Bachelor Thesis

Characterization of Wireless Millimeter Wave Systems Considering the Impact of Reflections and Imperfect Beam Patterns

Bachelor in Communication System Engineering

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Abstract

Communication on millimeter Wave (mm-Wave) frequencies is a key technology for next generation wireless networks. It allows multi-gigabit link speeds in highly crowded network scenarios, by leveraging directional communication. Due to quasi-optical propagation characteristics at mm-Wave frequencies, most works in scientific literature simplify directional links in that band to sharp-edged line of sight beams. However, measurements have identified certain objects to pose strong reflectors, rendering the former assumption unrealistic.

This thesis, analyses the impact of reflections and beam side-lobes on mm-Wave networks and studies the resulting impact on interference and coverage. To this aim, reflections and side lobes of off-the-shelf 60 GHz systems are analyzed in an extensive measurement campaign to then verify the established assumptions on mm-Wave propagation. Further, this work analyzes the frame flow of the used protocols to extract the general communication behaviour of the off-the-shelf 60 GHz system.

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1 Introduction

1.1 Purpose

This bachelor thesis studies the behaviour of off-the-shelf millimeter wave equipment. It reevaluates the common mm-wave sharp-edge beam assumption analyzing the performance of this technology with several measurement campaigns.

1.2 Motivation

With the appearance of the WiGig Alliance and the ratification of the IEEE 802.11ad standard, local area networks are evolving into the more sophisticated 60GHz wireless environment. The main characteristics of this mm-wave environment, are that they provide communication with very high bandwidth in an unlicensed frequency band and that they use directional antenna arrays, promising interference free and energy-efficient devices [1].

The use of antenna arrays is feasible due to their small size at these frequencies, posing many advantages as their high directivity with fast electronic bean steering or their efficient use of energy.

While 60GHz communication has been analyzed in terms of reflections [2], multipath [3, 4] or antenna characteristics [5], there does not exist to the best of our knowledge any work which analyzes the behaviour of off-the-shelf equipment working with real phased antenna arrays.

The purpose of this thesis is to study the behaviour of this first generation 60GHz equipment, including the reevaluation of common assumptions on mm-wave communications, the analysis of the performance of consumer mm-wave beamforming technology and the study of the behaviour of a complete system in a realistic environment.

1.3 Contributions

This thesis presents a detailed analysis of the Dell wireless docking station D5000 together with the Dell Latitude E7540, which are paired through a 60GHz WiGig link [6]. The study is performed by means of a frame level analysis, with the help of a 60GHz downconverter to overhear the communication of the off-the-shelf devices.

Our particular contributions are as follows:

First, we present a radiation pattern analysis for the analyzed devices which shows the impact of surrounding device components. Strong sidelobes were found for aligned transmissions and even stronger for unaligned.

Second, a study of the device discovery process is performed, finding it to achieve omni-directional coverage by sweeping multiple imperfect wide radiation patterns. We discover this WiGig device discovery to differ from the one from IEEE 802.11ad.

Last, we experimentally prove that reflections on 60GHz can lead to interference effects. With the use of a wireless HDMI transmitter working on the same frequency band than our WiGig devices, we found inter-system interferences when the HDMI signal was coming from a reflected path.

The study of these devices working under the WiGig protocol provides the first insights into what to expect from IEEE 802.11ad devices which are currently under development. Many of these insights will be transferable as the work of the WiGig Alliance was merged into the IEEE 802.11ad amendment.

1.4 Structure of this Document

Following the introduction, the background and the objectives of the project are presented. Then, measurement setup and experimental methodology are followed by an in depth discussion of the results of the measured campaign.

Future work, alternatives and conclusion are the sections that finalize this work showing the main keypoints of the results of the project as well as further promising research directions.

As annexes, the project scheduling and budget, a section describing the IMDEA Institutes (where the project was carried) and the entire set of patterns for device discovery measurements are attached.

To complete the project, a summary is enclosed.

2 Background

In this section we are going to give short descriptions of the basics of our work. We are going to explain how radiowave propagation is created with the movement of point charges and how a wireless transceiver can receive and transmit data together with its modulation process. We will finish this section explaining how the radioelectric spectrum is regulated and why there is an increase of its demand.

2.1 Radiowave Propagation

Transferring information between different points that are not interconnected by a conductor is called wireless communication. Wireless communications are based on the transmission of different forms of energy trough air or vacuum, nowadays the most commonly used ones are radiowave communications.

The main components and properties that take place in radiowave communications are going to be explained on the following sections:

2.1.1 Electromagnetic Fields

Electromagnetic fields are created when two point charges are near each other as they produce a force between them, creating the field which surrounds the point. This surrounding field is the electromagnetic field, whose unit of measure is volts per meter [7].

Electromagnetic waves are created when a electric field is synchronized with a magnetic field. These waves have a propagation speed equal to the speed of light.

Electromagnetic waves and fields follow the superposition principle; if different charges exist, which produce several fields in different locations, the total electromagnetic field in another point is going to be the sum of all of the different fluxes.

There are different phenomenas that affect the electromagnetic waves:

- **Reflection.** Some materials are strong reflectors of electromagnetic fields. Sometimes, the received field is the sum of the energies of the direct path of the radiated signal and reflections that can be produced by different surfaces (multipath components).

  The reflection coefficient tells us how much power has been reflected compared to the incident power. This coefficient varies with the frequency and the incident angle of the incident wave as well as on the different properties of the reflecting material.

- **Diffraction.** When a wave hits an obstacle's edge, some secondaries waves are created. This secondary wave can be produced with a phase displacement.

- **Dispersion.** Dispersion is created due to the reflections and diffractions multipath creation. This Dispersion is the difference of the beginning and the ending of a pulse, which is the quadratic mean of the different delays of the received signal.

- **Absorption.** Different materials absorbs and attenuates electromagnetic fields causing a difference in the received power, from air's water vapour to a concrete wall.

- **Attenuation.** Electromagnetic waves attenuate on free space following the Friis equation, which can be seen on Equation 1, where λ is the wavelength of the field, R is the distance, Pt is the transmitted power and Pr the received power. We can see that the attenuation grows exponentially with the grow of distance and frequency (as $\mathrm{f} = \frac{\mathrm{c}}{\lambda}$, where λ is the wavelength of the field, f the frequency and c the speed of ligth.)

$$\frac{\mathrm{Pr}}{\mathrm{Pt}} = \mathrm{Gt} \cdot \mathrm{Gr} \cdot (\frac{\lambda}{4 \cdot \pi \cdot \mathrm{R}})^2 \quad (1)$$

2.1.2 Antennas

An antenna is defined as the device in charge of receiving or emitting radiation of electromagnetic fields.

The most important antenna parameters are [8]:

- **Radiation pattern.** The amount of power radiated by an antenna depending on its angular position can be seen in its beam pattern. This pattern shows the main beam of the antenna (where most of the power is radiated) and the different sidelobes (other directions where the antenna radiates).

  From these radiation patterns, the following data can be obtained:

  - **Half Power Beamwidth:** Is the angular separation where the radiation power decreases -3dB (50%).
  - **Quarter Power Beamwidth:** Is the angular separation where the radiation power decreases -6dB (75%).
  - **Sidelobe Level:** Is the power level of the sidelobes compared to the main beam.
  - **Antenna Aperture:** Measures how effective is the antenna. Can be obtained using the following equation, where HPW is the Half Power Beamwidth and d is the distance between transmitter and receiver: $A = 2 \cdot cotangent(\frac{HPW}{d})$
  - **Directivity:** Measures how much power the antenna transmits into the main beam comparing it with an ideal isotropic antenna which radiates uniformly in all directions. We can obtain the directivity of the antenna as it is directly related with the effective aperture as the following equation tells, where λ is the transmitted wavelength and A the aperture: $D = (\frac{4 \cdot \pi}{\lambda^2}) \cdot A$

- **Bandwidth.** An antenna is limited to a range of frequencies. This group of frequencies where the antenna can work is the antennas bandwidth.
- **Directivity.** Directivity measures how much power an antenna transmits or receives into a particular direction.
- **Efficiency.** How much power the antenna will radiate compared to the input power. Takes into consideration the power that is dissipated due to the conductor and dielectric losses.
- **Gain.** The gain is just the product between the directivity and the efficiency.

There are different types of antennas depending on what it is needed for different applications. The main antenna types are described:

- **Wire antenna.** A wire antenna consists simply on one or several wires connected to the radio in one end, and the other end left in free space. The size of this antennas is smaller or equal to the length of the transmitted signal wavelength. The most common wire antenna are the monopole and the spiral antennas.
- **Aperture antenna.** To focus the transmitted and received electromagnetic flux the aperture antennas use surfaces. The gain and directivity of this type of antenna is directly related with the angle and area of its surface. The most common aperture antennas are the horn and parabolic antennas.
- **Planar antenna.** They are based on transmission lines working on a printed circuit board, which with different dielectric substrates can transmit electromagnetic signals.
- **Antenna array.** An antenna array consists in clustering a set of antennas where the phase difference between them determines the direction in which the individual beams will radiate. The individual signals can interfere either constructively or destructively with the others forming a beam with the signals that overlay [9]. Omnidirectional elements are used in antenna arrays so there are no beams that overlay.

All these types of antennas also vary for different bandwidths and frequencies, having different sizes, construction materials and shapes.

2.2 Wireless Transceiver Architecture

The transmitter is the device which transforms the electric power into a radio frequency current, a receiver is the device which transforms the radio frequency current into electric power. A transceiver is a combination of both, being able to transmit and receive radio frequency.

The radio transmitter consists on the following [10]:

- **Information source:** The information that is going to be transmitted is coming from this source. (AF input on Figure 1)

- **Oscillator:** Creates a sinusoidal signal with the demanded carrier frequency of the communication. (RF carrier together with the multiplier on Figure 1)
- **Modulator:** Takes the information source and the signal from the oscillator and combines them into an upconverted signal at the carrier frequency. Further details about the modulation process are explained in Section 2.2.1.
- **RF Amplifier:** Increases the power of the transmitted signal.
- **Antenna:** Takes the RF signal and radiates it in electromagnetic fields. (The antenna would be connected on the RF output port on Figure 1).

On Figure 1 it can be seen a transmitter block diagram where all the elements previously described are ordered.

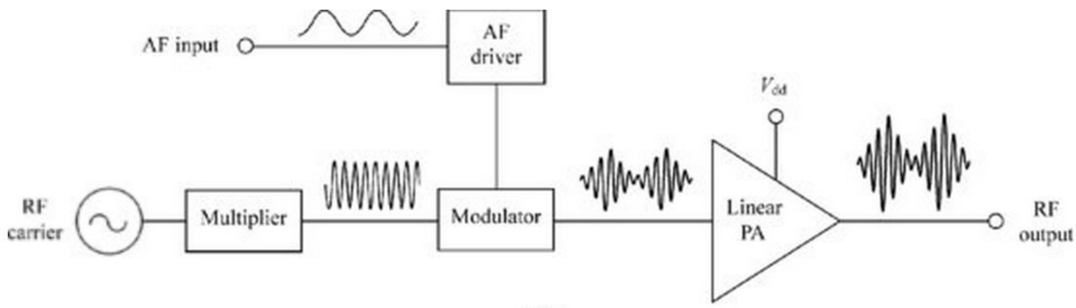


Figure 1: Transmitter block diagram [10].

The receiver part of a transceiver works under the same scheme but in reverse order: An antenna receives the electromagnetic field which is demodulated separating the carrier frequency from the main signal which is converted into bits.

