UNIVERSITAT POLITÈCNICA DE VALÈNCIA

School of Telecommunications Engineering

THz-band based wireless communications systems in trains

Master's Thesis

Master's Degree in Telecommunication Engineering

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ACADEMIC YEAR: 2022/2023

Abstract

The increase of wireless devices and the continuous upgrade of network services are among others the main causes of the saturation of the electromagnetic spectrum, and its consequent requirement for an extension, especially with the emergence of the new 6G networks, which require the use of the extended spectrum towards higher frequencies, such as millimeter waves, the THz band, including the sub-THz, and even communications in the visible spectrum. This work is aimed to study the particularities of communication systems using frequency waves in the THz band, in order to identify their potential and limitations in various 6G applications and scenarios. Specifically, the work will address the scenario of rail vehicles, and will aim to define the components and structure of the entire communications system proposed, based on a photonic generation scheme, identifying the range, capacity and performance of links between trains and train-ground, this latter being used for applications related to CCTV (Closed-Circuit Television).

Keywords: 6G, spread spectrum, millimeter waves, THz, visible spectrum, limitations, trains, CCTV.

Resumen

El incremento de dispositivos inalámbricos y la continua actualización de servicios de red son entre otras, las principales causas de la saturación del espectro electromagnético, y su consecuente requerimiento de una ampliación, especialmente con la llegada de las redes 6G las cuales requieren el uso del espectro extendido hacia frecuencias más altas, como son las ondas milimétricas, la banda de los THz e incluso las comunicaciones en el espectro visible. Este trabajo se centra en estudiar las particularidades de los sistemas de comunicaciones que emplean ondas de frecuencia en la banda de los THz, con el fin de identificar su potencial y sus limitaciones en diversas aplicaciones y escenarios 6G. En concreto, el trabajo abordará el escenario de los vehículos ferroviarios, y tendrá como objetivo definir los componentes y estructura del sistema íntegro de comunicaciones propuesto, basándose en un esquema de generación fotónica, identificando el alcance, capacidad y funcionamiento de enlaces entre trenes o tren-tierra, siendo este último utilizado para aplicaciones relacionadas con CCTV (Closed-Circuit Television).

Palabras clave: 6G, espectro extendido, ondas milimétricas, THz, espectro visible, limitaciones, trenes, CCTV.

Resum

L'increment de dispositius sense fil i la contínua actualització de serveis de xarxa són les principals causes de la saturació de l'espectre electromagnètic, i el seu conseqüent requeriment d'una ampliació, especialment amb l'arribada de les xarxes 6G les quals requereixen l'ús de l'espectre estés cap a freqüències més altes, com són les ones mil·limètriques, la banda dels THz i fins i tot les comunicacions en l'espectre visible. Aquest treball se centra en estudiar les particularitats dels sistemes de comunicacions que empren ones de freqüència en la banda dels THz, amb la finalitat d'identificar el seu potencial i les seues limitacions en diverses aplicacions i escenaris 6G. En concret, el treball abordarà l'escenari dels vehicles ferroviaris, i tindrà com a objectiu definir els components i estructura del sistema íntegre de comunicacions proposat basant-se en un esquema de generació fotònica, identificant l'abast, capacitat i funcionament d'enllaços entre trens o tren-terra, siguent aquest últim utilitzat per a aplicacions relacionades amb CCTV (Closed-Circuit Television).

Paraules clau: 6G, espectre estès, ones mil·limètriques, THz, espectre visible, limitacions, trens, CCTV.

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Chapter 1

Introduction

This document introduces the research and work carried out for the ”Master’s Degree in Telecommunication Engineering”, entitled “Wireless communication systems in trains based on the THz band”. Throughout this document, a THz communication system for CCTV (Closed-Circuit Television) image downloading application is proposed and its feasibility is assessed.

In this first chapter, emphasis will be placed on the motivation that led to the study of this work and the objectives that were taken into consideration. Furthermore, the methodology considered will be discussed and finally a presentation of the structure will be detailed for a better comprehension.

1.1 Motivation

Nowadays, society has become an ever-growing technological environment, particularly in terms of ICT (Information and Telecommunication Technologies), where the number of consumers and the use of wireless devices is increasing. The services provided by these devices are diverse and they simultaneously coexist and communicate with each other, i.e. mobile networks, satellite communications or even Radio and Television broadcasting.

For each of these applications, a different bandwidth is required. For example, maritime or navigation applications may involve lower frequency bands than applications based on satellite communications [1]. To simplify this, Fig. 1.1 below summarizes a representation of the different frequency bands expressed in wavelength. This diagram is known as the electromagnetic spectrum which, due to the increase in the number of wireless devices, is gradually reaching a saturation point, especially in terms of micro and milimetric waves.

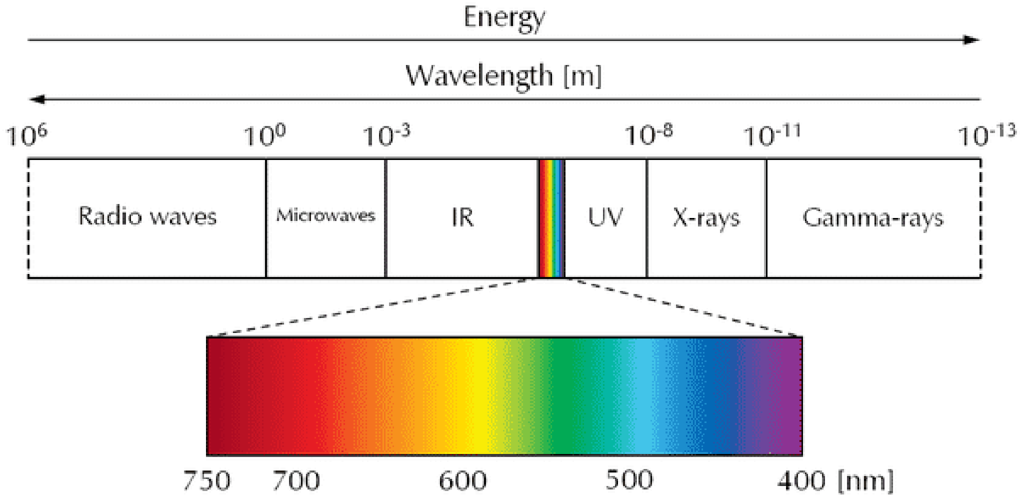


Figure 1.1: Radio spectrum [2]

The radio spectrum is defined as a limited natural resource, managed by the ITU (International Telecommunication Union). These frequency bands are used to offer communication services either through free space or by optical fiber as well as other physical means. Thus, it is particularly worth knowing the origin of the use of the spectrum in order to understand the application of this project.

At the end of the 19th century and the beginning of the 20th century the radio spectrum began to be used in terms of communications. These first communication systems consisted of radio waves for point-to-point links, most of them with military applications. Later, in the middle of the 20th century, radio and television emerged with the so-called broadcast technology, which was capable of sending information to different terminals and, therefore, meant an increase in the use of such radio spectrum [3]. Shortly after, the beginning of the telecommunications era would arise with the first analog telephone calls that, later, would give way to the current mobile and wireless telephony and the different generations and their consequent technological incorporations.

The basis of today's telecommunications technology was introduced in 1980 with the appearance of the first generation, 1G. The technology used was analog and allowed telephone calls to be made. From that moment on, new generations appeared approximately every 10 years until reaching the current 5G and future 6G.

The 2G involved the introduction of digital systems as opposed to the analog 1G, which together with the worldwide popularity of GSM (Global System for Mobile Communications), more than a billion people had access to this technology, which was based on mobile communications and the ability to send text messages from a mobile terminal (slow speed), bringing with it the need to explore an improvement to achieve higher data rates. This led to a type of technology called Code-Division Multiple Access (CDMA) used in 3G, a technology from which the well-known CDMA2000, TD-SCDMA and WCDMA would later emerge, providing much higher speeds of up to a few megabits per second. Subsequently, 4G emerged, based on multiple input multiple output (MIMO) and OFDM modulation, which boosted the sale of mobile devices globally and achieved higher traffic speeds.

Moreover, over the last few years, and especially with the arrival of the pandemic, special emphasis has been placed on creating much more secure and powerful networks capable of connecting not only people but also devices, in contrast to previous generations. This can be attained with the emergence of 5G, which is already set and used by a considerable amount of users.

Finally, regarding 6G technology, there have been many discrepancies and diversity of opinions on whether this new generation should be implemented or not. However, it is undeniable that technology will continue to advance, as new advences such as holographic communications, tactile internet or even a much more advanced virtual reality are expected to arise in society in the years beyond 2030 [4].

As mentioned above, as improvements increase, so does the required bandwidth of the radio spectrum. On the one hand, in 2G 900 MHz and 1800 MHz carriers are required, whilst in 3G the bandwidth increases up to 900 MHz and 2100 MHz for 4G applications. On the other hand, 5G covers from the sub-6G band to above 24 GHz, while 6G could cover a frequency range between 95 GHz and 3THz, which therefore belongs to the THz band.

Nowadays, the continuous advances in wireless communications have raised global concern over spectrum saturation. Between the years 2020 and 2030 it is expected that the networks will continue to grow and, therefore, some scenarios which will result in future requirements to be taken into account for the implementation of future generations are foreseen, in this case 6G. As a result, the ITU entity is in charge of approving the standards (ITU-R Requirements) in relation with spectrum efficiency among other purposes. The following list foresees the state of the network beyond 2020:

- First of all, it is expected that new markets will emerge for applications in the field of wireless communications such as intelligent transport, for example, and the requirements established so far do not mitigate these developments.
- In addition, data traffic has increased over the years and is expected to continue to increase, especially with the arrival of IoT devices.
- On the other hand, massive MIMO has been found to be easier to carry out using higher frequencies.
- Extended and contiguous bandwidths can lead to a reduction in hardware complexity
- Finally, a reduction in cells size is expected to increase communications capacity [5].

Additionally, a series of global traffic estimations have been established for the years between 2020 and 2030. Fig. 1.2 shows the estimated worldwide traffic evolution, and reflects an annual increase of 54% in mobile traffic.

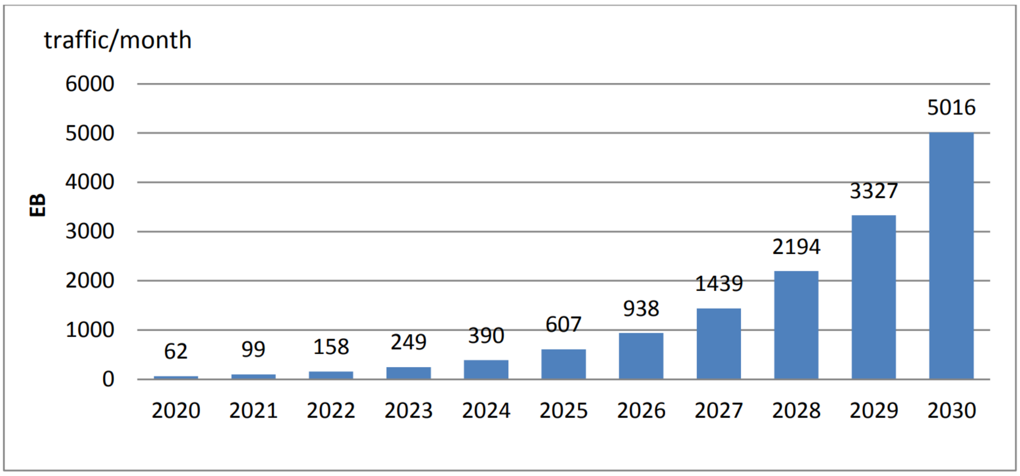


Figure 1.2: Estimation of global mobile traffic between 2020 and 2030 [6]

It is estimated that each user will consume around 39.4 GB of data traffic per month through 2025, a rate that will continue to increase as subscriptions grow to 257 GB by 2030.

Moreover, with the increase in traffic, and carrier frequencies moving further towards the visible spectrum, the advent of 6G brings with it a number of expected use cases likely to be in use by the year 2030, these are shown below [4]:

- Holographic Type Communication
- Extended Reality
- Tactile Internet
- Multisense Experience
- Pervasive Intelligence
- Intelligent Transport and Logistics
- Enhanced On-Board Communications
- Global Ubiquitious Connectability

On the other hand, in order to define 6G scenarios, the current 5G scenarios in 5G have been completed as follows:

- Enhanced mobile broad-band (eMBB)
- Ultra reliable low latency communications (URLLC)
- Massive machine type communications (mMTC)

It can be concluded that, those 5G usage scenarios cannot meet the requirements needed for 6G networks. The so-called Mobile Broad-Band (MBB) service is required to be accessible over the entire surface of the planet in order to enable high-quality on-board communications and global ubiquitous connectivity. With the upcoming 6G networks, those services will be known as uMBB (ubiquitous Mobile Broad-Brand). In addition, these uMBB services will be the basis for the Digital Twin, pervasive intelligence, enhanced on-board communications, and global ubiquitous connectivity [4].

Another concept to consider is the so called KPI (Key Performance Indicators), especially when applied to evaluate eMBB (enhanced Mobile Broad-Band). Some KPIs to be addressed for some of upcoming 6G scenarios are the following:

- **Peak data rate** estimated to reach 1 Tbps, i.e. 10 times that of 5G.
- **User-experienced data rate**. It is expected to be 1 Gbps, amounting to 10 times more than 5G.
- **Latency**. This data averages 4 ms in the current 5G network, but is expected to reach 100 us or even 10 us in 6G.
- **Mobility**. This data will reach 1000 km/h.
- **Connection density**. This data will reach 10^7 per Km^2 (10 times that of 5G).
- **Energy efficiency**. This data will be improved from 10 to 100 times that of 5G.
- **Peak spectral efficiency**. 6G networks are capable of reaching 3 times higher spectral efficiency.
- **Area traffic capacity**. This data will meet the expected 1Gbps/m^2.

Given the constant growth of networks, which have to support a greater number of services and consumers, the spectrum saturation is a well-known fact that leads to the study of higher frequency bands to alleviate this problem. As a result, this project will undertake the study of a communication system in the terahertz (THz) band, located just below the visible light, for train communications application. Thus, these high frequencies could provide greater speed and a set of benefits that will be further detailed below.

Subsequently, enabling technologies for the 6G network will be presented. In other words, those that allow reaching new spectrum bands not yet exploited by mobile communications, such as visible light or the terahertz band. These two bands are the first example of enabling technology since both have been considered for the use of 6G. However, the technology needed to manufacture antennas has not yet been achieved at an empirical level, since these, besides requiring high directivity, would also need very small electronics, in addition to high atmospheric losses. Also, as mentioned above, visible light could be used as a complement to radio communications, since this technology is more mature than the THz one. This could be achieved by using LEDs (Light Emitting Diode) [7].

Furthermore, modifications in terms of network architectures will have to be made to allow them to support data inputs of a few gigabits. This will give rise to the so-called multi-dimensional networks. Some proposals are listed below:

- **Heterogeneous access:** This refers to the end of the cells, i.e., user connectivity is no longer divided into cells but they connect to the network as a whole, since 6G envisages the use of multiple radio technologies, and therefore devices could connect through these multiple accesses.
- **3D networks:** This refers to the fact that 3D could provide terrestrial coverage with aero or even space technology.
- **Network virtualization:** This has already been considered for the fifth generation, and with the growth of networks, it is interesting to consider virtualization, either of functions or of the network itself, as networks will need more and more complements to support the increase in traffic.

Finally, It is expected that by using artificial intelligence and Machine Learning, terminals will be able to use information from past experiences to make future decisions and organize the amount of data to be transmitted. Since networks are often full of unnecessary data, which will increase with the advent of 6G networks, it is necessary to establish a centralized network capable of managing internal data and making decisions [7].

