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APPLIED RESEARCH

A Study on the Feasibility of LiFi in an Intra-Vehicular Data Transmission Application

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ABSTRACT Given the recent advances in information technology, speed has become an important requirement in data transmission. In this regard and given that an LED (light emitting diode) can turn on and off for several thousands, even millions, of times per second, then LiFi (light fidelity) technology has strong advantages over WiFi (wireless fidelity) in terms of speed in data transmission. In this research project, a consortium of industrial and academic partners have decided to evaluate the maturity of LiFi technology by designing a demonstrator that showcases an efficient and speedy intra-vehicle data transmission system. The demonstrator implements a two-way LiFi communication between the reading light of a vehicle and a portable device, such as a tablet or smartphone. This nomadic device must display, via an interface, receiving transmitted data in real time. The data is of type RNT (Digital Terrestrial Radio) and TNT (Digital Terrestrial Television) provided by an in-house antenna. LiFi depends on optical technology hence, the devices' optical characteristics have significant influences on the system. This paper presents various conducted experiments and techniques to improve the system's throughput, communication range, and reception area. For instance, by replacing the reading light with one of better optical characteristics, the communication range and reception area improve. By using symmetrical power supply, the throughput improves. In the same manner, by using optical filters that eliminate noise, throughput likewise improves. We have indeed demonstrated that LiFi data transmission in the vehicle is feasible; low-definition videos were successfully transmitted. The paper also presents various possible techniques to still improve the system performance.

INDEX TERMS Intelligent transportation system, intra-vehicular data transmission, LED, LiFi, light fidelity, optics, VLC, wireless communication.

I. INTRODUCTION

LiFi (Light Fidelity) [1], [2] is a wireless communication technology based on the use of visible light between 480 nm (670 THz) and 650 nm (460 THz), in contrast to WiFi which uses the radio part of the electromagnetic spectrum. See Figure 1. By turning an LED on and off several thousands, even millions, of times per second, it is then possible to transmit sound, video, or even the Internet with speeds that can range from order of 10 Gb/s, in theory.

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Visible light data transmission in LiFi involves using different wavelengths within the visible light spectrum to convey information. The visible light spectrum spans a range of wavelengths, each of which can have specific characteristics when employed for data transmission. Here's an overview of visible light data transmission characteristics at different wavelengths in LiFi receivers:

i Wavelength Range:
   - The visible light spectrum generally ranges from approximately 400 nanometers (nm) to 700 nm. Different colors correspond to different wavelengths, with violet/blue light having shorter

wavelengths, and red light having longer wavelengths.

ii Color and Wavelength Characteristics:
- Shorter wavelengths (blue and violet light) have higher frequencies, allowing for more rapid modulation and potentially higher data transfer rates.
- Longer wavelengths (red and orange light) have lower frequencies, which may result in slower modulation and lower potential data rates.

iii Blue Light (400-500 nm):
- Blue light has relatively short wavelengths and higher energy.
- Blue LEDs are commonly used in LiFi applications.

iv Green Light (500-600 nm):
- Green light occupies an intermediate position in terms of wavelength.
- While not as high-frequency as blue light, it can still offer reasonable data rates and may be used in certain LiFi implementations.

v Red Light (600-700 nm):
- Red light has longer wavelengths and lower energy compared to blue light.
- It may be used in LiFi, especially in scenarios where the emphasis is on longer-range communication rather than extremely high data rates.

vi Characteristics of Different Wavelengths:
- The choice of wavelength can impact the transmission range and the ability of light to penetrate obstacles. Shorter wavelengths, like blue light, may struggle to penetrate walls, while longer wavelengths, like red light, may have better penetration characteristics.
- Some factors such as interference from ambient light, sensitivity of the photodetector, and the spectral characteristics of the light source could influence the selection of a specific wavelength for data transmission.

vii Multicolor Approaches (Color Mixing):
- Some LiFi systems use multiple colors simultaneously, making used of color mixing to increase data rates and improve reliability.
- By modulating different colors, a system can transmit multiple parallel data streams, thus, enhancing overall throughput.

In general, the choice of wavelength in visible light data transmission for LiFi receivers involves a trade-off between data rate, transmission range, and other factors. The characteristics of different wavelengths within the visible light spectrum are strategically selected based on the requirements of the LiFi application, ensuring an optimal balance between performance and reliability

LiFi is used to describe VLC (Visible Light Communication) [3], [4] which is a high-speed wireless communication technology. It acquired this name due to its similarity with WiFi but using only light instead of radio waves. LiFi is mainly based on VLC governed by seven working groups of IEEE 802.15 standard, (IEEE 802, part 15, 2011) [5] standardizing all wireless communications using visible light. This standard defines the PHY (physical) and the MAC (media access control) layers. The standard imposes the delivery of sufficient bit rates to transmit audio, video, and multimedia services. It also considers the mobility of optical transmission, its compatibility with artificial lighting present in the infrastructure, and the deficiencies that may result from the interference generated by ambient lighting. The MAC layer makes it possible to establish the link with the upper layers of other protocols such as TCP/IP (Transmission Control Protocol/Internet Protocol). Finally, the standard complies with current regulations on user eye safety [6]. See Figure 2.

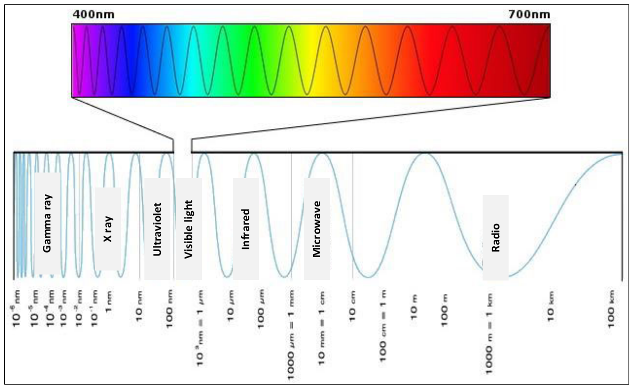


FIGURE 1. The electromagnetic spectrum.

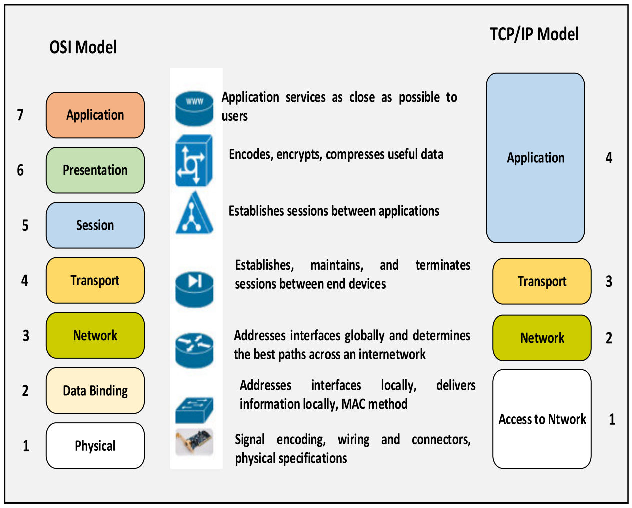


FIGURE 2. Functionality of different network layers.

The IEEE 802.15.7 standard [7], however, still fails to consider the latest technological developments in the field of wireless optical communications, in particular the introduction of O-OFDM (Optical Orthogonal Frequency Division Multiplexing) [8] which is a technical modulation and

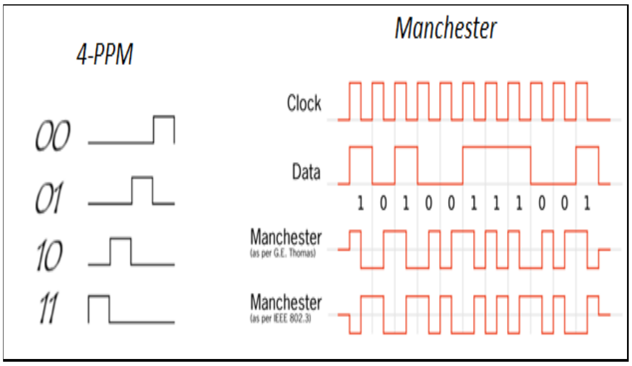


FIGURE 3. PPM and manchester coding.

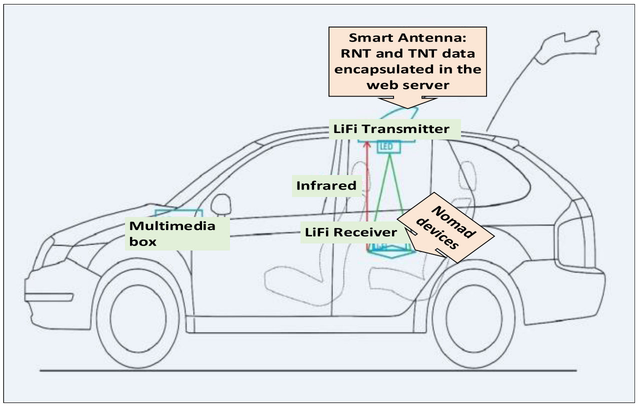


FIGURE 4. Design of LiFi intra-vehicular data transmission system.

optimization of data rate, multiple access, energy efficiency. The standard [9] defines three PHY layers according to the speeds considered, namely:

- PHY I: Outdoor applications, data rate from 11.67 kb/s to 266.6 kb/s.
- PHY II: Indoor applications, throughput from 1.25 Mb/s to 96 Mb/s.
- PHY III: multiple transmitting sources, CSK (Color-Shift Keying) modulation, data rate from 12 Mb/s to 96 Mb/s.

The recommended modulation formats for PHY I and PHY II are OOK (on-off keying) and VPPM (Variable Pulse-Position Modulation) coding [10]. Manchester coding [11] used for the PHY I and PHY II layers embeds the clock in the transmitted data by representing a logical 0 by an OOK symbol of "01" and a logical 1 by an OOK symbol of "10" with a DC component. This point is important because the DC component makes it possible to avoid the extinction of the light during a prolonged series of logical 0s. See Figure 3.

Indeed, based on the visible spectrum, as shown in Figure 1, for the purpose of transmitting and receiving information, LiFi operates on an unlimited band and does not require a license to transmit, therefore free band.

II. CONTEXT AND OBJECTIVES

The goal of this research project is to realize a demonstrator, such that within a vehicle, it is to broadcast data from an antenna to mobile devices, such as tablets or smartphones, using LiFi for the needs of rear passengers who are using a web application. See Figure 4.

This project aims to create a functional demonstrator of a two-way LiFi communication system between the reading light of a vehicle and a portable device such as a tablet or smartphone. This nomadic device must display, via a dedicated interface, the transmitted data in real time. The data is of type RNT (Digital Terrestrial Radio) and TNT (Digital Terrestrial Television) provided by an antenna developed in-house, which we will call *Smart Antenna*. This "information" is encapsulated in web pages hosted in the antenna.

The uplink, which is done in infrared, is used to call those web pages. Given that the user can see the uplink, we then use infrared in the uplink to avoid disturbing the eye of the user during uplink communication. Note that free internet surfing (listening to web radio, watching YouTube, etc.) is also possible. Initially, the study mainly targets only a single user. Sometime in the future, a multi-user prototype is to be considered, if the performances of the first one are validated.