2.2.1 Modulations

The general process where a signal with information is inserted inside a carrier signal is called modulation, and the process of extracting the signal with information from the modulated signal is called demodulation [11].

The aim of the modulation process is to use a carrier frequency as the guide of the information, being able to choose any frequency and bandwidth on the radioelectric spectrum.

Modulation is one of the most important key-points of wireless communications, as without a proper modulation and demodulation it would be impossible to make the devices interact. Modulations also allow the technique of multiplexing, where different devices can share the medium of the communication simultaneously.

There exists a wide diversity of modulations, and depending on the used one the communication can be more robust regarding error corrections or more efficient in the transmission bit-rate.

The three main classes of analogue modulations are frequency, amplitude and phase modulations. This modulation techniques can also be combined.

2.2.2 IQ Modulation

The WiGig standard, which is analyzed in this work, uses the IQ modulation: The IQ modulation is based on dividing the signal in two different components, the I (In-phase component) and the Q (Quadrature component).

In Figure 2 can be observed how the quadrature modulator works, upscaling the splitted mapped and shaped signal to the frequency Wc and shifting $\pi/2$ the phase of the Q channel, as it can be read in a more detailed way in [12].

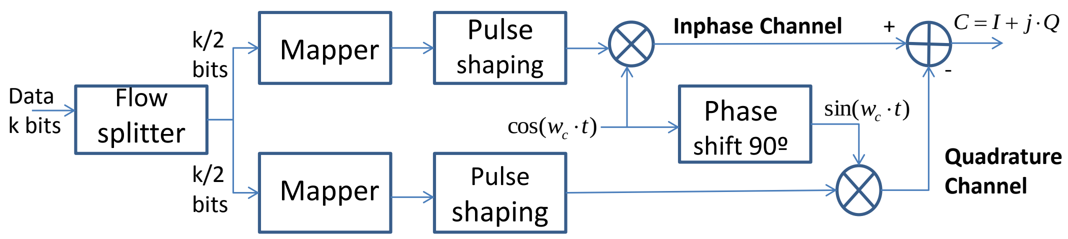


Figure 2: M-QAM modulator.

In Figure 3 can be observed the demodulation process followed by the system, which is also explained in [12]. It downscales the signal using the cosine and sine of the carrier frequency, filters it to avoid the effect of noise (n), compares it with the codebook and then merges both flows to obtain the estimated demodulated bits.

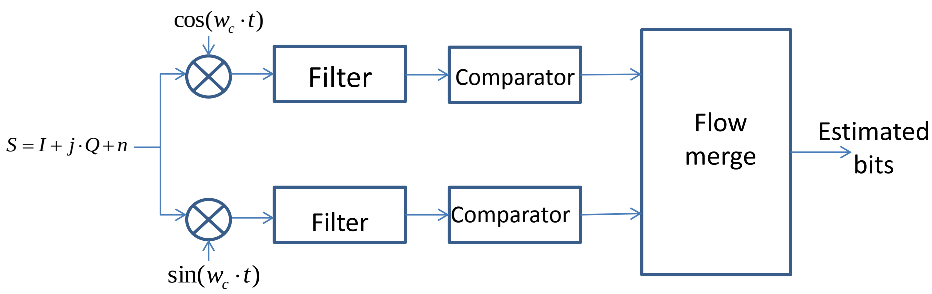


Figure 3: M-QAM demodulator.

2.2.3 Differential Signaling

The differential transmission technique ensures a high speed and robust communication. It employs two symmetrical signals which need to be subtracted at the receiver side to obtain the transmitted signal.

As the two signals are subtracted at the receiver side, interferences will be canceled as they would affect in the same way both signals.

The Vubiq system has four different channels, resulting from the I and Q signals received as differential signals. In order to obtain the received complex signal we need to do the operations described in the following equation (2), being C the final signal.

$$\mathrm{I} = \text{Channel 1} - \text{Channel 2} \tag{2a}$$

$$\mathrm{Q} = \text{Channel 3} - \text{Channel 4} \tag{2b}$$

$$\mathrm{C} = \mathrm{I} + \mathrm{j} \cdot \mathrm{Q} \tag{2c}$$

2.3 Radioelectric Spectrum

The radioelectric spectrum is the basis of all wireless communication. It is limited and needs to be shared in a highly efficient way among many users, otherwise, the different signals mix up and its not possible to properly receive the information.

The following section explains how the radio spectrum is regulated, how interference makes this regulation necessary, why we can use our wireless devices in some unlicensed frequencies, and how the growth of wireless technologies is pushing spectrum usage to different frequencies.

2.3.1 Radio Regulations

The radioelectric spectrum is limited so it needs to be regulated to avoid technical and legal issues. There are different agencies dedicated to its regulation:

There are different legislation authorities depending on the countries, but the most important ones to be mentioned worldwide are the ITU: The International Telecommunication Union, which was funded in 1865, and the FCC: The Federal Communication Commission, which was funded in 1934.

The International Telecommunication Union [13] is the United Nations specialized agency for information and communication technologies (ICTs). Among many things, the ITU is in charge of the regulation of the radioelectric spectrum and the telecommunication standardization sector.

From the different duties performed by the Radio Regulations Board from the ITU, the next ones should be outlined:

- Radio regulation and registration of the different frequency assignments made from the different states.
- Supervision of unresolved interference investigations from different administrations.
- Providing advice to radiocommunication conferences and assemblies.

The Federal communication Commission [14] is the primary authority for the communication law, regulation and technological innovation in USA, focusing into the communication policies without technical details. The FCC must take into consideration the regulations from the ITU.

Inside Spain, the CNAF [15] (Cuadro Nacional de Atribución de Frecuencias/ National Frequency Attribution Regulator) is the national authority, being the regulator of the radio spectrum.

The CNAF is in charge of the division of the frequencies in the spectrum as the ITU recommends as well as on the legislation and control of the licensed frequencies, charging the proper fees to their users. The CNAF always has to take into consideration the changes made by the ITU, as they are a higher authority.

2.3.2 Interference

As wireless technologies are spreading out and more users are buying and using wireless devices, the radioelectric spectrum is beginning to lack.

All wireless electrical devices, from cell phones to televisions are working on the same radioelectric spectrum, the reason that everything is working without many interferences is because different devices are using different carrier frequencies so their signals do not collide.

But when different devices are using the same carrier frequency or when their bandwidths are overlapping in the reception range of a receiver problems arise. When that happens, interferences can be created in the receiver side, as the different signals mix up and become inseparable.

An example of this problem could be when trying to connect a laptop to a WiFi access point of a very crowded place (like an airport or a conference room). The connection will be worse than if the laptop is connected in a place with less users. This reduction in bitrate will be due to the share of the medium, where now different stations need to share the frequency resources having a smaller transmission time, where also some retransmissions will be required as an effect of these interferences.

Those interferences are caused because WiFi uses omnidirectional antennas where power signal spreads out to every direction causing interferences in other users that might be using the same channel but in different access points.

Many wireless devices use a technique called carrier sensing to avoid interferences. With this technique, the devices define a schedule between them to know when they are going to transmit so their signals do not collide. The problem of this technique is that both transmitters and both receivers must be involved in this process, if one of the transmitters is out of the receiving range, is not going to be able to schedule itself, creating interferences on the communication. Different techniques of carrier sensing and collision avoidance can be found in [16].

2.3.3 Frequency Licensing

The unlicensed frequencies are the ones that everybody can use without needing to pay any kind of fares to the national authorities. Examples of different technologies inside this unlicensed frequencies of the radio spectrum could be WiFi or Bluetooth, or other devices as car key remote controllers or cordless phones.

What this non regulation causes, is that many times two different devices are using the same frequency and they can cause interference between them, as happens sometimes with cordless phones.

Other wireless communications, such as mobile phones or wireless television broadcasting, are held on the licensed frequencies. This means that each company pays for several frequencies of the spectrum to the regulators so only they can use them avoiding other devices to cause interferences.

There are also other frequencies owned by the government, that can be employed for different purposes as military or emergencies. Under this frequencies we can mention GPS devices, which was first a military technology, later used for civil usage.

2.3.4 Increasing Bandwidth Demand

There are different reasons to state that the available spectrum should be increased for future technologies. The reasons that are thoroughly discussed on [17] are:

- **Increase in number of devices:** If there are many devices in the same place, the only way to avoid interferences between them, without reducing their communication rate, is increasing the available bandwidth so each of them can use one carrier frequency. With the introduction of the Internet of Things, where many home devices are going to be connected to Internet, there is going to increase the number of devices exponentially [18].

- **Increase of device's bitrate:** Apart from modulations or robustness, giving higher bandwidth to a device is synonym of increasing its bandwidth as a rule of thumb. With the increase of demand on high quality video and audio, users need more resources for their mobile devices.

- **Robustness:** Having a higher bandwidth can also provide more robust communications as higher coding schemes to prevent errors in the communication.

As we can see, there are many good reasons to look for alternatives in order to look for higher bandwidths as the wireless technologies are spreading and their demand increase.

2.4 Evolution of IEEE 802.11

The most used wireless local area networks protocols are the different ratifications under the IEEE 802.11 standard. The most important changes on the different versions regarding to their web site [19] are:

as we can see on the following time line:

- **1997.** 802.11 standard is published achieving 2Mbps in the 2.4GHz band.

- **1999.** 802.11b updates previous 802.11 with widespreading use of WLAN technology, considering it the first generation of wireless local area network technology. 802.11a is also published, considering it as the second generation, using the 5GHz band reaching 54Mbps.

- **2003.** 802.11g allows the devices to use the 2.4GHz band as well as the 5GHz band achieving 54Mbps. It is considered the third generation.
- **2005.** 802.11e gives to the 802.11 standard quality of service features, having the option of prioritizing different data types. It works on the 5.85GHz band of the spectrum.
- **2007.** 802.11n works in the 2.4GHz and 5GHz bands with a maximum data rate of 450Mbps. It is considered the fourth generation. In 2009 a second revision of it reaches the 600Mbps of bitrate.
- **2011.** 802.11k improves the way wireless traffic is distributed in crowded areas from the access point. 802.11u makes the users to know what services an access point can offer.
- **2013.** 802.11ac is considered the fifth generation. It is designed only for the 5GHz band giving a maximum rate of 1.3Gbps. It allows the access point to send multiple streams to a single user.

We can see that the standard has always evolve looking for higher bitrates and better quality of service.

In 2012, the WiGig alliance [6] merged with the IEEE 802.11ad amendment, which will bring us in the near future the first 60GHz wireless network area to connect multiple devices promising a throughput of 7Gbps.

2.5 60GHz Communications

For several years from now, millimeter wave communications have been only used for static applications like backhaul links, but recently, with the formation of the WiGig Alliance [6], several mm-wave devices have been created for home applications as wireless docking stations and laptops. This bachelor thesis is centered on analyzing these off-the-shelf 60GHz devices.

The WiGig alliance was latter merged in 2012 into the IEEE 802.11ad amendment, which makes a unified millimeter wave communication standard for different uses, including dense deployment scenarios with mobility as described in [20].

The main properties of 60GHz communications are:

- **Transmission Characteristics.** Millimiter wave communications are characterized in a very different way than the non-commercial ISM frequencies that we are used to, which works bellow 6GHz. At 60GHz, attenuation of free space is increased 20dB compared to a transmission at 6GHz if we apply the Friis transmission equation, as the frequency increases ten times:

  We can demonstrate this through Equation 3, where Pt is the Transmitted power, Pr is the Received power, Gt and Gr the transmitter and receiver gains, λ the wavelength of the signal, R the distance between receiver and transmitter, f is the frequency of the signal and c is the speed of light. With this equation we can relate the received power of two transmiters under the same conditions but with different frequencies (3c) and see that with a given frequency 1 ten times bigger than a given frequency 2 (3d) we obtain a 20dB difference of power received (3e).