It is interesting to note that this project has been inspired by the work developed in a recent internship at Stadler RAIL, where on-board communications in rail vehicles, as well as the video surveillance system, have been thoroughly covered.

1.2 Objectives

The objective of this project is to develop a photonic signal generation system for on-board communications applications in trains. Specifically, this project will focus on the study and development of a system with the aim of downloading data from CCTV equipment through a train-ground link. The study will be carried out using software.

First of all, a study of THz waves will be carried out, deepening in its nature as well as its different applications in society and the reason why it is so important to extend the spectrum to such high frequencies. On the other hand, a transmission and reception scheme for THz frequencies will be proposed, including its real components and characteristics, which allows its application to a railway vehicle scenario. Finally, this scheme will be simulated by software to study the feasibility of the system.

1.3 Methodology

The tasks taken into consideration to achieve the objectives of the project are detailed in Table. 1.1.

	Months						
Tasks	**Jan.**	**Feb.**	**Mar.**	**Apr.**	**May**	**Jun.**	**Jul.**
Search for bibliography	■	■	■				
Validation of a system for photonic generation of THz signals		■	■	■	■	■	
Definition of train application scenario			■	■	■		
Software design				■	■	■	
Search for commercial components					■	■	
Cost analysis						■	
Writing					■	■	■

Tabla 1.1: Methodology

Two simulation and analysis softwares are considered during this project:

- Optisystem 20.0 by Optiwave [8]: The design and simulation of the communication schemes have been carried out using this software.
- Matlab [9]: This software has been used to represent the data from the simulation of the proposed schemes extracted from Optisystem.

1.4 Structure of the project

This structure represents the steps followed during the study:

- In chapter 2, the study of the channel applied to THz communications will be carried out. Moreover, a transmission and reception approach will be introduced including real components and their characteristics.
- In chapter 3, a train scenario will be introduced, as well as the simulation and analysis of the scheme proposed in chapter 2.
- In chapter 4, the general budget of the project will be carried out, including the reference of the components and the overall cost of the system.
- Finally, in chapter 5 conclusions will be discussed and future lines of action that may be required for this project will be proposed..

1.5 Sustainable development goals / SDGs

It is of interest to discuss how THz band communications can contribute to the sustainable development goals to meet the 2030 agenda [10]. In this section, both how these communications contribute to development and their application in rail vehicles will be discussed.

First and foremost, as mentioned above, communications in the THz band and, consequently, the arrival of 6G will represent a turning point in communications as they are known to date, since they will allow global coverage even in rural mountainous areas or high seas, as well as new forms of communication such as the emergence of the tactile internet and holograms. All of this falls under SDG9, i.e. Industry, Innovation and Infrastructure. In relation to the area of railway systems, the application it receives in terms of downloading CCTV content involves an increase in the speed of data transmission.

On the other hand, the fact that communications at such high frequencies can solve the problem of connectivity, especially in rural areas, could solve the problems of poor connections in isolated areas, thus promoting quality education (SDG 4), since having a better internet connection would allow access to many more resources. All this is purely related to communication systems in the THz band, in the same way that such communications also contribute to achieving sustainable cities and communities (SDG 11) as they facilitate connectivity, leading to more efficient networks and, consequently, reducing environmental impacts, as well as overly complex infrastructures.

Finally, for the sake of mentioning a requirement that can be applied to this project's objective, the downloading of the entire video surveillance content on trains can facilitate data processing and thus increase security. This belongs to the SDG 16 requirement: Peace, justice and strong institutions.

Chapter 2

Communication systems based on the Terahertz band

This chapter will cover the theoretical model of the THz band, its background, as well as the technology required to implement a system operating at such frequencies and, finally, applications this band may have in today's society.

2.1 The Terahertz Band

The THz band covers a range of frequencies between 100 GHz and 10 THz and is a key factor for the upcoming sixth generation communications known as 6G networks. However, although its inclusion in 6G wireless systems is increasingly being considered, there are still a number of obstacles to be tackled. These obstacles are mainly due to the high attenuation of the channel and the lack of equipment that can support the reception of signals at such high frequencies [11].

As previously mentioned, the THz band is located between the microwave and the infrared band, a schema of such can be seen in Fig. 2.1 for a better comprehension. And so, this allows it to share properties of both of them. The idea of using such high frequencies in communication is directly related to spectrum saturation.

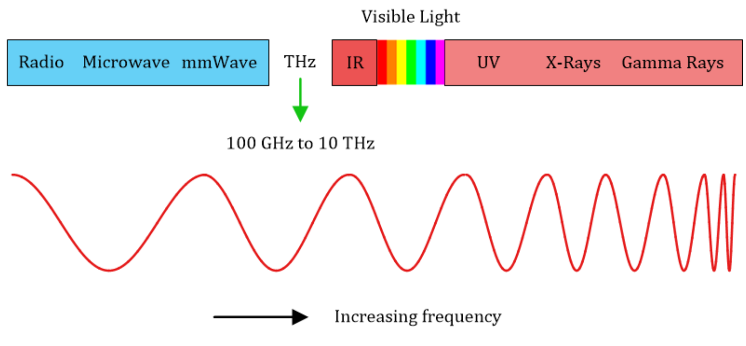


Figure 2.1: Radio spectrum [12]

Until now, radio and optical communications had followed separate paths. On the one hand, radio technologies covered short to medium range communications, whereas optical technologies covered long-range communications. Radio technologies require more and more bandwidth, to the point of using millimeter waves or even sub-THz frequencies. Consequently, both technologies are gradually approaching each other in terms of frequency in a way that the gap between them remains in a quasi-homogeneous environment.

Therefore, in terms of wireless communications, a change is now required, as the carrier frequency is getting closer and closer to the THz band. An increasingly promising approach is to consider optical technology in wireless communications, since it is very resourceful compared to radio technology, as part of a new infrastructure to accommodate new generations.

Both radio frequencies and optical communications characteristics have been discussed above. These technologies refer to different waves and frequency bands and are implemented and used in different situations depending on the objectives and type of communication. As regards radio frequencies, microwave band has been widely used despite its limited bandwidth, while RF and optics waves, millimeter band as well as visible light are still being implemented. Moreover, in terms of purely optical communication, the infrared frequency band has been used for free-space communications. There is justification for this since its components are considered to be very mature technology. However, it has a major drawback: its high sensitivity to atmospheric disturbances in the channel.

To summarize, the THz band can be defined as a set of frequencies that lies in between the millimeter and infrared bands and shares characteristics of both worlds. As for the IR (i.e. infrared) region, it is interesting to differentiate between short-wave infrared (SWIR) from 1.5 to 3 μm, mid-wave infrared (MWIR) from 3 to 8 μm, and long-wave infrared (LWIR) from 8 to 15 μm, as can be seen in Fig. 2.2, since the medium and long-wave (i.e. MWIR and LWIR) are both referred to as the upper THz band, and altogether with upper milimeter wave (lower THz band) clear the way for research and new potential alternatives in terms of wireless communication, although its limited technology. However, photonic technology offers solutions to break those limits [13].

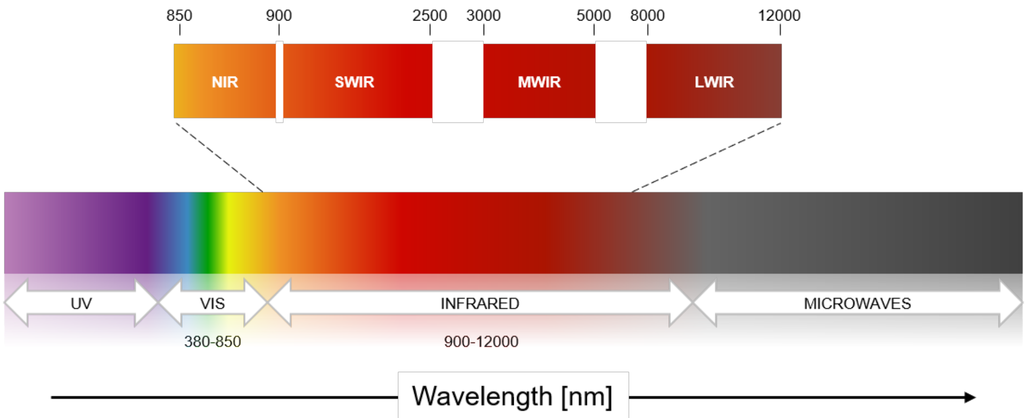


Figure 2.2: Infrared band [14]

Previously, the evolution of the different technologies up to the future networks based on the sixth generation has been discussed. The enabling frequencies for this technology are those in the THz and sub-Thz domain. The first standard related to the THz band and the sixth generation is 802.15.3d approved in 2017 [15]. This standard addresses wireless communications within the sub-THz band (between 253 GHz and 322 GHz).

This standard demonstrates that communications can indeed be carried out at such bands and, in addition, it identifies a number of applications that can be carried out with current electronics even if they are only restricted to point-to-point links, which reduces system complexity and interference.

While it is true that THz frequencies have high atmospheric losses, they are restricted to cover small areas. Although this does not satisfy all the applications expected for the sixth generation, communications based on these bands will provide a very high data rate. In order to carry out the relevant tests and applications in the THz range, a part of the spectrum, specifically 160 GHz, was freed up. Many bands could be used for future THz communications, even though the problem of interferences, especially in ground-to-orbit links, is still under study. Overall, the IEEE 802.15.3d-2017 standard collects specifications to mitigate interference problems and bottlenecks in communications. Although these conditions cannot be fulfilled, they will have to be solved to enable the THz band to be exploited in the future. Currently, advances and studies are being carried out in the 802.15 TAG THz and, in addition, progress is being found within the physical and MAC layers to find communications up to 100 GHz. In this way, the basis for future 6G communications can be established [15].

2.2 Channel

As regards channel characterization, in order to derive full benefit from the THz frequency band when implementing a communication system, it is necessary to put in place the appropriate channel models to achieve an improvement in spectral efficiency.

There is a need to study and develop new channel models for wireless communications in the THz band, since molecular absorption and channel losses, among others, affect the signal in a more significant degree. That is, communications at such high frequencies present some limitations especially in long distance scenarios, where the attenuation rate is rather high in comparison with conventional radio communications. For this reason, THz systems are envisioned to cover short range communications. In this project, an indoor communication will be carried out, and the fact of being placed in an indoor environment brings with it several issues to be considered[16]. In terms of propagation modeling, at frequencies higher than 100 GHz, SCM (Spatial Channel Model) models must be taken into account, in addition to propagation and molecular absorption analysis. As usual in this type of model, two cases should be considered when referring to a given communication: deterministic and stochastic modeling.

Within deterministic channel modeling, Ray-Tracing [1] is the most commonly used technique. This method can be applied to different static scenarios, such as offices, for example for both LOS (Line-Of-Sight) and NLOS (Non-Line-Of-Sight paths. Its functionality lies in the emission of rays at certain time intervals, which are eventually detected depending on the free space propagation [17].

On the other hand, the stochastic channel model is based on the collection of data for subsequent analysis of the channel. In most cases, these models are considerably simpler than deterministic models and require a smaller amount of resources. In this case, ray tracing simulations are required to obtain a stochastic model. In addition, both time and frequency domains are taken into account.

Furthermore, there are different situations in point-to-point communications that must be taken into account when developing a channel model. In other words, one can find a variety of scenarios, types of losses and methods when modeling the channel, as shown in Fig. 2.3, where a classification of the different types of channel model can be seen.

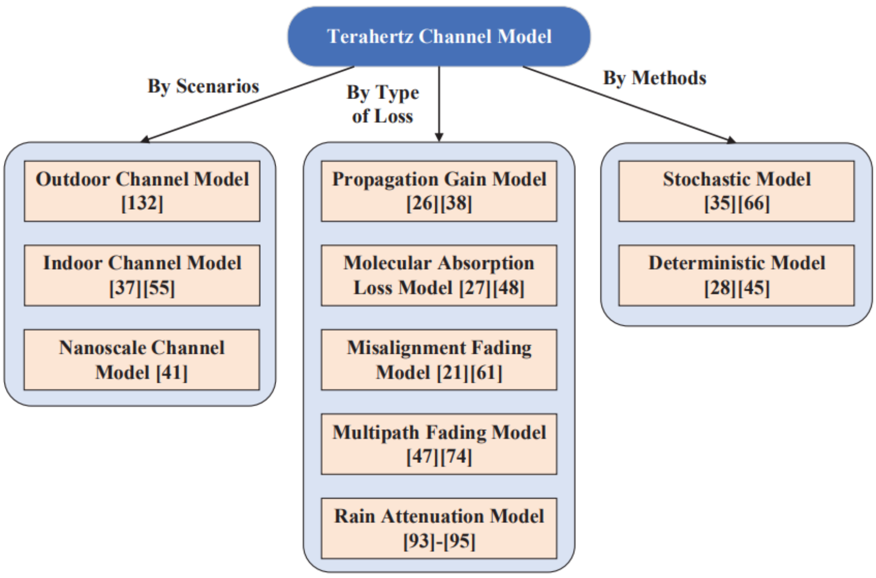


Figure 2.3: Channel model classification for THz band [16]

Considering all these factors, in the following sections a study of the main blocks to be considered regarding signal generation, as well as their channel characteristics, will be carried out.

2.2.1 Channel model

One of the most striking features in the field of nano-technology is its use in applications related to the monitoring of vital signs and the health sector. communication between these nano devices is carried out using frequencies between 0.1 and 10 THz, and therefore molecular absorption must be taken into account.

[1]The **Ray-Tracing** technique is merely a method used for the representation of electromagnetic propagation.

Normally, when talking about the channel and when designing a communication model, in this case in the THz band, the aim lies in obtaining an impulse response [2]. Therefore, the following paragraphs will discuss how to obtain the output of the system, along with the meaning of the terms of molecular absorption and transmittance, the latter referring to the proportion of the radiation able to propagate through the channel.

First of all, a study based on time domain will be performed. Fig. 2.4 shows a block diagram about a transmission system based on the latter premise. Furthermore, a further analysis of the results of this system for the THz band will be carried out following [18] for a better comprehension of the channel.

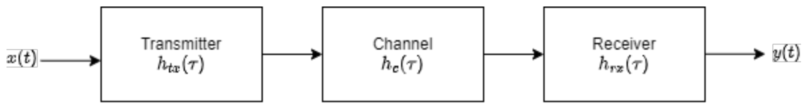


Figure 2.4: Transmission system

Prior to the study of the system, the concept of molecular absorption should be introduced, as this latter may be useful for further calculations. Basically, the molecular absorption consists of the absorption of light energy by a molecule that is exposed to light. This causes the molecule to transition from its ground state to its excited state.

Normally, the system is defined by a point-slope equation as defined in (2.1).

$$y = hx + n \tag{2.1}$$

Where h is defined as the channel coeficient and n is the Additive White Gaussian Noise. The channel coeficient is the result of considering the different channel losses and is described in (2.2).

$$h_c = h_p \cdot h_{molec} \cdot h_{mis} \cdot h_{whea} \cdot h_{multi} \tag{2.2}$$

Where h_p is the propagation gain and h_{molec} is the molecular absorption. Furthermore, h_{mis}, that is misalignment fading should also be considered in certain cases, as well as whether and multipath effects represented by h_{whea} and h_{multi}. Although, since an indoor communication is considered in this project, only propagation and molecular absorption losses will be contemplated.