In the context of a functional demonstrator of a two-way LiFi communication for the passenger compartment of a vehicle, the purpose is to determine the feasibility of this type of communication in an automotive context, to characterize its performances (throughput, error rate, influence of environmental conditions, etc.) and to see its complementarity in relation with other types of communication (such as Wi-Fi or Bluetooth). Depending on the results, the demonstrator will be integrated later in a PSA Peugeot-Citroen[1] vehicle, which is an integral partner in this research undertaking.

This study is carried out as part of a collaborative work of the LISV laboratory of the University of Versailles – Paris-Saclay.[2] Thus, the work focuses on the integration of a LiFi module provided by LISV (and developed by the start-up company OLEDCOMM[3]) for intra-vehicle communication, and the characterization of the performance of the prototype. Test and experiments were carried out mainly on the premises of LISV.

III. RELATED WORKS

Various works related to LiFi are available in the literature. For example, the subject of visible light communication to which LiFi belongs was extensively discussed in [3], [12], [13], [14], and [15]. LiFi's features including its capacity, efficiency, safety, deployment, and other issues are discussed in [16] and [17]. Various works discussed the comparison of LiFi against WiFi [13], [14], [18], [19] as well as the

[1]PSA Peugeot-Citroën is a French vehicle company, maker of Peugeot and Citroën vehicles.

[2]LISV (Laboratoire d'ingénierie des systèmes de Versailles) is a research laboratory of the University of Versailles – Paris-Saclay in Vélizy, France.

[3]OLEDCOMM is the leading LiFi research enterprise in France. Website: https://www.oledcomm.net/fr/

strengths, weaknesses, and application of LiFi in different environments. Leba et al. [20] discussed the challenges in the communication and modulation in LiFi. Likewise, [21] discussed the challenges in various LiFi applications. The LiFi-based IoT architecture was presented in [22]. In [23], the authors introduces different LiFi applications for various places (rooms, homes, and supermarkets). Another paper presents LiFi's application in constructions [24]. And yet another one discusses the suitability of LiFi in monitoring a billing application [25]. Another interesting LiFi application in the field of mobility is [26], which supports limited vision people by sending them audio feedback. The role of LiFi in safe communication in an intelligent transportation system [3], [27], [28] is discussed briefly in [29] and [30]. A vehicle-to-vehicle communication using LiFi is discussed in [31]. The treatment, however, of those papers in intelligent transportation system is, to us, shallow. In this paper, we are offering a profound work on LiFi for intelligent transportation system, in particular for intra-vehicular data transmission application. To be specific, we wish to contribute to the domain of exploring the role of LiFi in enhancing autonomous vehicles and intelligent transportation systems.

We believe that LiFi is going to be a game-changer in the realm of autonomous vehicles and intelligent transportation systems, where reliable, high-speed communication is crucial. In intelligent transportation systems, LiFi will play an important role in the vehicle-to-vehicle (V2V) and the vehicle-to-infrastructure (V2I) communications. For instance, traffic lights equipped with LiFi technology can transmit data to approaching vehicles, informing them about the status of the light or any upcoming traffic congestion. Similarly, vehicles can communicate their location, speed, and direction to nearby vehicles, preventing collisions and improving road safety.

This paper is a continuation of our previous paper [32] which was related to ADAS (advanced driving system) [33] where in that paper, we only presented a bird's eye view of LiFi in an intra-vehicular data transmission system. In this paper, we demonstrate the full details of our work. In principle, this work is functional, that is, we have proven that LiFi is feasible to be the communication medium for intra-vehicular data transmission system. It must be noted however that there are still several points for improvement of this research project.

IV. PRINCIPLE OF OPERATION OF LIFI

LiFi is a technology that transforms a light source into a broadcaster of digital content. By turning LED on and off thousands, even millions, of times per second, we can be able to transmit sound, video, or even the Internet with speed that can range in the order of 10 Gb/s, in theory. The architecture of a LiFi system includes a transmitter, an LED, and a receiver. See Figure 5.

The transmitter does modulate the data to be sent using a selected coding scheme and then control the LED source.

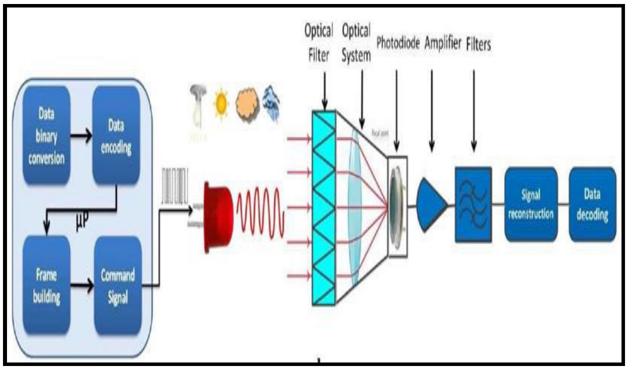


FIGURE 5. Principle of operation of LiFi.

Data is thus transmitted by switching on and off a high-frequency LED. A photodiode encapsulated in the receiver captures the light from the LED and transforms it into an electrical signal [34]. An optical filter system may be integrated in the photodiode in order to eliminate ambient lights. The electrical signal is then processed by an amplifier and filters it in order to reconstruct the useful signal. And finally, the demodulation of the signal is done to retrieve the sent signal [35]. It should be noted that a data frame comprising the message information, such as the start bit and the stop bit, as well as the length of the message, is essential for transmission.

In a LiFi system, visible light is used as a medium for data transmission, where an LED is used as a light source, transferring data at a lightning-fast speed [36]. The photodiode is used as a receiver that decodes the light signals at the receiver side [37]. The response frequency of an LED is a crucial factor affecting the transmission data rate. LED response frequency refers to how quickly a LED can modulate its light output to transmit data. In LiFi, data is encoded by varying the intensity of the light emitted by the LED at high frequencies. A higher response frequency allows the LED to change its light intensity more rapidly, enabling a higher data transmission rate. Therefore, the LED's capability to modulate light quickly becomes a critical factor in determining the overall performance and transfer speed of the LiFi system.

As a proof of concept, the work in [38] demonstrated the effect of response frequency of LEDs. First, the authors compared the performance of LEDs of same chip size with different power ratings (i.e., 20W, 30W, and 50W) for LiFi application. Next, they compared "cool" against "warm" LEDs, whose bandwidths are in the range of 3 to 4 MHz. When the bandwidth was extended, the results show that:

- the bandwidth of "warm" LED has increased to 17 MHz,
- the bandwidth of "50W cool" LED has increased to 33 MHz, and
- the bandwidth has increased to 36 MHz for "20W and 30W cool" LEDs.

TABLE 1. Comparison between LiFi and WiFi.

	LiFi	WiFi
Meaning	Light Fidelity	Wireless Fidelity
Invented by	Invented by Prof. Harald Haas in 2011	Invented by NCR Corp. in 1991
Standard	Uses IEEE 802.15.7 standard	Uses IEEE 802.11 standard
Working Environment	Highly dense environment where VSL (visible light spectrum) is less susceptible to external interference	Less dense environment due to interference-related issues
Transmission Speed	Very Fast, compared to WiFi	Very slow, compared to LiFi
Security	More secure data transfer since light cannot pass through walls	Radio frequency signals pass through walls. Secured data transfer is a challenge
Operation	Uses visible light spectrum for data transmission	Uses radio waves for data transmission
Coverage	Based on the medium of propagation; area of around 10 meters	An area of up to 32 meters away
Frequency Bands	Between 380 nm and 780 nm in the wavelength range	Operates on two frequency bands, 2.4 GHz, and 5 GHz
Bandwidth	Unlimited bandwidth is available	Limited bandwidth is available
Components	Uses light signals and LED bulbs for wireless data transmission	Uses modems and radio frequency signals
Cost	Installation cost is a bit high but lower than WiFi overall	Comparatively higher than LiFi
Effect on Health	No side effect	Radio wave side effect
Application	Used in healthcare, underwater communication, high-speed internet via streetlights, smart power plants, and Airlines	Used to browse the Internet via WiFi hotspot

At the end of the experiment, the finding is that the "cool" LEDs have more favorable performances than "warm" LEDs in terms of data transmission and bit error rate.

For its part, a photodiode is a light-sensitive semiconductor device that converts light into an electrical current. Photodiodes are commonly used as light detectors to receive the modulated light signals transmitted by an LED. The photodiode module is used to detect the light signal generated by the LiFi transmitter [39].

A. LiFi vs. WiFi

LiFi has many advantages that come from the use of visible light on the one hand, and the use of LEDs on the other. They are given below:

- LEDs can be easily modulated at very high speed, which makes it possible to achieve high data rates without using complex techniques.
- Visible light, unlike radio waves, cannot pass through walls which ensures the partitioning of data but its indoors range is limited.
- LEDs consume little energy and have a fairly long lifespan. The interior and exterior lighting of buildings, road infrastructures and automobiles can directly provide a pre-existing mesh for the deployment of LiFi.
- Unlike the radio wave that WiFi uses, LiFi's visible light has no influence on health.
- The light spectrum covers a frequency band of about 300 THz. The use of this band is also unregulated and is therefore free. LiFi and its 300 THz spectral band could therefore be used to relieve the radio band.
- LiFi improves indoor connectivity in high-speed vehicular networks and nullifies the repercussions of WiFi's highly radiated electromagnetic waves.
- LiFi improves indoor connectivity in high-speed vehicular networks, reducing handoff probability, average delay, and spectral efficiency compared to existing WiFi systems [40].
- LiFi technology uses LED light bulbs to transmit data at a high speed, and could achieve 1000 times faster than WiFi, making it suitable for vehicular applications like public internet access through streetlights and auto-piloted cars.

TABLE 2. Strength and weaknesses of LiFi.

	Advantages of LiFi	Disadvantages of LiFi
Speed	LiFi can transmit at the rate of 10 Gbit/sec. This is almost 250 times faster than any high-speed broadband connection	The modulation in LiFi is a challenge when the light illumination is low.
High-density coverage	LiFi is more ideal for a high-density coverage in contrast to WiFi which is more ideal for common purposes.	LiFi cannot provide an Internet connection when there is no light source. This may cause limitations for locations and situations where LiFi may be necessary.
Cost	LiFi technology is free.	Light cannot pass through physical barriers. This may cause certain limitations.
Larger spectrum	There are no restrictions to the capacity of LiFi. Visible light spectrum is about 10,000 times larger than RF spectrum.	The major drawback of LiFi is that it can be used only within the small area as it cannot penetrate through walls

The noise coming from many sources of ambient light, including the sun and artificial light, is a major drawback of LiFi. It can influence data transmission, even saturate the receiver, and thus block communication. On the other hand, LiFi is originally unidirectional. It must therefore be coupled with another technology (WiFi) or be used only in special cases (need only downlink speed). Indeed, we cannot have two light beams that intersect while simultaneously collecting data coming from the two beams. Often, the uplink is via infrared. Table 1 clearly illustrates the advantages and disadvantages of LiFi over WiFi. Table 2 [41], on the other hand, shows both the strength and weaknesses of LiFi.

B. LiFi vs. BLUETOOTH

LiFi and Bluetooth are both wireless communication media, but they have distinct characteristics and applications. While LiFi offers several advantages, it is not necessarily a direct replacement for Bluetooth in all scenarios, including intra-vehicular communication. Here are the major comparison between the two:

LiFi:

- *Communication Medium*: LiFi uses visible light for data transmission. Light signals from LEDs are modulated to carry information, providing potentially higher data rates compared to some traditional wireless technologies like WiFi and Bluetooth.
- *Data Rate*: LiFi can achieve high data rates, making it suitable for applications that require quick and efficient data transfer.
- *Security*: LiFi communication is confined to the area covered by the light, offering potential security benefits as it is more challenging to intercept signals outside the illuminated space.
- *Interference*: LiFi is less prone to interference from other wireless devices since it operates in the visible light spectrum.
- *Energy Efficiency*: LiFi systems can be energy-efficient, especially if LEDs are already used for lighting purposes.

