Design and Implementation of A Visible Light-Based Communications System

Diseño e implementación de un sistema de comunicaciones basado en luz visible

Desenho e implantação de um sistema de comunicações baseado em luz visível

Sebastian Caballero Barragan[1]
Fabio G. Guerrero[2]

Received: September 10th, 2018
Accepted: January 20th, 2019
Available: May 21th, 2019

How to cite this article:
S. Caballero-Barragán, F. G. Guerrero, "Design and Implementation of A Visible Light-Based Communications System", *Revista Ingeniería Solidaria*, vol. 15, n.° 2, 2019.
DOI: https://doi.org/10.16925/2357-6014.2019.02.03

Artículo de investigación. https://doi.org/10.16925/2357-6014.2019.02.03

1 Escuela de Ingeniería Eléctrica y Electrónica (EIEE). Facultad de Ingenierías. Universidad del Valle

ORCID: https://orcid.org/0000-0002-2773-5467

2 Escuela de Ingeniería Eléctrica y Electrónica (EIEE). Facultad de Ingenierías. Universidad del Valle

ORCID: https://orcid.org/0000-0002-5658-9497
E-mail: fabio.guerrero@correounivalle.edu.co

Abstract

Introduction: The publication is the product of the research "Prototipo de un sistema de telecomunicaciones basado en luz visible", carried out at Universidad del Valle in 2018.

Objective: The objective of this work was to build a functional prototype of a telecommunications system based on visible light through which the study of the most relevant characteristics, elements and behaviors in relation to this technology could be made.

Methodology: To study the behavior of the developed prototype, different tests were performed varying some of the variables present in this type of telecommunications system. In addition, the developed prototype was tested in simplex and halfduplex modes.

Conclusions: The results obtained when developing this work demonstrated the main characteristics of the prototype, its limitations, as well as the elements and variables that govern the most important aspects of its design.

Originality: The presented design proposes the development of a low cost prototype, capable of obtaining the data to be sent through the connection to other devices through different communication peripherals or using the ADC present in the processing device used.

Restrictions: Due to the reception elements used in the prototype there is a significant limitation on the maximum achievable transmission rate. In addition, it is important to mention that the conditions in which the prototype is deployed can affect its behavior, for example, elements that impede the line of sight between the telecommunications modules can stop the transmission.

Keywords: Visible Light Communications, Optical Wireless Communications, Optical Physical Layer. Manchester Coding, OOK Modulation.

Resumen

Introducción: El artículo es produto de la investigación: "Prototipo de un sistema de telecomunicaciones basado en luz visible", realizado en la Universidad del Valle en el año 2018.

Objetivo: El objetivo de este trabajo fue construir un prototipo funcional de un sistema de telecomunicaciones basado en luz visible a través del cual se pueda realizar el estudio de las características, elementos y comportamientos más relevantes en relación con esta tecnología.

Metodología: Para estudiar el comportamiento del prototipo desarrollado, se realizaron diferentes pruebas que variaron algunas de las variables presentadas en este tipo de sistemas de telecomunicaciones. Además, el prototipo desarrollado se probó en los modos simplex y halfduplex.

Conclusiones: Los resultados obtenidos al desarrollar este trabajo permitieron encontrar las características principales del prototipo, sus limitaciones, así como los elementos y variables que rigen un papel fundamental en su diseño.

Originalidad: El diseño presentado propone el desarrollo de un prototipo de bajo costo, capaz de obtener los datos que se enviarán a través de la conexión a otros dispositivos a través de diferentes periféricos de comunicación o usar el ADC presente en el dispositivo de procesamiento utilizado.

Limitación: Debido a los elementos de recepción utilizados en el prototipo, existe una limitación significativa en la velocidad de transmisión máxima alcanzable. Además, es importante mencionar que las condiciones en las que se implementa el prototipo pueden afectar su comportamiento, por ejemplo, los elementos que impiden la línea de visión entre los módulos de telecomunicaciones pueden detener la transmisión.

Palabras clave: comunicaciones basadas en luz visible, comunicaciones ópticas inalámbricas, capa física óptica, modulación OOK.

Resumo

Introdução: este artigo é produto da pesquisa "Protótipo de um sistema de telecomunicações baseado em luz visível", realizado na Universidad del Valle, Colômbia, em 2018.

Objetivo: o objetivo deste trabalho foi construir um protótipo funcional de um sistema de telecomunicações baseado em luz visível por meio do qual possa ser realizado o estudo das características, elementos e comportamentos mais relevantes relacionados com essa tecnologia.

Metodologia: para estudar o comportamento do protótipo desenvolvido, foram realizados diferentes testes que alternaram algumas das variáveis apresentadas nesse tipo de sistemas de telecomunicações. Além disso, o protótipo desenvolvido foi testado nos modos simplex e halfduplex.

Conclusões: os resultados obtidos ao desenvolver este trabalho permitiram encontrar as características principais do protótipo, suas limitações, bem como os elementos e variáveis que desempenham um papel fundamental em seu desenho.

Originalidade: o desenho apresentado propõe o desenvolvimento de um protótipo de baixo custo, capaz de obter os dados que serão enviados por meio da conexão a outros dispositivos por diferentes periféricos de comunicação ou usar o adc presente no dispositivo de processamento utilizado.