Fig. 2.5 shows how the absorption coefficient value increases according to frequency within the THz domain. In this project, a range frequency between 0.1 and 0.3 THz will be considered. Hence, as can be seen in the picture, from 0.3 THz onwards the absorption coefficient increases exponentially, this fenomena has already been mentioned in previous sections and will represent a problem in terms of wave propagation.

[2] The impulse response is the response obtained at the output after an impulse has been previously introduced at the input of a system.

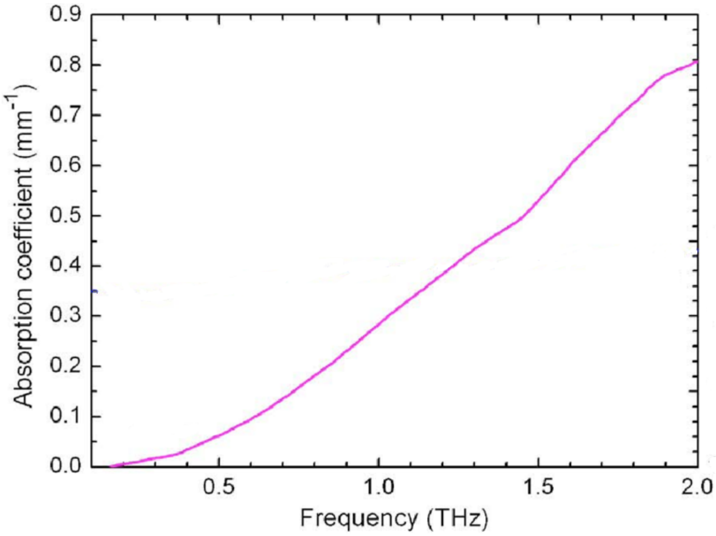


Figure 2.5: Wavelength propagation depending on the frequency

Based on the block diagram in the figure, there are three propagation effects caused by the transmitting antenna, the receiving antenna and the channel. The convolution of these three effects results in the impulse response defined in (2.3). Moreover, in (2.4), the received signal is obtained after a certain time. This is achieved by convolving the input signal with the impulse response.

$$h(\tau) = h_{tx}(\tau, z) * h_{rx}(\tau, z) * h_c(\tau, z) \tag{2.3}$$

$$y(t) = \int_{-\infty}^{\infty} h(\tau, z) \cdot x(t - \tau) dx \tag{2.4}$$

Considering the aforementioned considerations and due to the limitations regarding signal propagation, more exhaustive studies about different channel models should be carried out in order to establish THz-based technology in future communications. However, many studies have already been carried out theoretically and through simulations and most of them have been satisfactory, especially in indoor environments. Specifically, in [19] a study is carried out for different propagation models for frequencies higher than 100 GHz where it is concluded that for LOS scenarios there is hardly any difference between the different models, whilst for NLOS scenarios there is a significant difference between them mainly due to the reflected wave.

2.3 THz signal transmission

In this section two different approaches will be introduced as regards THz signal transmission.

2.3.1 All-electronic approach

Concerning waves propagating at frequencies belonging to the low THz band, in many cases these tend to share more radioelectric than optical properties due to their proximity to the millimeter band. For this reason, the all-electronics approach is the most suitable for wireless data transmission because of its previous experience in the millimeter band.

Using III-V and silicon technology, for carriers up to 300 GHz, many high-speed data transmissions have been carried out. For example, using the 120 GHz band it has been demonstrated that 10 Gbps can be achieved over a distance of 1 km. Moreover, for systems above 200 GHz millimeter-wave monolithic integrated circuits (MMICs) with InP and InGaAsP high electron mobility transistors (HEMT) as well as metamorphic HEMT are developed to generate and receive over 10 Gbps and can even reach 100 Gbps. Also, with silicon CMOS and SiGe BiCMOS heteroconjunction bipolar transistors (HBT) technology it has been demonstrated to reach 100 Gbps with 240 GHz or 300 GHz.

The generation and detection of high bandwidth signals above 300 GHz involves significantly greater challenges. Therefore, achieving high bandwidth together with high output power has not yet been demonstrated in the sub-millimeter region [13].

2.3.2 Photonic approach

Optical technologies are increasingly used in terms of wired communications. This has been seen over the last few decades with the replacement of coaxial cable with fiber optic deployments. This is due to the high bandwidth that can be achieved with optical communications, in addition to transmission speeds in the Tbps range. In addition, recent studies have shown that the high bandwidth properties of photonic technology can be used for RF applications [13].

On the other hand, with the discovery of UTC (Uni Traveling Carrier) type photodiodes, it has been possible to carry out transmissions above 200 GHz with satisfactory results. For example, a 100 Gbps multicarrier transmission was demonstrated for a frequency of 200 GHz using a laser-comb source [20] [13].

2.4 Photonic assisted THz signal generation

Generally speaking, in order to convert an optical signal to THz, a laser is used to initiate the heterodyning process of a signal, which is then modulated on a high speed photodiode, which takes the role of a mixer [21].

Signal generation operating in the THz range can be accomplished in different ways. In this work two systems will be studied and compared. The first one will employ two lasers shifted in frequency and the second one will use a single laser and a comb generator. However, only the first one will be simulated given its economic benefits and the fact that physically it would be a much more efficient and simpler circuit to implement.

2.4.1 Principle of operation

As mentioned above, the simplest way to generate a THz signal lies on using two lasers shifted in frequency, Fig. 2.6 shows a block diagram for THz wave generation using two lasers. In this case, a fixed laser and a variable laser are used. The frequency of the latter is adjusted in such a way that the frequency difference between the two lasers is the same as the one to be obtained at the output, in our case 0.3 THz (300 GHz). Normally, both lasers will be DML (Directly Modulated Laser) type, and the variable laser will introduce a signal at a frequency distance of 300 GHz.

Once both lasers have emitted the signal, these are combined using a 2x1 optical combiner and finally, the combined signal is modulated by a large bandwidth photodiode, which will convert the signal obtained from the lasers into current and, consequently, into the THz signal to be transmitted through an antenna to the receiver.

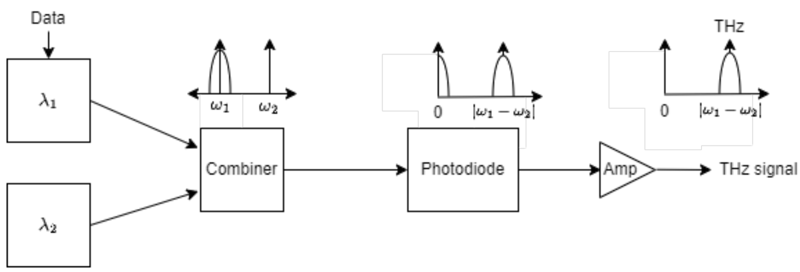


Figure 2.6: Simple scheme for photonic generation of THz signals using two lasers

In Fig. 2.6, one of the simplest circuits to generate a THz signal can be observed, this circuit is based on optical heterodyne photomixing. First, two optical signals at different angular frequencies, ω_1 and ω_2, are generated by semiconductor lasers. One of them is amplitude and phase modulated while the other is simply a carrier. Both signals can be expressed as in (2.5) and (2.6) [13].

$$E_1(t) = A_1\left(I + jQ\right) \cdot e^{-j(\omega_1 t + \varphi_1)} \tag{2.5}$$

$$E_2(t) = A_2 \cdot e^{-j(\omega_2 t + \varphi_2)} \tag{2.6}$$

Where I and Q refer to the orthogonally modulated components. On the other hand, A_1 and φ_1 correspond to the amplitude and phase, respectively, of the signal. While A_2 and φ_2 are the amplitude and phase of the carrier signal. Therefore, these two signals are combined and passed through the UTC-photodiode where the conversion efficiency η_{T_x} [3] is considered and the output is obtained as in (2.7).

[3] The conversion efficiency of a photodiode is a measure of how efficiently the device converts the incident light into an electric current. It denotes the ratio of the current generated by the photodiode and the optical power incident on it.

$$E_{output} = \eta_{T_x} \cdot [E_1(t) + jE_2(t)]^2 = E_{baseband}(t) + E_{THz}(t) \tag{2.7}$$

As can be seen in (2.7), at the output of the photodiode two components are generated, the first one being a baseband component and the other one an RF component in the THz band centered in $\omega_1 - \omega_2$. It is important to mention that, in most cases transmitter include a filtering process which, together with the antenna reach an output signal that only contains the THz component. This result can be seen in (2.8).

$$E_{THz}(t) = A_{THz}\left[I \cdot sin\left(\omega_{THz}(t) + \varphi_{THz}\right) + Q \cdot cos\left(\omega_{THz}(t) + \varphi_{THz}(t)\right)\right] \tag{2.8}$$

Knowing that the amplitude can be defined as $A_{THz} = 2\eta_{T_x} A_1 A_2$ and the phase as $\varphi_{THz} = \varphi_1 - \varphi_2$. As can be seen in (2.8) the linearity of the in-phase and quadrature components are mantained despite the nonlinearity of the heterodyne photodiode. And so, the output signal can be shifted in frequency and no distorsion would be spotted [13].

The photodiode is the most restrictive element, since the higher the frequency, the greater the attenuation of its response. Therefore, at frequencies around THz, very low output powers are achieved. To illustrate this on the basis of real data, one of the highest levels of power output obtained was 1 mW. It was achieved by combining two uni-traveling carrier (UTC) photodiodes, which have a higher bandwidth. Notwithstanding, those UTC photodiodes operate ahead of the -3 dB bandwidth when the frequency is higher than 200 GHz, that is 2 THz. Thus, an amplification process will be needed to achieve substantially higher output power.

Considering the aforementioned, communications in the THz range would not be possible at very long distances, so it would be unthinkable at present to imagine a mobile network operating at such frequencies, unless a very directive antenna is used. Therefore, communications at these frequency ranges could have indoor and confined space applications.

2.4.2 Transmitter Components

Laser

Lasers are the most important part of the system as they are responsible for the generation of the optical signal. There is a wide variety of such, notwithstanding in this case two non-coherent lasers are considered, which will be shifted a certain frequency. Three types of lasers have been chosen for this project, the first one is a direct modulated laser (DML) [22] with a 4 GHz bandwidth. On the other hand, a DFB laser whose bandwidth is 32 GHz and, finally, a tunable laser. The fact of using a tunable laser allows to experiment with more frequency ranges to get a better signal tuning.

The parameters of the fixed laser (DML) can be seen in Table 2.1. This laser has been chosen given that the bandwidth in which it operates is relatively low and, consequently, cost-effective. Moreover, it operates at the desired wavelength, i.e. 1550 nm. Fig. 2.7 shows a picture of the laser.

Parameter	Value
Model	DFB-1550-DM-4
Bandwidth	4 GHz
Center Wavelength range	1547 nm - 1550 nm
Operating current	250 mA
Threshold current	0.15 mA
Forward voltage	1.6 V
Output power	20 mW

Tabla 2.1: DML technical specifications

Figure 2.7: 4 GHz DML by Optilab [23]

Regarding the variable laser, two options have been considered, the first one is a DFB laser at a fixed bandwidth of 32 GHz, whose characteristics can be seen in Table. 2.2. A laser with a higher bandwidth than the fixed laser has been chosen in order to obtain a signal in the order of THz by subsequently using the photodiode and the signal amplification phase. This laser has a very similar structure to the previous one, which is shown in Fig. 2.8.

Parameter	Value
Model	DFB-1550-EAM-32
Bandwidth	32 GHz
Operating Wavelength range	1538 nm+/-10nm
Operating current	100 mA
Threshold current	35 mA
Forward voltage	2 V
Output power	5 dBm

Tabla 2.2: DFB laser technical specifications

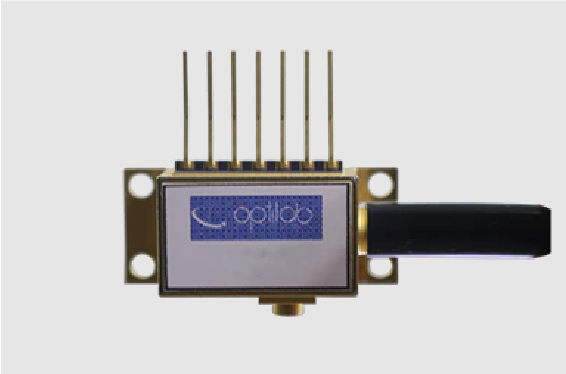


Figure 2.8: 32 GHz DFB laser by Optilab [23]

The second option in terms of variable laser is a tunable laser, which would enable testing for different frequencies and adjusting it to the most convenient one. This laser is capable of operating at THz frequencies, as shown in Table. 2.3 in addition to other parameters of interest. On the other hand, Fig. 2.9, shows a representation of the device, in this case it is not a reduced size sample but a heavier and larger device.

Parameter	Value
Model	TWL-C-B
Base Frequency Range	196.1 THz - 191.5 THz
Wavelength Range	1530 nm - 1565 nm
Wavelength Accuracy	± 1.5 GHz
Power Supply	80 - 240 V
Power Consumption	80 W
Optical Connectors	PM Narrow Key, FC/APC
Output power	20 mW
Output Power Adjustment	6 dBm to max.
Size	250 mm (W) x 300 mm (L) x 100 mm (H)

Tabla 2.3: C-Band Tunable laser technical specifications

Figure 2.9: Tunable laser by Optilab [23]

Combiner

The signal generated by both lasers is combined into a single signal for transmission, and several techniques and devices can be used. One of the most common techniques is to use beam splitters, which split the optical signal from each laser and combine it into a single output. On the other hand, optical couplers can also be employed, which merely combine the signal from both lasers into one signal, which is a much simpler process. In this project, the lasers are incoherent, so the use of an optical coupler could be much more efficient since it allows to mix both signals in the amplitude domain and, in this way, obtain a signal that shares characteristics of both lasers [24].

Therefore, for this project and as can be seen in Table. 2.4, a basic 2x1 coupler of 50:50 ratio has been considered, with a wavelength of 1550 nm. A representation of this coupler can be seen in Fig. 2.10.

Parameter	Value
Model	TW1550R5F1
Coupling Ratio	50:50
Center Wavelength	1550 nm
Max. Power Level	1 W with connectors or bare fiber 5 W spliced
Fiber Type	SMF-28
Connectors	2.0 mm Narrow Key FC/PC

Tabla 2.4: Wideband Fiber Optical Coupler technical specifications

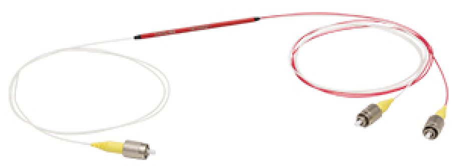


Figure 2.10: 1x2 coupler by Thorlabs [25]

Photodiode

Fundamentally, a photodiode is a semiconductor element used to convert a light signal into an electric current. Typically, for this type of communication at such high frequencies, a UTC type photodiode should be used, which has already been introduced in previous sections. The problem is that very few suppliers provide devices that can cover such high bandwidths, most of them reach up to 40 GHz at most. Therefore, in some cases a PIN photodetector can also be considered as an alternative.

Two proposals have been considered for this project. The first one, is a UTC photodiode manufactured by NTT Electronics. This photodiode is capable of reaching frequencies even higher than 300 GHz, and was first implemented by the Japanese company Nippon Telegraph and Telephone Corporation [26]. The second proposal is a photodetector implemented by Optilabs [23] that reaches 100 GHz.

As mentioned above, in an optimal case, a UTC-Photodiode would be used for this type of communication, notwithstanding this type of device is difficult to find since it has to be implemented especially for each order, and not all companies work with this type of technology. NTT Electronics has a license from Nippon Telegraph and Telephone Corporation to implement this type of photodiode. They are currently studying and developing an improvement in the efficiency of the connectors, which used to be W1 (1 mm connector) and 0.8 mm connectors. In Table. 2.5, more features about this this UTC-photodiode can be seen, additionally a picture of such photodiode can be observed in Fig. 2.11.