Bluetooth:

- *Communication Medium*: Bluetooth uses radio waves for communication and is well-established for short-range wireless connections.
- *Data Rate*: Bluetooth data rates vary but are generally lower than what LiFi can achieve. Bluetooth is often used for applications that do not require extremely high data transfer rates.
- *Security*: Bluetooth technology has evolved and provides robust security features, making it suitable for various applications, including secure data transfer.
- *Interference*: Bluetooth operates in the 2.4 GHz frequency band, which is a shared spectrum. While Bluetooth has mechanisms to manage interference, it can still be affected in crowded wireless environments.
- *Ubiquity*: Bluetooth is widely adopted and integrated into a broad range of devices, making it a standard choice for many applications, including intra-vehicular communication.

Table 3 [42] shows the comparison between LiFi and Bluetooth

A recent work [43] describes the possibility of the limited replacement of the Bluetooth technology by a visible light communication. Here, in general, are the major considerations for intra-vehicular communication:

- *Data Requirements*: If intra-vehicular communication requires high data rates, LiFi could be a suitable choice. For instance, for applications such as high-quality video streaming or large file transfers within the vehicle, LiFi speed of transmission is an optimal choice.
- *Device Compatibility*: Bluetooth is a mature and widely supported technology. If existing devices and systems within the vehicle are designed to work with Bluetooth, transitioning to LiFi might require significant infrastructure changes.
- *Range*: Bluetooth typically has a longer range compared to LiFi, making it more suitable for certain intra-vehicular communication scenarios where devices are not in direct line of sight.

In summary, while LiFi offers unique advantages, including high data rates and potential security benefits, it may not be a direct replacement for Bluetooth in all intra-vehicular communication scenarios. The choice between LiFi and Bluetooth would depend on specific requirements, existing infrastructure, and the nature of the communication needs within the vehicle. Additionally, hybrid solutions that leverage both technologies for different purposes may be considered to achieve a balance between data rates, range, and compatibility.

TABLE 3. Comparison between LiFi and bluetooth.

	LiFi	Bluetooth
Frequency	Light does not require frequency	2.4 GHz
Range	Based on LED light	10 meters
Availability	Wherever light is available	WPAN
Data transfer	> 1 Gbps	800 Kbps
Power consumption	Medium	Low
Cost	Low	Low
Security	Highly secured	Less secured
Usage	Anywhere where there is availability	Can be used anywhere
Operating band	Operates at visible light band	Operates at 2.5 MHz

TABLE 4. Comparison of four wireless communication technologies.

	WiFi	LiFi	Bluetooth	ZigBee
Mode of operation	Using radio waves	Using light waves	Using short wavelength UHF radio waves	Using radio waves
Coverage distance	32 m	10 m	10 m, 100 m based on classes	10 – 100 m
Frequency of operation	2.4 GHz, 4.9 GHz, and 5 GHz	10,000 times radio waves	2.4 – 2.485 GHz	2.4 GHz
Speed of transmission	150 Mbps	1 Gbps	25 Mbps	250 kbps

C. LiFi vs OTHER WIRELESS TECHNOLOGIES

Table 4 [41] shows a general table of comparison among four wireless communication technologies:

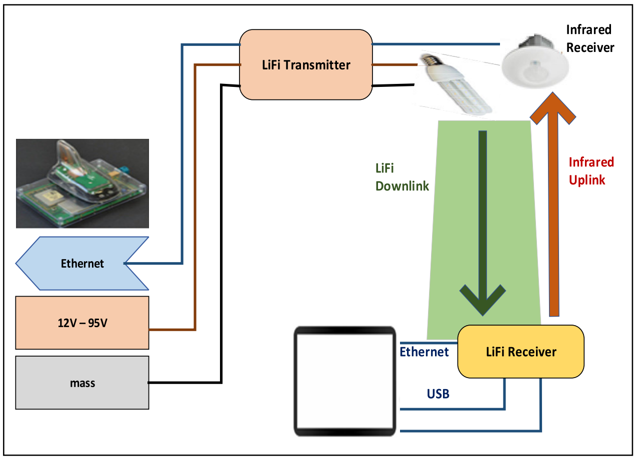


FIGURE 6. Schema of data flow in the intra-vehicular data transmission system.

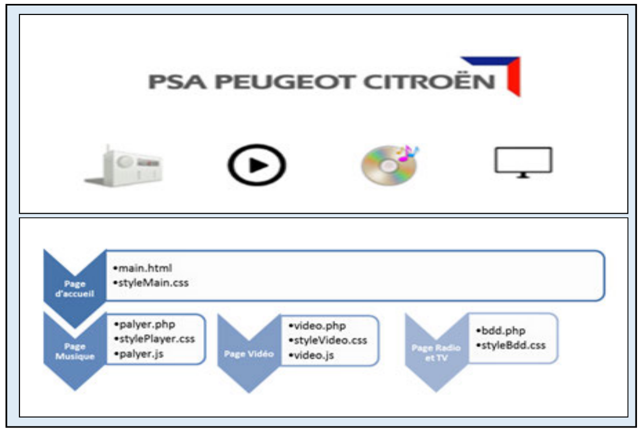


FIGURE 7. Visualization of the application's interface and its program implementation.

D. APPLICATIONS OF LiFi IN VARIOUS DOMAINS

LiFi has many advantages that come from the use of visible light on the one hand, and the use of LEDs on the other. Having taken note of the advantages of LiFi, various applications are possible:

- By taking advantage of the security benefit of LiFi, it can then be installed in companies, banks or in the military in order to ensure security of information.
- It can be used in the smart city project, allowing Internet access by taking advantage of the existing lighting.
- LiFi devices are already installed in some supermarkets for geolocation application.
- LiFi could also be used for "connected vehicle" automotive projects. Or, in this paper, it allows us to have entertainment (audio, video, radio) connection while travelling.

V. EVALUATING THE FEASIBILITY OF LiFi IN INTRA-VEHICULAR DATA TRANSMISSION

This section provides details about the experimentation on the use of LiFi in intra-vehicular data transmission. The set-up is such that there is a vehicle and a passenger at the back seat of the vehicle, and the smart antenna would be transmitting data (i.e., music, audio, video, etc.) towards a mobile device (e.g., laptop, tablet, etc.) using LiFi. This work was made possible through the collaborative efforts of PSA Peugeot-Citroen, OLEDCOMM, and LISV Laboratory.

A. SCHEMATIC DIAGRAM OF INTRA-VEHICULAR DATA TRANSMISSION SYSTEM

The functional diagram of Figure 6 presents the different parts of our LiFi intra-vehicular communication system.

Powered by a DC current of 12V to 95V, the LiFi transmitter modulates the data from the Smart Antenna via an Ethernet cable; it then controls a LED (Nichia LED installed in PSA reading light) which lights on and off at a preset frequency. The modulated data in binary format is transmitted according to the flashing speed of the LED. A LiFi receiver is installed in the illumination area of the LED in order to receive and reconstruct the data. The first is powered using two USB cables linked to the mobile device. Data transmission between the receiver and the mobile device is done via Ethernet.

For security reason, the PSA Smart Antenna could not be moved outside the PSA office site. For this reason, it becomes necessary to first model a web server in LISV laboratory by encapsulating the audio/video data and implement it in a Raspberry Pi 3 card. Only when the LiFi module works well with the Raspberry Pi 3 that the actual tests could be done using the Smart Antenna.

The LiFi module used in this project is developed by OLEDCOMM, allowing Internet access to computers using LEDs of more than 20W. To integrate it into this application, a less powerful LED (PSA reader) of 500 mW, instead of 20 W, must be used, along with mobile devices, such as tablets or smartphones. Once the module becomes functional, this demonstrator is evaluated using all parameters that affect its performance.

B. MODELING OF SMART ANTENNA

A local web server that models the PSA Smart Antenna was developed, and was implemented in a Raspberry Pi 3 board, an ARM-based single-board nano-computer. The local web server was developed using EasyPHP. The web application itself is programmed using HTML, CSS, PHP, JavaScript, and MySQL. The chosen development environment is EasyPHP because of its features. EasyPHP is a Web development platform, allowing PHP scripts to run locally (without connecting to an external server). EasyPHP is not in itself a software, but an environment comprising two servers (an Apache web server and a MySQL database server), a script interpreter (PHP), as well as an SQL administration component, phpMyAdmin. It has an administration interface to manage aliases (virtual folders available under Apache), and the start/stop of servers. It is possible to install every-

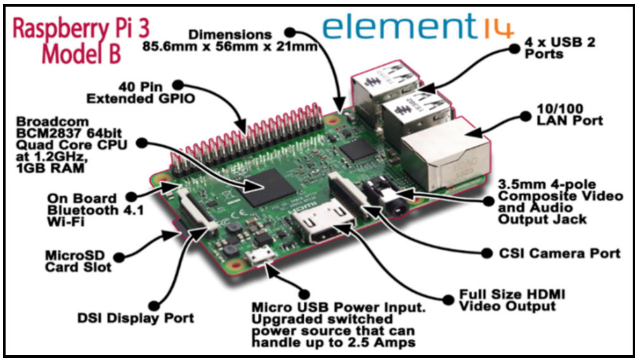


FIGURE 8. Composition of a Raspberry Pi.

thing necessary for the local development of PHP in one go. By default, the Apache server creates a local virtual domain name 127.0.0.1 or localhost. Thus, when choosing "Local Web" in the EasyPHP menu, the browser opens on this URL and displays the index.php page of this site which in fact corresponds to the content of the EasyPHP "www" folder.

For this application, the content and aesthetics of the server were defined. Four menus (Radio, TV, Music, and Video) and a company logo appeared on the home page. See Figure 7. When the "Radio" menu is selected, a submenu of three choices (FM, AM, RNT) is displayed. When one of the menus is clicked, another "Playlist" page opens up. If one of the playlists is clicked, the music or video starts. The webpage is programmed using the usual HTML language, along with CSS codes to render style to the webpage. This predefined part is called the static display. For dynamic display, the page content is based on the results of a database query. A database in which each element must have all the characteristics necessary to make a MySQL query was created using the SQL administration component, phpMyAdmin. The PHP language is then used to connect to the database, make some MySQL query and display its result, and finally to disconnect from the database. JavaScript is used for event management, i.e., start, pause, or stop a chosen music/video, adjusting the sound, or even the progress bar.

