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DYRP-VLC: A Dynamic Routing Protocol For Visible Light Communication Networks

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Dissertação apresentada ao Programa de Pós-Graduação em Ciência da Computação da Universidade Federal de Juiz de Fora, como requisito parcial para obtenção do título de Mestre em Ciência da Computação.

Orientador: Alex Borges Vieira

Coorientador: Marcos Augusto Vieira

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*"I dreamed I was a butterfly,
flitting around in the sky; then I
awoke. Now I wonder: Am I a
man who dreamt of being a
butterfly, or am I a butterfly
dreaming that I am a man?"*

Zhuangzi

ABSTRACT

In the last decade, the interest in Visible Light Communication (VLC) has increased considerably, from both academic and commercial perspectives, due to factors such as the growing demand for wireless resources and the advantages offered by the transmission of data through visible light. However, the use of light as a communication medium, especially in indoor environments, offers several challenges, which includes shadowing and interference caused by obstacles. At the same time, this type of environment offers a rich infrastructure of light sources, which can be used to aid communication through multi-hop mechanisms. Most of the works present in the literature adopt simple techniques to construct multi-hop mechanisms in VLC networks, focusing mainly on increasing distance.

In this thesis, we developed DYRP-VLC (Dynamic Routing Protocol for Visible Light Communication), a reactive routing protocol which aims to increase the performance of VLC systems in dynamic environments, while reacting to obstacles by constructing alternative routes in the network. The evaluation of the protocol was performed in a real environment, using OpenVLC 1.0 embedded platform and adopting metrics for routing problems. The results show that, by using DYRP-VLC, the network was able to adapt to dynamic changes in communication, such as shadows and obstacles, with low overhead.

Key-words: Reactive routing, Visible Light Communication, VLC.

RESUMO

Na última década, o interesse (acadêmico e comercial) em torno da Comunicação por Luz Visível (VLC) aumentou consideravelmente, devido a fatores como a crescente demanda por recursos sem fio na Internet e às vantagens oferecidas pela transmissão de dados através da luz visível. Entretanto, a utilização da luz como meio de comunicação, principalmente em ambientes internos, oferece diversos desafios, como interferência e bloqueios criados por obstáculos. Ao mesmo tempo, este tipo de ambiente oferece uma rica infraestrutura de fontes de luz, que podem ser utilizadas para auxiliar na comunicação através de mecanismos *multi-hop*. A maioria dos trabalhos presentes na literatura adotam técnicas simples para construção de mecanismos *multi-hop* em redes VLC, focando principalmente em aumento de distância.

Neste trabalho, foi desenvolvido um protocolo de roteamento dinâmico, DYRP-VLC (Dynamic Routing Protocol for Visible Light Communication), que tem como objetivo aumentar o desempenho de sistemas VLC em ambientes dinâmicos, enquanto reage à obstáculos construindo rotas alternativas na rede. A avaliação do protocolo foi realizada em um ambiente real, utilizando a plataforma embarcada OpenVLC 1.0 e métricas adotadas para problemas de roteamento. Os resultados obtidos mostram que, usando o DYRP-VLC, a rede foi capaz de se adaptar a mudanças dinâmicas na comunicação, como sombras e obstáculos, com pouca sobrecarga.

Palavras-chave: Comunicação por luz visível, VLC, roteamento reativo

LIST OF FIGURES

LIST OF ACRONYMS

VLC	*Visible Light Communication*
OWC	*Optical Wireless Communication*
LED	*Light Emitting Diode*
CFL	*Compact Fluorescent Lamp*
MANET	*Mobile Ad-hoc Network*
FOV	*Field of View*
LOS	*Line of Sight*
MAC	*Medium access control*
CSMA	*Carrier-sense multiple access*
CSMA/CA	*CSMA with collision avoidance*
RREQ	*Route Request*
RREP	*Route Reply*
RERR	*Route Error*
ReqId	*Request Id*
RepId	*Reply Id*
ACK	*Acknowledgement*
OOK	*On-Off Keying*
VPPM	*Variable Pulse Position Modulation*
CSK	*Color-Shift Keying*
BER	*Bit Error Ratio*
PRR	*Packet Reception Ratio*

SUMÁRIO

1 Introduction

Visible Light Communication (VLC) is a type of communication that uses the visible light band of the electromagnetic spectrum (ranging from 380 nm to 750 nm) to transmit data. It has been studied and used in several applications during human history, from fire beacons and smoke signals, widely used in the ancient history [Burns, 2004], to the adoption of VLC in the next generation of cellular networks (5G) [Wu et al., 2014]. During the last decade, more specifically, VLC has become very popular among both academic and industrial communities due to the current challenges faced by the wireless communication field. Consequently, the use of visible light to exchange information has been considered for a wide range of applications, such as indoor communication [Lee et al., 2011], vehicular systems [Okada et al., 2009], localization systems [Li et al., 2014] and underwater communication [Kaushal and Kaddoum, 2016].

VLC systems consist of two main components: transmitter and receiver. Light Emitting Diodes (LEDs) are most commonly used as transmitters, although natural light (i.e. sunlight) can also be used as light source [Wang et al., 2016]. The transmitter is responsible for modulating the intensity of light (Intensity Modulation) in order to transmit data. At the receiver side, photosensors are used to capture light directly (Direct Detection). LEDs transmit light based on its Field of View (FOV), which leads to a limited angle of emission. Therefore, VLC works based on the line of sight (LOS) between transmitter and receiver.

The ever-increasing demand for wireless resources over the last decade has made the radio frequency (RF) spectrum very scarce and crowded, aside from the current bureaucracy regarding regulations on this part of the electromagnetic spectrum. In that scenario, Visible Light Communication offers a good perspective on the future of wireless technologies because it uses a license-free part of the spectrum, with a wider range of frequencies.

Despite being considered as a major candidate for the next generation of wireless technology, researchers still have many issues to address regarding indoor VLC, such as (i) improving data rate, (ii) channel modeling and characterization, (iii) multi-hop mechanisms, (iv) mobility and (v) shadowing. Some of these issues tend to highly increase the complexity in wireless systems that may use visible light [Pathak et al., 2015].

1.1 Problem definition

During the past decade, LEDs light bulbs went from being very expensive light sources to becoming the most popular light source in the world, replacing other well-established lighting technologies, such as incandescent and CFL lights. Advantages such as energy-efficiency, longer lifetime and safety are some of the reasons behind the adoption of LEDs. This scenario revolutionized indoor lighting, which now has a secure and efficient infrastructure made by components that share a unique characteristic of high switching rate, providing a great opportunity for the deployment of VLC systems.

However, there are many issues regarding the adoption of VLC systems in indoor environments. The dynamic environment created by the multiple light sources and interference due to factors such as shadowing and obstacles can have a great impact on communication performance [Xiang et al., 2014, Komine et al., 2005]. In addition, most VLC systems proposed in the literature are LOS-based. In other words, transmitters and receivers must have Line-of-Sight in order to be able to establish communication.

Such a dynamic scenario requires solutions that go beyond hardware and channel characteristics. At a systems network perspective, the resourceful environment provides opportunities for multi-hop cooperative protocols. So far, there are few works in the literature that focus on multi-hop VLC from a low-level perspective [Kim et al., 2016, Ahmad et al., 2017, Klaver and Zuniga, 2015]. However, none of these works target the dynamic environment in which VLC systems will be deployed.

Based on the prerogatives of an indoor VLC scenario and taking into consideration the rich light infrastructure present in these environments, simple multi-hop techniques will fail to deliver a good approach when dealing with the dynamic behavior of the network. One node may be available at a point, but with a simple shadow caused by the movement of a human or object, it will fail to receive the data.

1.2 Contributions

In this dissertation, we present DYRP-VLC (Dynamic Routing Protocol for Visible Light Communication), a fully functional cross-layer dynamic routing protocol for Visible Light Communication networks. DYRP-VLC is based on other on-demand approaches for Mobile Ad-hoc Networks (MANETs), such as DYMO [Perkins et al., 2013], in order to behave according to a dynamic scenario.

In addition, we have developed two different approaches, DYRP-RT and DYRP-RC, to perform route maintenance routines, which relies on network and MAC layers respectively. DYRP-RT (Route Timeout) maintains a route based on its life time parameters, while DYRP-RC (Reference Counter) explores the MAC layer in order to decide whether to break or not a route. In a nutshell, DYRP-VLC explores resources from lower layers in order to create and maintain on-demand routes based on the current state of the network. In our protocol, idle nodes can cooperate dynamically and serve as complementary routes based on the network needs. Our approach differs from others in the literature in a way that we present a reactive routing protocol for VLC that is able to use information from the MAC layer in order to increase the performance under dynamic scenarios, and offer a real-world evaluation of the protocol. In addition, we also propose and analyze DYRP-RT and DYRP-RC, two different approaches for DYRP route maintenance.

We evaluate DYRP-VLC by implementing the protocol in OpenVLC 1.0[1], a well-known open-source platform designed for VLC research. We then propose scenarios in which we can evaluate the behavior of the protocol in a dynamic network where a link may be broken at any time. Our results show that, by using a reactive dynamic routing protocol, communication performance under dynamic scenarios can have a significant increase. DYRP presents negligible ovehead. In fact, the use of DYRP-RC only increases network traffic in about of 1% of its original size, while DYRP-RT presents about 10% of PDU overhead. In terms of overhead, for example, DYRP-RC presents less than 1%, while DYRP-RT presents less than 10%. In terms of throughput, DYRP-RC presents higher performance for direct communication (10.96 Kbps) and satisfactory performance for multi-hop communication (up to 3.75 Kbps), given the impact of factors such as platform hardware and medium access protocol.

1.3 Thesis organization

This dissertation is organized as follows. Chapter 2 offers an overview and fundamentals of Visible Light Communication and the specific problem targeted by our proposal. Next, in Chapter 3, we give a comprehensive analysis of our dynamic routing protocol. In Chapter 4, we discuss the results achieved by the implementation of the protocol in the OpenVLC 1.0 open-source platform. We then review all relevant research topics related to our proposal in Chapter 5. Finally, our conclusions and future work perspectives are presented in Chapter 6.

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[1] http://www.openvlc.org/home.html

2 Visible Light Communication

Visible Light Communication (VLC) is a type of communication in which data are sent through the modulation of lightwaves from the visible spectrum, ranging from 380 nm to 750 nm in terms of wavelength. In practical terms, a system capable of transmitting information using any type of light perceptible by human eyes can be identified as Visible Light Communication system. However, the idea of VLC is to transfer data without harming human vision, so that what is seen is only the regular environment illumination, without any noticeable changes.

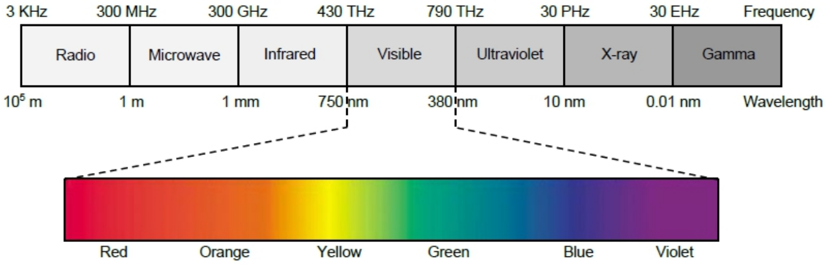

Figure 1 – Electromagnetic spectrum.

Figure 1 presents the range of the electromagnetic spectrum from low frequencies, where radio waves are located, to higher frequencies where X-ray and gamma radiation are located. The human eyes are able to detect frequencies that vary from 430 THz to 790 THz. The radio spectrum covers frequencies from 3 KHz to 300 GHz, which is 10,000 times shorter than the visible spectrum. Radio waves are extremely common in our everyday life, being used by many technologies such as radars, satellites, FM, AM, RFID, and Wi-Fi.

There are several other types of communication that use optical waves as the medium, such as Optical Wireless Communication (OWC) [Takai et al., 2014], Free-Space Optical Communication (FSOC) [Chan, 2006] and Light Fidelity (Li-Fi) [Haas et al., 2016]. The difference between these nomenclatures is further explained in what follows:

- owc: Optical Wireless Communication involves any type of communication in which the optical spectrum is used. In other words, the entire spectrum of light can be used as a form of communication, be it infrared, visible or ultraviolet [Uysal and Nouri, 2014]. Some examples of OWC are: Wireless Infrared Communication [Kahn and Barry, 1997], Ultraviolet Communication [Drost and Sadler, 2014] and Visible Light Communication.

- FSOC: Despite having a similar concept to OWC, this nomenclature has been widely explored for large-scale transmissions, such as communications between satellites and towers on Earth [Chan, 2006]. Communication in free space involves data transmission in a medium without barriers, such as air, atmosphere, and space. Differently from VLC, FSOC applications tend to be very complex, involving atmospheric turbulences [Zhu and Kahn, 2002, Hou et al., 2015] and high-cost equipment [Khalighi and Uysal, 2014].

- Li-Fi: The term Li-Fi was coined in 2011 during a TED Talk by Professor Harald Haas, in which he gave a practical demonstration of the potential of the technology. Li-Fi can be considered a type of VLC [Tsonev et al., 2013]. However, the creator of the term published a paper in 2015, highlighting the main differences between VLC and Li-Fi [Haas et al., 2016]. Among the differences between the two technologies, we can highlight the two-way multi-user communication and high speed.

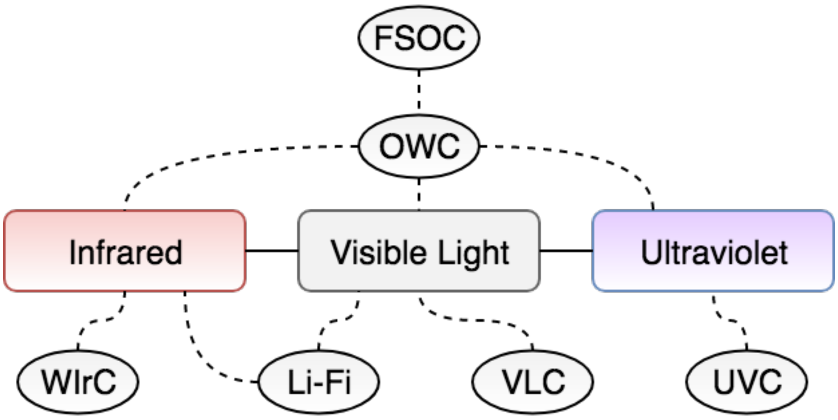

Figure 2 – Types of communication within the light spectrum.

2.1 A Brief History of VLC

Despite the recent interest in VLC, studies involving light-based communications systems can be found over the past centuries. Light has always been among the elements used by humans to communicate with each other. Since the earliest times, the use of light as a means of communication was already seen in many cultures around the world, whether in the use of smoke signals or torches, for example. In this sense, a great example of a functional Visible Light Communication system was registered centuries ago, in Ancient Greece. Historian Polybius developed a communication system in which torches were used in order to exchange information. This was done by establishing an agreement between emitter and receiver, and the alphabet was represented by a set of 5 torches [Holzmann, 2007].

By the end of the eighteenth century, in Napoleonic France, engineer Charles Chappe invented the optical telegraph [Dilhac, 2001]. This mechanism consisted of two lateral bars, called indicators, attached to a long bar, called the regulator. Through the rotation of the lateral stems, it was possible to create a series of different symbols. These equipment were placed in towers, at a distance of 10 to 15 kilometers. Using this structure and efficient coding, it was possible to create up to 98 different combinations, which could be seen from miles away. In a few decades, France was already equipped with hundreds of telegraphs, forming a large communication network, which served French interests for more than 50 years and was later replaced by the electric telegraph system.