Parameter	Value
Model	IOD-UPD-20001
f_{3dB} Bandwidth	90 GHz
DC Responsivity	0.4 A/W
Operation Wavelength	1550 nm 1300 nm
Max. photocurrent	<10 mA
DC bias voltage	1 $\sim$3V
Dark current	<1 μA

Tabla 2.5: UTC-Photodiode technical specifications

Figure 2.11: UTC-Photodiode by NTT Electronics [27]

Although this photodiode operates in the sub-THz band. This is the highest that could be obtained from one of the only companies that manufactures photodiodes of this type.

On the other hand, a PIN photodetector has been considered. this device fulfills the same function as a photodiode, which consists in the convertion of an optical signal into an electrical one.

In this case, a 100 GHz PIN photodetector has been employed to reach the desired THz band, which reaches the wavelength of 1550 nm, as well as other characteristics that can be observed in Table 2.6. Furthermore, its representation can be seen in Fig. 2.12.

Parameter	Value
Model	XPDV4121R
f_{3dB} Cut-Off current	100 GHz
DC Responsivity	0.6 A/W
Operation Wavelength	1550 nm
DC bias voltage	2V
Dark current	5 nA

Tabla 2.6: 100 GHz photodetector technical specifications

Figure 2.12: 100 GHz photodetector by Finisar [28]

Antennas

Antennas operating in the terahertz band are characterized by a very small size, in addition to a high data rate and a wide bandwidth. However, they also present a series of limitations, the most restrictive is the high attenuation loss as well as the lack of precision when manufacturing them due to their small size. Moreover, they are a fundamental part of any wireless system and in the case of THz band communications, antennas were developed rapidly since their inception.

A first communication at 0.12 THz was carried out about the year 2004 and in only 10 years after this first communication, the first communication system operating at 0.3 THz was assembled. As mentioned above, the fact of working in an intermediate space between millimeter waves and visible light means that a combination of both worlds is required in terms of signal generation.

Therefore, the photoelectric conversion is included and follows different dynamics depending on the scenario:

1. Indoor scenario: Uni-traveling carrier photodiode and planar slot antenna as well as silicon lens are used as transmitters.

2. Outdoor scenario: Gaussian optical lens and gains of at least 50 dBi should be used in order to reduce or even banish atmospheric loss.

Antennas for THz communications need to be further investigated in order to reach a substantial application in our society as they remain at a rather early stage of exploration. Although array antennas have been proved to be highly efficient in terms of indoor wireless communications.

The surface of the antennas at THz has to be rough because the wavelength is significantly shorter than that of the well-known millimeter waves, where a smooth surface predominates. This feature leads to a decrease in performance [29].

Two THz antenna manufacturing processes are listed below:

1. 3D printing technology is used for waveguide, horn antennas or THz lens manufacturing. It features high precision and low cost.

2. For the manufacture of more complex antennas, it is necessary to resort to the so-called Focused ion beam technology.

In this project, a horn type antenna will be considered whose characteristics can be seen in Table. 2.7, given its rather basic structure and good performance. In addition, these antennas are the most commonly used type in the field of THz band communications. This antenna is manufactured by TeraSense, a company dedicated to the manufacture of terahertz equipment fot THz imaging, and will operate at 300 GHz [30]. A picture of the antenna is shown in Fig. 2.13.

Parameter	**Value**
Frequency range	280 GHz $\sim$290 GHz
Beam shape	Gaussian
Gain	24 dB
Mounting option	WR-3.4
Weight	0.02 Kg
Size	43 x 19 mm

Tabla 2.7: 300 GHz horn antenna technical specifications

Figure 2.13: Terasense high gain horn antenna operating at 300 GHz [30]

Amplifier

This stage is crucial to amplify the power of the signal coming from the photodiode, since the signal generated by these type of devices is usually weak. On the other hand, it compensates for signal losses from the lasers through the system, in addition to compensating for added thermal noise or noise from the photodiode. This amplifier has a Gain level of 10 dB and is able to operate within the THz at a frequency of 100 GHz and beyond. Other parameters can be seen in Table 2.8, Moreover Fig. 2.14 shows a representation of the amplifier.

Parameter	Value
Bandwidth	$\geq$ 100 GHz
Gain	10 dB
Power Consumption	2 W
Voltage at RF Output	$\pm$ 5 V
Maximum RF Input	4 dBm 1 V
Input Connector	1.0 mm female
Output Connector	1.0 mm male
Dimensions	30 x 54.7 x 31.8 mm

Tabla 2.8: RF amplifier technical specifications

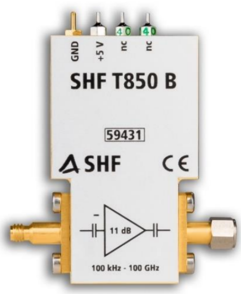


Figure 2.14: RF 100 GHz amplifier by SHF [31]

2.4.3 Receiver

Both transmitters and receivers can be classified into two groups, given that, as mentioned above, THz frequencies are at an intermediate point between visible light and microwave waves. Therefore, the frequencies are too high for today's electronic technology and the photon energies are too low for lasers and detectors. Concerning the receiver, several techniques can be carried out, one of them is the well-known direct detection which can be accomplished by using a Schottky diode. On the other hand, heterodyne receivers are also widely used, and represent another alternative to direct detection. In this latter case, a local oscillator and a signal filtering process would be needed, this technique provides higher sensitivity and bandwidth for intermediate frequencies [32].

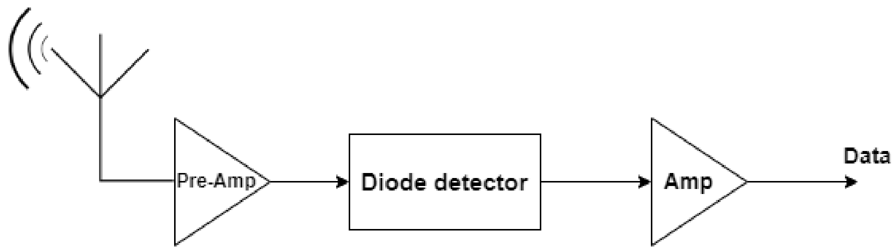


Figure 2.15: Receiver block diagram

The amplifier comprises two types depending on where it is placed in the system: power amplifier or low noise amplifier. The former is normally placed in the first stage of the receiver, while the latter is the last element and is directly attached to the antenna.

The manufacture of these solid state amplifiers is expensive, which is why there is a tendency to focus further on the development of mixers and multipliers based on Shottky devices [33].

2.4.4 Receiver components

Schottky Barrier Diode

Regarding the components and as mentioned above, Schottky Barrier Diodes share optimal characeristics for this type of communications in terms of receiving block. Therefore, a Schottky barrier diode implemented by SHF [31]. This diode operates within the W Band, that is, sub-THz band, and its parameters can be seen in Table. 2.9

Parameter	Value
Model	MADZ-011002
Intrinsic Cutoff Frequency	1 THz
Extrinsic Cutoff Frequency	62 GHz
Forward Voltage at 1 mA	10.7 V
SSB Noise Figure	6.5 dB
Series Resistance	3.35 Ω

Tabla 2.9: Schottky Barrier Diode technical specifications

Low Noise Amplifier

On the other hand, as regards the amplifiers, there are reasons to believe that pre-amplifiers with low noise figure are a good and effective option, since they are of great interest when the sensitivity needs to be increased. Therefore, three types of LNAs have been considered for different bandwidthe, whose characteristics can be seen in Table. 2.10. This devices has been implemented by Virginia Diodes Inc. [34] and its represetnation can be seen in Fig. 2.16.

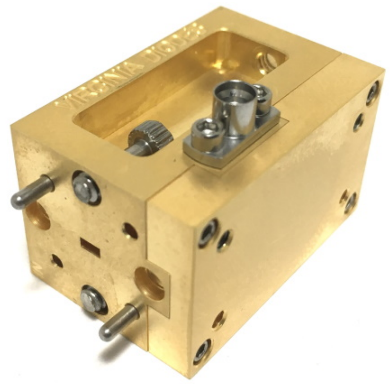


Figure 2.16: Low Noise Amplifier by VDI [34]

Parameter	WR8.0AMP-LN	WR6.5AMP-LN	WR5.1AMP-LN
Amplifier Band	(95-130) GHz	(110-170) GHz	(140-220) GHz
Waveguide Intereface	WR-8.0	WR-6.5	WR-5.1
Gain	18 dB	20 dB	20 dB
Noise Figure	4.5 dB	6.5 dB	6 dB
Maximum RF Input Power	-20 dBm	-20 dBm	-20 dBm
Bias Connector	SMP (m)	SMP (m)	SMP (m)
Current Draw	∼100 mA	∼50 mA	∼20 mA

Tabla 2.10: Low Noise Amplifier technical specifications

Limitting amplifier

Eventually, after the Schottky diode a limiting amplifier will be used to protect other circuits and devices subsequent to the barrier diode. For this project a transimpedance amplifier manufactured by Micram will be used.

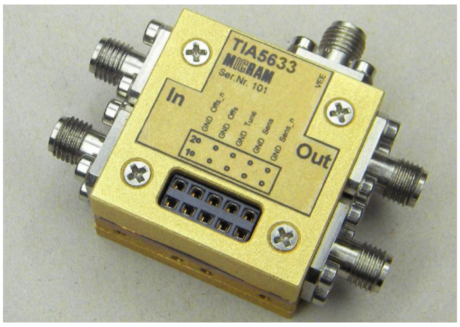


Figure 2.17: Limiting amplifier by Micram

Parameter	Value
Model	TIA5633
Power Supply	(-3.1,-3.5 V)
Current Consumption	75 mA @ -3.3 V
Gain	$\sim$38 dB
Cut-off Frequency	35 GHz
f_T/f_{max}	170/250 GHz

Tabla 2.11: Limiting amplifier technical specifications

2.4.5 Other photonic approach using comb generator

Within the THz frequency domain a multitude of bandwidths can be considered. There is a standard that considers a bandwidth of 73 GHz, from 252 GHz to 325 GHz, the IEEE 802.15 TG3d. However, optical systems such as typical commercial modulators used in this type of communications are not sufficient to overcome such a high bandwidth. In addition, the fact that an entire bandwidth is dedicated to a single user would not be a realistic case, rather, it would be efficient to consider a multiband signal structure, i.e. the truncation of spectrum into different bands for different users.

Previously, a circuit based on the generation of two signals from two different lasers has been defined. This type of configuration, in most cases, does not provide the best results due to the incoherence of the lasers, i.e. the fact that the signals are not synchronized in time, apart from what has been exposed in the previous paragraph. Thus, the idea of using an optical frequency comb generator is very attractive because it reduces the signal to noise ratio and increases the frequency accuracy of the signals. Fig. 2.18 illustrates an alternative scheme which involves the use of a single laser, in this case a frequency comb generator is used to split the signal into several tones. Subsequently, a filter is used to obtain two separate tones at the frequency of interest and then the signal is modulated using a modulator, which can be for example a Mach-Zehnder, and a photodiode which, as mentioned in previous sections, must be of large badwidth or UTC type. Finally, the signal is amplified and transmitted to the antenna.

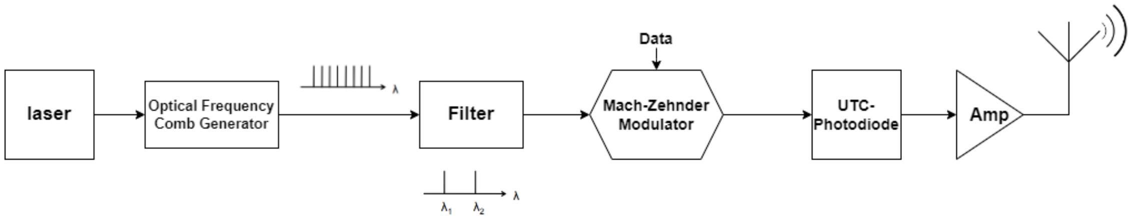


Figure 2.18: Simple scheme for photonic generation of THz signals using comb generator

This approach has more stages and components than the initial scheme considered using two lasers, therefore the general complexity of the system would increase, especially due to the use of a comb generator.

2.5 Applications

In this section, a few applications of future THz communications will be carried out, including different scenarios such as space communication networks or even wireless mobile communications, taking into acount the limitations the THz band presents.

As mentioned in previous sections, the most restrictive limitation is directly related to the transmission distance, and so most applications are thought to cover especially indoor communications.

2.5.1 Wireless Mobile Communications

As regards wireless communication, three types of area networks can be established for indoor scenarios: WPAN (Wireless Personal Area Network), WLAN (Wireless Local Area Network) as well as mobile networks.

Grosso modo, systems based on WPAN offer services to devices whilst those based on WLAN offer services to places (E.g., libraries). In this latter scenario, users connect to an AP (Access Point) and it is important to mention that, those operating in the THz band are able to send information to multiple users in different directions at the same time by using array antennas, as specified in previous sections. The upgrade of these APs could result in a series of improvements in current technologies, such as video quality in holographic videoconferencing or even VR (Virtual Reality) in which the user experience can be enhanced comparing to current non-wireless systems.

As regards the last scenario, Communications based on the THz band are used for indoor mobile networks to offer high-speed data to both static and dinamic (or mobile) users [33].

2.5.2 Secure communication

One of the most striking features of THz links, besides their high capacity, lies in the fact that highly directional beams can be obtained using microscale antennas. Altogether, these features provide the basis for secure communications. This is due to the fact that the transmission cannot be intercepted or even noticed, only within the beam. In fact, in military the use of narrow beams to protect signals and information is a common practice. And now, this has been extended to civil use as well [35].

2.5.3 Space Communication Networks

As mentioned in previous sections, the so-called spectrum saturation results in an increasing need for new bands, even in space communications. At this point, one might doubt the effectiveness of using signals in the THz band due to its high attenuation. The point is that such attenuation is purely due to the atmosphere, so space communications in the free space domain do not suffer from it. In fact, ground-to-satellite communication has less attenuation compared to other communication systems such as lasers.

In most cases, the use of THz-band based systems simplifies the complexity of the well-known and established Ku- or Ka-band technology for space communications.

Although the THz band is still a more theoretical than practical concept and complete communication systems have not yet been established, some of its technology has been implemented in several systems. NASA during the last two decades has included in its satellites technology such as sensors to carry out space communications [33].

2.5.4 Small-scale devices connection

At this point, it is a well-known fact that THz-based systems require very small equipment. This premise could be expanded to the field of nano-robots, where having the ability to recreate micro transmitters and receivers could be of great advantage over the precarious technology used by such robots. The aim is to build a micro-robot network capable of accomplishing tasks beneficial to society [35].