The signal drop with blockage of obstacles also increases as the frequency increases [21]. This attenuation is tried to be overcome using directional antennas. It is important to mention that it is very difficult to achieve omni-directional communication at the mm-wave range as planar antennas arrays are used for this kind of communications [22].

- **Increase in bandwidth.** One of the main features when developers chose the 60GHz region was the big amount of unlicensed bandwidth that is available on this part of the spectrum, which varies from 6 to 9 Ghz depending on the country. This bandwidth increase promises high throughput with capacity for many devices and together with its high attenuation, very high spatial reuse.

- **Phased antenna arrays.** With the increase of attenuation, directionality has gained a central role for the mm-wave communications. Thus, directionality will signify more energy efficient and interference-free devices. Dense antenna arrays could be implemented in small devices for this mm-wave communications as the size of each element on the array only needs to be $\frac{\lambda}{4}$, being 1mm.

- **Device discovery.** As true omni-directional communication is not possible in antenna arrays, there is a need on steering the main beam to find devices. This steering relies on codebooks of predefined beam patterns to simplify the complexity of the transceivers, as explained in [9].

- **Beam training.** As the antenna arrays used in this 60GHz transmissions are highly directional, the transmitter needs to focus its antenna's main beam to the receiver. As the devices can move while they are connected, they need to train their beams to the newer position so the communication is always optimum.

$$\frac{Pt}{Pr} = Gt \cdot Gr \cdot (\frac{\lambda}{4 \cdot \pi \cdot R})^2 \tag{3a}$$

$$\frac{Pt}{Pr} = Gt \cdot Gr \cdot (\frac{c}{4 \cdot \pi \cdot R})^2 \cdot (\frac{1}{f})^2 \tag{3b}$$

$$\frac{Pr_1}{Pr_2} = (\frac{f_1}{f_2})^2 \tag{3c}$$

$$f_1 = 10 \cdot f_2 \tag{3d}$$

$$\frac{Pr_1}{Pr_2}[dB] = 10 \cdot \log(100) = 20dB \tag{3e}$$

3 Objectives of the Thesis: Analyzing mm-Wave Networks

With this bachelor thesis it is going to be presented an in-depth beamforming and reflection analysis of the off-the-shelf Dell 60GHz communication systems with phased antenna arrays.

First generation 60GHz commercial devices are black boxes as the standards are not public and devices do not offer information or configuration of the internal working. Our intention is to extract detailed information about their behaviour from a frame level analysis through different measurement campaigns.

The analyzed 60GHz off-the-shelf equipment consist on a wireless docking station together with its notebook, the 'D5000' and the 'Latitude E7450' from Dell.

The different objectives are: extract information about their beam patterns, know how a device discovers an other device and pairs with it and finally see how do reflections behave.

3.1 Beam Pattern Measurement

Theoretical reports, as [23, 24, 25] declare that phased antenna arrays transmit power in a very directional way, without considering the impact of any side lobes, but there are not many reports about the real performance of this arrays and how the sidelobes can affect the communication.

In this work we are going to measure the 8x2 antenna array beam pattern and see how it changes for an unaligned receiver. Both patterns will be measured, the laptop's and the wireless docking station's.

3.2 Device Discovery

As directional antenna arrays are used, the devices need some technique to discover and set up the communication between them. We are going to go through a detailed description on how the wireless docking station pairs with the laptop and how the beamforming training behaves on them.

In the IEEE 802.11ad standard, the transmitter divides the transmitting area in several virtual sectors and makes beam sweeps looking for the optimum transmit sector. Once the receiver finds the sector with the strongest reception, acknowledges it to the sector sweep. This process can be seen described on [20].

We want to analyze if our WiGig devices behave in the same way for device discovery as IEEE 802.11ad does or not.

3.3 Reflections

60GHz communication has been studied in terms on reflections [2], but this studies have always been done in terms on directional antennas as horn antennas, but not for real phased antenna arrays.

This measurement campaign shows how phased antenna arrays create reflections in an office environment. This reflections could increase the coverage area if the direct path is blocked, or could lead to additional interferences distorting the received signal.

4 Experimental Methodology

4.1 Equipment

As it was mentioned on Section 3, the off-the-shelf equipment that is going to be analyzed is treated as black box. What this means is that we need some external devices to capture the communication between the 60GHz system to see how it behaves.

The following sections describe the used equipment for creating, capturing and analyzing the 60GHz communications.

4.1.1 Creating 60GHz Communication

In order to setup the 60GHz communication we have used the Dell 'Latitude E7450' laptop together with its wireless dock 'D5000'. First, we needed to install the Dell 1601 WiGig card into the laptop, as it does not come installed with it from the factory. Once the card was installed with all the needed drivers, the wireless docking station appears using its own program as an access point. Once it is selected, the wireless docking station works as a normal wired one.

In order to have a continuous data traffic flow from the laptop to the docking station, we have been playing a random noise video on the screen connected to the docking station. It was chosen a random noise video to make sure that the data was not going to be compressed.

This system uses the WiGig protocol [26], which delivers a multi-gigabit speed low latency communication making possible to have 3 different 3.0 USB ports and two high definition screens on the wireless dock.

The protocol has four available channels with 2.16GHz bandwidth each. We have always left the channel fixed at 61.56GHz so we do not observe changes on the medium.

In order to see which kind of antenna arrays were used in the system, they were disassembled. The docking station and the laptop use a 8x2 antenna array as we can observe on the photograph at Figure 4.

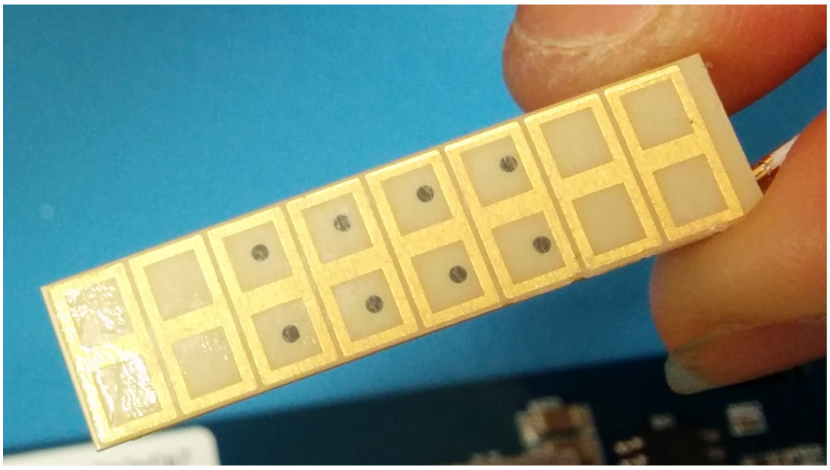


Figure 4: 8x2 Antenna array.

For the interference study done in the reflections setup, we have used a second device to create 60GHz communications under a different protocol to produce inter-system interferences. We used the HDMI DVDO Air [27], which is a low latency non compressed video transmitter working under the WiHD protocol [28] which uses very wide patterns under a robust modulation.

4.1.2 Capturing 60GHz Communication

In order to capture the frames we have used an oscilloscope together with a 60GHz reception system:

The reception system is a Vubiq 60GHz development system. The Vubiq system captures the WiGig communications in differential mode as explained in Section 2.2.1. The Vubiq can be tuned with its own driver, the most important parameters that we can choose are: the centre frequency of the transmission, the attenuation from the antenna to the equipment and the protocol characterization of the transmission [29].

The antenna attached to the Vubiq system can be of different types. In the beginning of the experiments, when learning how to use everything, we have been using a general open wave guide antenna, but latter a more directional horn antenna was used for the different tests.

The oscilloscope used is an Agilent MSO-3034A with an analogue AD converter of 350MHz bandwidth and a maximum sampling rate of 2 gigasamples per second. The samplerate might be reduced in our tests in order to obtain longer data captures. The oscilloscope includes a LAN TCP/IP module so it can be easily attached to a computer in order to save the data.

The bandwidth of the oscilloscope is much smaller than the one used by the studied equipment, but as we are going to do a energy level analysis we do not need the full bandwidth.

What we receive in the oscilloscope during the transmissions can be seen in Figure 5. The received signal is divided into four channels, which we will call from now on Channel 1, 2, 3 and 4, being Channel 1 the one on the top and Channel 4 the one on the bottom.

We obtain traces of the analog differential I/Q modulation at the output of the Vubiq receiver where timing and amplitude can be extracted. I/Q modulation is widely explained in Section 2.2.2.

From Figure 5 we can distinguish the different frames from the noise, as well as we can also distinguish which frames are transmitted by the laptop and which frames are transmitted by the docking station:

As the direction of the communicated data was from the laptop to the docking station, we can observe that the laptop's frames are longer that the docking station ones, that are likely just simple acknowledgements. On Section 5.1.1 we will describe an extended analysis of the frame format of the communication.

In the example that can be seen on Figure 5, the antenna was focusing the laptop, so we can see that the laptops frames are received with more energy than the frames received by the dock.

In Figure 6 we can see a different capture, where the power received from the frames is much lower than the one in Figure 5. We obtain this power difference

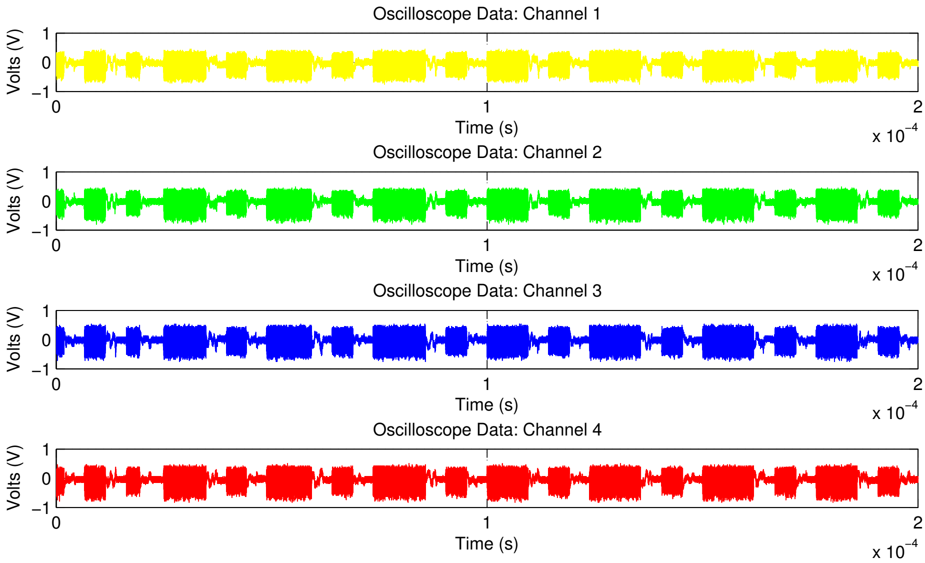


Figure 5: Link capture: High amplitude capture.

because now, the antenna was focusing to a different place where we do not receive much energy from the systems. In the post-processing of this type of captures it is more difficult to distinguish the frames from the noise than in the previous capture shown in Figure 5.

From now on we will just plot one of the channels from the oscilloscope instead of the four channels, as we are only interested in their main shape and this will make the document more readable.