Later, by the end of the nineteenth century, Alexander Graham Bell and his assistant Charles Tainter established communication at a distance of 213 meters using the Photophone [Bell, 1880]. This device, created by Graham Bell himself, was formed by a transmitter and a receiver. Briefly, the system worked as follows: the sunlight was reflected in a mirror, reaching a thin surface of a glass, which vibrated according to the person's voice. Thereafter, the light was transported through a secondary lens to the receiver, where a parabolic mirror reflected the light in a selenium cell, whose resistance varied according to the intensity of light received. Despite the popularity of the telephone, another device patented by Graham Bell, the scientist has always considered the photophone his greatest invention.

Communication through optical media only gained attention in the 1970's. On that period, studies demonstrated the potential of wireless optical communication (in this case, infrared) in an internal environment where it was possible to explore bands of the Electromagnetic spectrum on a scale of THz-[Gfeller and Bapst, 1979]. Such systems were able to reach up to 1 Mbps. More recently, in the late 1990's, infrared systems were able to achieve up to 50 Mbps data rate [Marsh and Kahn, 1996].

In the early 2000's, LED bulbs were first considered for experiments involving VLC. Tanaka *et al.* [Tanaka et al., 2003] used a white LED bulb for lighting and communication in an indoor environment, reaching up to 400 Mbps communication data rate [Tanaka et al., 2003]. This was the first step in a wide range of VLC works in the 21st century. After this work, other researchers came with great innovations, such as new modulation techniques and new technologies of LED bulbs.

2.2 Advantages of Visible Light Communication

In the last decades, the world has made great strides in communication technologies. In terms of wireless communication, Wi-Fi has become the dominant means of access to the Internet. However, factors such as the Wi-Fi spectrum crisis and the high demand for wireless communications, drive new technologies and research. In this scenario, VLC studies focus mostly on its use as a complement to Wi-Fi.

A major advantage of VLC is the use of existing infrastructure also to provide communication services. LED light bulbs, widely used these days, already play the role of lighting. With VLC, these light bulbs transmit data through lighting. That is, the energy used for the communication would not increase the costs [Burchardt et al., 2014]. In addition, many of the research of recent years have focused on the use of low-cost devices in the implementation of VLC systems, such as Wang *et al.* [Wang et al., 2015], which used single-board computers (Beaglebone) and low-cost LEDs for the development of an open-source platform for studies in the area [Wang et al., 2015]. Another important example in the literature is the work of researchers at Disney Research Center, responsible for the development of a VLC system that makes use of commercial LEDs [Schmid et al., 2014].

An advantage of visible light is the size of the spectrum, compared to radio frequency. The frequency allocation in the radio waves band of the electromagnetic spectrum is extremely restricted, being regulated by each country, and coordinated by international telecommunication institutions. Thus, each country has its own regulation regarding frequencies allocated for each type of use, ranging from military use, to broadcasts of content on AM and FM radios. As a relatively new technology, WiFi devices transmit the signal in two bands: 2.4 GHz and 5 GHz, both located in regions of the spectrum intended for unlicensed devices. However, the situation is different with light. The spectrum of visible light is totally free, generating diverse commercial and academic possibilities [Burchardt et al., 2014].

	Wi-Fi	VLC
Spectrum	2.4 GHz / 5 GHz	$\sim$ 400 THz
Infrastructure	Access Point	Illumination
Noise and interference	Low	High
Security	Limited	High
Coverage	High	Limited
System complexity	High	Low
Electromagnetic interference	Yes	No

Table 1 – Comparison between Wi-Fi and VLC, adapted from [Karunatilaka et al., 2015].

Due to its propagation properties, light offers security advantages when compared to radio waves. When a Wi-Fi access point is configured, radio waves can propagate according to the antenna's broadcasting capacity, which can reach hundreds of meters. In this process, waves surpass walls and other solid surfaces and may pose a security risk, since eavesdropping and sniffing attempts may occur [Burchardt et al., 2014]. Light, in turn, does not follow this behavior. Its waves do not go beyond walls and other surfaces, offering a much safer environment, where basically what is being transmitted is what you see [Rohner et al., 2015]. This possibility of manipulating lightwaves is another great advantage of this form of communication.

Finally, one of the major advantages of light as a form of communication is the high frequency of waves (in the THz magnitude), which allows for very high data rate communication. Currently, in terms of Wi-Fi, the highest data rate achieved is close to 1 Gbps, in the standard WiGig [Hansen, 2011]. Thanks to the high frequency of lightwaves, VLC researches have already obtained impressive results, reaching speeds of 100 Gbps [Azhar et al., 2013, Gomez et al., 2015].

2.3 VLC Architecture

Visible Light Communication uses light to transmit information. The idea behind VLC applications is to provide both lighting and communication at the same time. Thus, VLC systems will always have components to transmit and receive light. In the vast majority of work available in the literature, LEDs are used as transmitters. These LEDs are used to modulate the intensity of light in order to send data. On the receiver side, photosensors are responsible for capturing this light directly (Direct Detection), converting it into data stream [Medina et al., 2015]. This mechanism is known as Intensity Modulation/Direct Detection (IM/DD), which is the pillar to most VLC systems found in literature. Therefore, it is important that lighting illumination brightness is not affected by the manipulation of light while transmitting information, hence the type of LED has an impact on the performance of a VLC system.

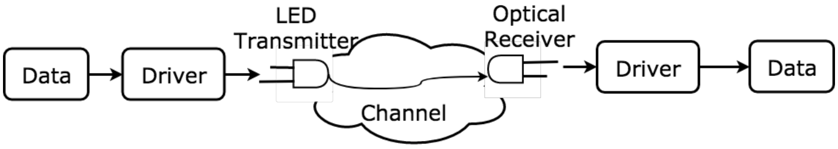

Figure 3 – VLC communication architecture.

Figure 3 gives an overview of the architecture of a VLC system. Data are modulated by the driver, and sent to the LED, which is responsible for transmitting the light. The receiver must be in the line of sight of the LED so that it captures the lightwave containing the information. During the transmission, signal quality will be lost due to particles diffusion and the inherent interference of ambient light. To reduce interference, filters may be used. At the receiver node, light is incident on the photosensor, directly altering the current. Amplifiers are used to make signals are less prone to interference and noise [Schmid et al., 2014]. Finally, the signal is demodulated to retrieve the original information. In what follows, we detail each component of a VLC system:

- Transmitters: In general, LEDs are used as transmitters in VLC systems. Most commercially available light bulbs contain several LEDs. These light bulbs contain a driver responsible for controlling the current passing through the LEDs, directly influencing the intensity of the illumination. In other words, the current arriving at the LED is controlled by transistors, which manipulate the light signals that the

LED emits at high frequency, and thus makes the communication imperceptible to human eyes [Pathak et al., 2015];

- Receivers: Receivers are responsible for capturing light and converting it into electrical current. Normally, photodiodes are used as receivers in Visible Light Communication systems [Schmid et al., 2014]. However, photodiodes are extremely sensitive, and capture waves beyond the spectrum of visible light, such as ultraviolet and infrared [Wang et al., 2015]. They also saturate easily, in an external environment and exposed to sunlight, for example, and the photodiode would fail to receive data due to high interference. For this reason, other components can be used to capture light. One of them is the smartphone camera itself, which allows any cell phone to receive data sent by a VLC transmitter. In addition to these devices, LEDs themselves can be used as receivers because they feature photo-sensing characteristics[1] [Wang et al., 2014].

Unlike photodiodes, LEDs have properties that make them efficient in certain situations. An LED detects a reduced frequency range when compared to photodiodes, reducing the presence of noise and interference. In addition, the sensitivity of LEDs is stable over time. The main advantage is the fact that LEDs can function as both transmitters and receivers, which makes it possible to create a system with only one LED at each point.[2], besides being very accessible and popular components, making VLC applications even easier to use.

2.3.1 Physical Layer

The Physical layer is responsible for transmitting data (bits) through a communication channel, such as a twisted pair or radio waves. The issues that need to be addressed in the physical layer of a system involve aspects such as the representation of signals, how these signals will be sent, the establishment of communication, involving elements of electronic interface and synchronization [Tanenbaum et al., 2003] . Physical layer performs similar function also in VLC, but in this particular case, light is used as the transmission medium. In what follows, we present a number of aspects that influence decisions regarding the implementation of the physical layer in VLC systems:

- Path Loss: A physical layer design in VLC needs consider the fact that LED light bulbs present two main functions: **illumination and communication**. Therefore, it is necessary to understand the requirements in terms of brightness for communication to occur in a satisfactory manner. The photometric parameters determine

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[1] (LED Sensing - `www.thebox.myzen.co.uk/Workshop/LED_Sensing.html`, 2017.

[2] How to Use LEDs to Detect Light - `http://makezine.com/Projects/make-36-boards/how-to-use-leds-to-detect-light/`, 2013.

a series of characteristics of light, such as brightness, color, among others, from a human vision perspective. On the other hand, the radiometric parameters measure the energy of the electromagnetic radiation of light. Through these parameters, we can calculate the luminous flux, which represents the quantity of the energy of the light emitted. Based on the luminous flux, it is possible to calculate an important value for the physical layer: the path loss [Cui et al., 2010];

- Propagation: Lightwave propagation is also a property that is important to consider to develop VLC Physical layer. In indoor environments, usually there are multiple transmitters, such as LED light bulbs and surfaces that may reflect light. Therefore, it is important to understand the impact of reflected light on VLC systems;
- Noise: In a VLC system, noise is an important factor to consider for communication performance. During the day, in an outdoor environment, for example, sunlight can either cause VLC to fail or degrade significantly due to light interference. In this case, filters can be used to prevent photo sensor saturation. Some work uses LEDs as receivers, since they are considered “selective photodiodes”, to address this issue partially.

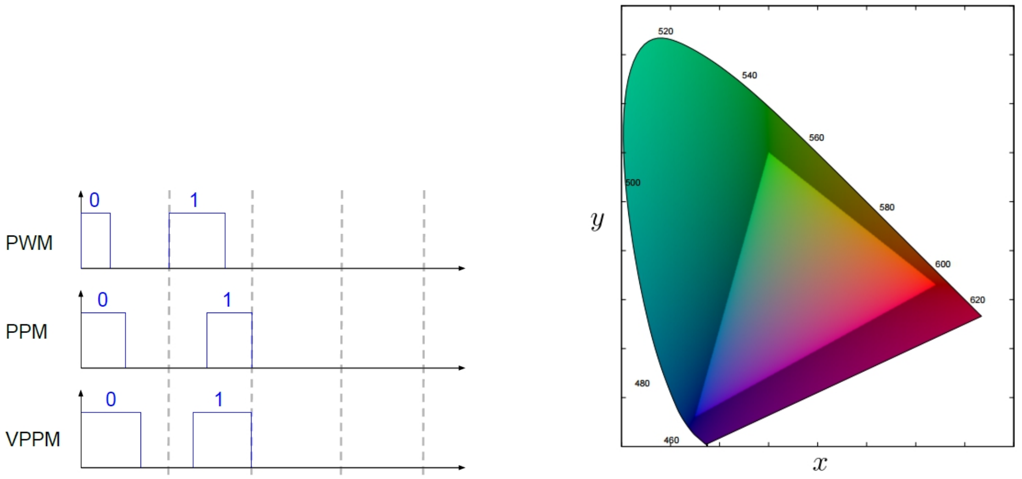
Light modulation is another essential point of the VLC physical layer. In VLC, some aspects of light, for example, intensity, must be converted to digital signals to represent the bits. Unlike other types of communications, light modulation must seek a high rate of data while not interfering with the light perceived by humans [Arnon, 2015]. One of these requirements is *dimming*. Light bulbs from various residential and corporate locations are equipped with dimmer circuits so that light intensity can be controlled, to provide adequate and comfortable light in an environment. In this sense, according to the IEEE 802.15.7 standard, Visible Light Communication must still be possible at reasonable performance even with light bulbs that support this dimming feature. The second requirement concerns oscillation of light, also known as *flickering*. The applied modulation technique cannot cause any kind of oscillation perceptible by human vision [Roberts et al., 2011]. In what follows, we present the main modulation techniques for Visible Light Communication found in the literature:

- On-Off Keying (OOK): OOK modulation is a very simple type of modulation, considering the operation of LED. In this form of modulation, bits 0 and 1 are transmitted through the lights off and on, respectively. In this case, bit 0 can be represented by decreasing the light intensity, rather than turning it off completely. This method is practical and easy to implement, which is its main advantage. Much current works uses this type of modulation in their systems [Wang et al., 2014, Schmid et al., 2015]. As previously stated, the modulation used must take into account the human perception of light. Therefore, OOK modulation presents a setback: if the value 100001 is sent, in theory, the LED would be turned off for a long time and could cause oscillations perceptible to human eyes. To overcome this issue, there are some measures proposed in IEEE 802.15.7. The first technique is to reset the ON and OFF levels, that is, bit 0 is represented by another light intensity. Another possibility is to use variations of the OOK, such as Variable OOK, where it is possible to obtain dimming, which is done by inserting compensation periods in the modulated wave, depending on the desired level of dimming. By default, signals in OOK modulation are always sent with a symmetric Manchester symbol;

- Variable Pulse Position Modulation (VPPM): Another technique widely used in VLC systems is VPPM. This method makes use of two different modulation types: Pulse Position Modulation (PPM), used to prevent light intensity oscillation, and Pulse Width Modulation (PWM) to allow dimming. Pulse Position Modulation works as follows: the symbol duration is divided into a number of slots of the same duration, and a pulse is transmitted in one of these slots. The position of the pulse determines its value [Elgala et al., 2011]. One of the advantages of PPM is the ease of implementation. However, only one pulse is emitted for each symbol, which causes the data rate to be limited. Besides that, PWM method adjusts the pulse lengths according to the desired dimming level, and the pulses carry the modulated signal in the form of a square wave [Pathak et al., 2015]. Figure 4a presents the operation of each of the modulations discussed here;

- Color Shift Keying (CSK): In CSK, the signal is modulated according to the intensity of the three colors that make up a type of LED known as multi-chip. This LED is composed of three or more LED chips, usually red, green and blue. These three colors, together, are used to generate white light. The OOK and VPPM modulations have low data rates, so the IEEE 802.15.7 standard proposes CSK modulation as a solution to increase data rates, specifically for Visible Light Communication systems. The CSK modulation is based on the CIE 1931 chromaticity diagram [Schanda, 2007], as seen in Figure 4b. There are seven wavelength bands available, from which the RGB source can be chosen. This origin determines the vertex of a triangle in which the constellation points of the CSK symbols are. The color point of each symbol is produced by modulating the intensity of the RGB chips. Singh *et al.* [Singh et al., 2013] performed a detailed study where they present the first evaluation of CSK modulation proposed in [IEEE, 2011] for different combinations of color bands (CBC), taking into account parameters such as energy efficiency and Bit Error Rate (BER) [Singh et al., 2013];

- Orthogonal Frequency Division Multiplexing (OFDM): In this modulation, the channel is divided into multiple orthogonal sub-carriers, and data are sent in modulated sub-streams on top of the sub-carriers. One of the great advantages of this modulation method is the reduction of inter-symbol interference.