Limitação: devido aos elementos de recepção utilizados no protótipo, existe uma limitação significativa na velocidade de transmissão máxima alcançável. Além disso, é importante mencionar que as condições nas quais o protótipo é implantado podem afetar seu comportamento, por exemplo, os elementos que impedem a linha de visão entre os módulos de telecomunicações podem deter a transmissão.

Palavras-chave: comunicações baseadas em luz visível, comunicações ópticas sem fio, capa física óptica, modulação ook.

1. Introduction

The current social trend of being persistently connected to the Internet has brought about a significant increase in the use of diverse Internet-enabled devices such as smartphones, video game consoles, music players, etc. This trend is causing some problems as the number of people connected increases. Other associated problems include exposure of personal information —security—, increased radioelectric spectrum utilization generating potential problems of congestion in networks, among others.

In this paper we present the development of a communications system prototype which operates using visible light as its basic transmission technique, a technology known nowadays as visible light communication or VLC. In this type of system, the fast switching response property of LED (Light-Emitting diode) lights, which are widely used as lighting sources, are employed as the core of the transmitter. Information is encoded as ON-OFF states of light [1], giving to VLC systems the ability to provide lighting and communication at the same time.

Several advantages can be identified when comparing VLC systems with other communication systems that use radiofrequency, making the VLC technology attractive. Some advantages and applications of the VLC system are presented below:

- Use of visible light as a source of information makes it possible to know the equipment that sends and receives data at a given moment, which provides an infallible security control to detect attempts to steal information by intruders [2].
- Feasibility of merging the existing lighting infrastructure with communication systems based on visible light.
- Transmission of information using visible light does not pose a risk to the health of people and does not generate electromagnetic interference, this is because VLC systems do not use radio frequency for the propagation of information [3].
- Use of visible light for communications is totally free unlike the use of radio frequency for the same purpose, the latter is regulated, and its use represents a cost for the operators of this type of communications.
- As mentioned in [4], VLC systems do not produce any type of interference in the ISM band.
- Electric power used for the VLC systems can be considered as almost free, since they work on the existing lighting systems, only extra energy is used in the process of control of the circuits needed to make the switching of the light source.
- Due to the high switching rates of light emitting diodes, it is possible for VLC systems to reach high data rates, such as some prototypes shown in [5] which reach transmission rates near to 1 Gbit/s.

In [6], the prototype of an embedded realtime audio transmission system that uses VLC is presented. A computer sends the audio to be transmitted to an embedded system, which digitizes and controls the LED lights; the receiver processes the VLC packets and converts the audio back into digital to be played on a speaker at a maximum separation distance of 3 meters.

[7] presents how smartphones can be used to design VLC applications, the article shows how LED lamps in telephones are switched to different frequencies, in order to achieve communication using visible light at a maximum transmission rate of 5 kbps. Finally, in [8] another prototype is presented. It shows how VLC systems can be used to develop indoor location tools; in this the broadcast mode is used as the basis of operation and a range of 2.8 meters is reached.

The above-mentioned advantages and applications represent a promising scenario for this type of communications system, which highlights the importance of the prototype development discussed in this document. Also, this is an opportunity to venture into the area of new communications technologies in the country, conduct a research approach to its operation and open the way for new projects that can be based on the results found and exposed in this document.

The aim of this paper is to show the design and implementation of a prototype that provides an approach to the physical layer of the VLC systems in its simplex and half-duplex communication modes and bases its operation on a single method of modulation and coding.

The rest of this paper is as follow: Section 2 shows the methodology used to design and implement the prototype, in Section 3 we present the prototype test as a communication system as well as perform a functional test of the hardware and software of which the system is comprised. Section 4 consists of results and analysis of the prototype performance, discussions and conclusions are presented in Section 5.

2. Methodology

In this section, the design and implementation specifications of the developed VLC prototype will be presented, as well as its implementation and each of the elements necessary for its operation. Figure 1 shows a block diagram that generally represents the VLC modules of the prototype, which consists of different components: power, processing, transmission and reception components.

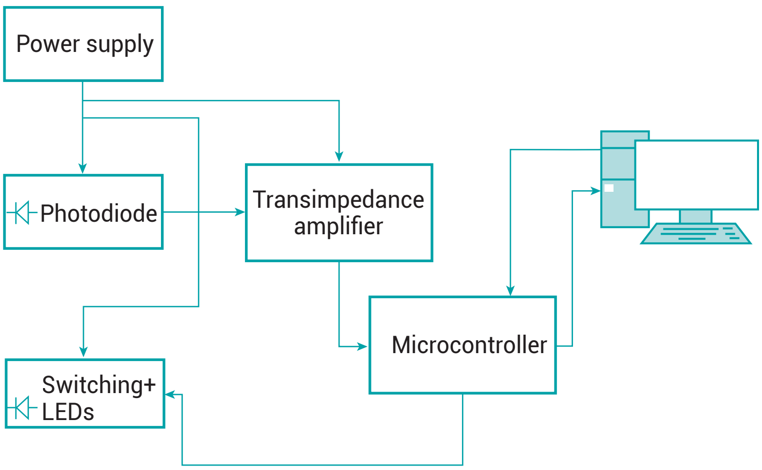

Figure 1. VLC module block diagram.
Source: own work

The final developed prototype has two VLC modules like the one presented above. It should be noted that, for simplicity's sake, when designing the software and hardware that make up these modules, the transmission and reception components were developed individually before being joined at the software level.