4.1.3 Measurement Data Management

All the measurement setups are controlled and measured through Matlab [30] as it is a powerful platform that can control all the external devices that we need during the measurements. It is also the tool that we will use to process the obtained data so we are not having compatibility problems when importing the data files.

In order to store the data received from the oscilloscope, we have used its LAN TCP/IP module connected to the laptop. To set up the communication between the computer and the oscilloscope, a VISA instrument object is created with the Keysigh IO libraries Suite from Agilent [31] together with the Matlab's Instrument control toolbox [32].

When creating the VISA object of the oscilloscope in Matlab, it is needed to give as arguments the IP of the oscilloscope, the input buffer size and the most significant bit byte order (little endian in our case).

4.1.4 Rotatory Stage

For the reflection measurements we need a rotatory stage to put it together with the receiver. Also, to study the device discovery mechanism, a rotatory stage to attach the dock results very serviceable so we can measure it faster and in a more

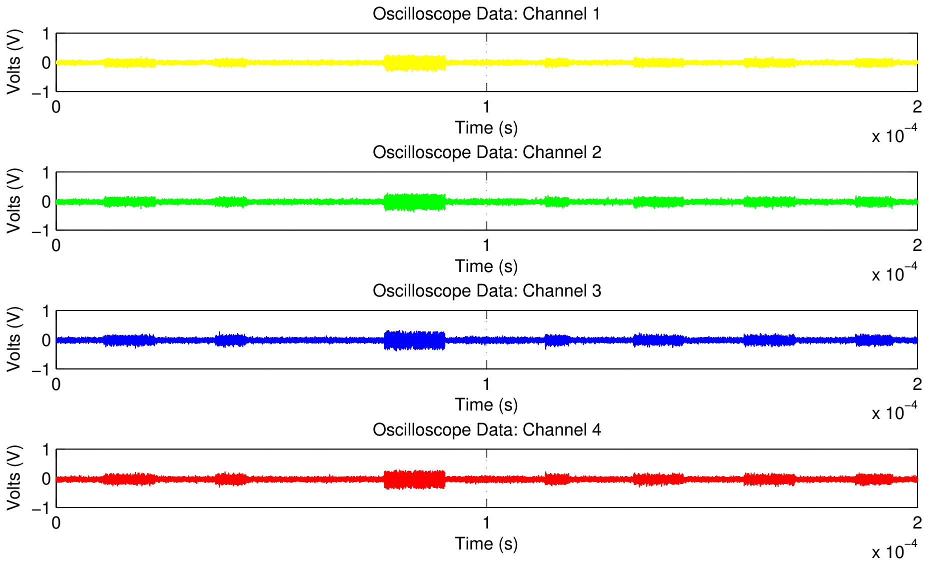


Figure 6: Link capture: Low amplitude capture.

precise way. Buying one rotatory stage was not necessary as we decided to build one by ourselves.

In order to build it, we have used an Arduino as microcontroller and a stepper motor. An H-Bridge was needed to feed the motor with enough power to move the system.

We chose Arduino as the microcontroller to drive the motor because, as they mention in their web page, an Arduino is "an open-source electronics platform based on easy-to-use hardware and software. It's intended for anyone making interactive projects" [33], so it is easier than different microcontrollers as it could be the PIC18F2525.

One of the main advantages when using Arduino for this project was that it has its own libraries for the use of stepper motors [34], so the coding of this rotatory stage was much more easier.

Once the rotatory stage was ready, we decided to install a wireless module between the Arduino controller and the computer to have a more flexible rotatory stage avoiding the use of USB cable between the station and the computer. We used a pair of APC220 transceivers from APPCON Technologies [35], which are wireless RF transceivers working at 433MHz which come with an USB to serial converter so one of them can be connected to the Arduino and the other to the computer.

Arduino and the RF controller use serial communication, so it is easy to communicate with them through Matlab. When creating the serial object in Matlab we just need to clarify which serial COM port is using and what baud rate (Symbol rate) we want to use between them.

4.2 Measurement Setups

In order to do the beam pattern and the reflection measurements, we first need to set up the link between the laptop and the wireless docking station and set the data transmission between them.

For the beam pattern measurement we need to go through a semicircle around the analyzed device taking captures with the receiving system, which is composed by the Vubiq receiving system connected the oscilloscope which saves the traces on the laptop.

For the reflection measurement we need to place the reception system on the rotatory stage so we can capture the energy coming from different angles.

For the device discovery measurement, we need to place the unpaired docking station on top of the rotatory stage and focus the receiving system onto it. As the docking station will be rotating, the receiving system will capture the radiated power from every angle of the dock.

4.3 Measurement Postprocessing: Obtaining the Signal Strength

In order to find the signal strength received by the Vubiq system what we need to obtain is the amplitude of the signal.

To find the amplitude we need to calculate the square root of the sum of the squares of the I and Q components as shown in Equation 4. We can see the results in Figure 7.

$$Amplitude = \sqrt{(I^2 + Q^2)} \tag{4}$$

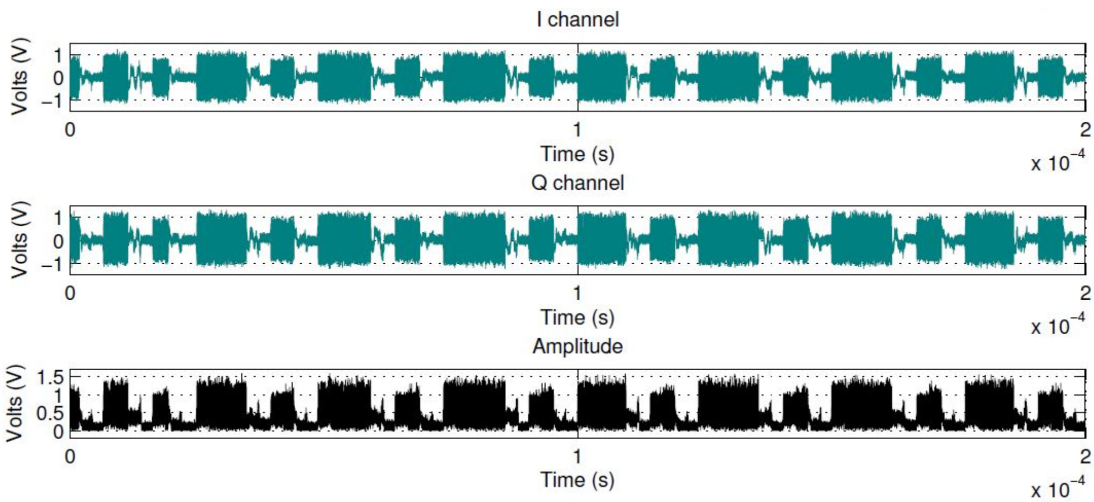


Figure 7: Received I and Q components and signal strength.

Once we have detected the frames from the transmitter, we calculate the amplitude of all the vector points in the frame to obtain the average energy of the signal.

5 Measurement Results

In this section we present the results of the different measurement campaigns, as well as explaining their setup and analysis. We begin with the analysis on the frame flow protocol of the WiGig devices followed by the laptop's and docking station's beam patterns, the docking station's device discovery process analysis and we finish with the reflection test and their impact on interference.

All the results from the different testbeds are given in decibels, where the dB conversion was realized using the highest value of the measurement as reference for the 0dB value.

5.1 Frame Format Analysis

In order to obtain conclusions from the different measurement campaigns, we first investigate the behaviour of the frame format of the systems. With this section we explain how the data transmission protocol and the device discovery process behaves in these devices.

5.1.1 Data Transmission Protocol Analysis

The data is transmitted through frames bursts, having always one beacon frame from each device at the beginning and at the end of every burst. This beacon frames are transmitted with more power than normal data frames.

In the transmission bursts we can see a clear structure of data frames and acknowledgement frames. Data frames are longer in time than Ack frames, as they transmit more information.

In order to achieve this conclusions we have been looking for repetitive patterns in the transmission as well as setting special transmission conditions like different types of data transmission to observe the resulting traffic patterns. We have also compared this patterns with the related 802.11ad standard, which also has beacons before and after every burst of frames and when there is no transmission as a keep alive frame.

Figure 8 shows the typical frame format for a data transmission from the notebook to the docking station.

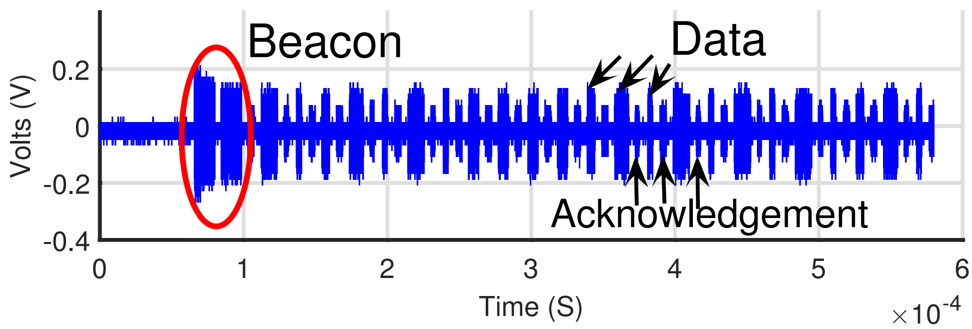


Figure 8: Dell D5000 frame flow.

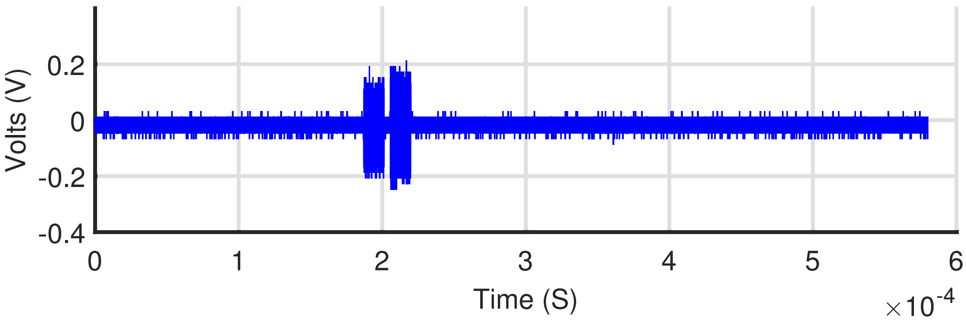


Figure 9: Dell D5000 keep alive frame.

In Figure 9 we can see how the keep alive frames behave. As well as the beacon frames, they are transmitted with more power than normal data-ack frames. This keep alive frames are transmitted periodically every 1.1 millisecond when there is no data transmission between the stations.

5.1.2 Device Discovery Protocol Analysis

During the device discovery process we have distinguished two different processes which will be shown on the Figures 10 and 11.

The device discovery is performed by the wireless docking station. On Figure 10 we can see how the energy of the docking station varies in 32 different sections, which means that the docking station is doing a beam sweep looking for new devices.

This 32 sub-elements reception is always the same in amplitude and shape if the location of both docking station and Vubiq remains the same. If we change the Vubiq receiver to a different place, we will receive the same scheme of the 32 sub-elements frame, but their signal levels would vary, some of the elements will be received with more power, and some with less.

This device discovery frame is always sent with a fixed frequency of 102.4 ms if the docking station is not paired to any device.

It can also be seen that the docking station transmits more power when doing this device discovery process that when it is transmitting data to a paired device. This increase of transmitted power is due to the fact that the docking station is looking for devices everywhere in the room.