(a) (b)

Figure 4 – Modulation schemes for VLC

The use of LEDs in VLC enables MIMO (Multiple-Input-Multiple-Output) communication because many light bulbs are made up of multiple LEDs. Each LED can be considered a transmitter, thus having multiple transmitters per light bulb. MIMO techniques are widely used in radio-frequency communications, to increase data rates. Among the MIMO algorithms used in VLC are Repetition Coding, Spatial Multiplexing and Spatial Modulation [Dimitrov and Haas, 2015]. Many papers in the literature implement this technique with the objective of increasing communication speed, reaching rates of up to 1.1 Gbps [Azhar et al., 2013].

In general, the main features of Visible Light Communication are located at the physical layer. The VLC physical layers propose new approaches by taking into account the properties of visible light, which differs significantly from radio frequency. There is an effort on the part of the academic community and members of standardization institutions so that the main issues related to the VLC physical layer are solved, especially with respect to aspects such as modulations and coding mechanisms, as well as their influence on factors such as oscillation and dimming of the light.

2.3.2 MAC Layer

Many VLC applications target multiple users or scenarios that support multiple transmitters and receivers. In an indoor environment, such as corporate buildings and residential buildings, there may be more than one person connected to a VLC access point (LED light bulb). With many devices connected at the same time, it is necessary to create mechanisms to control access to the medium, manage device to access point association and to allow mobility [Pathak et al., 2015]. This section presents the three types of methods for multiple access to the medium (MAC) defined in the IEEE VLC standard: Carrier Sense Multiple Access (CSMA), Orthogonal Frequency Division Multiple Access (OFDMA) and Code Division Multiple Access (CDMA).

Carrier Sense Multiple Access (CSMA): In IEEE 802.15.7, two types of CSMA protocols are proposed. In the first, the signals emitted by the coordinator are disabled. Thus, an unallocated random access channel is used for the CSMA. Therefore, if a device wants to transmit, it must first wait for a random time, known as a back-off period, and then check whether the channel is free. If the channel is busy, the device waits again for a random period before attempting to access the channel again. In the second type of CSMA proposed in the standard, coordinator signals are enabled, and time is divided into signal intervals. A frame within a signal range contains information such as Contention Access Period (CAP) and Contention Free Periods (CFP). If a device wants to transmit on the channel, it must first locate the start of the next back-off slot, and wait for a random number before executing the Clear Channel Assessment (CCA). If the channel is idle, the device starts broadcasting. Otherwise, wait for more back-off slots before running the CCA again. This protocol has already been implemented in some research in the literature, such as enhanced CSMA/CA to guarantee bidirectional communication between LEDs [Wang and Giustiniano, 2014].

Orthogonal Frequency Division Multiple Access (OFDMA): In OFDMA, multiple users receive different resource blocks for communication, the subcarriers. Just as OFDM modulation is used at the Physical layer, OFDMA is used for multiple access. The main challenges in implementing this protocol in VLC systems concern energy efficiency and decoding complexity [Dang and Zhang, 2012]. A recent OFDMA-based VLC system achieved data rates of up to 13.6 Mbps [Sung et al., 2015]. Another work proposed a bidirectional VLC system where the NOMA-OFDMA protocol is used to achieve a flexible bandwidth and greater user capacity [Lin et al., 2017].

Code Division Multiple Access (CDMA): CDMA for Visible Light Communication, also called Optical CDMA (OCDMA), consists of orthogonal optical codes (OOC) which are distributed in order to have access to the same channel by different users, a technique already used in fiber-optic networks [Pathak et al., 2015]. In OCDMA-VLC, a code is assigned to each device so that the data can be coded in the time domain through the on and off LED states. OOC codes tend to be long, to ensure optical efficiency, which can reduce the performance of communication.

A recent work on Carrier Sensing Multiple Access/Collision Detection and Hidden Avoidance (CSMA / CD-HA) protocol ensures fair channel use among all VLC nodes connected to the network and reduces the impact of collisions and hidden nodes [Wang and Giustiniano, 2016]. In their work, the hidden nodes problem is mitigated to a large extent because frames of the protocol have dual-usage: on the one hand, they send additional information in bandwidth, and on the other hand, they act as an active acknowledgment of data reception, protecting the primary transmitter from hidden nodes. Channel utilization is increased by terminating the main frame transmission when HIGH-HIGH signal detection occurs (an invalid sequence) for a predefined number of times.

2.3.3 VLC Standards

The first effort to standardize Visible Light Communication happened in 2003, followed by the creation of the Visible Light Communication Consortium (VLCC) in Japan. At that time, some work explored VLC around the world. However, applications such as VLC-based positioning were already being researched in Japan. A few years later, in 2007, two standards were included in JEITA (Japan Electronics and Information Technology Industries Association): the JEITA CP-1221, which covers the basics of VLC systems, and JEITA CP-1222, a standard for Visible Light ID Systems [Haruyama, 2010].

Due to the growing interest in VLC systems by the universities and industry, there was a need to standardize certain aspects of this type of communication. To this end, in 2011, the IEEE 802.15.7 Visible Light Communication Task Group developed the first draft of the official **IEEE 802.15.7** standard, in which the Physical and MAC layers for Short-Range Wireless Optical Communication Using Visible Light [IEEE, 2011] are defined. The standard covers aspects necessary to ensure the delivery of data at rates sufficient to support services such as multimedia and audio, as well as ensuring compatibility with the visible light infrastructure. In addition, the standard covers the effects of VLC on health and the environment. In general, the standard addresses issues such as network topologies, devices considered for VLC, communication architecture, physical layer characteristics, and MAC with dimming and flickering support, as well as security specifications. Details of these aspects are presented below.

Initially, the document addresses the types of devices in VLC systems, including infrastructure, mobile and vehicles, each with its own features. The standard also specifies topologies and modulation mechanisms for VLC systems.

Much of the IEEE 802.15.7 standard is focused on physical and MAC layer characteristics. In general, the IEEE standard divides the physical layer into three modes of operation: PHY I, PHY II and PHY III. Any IEEE 802.15.7 compliant system must implement at least the PHY I or PHY II modes. The system that implements the PHY III mode must also implement the PHY II.

The PHY I mode of operation is designed for external applications with short frames. PHY II and PHY III modes support only one type of encoding. PHY I mode

Modulation	RLL code	Optical clock rate	FEC		Data Rate
			Outer code (RS)	Inner code (CC)	
OOK	Manchester	200 kHz	(15,7)	1/4	11.67
			(15,11)	1/3	24.44
			(15,11)	2/3	48.89
			(15,11)	none	73.3
			none	none	100
VPPM	4B6B	400 kHz	(15,2)	none	35.56
			(15,4)	none	71.11
			(15,7)	none	124.4
			none	none	266.6

Table 2 – PHY I in IEEE 802.15.7 Standard [IEEE, 2011]

Modulation	RLL code	Optical clock rate	FEC	Data Rate
VPPM	4B6B	3.75 MHz	RS(64,32)	1.25 Mb/s
			RS(160,128)	2 Mb/s
		7.5 MHz	RS(64,32)	2.5 Mb/s
			RS(160,128)	4 Mb/s
			none	5 Mb/s
OOK	8B10B	15 MHz	RS(64,32)	6 Mb/s
			RS(160,128)	9.6Mb/s
		30 MHz	RS(64,32)	12 Mb/s
			RS(160,128)	19.2 Mb/s
		60 MHz	RS(64,32)	24 Mb/s
			RS(160,128)	38.4 Mb/s
		120 MHz	RS(64,32)	48 Mb/s
			RS(160,128)	76.8 Mb/s
			none	96 Mb/s

Table 3 – PHY II in IEEE 802.15.7 Standard [IEEE, 2011]

Modulation	Optical clock rate	FEC	Data Rate
4-CSK	12 MHz	RS(64,32)	12 Mb/s
8-CSK		RS(64,32)	18 Mb/s
4-CSK	24 MHz	RS(64,32)	24 Mb/s
8-CSK		RS(64,32)	36 Mb/s
16-CSK		RS(64,32)	48 Mb/s
8-CSK		none	72 Mb/s
16-CSK		none	96 Mb/s

Table 4 – PHY III in IEEE 802.15.7 Standard [IEEE, 2011]

data rates range from 11 kbps to 266 Kbps, while PHY II mode data rates range from 1.25 Mbps to 96 Mbps . The PHY III mode of operation contemplates data rates from 12 Mbps up to 96 Mbps. PHY III operating mode has a modulation scheme developed for multi-chip LEDs. Tables 2, 3, and 4 provide details of each mode of operation as well as modulations and encodings supported by them.

In addition, important concepts such as dimming and flickering are covered in detail in the standard, since a VLC system must allow manipulation of the light intensity in a way that does not influence the communication itself.

The standard also addresses security issues in VLC. In this sense, light has different properties than the radio waves, allowing new guidelines when dealing with the safety of VLC systems. As the lightwave is directed and visible, an unauthorized interception of the signal can be easily detected. Even so, the proposed cryptographic mechanism is based on symmetric keys, generated by the upper layers. Among the security services offered by the encryption mechanism are confidentiality, authenticity and replay protection.

2.4 VLC Research Platforms

As discussed before, the aim of the present work is to provide a solution to dynamic routing in Visible Light Communication networks and evaluate it by implementing in a real-world setup. Therefore, we have conducted a comprehensive review of the literature regarding VLC platforms found in literature in order to justify the adoption of OpenVLC 1.0.

Over the past years, academic researchers have made an effort to develop open-source VLC platforms. These platforms differ in terms of hardware and software design, as well as in terms of capabilities and features they offer, as summarized in Table 5. This table summarizes some of the main elements of these platforms, such as hardware and software components, as long as well-known challenges of the area, which includes operational range and data rate. Most of the platforms present low data rates, when compared to the PHY I specification (11.67 kbps), which is the lowest data rate presented in the IEEE 802.15.7 standard, except for the most recent work developed by Yin *et al.* [Yin et al., 2018], which reached up to 100 kbps. In general, the purpose of such platforms is to foment studies in the field, therefore many of them are open-source initiatives, which are being constantly updated to improve technical elements and add new features [Wang and Giustiniano, 2016, Schmid et al., 2016b]. We go further by analyzing two aspects of these platforms: **hardware**, in which we give an overview of the hardware components of the current VLC platforms, such as electronic devices, microcontrollers and types of transceivers and **software**, where we also discuss how software and hardware elements are interconnected, in addition to the main approaches regarding the development of drivers, Physical and MAC layers.

2.4.1 Hardware Design

A VLC system works by modulating signals using the light as medium. In general, we can divide the hardware part of any VLC system into three modules: the baseband generator, responsible for converting information into modulated signals, the driver circuitry, which controls the current flow and transforms the modulated signals into electrical

	[Dietz et al., 2003]	[Wang et al., 2014]	[Klaver and Zuniga, 2015]	[Hewage et al., 2016]	[Schmid et al., 2016b]	[Yin et al., 2018]
Platform	iDropper	OpenVLC	Shine	modBulb	Enlighting	PurpleVLC
Hardware	MCU (PIC16LF628)	BeagleBone Black + OpenVLC Cape	Arduino (ATMega 328p)	FPGA (AGLN250) MCU (CC3200)	Arduino + Atheros AR9331	BeagleBone Black
Software	Firmware code	Kernel module	Firmware code	Firmware code	Firmware Code	Kernel module + PRUs
Range	Few centimeters	6 m	1 m	1 m	5 m	6 m
Data rate	250 bps	12 Kbps	1 Kbps	1 Mbps	600 bps	100 Kbps
Features	Bidirectional LED-to-LED	Bidirectional Multiple transceivers TCP/IP integration	Bidirectional Multi-hop	Hybrid Architecture (FPGA + MCU)	Localization service LED bulbs Multi-hop	Full-duplex Channel Isolation Multi-hop

Table 5 – State-of-the-art of VLC platform researches.

fluctuations and the light source/receiver, which transfer the electrical current to visible lightwaves [Hewage et al., 2016]. Microcontrollers (MCUs) are widely used in VLC general platforms, but other components such as FPGA and even single-board computers are also used. In the following, we discuss each of these approaches in details.

2.4.1.1 Microcontroller-based VLC

One of the pioneer VLC platforms was the *iDropper*. Dietz *et al.* [Dietz et al., 2003] were one of the first authors to build a bidirectional visible light communication system. Moreover, they were the first to explore the concept of LEDs as receivers [Dietz et al., 2003]. The *iDropper* is a device capable of receiving, storing and transmitting data over light, similar to RFID systems. The bidirectional LED interface is built using two LEDs, and one of them is reverse-biased to work as a selective photodiode. The hardware is composed of a PCB, in which a button, an MCU (Microchip PIC16LF628), an LED, a coin-cell battery, a capacitor and two resistors. The system was designed in a way that *iDroppers* could be used as intelligent keys, capable of peer-to-peer communication.

The Arduino is one of the most well-established MCUs and offers many advantages when used to prototype VLC systems. A fully functional VLC system between two Arduino was developed by Jonathan Piat, using only off-the-shelf LEDs and a pair of resistors [3]. At the transmitter side, data are encoded using Manchester encoding and modulated using OOK mechanism, to avoid flickering. At the receiver side, a reverse-biased LED is used to capture light. The system can reach data rates up to 600 bps, and works in distances up to 3 m, depending on the type of LED used. Although Arduino is known for being a cheap and simple alternative, robust systems based on Arduino can also be found in the literature. Klaver *et al.* [Klaver and Zuniga, 2015] developed Shine, a platform that can function as an Arduino, by loading the bootloader, or as a generic ATMega 328p processor [Klaver and Zuniga, 2015]. The platform can establish communication at a distance of up to 1 m, and an average of 1 kbps data rate. Shine offers two main features: 360° LED coverage and serial interface, to provide connection with various devices. Based on these functionalities, the authors were able to develop a multi-hop mechanism, providing

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[3] Arduino simple Visible Light Communication - `https://github.com/jpiat/arduino/wiki/Arduino-simple-Visible-Light-Communication`, 2017.

a preliminary study of a miniature SmartCity, in which static nodes have to communicate with mobile nodes.

Generally, MCU-based platforms aim at a generic implementation and flexible hardware and are more common due to the advantages of MCUs, such as ease of programming and use. However, the main issue with this type of VLC platforms is the limited GPIO toggling frequency, such as the case of Arduino-based MCUs, whose clock frequency runs at 8-64 MHz [Yin et al., 2018]. In order to increase data rate, one of the alternatives is to increase clock frequency. MCUs also have a limited number of GPIOs, and it is difficult to control them independently, limiting these systems to half-duplex communication.

2.4.1.2 FPGA-based VLC

FPGA (Field-Programmable Gate Array) are also great alternatives to implement VLC platforms. It allows a much more precise control of the signal generated and works at a much higher clock frequency when compared to MCUs [Tian et al., 2016]. Hewage *et al.* [Hewage et al., 2016] presented modBulb, a generic, open source transmitter for VLC build on top of both MCU and FPGA [Hewage et al., 2016]. The transmitter can work based on the needs of the user, benefiting from the advantages of the MCU, such as flexibility, as well as the high performance supported by the FPGA. In addition, two different approaches are proposed for the driver circuit: linear regulator and switching regulator, which have a direct impact on the energy efficiency and noise in the circuit. The authors evaluated the system by designing a light receiver with a photodiode, and showed that by using an FPGA baseband generator, the transmitter data rate goes from Kbps to Mbps.