2.5.5 Biomedicine and imaging

The penetration capacity of THz waves is remarkably high, as expected. Therefore, in medical fields, systems based on frequencies in this range have been widely exploited at an experimental level and several significant scientific findings have been made. One of the most important is the experiment carried out by Hu and Fitzgerald in which it is demonstrated that through the use of THz signals, these are able to differentiate different types of tissues, with this experiment it was corroborated that these frequencies could indeed be used in the clinical area. Furthermore, they are also capable of distinguishing between white and gray matter of the brain. An example of such can be found in [32]

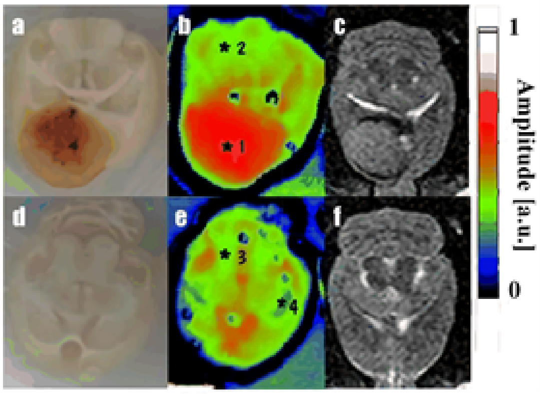


Figure 2.19: Comparison between THz image and conventional image of a brain [32]

As observed in Fig. 2.19 it can be concluded that THz waves offer images of different tissues very similar to those obtained at other more harmful frequencies and are therefore a good resource for the medical field and detection of pathological diseases.

2.5.6 Atmosphere monitoring

In [36], a study is carried out on the detection and classification of vapor particles in closed environments by means of smart reflective surfaces incorporated in THz systems.

Throughout this document the fact that THz signals present degradations has been mentioned in several occasions, on the one hand because of the fact that they operate at very high frequencies and therefore there is an atmospheric attenuation and, on the other hand, because of phenomena originated in the environment itself, such as clouds of aerosol particles that condense and cause a degradation of the signal. Nevertheless, it has been concluded that THz signals could be useful to carry out particle detection tasks in a confined environment. One of the most commonly contemplated cases, and the one used as a basis for the experiment described above, is the case of a person coughing and therefore the detection of the particles ejected from the mouth.

Many research studies have been carried out on the detection of human activity in order to find out if there may be an increase in signal degradation. The aim is to be able to detect the source of degradation, to classify it and, based on that, model the propagation of the signal to reduce its degradation. Fig. 2.20 and Fig. 2.21 shows an approach of signal detection of a person coughing in a room.

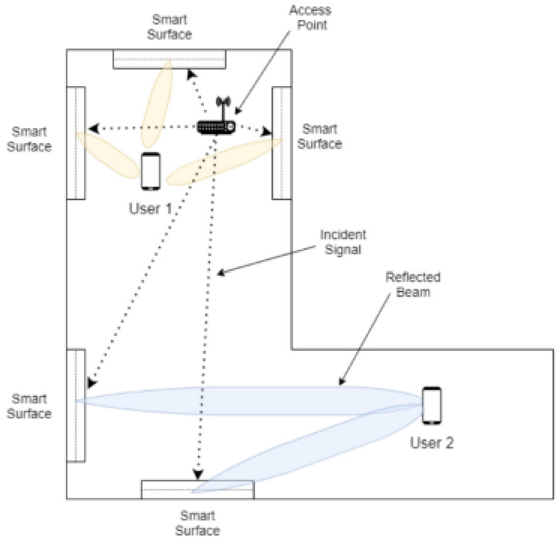


Figure 2.20: Smart surfaces system [36]

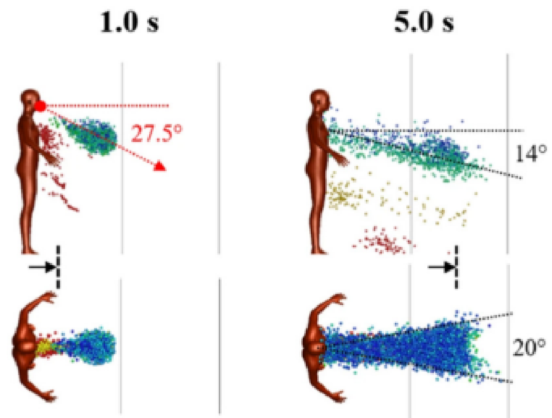


Figure 2.21: Cough evolution in time domain [36]

The first step is to detect aerosol clouds in an enclosed environment by comparing the received power and attenuation between a scenario full of clouds and another one with none. Once the detection has been carried out, the classification takes place, this latter is carried out by means of a linear regression model.

Chapter 3

Design of a train - earth system

In this chapter, a study on conventional train to earth and cab to cab communications for rail vehicles will be carried out. After that, the design of a train-earth communication system based on the THz band will be executed and, eventually, compared to the conventional one. For futher information about the advantages of using such a high frequency, the simulation of the previously mentioned sytem will be accomplished.

3.1 Railway vehicles communications

Communications in rail vehicles may vary depending on the client's requirements as well as on the supplier who develops the system. However, cab to cab communications are usually executed by means of an ethernet ring as shown in Fig. 3.1, which also interconnects other Passenger Information System devices such as intercoms and displays. Moreover, a physical line connecting both cabs apart from the intercoms is also considered in case of a network outage.

Notwithstanding, communications between the vehicle and the central station are usually carried out by radio signals as a train-earth communication. In this case, it is necessary to carry out a study for the correct positioning of the antennas on the vehicle. In this case, the communication is controlled by a GSM terminal (Global System for Mobile Communications), this device is connected to the train, which uses a GSMR system (Global System for Mobile Communications - Railway) specially adapted for railway vehicle communications in order to avoid the problematic of interferences in GSM networks.

In the first case, the communication is based on VoIP (Voice over IP) and SIP (Session Initiation Protocol) protocols. The SIP protocol is used to establish the connection, but once set up the communication is carried out using the RTP (Real-time Transport Protocol) protocol.

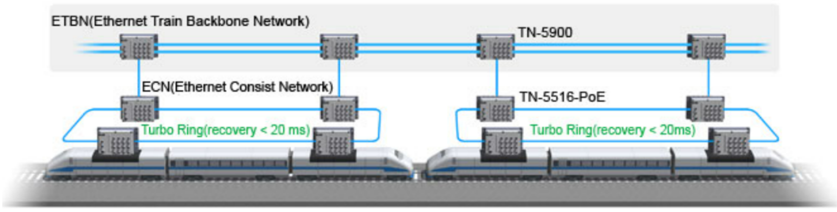


Figure 3.1: Ethernet ring in rail vehicles [37]

A priori, the idea of a cab to cab system based on the THz band had been considered. However, this system would not be as efficient as the already implemented one (Ethernet ring), since all the connections inside the train are carried out through this ring, therefore an alternative system should be implemented only for cab to cab communication, which would result in an increase of cost and weight inside the vehicle.

3.2 Video-surveillance recorders

A potential application for the use of THz in on-board communications in railway vehicles concerns downloading information from CCTV recorders.

When the vehicle arrives at the garage, all the videos belonging to the video surveillance system are usually downloaded via a local WiFi network. This is often a problem due to the high capacity occupied by these recordings and the rather standard speed of the network. Therefore, a system based on high frequencies could be an interesting application to alleviate the problems of download speeds. In Fig. 3.2, a representation of how a recorder gathers the different data from different CCTVV devices is shown, this data is then processed and sent by a router to the command for rail server, where the information can be analized from different technologies such as computers.

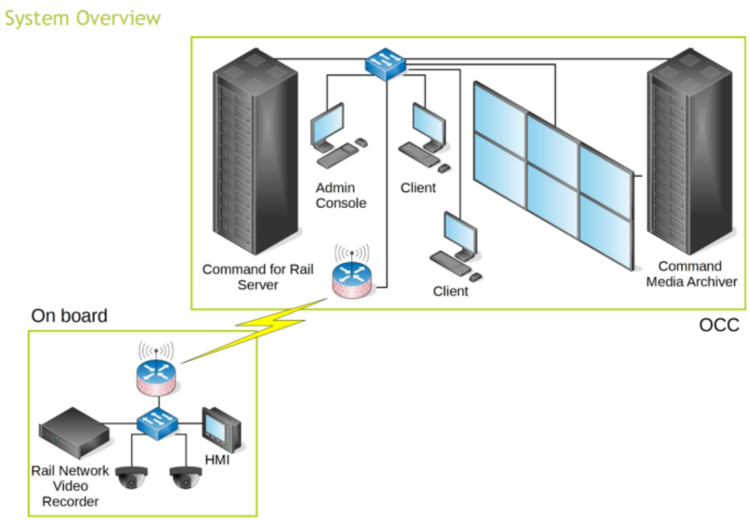


Figure 3.2: CCTV system overview [38]

Therefore, the application of this project consists of implementing a communication system in the THz band as discussed in previous chapters with the aim of downloading video surveillance images and videos from rail vehicles in a much more efficient way than the system already in use.

Commonly, the complete recorder typically used has a capacity of 5.Tb for a 30-day recording. This is about 195 Gb of storage per day, or rather the capacity that should be transferred from train to ground on a daily basis. In addition, on average trains are in the garage for about 5 hours. Also, it should be taken into account that very often more than one train is in the garage at a time.

3.3 Design of a THz communication based on a photonic approach

For the simulation of the environment, Optisystem software from Optiwave [8] has been employed, a tool used to design and simulate optical links in the transmission layer. This software has several component libraries whose parameters can be adjusted to obtain results as close as possible to those expected with real components.

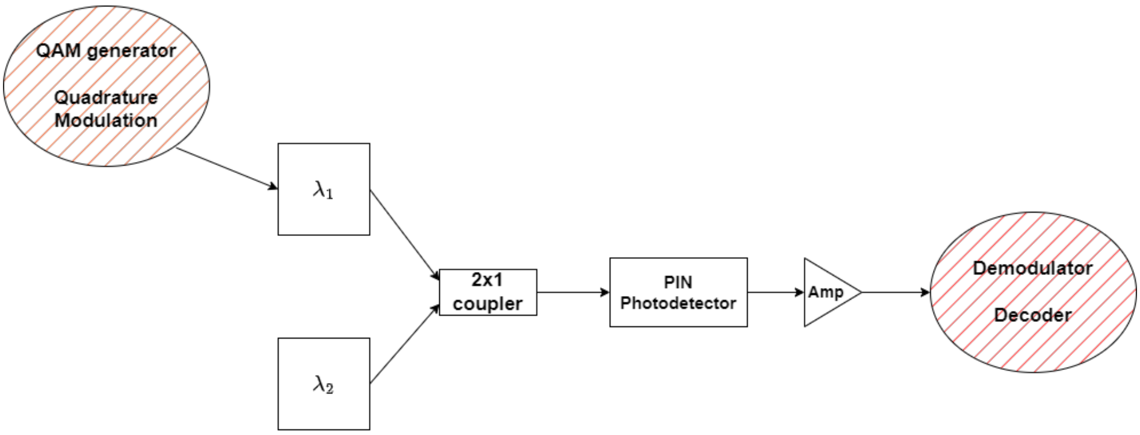


Figure 3.3: System overview using Optisystem

Therefore, Fig. 3.3 shows the scheme considered for the simulation of a system based on the combination described in section 2.4.1. As regards the main components, a DML and a CW type laser have respectively been considered for both the fixed and variable lasers, a priori both share the same characteristics except for the frequency which will have a difference equal to the frequency expected to be obtained at the output, in this case three freqencies have been studied: 100 GHz, 200 GHz and 300 GHz, so that the fixed laser will always be at 193.1 THz, while the variable laser will have a frequency of 193.2 THz, 193.3 THz and 193.4 THz. The first step consists of generating a QPSK signal, which is then modulated and sent to the fixed laser. While the variable laser merely generates a cw signal.

Subsequently, the signal from both lasers is combined using a 2x1 coupler, so that the representation of both signals separated at the considered frequency is obtained. The combined signal then passes through the photodiode, in this case a PIN photodetector. Finally, the signal is amplified and the output constellation of the signal can be observed after a demodulation process.

Fig. 3.4 shows the circuit employed using the Optisystem [8]. In the figure, there is a generator block directly connected to the fixed laser. On the other hand, there is the system initially designed with two lasers and, finally, the signal demodulator block to evaluate the efficiency of the signal and the system itself. Notwithstanding, the study will only focus on the circuit module.

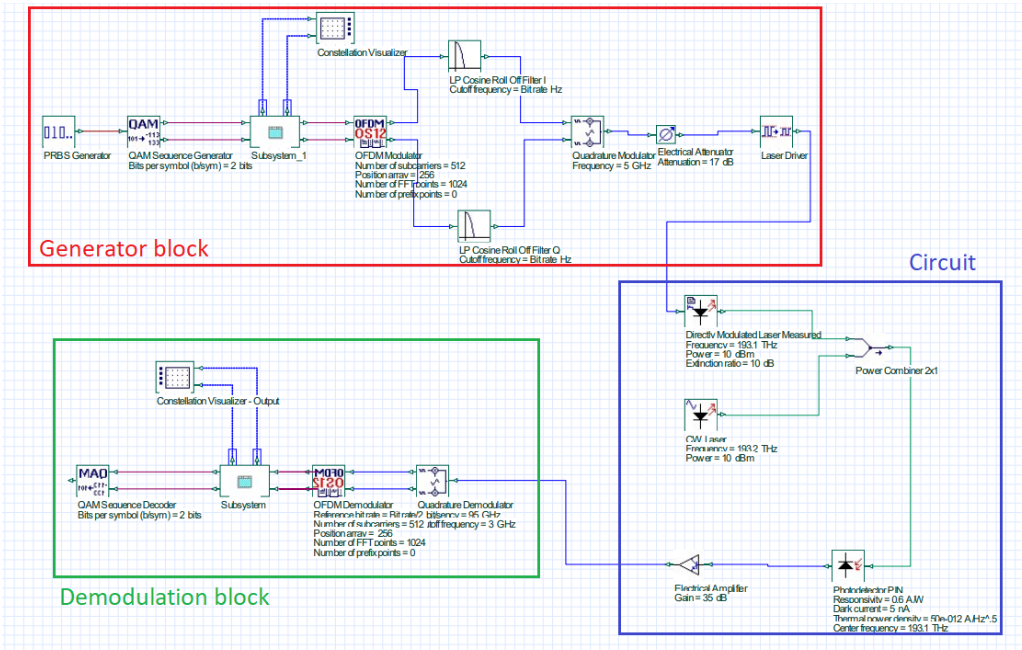


Figure 3.4: System overview using Optisystem

In first instance, and as shown in Fig. 3.5, a QPSK signal is generated. This signal is then modulated by OFDM with 512 subcarriers. The modulation results in two components in phase and quadrature, which as can be seen are filtered by an LP cosine filter. This filter helps to prevent interference between adjacent subcarriers. Finally, both signals are modulated in quadrature with an intermediate frequency of 5 GHz.

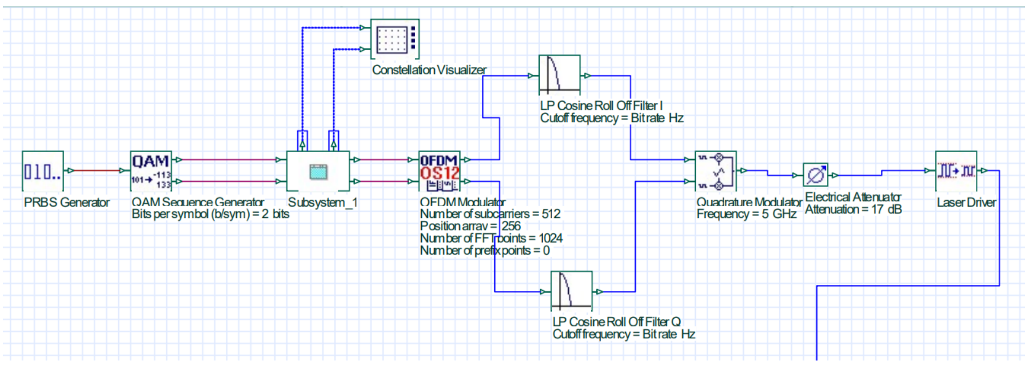


Figure 3.5: Generator block

Regarding the circuit block, Fig. 3.6 shows the different equipment corresponding to the circuit introduced in Fig. 2.6 in the previous chapter.