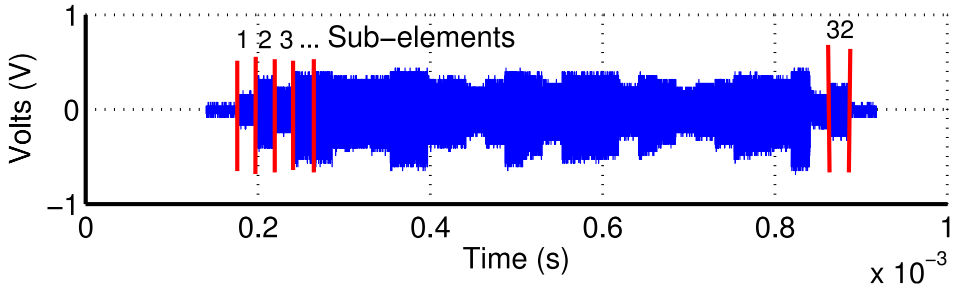


Figure 10: Device discovery process.

When the searching device finds the receipting device, they proceed to establish their connection showing the handshake that can be seen in Figure 11. In this figure we can see how firstly a beacon frame is interchanged and then different small bursts are sent together with some beacon frames.

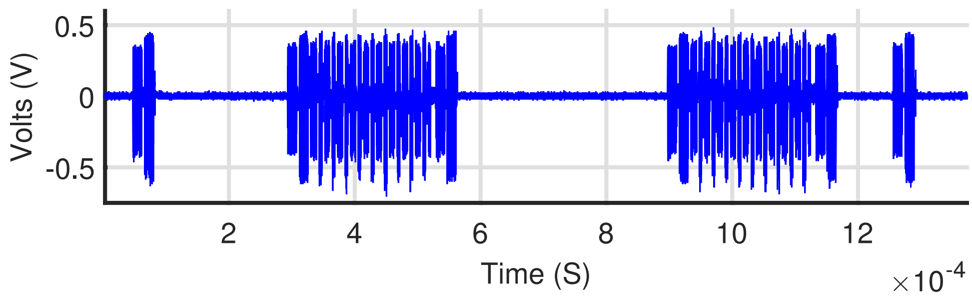


Figure 11: Device discovery handshake.

In Section 5.3 we show how the 32 sub-elements behave from a beamforming point of view, extracting the beam patterns of all the sub-elements.

5.2 Beam Pattern Analysis

5.2.1 Setup

In order to measure the beam pattern of both devices we need to do the following:

It has been measured the beam pattern in the azimuthal plane on 100 equally spaced measurement locations on a 3.2m radius semicircle around the device under test. This setup can be seen in the scheme from Figure 12. It has been used a highly directional horn antenna on the Vubiq receiver.

We have made sure that we were only going to capture the power radiated by the tested device by aligning correctly the Vubiq receiver with the measured device, the impact of the received signal from the second device is almost imperceptible. The testbed was realized outdoors in a big and empty field to avoid any kind of reflections from both devices.

When processing the frame traces,there were only extracted the ones sent from the studied device, also taking care of discarding the control frames as the beacons and keep alive frames because this management frames are transmitted with higher power and in wider antenna patterns as was explained on Section 5.1.1.

5.2.2 Notebook Beam Pattern Results

The beam pattern of the notebook was measured being perfect aligned with the wireless dock, making $\theta_{LOS} = 0^o$. In Figure 13 we can see the beam pattern of the laptop as a polar plot. In Figure 14 we can see the beam pattern of the laptop as a linear plot, together with marks at $-3dB$ and at $-6dB$ so we can make a better analysis of the pattern.

Now we will proceed to compute the more significant parameters from the radiation pattern:

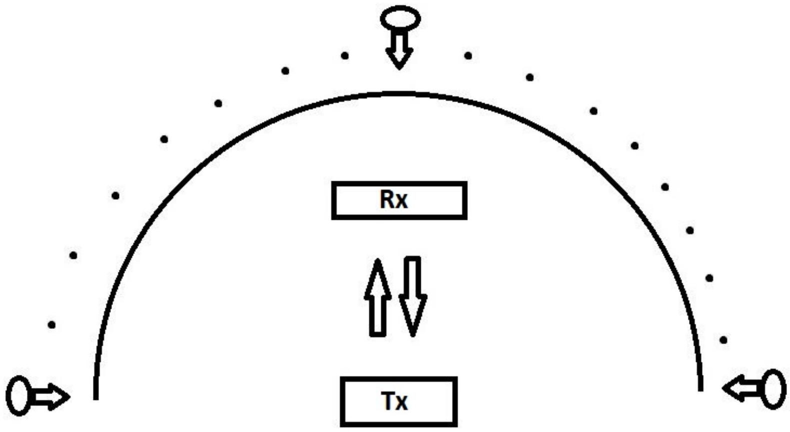


Figure 12: Beam pattern setup.

- **Half Power Beamwidth:** We can directly see from Figure 14 that $HPW = 16^o$.
- **Quarter Power Beamwidth:** We can directly see from Figure 14 that $QPW = 20^o$.
- **Sidelobe Level:** The larger sidelobe, placed at 22º has a power level of $-2dB$, while the ones placed at 18º, -50º and -18º are all of them between -3 and -4 dB. At -70º and 65º there two wide sidelobes with a power loss of $-5dB$. We can also appreciate at -30º and at 30º two sidelobes with a power loss of $-6dB$.
- **Antenna Aperture:** We can just compute the aperture as:

$$Aperture = 2 \cdot cotangent(\frac{16^O}{3.2}) = 229.17$$

- **Directivity:** Directivity is going to be equal to:

$$D = (\frac{4 \cdot \pi}{0.005^2}) \cdot 229.17 = 1.15 \cdot 10^8$$

From this measurement, we can see that this 60GHz antenna array is very directional, but the sidelobes are strong enough to interfere with other devices. This 60GHz antenna array is not as directional as the theoretical reports stand as we mentioned on section 3.1.

We can see that we are not obtaining a symmetrical pattern as we are used to see as the antenna of the laptop is placed in one side of the lid. This means that the radiation of one side needs to go through more materials than in the other side, making imperfections on the pattern.

5.2.3 D5000 Wireless Dock Beam Pattern Results

The wireless docking stations beam pattern was measured in two different ways:

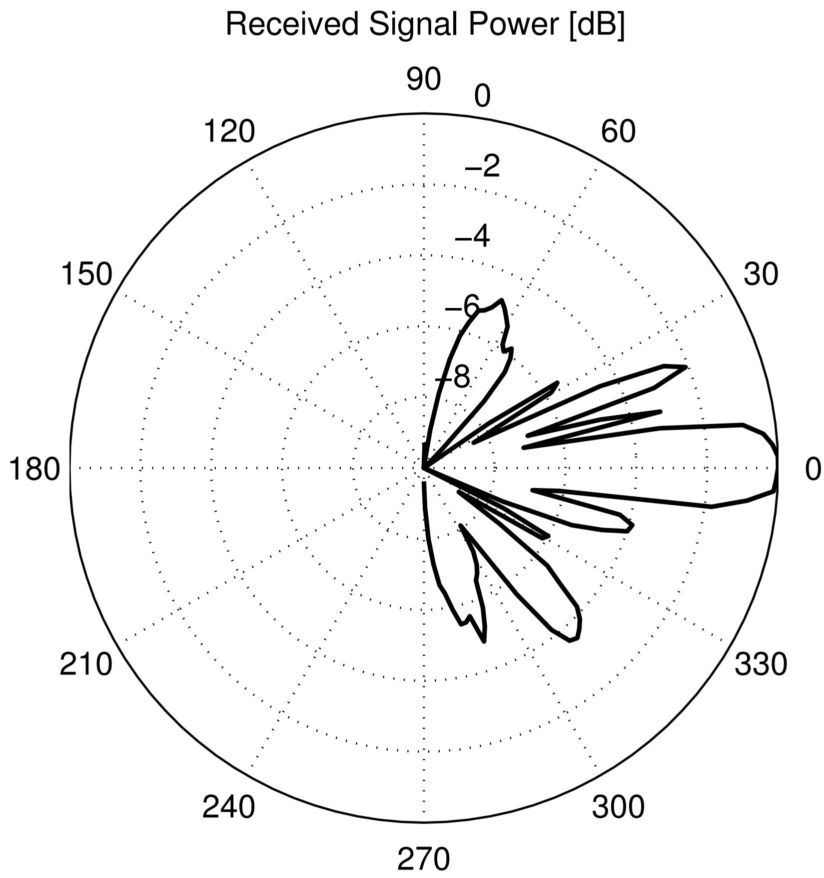


Figure 13: Laptop beam pattern (polar representation).

First, the beam pattern of the D5000 wireless docking station was measured being in perfect alignment with the laptop, making $\theta_{LOS} = 0^o$. Then, the beam pattern of the D5000 wireless docking station was measured unaligned with the laptop, adjusting the misalignment to $\theta_{LOS} = 30^o$.

In Figure 15 we can see both beam patterns as a polar plot, being the unaligned measurement in red and the aligned one in black. In Figure 16 we can see both beam pattern as a linear plot, together with marks at $-3dB$ and at $-6dB$ so we can make a better analysis of the pattern. For the Figures 15 and 16 of the radiation pattern, it has been shifted 30^o the unaligned pattern so we can observe their differences in a more visual way.

We are going to first carry out the analysis of the aligned measurement:

- **Half Power Beamwidth:** We can directly see from Figure 16 that $HPW = 18^o$.
- **Quarter Power Beamwidth:** We can directly see from Figure 16 that $QPW = 22^o$.
- **Sidelobe Level:** The two largest sidelobes are placed on -15^o and on -35^o, with a power loss of $2.5dB$, the sidelobe at -35^o is much wider and has a power peak at -30^o. There is also a wide sidelobe centered on 50^o with a

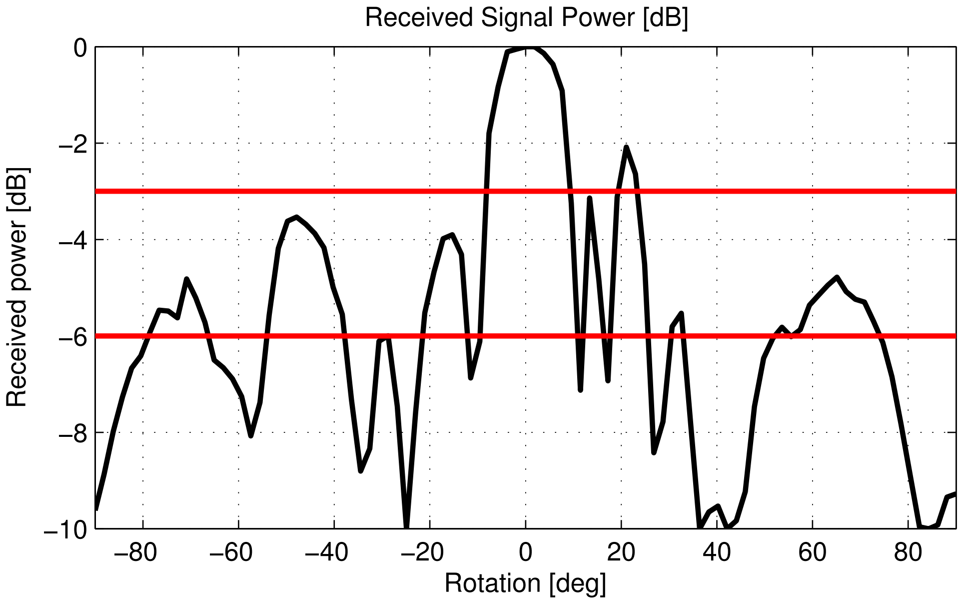


Figure 14: Laptop beam pattern.

power loss of $3.5dB$. With a power loss of $6dB$ there is a sidelobe at 20º. At -70º there is a sidelobe with $8dB$ loss and with a peak at -70º with -6dB loss.