2.1 Power supply

This component is responsible for delivering the electrical power necessary for the operation of each of the elements that make up the modules. First, each module is powered by a dual source of +/- 12 VDC, and then these voltage levels are distributed and adjusted to those needed for each of the different components of the system.

2.2 Processing unit

It was determined that the appropriate device for the development of the prototype was the Atmega328p microcontroller from Atmel Corporation. This was selected because, compared to other processing systems, it has a lower cost, a smaller size and is easy to acquire.

The main characteristics of the selected device that were considered for the development of the prototype are listed below:

- Maximum clock frequency of 20 MHz.
- Integrated analog comparator.
- Low power consumption.
- A/D converter.
- Communication ports (notably a serial port).
- Device size.

The device in charge of the processing in the VLC modules of the prototype has both functions related to the transmission and the reception of information. In terms of transmission, it is responsible for taking the data to be transmitted, coding it, and then transmitting it through one of its output ports so that said information reaches the LEDs and can be sent.

Its function in the reception component is to take the voltage signals delivered by the photodiode array and operational amplifiers of said component and compare them with a predetermined voltage level in order to determine if what it receives is a logical zero (values less than the predetermined voltage) or a logical one (values greater than the predetermined voltage), to then decode the received message.

e-ISSN 2357-6014 / Vol. 15, n°. 2 / mayo 2019 / Bogotá D.C., Colombia
Universidad Cooperativa de Colombia

2.3 Transmission unit

Within the VLC modules this component is responsible for adapting the signal coming from the microcontroller so that it arrives in an appropriate way to the light source of the module. They transmission component consists of an operational amplifier (OP AMP), a MOSFET transistor, and the LED lights that send the information by visible light to the other module.

As has been explained before in this document, in VLC systems, the information to be sent is transmitted by light, which in this prototype is provided by three white LEDs each of 1 Watt of maximum power.

The selected LED lights have the following characteristics according to the manufacturer's data sheet:

- Maximum power dissipation of 1 Watt.
- Maximum 120 lm at maximum power.
- Viewing angle 130° without secondary optical amplifiers.

In addition to the LED lights, an optical lens with a 30° angle of view will be used. This allows the LED radiation pattern to not be so wide, which leads to a better direction of the light and the range of the prototype increase.

An operational amplifier is also part of the transmission component. The OP AMP must take charge of carrying the signal coming from the microcontroller, in which the information to be sent is already encoded, from its original values of 0 to 5 VDC up to 0 to 6.3 VDC. This is with the aim of delivering an adequate voltage value to the gate of the MOSFET transistor and make it allow for the passage of current (or not) between drain and source according to the changes in the signal sent from the microcontroller.

For the implemented prototype, the decision to use an LF353 operational amplifier was made. This has, according to its data sheet, a gainbandwidth product of 4 MHz and response times of less than 0.2 μs when working with signals less than 200 mV and times less than 2 μs when working with higher voltage signals. The MOSFET transistor is the switching element of the module and is responsible for allowing the LED lights to be polarized or not according to the message sent from the microcontroller.

2.4 Reception unit

This component is responsible for converting the optical signals, sent from the other VLC module, to voltage signals treatable by the microcontroller and is composed of a photodiode and two operational amplifiers.

The photodiode has the function of converting the optical signals received into electrical current signals, allowing the passage of this in the presence of light or preventing its flow in the absence of optical excitation. The device selected for the design was the photodiode PD 204-6C, this device can respond with an efficiency greater than 0.2 for wavelengths between 300 nm and 1200 nm, with its peak efficiency at 940 nm. For the wavelengths of the visible light spectrum, its efficiency moves between 0.5 and 0.8. The angle of view of the selected device is 45°.

In this component there are two OP AMPs, one of them works as a current-to-voltage converter, which takes the current signals delivered by the photodiode. These are in the order of microamps, and converts them into voltage signals, that come to be of the order of millivolts. The second operational amplifier takes this voltage signal and amplifies them to suitable levels to be used by the microcontroller.

2.5 Hardware design

There are different methods of modulation and coding that permit the sending of information by visible light. One of them is known as ON-OFF modulation, this consists of using the two states of the light source to perform the modulation of information. This method of modulation combined with one of coding known as Manchester coding, were the methods selected to develop the prototype discussed in this document. These were chosen based on the recommendation for PHY I of the standard IEEE 802.15.7 [9].

In order for the LED lights used in the prototype to send the information already suitably encoded, a circuit was designed. The circuit takes the signals sent by the microcontroller and adjusts them so that the LED varies its ON and OFF states according to the message sent from the processing component.

The reception component is responsible for converting the optical signal that the photodiode receives and delivers it to the microcontroller as a voltage signal that varies between 0 and 5 VDC.