2.4.1.3 Single-board computers VLC

A number of VLC systems are built on top of single-board computers that run Linux, integrating lower layers with upper layers [Wang et al., 2015, Schmid et al., 2016b, Yin et al., 2018]. Wang *et al.* [Wang et al., 2014] have developed OpenVLC, an open-source general-purpose software-defined networking platform, which runs on BeagleBone Black board (BBB), a cost-effective, easy to use and powerful embedded board [Wang et al., 2015]. The front-end of the OpenVLC platform is built as a cape for the BBB. In terms of transceivers, the cape consists of a High-Power LED (HL), a Low-Power LED (LL), and a photodiode (PD), which are used to establish communication between two or more platforms. The components are connected to the BBB GPIO headers through the cape.

Both HL and LL can be chosen as the transmitter, through the software-defined selector. The cape also a DC/DC converter in order for the HL to work properly. Besides consuming more power than the LL, the HL also transmits light in all visible spectrum, as it is usually represented by a white LED. The LL are the simplest types of LEDs (5mm), with very low power consumption, in order of mW, and they emit light in a narrower optical spectrum, according to their color. The relationship between transmitters and receivers, as well as the software-defined configurations, can be seen in Figure 5.

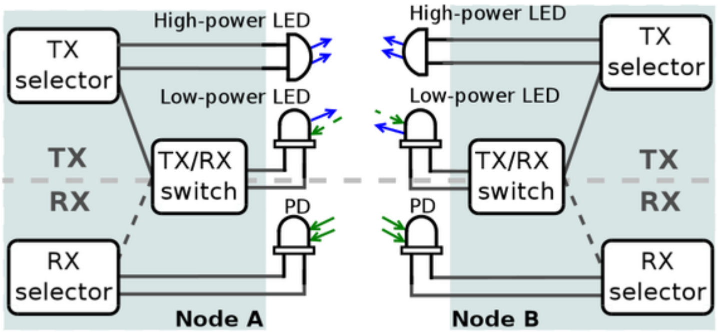

Figure 5 – OpenVLC 1.0 transceivers [Wang et al., 2014].

This approach brings several advantages, because TCP/IP stack is already defined in the Linux environment, so there is no need to implement the upper layers. In addition to that, some Internet measurement tools, such as *ping* and *iperf*, are well established in the literature, and can be used to measure system performance.

This type of architecture can be found in other studies in the literature, such as Enlighting, a fully functional VLC system with commercial LED light bulbs presented by Schmid *et al.* [Schmid et al., 2016a], which is an evolution of previous research presented by the same authors [Schmid et al., 2013, Schmid et al., 2014, Schmid et al., 2015]. This approach combines two hardware elements: the VLC firmware is developed in a ATmega328p, and it is connected via UART to an Atheros SoC AR9331, which runs a Linux distribution for embedded wireless system (OpenWrt). Physical and MAC protocols are implemented on the MCU. A conventional LED light bulb was modified to be attached to the platform. The platform allows multi-hop communication, and a localization service was also implemented and evaluated. The system is able to communicate at distances up to 5 m, with a data rate of 600 bps.

Another Linux-based platform was presented by Yin *et al.* [Yin et al., 2018], also built on top of a BeagleBone Black board. Purple targets the main issues of previous approaches by changing the transceiver design and performing I/O offloading, allowing multi-transmitters in a full-duplex communication mechanism, at a higher data rate. The transceiver is built as a BBB cape, and supports LED-to-LED or LED to photodiode communication. The current platform supports 4 LEDs as transmitters and 2 as receivers, in addition to the photodiode. Both the amplifier and the ADC support 2-channel data acquisition, so concurrent channels can be achieved at a hardware level. Another issue addressed by the authors is related to transmission power control. By increasing the number of LEDs used to transmit, the user can adjust transmit power control. In order to achieve a concurrent communication between two channels, they used cylindrical LED cases with polarizers on the front of the transceivers to cancel mutual interference, so that each channel can communicate independently. In that case, the angle of the polarizers must be aligned between transmitter and receiver. Authors have reached data rate up to 100 kbps with a full-duplex configuration at a distance of 2.5 m.

2.4.2 Software Design

The software design of VLC systems is directly related to the hardware used. MCU-based and FPGA-based platforms have their codes written directly in the firmware. Therefore, the implementation of Physical and MAC layers can be fairly low-complex and flexible, such as Arduino-based alternatives [4]. The system designed by Jonathan Piat uses Manchester Encoding alongside OOK modulation to transmit a 38 bytes frame, and each byte is serialized with a start and stop bit. A preamble is attached to the frame to help with synchronization. Shine, for example, is designed using the same microcontroller supported by Arduino (ATMega328p), which allows the usage of Arduino libraries [Klaver and Zuniga, 2015]. The authors built a Physical Layer Data Unit containing the preamble, the size of the payload and the payload itself, which are the information needed for synchronization, timing and decoding of data. An adaptative symbol thresholding is designed so that the system can distinguish between 0s and 1s. On top of the PHY layer, an API was developed in C++, to build upper layer protocols. A simple MAC Layer was developed using the API, consisting of a simple CSMA, able to perform neighbor discovery to achieve multi-hop communication.

Enlighting also has all PHY and MAC layers protocols written directly in the MCU [Schmid et al., 2016b]. The system operates based on three modes: idle, TX or RX. During the idle period, the driver transmits the idle pattern, appearing to be constantly on. During TX mode, the device transmits tha data using 2-Pulse Position Modulation (2-PPM), which leads to the same number of on and off symbols, avoiding flickering. Authors also proposed an adaptive threshold parameter (THRS), which is measured after decoding the preamble, so that the receiver can properly differentiate the symbols. The MAC layer is developed as a provider that serves both PHY and upper layers. Two types of frames are proposed: DATA and ACK, and a Carrier Sense Multiple Access with Collision Avoidance protocol is designed to control access to the medium. In the other hand, modBulb is designed as an FPGA-based transmitter, which is significantly more complex to program. The authors focus on the hardware perspective of the transmitter, considering the signals modulated in specifics modulations mechanisms (OOK, BFSK and PPM).

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[4] Arduino simple Visible Light Communication - `https://github.com/jpiat/arduino/wiki/Arduino-simple-Visible-Light-Communication`, 2017.

OpenVLC benefits from the integration with the BeagleBone Black board. The BBB allows the installation of Linux distributions in its embedded memory. The idea behind VLC driver is to develop the primitives of the PHY and MAC layers as a loadable kernel module, which is interconnected with the upper layers of the Linux TCP/IP network stack. Interruption handling and thread scheduling are performed with the support of Xenomai[5], an open-source Linux real-time framework.

Some of the primitives implemented at the lower layers are: signal sampling, symbol detection, coding, decoding, channel contention, and Internet Protocol interoperability. At the Physical Layer, On-Off Keying (OOK) is adopted as the modulation mechanism, along with Manchester Run-Length Limited (RLL). In addition, Reed-Solomon correction code is also implemented at PHY layer. At the MAC layer, there are two types of frames: Data and acknowledgment. Analogously to MAC protocols present in other wireless technologies, carrier sensing is implemented to avoid collisions. In this particular case, there are two different types of carrier sensing: basic and fast sensing, and both are functions of the PHY layer. Every time a frame is ready to be transmitted, OpenVLC performs the basic sensing mechanism (CSMA/CA). If the channel is free, data are transmitted. However, if the basic sensing detects a busy channel, a back-off counter is initialized with a random value between 0 and the contention window size. The sensing continues to be performed, and each time the channel is detect as free, the counter is decremented, until it reaches 0, and the frame is transmitted. During transmission, the fast sensing can be performed in order to detect a busy channel and interrupt communication (CSMA/CD). The software-defined lower levels of OpenVLC are transparent to the application.

Purple platform follows the same principle of OpenVLC, in the sense that both use BBB to integrate the front-end device to a Linux-based embedded system. However, in terms of software, Purple goes one step further by offloading the control of IO operations from the processor to the Programmable-Real-Time Unit (PRU), a 32-bit RISC processor at 200MHz that functions as an auxiliary component to the BBB, achieving a high frequency GPIO control. The PRU is embedded on the BBB, enabling a clock frequency of MHz without adding any new hardware. Due to its transceivers modifications, PurpleVLC has some significant improvements in its software implementation. The manipulation of multiple LEDs as transmitters and receivers requires careful synchronization between them. By using the PRU, PurpleVLC can control multiple GPIOs in concurrent manner, and synchronize the transmission precisely. PurpleVLC also differs from OpenVLC by adopting an implementation based on polling, instead of interruptions.

As seen in this Section, VLC platforms are becoming popular, and can be used for research purposes. For the purposes of the present work, we are going to use OpenVLC 1.0 to perform all protocol evaluations, which will be further discussed in the next chapters.

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[5] Xenomai - `https://xenomai.org/`, 2017.

3 DYRP-VLC - Dynamic Routing Protocol for Visible Light Communication

Visible Light Communication indoor scenarios offer a series of challenges related to obstacles, shadowing and LOS limitations, as discussed before. In this chapter, we present DYRP-VLC, a solution that makes use of the rich environment offered by light infrastructure and dynamic path construction/maintenance to mitigate communication issues, while offering Internet connectivity capabilities. The main goals of DYRP-VLC are listed below:

- Be a fully distributed routing protocol, without centralization;
- Adaptive to topology changes;
- Route discovery and maintenance involve a minimum number of nodes in the network;
- Guarantee loop-freedom;
- Avoid stale routes;
- Converge to optimal routes very fast and dynamically.

3.1 Protocol Overview

DYRP-VLC is based on MANETs routing protocols (AODV, DSR). Visible Light Communication networks may have similar characteristics to Mobile Ad-hoc Networks, especially when considering mobility, limited bandwidth, unreliability and physical layer constraints. Another factor that is important to consider in VLC networks is related to obstacles. By using an approach similar to reactive protocols for Ad-hoc networks, we aim to target these problems that may cause huge drawbacks in VLC scenarios. Therefore, the main idea behind this protocol is to adapt dynamically to changes in the network due to its reactive characteristics. In other words, every time a node wants to communicate with another node that is not in its routing table, it tries to build a route to the destination. If the route is successfully built, a bidirectional link is created between them. The protocol has two main features: *route discovery* (Section 3.3) and *route maintenance* (Section 3.4).

DYRP-VLC only maintains routing information between active nodes, due to its on-demand behavior, therefore it has a considerable advantage in terms of memory consumption. Each node in the network has a data structure that represents the route table. In our approach, we designed a simple route table to fulfill the requirements for multi-hop dynamic communication. In that way, the table has the following fields:

- Destination Address: The destination IP address of the route;

- Next Hop Address: The IP Address of the neighbor node on the path to the destination;
- Sequence Number: The sequence number of the route. This value is stored to assure that the route is always fresh, guaranteeing loop freedom in the network. The sequence number is incremented each time the node sends a route request message.;
- Expiration Time: The expiration time is used to control the current status of the route to a certain destination (further discussed in Section 3.5).
- Life Time: Special variable used by DYRP-RT protocol;
- Hop count: Number of hops to get to the destination;
- Status: Status of the route, which can vary from Active, Idle to Expired or Broken (further discussed in Section 3.5).

DYRP-VLC works based on a default metric: number of hops (hop count) from source to destination. Together with the sequence number, this information is essential to guarantee loop freedom in the network. Considering that, any node that receives routing information will always create one fresh loop-free route towards destination when considering the following guidelines: (i) if the node is receiving a route message whose sequence number is less then the route's sequence number (in the routing table), this route message is obsolete and, consequently, it is discarded, (ii) afterwards, the node checks the hop count parameter and compares it to the table entry in terms of cost. If it is more costly (more hops towards destination), the node discards the message. If the route message is new and less costly, the node updates its route table with the new entry.

Route construction starts with a source node broadcasting a route request message (RREQ) in order to find a valid path to the destination. The message travels around the network in a hop-to-hop mechanism, where each intermediate node saves a route towards the source and passes the message through. When the destination receives the RREQ, it builds a complete route towards the source node and unicasts a route reply message (RREP), which passes through each node present in the unique path. When the source node receives the RREP within time, it establishes a route to the destination, and starts using it to send packets. Each node in the path acts as relay nodes.

After a route is established and further used to transmit data, the maintenance mechanism is responsible for assuring the route is always fresh and active. Each time a node uses a route, it extends the route lifetime. If a node receives a packet to forward via a path which is not currently valid, it informs the source node that route is broken by sending a route error message (RERR). Each upstream node that receives the message will break the route, making it necessary to build a new one in case another packet is sent to the destination.

3.2 Integration with OpenVLC 1.0

As discussed in Chapter 2, OpenVLC 1.0 is an open-source platform developed for VLC research purposes. The platform provides a great environment to be studied and tested, due to its integration with the Linux network stack, allowing the interaction with the network layer. We developed the protocol in OpenVLC 1.0, in order to analyze the system's behavior in a real-world scenario, where we could demonstrate a very dynamic network, due to obstacles and shadows. In what follows, we further explain the integration of our protocol with OpenVLC 1.0.

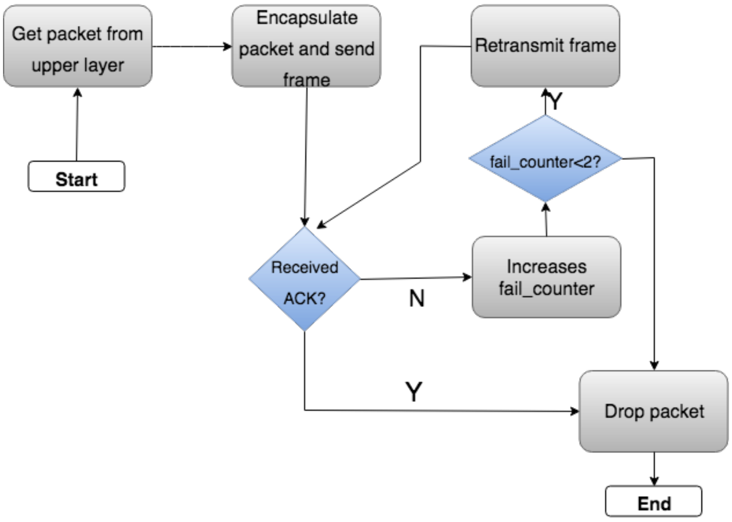
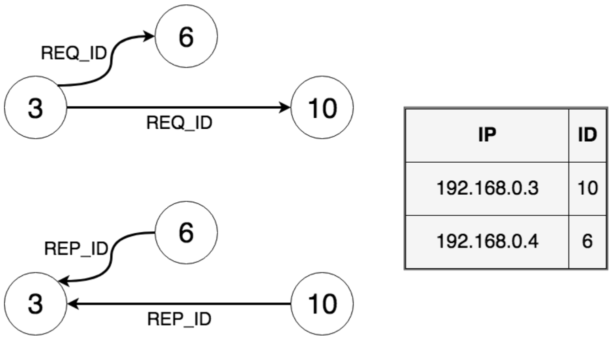


Figure 6 – Node behavior without Dynamic Routing Protocol

Figure 6 presents a flowchart showing the behavior of an OpenVLC 1.0 node in the network. Every time a packet is received from the upper layer, the MAC layer is responsible for making sure it will get to the other node. For that purpose, a series of mechanisms were developed on the native OpenVLC 1.0 (CSMA/CA, error detection). The packet is encapsulated and the frame is sent through the channel. Upon receiving the packet, the destination node answers with a simple ACK. If the ACK is not received after 3 attempts, the packet is dropped, and the process continues. This is a very simple mechanism, which showed good results in terms of packet reception rate (PRR) [Wang et al., 2014].