C. THE RASPBERRY PI 3 COMPONENT

The Raspberry Pi, as shown in Figure 8, is a single board nano-computer with an ARM processor. This computer, with the size of a credit card, allows the execution of several variants of the free operating system GNU/Linux and compatible software. Several models exist: Model A (A+), Model 1 B (B+), Model Zero, Model 2 B and Model 3 B released in February 2021. The one used in this project is the Raspberry Pi 3 Model B. It has a Broadcom BCM2837 64-bit quad-core ARM Cortex-A53 1.2 GHz processor and an integrated 802.11n WiFi and Bluetooth 4.1 chip. It has the same dimensions and connectors as the Pi 2 and B+64 models. The clock speed is 33% faster than the Pi 2, allowing for around 50-60% performance gain in 32-bit mode. In this work, the Raspberry Pi 3 is used as a web server. In terms of

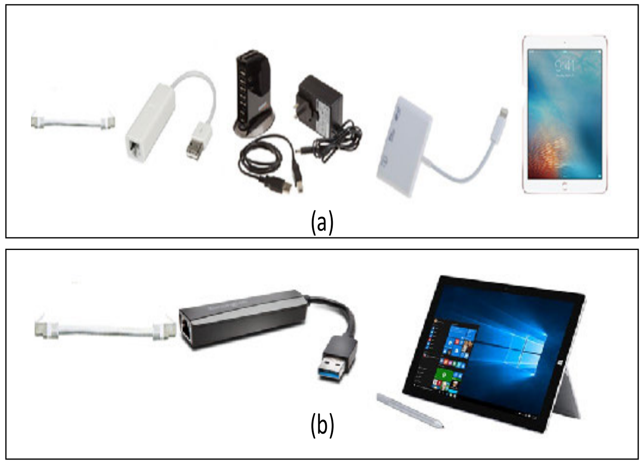


FIGURE 9. Connecting nomad devices to Ethernet (a) IpadPro, (b) Microsoft Surface 3.

operating system, the Raspberry Pi Foundation recommends using Raspbian, a GNU/Linux distribution optimized for the Raspberry Pi hardware. Raspbian is based on Debian, embedding the LXDE desktop environment and the Midori web browser.

Once the necessary web servers were installed, the previously developed server has to be integrated into the Raspberry Pi. Two approaches are possible:

- Copy to a USB key the directory containing all the files of the server in the directory /var/www/html of the Raspberry Pi by Linux commands.
- There is also an SSH Client for Windows users to control the Raspberry Pi remotely. Copy the directory using an SSH Client FileZilla Client in the /var/www/html directory of the Raspberry Pi.

The local IP address defined by default by the Apache server is 127.0.0.1, while the address of the Smart Antenna is 10.6.5.101, so the server IP address must be changed. Doing that, the local server becomes functional.

D. INTEGRATION OF LiFi MODULE IN INTRA-VEHICULAR COMMUNICATION

After finishing the modeling part of the Smart Antenna, the integration of the LiFi module of OLEDCOMM in the intra-vehicle communication is implemented next. Referring back to Figure 6, the LiFi diagram in our application, the LiFi module developed by OLEDCOMM integrates with the PSA reader and different types of mobile devices.

The data transmission between the LiFi receiver and the mobile devices is done by Ethernet. In order to test compatibility with different types of devices, four tablets of different brands are used: the *Samsung Galaxy Note 10.1*, the *Huawei M2*, the *iPad Pro* and the *Microsoft Surface 3* as well as a *Huawei smartphone*. However, the Samsung Galaxy Note 10.1, Huawei M2 tablets and the Huawei smartphone do not have a driver capable of supporting the Ethernet connection. There were also independently developed drivers

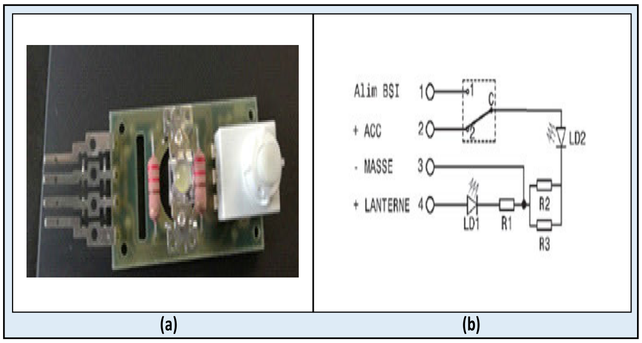


FIGURE 10. **The PSA e-reader: (a) – physical sample without housing or case, (b)its electric diagram.**

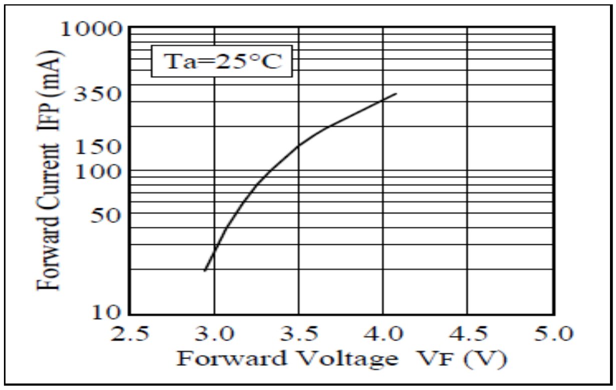


FIGURE 11. **Current-voltage characteristic of the Nichia LED.**

for accessing Ethernet using an Ethernet-Mini USB adapter, but this was only suitable for dedicated applications. On the other hand, the iPad Pro and the Surface 3 have the Ethernet connections.

1) INTEGRATION OF A NOMAD DEVICE–IPAD PRO

Access to Ethernet for iPad was not so simple. See Figure 10(a). There was the Ethernet driver in the IOS 9 system, but there was no Ethernet – Lightning adapter (power socket for new Apple brand devices). Here are the hardware needed to connect the iPad to Ethernet: (i) Lighting to USB Camera Adapter, (ii) USB-Ethernet adapter, (iii) USB power socket (powered at 220 V and a USB type B - USB type A cable), and (iv) Ethernet cable. It should be noted that the USB Hub is essential to power the Ethernet-USB adapter. On the other hand, the USB Hub had to be powered at 220V, which is impossible in a vehicle. Moreover, the receiver of the LiFi module is powered by two USB cables. This can be easily managed by a USB Hub.

2) INTEGRATION OF A NOMAD DEVICE–MICROSOFT SURFACE 3

Unlike the iPad, the Microsoft Surface 3 only needs an Ethernet–USB adapter to have the Ethernet connection, because it has by default a USB interface and a driver allowing Ethernet access. See Figure 9(b).

To conclude this sub-section, the module is only compatible with certain mobile devices such as the iPad Pro and the Surface 3. And in this application, given the power supply constraint in a vehicle, the iPad Pro is not embeddable. It may also be compatible with some devices that have not been tested in this experiment. Given the advancement in LiFi technology, it is very likely that major smartphone and tablet device vendors will integrate a LiFi chip within them in the future. The purpose of this application is above all to make a first demonstrator.

E. INTEGRATION OF THE PSA READER

With the arrival of the LiFi module, it became possible to integrate the PSA reader into the LiFi module. A Citroën C4 Picasso car was chosen to set up the demonstrator. The LED to be integrated is therefore a reading light (composed of an LED, two resistors and an optic) used in the C4 Picasso. This LED is provided by Nichia.

In this part, the specifications of the reading light as well as that of the LED and the work that was carried out are presented. The integration part of the reader makes it possible to test hypotheses, analyze the results, and see if the changes made to the system have been useful. The process repeatedly comes down to analyzing the result and identifying the problem. The work is presented in the next sub-sections. Only representative measurements are discussed to simplify the analysis of the result.

1) THE READER'S SPECIFICATIONS

Here are the electrical specifications of the reader:

- Power supply under 13.5 V
- Switching position 1: closed circuit AND power supply with +BSI signal
- Switching position 2: closed circuit AND power supply with +ACC signal

When the reader is supplied with 13.5 V on +ACC and ground, LD2 lights up. The PSA e-reader without housing (case) is shown in Figure 10(a) while the electric diagram of the e-reader is shown in Figure 10(b). See Appendix A – Important Characteristics of the Standard PSA E-Reader for further details.

2) THE NICHIA LED SPECIFICATIONS

The specification of the LED (see Figure 11) in this application is given below:

- Forward Current (Absolute Maximum Rating) IF: 180 mA
- Forward Voltage (IFc = 150 mA) typical VFt: 3,5 V
- Forward Voltage (IFc = 150 mA) maximal VFm: 3,8 V

F. THE VOLTAGE REGULATOR

The first problem to consider during system integration is the power supply of the LiFi receiver. As per specification, the power supply of the transmitter is 12V to 95V, while that

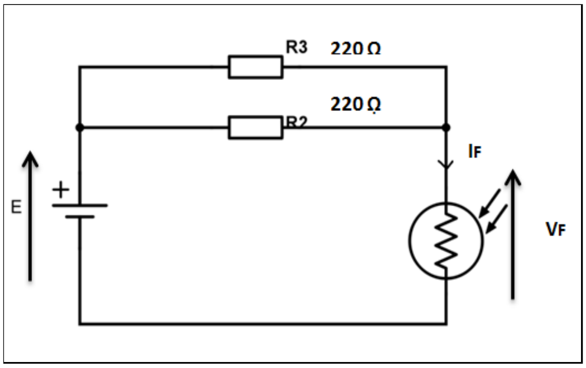


FIGURE 12. Electrical diagram of the e-reader.

of the reader is 13.5V. The power supplied inside the car is 13.5V. If the transmitter of the LiFi module is powered under 13.5V, the output of the transmitter, which will power the reading light, is approximately 9V according to measurements. It is therefore lower than the power supply required for the 13.5 V reader. This can influence the performance of the reader, in particular on the power of the LED and the illumination emitted. To solve this power problem, a voltage regulator (DC-DC converter) has been built into the transmitter, so the regulator settings need to be changed so that the transmitter output is 13.5V. OLEDCOMM modified the parameters of the regulator, obtaining the same output voltage as the input.

G. EVALUATING THE PSA READER

The first test on the module was carried out by integrating the PSA reader for the transmission of data between the Internet and a Linux computer. It is also necessary to define the terms "downstream flow" and "upstream flow":

- Downstream rate: represents the information flow received from the antenna (Internet, DTT, RNT, etc.)
- Upstream rate: represents the flow of information sent by devices (tablets, smartphones, etc.) to the antenna.

Based on the measurements conducted, with a 13.5 V power supply, the current flowing through the LED was 0.13 A. There was no downlink throughput by LiFi, and from 8 Kb/s to 24 Kb/s uplink by infrared.

1) FIRST CONNECTION

As stated, the LED used is 20 W, whereas according to the specifications of the Nichia LED:

- Typical electrical power: VFt $*$ IFc $=$ 3.5 V $*$ 150 mA $=$ 0.525 W
- The maximum electrical power: VFt $*$ IFc $=$ 3.8 V $*$ 150 mA $=$ 0.57 W

Comparing this test with the one performed at OLEDCOMM, the most obvious difference was that the power of the Nichia LED (0.525 W in theory) is much lower than that of the LED used by OLEDCOMM (20 W). It is therefore necessary that the power of the LED be studied first.

The electric circuit of the reader (see Figure 12) is simply made up of two resistors in parallel and then with an LED in series, powered by a DC voltage. The current flowing through the LED can be increased by increasing the supply voltage, because IF= 2(E-VF)/R. As per the LED specification, the maximum current that can flow through the LED at a fixed time (Pulse Forward Current) is 350 mA. The supply voltage can therefore be increased a little in order to improve the power of the LED, and thus to try to have a downward flow via LiFi.

A remarkable download rate of 200 Kb/s at a distance of less than 15 cm was noted, when the transmitter was powered at 15 V and the current flowing through the LED was 0.15 A. This result was not representative of a vehicle environment. However, it showed us the possibility of having a LiFi connection with the standard PSA reading light. The rest of the work was therefore to improve performance such as throughput and distance.