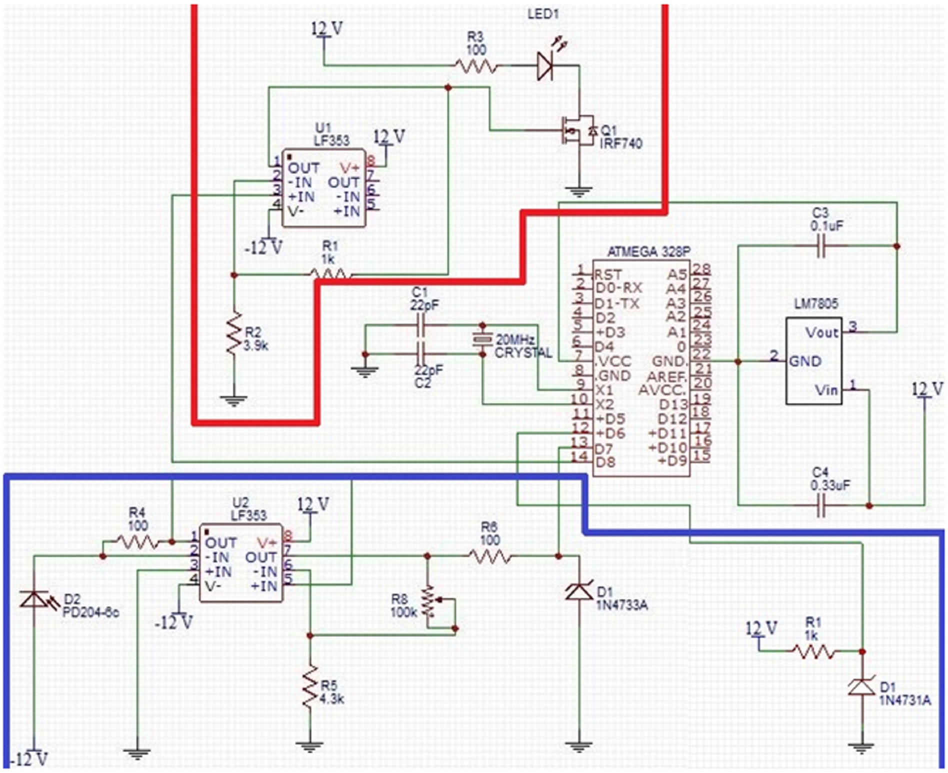

Figure 2. VLC module schematic.
Source: own work

Figure 2 shows the final schematic design of the VLC modules, the blue mark groups the reception component and the red mark groups the transmission component. The schematic diagram presented also shows some extra elements that were attached to the microcontroller. These correspond to the external crystal oscillations of 20 MHz that the microcontroller uses for its operation at maximum clock frequency and a voltage reference of 4.1 VDC that was made with a Zener diode model 1N4731A. This is used as a threshold in order to decide if the signal received by the photodiode is a “1” or a “0”.

At the end of the reception component in Figure 2 there is another Zener diode. This will be polarized when the optical signal received correspond to a logic “1” and so in this way, the circuit can send a 5 VDC value to the microcontroller.

2.6 Software design

For the software design of the module, the transmission of the data was first thought of. The following describes the process of data transmission implemented in the prototype.

After preparing the data to be sent (they can be loaded in memory directly or use one of the available methods to connect the microcontroller to a computer), each of the bits to be transmitted and its complement were shown in one of the pins of the microcontroller for a time "T" / 2 each thereby achieving Manchester coding.
The total duration time of an already coded bit is "T" seconds, where the time "T" is the same optical clock period. This time varies according to the transmission rate at which the module is configured. It is worth mentioning that before sending each group of 8 bits, a high state is placed on the output pin with a "Tinicial" duration, in this case the "Tinicial" time has a duration that varies according to the transmission rate used. This time is intended to be used as an aid during synchronization with the reception component.

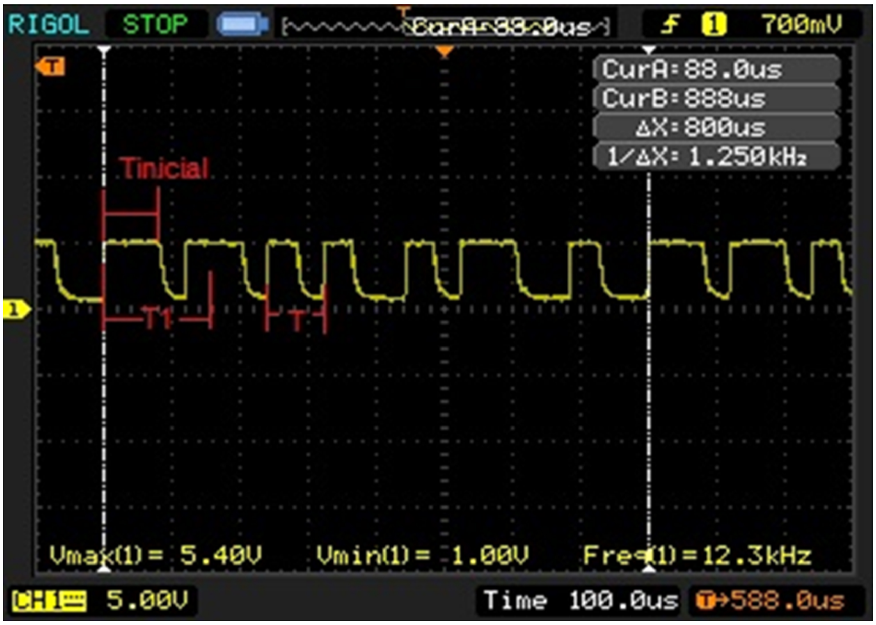

Figure 3. Received signal and its decoding process.
Source: own work

The decoding process was implemented by using the analog comparator of the microcontroller as follows: when an incoming signal —message received from the photodiode and the current-to-voltage converter— exceeds the aforementioned 4.1 VDC threshold, this is interpreted by the microcontroller as a logical "1".