The authors have developed the MAC frame structure in order to support IDs for each node in the network. However, the integration between MAC and Network layer is not present on OpenVLC 1.0. DYRP-VLC works based on a network where nodes know their neighbors, therefore, we developed a simple mechanism through which neighbors nodes can know each other. The Neighbor Recognition Protocol (NRP) is used every time a node enters the network. It then sends a request message, and each node that receives the message replies with its own MAC/IP addresses. It is important to observe that this behavior depends on the MAC protocol adopted by the platform (CSMA/CA). Figure 7



IP	ID
192.168.0.3	10
192.168.0.4	6

Figure 7 – Neighbor Recognition Protocol

presents the basic mechanism behind the exchange of addresses. By assuring that each node in the network knows its neighbors, DYRP-VLC can be used in the correct way.

Our protocol behavior can easily be attached to the OpenVLC 1.0 regular behavior, by adding the procedures related to routing information to it, as shown in Figure 8. With our approach, every time a packet is received from the upper layer, we go through the standard routing mechanism, which is: firstly, the source node checks if the destination IP is in the routing table, and if it is not, it tries to build a route to the packet destination address. This procedure is performed for a pre-configured number of times, until the source node receives an RREP, signaling the successful construction of a route. However, if the node fails to build a route after the attempts, it drops the packet and waits for a period of time until getting the next packet. If a valid route to the destination is found, the source node looks for the next hop in the routing table, and attach its ID to the frame.

In order to perform route maintenance, We have developed two different approaches, DYRP-RC (Reference counter), which relies on the information taken from the MAC layer to break a route, and DYRP-RT (Route Timeout), which relies on each route's life time to decide whether to break or not a route. Both approaches will be further explained in the next sections. These two approaches are attached to Figure 8, in order to show how they connect to the overall behavior of a node.

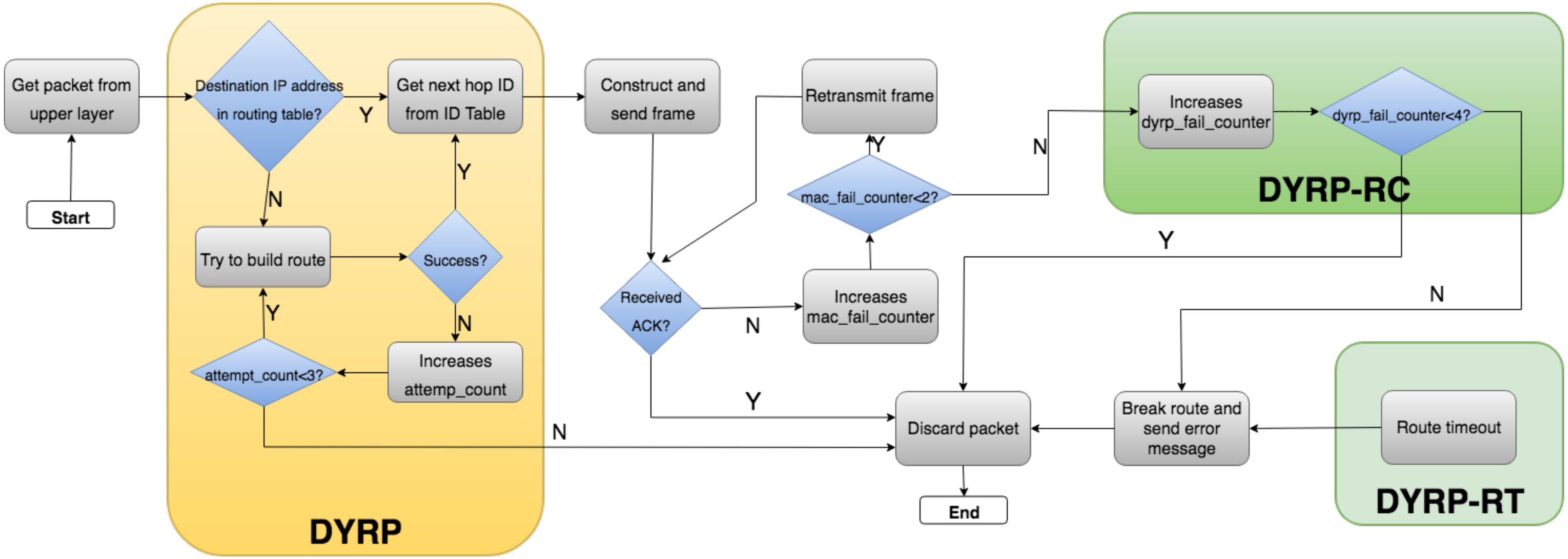


Figure 8 – Node behavior with Dynamic Routing Protocol

3.3 Route discovery

As presented in Figure 8, every time a node gets a packet, it looks for the destination address in its routing table. If it doesn't find it, the route discovery process starts. This process involves the transmission of an RREQ message, followed by the wait for an RREP message. These two routing messages share the same structure, but they differ in the way they are sent through the network.

```
route discovery process;
begin
    rreq_timeout_counter = 0;
    rreq_attempts_counter = 0;
    get packet from upper layer;
    look for IP in route table;
    if route to destination exists then
        send packet to next hop;
    else
        start route discovery process;
        while rreq_attempts_counter < ROUTE_DISCOVERY_MAX do
            rreq_attempts_counter++;
            send RREQ and starts timeout counter;
            while rreq_timeout_counter < ROUTE_RREQ_WAIT_TIME do
                rreq_timeout_counter++;
                if RREP received then
                    update route table;
                    send packet to next hop;
                    break;
                end
            end
        end
        discard packet;
    end
end
```

Algorithm 1: Route discovery process.

	Header		Body				
Field	Hop limit	Hop count	Source IP	Destination IP	Sequence Number	Path size	Path Information
Size (bytes)	4	4	4	4	4	4	...

Table 6 – RREQ message structure

Route discovery must be very controlled, to avoid loops and stale routes in the network. For that, every time a node sends an RREQ message, it waits for the RREP message for a period of time. If the node fails to create a bidirectional route to the destination, it tries again for a certain number of times. By the end of the attempts, if a route is not discovered, a failure is considered and the node has to wait for another period

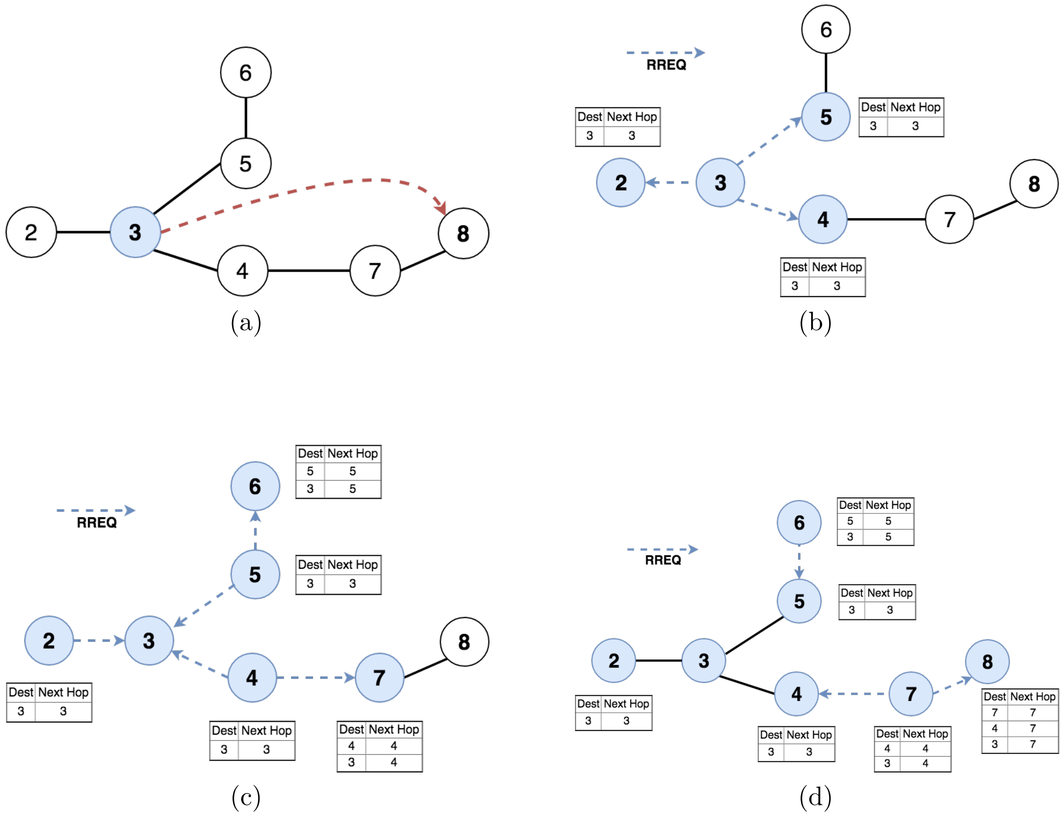


Figure 9 – RREQ - Route discovery process where node 3 tries to build a route to node 8.

until trying again. Table 6 presents the structure of the route messages, and the route discovery process is further described in Algorithm 1.

An example of route discovery towards the destination is shown in Figure 9. We will discuss each step of the figure in order to explain the operation mechanism of the protocol.

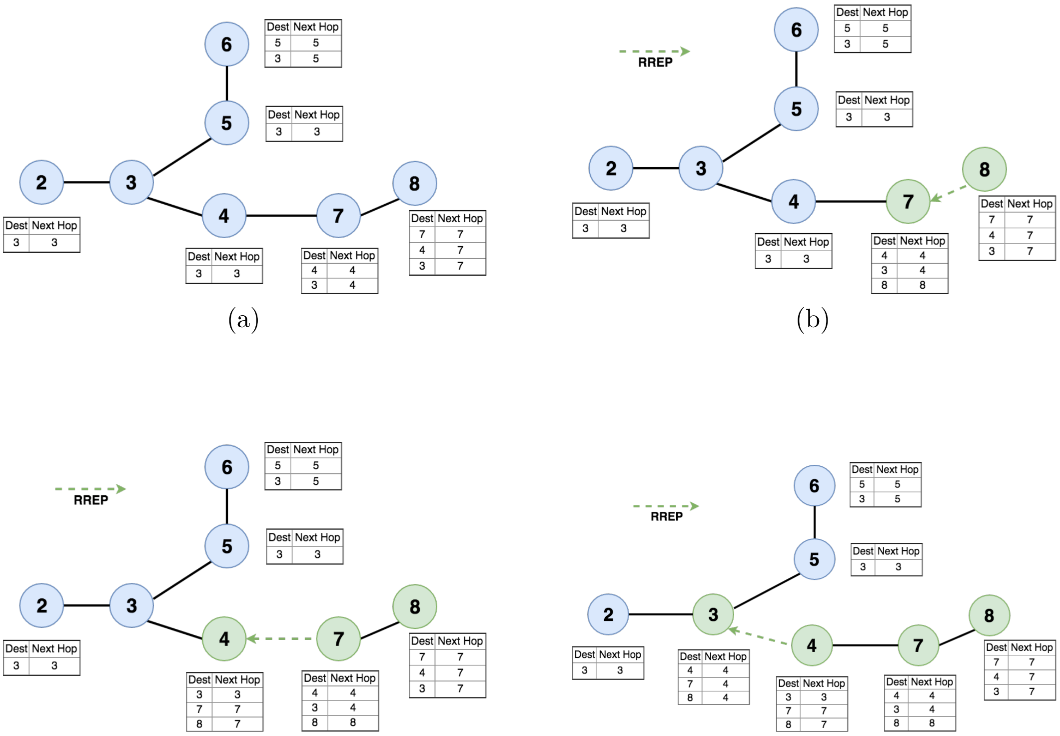
(a) Route discovery mechanism starts when a node in the network (3) wants to transmit to a destination that is not currently in its routing table (8) (Figure 9a). Note that neighbors are already set in the network. At that point, node 3 generates an RREQ message containing the following information (Table 6): (i) hop limit (pre-determined value), (ii) hop count, which is set to 0 whenever a new route request is created, (iii) source IP address, (iv) destination IP address and (v) sequence number, which is set to 1 the first time a route is created.

(b) Node 3 broadcasts the RREQ. Each adjacent node (in this case, 2,5 and 4) receives the frame set to broadcast address. Then, they check the information contained in the RREQ message, and perform the procedures to check if the incoming route is fresh and new. If the route is fresh, they add the source node to its own routing table, along with the information contained in the message.

(c) Each of these nodes (i) add their IP addresses, (ii) update hop count, (iii) attach this information to the RREQ message and broadcast it to the network. It is important to notice that at this point, node 3 also receives the RREQ, but the message is discarded because node 3 is already the source of the RREQ. Nodes 6 and 7 also receive the RREQ, and update their routing information.

(d) Nodes 6 and 7 update the RREQ and broadcast it. Node 5 and 4 receive the message and discard it, and finally it arrives at the destination address (node 8), which updates its routing table with the reverse path and prepares the RREP.

The reverse path is presented in Figure 10, where the RREP message travels all the way back to the source node. The step-by-step works as follows:



(a) (b) (c) (d)

Figure 10 – RREP - Route reply message following the reverse path.

(a) After the RREQ floods the network, all the nodes that received it have a reverse path to the source IP address. Node 8, in this case, after updating its routing table, creates an RREP frame containing the following information: (i) maximum number of hops, which is set to the hop count provided by the RREQ message, (ii) hop count, set to 0, (iii) source IP address, (iv) destination IP address, (v) sequence number, which is incremented by 1. At this point, the MAC layer already knows the IP address of the next hop (which leads to the destination node), and updates the frame with the next hop ID.

(b) Node 8 sends the RREP upstream, which is then received by node 7. The routing table is updated with incoming information, the RREP is updated with the addition of the IP address and sequence number and another RREP is sent.

(c) Node 4 receives the RREP, updates its routing table and repeat the process, adding the IP address to the message.

(d) Finally, the RREP message arrives at the destination. Node 3 updates its routing table with the incoming information and successfully builds a bidirectional route towards destination.

3.4 Route maintenance

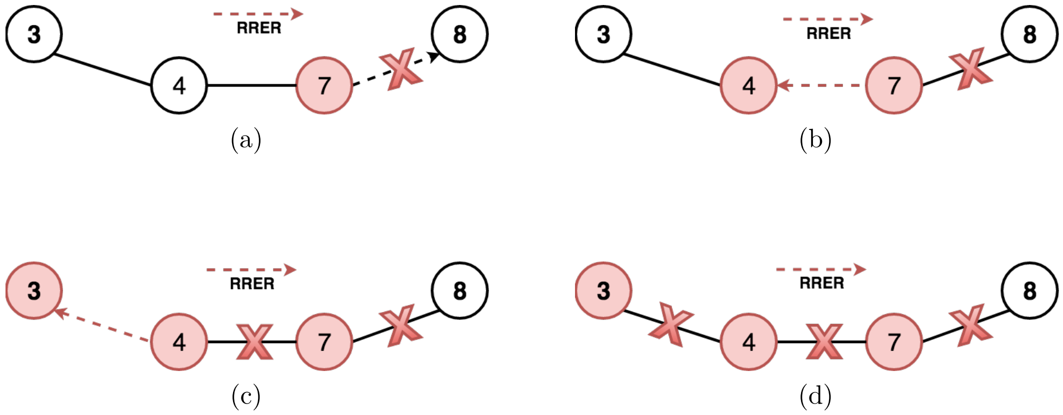
After a bidirectional route is created between two nodes in the network, packets start to be forwarded until arriving at the destination. At any time, the light can be obstructed, interrupting the link between two active nodes. The routing protocol must respond to such situations in order to avoid sending packets to broken/invalid routes.