The intra-vehicle communication application implies a minimum speed of 5Mb/s for the RNT (Radio Numérique Terrestre or Digital Terrestrial Radio) to pass correctly. Regarding the distance, it takes at least 60 cm, which in concept is approximately the distance between the roof of the vehicle and the knees of the passenger.

2) RECEIVER MODIFICATIONS

The performance of the LiFi receiver mainly determines that of the LiFi system. They determine, on the one hand, the communication range, and the resistance against ambient light noise, on the other hand. The photosensitive elements of the receiver with high bandwidth offer the possibility of high-speed communication. Our studied photodetector is based on a photodiode, operating in photoconductor mode, which generates a current that is proportional to the incident light. The value of the photocurrent also depends on the spectral sensitivity of the photodiodes. Then, thanks to the amplifier mounted in transimpedance, the photoelectric current is transformed into a voltage. Digital filters are then applied to eliminate the noise and reconstruct the signal.

a: CHANGING THE FILTER'S SETTINGS

As stated, the power of the Nicha LED is much lower than that of the LED used by OLEDCOMM, the emission flux is therefore much smaller, thus the SNR (signal-to-noise ratio) becomes greater. This can massively disrupt signal reconstruction on the receiver side. There is a need to modify the parameters of the high pass filters in order to eliminate ambient light as much as possible but retain as much of the light coming from the reading light as possible. That being said, it did not provide us any performance improvement.

b: INTEGRATION OF A TRANSIMPEDANCE CIRCUIT

A test on the possibility of integrating a specific transimpedance circuit, published in a scientific article, into the receiver in order to improve the SNR was considered. Indeed, when the photodiode is illuminated by a beam of light,

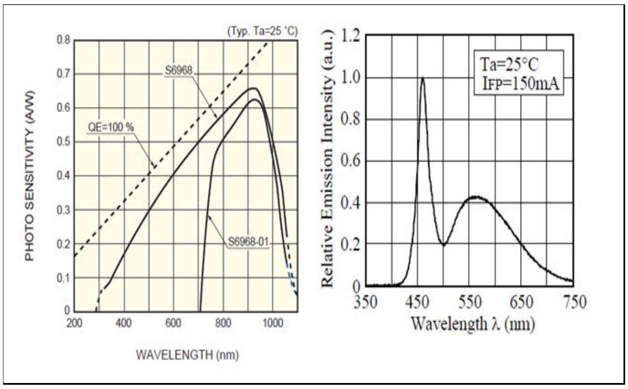


FIGURE 13. Comparison of spectrum diagrams of a photodiode and an e-reader.

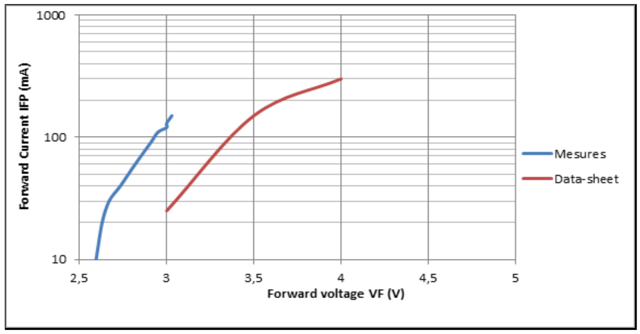


FIGURE 14. Comparison of the measured current-voltage relationship and that in the datasheet.

a photoelectric current is generated. In most applications, fluctuations in such current must be amplified and analyzed. The main problem with classic transimpedance is that it creates a very strong shift caused by the addition of DC component. The circuit proposed in this article makes it possible to automatically remove the offset (continuous component) of the output voltage so as to maximize the voltage oscillation of the alternating component while introducing the minimum possible electronic noise. See Appendix B – Comparison of Classical Transimpedance and Transimpedance Studies for further details.

After conducting studies on the performance of this circuit and applying it, it did indeed improve the SNR by a great deal. However, we noticed a bandwidth of 53 kHz which was lower than that of the classic circuit of 308 kHz. To conclude this part, despite the reduction in noise, this circuit cannot be integrated into the receiver because of its very low bandwidth.

c: CHANGING THE PREAMPLIFIER POWER SUPPLY

After analysis, we realized that another element which could influence the performance of the receiver came from the fact that the preamplifier was powered asymmetrically (+5 V by USB), whereas it would be more efficient to use a symmetrical +/−5 V (or +/−12 V) power supply, which, in the case of automobiles, can only be manufactured from 12 V batteries. This would involve quite bulky voltage regulators. Modifying the preamplifier circuit is therefore a possible approach but not a priority. It is also possible to add an optical filter before the photodiode, but given the time and cost constraints, this is a feasible option.

d: INCREASED SENSITIVITY OF THE PHOTODIODE

Another element which depends on the value of the photocurrent is the spectral sensitivity of the photodiode (see Figure 13). The reception principle consists of converging the maximum amount of radiation onto the photodiode using a large lens. This photodiode, which must be as sensitive as possible, ensures the direct conversion of the energy received in the form of a modulated current. This signal can then be processed by a chain of low-noise amplifier stages.

We then studied the photodiode. Indeed, the photodiode used in the LiFi module is ES S6968, which is more sensitive to red light, while the light emitted by the PSA reading light is closer to blue. This meant that little useful light was captured by the photodiode. It is therefore necessary to use a photodiode that is more sensitive to blue light. According to our research, almost all existing photodiodes on the market are Silicon photodiodes so they all have almost the same spectral sensitivity, which showed us that there was no better choice.

Concerning the photodiode's role in improving the LiFi module's performance, we contend that the photodiode can always bring some improvement. However, in our case, the bandwidth of photodiode is much larger than that of LED, hence, any improvement is negligible. See Figure 13.

e: INCREASE IN THE RECEIVING SURFACE OF THE PHOTODIODE

Increasing the receiving surface of the photodiode, however, would make it possible to capture more light. On the other hand, it could also increase the capacity of the circuit, thus reducing the bandwidth. We still tried with another photodiode of larger size, making a compromise between the amount of light captured and the bandwidth. The result showed us that the communication range was improved by up to 30 cm. However, the reception cone is smaller, and we had difficulty finding the operating point. Considering the fact that the user cannot take the devices in a fixed point in order to have a connection in a vehicle, it is then not possible to address this approach in our application. From the previous analysis and tests, we can conclude that changing the photodiode will not bring any improvement to the performance of the LiFi module.

3) MEASUREMENTS AND ANALYSIS OF THE STANDARD PSA E-READER

After conducting studies on the receiver, we find almost no approach that will improve the performance of the receiver in the application. We therefore carried out more in-depth

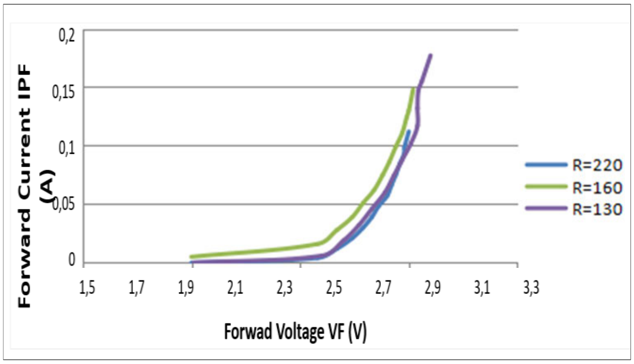


FIGURE 15. Measured current-voltage relations of the original and modified e-readers.

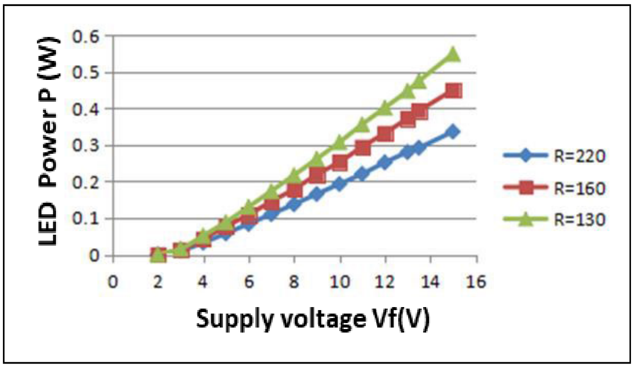


FIGURE 16. Electrical power of the original e-reader and modified e-readers.

studies on the e-reader, particularly in terms of electrical power and light illuminance.

a: ADDING A LENS

Adding a lens to the reading light would focus the emitted light, thus providing more optical flow upon reception. However, the focus point was very precise, which was not suitable for our application.

b: ELECTRICAL MEASUREMENTS AND ANALYSIS OF THE E-READER

We then returned to the original problem: the electrical power of the LED. According to the specification, the power of the LED had to be at least 1.5 W for the LiFi module to work well. It is complicated to change the e-reader because the goal is to use LiFi on an already existing source to be able to analyze the adaptability of the system. However, we found a solution that could increase the power of the LED by studying the electrical diagram of the e-reader. See Figure 14.

First, we studied the current-voltage characteristic of the original LED. We noticed that the current-voltage relationship does not correspond exactly to that written in the specifications. The power was only 292 mW instead of the theoretical 525 mW. This could be caused by many things,

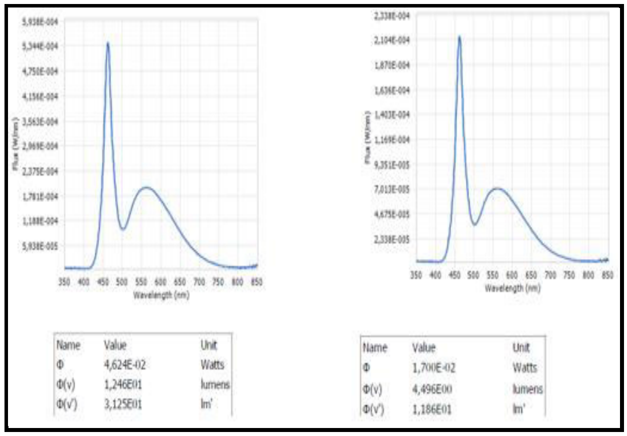


FIGURE 17. Spectrum diagram measured on the original e-reader with and without the case.

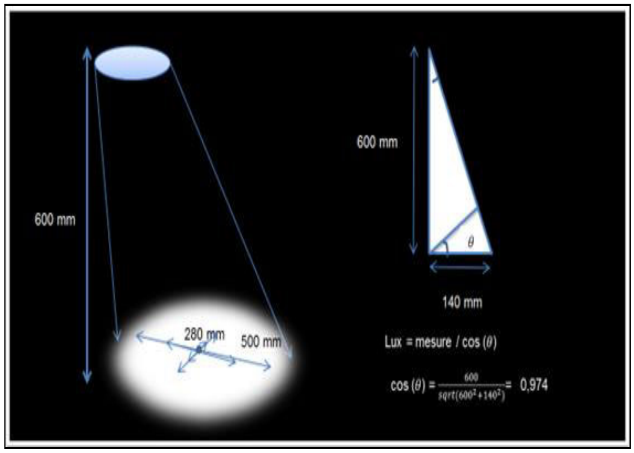


FIGURE 18. Reading light illuminance test plan.

including some issues during the manufacturing of the LED. Moreover, according to these measurements, the voltage across the VF LED varies between 2.7 V and 3 V. The current passing through the IF LED increases by decreasing the value of the resistors, the power of the LED thus increases following the increase in current. See Figure 15. We decided to change the values of the two resistors to 160 Ω and 130 Ω. The measurements of the current-voltage characteristic as well as the power-supply-voltage relationship (see Figure 16) are illustrated below:

We noticed that the current-voltage relationship does not change by decreasing the resistance values, which is logical because it is the characteristic of the LED which has no relationship with the value of the resistance with which it is in series in the circuit.