Figure 3 shows an example of the times that are taken into account when performing the decoding on a signal received by the corresponding component of the VLC module. The received signal is an 8-bit data at a transmission rate of 10 kbit/s. The time "T1" corresponds to a time of alignment of the reading period of the received data and this has a duration close to "T" + "Tinicial", where "Tinicial" is a time used by the microcontroller to know that it will receive a message.

The decoding process then occurs as follows: the microcontroller receives a signal that tells it to start decoding once the comparator sets its output to high for the first time, then a time "T1" is expected and the first bit of the data received is read. The reading of the encoded bits occurs a few microseconds before the end of its period of duration, therefore, based on the manner in which the bits are interpreted in Manchester coding, the complement of the comparator output will indicate the already decoded received bit. Finally, the reading of the comparator output is repeated every "T" seconds until the 8 bits have been read, since the already decoded bits are joined in a single 8-bit variable.

In order to verify the operation of the hardware and software designed, a simple test of sending and receiving bits was performed.

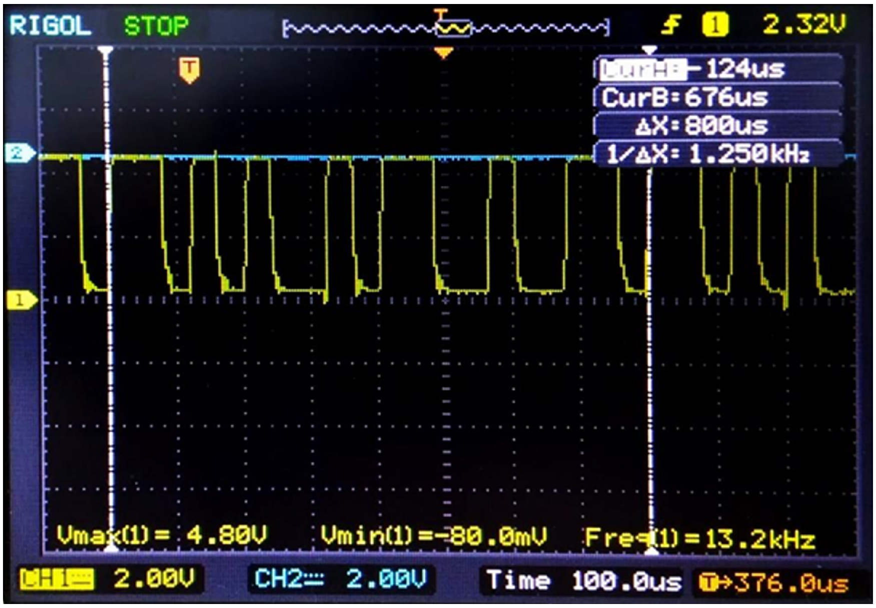

Figure 4. Signal received by one of the VLC modules.
Source: own work

Figure 4 shows the signal received during the hardware and software test of the VLC module, which shows that the transmission times are met for a transmission rate of 10 kbit/s and it can also be seen that the Manchester coding is carried out properly.

Finally, one of the implemented VLC modules is shown in Figure 5 (which indicates the different components that each module are made up of).

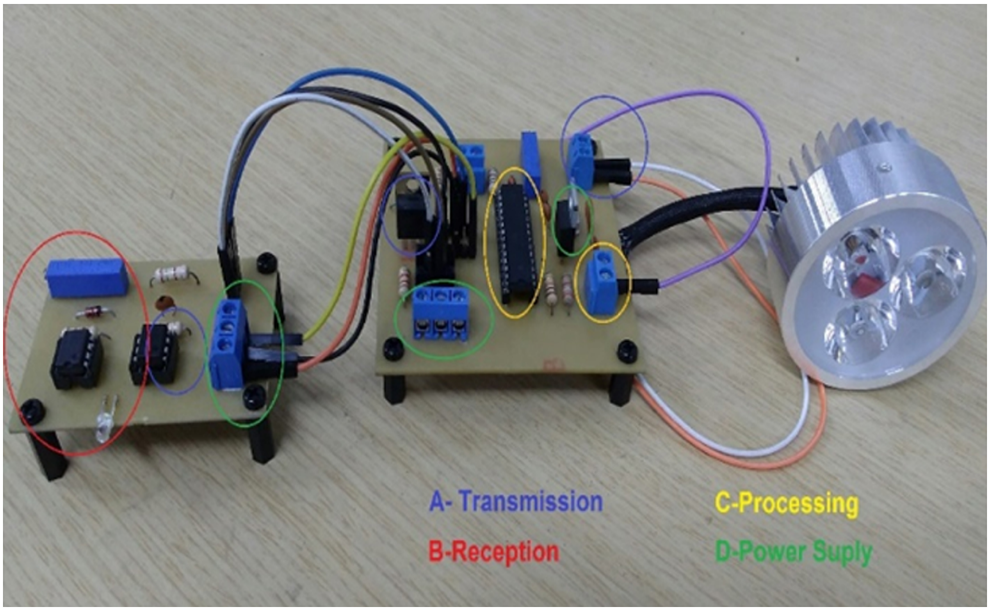

Figure 5. Final implementation of the VLC modules.
Source: own work

3. Prototype Test

In this section we want to present a short description of each of the tests that were carried out to characterize the operation of the prototype.