	Header		Body	
Field	Hop limit	Hop count	Source IP	Unreachable IP
Size (bytes)	4	4	4	4

Table 7 – Error message structure

The process of breaking a route works as follows: at any time, given a specific parameter, a route status can be set as broken. This happens if the node fails to forward the packet towards the path to the destination. If that happens, the node generates an RERR message, which travels upstream until reaching the source node.

The error generation process is presented as an example in Figure 11. This figure shows the route built on the pictures above, and data are sent from node 3 to node 8.



(a) (b)

(c) (d)

Figure 11 – RRER - Route error message example

(a) At a point, the link between node 7 and 8 breaks. The mechanism to consider a route as broken will be discussed further.

(b) Node 7 marks its route to 8 as Broken, generates an RERR message containing the following information: (i) maximum number of hops, (ii) hop counter, also set to 0, (iii) IP address and (iv) unreachable IP address (Table 7). After that, it sends the RERR it upstream.

(c) Node 4 receives the RERR message and verifies if the next hop to the unreachable destination IP address is the source IP address contained in the incoming RERR. If so, node 4 marks its route to node 8 as Broken and updates the RERR, replacing the previous IP with its own IP address, decrementing the maximum number of hops by one and maintaining the unreachable IP address. Then, the RERR message is sent to the network.

(d) Node 3 receives the RERR message and repeats the process done by node 4. Breaks the route to node 8, updates the RERR and, if the maximum number of hops is greater than 0, sends it to the network.

The process of breaking a route to a certain destination is spread through the network, and can go beyond the source node of the packet. However, the process works as a controlled flooding, because the field containing the maximum number of hops is firstly set to a fixed value MAX_HOPCOUNT which is the same value used in the route discovery mechanism. This value is then decreased hop by hop, until reaching 0, being discarded. In that way, the RERR message will be able to get to the source node, without causing loops.

3.5 Route status

Any route entry stored in the routing table structure can be used to forward packets according to some validity parameters. All entries have an expiration time which is responsible for controlling the current status of the table, which can be Active, Idle, Expired or Broken.

Figure 12 presents all possibilities in terms of status. Before using a route to forward an incoming packet, the node always checks for its validity. All nodes are constantly decreasing the expiration time from the table entries. An Active route remains active until the expiration time is less than ACTIVE_INTERVAL. After that, the route becomes Idle. If the route is used while in Idle state, it becomes Active again. The route remains idle until the countdown reaches MAX_IDLETIME value. Then, its status is set to Expired. Expired routes cannot be used to forward packets, but their Sequence Number can be

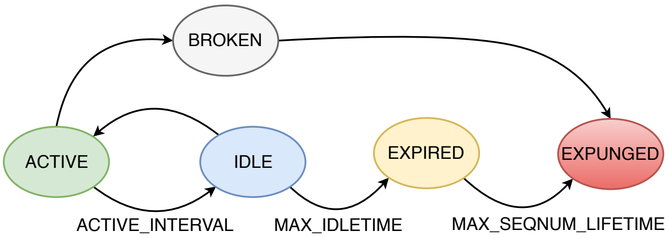


Figure 12 – Possible states of a route in the network

used to check for incoming routes freshness. After MAX_SEQNUM_LIFETIME, this route is expunged from the table.

A node must be able to detect when the link is broken. Visible Light Communication systems are very susceptible to interference, in a way that any shadow or movement can block the communication. In order to deep analyze how the routing behavior affects performance, we propose two different approaches for DYRP:

- DYRP-RC (Reference counter): In this solution, the cross-layer routing protocol is always aware of the MAC layer transmission. If the link is broken, eventually, the node sending the frame will not receive its ACK. DYRP collects this information and makes a decision of breaking the route based on that. If the ACK is not received for a certain amount of times, the link is considered broken and RERR is sent upstream. However, if the MAC layer receives an ACK after a certain amount of attempts, the counting is cleared and starts over again.
- DYRP-RT (Route Timeout): Considering that we are dealing with a very dynamic scenario, waiting for the lower layer to trigger the broken link may cause excessive link failures and overload the network with RERR messages and route discovery retries. In order to avoid that, this solution explores the route timeout as the trigger to break the route and send RERR.

In this Chapter, we have covered the main aspects of DYRP-VLC, which includes routing mechanism, route status, route discovery and maintenance, integration with OpenVLC 1.0. That being discussed, in the next chapter we perform several experiments for both approaches in order to analyze their behavior.

4 Results

In this chapter, we present the main results achieved during evaluation. For that, we first present the methodology used to perform the experiments, along with the metrics analyzed. Then, we go through the results exploring both static and dynamic scenario.

4.1 Methodology

We used the OpenVLC 1.0 platform to perform our experiments. As discussed in Chapter 2, OpenVLC is a software-defined open platform for research related to VLC. It allows the use of LEDs and photodiodes as as *front-end.* At the physical layer, ON-OFF Keying (OOK) is implemented. The medium access is performed using CSMA/CA method. The driver is implemented as a Linux kernel module.

Parameter	Value
Transmitter	Red LED (TLCR5800-ND)
Receiver	Photodiode (OPT101)
Symbol Rate	50 kHz
Frame Payload Size	255 Bytes
Ambient Light	120 lx
Modulation Scheme	OOK
MAC protocol	CSMA/CA

Table 8 – Parameters considered for evaluation.

We set the parameters of OpenVLC 1.0 driver according to the current state-of-the-art, presented in [Heydariaan et al., 2016]. Table 8 presents the parameters used for the evaluation of the protocol. We used up to four OpenVLC 1.0 platforms to perform the experiments, organized in two different scenarios: static and dynamic. However, the network must be planned considering the viewing angle of the LED, which is 8° our case.

We configure all nodes with fixed IP addresses and IDs, in a way that all nodes in the network know its neighbors. In that way, ReqId and RepId are not used, as we want to evaluate only the route mechanism. The network considered in the present work does not have a central node. All nodes can communicate with each other as long as their IPs belong to the same LAN, which is the our case (IPs are configured as 192.168.0.x). The Red LED was chosen due to its better performance compared to other colors [Heydariaan et al., 2016].

4.2 Metrics

When dealing with multi-hop Visible Light Communication networks, there are several metrics that are used among the works in literature. Many works consider multi-hop at a physical perspective, and for those works, metrics such as Received Optical

Power and Bit Error Rate (BER) are mostly used [Kim et al., 2016, Ahmad et al., 2017, Narmanlioglu et al., 2017]. However, when the analysis of multi-hop networks moves to an upper perspective (MAC and Network layers), Throughput becomes the most used metric [Le et al., 2011, Wu, 2012, Wang et al., 2014]. On the other hand, routing protocols evaluation usually uses other metrics, such as number of hops, delay and routing overhead. In the present work, we have chosen the following metrics to evaluate DYRP-VLC:

- **Throughput(Kbps):** We calculate throughput with the *iperf3* tool [Mortimer, 2018]. This is one of the main advantages of using OpenVLC 1.0. Due to the integration with Linux network stack, we can explore a rich repository of network measuring tools. We configure the *iperf* to send 0.8 KB UDP packets;
- **Routing overhead:** The routing overhead is identified by the total number of routing packets transmitted during the experiment [Gupta et al., 2013]. We first estimate the routing overhead taking into consideration the properties of DYRP-VLC. Then, we apply the theoretical analysis to a real world scenario, considering the two-hop scenario;
- **Route discovery time:** According to [Gupta et al., 2004], the Route Discovery Time can be defined as the elapsed time between sending an RREQ and receiving the corresponding RREP.

4.3 Static scenario

The static scenario is presented in Figure 13, and contains up to 4 nodes which are able to communicate only with its neighbors. In addition, we explore a scenario in which obstacles can interfere with communication, in order to analyze how DYRP-VLC adapts to changes in the network.

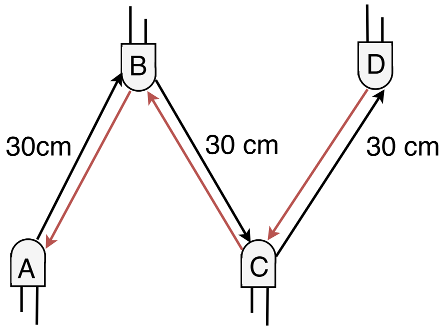


Figure 13 – Static scenario with up to 4 nodes.

4.3.1 Route discovery time

Firstly, we analyzed the route discovery time, which is a metric that is not influenced by the different route maintenance approaches (DYRP-RT and DYRP-RC). The route discovery mechanism is directly influenced by the size of the network. We analyzed route discovery time given the parameters presented in Table 8. After that, we take into consideration the particularities of the protocol, and study the impact of route timeout and reference counter on the following metrics: throughput and routing overhead. Considering the setup presented in Figure 13, the route discovery mechanism was performed between the following nodes:

- One-hop: Node A → Node B
- Two-hop: Node A → Node C
- Three-hop: Node A → Node D

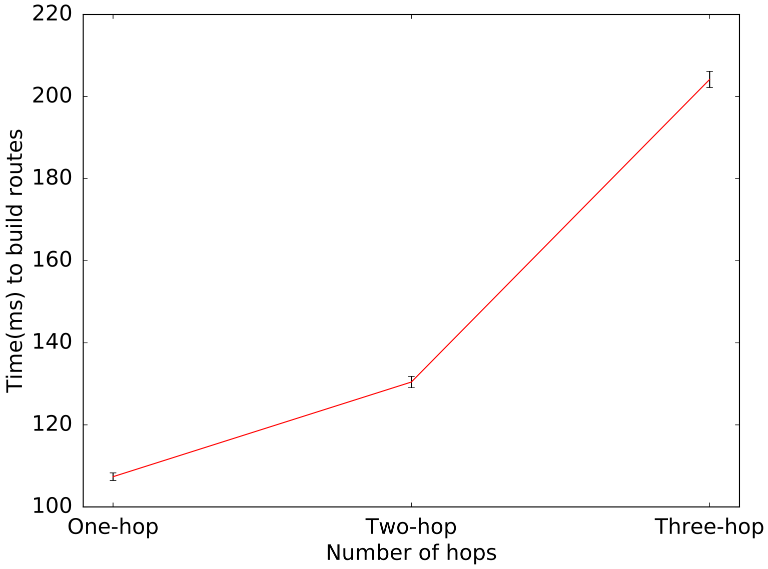


Figure 14 – Route discovery time (ms) for different number of hops.

Figure 14 presents the results for route discovery time considering multiple hops. As expected, the time to build routes increases when more hops are added to the route. In the one-hop scenario, it takes an average time of 107 ms to discover a route to destination. This scenario is straightforward, and while the source node has the destination IP address in its Neighbors table, it must create a route towards the neighbor in order to add the routing parameters. In a two-hop scenario, it takes 130 ms to perform route discovery. By adding a hop, the complexity increases because each node has to process the RREQ received, update its route table with the received information and prepare the RREP message with its own information attached to it. Therefore, the difference between one to two hop (∼23 ms) is lower than the difference between two to three hops (∼70 ms).

In the next set of experiments, we will analyze the impact of DYRP-RT and DYRP-RC on the network performance. For that, we will use the configuration presented in Figure 13, considering a two-hop scenario, generating UDP packets from source to destination for 150 s. As discussed in Chapter 3, the two approaches differ in terms of route maintenance decisions. DYRP-RC is aware of the lower layer condition, and decides to break a route based on the MAC layer failures. In the other hand, DYRP-RT establishes a life time for each route, and breaks it when the life time is over.

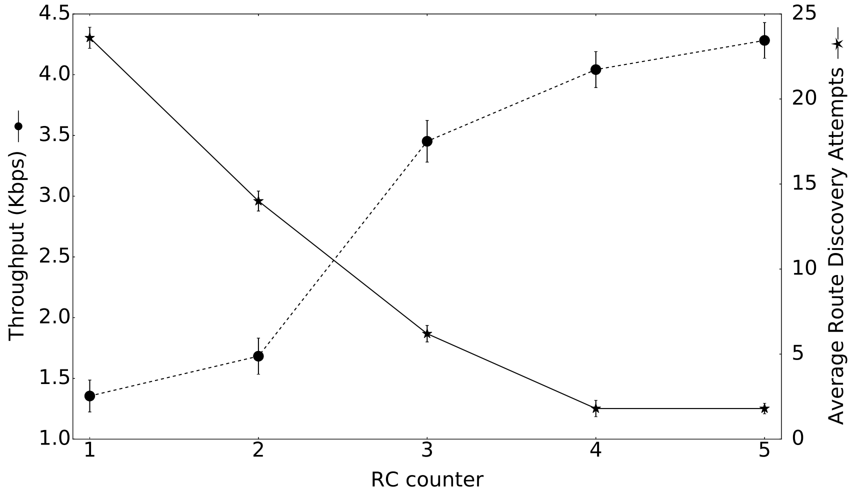


Figure 15 – Trade-off between reference counter and average route discovery attempts.

Figure 15 shows the trade-off between average route discovery attempts and average throughput, considering different RC counters. For RC = 1, for example, the route is considered to be broken when the MAC layer fails one time. Naturally, due to factors such as noisy medium, LED field-of-view and medium access protocol used, it is very common for a node to miss an ACK. Consequently, the source node tries to rebuild the broken route, which has a direct impact on network performance, as packets are enqueued while the route is not established. Therefore, for RC = 1, there are an average of 24 route discovery attempts, resulting in an average throughput of 1.4 Kbps. By increasing the reference counter, we give the MAC layer a margin of error to work with. This strategy has a direct impact on performance, because less route discovery retries will be made, achieving a higher throughput. Also, for DYRP-RC, network performance stabilizes for RC = 4, achieving an average throughput of up to 4.3 Kbps.

The rules to break a route in DYRP-RT also have a significant impact on the network performance, as shown in Figure 16. By configuring higher lifetimes to routes, the source node makes less route discovery attempts, achieving higher throughput. For a lifetime of 2 s, for example, there was an average of 24 route discovery attempts, resulting in an average throughput of 1.4 Kbps. By increasing the route lifetime linearly (5,10,15,20),

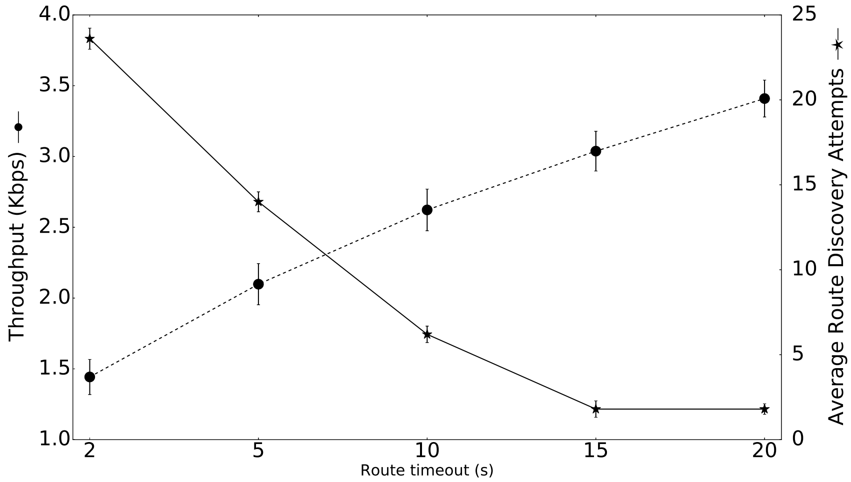


Figure 16 – Trade-off between route timeout and average route discovery attempts.

the average throughput increases linearly as well, reaching its peak at 3.4 Kbps, where RT = 20 s.