- **Antenna Aperture:** We can just compute the aperture as:

$$Aperture = 2 \cdot cotangent(\frac{18^o}{3.2}) = 203.7$$

- **Directivity:** Directivity is going to be equal to:

$$D = (\frac{4 \cdot \pi}{0.005^2}) \cdot 203.7 = 1.023 \cdot 10^7$$

If now we make the analysis of the unaligned measurement, we obtain the following results:

- **Half Power Beamwidth:** We can directly see from Figure 16 that $HPW = 16^o$.

- **Quarter Power Beamwidth:** We can directly see from Figure 16 that $QPW = 20^o$.

- **Sidelobe Level:** The larger sidelobe, placed at -60º has a power level of $-0.5dB$, while the ones placed at -90º and -35º are $-1dB$. At -15º and at 30º there are two sidelobes with a power loss of $-2dB$. We can also appreciate at -25º (pairing up -90º and -35º sidelobes) and at -75º two sidelobes with a power loss of $-3dB$.

- **Antenna Aperture:** We can just compute the aperture as:

$$Aperture = 2 \cdot cotangent(\frac{16^o}{3.2}) = 229.17$$

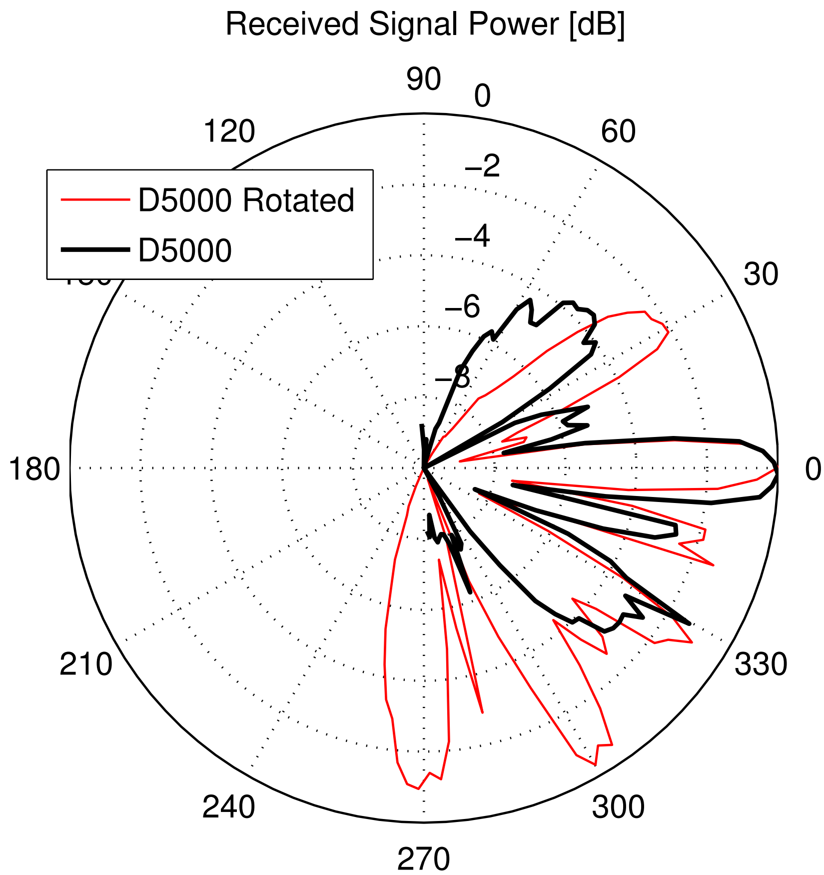


Figure 15: Wireless dock beam pattern (polar representation).

- **Directivity:** Directivity is going to be equal to:

$$D = (\frac{4 \cdot \pi}{0.005^2}) \cdot 229.17 = 1.15 \cdot 10^8$$

From the aligned measurement we can see that the docking station is not as directional as the laptop is, as there are higher and wider sidelobes. But we can still say that it is a very directional transmission (but not as directional as mentioned on section 3.1).

With the rotation shift, we can see that the beam pattern changes into a less directional pattern, having much bigger side lobes, but it can still considered a directional communication as the higher power beam points at the position of the laptop (but not as directional as mentioned on section 3.1).

From the directivity equation results, we might say that the rotated dock is more directive than the non rotated. We obtain this result because the directivity equation does not take the sidelobes into consideration, taking only the main beam aperture.

5.2.4 Conclusion

From this measurement, we can see that the mm-wave atenna arrays are very directional when they are aligned perfectly, but they still have big enough sidelobes

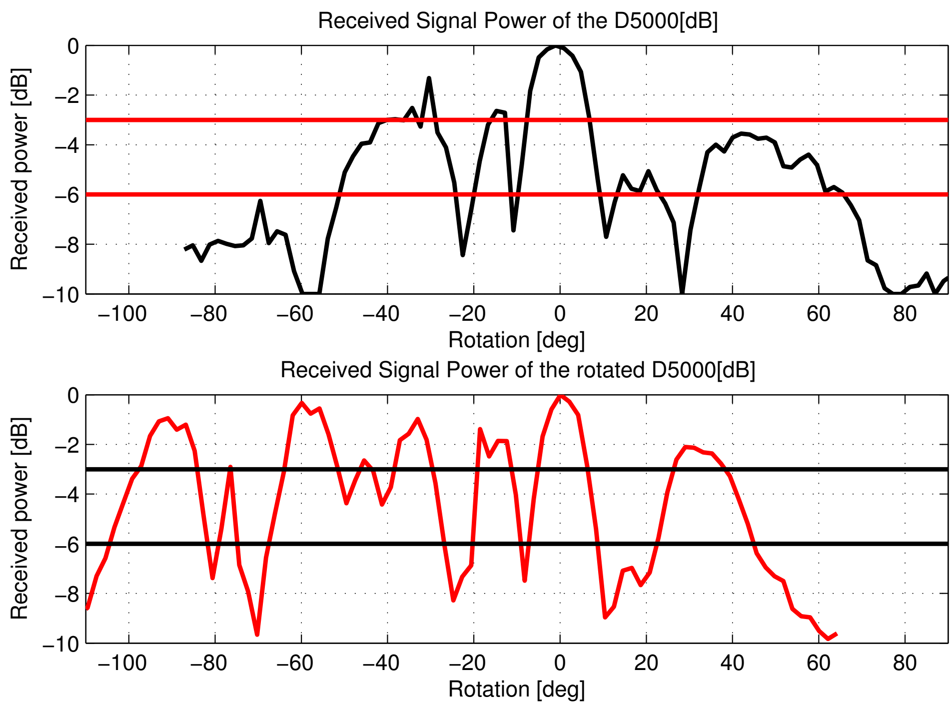


Figure 16: Wireless dock beam pattern.

to interfere with other devices, so we can say that is not as directional as the theoretical reports stand as we mentioned on section 3.1.

It is needed to mention that with non-aligned transmission, the devices would cause many interferences with devices in the same area as it leads to a transmission with more and stronger sidelobes than aligned transmissions.

What we also need to take into consideration is that we have analysed 8x2 element antenna array, and this is a technology which is supposed that will grow in number of elements in the future, so directionality will evolve as the arrays antennas evolve too.

5.3 Device Discovery

5.3.1 Setup

For the device discovery process it is needed some omnidirectional pattern to find the devices, instead, in Section 5.1.2 we have seen that the device discovery protocol shows a 32 sub-element frame with particular beampattern properties. With this measurement setup we are going to see how these sub-elements behave.

To see how these 32 sub-elements of the device discovery frame evolve for different positions, we need to do the same setup than the mentioned for the beam pattern in Figure 12, but instead of doing it like this, we used the rotating table to save time and gain precision.

We positioned the wireless dock on top of the rotating table and made the measurements with a high directional horn antenna in an outdoor court to avoid reflections.

5.3.2 Results

For device discovery and beam training, omnidirectional patterns are needed, however, as this omnidirectional patterns are a big challenge for millimeter wave communications [22], different quasi omnidirectional patterns are swept form the wireless dock.

In the Annex C can be observed the 32 different patterns radiated by the dock. In Figure 17 we can observe 4 out of the 32 different patterns.

We can see that the patterns have a large aperture and with small gaps on their main lobes. These small gaps will make the receiving device to know which is the element that suits better for the receiving lobe as it will make easier the localization.

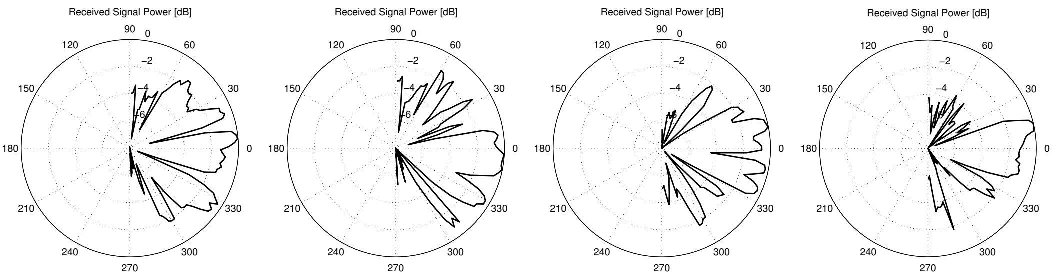


Figure 17: Quasi omnidirectional beam patterns swept by the D5000.

5.3.3 Conclusions

We have seen that our WiGig devices do not perform a beam sweep through different virtual sectors as the devices complaint to IEEE 802.11ad standards do. Instead, our device uses a different technique making different quasi omnidirectional beam patterns.

Omnidirectional patterns are hard to achieve on mm-wave antenna arrays [22], but this approximation of sweeping quasi omnidirectional beam patterns is a good approach to discover the devices and establish initial communication.

Once the laptop receives the device discovery information from one of the frame sub-elements, the beamforming training is started, optimizing the radiation patterns of both devices to achieve optimum link conditions.

5.4 Reflection Analysis

In this experiment we want to measure how mm-wave signals reflect in an office room to see how it could affect different devices in the same room.

5.4.1 Setup

For the measurement campaign, we used the room described in Figure 18, a rectangular 9m x 6.15m room which had one full wall made of glass, one made of a wooden furniture, one made of bricks and another one made of bricks with different windows on it.

The room had four long tables where the laptop and the docking station where positioned as can be seen on Figure 18, having a 45 degrees crosswise angle with respect to the walls. In the same figure we can see the different positions (letters from A to F) where the rotatory stage was set up for the different measurements.

