as a consequence, both the bandwidth of the channel and the resources of the LiFi communication system. In addition, when employing these error detection and correction codes, reliability of communication is improved (the LiFi communication system provides a high quality of services even under increased noise, enabling its use for special transmissions that regard critical applications, such as: emergency communication, real time transmissions, etc.);
- The experimental tests show that the error detection and correction algorithm, based on the enhanced Hadamard code, entirely corrects the incorrect code words, with 100% certitude, in the case when the AP and the UE are fixed and perfectly aligned (there is a LOS channel between them) and are located at a distance ranging between 30 [cm] and 440 [cm]. In the experimental tests, both the UE and the AP include a LiFi IPMS 1GHS hotspot manufactured by Fraunhofer Institute for Photonic Microsystems (IPMS), in Germany;
- The implementation of the LiFi technology in the industrial environment might improve the capacity of the manufacturers to collect critical information in real time, to analyze such information and to respond to such information, which is the key factor contributing to the increase of productivity, profitability and the diminishing of the drawbacks exhibited by the other technologies that are used nowadays;
- The use, in the industrial environment, of a series of input/output modules relying on LiFi technology (UEs that might display 4/ 6/ 8 analogic inputs/outputs, 4/ 6/ 8 digital inputs/outputs, etc.), enables the location of such modules near the automatized process, determining the increase of flexibility, of energy efficiency (cable lengths and power losses are decreased), and of the reliability of the entire automation system. In accordance, APs also rely on LiFi technology, but the connections between them might use various network topologies, where the communication between the APs occurs by means of ModBus, ProfiBus, FieldBus, Ethernet, etc. protocols;

- The use of the LiFi technology in the industrial environment is able to decentralize automation panels, determining a decrease of the initial and maintenance costs as well as the increase of flexibility and reliability of this environment;
- The use of the LiFi technology for the decentralized monitoring of the parameters of industrial processes allows the real time monitoring of the parameters (pressures, temperatures, etc.), data safety, production digitalizing and the increase of the digital IQ of the goods and services manufacturers, in the context of Industry 4.0.

B. Contributions

The main contributions of the doctoral thesis are the following ones:

1. Analysis, through the numerical simulation in Matlab-Simulink as well as through experimental simulation, of the main DC-DC convertors (buck, boost and buck-boost), which are used as LED drivers in the access points (APs) and user equipment (UE) associated with LiFi technology;
2. Analysis, through numerical simulation in Matlab-Simulink, of the series resonant DC-DC convertors, used as LED drivers;
3. Presentation and analysis, through simulation in LTSpice, of three new topologies of DC-DC convertors that do not include large electrolytic capacitors, used for the APs and UEs associated with the LiFi technology;
4. Presentation of the most relevant researches and results obtained in the domain of the mathematical modelling of the LiFi communication channels, assuming that both the AP and the UE are fixed;
5. Matlab simulation program enables both the pinpointing of the impulse response of the LOS and NLOS communication channels and of the SNR, in decibels, depending on the distance between the AP and UE. The simulation program relies on the non-parametric mathematical model based both on the room geometry and on the diffuse reflections of the objects and walls in the room;
6. Experimental analysis of the buck DC-DC convertor that do not include large electrolytic capacitors, used as a LED driver;
7. Experimentally getting the parametric mathematical model of the LiFi communication channel, based on FLANN neural networks (Functional Link Artificial Neural Networks), which employs orthogonal Laguerre function/ generalised Laguerre function, the parameters of the neural network being determined based on an off-line algorithm;
8. Presentation and analysis, through simulation in Matlab, of the encoding/decoding algorithms, of error detection and correction algorithms and of enhanced Hadamard and 3D Hadamard algorithms;

9. Experimental testing of the enhanced Hadamard algorithm in a LiFi communication system where both the AP and the UE include a computer and a LiFi (IPMS 1GHS) hotspot, manufactured by Fraunhofer Institute for Photonic Microsystems (IPMS), in Germany;
10. Presentation of two industrial applications that use LiFi technology. The first application displays the controlling module of a series of electro valves while using LiFi technology and RS485; the second application displays a system for monitoring the pressures and temperatures of a series of heat exchangers, where the interface between the automation panel and the computer where the acquired data are saved occurs through LiFi technology. Besides, as part of the first application, a new concept regarding the decentralised automation relying on input/output modules associated with LiFi technology is set forth.

C. Proposals

The main proposals and research paths that might be approached in the future are the following ones:

- Development of the techniques for distributing the resources of LiFi networks. At present, this research path is still at the beginning. For instance, NOMA techniques for uplink are in the pioneering stage (most researches focus on downlink). In addition, the performance of LiFi networks, where resource distribution is made through NOMA techniques, requires supplemental researches (especially in the case of the networks with several UEs);
- Designing performant and efficient LED drivers, able to provide: complex modulations of signals (multi-carrier modulations); an optimal compromise between the lighting and communication functions (in case of APs); a high bit rate, etc. In accordance, new types of DC-DC multi-phase convertors without large electrolytic capacitors might be developed;
- Mathematical modelling of downlink and uplink channels in the LiFi systems, which represents another research path that might be developed. A tremendous research potential is also displayed by the on-line mathematical modelling of the LiFi communication channels, while pinpointing the scenarios where UE is mobile (UE moves and displays different time locations within the LiFi networks) and is randomly oriented towards the APs in the LiFi network. A proposal with this in view relies on getting the on-line mathematical models of the downlink and uplink communication channels, relying on FLANN neural networks, where the parameters of the neural network are determined through an on-line technique. In the future, when employing the FLANN neural networks for the mathematical modelling of the LiFi communication channels, other types of orthogonal functions, such as: Legendre, Cebasev, Hermite, etc., might be used;
- The management techniques for the handover of the UEs that move within the LiFi networks represent another very important research path that might be developed in the future. The choice of decisional algorithms used with this in view is a difficult task, relying on a compromise

between the calculation complexity of the algorithm (processing time) and the performance obtained (UE speed, data rate, quality of the channel, etc.);

- The “large scale” implementation of the LiFi technology in industrial applications, in the context of Industry 4.0, represents another new, very important research path that should be investigated both theoretically and experimentally. The main proposals with this in view regard the implementation of the LiFi technology in SCADA (Supervisory Control and Data Acquisition) systems, for flexible manufacturing lines, industrial robots, operational elements, transmitters, etc.

Taking into account the progress of the last years regarding the data transmission speed and the architectures employed, LiFi technology becomes more and more credible and promising. The possibilities for using the LiFi technology are numberless: road networks, automotive field, geolocation, industry, underwater communication, medicine, etc.