For the two-hop scenario evaluated, the trade-off between DYRP parameters and network performance is very clear. However, the choice of parameter for both DYRP-RC and DYRP-RT cannot only take into consideration the behavior discussed earlier. A clear example of this can be for DYRP-RT, for example, which showed better performance for RT = 20 s. In a scenario where changes can occur frequently, 20 s may be bad for the network, as will be shown further. The same can be assumed for DYRP-RC. If we increase our threshold, the impact on dynamic networks can be higher.

4.3.2 Overhead Analysis

The decision to break a route is driven by protocol-specific parameters (reference counter or route timeout). Depending on the parameter, route breaking occurs more frequently, which consequently leads to more route discovery attempts, having an impact on the network in terms of overhead. In order to analytically study the overhead caused by the protocol, three equations are going to be used, one for each case in which routing messages are sent through the network.

It is important to observe that the scenario studied in this work is a simple scenario, in which routes are built with only two hops. Equations 4.1 to 4.3 show a general case for route discovery process. The equations used in this work will derive from these 3 general equations, which are considered for a scenario as shown in Figure 17.

- Route discovery success: In Equation 4.4, n is the number of hops from source to destination. In DYRP-VLC, routing messages have a standard size of 24 bytes, as

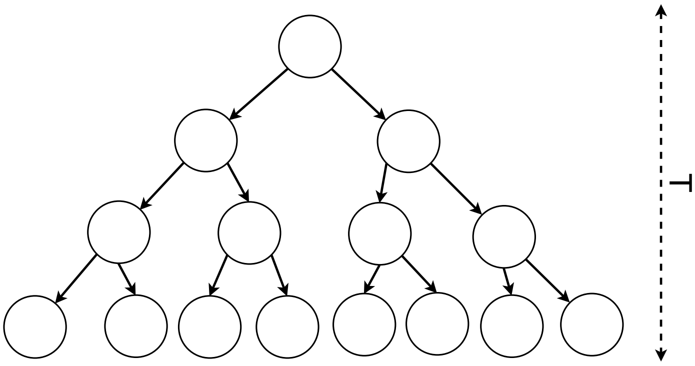


Figure 17 – General case

discussed in Chapter 3 and shown in Equation 4.1.

$$\begin{aligned} routeMessageNoTrail = {} & hopLimit + hopCount + sourceIP + destinationIP \\ & + sequenceNumber + pathSize \end{aligned} \tag{4.1}$$

$$addedNode = NodeIP + SequenceNumber \tag{4.2}$$

After the first message is sent, for each node RREQ/RREP pass through, 8 bytes are added to it (IP address and Sequence Number), as shown in Equation 4.2. If a route discovery attempt is **successful**, it means that the RREQ message traveled all the way to the destination, while RREP traveled the reverse path, reaching the original source node.

Firstly, we developed a general equation for a general case considering a homogeneous and uniform network where nodes have the same cardinality g and route discovery process floods the entire network, from the source to each possible path for T layers. Figure 17 shows an example for $T = 3$ and $g = 2$. When the route discovery process start, the RREQ message reaches every possible node, direct or indirectly connected to the source node. Therefore, the general equation for overhead is presented in Equation 4.3, and involves the exponential flooding of the network given T and g and the number of hops to destination.

$$S(n) = (\sum_{i=1}^{T} routeMessageNoTrail + (addedNode \times (i - 1))) * (g^T + 1) \tag{4.3}$$

In our case, the flooding does not affect the network exponentially, and because of that we can work with a simpler version of Equation 4.3. Therefore, in order to achieve the total overhead caused by route messages, we use a summation that goes from 1 to the number of hops, adding the overhead contribution node by node, and multiply it by 2 (the reverse path), as shown in Equation 4.4.

$$S(n) = (\sum_{i=1}^{n} routeMessageNoTrail + (addedNode \times (i - 1))) * 2 \tag{4.4}$$

- Route discovery failure: When an RREQ is sent through the network, the source node waits for the incoming RREP, which should arrive, within the waiting timeout. When it doesn't, the node sends another RREQ, and this procedure is made for a MAX_ATTEMPTS number of times, which in this case is 3. Therefore, the worst case scenario for route discovery failure involves sending RREQ three times, while the RREP travels back to the node before the source node, failing to be delivered at that point. Equation 4.6 summarizes this scenario. Basically, we consider the failure scenario to be the success scenario without one final RREP message (Equation 4.5).

$$LN(n) = routeMessageNoTrail + (addedNode \times (n - 1)) \tag{4.5}$$

$$F(n) = (S(n) - LN(n)) \times 3 \tag{4.6}$$

- Route maintenance: When a route breaks, RERR is sent upstream. This process is straightforward, and the 16 bytes RERR message does not change while traveling through the network, but is forwarded until reaching the source node, which is shown in Equation 4.7

$$E(n) = routeRERR \times n \tag{4.7}$$

Given that properties, for our scenario, the total number of bytes spent with routing messages can be specified as:

$$Overhead(n) = S(n) * nSuccess + F(n) \times nFailures + E(n) \times nMaintenance \tag{4.8}$$

It is important to highlight that we can recover the number of success (*nSuccess*), number of failures(*nFailures*) and number of errors(*nMaintenance*) directly from the kernel in OpenVLC 1.0. In what follows, we discuss the results obtained from the experiments.

According to Figure 18, by increasing DYRP-RT timeout parameters, and giving more time for each route to maintain itself, less failures occur, causing less route messages to be sent. The impact on the network is clear: for RT = 2 s, more than 30 % of the

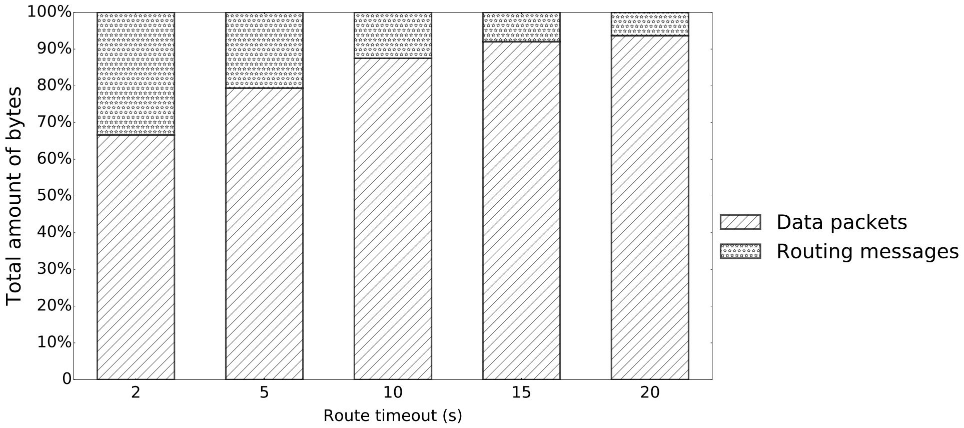


Figure 18 – DYRP-RT overhead for a two-hop scenario.

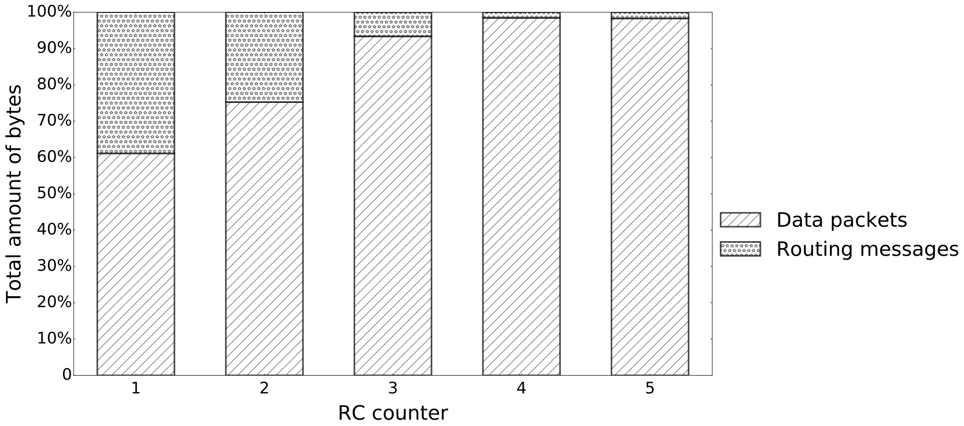


Figure 19 – DYRP-RC overhead for a two-hop scenario.

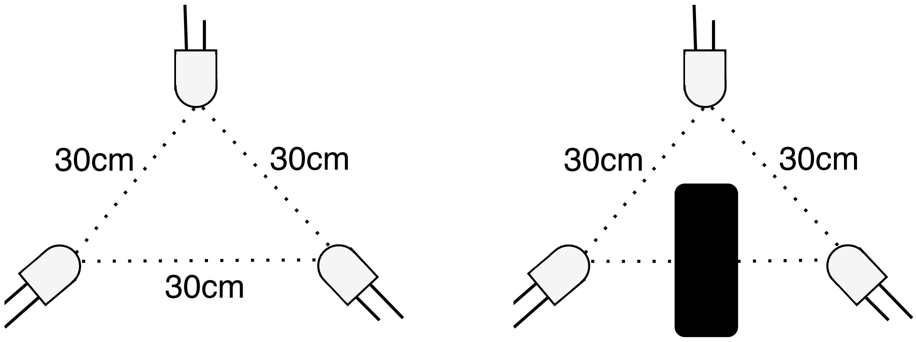
total amount of bytes belongs to route messages. For RT = 20 s, the percentage of route messages decreases to less than 10 %.

The same behavior was achieved for DYRP-RC. Figure 19 shows that, by increasing DYRP-RC threshold parameter, the overhead caused by the protocol decreases significantly. For an RC = 1, routing messages represents more than 40 % of the total amount of bytes. This happens because route maintenance detects broken links more often, leading to more discovery attempts and more error messages. By increasing RC counter, the overhead is decreased, reaching a point where, for example, for RC = 5, routing messages represent less than 1 % of the total bytes.

In general, the results presented show that the relationship between route maintenance parameters and average overhead is straightforward: the more route discovery attempts made and broke links detected, the more overhead. The overhead caused by the specific parameter such as route timeout or RC counter has a direct impact on the network behavior. Again, the two-hop scenario considered in this experiment is obstacle-free, and this behavior may not be reflected in a dynamic scenario.

4.4 Dynamic scenario

For that purpose, we prepared a setup containing 3 nodes, shown in Figure 20, which are able to reach each other. We start by sending UDP packets between two nodes. At a given time, we interrupt the communication by adding an obstacle, which theoretically triggers the route discovery mechanism, resulting in a scenario in which an extra node is used to forward packets to destination. For both scenarios, we performed the experiments for 100 s, and repeated it 5 times, with a confidence interval of 90%.



(a) No obstruction (b) Obstruction event

Figure 20 – Dynamic scenario.

4.4.1 Throughput analysis

For the next set of experiments, we analyzed the behavior of the network considering both DYRP-RC and DYRP-RT, in a dynamic scenario in which obstacles are inserted from time to time. For that, we will consider the setup presented in Figure 20a, in which three nodes are configured in a way that they are able to communicate with each other. Obstacles are put between two nodes that are communicating between intervals from 30 s to 60 s and from 90 s to 120 s, as shown in Figure 20b. The shaded regions in the following figures represent the obstruction moments.

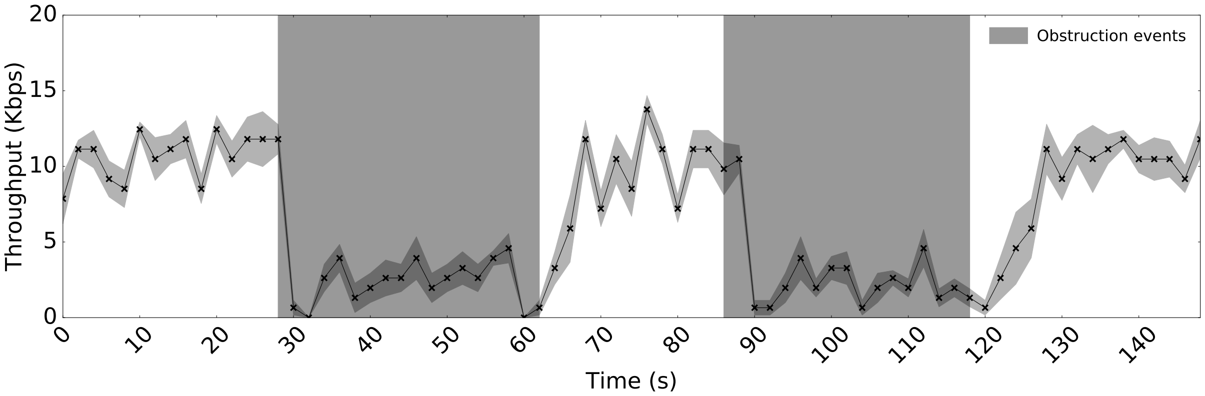


Figure 21 – Network performance over time using DYRP-RC approach (RC = 2).

Figure 21 presents the results for a dynamic scenario in which DYRP-RC is used (RC = 2). As seen in the Figure, during the direct communication, average network throughput can reach up to 11 Kbps, even with a number of falls. When the obstacle is added to the scenario, the network tends to achieve lower throughput, which is seen in the two shaded regions. This occurs because of two main factors: firstly, nodes have to be forwarded by the intermediate node, which causes a delay in message delivery. Secondly, more link failures occur in multi-hop, as discussed before. As soon as the obstacle position is changed, network performance increases again.

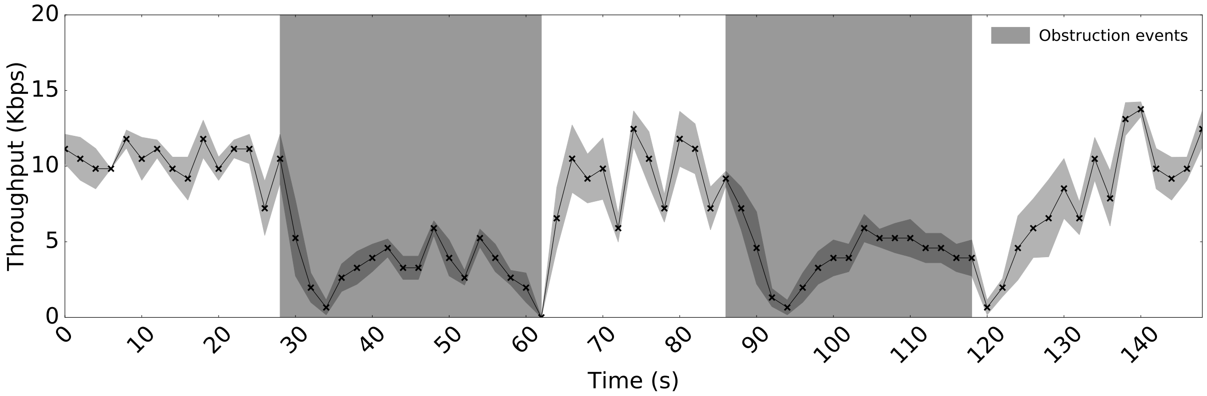


Figure 22 – Network performance over time using DYRP-RC approach (RC = 5).

Figure 22 presents the results for DYRP-RC where RC = 5. At 30 s, for example, an obstacle is added to the network, which immediately interrupts communication between the two nodes. The interruption process takes longer in this case, due to the delay in route maintenance when compared to RC = 2. As seen in the figure, the first obstacle is removed at t = 60 s, which leads to a rediscover process, generating the same direct route from the beginning. This process is repeated one more time, from t = 90 s to t = 120 s. In this case, while in multi-hop, an average performance of up to 34%(4.69 Kbps) of the direct link was achieved.