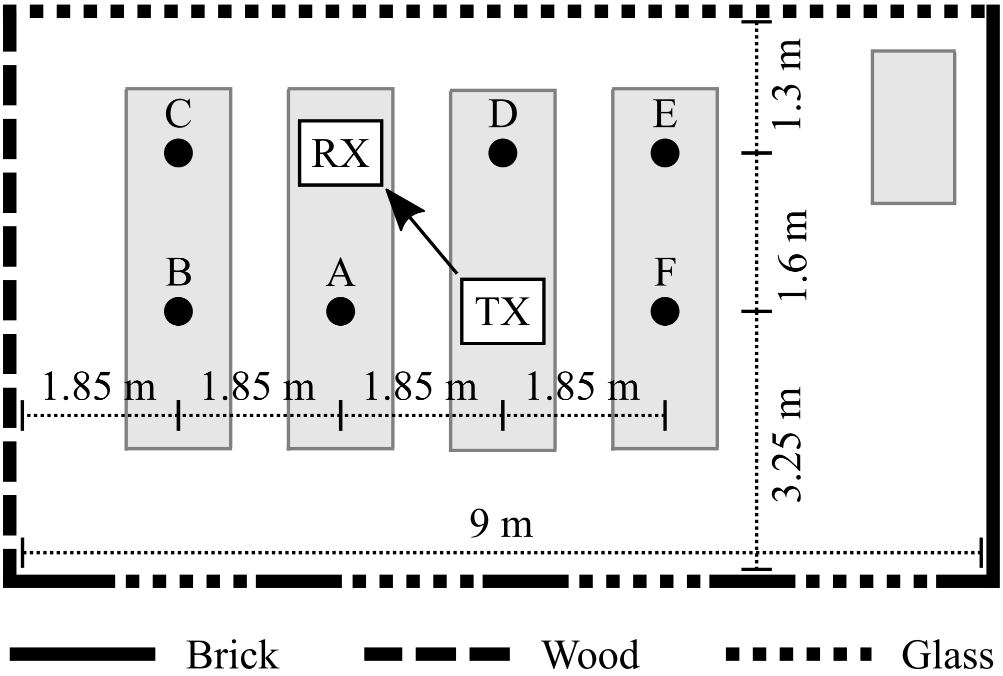


Figure 18: Reflection test setup.

5.4.2 Results

Reflections for the WiGig link can be seen in Figure 19.

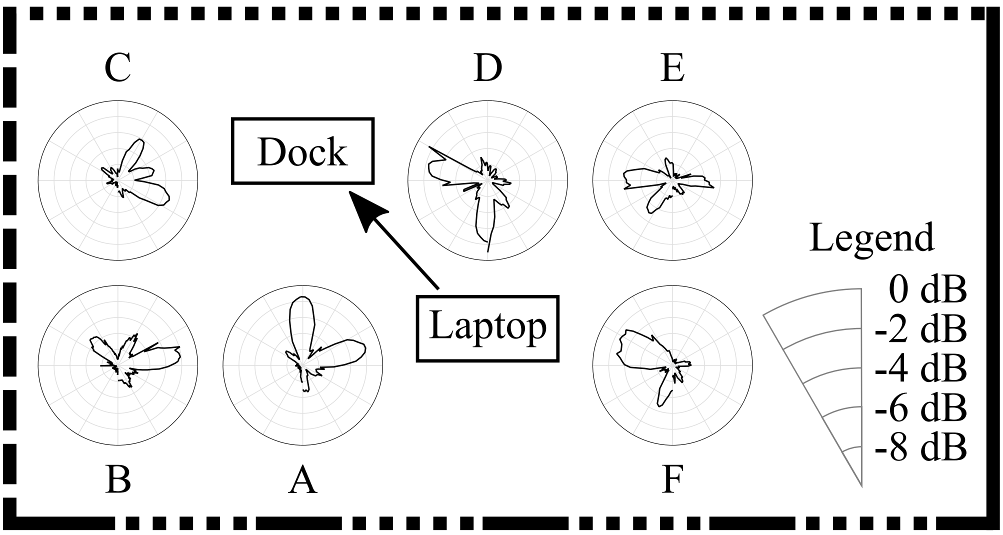


Figure 19: Reflection test result: WiGig link.

We can observe that from the different positions we have a big impact from the direct path of the docking station and laptop, as both have powerful sidelobes as discussed on section 5.2. In all the positions except from F we can clearly distinguish how the direct path of both stations are received from their locations. In F we can not differentiate the stations as both are merged into the same lobe.

In addition to the impact of the direct path of the transmitters, we can see in all the measured positions a considerable amount of power coming from reflections:

- Position A shows a -7dB reflection coming from the window of the wall as well as one coming from the glass wall and wooden furniture corner.
- Position B shows a -5dB reflection coming from the wooden furniture, which previously was reflected on the glass wall.
- Position C shows a -4dB reflection coming from the glass wall. We can observe that the reflected power is 1dB higher than the direct path of the dock and 1 dB smaller than the direct path of the laptop, so reflections would have a big impact there.
- Position D shows some small reflections from the glass wall as well than from the brick walls corner. This position does not have a big impact from reflections
- Position E shows a strong reflection from the glass wall as well as a very strong reflection from the brick wall. This second reflection coming from the brick wall is only half decibel weaker than the most strongest beam which is comming from the docking station.
- Position F shows a wide beam that covers both docking station and laptop without giving the possibility to differentiate them from their power level. It also shows a strong reflection coming from the windowed wall as well as two smaller reflections coming from the non-windowed brick wall.

5.4.3 Interference Impact

In order to see how reflections could affect in terms of interference, we have placed a different 60 GHz system under the same setup. The system is a HDMI DVDO Air 3 [27], which is a low latency non compressed video transmitter working on the same 60GHz frequency band under the WiHD protocol [28].

The reflection results obtained from this Wireless HDMI, which can be seen in Figure 20 have different reflection components than the ones obtained by the laptop and docking station seen in Figure 19. We can see that the most strong components are the ones which are coming from the direct path of both devices in both setups, but we can also see that the wireless HDMI produces more reflections.

In order to see how this reflections could affect to a parallel link, we have placed the notebook on position F and the wireless dock on position E. In order to avoid the interference caused by the direct path, we have isolated the direct path between the Wireless HDMI link and the dock and notebook as we can see on Figure 21.

With this setup we have seen many interferences on the WiGig system as we can see on the captures ploted on Figures 22a or 22b. In order to obtain this conclusions we observed the WiGig data transmission with the Vubiq receiving

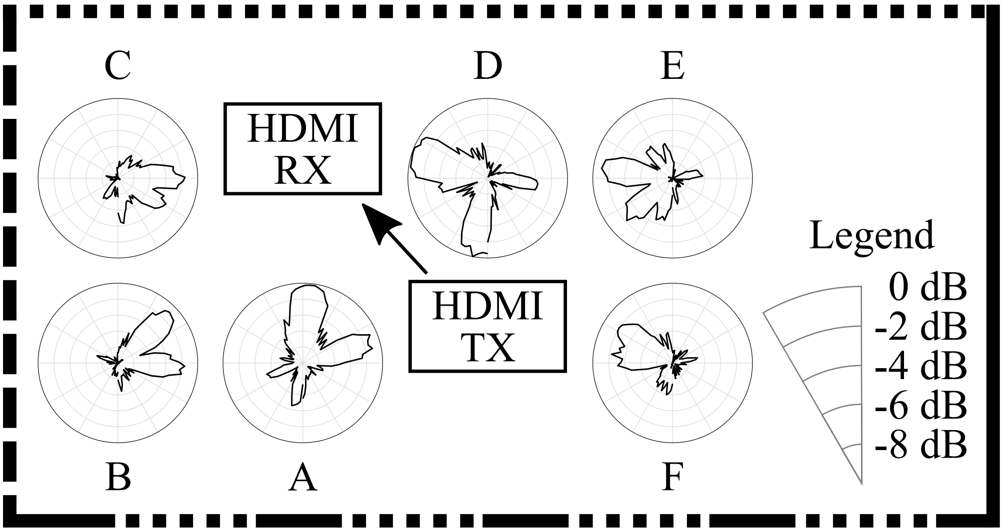


Figure 20: Reflection test result: Wireless HDMI.

system while the wireless HDMI was transmitting. We looked for unusual patterns in the data-ack frame format from the notebook-docking station finding frame losses and retransmissions.

In Figure 22a we can see how the data-ack pattern carried by the laptop and docking station fails. Some interference is received at 0.2 milliseconds when the laptop sends a frame at the same time that it receives a reflected wireless HDMI frame. As it is not properly received, it does not receive an ack frame and tries to retransmit it, failing again. After this failed retransmission attempt, it waits and begins a new data burst successfully.

In Figure 22b we can see how the interferences breaks the transmission making the data-ack pattern end. When it tries to setup again the data transmission with a new burst, fails again as it does not receive an acknowledgement. After the second attempt, the link is settled again.

5.4.4 Conclusions

From the above results we can conclude that reflections can be a strong source of decisions for mm-wave communications, making them constructive or destructive. Taking that into account, we can observe that from some of the measured positions the reflections are almost as strong as the received signal from the direct paths.

If we block the direct path between the measured positions with respect to the docking station and the laptop communication, the reflections have shown to cause interference effects to a system that is using the same frequency on that same room, making the receiver mix the signals from its paired transmitter with the reflected transmitter without being possible to differentiate them.

But if we move the dock or the laptop into those places and block their direct path, we know that they would be able to keep communicating as they are going to manage to use the reflectors as the new path.

This result verifies that even with a blocked path we might share the channel bandwidth with different devices from different communication areas by means of their reflections. Carrier sensing is going to be necessary if multiple access

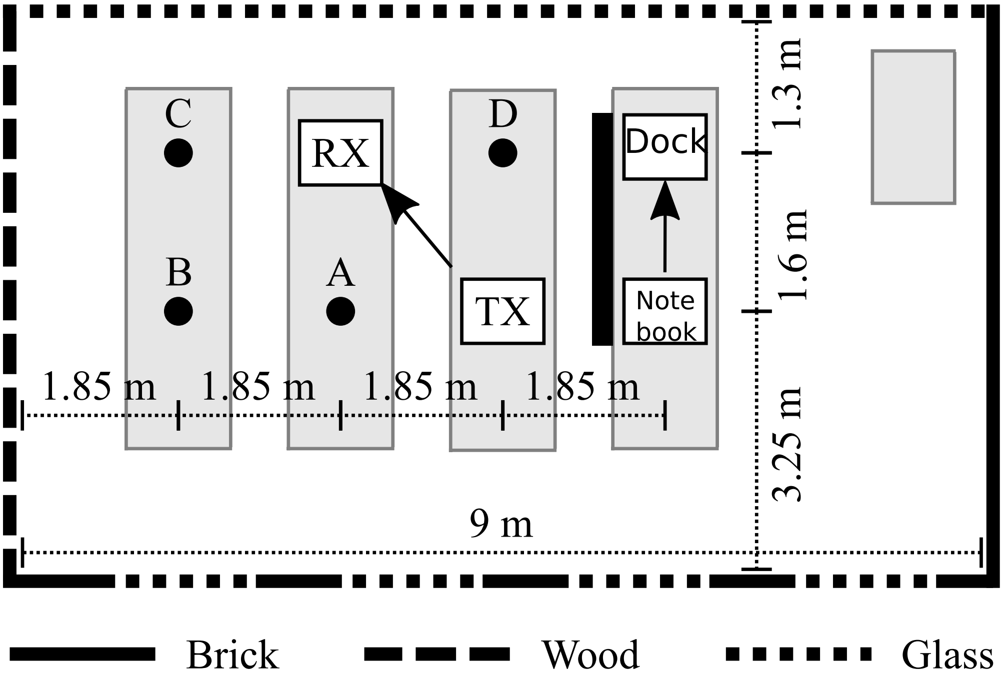
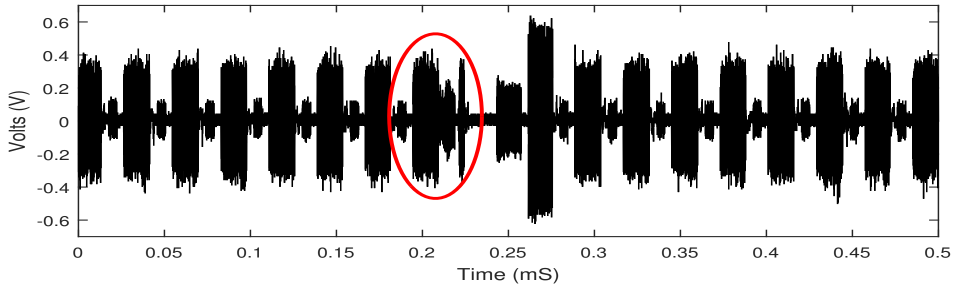
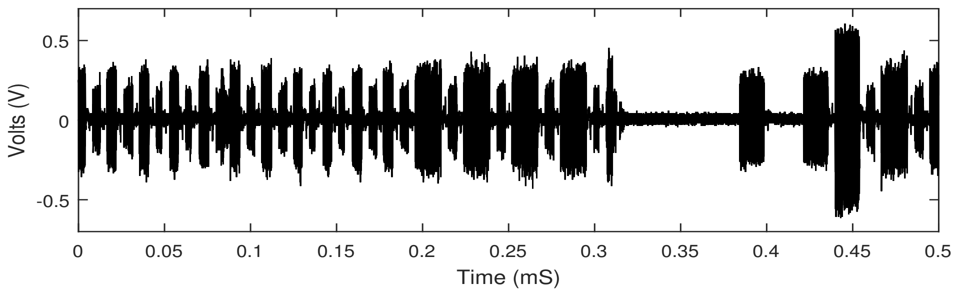


Figure 21: Reflection test setup with blocked path.