The power of the LED, however, increases by decreasing the resistor values, up to 474 mW with two 130 Ω resistors when the e-reader is powered at 13.5 V. This showed that the electrical power could be increased by reducing the resistor values, hence, the performance of the LiFi module could be improved.

Another test was then carried out using the modified e-reader with two 130 Ω resistors, the result showed that there was very little improvement in communication range as there should have been in theory. This is analyzed below through measuring the optical characteristics.

c: OPTICAL MEASUREMENTS AND ANALYSES OF THE E-READER

Considering the fact that the photodiode transforms, in effect, the light flux that it detects into an electrical signal, the light illuminance at the position of the photodiode is more representative in relation to the electrical power. We decided to measure and analyze the e-reader from an optical point of view to explore the problem further. Figure 17 shows the spectrum diagram of the original PSA e-reader with and without the case/housing. Indeed, Figure 17 illustrates the real emitting power of an existing LED inside the vehicle. The left diagram/graph in the figure shows the LED sources with its original box package. This box has some optical channel and some optical filters. Hence, on the right diagram/graph of Figure 17 is shown the power of LED sources without this box.

Firstly, the measurements of total flux and spectrum on the LED (with the original reader) were carried out with the integrating sphere (see Figure 16) in order to compare with the data in the datasheet (see Figure 12).

These measurements showed us that the LED complied with the datasheet in terms of spectrum. As per specification, a minimum of 55 lux is required for the module to operate in normal mode. According to the specifications, the functional lighting of the reading light, the illuminance (measured at 600 mm from the source):

- Value registered in a diameter of 280mm: average > 65 lux
- Value registered in a diameter of 500mm: average > 55 lux

Secondly, we carried out illuminance measurements at 600 mm from the source in order to confirm the values in the specifications. The test bench is illustrated in Figure 18.

The e-reader was powered at 13.5V with a current of 0.098A. During the measurements, the reading light was fixed at the height of 600 mm. The center was evaluated by the point which had the highest illuminance (in lux). For each diameter (280 mm and 500 mm), we made four groups of measurements in four directions (vertical and horizontal). In each group of measurements, we took four measurements in order to calculate the average.

As the light meter sensor has a diameter of approximately 30 mm, its surface cannot be neglected. The measured value has already been divided by the surface of the sensor (surface which receives the light), the actual lux in the vertical direction of the light is therefore the measured value/cos Θ. The final result was obtained by averaging the results of the four groups of measurements.

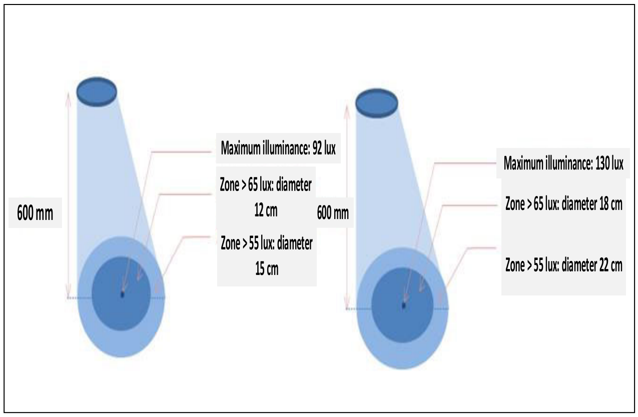


FIGURE 19. Illumination zone measured for 65 lux and 55 lux.

TABLE 5. Measurements from original reading light (with and without housing/case).

Distance from source (mm)	Zone diameter (mm)	Resistance	Average illuminance measured with housing (lux)	Average illuminance measured without housing (lux)
600	280	R = 220 Ω	29.659	18.686
		R = 130 Ω	35.638	32.171
	500	R = 220 Ω	3.932	14.345
		R = 130 Ω	3.378	22.657
200	200	R = 220 Ω	39.504	132.231
		R = 130 Ω	6.225	177.343

Some groups of measurements (see Appendix C – Tables of Illuminance Measurements) were carried out on the original reading light with the housing/case and without housing/case, also the same measurements on the modified reading light (R= 130 Ω). The results are illustrated in Table 5.

These measurements initially showed us that the illuminance in a diameter of 280 mm and 500 mm did not correspond exactly to what is in the specifications. During the measurements, we noticed that the light illuminance decreased very quickly as we moved away from the source. We therefore decided to take the next measurements on the original reading light in order to determine the zones where the illuminance is greater than 65 lux and 55 lux which should be the operating zones of the LiFi module according to the information.

The results (see Figure 18) showed us that the e-reader did not comply with the illuminance level. The zones corresponding to the values of 65 lux and 55 lux are more restricted than those in the specifications. In concept, the LiFi module should still work in the 150 mm diameter area at a distance of 600mm from the source. See Figure 19.

Confirmatory tests were then carried out at a distance of 600 mm from the source. This showed us that the LiFi connection was not stable, even in areas where the illuminance was above 100 lux. After evaluation, we decided to use an older version of receiver that was larger but had better EMC (electromagnetic compatibility). With this new

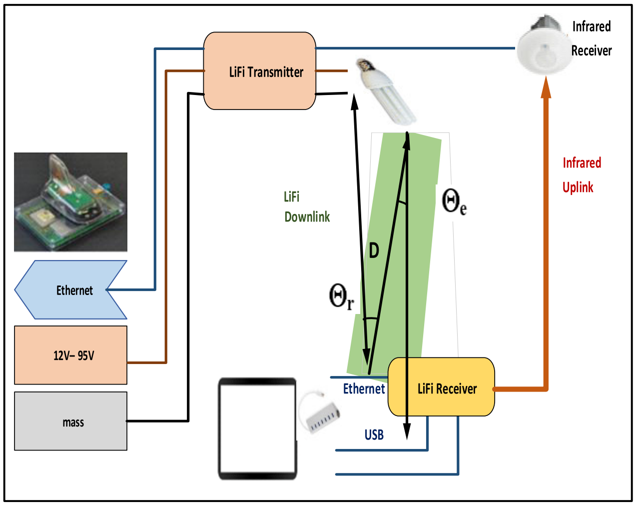


FIGURE 20. Assembly diagram.

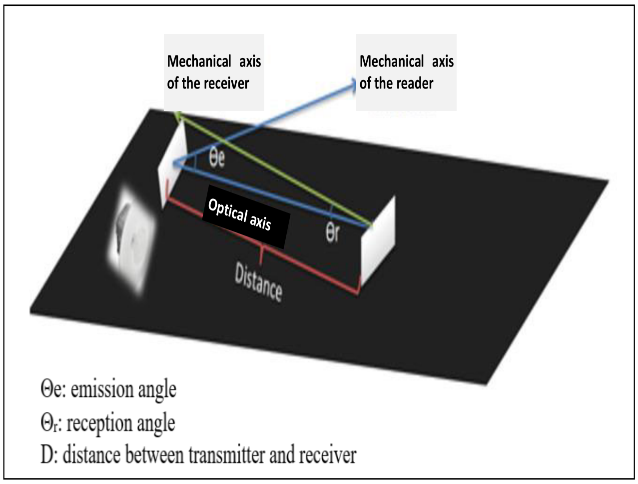


FIGURE 21. Benchmark diagram.

receiver, we had a LiFi download rate of 200 Kb/s to 300 Kb/s at a distance of 600 mm from the source.

This project experiment was aimed at resolving the issue of data transmission and communication inside the vehicle. Hence, when passengers sit down in the car, they do not move a lot. As shown in Figure 18, our system has a zone coverage that allows it to have a stable communication. It needs alignment but it can also work with some angle deviation if the receiver is within the light coverage zone.

VI. CHARACTERIZATION OF THE PROTOTYPE

By trying all the proposed solutions previously described, the performance finally improved somehow. To establish the influence on the quality of communication to find the best configuration for maximum throughput, as well as a representative communication range, we decided to carry out high-level performance tests (throughput, distance, emission angle, reception angle, measurement condition, etc.).

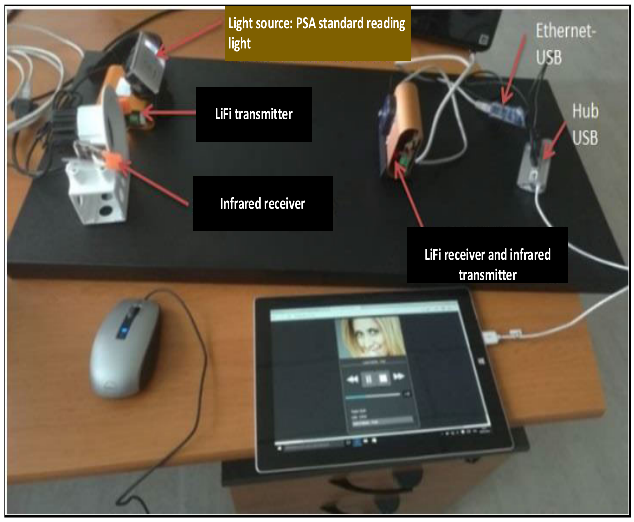


FIGURE 22. Flow measurement with ambient light.

A. PERFORMANCE TESTS

For each measurement, the following parameters were recorded: (i) Distance from source, (ii) Angles between the transmitter and receiver, (iii) Brightness, (iv) Speed, and (v) Measurement conditions. Figure 20 illustrates the measurement diagram.

A first group of measurements was carried out in the laboratory (see Figure 21), with a closed white curtain, shaded sky. Figure 22 demonstrates all the materials used in implementing the measurements tests. It should be stated that the emission and reception angle are noted in the test plan, but it was ultimately not possible in practice due to a problem that occurred: it was difficult to find the operating point in order to have the LiFi connection every time the relative position between the e-reader and the receiver changed, even if the light illuminance is greater than 130 lux. Indeed, from subsequent error rate measurements, we noticed that when the reception angle changed, the error rate became very high, so it was difficult to find the connection while moving the receiver, especially the reception angle.

The results presented in Table 6 show us that at a distance less than 600 mm from the source, the speed is between 200 Kb/s and 300 Kb/s. When the distance varies from 600 mm to 900 mm, the throughput varies from 0 Kb/s to 200 Kb/s.

It was also necessary to do the same tests in the dark. See Table 7. Furthermore, according to our optical measurements on the modified e-reader with a smaller resistor (R=130 Ω), the illuminance is higher than for the original e-reader in the same position. It is therefore also interesting to make the same measurements with the modified e-reader.

From the results in the table above, we can also notice that there is little effect on throughput with the modified e-reader. Indeed, according to optical measurements subsequently, we noticed that the communication range was

TABLE 6. Measurements obtained from the prototype under closed curtain condition.

V=12V, R= 220Ω, Closed white curtain, nuanced sky, Room R214 at LISV, 21 July 2023			
Light meter Test 545 (OLEDCOMM)			
Distance (mm)	300	600	900
Reading light on (lux)	466	230	186
Illuminance ambient light (lux)	316	182	157
Reading light (lux)	150	48	29
Bit Rate (kb/s)	200-300	200-300	0-200
Video effect	Format 1280 * 720, a little blocked	Format 1280 * 720, a little blocked	Format 1280 * 720, quite blocked
	Format 480 * 360, no blocking	Format 480 * 360, no blocking	Format 480 * 360, a little blocked
Music effect	No blocking	No blocking	A little blocked

TABLE 7. Measurements obtained from the prototype under a dark condition.