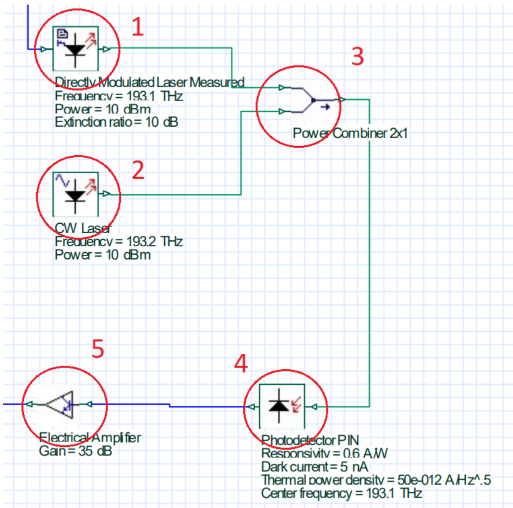


Figure 3.6: Scheme overview using Optisystem

In (1) there is a fixed DML laser at 193.1 THz, whose characteristics can be seen in Table. 3.1, and in (2) a variable CW laser, whose characteristics are shown in Table. 3.2

Parameter	Value
Frequency	193.1 THz
Threshold current	21 mA
Slope efficiency	0.4 W/A
RIN	-155 dB/Hz
Linewidth	10 KHz
Noise bandwidth	1 THz

Tabla 3.1: DML technical specifications in simulator

Parameter	Value
Frequency	193.2 THz
Power	5.299 dBm
Linewidth	10 KHz

Tabla 3.2: CW laser technical specifications in simulator

The signals generated by both lasers are combined in (3) where a 2x1 coupler is located, the parameters of such can be seen in Table. 3.3.

Parameter	Value
Loss	0 dB

Tabla 3.3: Combiner technical specifications in simulator

Finally, the signal passes through the PIN photodetector in (4) and is amplified in (5), whose characteristics can be found in Table. 3.4 and Table. 3.5, respectively.

Parameter	Value
Responsivity	0.5 A/W
Dark current	5 mA
Thermal power density	$50{\cdot}10^{-12}$ A/Hz^5
Center frequency	193.1 THz
Modulator bandwidth	2 GHz

Tabla 3.4: PIN photodetector technical specifications in simulator

Parameter	Value
Gain	35 dB
Noise power spectral density	-60 dBm/Hz

Tabla 3.5: Amplifier technical specifications in simulator

The main objective consists in determining the parameters that provide the best signal level at the output. Thus, it is essential to evaluate the EVM (Error Vector Magnitude) value at the output of the transmission system. This value in optical communications denotes the accuracy of how closely the transmitted signal matches the original reference signal, and is used as a measure of the quality of the transmitted signal in digital modulation systems. Fig. 3.7 shows a part of the demodulation module, the EVM values can be determined by means of the constellation visualizer.

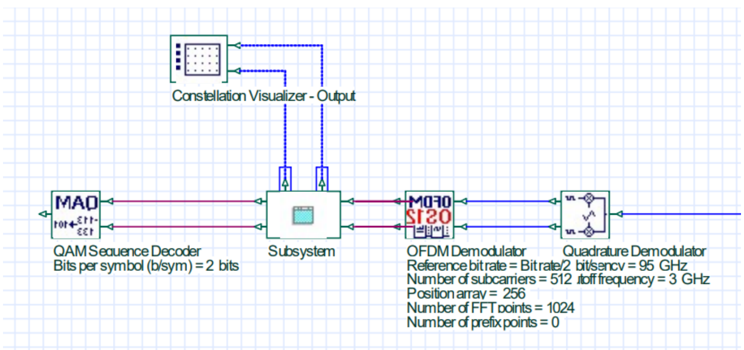


Figure 3.7: Overview of the output constellation visualizer

In this block the demodulation of the signal obtained at the end of the system is carried out. In the generator block, a QPSK signal modulated by OFDM had been generated, the same procedure takes place in this module using OFDM but in reverse. First, the signal obtained is demodulated by a quadrature demodulator to obtain two components in phase and quadrature which in turn are demodulated by OFDM and, finally, the QPSK signal is generated and can be observed by means of a constellation visualizer. In the quadrature demodulator, it can be seen that the frequency used is 95 GHz, this is adjusted to the frequency used in the circuit. That is, if the signal of the lasers is separated by 100 GHz, this value will be 95 GHz. But, if a 200 GHz or 300 GHz separation is used, this value will be of 195 and 295 GHz, respectively.

After determining the optical characteristics for the circuit, the different components will be configured and the evolution of the signal along the system will be observed graphically.

3.4 Simulation of a THz system using two lasers

3.4.1 Proof of concept

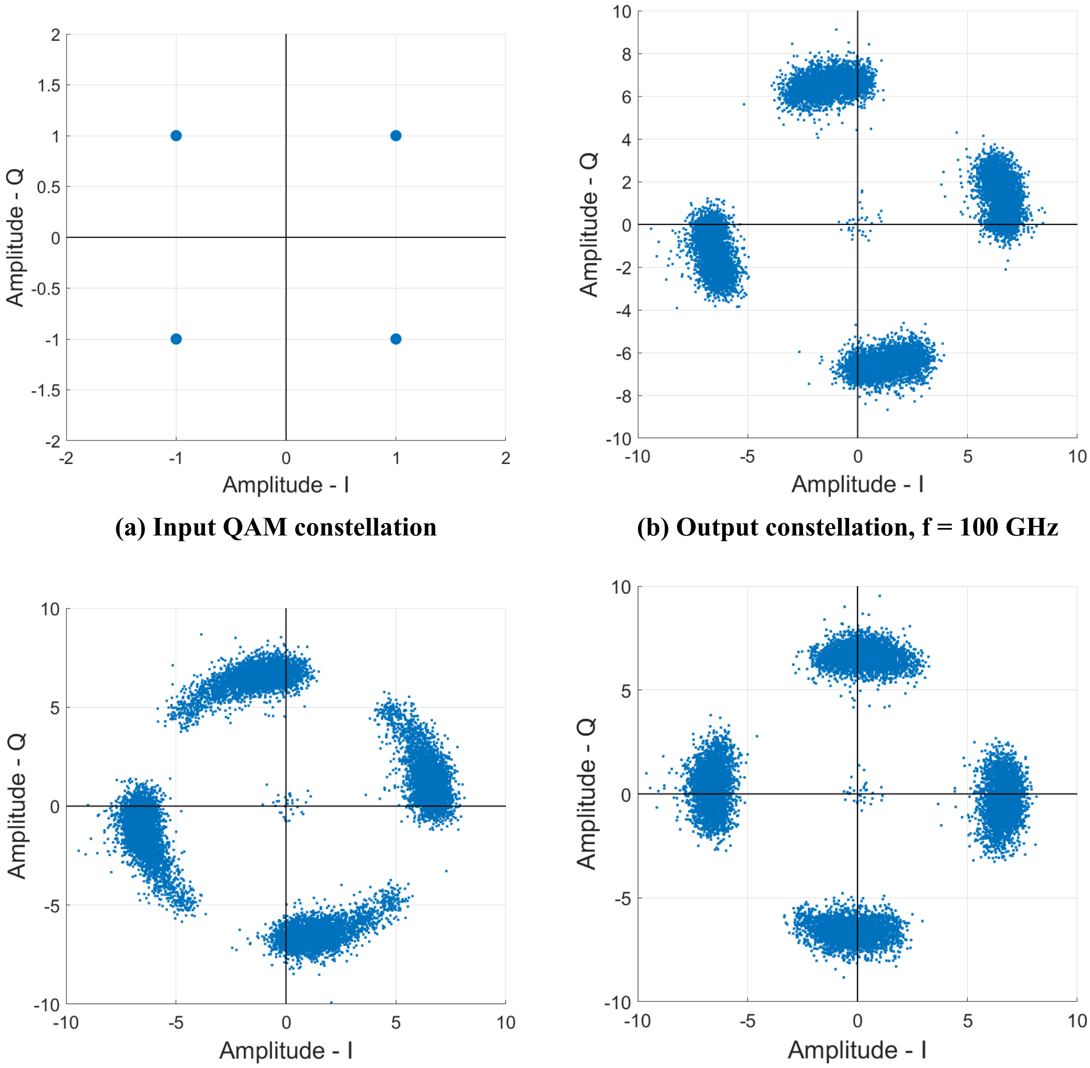
As mentioned above, a study needs to be carried out for the different power and frequency levels. These values are changed in the variable laser (CW), since the fixed laser (DML) will always have the same frequency, i.e. 193.1 THz, and its output power is 5.299 dBm.

To configure the variable laser, the data shown in Table. 3.6 have been considered. When a 100 GHz signal is desired, the variable laser must be configured with a frequency of 193.2 THz.

Table. 3.6 shows the EVM values obtained for the different configurations. Note that this value should be as low as possible, since EVM threshold for QPSK signal is 17,5 %. Hence, it is observed that power values between 5.299 dBm and 10 dBm in the variable laser offer better results. It is important to mention that lasers with linewidths of 10 KHz were considered in these simulations.

	- 10 dBm	**-5.299 dBm**	**0 dBm**	**5.299 dBm**	**10 dBm**
100 GHz	58.3%	44.4%	22.4%	10.2%	14.1%
200 GHz	56.1%	42.6%	24.2%	10%	17%
300 GHz	46.9%	43.9%	22.5%	9.8%	15.4%

Tabla 3.6: EVM values



(a) Input QAM constellation **(b) Output constellation, f = 100 GHz**

(c) Output constellation, f = 200 GHz **(d) Output constellation, f = 300 GHz**

Figure 3.8: Output constellation for 5.299 dBm output power value for different frequencies

In Fig. 3.8, a representation of each output constellation for different frequencies can be seen, for an output power of 5,299 dBm in both lasers. As can be seen, at 100 GHz the constellation obtained is significantly more accurate, with more defined and sharper points, although out of phase since a QPSK representation as shown in Fig. 3.8a is sought . The latter may be due to several factors, among them:

- **Phase imbalance:** since QPSK signals consist of phase modulations and if any imbalance occurs this could cause the constellation to rotate.
- **Power imbalance:** if any, it can also influence the output constellation, since in a QPSK constellation the four points of the constellation must have the same power, so it is important for the lasers to be well balanced.
- **Non-linear effects:** although, this would be more applicable for practical purposes and are

due to the presence of non-linear effects in the optical components or even in the signal amplification stage leading to deformations in the output constellation.

3.4.2 Spectral analysis

As mentioned above, a series of simulations will be carried out at different points of the circuit in order to observe how the signal evolves throughout the system. In Fig. 3.9, a representation of the complete system is shown with the different points where a display will be placed to observe the signal graphically.

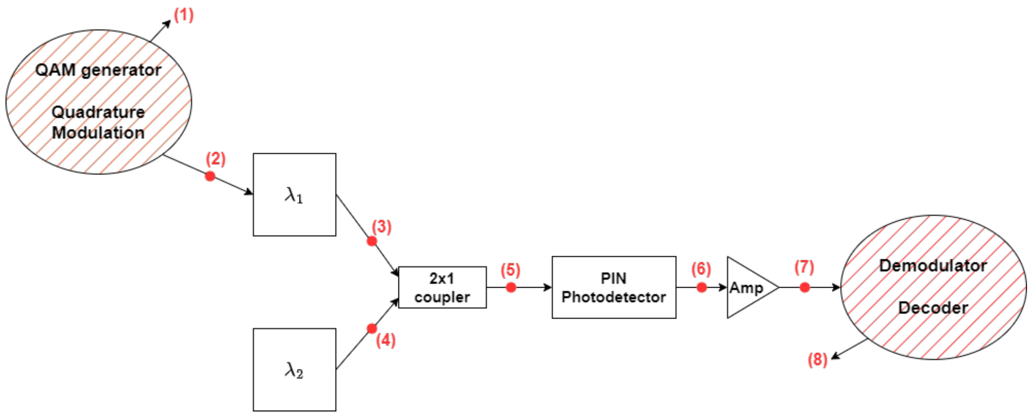


Figure 3.9: System overview using Optisystem

In (1) the constellation of the generated QAM (QPSK) signal has already been introduced in Fig. 3.8a, this constellation will be common to all the simulations. On the other hand, in (2) it is interesting to see the signal before entering the fixed laser, which will also be common to all simulations. The spectrum of the signal can be seen in Fig. 3.10.

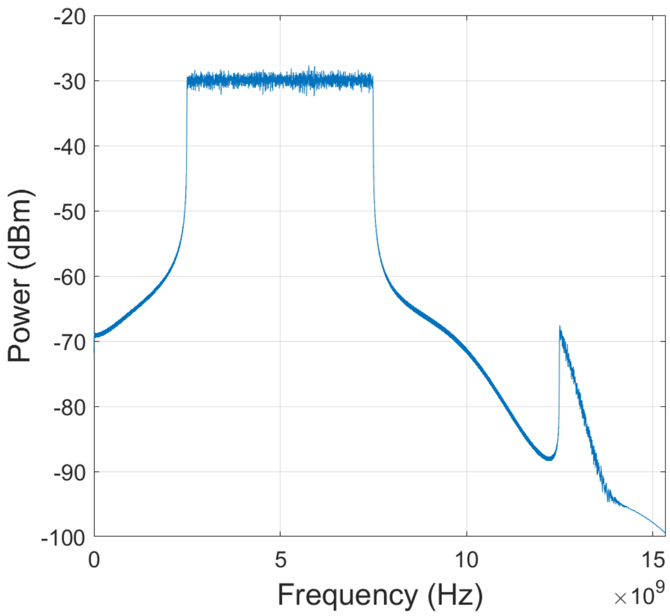


Figure 3.10: RF Spectrum input

The optical carrier represents the center frequency of the signal and as can be seen in Fig. 3.11, this carrier is located at 1.55253 μm. Knowing that $f = c/\lambda$, and that $c = 3 \cdot 10^8$, the central frequency is 193.2 THz.

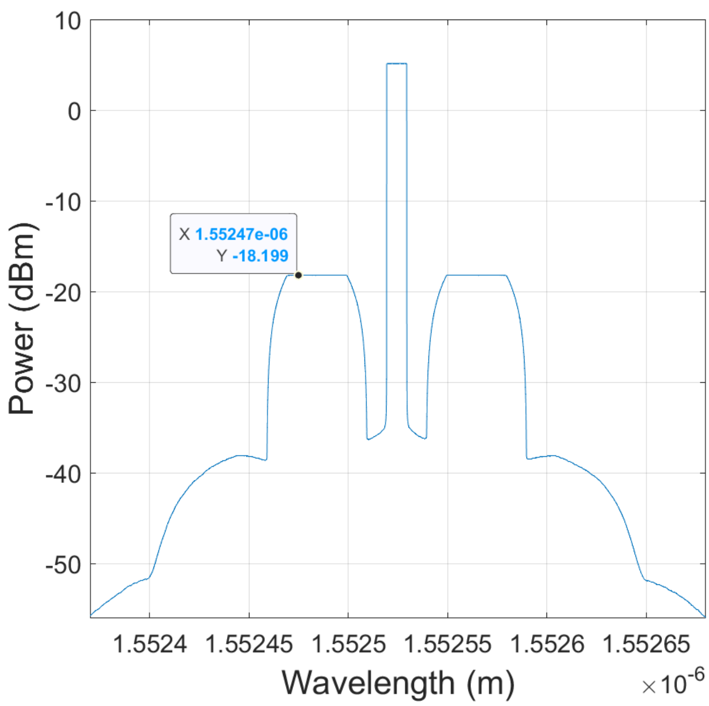


Figure 3.11: Optical Spectrum emitted by a fixed laser

On the other hand in Fig. 3.12, the variable laser signal is at 1.55172 μm, applying the same relation as above, a frequency of 193.3 THz is obtained. It can be concluded that both lasers are 100 GHz out of frequency.