As mentioned in previous sections of this document, it is possible to change the transmission rate of the developed communication system, modifying the times that interact with the sending and receiving of data. For simplex and half-duplex operation modes, three different transmission rates were tested. For simplex mode it has 10 kbit/s, 25 kbit/s, and 50 kbit/s and for half-duplex mode you have 10 kbit/s, 23 kbit/s, and 40 kbit/s.

What follows is a description of the different tests that were performed.

3.1 Transmission rate vs distance between modules

To study the dependence of the transmission rate achievable by the prototype with respect to distance, a test was carried out that included changes in only these two variables.

The tests were performed for all the transmission rates available in simplex operation mode. The distance in the tests was varied with intervals of 0.5 m —this being the initial intermodule distance— with the maximum separation distance being provided by the distance at which the receiver could not respond in the appropriate way. This is when, with the maximum amplification of the reception component, the received signals did not reach the 5 VDC levels necessary for its correct reading by the processing component.

3.2 Transmision rate vs ambient light levels

The dependence of the transmission rate on ambient lighting levels was studied with a test that consisted of transmitting information using the prototype under two different lighting levels. The test was performed in both operating modes of the prototype, with all available transmission rates, first with an illumination of 0 lx and then with 109.7 lx.

3.3 Distance between the modules vs transmission power

The transmission power in this case is the same power dissipated by the LEDs at the moment of transmitting the data and it is possible to modify it by varying the current that reaches the light emitting diodes.

This test was carried out to study the dependence of the distance between the modules with respect to the transmission power, for which a determined number of bits were transmitted at a fixed transmission rate for both modes of operation. The total transmission power was varied between 0.9 W for a luminous flux of 108 lm, 1.5 W for a luminous flux of 180 lm, and 2.97 W for a total luminous flux of 356 lm. The distance was also varied every 0.5 m until reaching the distance limit for each transmission power.

3.4 Function test without optical lens

To study the behavior of the system developed by removing the optical lens from the LEDs that are part of the transmission component, a test based on the bit error rate was performed. The mode of operation in this test was simplex mode, with a transmission rate of 10 kbit/s. For this test, the distance was varied from 0.5 meters to the maximum distance of separation between the modules to which they could respond adequately.

3.5 Bit error rate

All the aforementioned tests were carried out basing their analysis on the bit error rate. This was with the aim of having a clear point of comparison between each of them.

To perform the tests using the bit error rate, it was necessary to write a code capable of generating pseudorandom bit sequences. These were generated taking into account the recommendation ITU-T O.150: Digital test patterns for performance measurements on digital transmission equipment of the ITU for transmission rates lower than 64 kbit/s [10].

It was possible to acquire and store the data received in each test thanks to the existing serial connection between the VLC modules and a PC. The received data was compared with sent data with the help of a spreadsheet and various functions provided by it.

4. Results

In this section the results obtained by implementing the characterization tests described above are presented, as well as the analysis that describes the operation of the developed prototype with respect to the main variables that interact with it.

4.1 Transmission rate vs distance

In Table 1, it can be seen that for the tested transmission rates, no erroneous bits arrive until the intermodule distance of 2 meters is exceeded. In addition to this, the results show that the behavior of the bit error rate does not vary significantly with changes in the transmission rate.

Table 1. GNSS Stations used in the study.

Distance	BER at 10 kbit/s	BER at 25 kbit/s	BER at 50 kbit/s
0.5 m	0	0	0
1 m	0	0	0
1.5 m	0	0	0
2 m	0	0	0
2.5 m	0.060732	0.049634	0.047561
3 m	0.100854	0.085671	0.083963

Source: own work

As shown in Table 1, the difference between the measured bit error rates does not exceed 1.6 %, which is a good indicator to say that the transmission rate is not affected significantly by the distance of separation between the modules and vice versa.

4.2 Transmission rate vs distance

The results of this test are shown in Table 2; As can be seen, for most transmission rates, in both operating modes, the bit error rate is 0 %, which indicates that the ambient lighting levels under which the prototype was tested does not affect their behavior.

Table 2. Bit error rate in the test of transmission rates vs ambient lighting levels.

	Data rate	0 lx	109 lx
Simplex	10 kbit/s	0	0
	25 kbit/s	0	0
	50 kbit/s	0	0
Half-duplex	10 kbit/s	0	0
	23 kbit/s	0	0
	40 kbit/s	0.498353	0.498353

Source: own work

However, it was found that for the half-duplex mode, at a transmission rate of 40 kbit/s, the bit error rate is close to 50 %, for both levels of illumination. This behavior is due to the way in which the reception component responds to optical switching frequencies greater than 64 kHz. The above shows that there is not a considerable relationship between the transmission rate and ambient lighting levels, but it does show a direct relationship between the response times of the photodiode used in the reception component and the maximum transmission rate achievable with the developed prototype.