V=12V, In the dark with lamp light, LISV Storage Room, 21 July 2023			
Light meter Testo 545 (OLEDCOMM)			
Distance (mm)	300	600	900
original reading light (lux)	140	46	27
Bit Rate (kb/s)	200-300	200-300	0-200
Modified reading light (lux)	170	65	40
Bit Rate (kb/s)	150-320	150-300	0-200
Video effect	Format 1280 * 720, a little blocked	Format 1280 * 720, a little blocked	Format 1280 * 720, quite blocked
	Format 480 * 360, no blocking	Format 480 * 360, no blocking	Format 480 * 360, a little blocked
Music effect	No blocking	No blocking	A little blocked

slightly improved up to 80 cm by having a speed of 200-300 Kb/s with the modified e-reader.

From the measurements carried out, we can conclude that the module is functional at a distance of less than 70 cm with the original e-reader and 80 cm with the modified e-reader with a throughput of 200-300 Kb/s.

B. BER TEST BENCH (ERROR RATE)

OLEDCOMM uses 4-PPM (4-Level Pulse Position Modulation) coding scheme in its LiFi module. PPM modulation consists of transmitting pulses at constant amplitude and encoding the information according to the position of the pulse. See Figure 23.

The 4-PPM is a type of pulse modulation where information is encoded by varying the position of pulses in a sequence of time slots. Here, there are four possible positions for the pulses within each time slot, representing distinct signal states. These positions are assigned binary values (00, 01, 10, 11), hence enabling the transmission of two bits per symbol. 4-PPM is suitable for intra-vehicular data transmission applications because it is fast, secured, and resilient to security attacks and has an efficient demodulator performance.

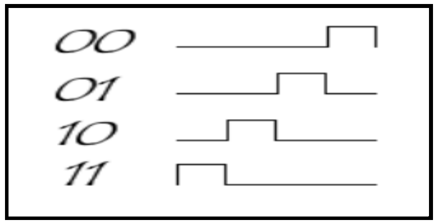


FIGURE 23. Possible positions of 4-PPM coding.

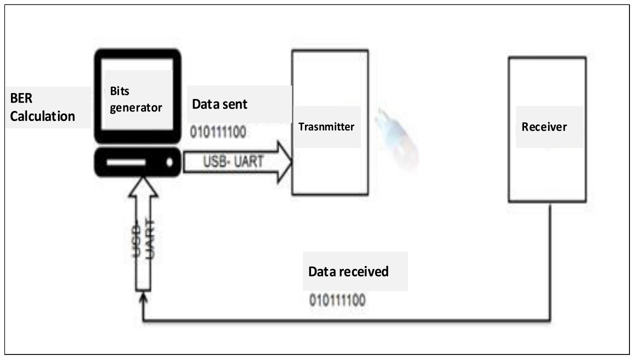


FIGURE 24. Architecture of the BER test bench.

Given below are some advantages of using 4-PPM modulation scheme:

- *Efficient Spectrum Utilization*: 4-PPM efficiently utilizes the available bandwidth by transmitting multiple bits in each symbol. This is advantageous when bandwidth is limited, hence, making it appropriate in intra-vehicular data transmission application where spectrum efficiency is crucial.
- *Robustness to Noise*: In general, Pulse Position Modulation, including 4-PPM, demonstrates a decent degree of resilience to noise. Its pulse positions enhances error detection and correction, which enforces the reliability of data transmission in a noisy environment.

One of the difficulties in implementing this modulation technique is due to the fact that the receiver must be perfectly synchronized to adjust its clock at the start of each symbol. As a result, it is often implemented differentially, which means that the coding of each symbol is done relative to the previous one. The advantage of this type of coding arises from the fact that this implementation is non-consistent. The receiver therefore does not need a phase-locked loop (PLL) to detect the phase of the carrier. This makes this modulation a good modulation technique for optical communications in which phase-coherent modulation and its detection are difficult to guarantee and are very expensive.

The disadvantage of this modulation technique is its susceptibility to multipath interference on e-reader surfaces that can occur in the channels. The receiver thus receives several replicas at different times of each transmitted pulse. As the coding follows a differential logic of arrival times, it is difficult or impossible to determine the correct position of the pulse which corresponds to the one that is transmitted.

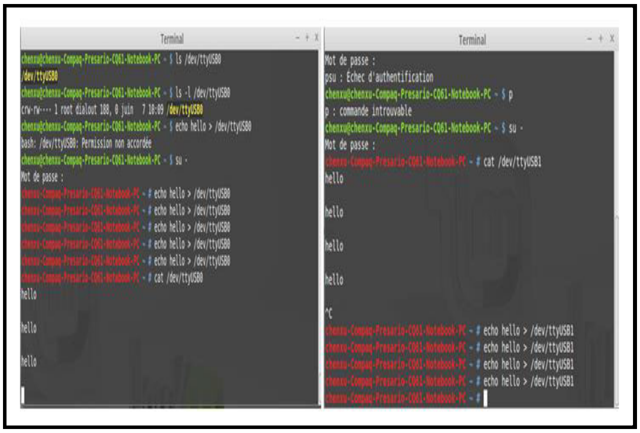


FIGURE 25. Data transmission between two FTDI's.

As the SNR is quite large in our case, 4-PPM coding is probably not suitable for our application. It would be interesting to measure the error rate (BER: Bit Error Ratio) in order to analyze the influences of coding on performance, and possibly compare the different types of coding such as 4-PPM coding and Manchester.

Since Ethernet-transmitter and receiver-mobile devices communication is done via Ethernet, it introduces errors due to the Ethernet link. To make the measured error rate truly due to LiFi communication, we used the UART-USB adapter provided by FTDI (Future Technology Devices International) instead of the Ethernet cable. A BER test bench was developed in C under Linux. The architecture of the bench is represented below. See Figure 24.

1) UART-USB INTERFACE

It was first necessary to ensure UART-USB communication between two adapters linked by wired connection instead of the LiFi connection on a Linux computer. The two FTDI adapters were recognized by computer as ttyUSB0 and ttyUSB1 interface. The sending of the message by these interfaces in console is done by the echo command, and the reception is done by the cat command. Figure 25 represents the sending and receiving of data between the two FTDI adapters.

2) BER TEST BENCH DETAILS

It was then necessary to develop the BER test bench to automatically generate the data and send it through one of the adapters, then receive it through the other, and finally calculate the BER. The program therefore consisted of five parts: (i) the bit generator, (ii) the UART communication setup, (iii) the sending of data, (iv) the receiving of data, and (v) the error rate calculator. The program architecture is represented by Figure 26.

The *random.c* program allows us to automatically generate data whose quantity is defined by a variable. In other words, we can generate as much data as we want. The data is saved in a *sample.txt* file, then read by the *send.c* program and sent character by character via the properly configured ttyUSB0 port. On reception, the *receive.c* program allows us to receive the data coming from the configured ttyUSB1 port and save it in a *receive.txt* file which will subsequently be used to calculate the BER by *compare.c*.

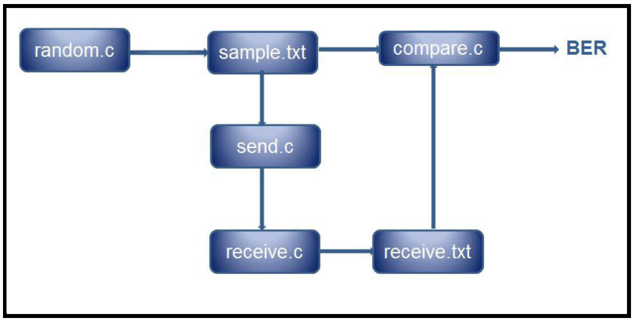


FIGURE 26. Architecture of the test bench program.

Compilation is done using the installed gcc compiler, which allows the program to be compiled and the executable to be generated directly. Execution is then started with the *command./executable_name*. The compilation and execution chain in Linux is represented by Figure 27. As this is done by wired connection, the error rate is 0.

Once the test bench was ready, BER tests were carried out following a test plan whose objectives were firstly to estimate the significant size of data to send. Second, to determine the relationship between the BER and the distance from the source. And finally, to find the acceptable operating zone for each distance. See Figure 28.

According to initial tests at 30 cm at the center of illumination of the e-reader, two files of size 1.2 Mbits and 12 Mbits were chosen to measure the BER. Tests were then carried out at the illuminance center of the e-reader at a distance of 30 cm, 40 cm, 50 cm, 60 cm, and 70 cm to determine the relationship between light source distance and BER. The results (see Appendix D – BER Measurement Tables) showed us that the BER was lower, which was a very good order of magnitude for wireless communication. BER tests were also carried out to determine the acceptable zone at the distance of 60 cm which was in our specifications. The results showed us that the BER was lower than in a diameter area of 20 cm to 60 cm from the light source with the light of a lamp. Tests with the modified e-reader are carried out in order to study the improvement in performance. Other tests must also be carried out by changing the reception angle in order to study the mobility of the module.

C. SYSTEM PERFORMANCE MEASUREMENT

We use iperf to measure the system performance. Iperf is a network testing tool that creates TCP and UDP data streams and measure the throughput of a network that is carrying them. Given that our system creates a network interface, we then used a network evaluation tool like iperf to evaluate the system performance.

To conclude this section, the module is functional at a distance of less than 70 cm with a throughput of 200-300 Kb/s.

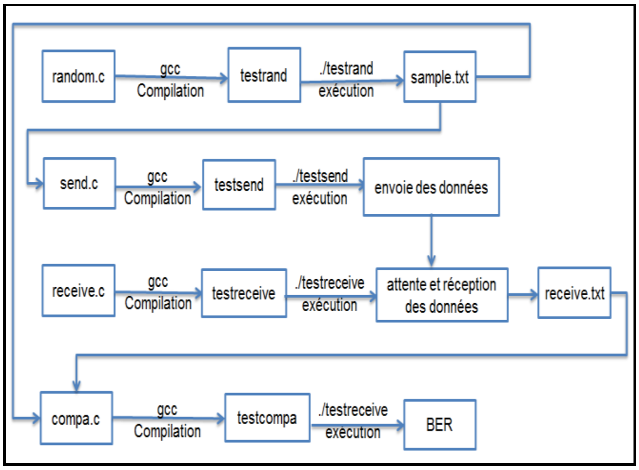


FIGURE 27. Program compilation chain.

The communication range will be enough for intra-vehicle application. However, the speed of 200-300 Kb/s only allows low-definition videos to be played. Since April 2021, RNT has moved to HD (High Definition) which implies a speed of 10 Mbit/s, the speed therefore remains to be improved. The reception area is 20 cm in diameter at a distance of 60 cm due to the restricted illumination area of the e-reader. It will be better to also improve the reception area to be connected more easily.

VII. RESULTS AND DISCUSSION

Being a new technology, LiFi still has many technological challenges whether in the modulation method or in optical elements such as LED and photodiode. For example, the LED used in this project was not homogeneous, and the light received was not direct. This could make the SNR low, and signal reconstruction difficult. Also, the existing photodiodes on the market are Silicon photodiodes. This greatly limits the spectrum of light received. Additionally, it often requires a tradeoff between throughput and communication range. Moreover, LiFi is very sensitive to interference; noise filtering and signal reconstruction becomes essential yet very complex.