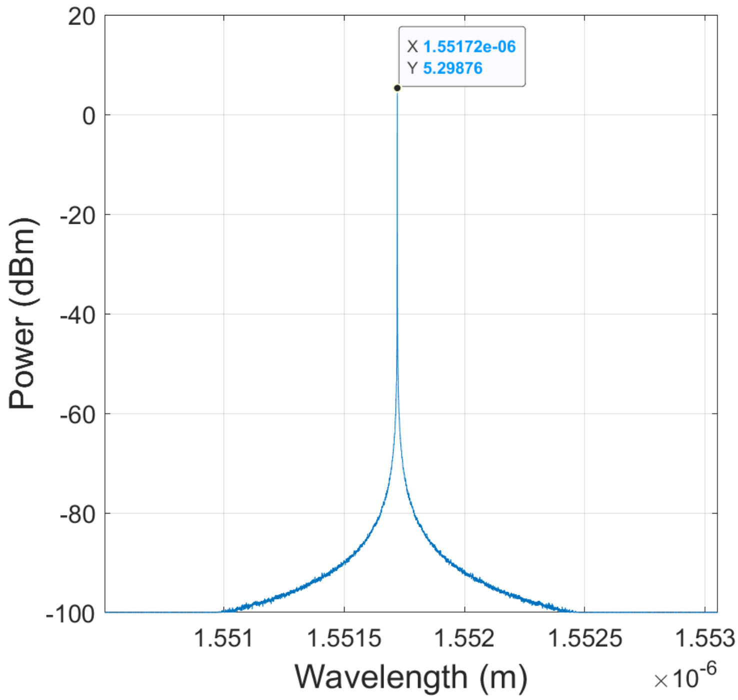


Figure 3.12: Optical Spectrum emitted by variable laser

To observe in more detail the separation of the signals emitted by both lasers, Fig. 3.13 shows a representation of these signals separated by a frequency of 100 GHz.

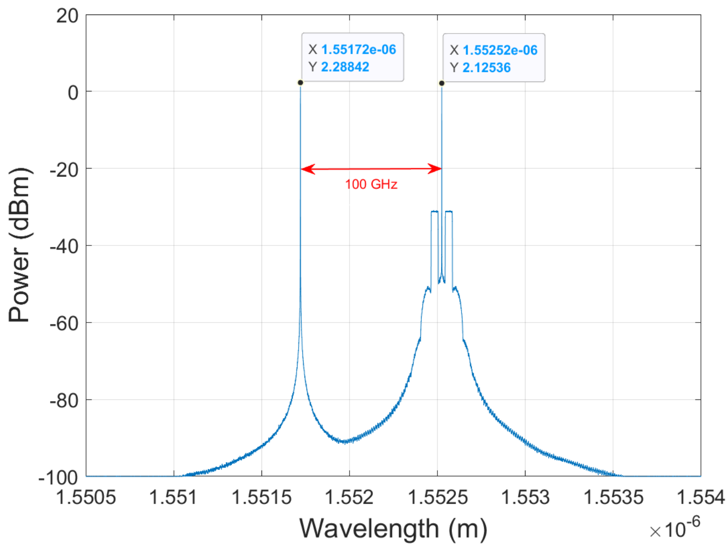


Figure 3.13: Optical Spectrum after combination of both Lasers

In Fig. 3.14, the signal at the output of the photodetector can be seen. At this stage the signal has just been converted into an electric current, so an RF visualizer has been used to obtain the graph. As can be seen, the carrier is centered at 100 GHz, just where it was intended to be obtained, in addition to lateral components related to the modulation characteristics of the optical signal itself. Moreoever, the output power of the signal reaches approximately -73 dBm.

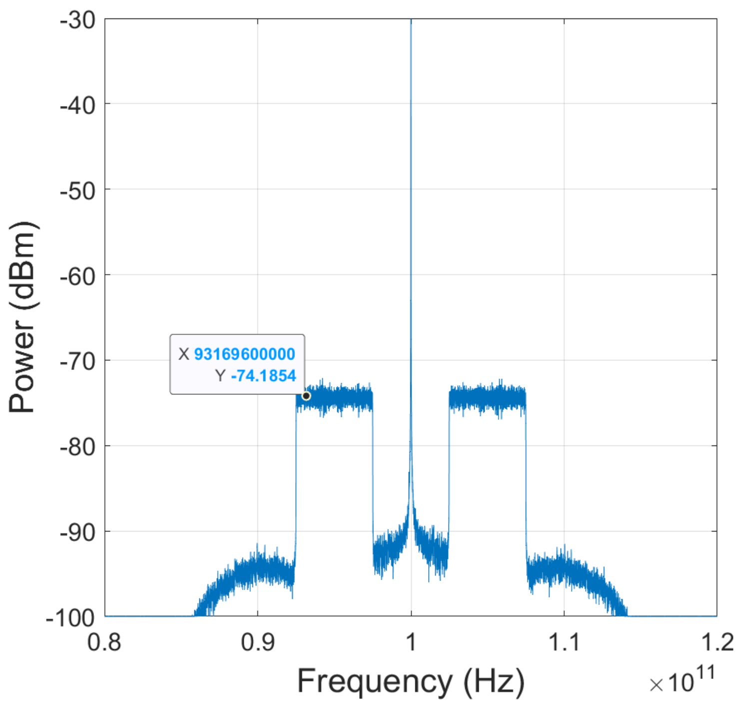


Figure 3.14: RF Spectrum after Photodiode

Finally, Fig. 3.15, shows the output signal after the RF amplifier, whose gain is 35 dB, that will be transmitted by the antenna. This signal, as can be seen, is very similar to the output signal after the photodiode, although amplified. The carrier is at 100 GHz as in the previous case, but this time it reaches -40 dBm of power.

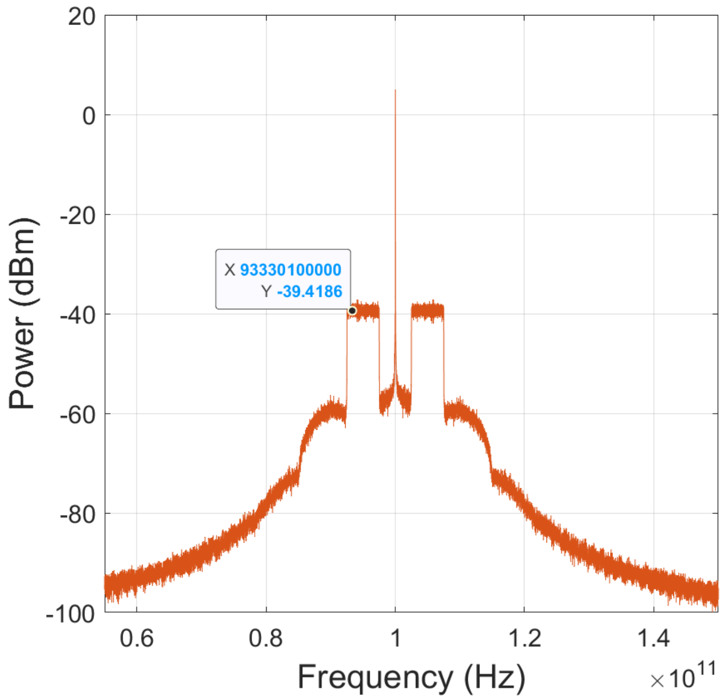
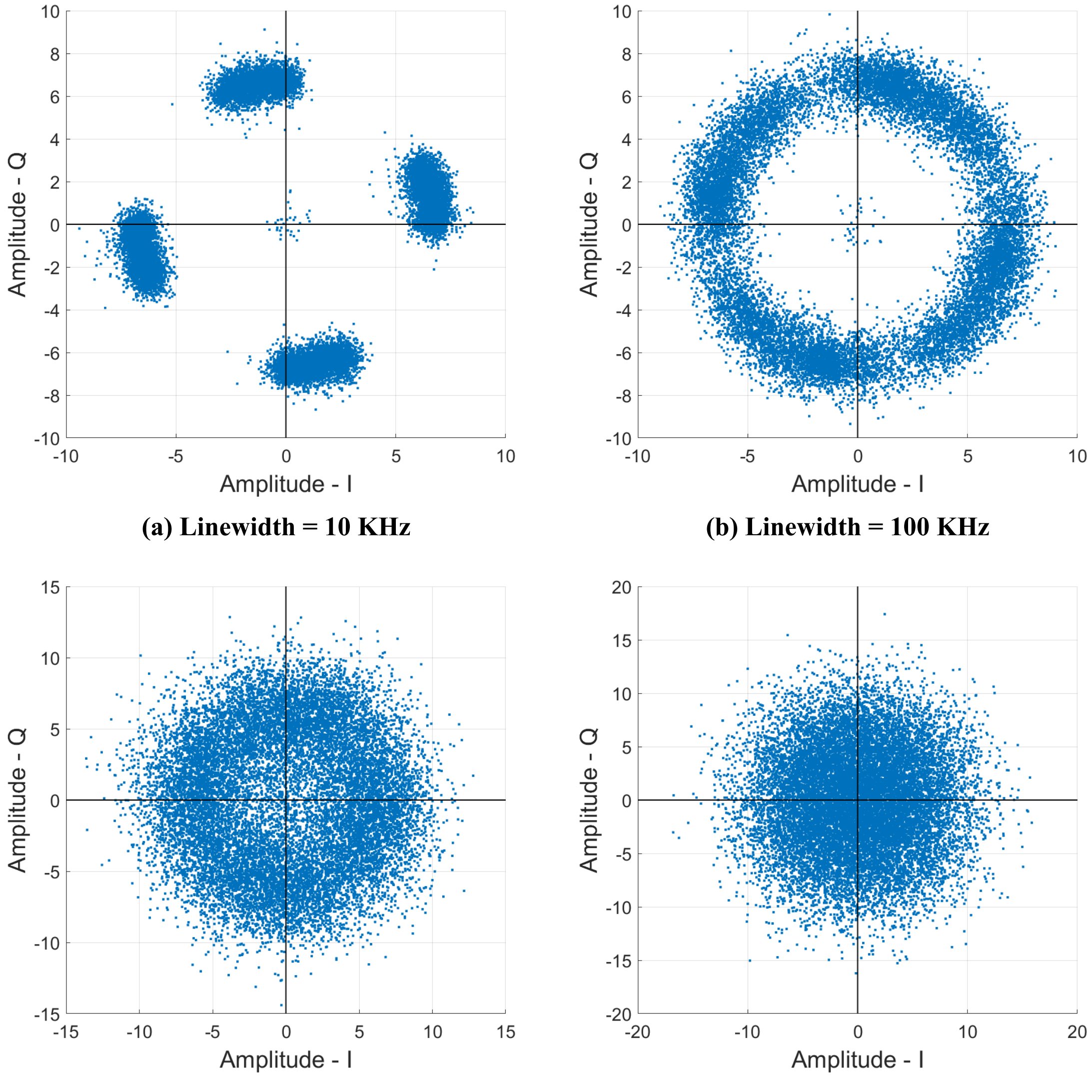


Figure 3.15: RF Spectrum after Amplifier

3.4.3 Impact of the laser linewidth

The linewidth of a laser denotes the spectral extent of light, i.e. the number of frequencies emitted by the laser. That is why in optical communications, it is preferable to maintain linewidths as narrow as possible in order to have greater coherence in the phase and frequency of the light emitted by the laser, and to avoid possible interferences.

In this work, four different linewidths have been considered: 10 KHz, 100 KHz, 1 MHz, and 10 MHz. In Fig. 3.16, it can be seen how the output constellation worsens as the linewidth increases, and at 100 KHz the four points of the initial QPSK signal are no longer distinguishable.



(a) Linewidth = 10 KHz

(b) Linewidth = 100 KHz

(c) Linewidth = 1 MHz

(d) Linewidth = 10 MHz

Figure 3.16: Output constellation for 5.299 dBm output power, 100 GHz frequency and different linewidth values

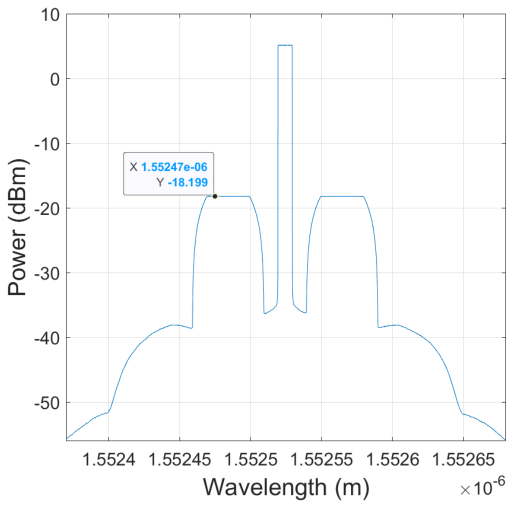
In order to see the degradation of the signal through EVM values, Table. 3.7 shows the different EVM values for different linewidths considering a frequency of 100 GHz and the same power in both lasers.

Linewidth	**10 KHz**	**100 KHz**	**1 MHz**	**10 MHz**
EVM value	0.102	0.104	0.111	0.126

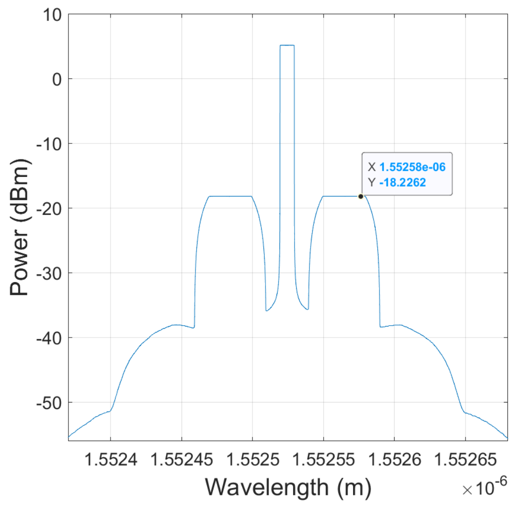
Tabla 3.7: EVM values for different bandwidths

The constellation is significantly distorted after increasing the linewidth, however, the EVM values do not vary greatly.

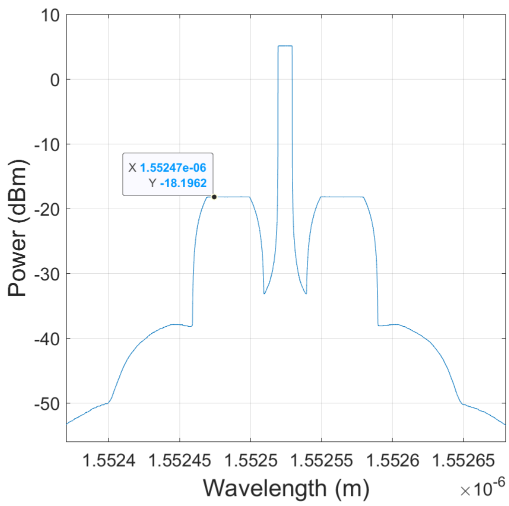
Furthermore, it can be observed from the beginning how the signal varies when the linewidth of the lasers is changed. To begin with, Fig. 3.17 shows the evolution of the signal after being generated by the fixed laser. It can be seen how the two components next to the carrier are increasingly less distinguishable and more irregular.