4.3 Distance between the modules vs transmission power

According to its data sheet, the change in power consumption by the LEDs used in the transmission component of the prototype has a direct relationship with the illumination flow. Figures 6 and 7 show the way in which the bit error rate varies for each operating mode, simplex and half-duplex respectively, at different separation distances between the VLC modules when the transmission power is changed.

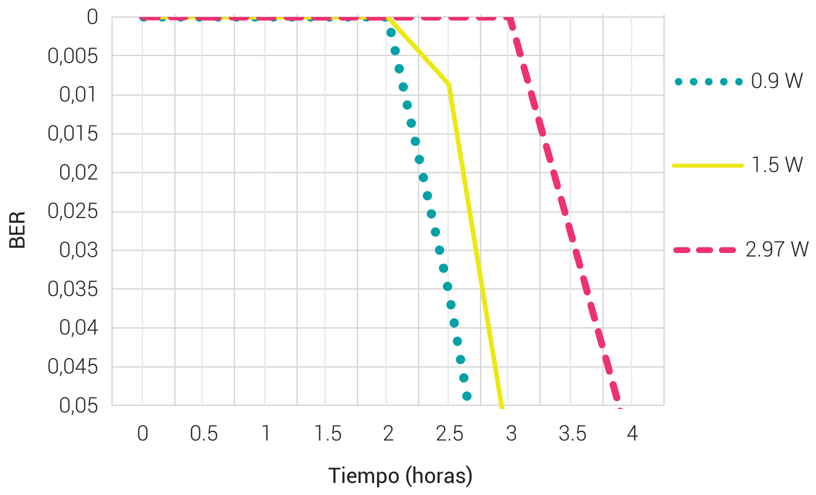

Figure 6. BER in the test distance between the modules vs transmission power (SIMPLEX).
Source: own work

Figure 6 shows that the increase in transmission power leads to a significant increase in the maximum separation distance between the modules without having an error rate greater than 0 %. For this mode of operation —simplex—, the maximum distance reached without errors is 3 meters. This happens when the transmission power is 2.97 W. With a transmission power of 1.5 W can have a maximum distance of 2 m without errors or 2.5 m with a bit error rate of 0.86 % and lastly, when the transmission power is 0.9 W, a maximum distance of 2 m is achieved with a bit error rate of 0 %.

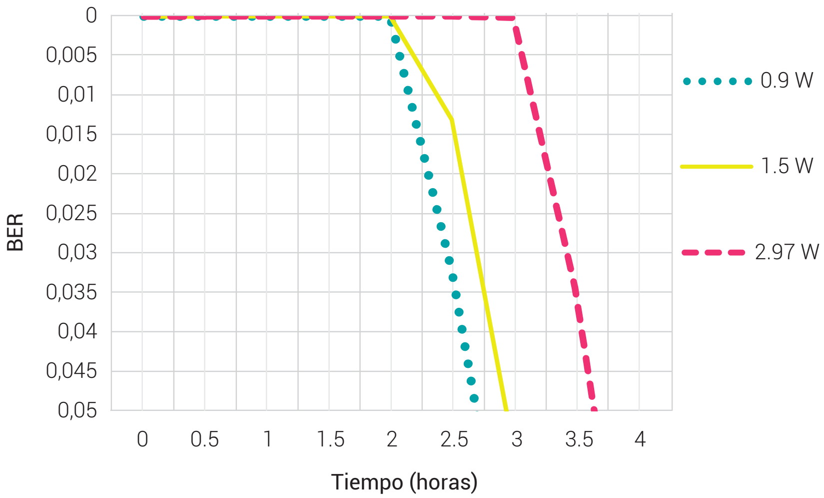

Figure 7. BER in the test distance between the modules vs transmission power (HALF-DUPLEX).
Source: own work

As in the simplex mode, Figure 7 manages to highlight the relationship between the power increase of the LEDs and the increase of the maximum separation distance of the VLC modules. This shows that the higher the power in the LEDs the greater the achievable distance of operation.

4.4 Function test without optical lens

When performing a transmission test in simplex mode, without an optical lens, the behavior was much lower than that of the tests in which the lens was used. The maximum separation distance achieved, without error, decreased considerably. These results are shown in Table 3.

Table 3. Bit error rate in the test of transmission rates vs ambient lighting levels.

Distance	0.1 m	0.2 m	0.3 m	0.4 m	0.5 m
BER	0	0	0.1491	0.2808	0.5125

Source: own work

Table 3 shows that the maximum separation distance between the developed VLC modules decreases considerably when an optical lens is not used in the LEDs.

5. Discussions and Conclutions

5.1 Discussions

During the tests it was found that the relationship between data rate and distance kept constant for a given range. Clearly, when a certain distance is exceeded —in this case during the 3-meter test—, the modules no longer receive the data sent in an adequate way. This is mainly influenced by the luminous flux perceived by the photodiode at the reception stage. As was confirmed in the results presented in Figure 6 and 7, this is because as the separation between the modules increases, the light perceived by them is smaller, generating a lower voltage in the pulses received by the processing stage, which can cause reception errors when the threshold voltage is not exceeded adequately.