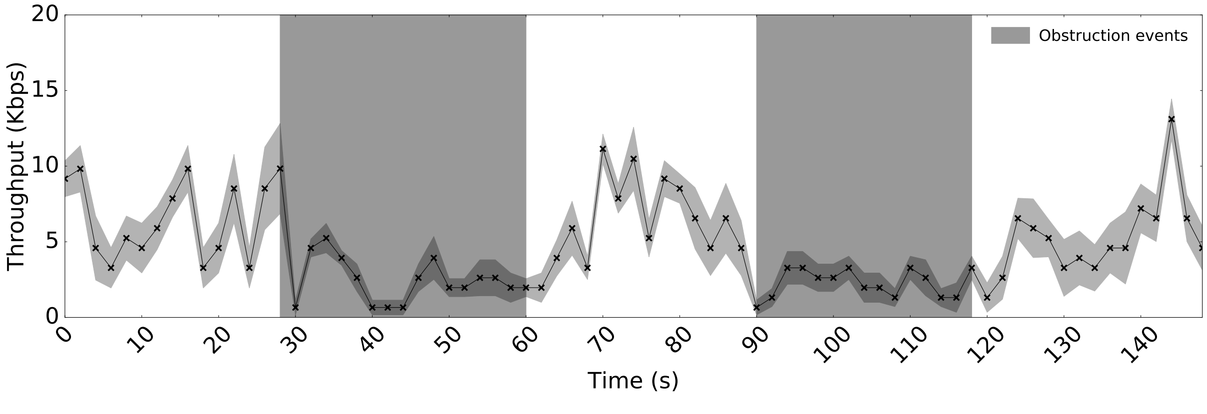


Figure 23 – Network performance over time using DYRP-RT approach (RT = 5).

Figure 23 shows the results for RT = 5. The first aspect to be noticed in this scenario is the lower performance in direct link. This is due to the route timeout value being low (5 s). Therefore, even if the communication is being successfully performed between two neighbors, the route will always have to be reconstructed from time to time. When the obstacle is added, the route is updated and reconstructed from 5 s to 5 s. Route reconstruction in multi-hop may fail several times, leading to a poor performance while in multi-hop (average 2.34 Kbps in multi-hop and 6.69 Kbps in direct link).

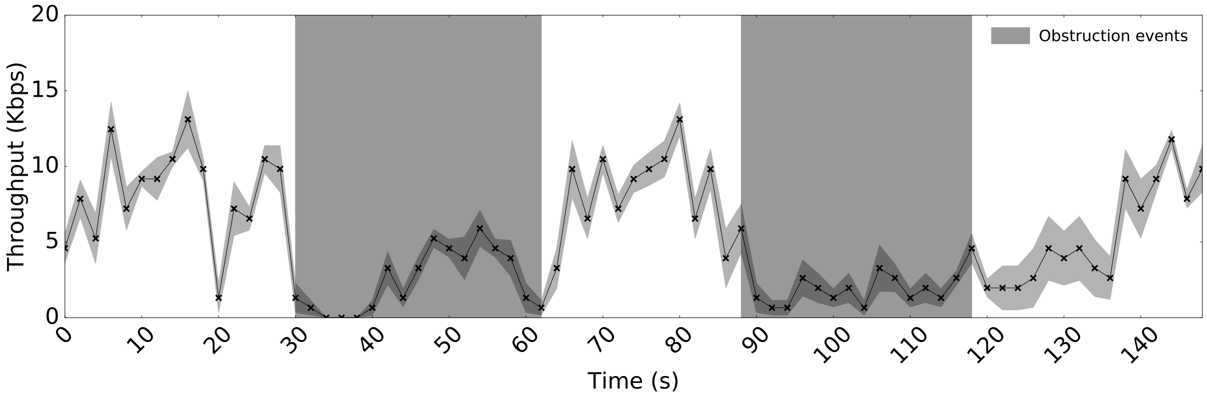


Figure 24 – Network performance over time using DYRP-RT approach (RT = 20).

The last experiment was performed with RT=20 s. Figure 24 presents the results. Some interesting points can be highlighted in this case. Firstly, it can be noticed how RT parameters affect even the direct node, which also happened in RT=5 s. At 20 s, the route is reconstructed, which in this case lead to a huge drop on throughput. Another interesting factor can be noticed from 30 s to 40 s, which is repeated from 90 s to 100 s. RT is set to be 20 s, while the obstacle is added at 30 s. Until the route expires, data will be sent directly, without reacting to the obstacle. In other words, when considering route properties to perform maintenance (in this case, route timeout), nodes may not react properly to network changes. This is a significant drawback of DYRP-RT, that can highly affect network performance, as seen in this experiment.

When comparing both DYRP-RC and DYRP-RT, the first aspect to be observed is the lower performance on direct link when using DYRP-RT. The average throughput achieved for the direct link when considering RT=5 s was 6.69 Kbps. For RT=20 s, the average throughput achieved was 8.27 Kbps. In that case, the scenario is better for DYRP-RC, because in direct communication there are less MAC layer failures, assuring the continuous communication between the two nodes. For RC=2, the average throughput was 10.96 Kbps, and for RC=5, 9.70 Kbps. However, the behavior changes for the multi-hop scenario. For RC=2, the average throughput is 2.85 Kbps, which is only higher than 2.34 Kbps, achieved using RT=5 s. The best results for that scenario were achieved for RT=20 s and RC=5, which achieved 3.85 Kbps and 3.75 Kbps, respectively. In a nutshell, these results show how route maintenance mechanism has a great impact on communication, and how multi-hop may require a less robust mechanism, while direct communication performs better with DYRP-RC.

In this chapter, we have performed several experiments under different scenarios to evaluate the performance of DYRP-VLC in a realistic scenario. Especially, the behavior shown from Figures 21 to 24 offers a number of insights related to the routing protocol. Firstly, it shows how efficiently the protocol handles interruptions, and how protocol parameters such as RREP waiting time and time between route discovery attempts impact the network. By using DYRP-VLC, nodes will always try to find a way to the destination, as long as intermediate nodes are available. However, throughput suffers a significant drop when the network changes to a multi-hop configuration. Despite the natural drop suffered by having an intermediate node forwarding packets, there are a number of factors that contribute to this low performance, which are:

- Medium-access protocol: The MAC protocol adopted in the OpenVLC 1.0 platform is CSMA/CA. This protocol, along with a decentralized network, can cause conflicts during its operation. Hidden nodes can impact the performance of this protocol, which consequently leads to more route failures, causing a higher overhead in the network.
- Half-duplex communication: OpenVLC 1.0 does not provide full-duplex communication. As a consequence, the intermediate node must handle the messages individually, which takes more time to forward the packets.

5 Related Work

The rapid adoption of LEDs and consequent popularization of Visible Light Communication applications has given space to many new research topics during the last decade. Multi-hop VLC is one of these topics, and it has been proposed by several works in literature as a solution to some of the main issues regarding the communication. In this chapter, we give a detailed review of the state-of-the-art related to our proposal, which is also shown in a succinct way in Table 9.

Le *et al.* [Le et al., 2011] proposed a cooperative MAC protocol for LED-ID Systems. This was one of the first research to present a model for cooperative transmission in a LED-ID VLC network. The protocol is based on the IEEE 802.15.7 MAC standard [IEEE, 2011], and proposes multi-node cooperation in which relay nodes between the sender and receiver work cooperate when the current link fails and becomes unable to offer enough bandwidth and QoS requirements for the network. Cooperation begins when the number of packets lost reaches a pre-defined threshold, and follows the following pattern: (i) Sender and Receiver broadcast *relay request* messages, (ii) an intermediate node receives both messages, and if the they are received with high quality, keep the ID addresses, (iii) the node decides to act as a relay and broadcast their information with receiver and sender nodes. The authors perform both theoretical and simulation evaluations, achieving significant enhancements and reliability to the network modeled.

Another model for VLC applications is presented in [Wu, 2012], where the author proposes a multi-hop solution for multiple access in indoor VLC scenarios, taking into consideration two main challenges in such scenarios: (i) LOS and (ii) directionality. Based on these challenges, the author offers two different network solutions: peer-to-peer and peer-to-host. These protocols are equipped with a simple network routing construction, in which when a device wants to communicate with another, it tries to build a route by checking its neighbors, looking for a rendezvous node to act as a relay. These protocols don't have mechanisms to assure loop freedom, route freshness, route maintenance and metric information. We go further by proposing a new dynamic routing protocol and implementing it in a real-world scenario. In other words, we further explore the characteristics of the routing protocol in a VLC scenario.

The idea of a multi-hop VLC network has also been considered to mitigate two common issues in this type of scenario: signal coverage and communication range. In this sense, the work of [Chowdhury and Katz, 2013] analyzed the multi-hop technique using relay nodes to increase VLC connectivity. The authors first developed a coverage model for indoor VLC considering parameters such as radiant intensity, LED angle and degree of uniformity. Then, simulations were performed using Monte-Carlo method, while taking into consideration relay selection and mobility. According to the results obtained, multi-

	Type	Platform	Application	Cooperation	Dynamic
[Le et al., 2011]	Theoretical and Simulation	ns-2 (Simulation)	Indoor	Yes	Yes
[Chowdhury and Katz, 2013]	Simulation	-	Underwater	No	No
[Kim et al., 2016]	Practical	Custom	Indoor	Yes	No
[Cherntanomwong and Namonta, 2015]	Practical	Arduino Uno	Indoor	Yes	No
[Klaver and Zuniga, 2015]	Practical	Generic / Arduino	Indoor	Yes	No
[Schmid et al., 2016b]	Practical	Arduino	Indoor	Yes	No
This work	Practical	OpenVLC 1.0 (BeagleBone Black)	Indoor	Yes	Yes

Table 9 – State-of-the-art of multi-hop VLC research.

hop communication using relay nodes improve the overall network performance. The work of [Schmid et al., 2016b] also evaluated the use of multi-hop communication to increase communication range, reaching a distance of up to 4 meters between transmitter and receiver, while using two intermediate nodes as relays. Authors used Optimized Link State Routing to build static route between source and destination, and did not evaluate the impact of obstacles in the communication. Authors in [Cherntanomwong and Namonta, 2015] presented The Repeater, an approach that uses a relay node to increase communication range. The authors implemented a transceiver equipped with LEDs and photodiodes, and a repeater, which is basically two sets of transceivers: one that is responsible for getting the light signal and forwarding it to the other set, which forwards the signal. The main idea of this work is to increase communication range by putting repeaters as intermediate nodes between source and destination.

Visible Light Communication has also been considered to be a complementary technology to underwater applications. However, one of the main drawbacks of optical waves in such scenarios is the high scattering of signal, which are absorbed in few meters [Vieira, 2012]. Multi-hop techniques can be used to increase communication range in such scenarios, which has been shown in [Kim et al., 2016, Ahmad et al., 2017]. Kim *et al.* [Kim et al., 2016] propose a multi-hop relay VLC system for maritime applications and evaluate by performing simulations under realistic sea state parameters (e.g. wind speed, average wave period) and different atmospheric turbulence conditions (weak, moderate and strong). The authors analyzed the bit error rate (BER) considering three different combining schemes: selection combining, equal gain combining and maximal ratio combining, which provided good link quality in a distance of up to 5 km, with 4 relay nodes. A more practical work was presented by Ahmad *et al.* [Ahmad et al., 2017], where the authors developed and demonstrated a full-duplex underwater multi-hop VLC system in a real scenario considering three different types of water (tap, canal and sea). Authors measured the received optical power at direct link scenario, and compared it to the multi-hop scenario. Authors concluded that, by adding a relay node, the frame success rate increases and the link distance can be further increased within the multi-hop scenario.

The authors behind OpenVLC 1.0 also made some experiments regarding multi-hop communication [Wang et al., 2014]. However, at the given time, OpenVLC 1.0 was still in early development, therefore the maximum throughput achieved in a direct link scenario was 1.6 kb/s. Considering a two-hop topology, the maximum throughput achieved is near 0.6 kb/s. According to the authors, one of the reasons behind the drop in data rate is the higher number of channel collisions, due to the adoption of CSMA at the MAC layer. Unfortunately, the authors did not give more information about the routing mechanism as well as the setup configuration for experiments.

Another example of a research platform used for VLC multi-hop communication is presented in [Klaver and Zuniga, 2015]. The Shine is a generic Arduino-based platform that explores the coverage issue in VLC application by using 20 LEDs as transmitters and 4 photodiodes as receivers, providing a 360° communication coverage. In terms of data rate, the Shine platform is limited to the micro-controller sampling rate, which is 1 MHz. In practical terms, the achievable data rate is 1 Kbps. The authors explore the exposure and directionality of LEDs to implement a multi-hop scenario in which mechanisms such as packet forwarding and neighbor discovery are implemented. The algorithm has been built in C++ on top of the MAC layer.

6 Conclusion

In the past decade, Visible Light Communication has gained a lot of attention from both academic and commercial areas. The efforts to standardize and integrate VLC to the wireless infrastructure is evident, which are remarkable, considering the great novelties developed in the past years, from a physical perspective (modulations, LED technologies) to applications (localization, underwater). VLC-based applications have many issues, due to limitations such as LEDs Field-of-view (FOV) and directionality, node mobility, shadowing and obstacles.

In this thesis, we have presented DYRP-VLC: a new cross-layer dynamic routing protocol for Visible Light Communication networks. Our approach is based on reactive routing protocols, in which routes are built and maintained according to network demands. In order to avoid stale routes and loops, we use sequence numbers and a standard metric, which is the number of hops from source to destination. By adopting this protocol, any intermediate node can become part of a route to destination, and starts to forward packets until the route is broken or expired.

In addition, we have developed two different approaches to perform route maintenance: DYRP-RC, which uses statistics from the MAC layer to decide whether to break or not a route, and DYRP-RT, which establishes a timeout for every route created. Both approaches can have a very low overhead, depending on the parameter used. DYRP-RT presents less then 10% overhead, while DYRP-RC presents less than 1%. However, when considering dynamic scenarios, the impact on communication can be more evident. DYRP-RT is an approach based on route timeout, which has a direct impact on both direct and multi-hop communication, while DYRP-RC explores information from the MAC layer, making it more aware of network condition.

We evaluated the protocol by implementing it in an open-source VLC platform, OpenVLC 1.0. Our results show that, by using DYRP-VLC, the network becomes aware of obstacles, and reacts to it by creating alternative paths between source and destination, while forwarding the packets to destination.

6.1 Future directions

This thesis covers routing in VLC, which is very rare in literature. By implementing, testing and analyzing the protocol, we can consider a number of issues and future directions, for both protocol characteristics and the integration with OpenVLC 1.0. In the following, we highlight some future directions:

- Analyze the impact of other protocol timers such as RREP waiting time, wait time to perform another route discovery attempt, idle and active timers. As discussed in [Perkins et al., 2013], these parameters should be configured according to network characteristics.

- Comparing DYRP-VLC with other reactive protocols (AODV, DSR): this will give a good insight on how cross-layer protocol differs from other which adopt upper layers properties.
- Develop a more efficient medium access mechanism to handle forwarding: CSMA/CA can fail to address some requirements for multi-hop communication. Other protocols such as TDMA-based alternatives can be pointed as good options to multi-hop scenarios. However, the adoption of a time-based medium access protocol can have many drawbacks, which should be covered.
- Develop simulations to analyze factors that are difficult to analyze in real-world scenario, such as scalability.

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