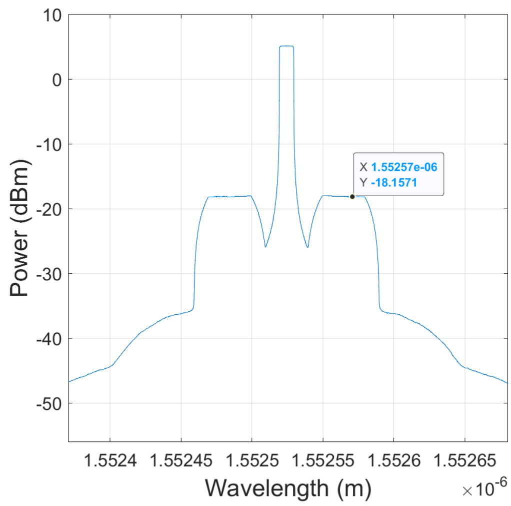
(a) Linewidth = 10 KHz



(b) Linewidth = 100 KHz



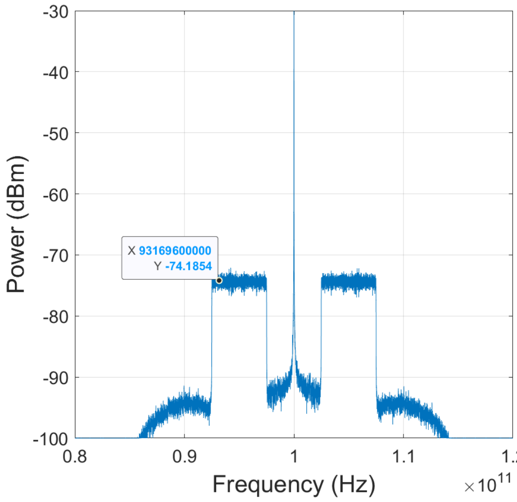
(c) Linewidth = 1 MHz



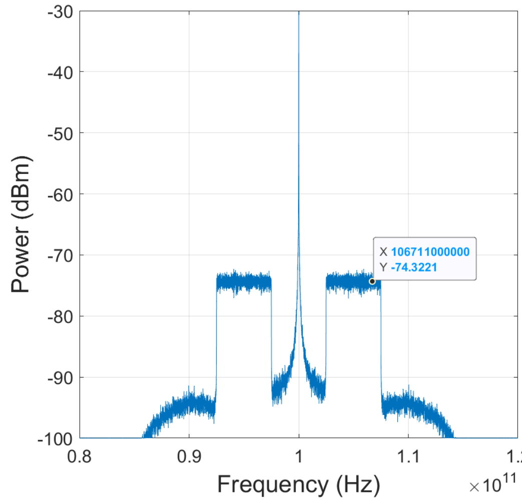
(d) Linewidth = 10 MHz

Figure 3.17: Optical spectrum after the fixed laser for 5.299 dBm output power, 100 GHz frequency and different linewidth values

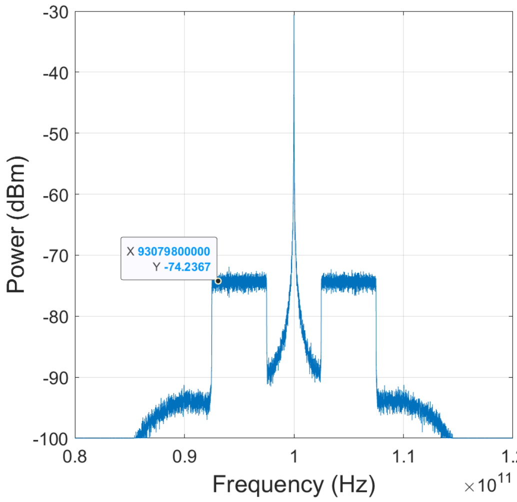
Similarly, in Fig. 3.18, the RF spectrum of the signal can be seen after being combined and passing through the photodiode. Especially when the linewidth is 10 MHz, the deformation of the signal and its components on each side of the central carrier are irregular, similar to what occurs in Fig. 3.17.



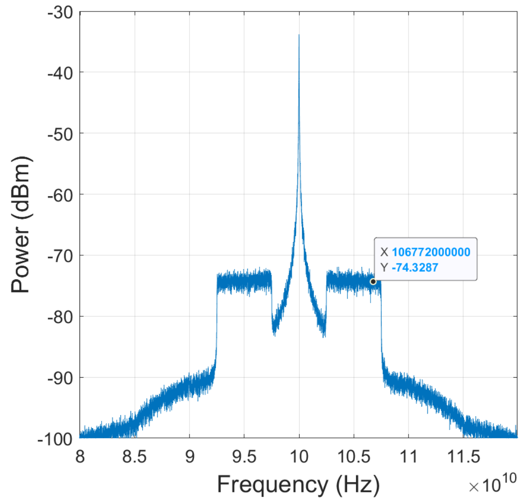
(a) Linewidth = 10 KHz



(b) Linewidth = 100 KHz



(c) Linewidth = 1 MHz



(d) Linewidth = 10 MHz

Figure 3.18: RF spectrum after photodiode for 5.299 dBm output power, 100 GHz frequency and different linewidth values

As a conclusion, and as shown in the previous figures, the increase in the linewidth values affects the signal in such a way that it seems to have undergone a high amplification process, increasing its gain and, consequently, the irregularity of the signal, causing the received signal to be difficult to distinguish and with a greater dispersion of the points in a QPSK constellation.

3.4.4 Impact of received optical power

Finally, simulations have been carried out considering an attenuator placed just before the photodetector. At such high frequencies together with a reduced power level, the attenuator decreases the power level even more and, consequently, hinders the correct detection and signal processing performed by the photodetector. In Fig. 3.19, a study of the EVM value has been carried out for different attenuation and frequency levels, specifically 100 GHz, 200 GHz and 300 GHz. For this study, the power level obtained after attenuation when both lasers operate at the same power (5,299 dBm) and the EVM value at the output have been considered. With these data it can be concluded that the lower the attenuation, the higher the RoP (Received optical Power) and, therefore, the lower the EVM value, i.e. the better the quality of the output signal. In particular, good EVM levels are obtained when the power is lower than approximately 3 dBm, as they remain below the threshold level of 17.5 % [39].

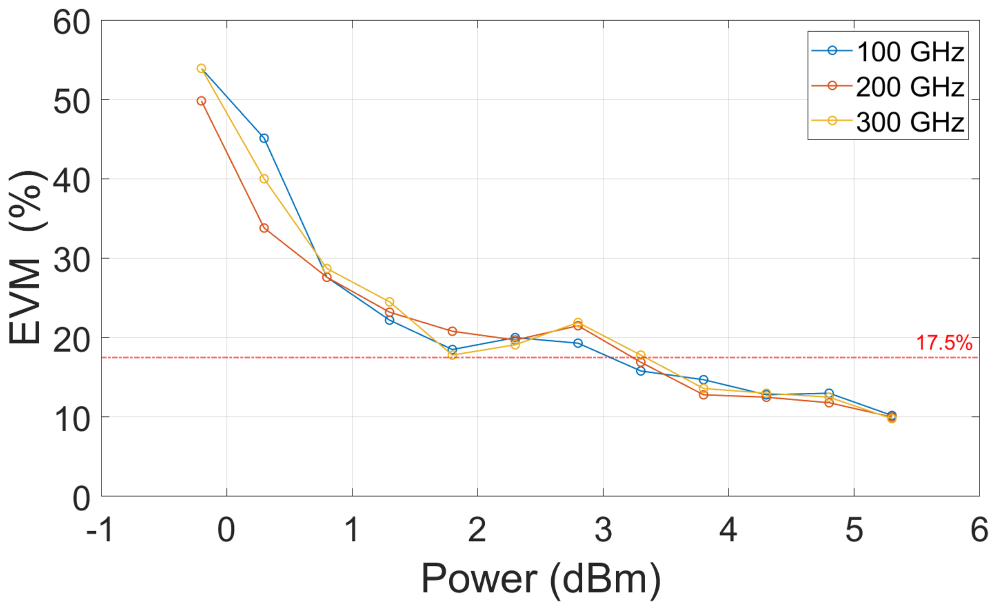


Figure 3.19: EVM vs. RoP

Chapter 4

General Budget

Finally, in this chapter, an analysis of the proposed system overall budget will be carried out. The cost of each component will be analyzed in order to conclude the feasibility of the approach at the present time.

Due to the fact that this technology is still in an experimental phase, many components are either not commercially available or do not meet all the necessary requirements. In addition, many of the studies that have been carried out on the THz band by research teams, for example, use devices implemented by themselves or have systems developed by external suppliers that are adapted to their needs. This latter leads to an exponential increase in the final price.

Below a detailed budget for both the transmission and reception systems will be introduced. The cost of each component can be seen in Table. 4.1 and Table. 4.2 for the transmitter and receiver respectively.

Component	**Provider**	**Model**	**Price (€)**
DML	Optilab	DFB-1550-DM-4	687,77
DFB Laser	Optilab	DFB-1550-EAM-32	1.467,2
Tunable Laser	Optilab	TWL-C-B	4.566,79
Coupler	Thorlabs	TW1550R5F1	277,35
PIN-Photodetector	Finisar	XPDV412xR	25.792,91
UTC-Photodiode	NTT Electronics	IOD-UPD-20001	14.045,00
RF Amplifier	SHF	SHF T850 B	15.255,00
Antenna	TeraSense	High-gain horn	1.160,24

Tabla 4.1: Cost analysis of the Transmitter

Component	Provider	Model	Price (€)
Antenna	TeraSense	High-gain horn	1.160,24
Schottky Barrier Diode	Macom	MADZ-011002	Not provided
LNA WR6.5	VDI	WR6.5AMP-LN	7.786,42
LNA WR5.1	VDI	WR5.1AMP-LN	8.244,45
Limitting amplifier	Micram	TIA5633	Not provided

Tabla 4.2: Cost analysis of the Receiver

As for the receiver, only the antenna and the pre-amplifier have been budgeted, depending on the characteristics, the price of the latter ranges from approximately 7.000 € to 8.000 €. Considering the high prices, the total price of the receiver could cost around 30.000 € taking into account the other elements.

For the transmitter, different combinations can be considered:

- DML + DFB + PIN-Photodetector - 44.640,47 €
- DML + DFB + UTC-Photodiode - 32.892,56 €
- DML + Tunable laser + PIN-Photodetector - 47.740,06 €
- DML + Tunable laser + UTC-Photodiode - 35.992,15 €

Thus, the total price of the system is estimated to range between 72.000 and 75.000 euros.

As a conclusion, and taking into account that each transmitter must be placed in each train unit to send the information, it is an expensive system at present, since, as mentioned above, THz technology is still very immature and many elements are custom-made. Over the years, these elements will become more widely used in society and their prices will be increasingly reduced.

Indeed, THz communications are considered one of the enabling technologies for future 6G networks, therefore costs will continue to decrease until this technology embraces the latest advances in technology.

Chapter 5

Conclusions and future lines

In this work, a study of communications in the THz band has been carried out. In addition, it has been demonstrated the possibility of implementing a system based on the combination of the signal generated by two lasers and direct detection for the photonic generation of THz signals, as well as the introduction of its application in railway environments. Specifically, for train-earth communications. Furthermore, a search for components belonging to a technology not too commercialized has been carried out, involving contact with several companies and suppliers in order to obtain more data about their characteristics and commercial prices. Also, the performance of the proposed scheme has been evaluated for different parameters of frequency, power and linewidth by means of a commercial software. Finally, the budget for implementing such a communication network has been calculated.

After having disclosed the final results for this project, it can be concluded that there is still a lot of study needed behind communications in the THz band, apart from a considerable amount of time for it to be a mature enough technology in order to be established in society. On the one hand, the problem of the scarcity of devices that can operate in this band slows down any research process, in addition to raising their prices. After having been in contact with several companies that provide broadband technology as well as several researchers, it has been possible to conclude that many devices are developed and customized for a specific appliation by external companies, or are simply developed by the research team itself, which exponentially increases the price.

On the other hand, it is true that the THz band is becoming a reality, mainly due to the saturation of the spectrum, the increase in consumers per year, and the improvements and updates within the field of communications. It is necessary to focus on higher frequencies and, in addition, it is one of the objectives of the 2030 agenda where applications such as tactile internet are named that can only be achieved with this type of technology. However, the limitations must also be taken into account, when working with such high frequencies, since communication in the open air becomes difficult due to the high attenuation, which only allows for a few meters indoor links.

Regarding the system developed, there are other options to transmit a THz signal. In this project, an attempt has been made to develop a system as simple as possible with the best signal level at the output, this characteristic is very interesting for our system since, in rail vehicles there is a limitation in terms of weight, and sometimes it is hard to stick to the limit. Therefore, adding too complex systems could be a limitting factor.

The results obtained in this project have demonstrated that communications in the THz band is possible maintaining a simple system, with the same power in both lasers and with the minimum possible linewidth, despite the limitations in terms of technology available in the market, high prices, and significant attenuations.

However, considering the results obtained in the graphs, it can be concluded that a transmission using the THz band is possible, and the results are optimal when the power of both lasers is the same, for a range of frequency between 100 GHz and 300 GHz. In the final constellation considering the same power in both lasers and a 10 KHz bandwidth, in Fig. 3.8 the 4 points of the QPSK can be distinguished, although the constellation is rotated. This could be corrected by using a more extended demodulator module, but has not been implemented in this master's thesis due to the limitations.

Therefore, by maintaining a simple system, a THz communication of a few meters can be originated. Despite not having a mature technology at the moment, in the future Communications at 300 GHz could be achieved with satisfactory results in reception.

GLOSSARY

AP	Acces Point
CCTV	Closed-Circuit Television
CDMA	Code Division Multiple Access
CW	Continuous Wave
DFB	Distributed Feedback
DML	Directly Modulated Laser
eMBB	enhanced Mobile Broad-Band
EVM	Error Vector Magnitude
GSM	Global System for Mobile Communication
GSM-R	Global System for Mobile Communication - Railway
HBT	Heteroconjunction Bipolar Transistor
HEMT	High Electron Mobility Transistor
ICT	Information and Communication Technology
IoT	Internet of Things
ITU	International Telecommunication Union
ITU-R	Intenational Telecommunication Union - Requirements
KPI	Key Performance Indicator
LED	Light Emitting Diode
LNA	Low Noise Amplifier
LOS	Line Of Sight
LWIR	Long Wave Infrared

M2M	Machine to Machine
MAC	Medium Access Control
MBB	Mobile Broad-Band
MIMO	Multiple Input Multiple Output
MMIC	Milimeter-wave Monolithic Integrated Circuit
mMTC	massive Machine Type Communication
MWIR	Medium Wave Infrared
NLOS	Non Line Of Sight
NTT	Nippon Telegraph and Telephone
OFDM	Orthogonal frequency-division multiplexing
OOK	On-Off Keying
QAM	Quadrature Amplitude Modulation
QPSK	Quadrature Phase Shift Keying
RF	Radiofrequency
RoP	Received optical Power
RTP	Real-time Transport Protocol
SCM	Spatial Channel Mode
SDG	Sustainable Development Goals
SIP	Session Initiation Protocol
SWIR	Small Wave Infrared
TD-CDMA	Time-Division Code-Division Multiple Access
uMBB	Ubiquitous Mobile Broad-Band
URLLC	Ultra Reliable Low Latency Communication
UTC	Uni Traveling Carrier

VoIP	Voice over IP
VR	Virtual Reality
WCDMA	Wideband Code Division Multiple Access
WLAN	Wireless Wocal-Area Network
WPAN	Wireless Personal Area Network

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