Also, it was found that there is no influence of external lighting on the behavior of the prototype. This is due to two reasons. The first is that the ambient light that illuminates the room where the tests were carried out only adds a low DC level that does not exceed the comparison threshold used in the component of reception of the VLC modules. The second reason is due to the arrangement of the modules inside the room; the viewing angle of the photodiode used is 45°, with its maximum efficiency of light conversion to current at 0°. The lights of the test room form angles greater than 45° with respect to the position of the photodiode in the VLC modules, thus resulting in the light perceived by this to be considered negligible.

The decrease in the range of the prototype when optical lenses are not in use is because the radiation angle of the LED without them, rises to 130° (according to the data sheet), thus making the levels of illumination perceived by the photodiode at the distances shown in Table 3, low in comparison with the levels of illumination perceived in the tests where optical lenses were used.

5.2 Conclusions

In this document, the implementation of a prototype of a visible light-based communication system was described and itsdesign details and experimental results are presented. It can be concluded that with this prototype it is possible to communicate by using visible light in two different communications modes, simplex and half-duplex and with a maximum data rate of 50 kbit/s and 23 kbit/s respectively.

In addition, it was found that the maximum reachable distance between two modules of the prototype is 3 meters with a BER of 0% when the LED light power is 2.7 W.

It was also found that, as long as the signal levels at the detector keep above a suitable level, regardless of the operational transmission rate of the prototype VLC modules, the maximum achievable distance between them is not significantly affected. That is, as long as the distance is maintained within the maximum range achievable according to the luminous flux —LED power—, lower transmission rates do not cause the maximum separation distance between the modules to increase, nor that higher transmission rates cause this to decrease. This happens also because the response time of the photodiode used for the reception of the data is not affected by the distance changes between transmitter and receiver.

The study of the changes of ambient lighting levels in the room where the prototype was tested showed that these do not have a considerable effect on the operation of the prototype, this is due to the design of the reception component, the arrangement of the detectors in the test space and their angle of vision.

It was found that the the response times of the photodiode used in the reception of the developed prototype are the main limitation when increasing the transmission rate. This happens because by raising the optical switching frequency, the photodiode is not capable of adequately replicating the signal, thus generating a greater number of errors at the time of decoding the data.

The behavior of the prototype developed with, and without, the use of optical lenses for the light source was studied, thus verifying that it is possible to achieve greater separation distances between the modules when the scattering of light is reduced by an optical lens.

Finally, the result of studying the changes of the power in the light source used as a transmitter showed that a higher luminous flux increases the maximum separation distance between the VLC modules. This happens due to the response nature of the photodiodes, in which, the greater the light perceived in their detection area, the greater the amplitude of their response

6. Acknowledgments

The work in this publication was supported by the Universidad del Valle's research group in telecommunications systems (SISTEL-UV).

7. References

[1] S. Arnon, Ed., *Visible Light Communication*, 1st edition, Cambridge University Press, pp. 29-30, United Kingdom, 2015. doi: https://doi.org/10.1017/CBO9781107447981

[2] H. Burchardt, N. Serafimovski, D. Tsonev, S. Videv, H. Haas, "VLC: Beyond point-to-point communication", *IEEE Communications Magazine*, vol 52, n° 7, pp. 98-105, 2014. doi: 10.1109/MCOM.2014.6852089.

[3] F. Khan, S. Jan, M. Tahir, S. Khan, Applications, limitations, and improvements in visible light communication systems. *International Conference on Connected Vehicles and Expo (ICCVE)*, pp 259-262 (2015). doi: 10.1109/ICCVE.2015.46.

[4] S. Arnon, J. Barry, G. Karagiannidis, R. Schober, and M. Uysal, Eds., *Advanced Optical Wireless Communication Systems*, pp. 352-353, 1st edn, Cambridge University Press, United Kingdom (2012). doi: https://doi.org/10.1017/CBO9780511979187

[5] Visible Light Communication. *Tutorial*, p. 23, 2008. [Online]. Available: http://ieee802.org/802_tutorials/2008-03/15-08-0114-02-0000-VLC_Tutorial_MCO_Samsung-VLCC-Oxford_2008-03-17.pdf.

[6] M. Gujar, S. Velankar, A. Chavan, Realtime Audio Streaming using Visible Light, *International Conference on Inventive Computation Technologies (ICICT)*, 2016. pp. 1-3. doi : 10.1109/INVENTIVE.2016.7830184.

[7] C. Wang, Z. Zhang, M. Zhang, et al., Visible light communication application scenarios based on Android smart devices' LED lamp, *Photonic Network Communications,* 32, pp. 174-178 2016. doi: https://doi.org/10.1007/s11107-016-0605-8

[8] S. Juneja and S. Vashisth, Indoor Localisation System Using Visible Light Communication. *International Conference on Computing and Communication Technologies for Smart Nation (IC3TSN)*, pp. 79-83, 2017, doi: 10.1109/IC3TSN.2017.8284455.

[9] IEEE Standard for Local and Metropolitan Area Networks--Part 15.7, "Short-Range Wireless Optical Communication Using Visible Light," *IEEE Std 802.15.7-2011* , vol., no., pp.212-213, 2011. doi: 10.1109/IEEESTD.2011.6016195.

[10] ITU: O.150, *Digital test patterns for performance measurements on digital transmission equipment,* p. 3, 1992. [Online]. Available: https://www.itu.int/rec/T-REC-O.150-199210-S