LiFi technology depends a lot on optical technology. The optical characteristics have significant influences on those of the LiFi system. Despite the challenges, we managed to carry out various measurements and technical analyses. In this way, we have come to achieving our goal of studying the feasibility of implementing LiFi technology in intra-vehicle communication. In order to improve the performance of the module in terms of throughput, communication range, or reception area, different avenues could be provided. Firstly, replacing the reading light with another lamp that is more powerful and better in optical characteristic can improve the communication range and reception area. Secondly, it will be interesting to test the symmetrical power supply for the preamplifier in order to have a better signal to reconstruct thus a better throughput. In practice, it is too bulky compared to

FIGURE 28. Program compilation chain BER test for wired link.

our application, but we can always study its influence. We can also try using optical filters to eliminate noise as much as possible, thus improving throughput. In addition, the order of magnitude of BER shown by the tests for 4-PPM coding is quite good, but the area is very limited, it is also interesting to study Manchester coding or even O-OFDM. According to our research, an infrared part could be integrated in order to increase the flow rate. Moreover, we can continue to carry out tests to study performance and potential causes of problems in order to find other avenues for improvement.

To the best of our knowledge, most of the studies conducted on LiFi try to achieve vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication. Our system is different in the sense that it concerns about the data communication inside the vehicle, with many constraints:

- The lighting system in the car is a special case, with special optical channels and optical filters. Moreover, the power of this light is limited and is not so strong. Likewise, the coverage zone of this light is not so big.
- The computing resource is very limited in the embedded system.

We have developed our system, taking the above-mentioned constraints into consideration. We used the 4-PPM modulation technique to achieve a more robust communication performance. Given that the resource is limited, the modulation and demodulation techniques of 4-PPM do not need much calculation similar to that of OFDM modulation and demodulation.

VIII. CONCLUSION

In spite of all the challenges encountered throughout this project, this work is able to first, assess the maturity of LiFi technology, and second, to study in more depth the functioning of each part of the LiFi system in intra-vehicle communication, as well as configuring elements that can influence performance in the application. This project is a rediscovery of the world of automobiles and the new LiFi technology which relies on different areas of expertise, whether electronics or on-board systems or even optics.

(1) Absolute Maximum Ratings (Ta=25°C)

Item	Symbol	Absolute Maximum Rating	Unit
Forward Current	IF	180	mA
Pulse Forward Current	IFP	350	mA
Allowable Reverse Current	IR	85	mA
Power Dissipation	PD	684	mW
Operating Temperature	Topr	-40 ~ +100	°C
Storage Temperature	Tstg	-40 ~ +100	°C
Dice Temperature	Tj	110	°C

IFP Conditions : Pulse Width ≦ 10msec. and Duty ≦ 1/10

(2) Initial Electrical/Optical Characteristics (Ta=25°C)

Item		Symbol	Condition	Typ.	Max.	Unit
Forward Voltage		VF	IF=150[mA]	3.5	3.8	V
Luminous Flux		ϕV	IF=150[mA]	(20.0)	-	lm
Chromaticity Coordinate *	x	-	IF=150[mA]	0.31	-	-
	y	-	IF=150[mA]	0.32	-	-

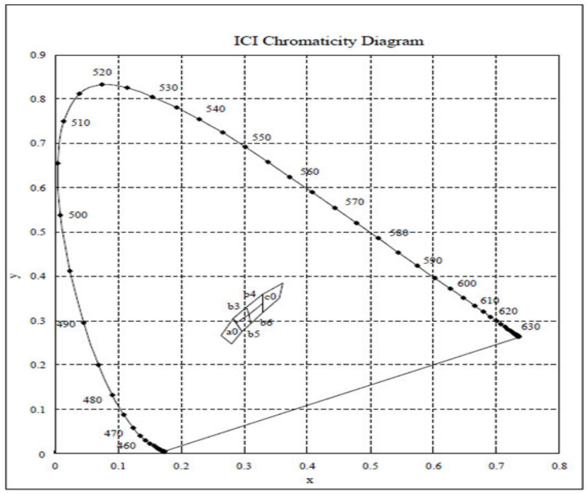
* Please refer to CIE 1931 chromaticity diagram.

FIGURE 29. Optical and electrical characteristics of the standard PSA e-reader.

	X	Y
C1	0,300	0,312
C2	0,326	0,300
C3	0,304	0,266
C4	0,278	0,279

Coordinates of the points of the standard PSA e-reader

FIGURE 30. Coordinates of the points of the PSA e-reader.



* Color Coordinates Measurement allowance is ± 0.01.

FIGURE 31. ICI chromaticity diagram of the PSA e-reader.

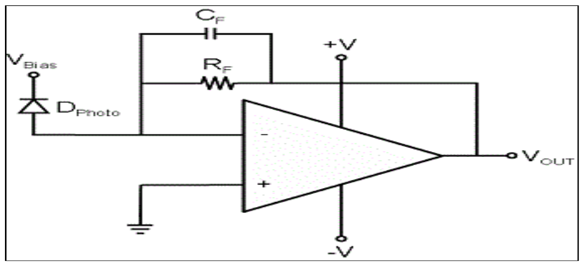


FIGURE 32. Diagram of the classical transimpedance.

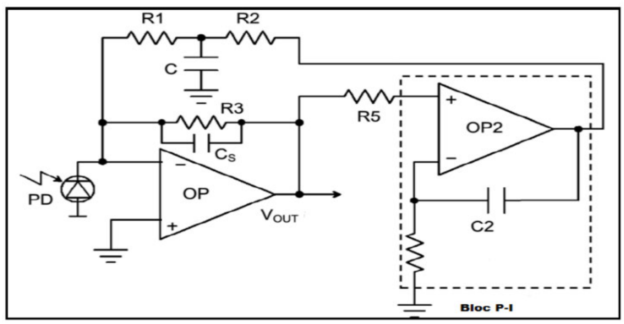


FIGURE 33. Diagram of transimpedance studied.

This exercise demonstrates that there is always a difference between what we imagined and what really happened. This did not mean that things were not going well, it was in fact just a normal phenomenon that we have to accept. At the end of this study, we can conclude that the prototype module is functional at a distance of less than 70 cm with a throughput of 200-300 Kb/s. The communication range will be enough for intra-vehicle application. The bit rate speed of 200-300 Kb/s only allows low-definition videos to be played. This is a step in the right direction. We have demonstrated that LiFi data transmission in the vehicle is feasible and that low-definition videos were successfully transmitted from the source to the destination via LiFi.

The shortcoming noted in this work is that there is a need to adapt our system according to the power and the coverage of the existing light in the car used in the experiment. That being said, we can still improve our lighting system. In the future, we can also improve our reception system by using some artificial intelligence algorithms in relation to the filtering part as well as in the adaptive gain part. It is also a possibility that the new generation of smartphones may be equipped with photodiodes or have a camera for high-speed data transmission and reception because in the actual system, we need to use an external USB dongle.

As a future work, we have noted that as of April 2021, RNT has moved to HD (High Definition) which implies a speed of 10 Mbit/s, the LiFi transmission speed therefore needs to be improved. It will also be better to improve the reception area for ease of connection, as well. In addition, we have an ongoing discussion with Ifsttar Institute[4] to reserve their testing road in order for us to test our system using real car with real driving conditions. This along with other experimentations will form part of our next publication.

APPENDIX A: IMPORTANT CHARACTERISTICS OF THE STANDARD PSA E-READER

See Figures 29–31.

[4]Ifsttar Institute: IFSTTAR is the French Institute of Science and Technology of Transport, Development and Networks. Website: https://www.id4mobility.org/membres/ifsttar

TABLE 8. Measurements using reading Light with Housing/Case: distance of 280 mm.

Lux measurement of the reading light with housing						
Distance = 280 mm			lux center = 82.8 lux			
					Average	
Measurements Point 1 (lux)	28.3	25.9	26.9	25	26.525	The vertical direction of the e-reader
Real lux Point 1	29.055	26.591	27.618	25.667	27.233	
Measurements Point 2 (lux)	25.1	26.8	25.9	25.3	25.775	
Real lux Point 2	25.770	27.515	26.591	25.975	26.463	
Measurements Point 3 (lux)	32.9	32.1	32.4	31.7	32.275	The horizontal direction of the e-reader
Real lux Point 3	33.778	32.957	33.265	32.546	33.137	
Measurements Point 4 (lux)	31.9	34.3	31.1	32.7	32.500	
Real lux Point 4	32.752	35.216	31.930	33.573	33.368	
Average					29.659	

TABLE 9. Measurements using reading Light with Housing/Case: distance of 50 mm.

Distance = 50 mm			lux center = 82.8 lux			
Measurements Point 1 (lux)	1	1.1	1	1	1.025	The vertical direction of the e-reader
Real lux Point 1	1.083	1.192	1.083	1.083	1.111	
Measurements Point 2 (lux)	1.2	1.1	1.3	1.2	1.200	
Real lux Point 2	1.300	1.192	1.408	1.300	1.300	
Measurements Point 3 (lux)	9.3	10	10.2	8.7	9.550	The horizontal direction of the e-reader
Real lux Point 3	10.076	10.834	11.051	9.426	10.347	
Measurements Point 4 (lux)	2.3	3.7	3.3	4	3.325	
Real lux Point 4	2.492	4.009	3.575	4.334	3.602	
Average					3.932	

TABLE 10. BER measurement, data transmission of various data sizes.

Data size (Mbit)	Distance (cm)	Luminous illuminance (lux)	Emission angle	Receiving angle	Transmission time	BER (%)
1.2	30 cm	220	25°	15°	2 min	0
12					15 min	0
25.2					30 min	0
12					10 min	0
24					20 min	0
12					2 hr 30 min	0

APPENDIX B: COMPARISON OF CLASSICAL TRANSIMPEDANCE AND TRANSIMPEDANCE STUDIED

See Figures 32 and 33.

APPENDIX C: TABLES OF ILLUMINANCE MEASUREMENTS

See Tables 8 and 9.

APPENDIX D: BER MEASUREMENT TABLES

See Tables 10–12.

TABLE 11. BER measurement, reading light of various illuminance and various distances.

Distance (cm)	Lighting of the reading light in the center (lux)	Data size (Mbit)	Emission angle	Receiving angle	Transmission time	BER (%)
30	220	1.2	25°	15°	2 min	0
		12			15 min	0
40	120	1.2	25°	15°	2 min	0
		12			15 min	0
50	80	1.2	25°	15°	2 min	0
		12			15 min	0
60	64	1.2	25°	15°	2 min	0
		12			15 min	0
70	43	1.2	25°	15°	2 min	0
		12			15 min	0

TABLE 12. BER measurement, data transmission of fixed sizes, reading light of various illuminance and fixed distances.

Distance (cm)	Illumination (lux)	Data size (Mbit)	BER (%)
60	60	1.2	0
		12	0
	50	1.2	0
		12	0
	40	1.2	0
		12	0
	30	1.2	0
		12	0
70	30	1.2	0

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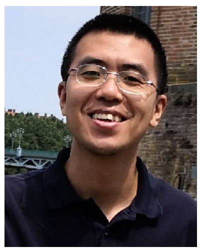

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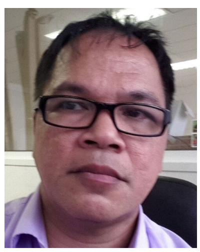

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