(a) Retransmission I.



(b) Retransmission II.

Figure 22: Interference impact.

points working under the same protocol overlap their communication areas through reflections, making a decrease on their bandwidths.

6 Future work

This work opened the way to many future research questions as now we have a deeper understanding on the analyzed systems and gained knowledge on how to do different measurements. These ideas are going to be briefly discussed in this section:

6.1 Interference Study

As well as we have gone through the problem of the side lobes in these 8x2 antenna arrays and how important reflections are, question arises on how this characterizations may affect other devices that could be transmitting on the same area at the same frequency bands.

Such an extended analysis could consist of the link usage of one laptop communicating with one wireless docking station and then compare that link usage with the obtained with two laptops and two docking stations.

If the link usage of two laptops and two wireless docking stations transmitting at the same time doubles the link usage to only one laptop and one docking station, that would mean that there are no retransmissions, so there would not be interferences, but if this link usage is much larger, it would mean that there are interferences causing collisions and retransmissions.

Studying this link usage percentage for different positions and with different reflectors would help us to know how all this interferences behave and how many devices can share the channel.

Another interesting way of studying the interferences, would be using the information achieved from the reflections experiments from Section 5.4, watching how the reflections can produce interferences and retransmissions.

6.2 Analysis of Packet Collisions

We have analyzed how other devices with different protocols can produce interferences producing frame losses and retransmissions. It would be interesting to analyze how interferences from different devices could produce packet collisions and what this would mean.

These packet collisions could provoke the devices to coordinate in a more efficient way or they could just create retransmissions, higher link usage or a decrease on the bitrate.

6.3 The Wireless HDMI Standard

In the market there are other home-devices working at 60GHz, as the wireless HDMI DVDO Air 3 [27]. This particular device is a low latency transmitter of non compressed HDMI signals which works with the WiHD protocol [28].

It would be interesting to analyse the behaviour of this device, as well as its beam pattern and device discovery protocol and compare them with our study.

It would also be interesting to see if this device creates interferences with the D5000 wireless docking station analyzed in this work and how both interact together as they are using different protocols.

6.4 Dense Antenna Arrays

In this work we have analyzed a relatively small antenna array of 8x2 elements, giving as conclusion that it works in a directional way, but it could be improved.

Analysing the behaviour of bigger antenna arrays, as 5x5 or 10x10 antenna arrays would be a good experiment to know if the lack of directionality on the analyzed system is due to the performance the equipment, or it is because a 8x2 antenna array can not perform better.

These denser antenna arrays are not available on the off-the-shelf market yet, so it is still not possible to do this kind of analysis.

7 Alternatives

Some alternatives that could have been applied to this work are the ones described in the following subsections. These alternatives have been based on the different researching hardware and software tools and applications that exist.

7.1 Analysing Components Separately

In this work we have gone through the analysis of the performance of a full system, without stopping to analyse the different components of the system separatelly.

There exist some works which analyse the different components separately, for example, [36] shows an intensive analysis on the chipset of a phased-array transceiver, and [37] shows an intensive analysis on different types of antennas.

An alternative to our work could have been analysing the different components separately as these publications do, but in order to do so we would need different equipment than the one used in this work.

The drawback of doing this type of analysis is that we could not have noticed the joint effects of a full system, as for example the asymmetric beam pattern due to the positioning at the side of the notebook lid.

7.2 Using Artificial mm-Wave Signal Sources

Our purpose in this study has been the characterization of an off-the-shelf mm-wave system. There are other studies which are more focused on the characterization of the mm-wave communications itself.

For example, [2] makes a study on the spatial and temporal characteristics of 60GHz indoor channels, studying the behaviour of the 60GHz communications created by an artificial generator with different propagation and reflection experiments.

We could have done something similar to this publication if instead of using our wireless docking station and notebook we would have used the Vubiq system together with a signal generator to create the analysed signal.

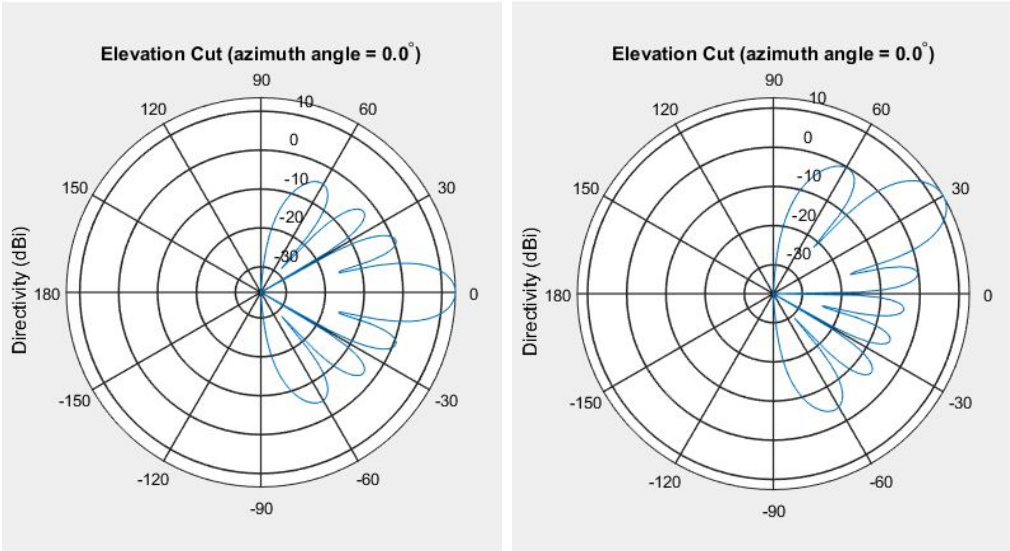
The disadvantage of this approximation is that the reflections of the imperfect beam sidelobes would have not been detected and studied.

7.3 Analysis by Simulation

In this work we have been analysing how this 60GHz system works in real world environments through the different testbeds. An alternative of this work would have been the analysis of the mm-wave communications through different simulations.

For example, with Matlab's 'Sensor Array Analyzer Toolbox' [38] we can obtain a radiation pattern of a phased antenna array.

We have done this simulation, which can be seen on Figure 23. We have simulated the radiation diagram for an aligned receiver (23a) as well as for a 30° shift receiver (23b). We can see from this simulation that the results differs from our measurement analysis. This is because simulations do not take many 'real life imperfections' into account, as the laptop or docking station casing, which modify the antenna parameters.



(a) Aligend receiver. (b) 30º disaligend receiver.

Figure 23: 60GHz 8x2 antenna array simulation.

Other simulation that could be done is with the NS-3 simulator. With this simulator we could see the behaviour of a given protocol (WiGig or IEEE 802.11ad for millimiter communications) and the communication between the different layers and how do they interact. For example we could observe what could affect the different devices to change their modulation format.

The drawback of the NS-3 simulator is that it can not perform as a real environment and there would be many impacts that it would not take into consideration.

8 Conclusions

With this work we have analyzed the behaviour of the first generation millimeter wave off-the-shelf systems. To do so we carried out different measurement campaigns which gave us different insights about how this equipment behaves.

We have seen that these first devices are equipped with a 16 element antenna array. This array, being the first of its class to be in the market, is not as effective as theoretical reports [23, 24, 25] claim:

We found very strong sidelobes for the Dell D5000 docking station as well as for the connecting notebook, the Dell Latitude 7540 for aligned transmissions. For unaligned transmissions, even stronger sidelobes were measured. This shows that antenna arrays are directional, but still need to improve to achieve their theoretical targets for next generation mm-wave systems.

With the analysis of the Dell D5000 device discovery process we have seen that even if it is not possible to achieve true omnidirectional patterns in mm-wave antenna arrays [22], the station can change through different quasi-omnidirectional antenna patterns to be able to search for devices. This device discovery has been found to be different from the device discovery established by the incoming IEEE 802.11ad standard which is described in [20].

Further, with a mm-wave reflection measurement setup we found strong reflections in many different positions from an habitual office environment, making the connection of devices possible even if there is some blockage between them.

But we have also seen a drawback of these reflections. They can cause interferences implying packet losses and retransmissions to other devices working at the same frequency with a different protocol, even if their direct path is blocked.

To sum up the results of our measurement campaign, we found that this first generation 60GHz equipment is working correctly, but still needs to keep evolving. While this is not surprising, as the mm-wave technology is still in an early phase, the results point out important facts for further system development and protocol design.

Also, with deeper understanding on the analyzed systems, ideas for future research lines arise, as for example an extensive interference and packet collision study, as well as analyzing other 60GHz transceivers with different protocol or with more antenna array elements.

Several alternatives to the performed measurements were considered, as analysing individually components from a transceiver, using signal generators for the different measurement campaigns or the use of software to go through different simulations. Those methods were however rejected, as they would not analyze the real performance of an off-the-shelf system in realistic environment.

A Annex 1: Project Scheduling and Budget

A.1 Planification

In this annex we can observe how much time has the project taken and how the time was employed by the student. In Section A.1.1 can be observed how much time the different activities took, in Section A.1.2 can be observed the initial PERT diagram on how the project could have been done and in Section A.1.3 can be observed the GANTT diagram that was finally taken by the student.

A.1.1 Activities Time Table

In Table 1 we can observe the different duties taken during the project and the time they took. In Section A.1.4 can be read the description of each activity.

Task		Duration	ID
Documentation read		45 hours	A
60GHz equipment preparation			
	Setting up communication	5 hours	B
	Capturing the communication	10 hours	C
Rotatory stage setup			
	Software development	5 hours	D
	Hardware building	5 hours	E
Matlab coding			
	Capturing script	15 hours	F
	Beam pattern processing	20 hours	G
	Device discovery processing	20 hours	H
	Reflections processing	25 hours	I
Measurements campaign			
	Beam pattern	20 hours	J
	Device discovery	5 hours	K
	Reflections	25 hours	L
Result analysis			
	Beam pattern	5 hours	M
	Device discovery	5 hours	N
	Reflections	10 hours	O
Mentorship with advisors		20 hours	P
Thesis preparation			
	Written redaction	45 hours	Q
	Oral presentation	15 hours	R
TOTAL		300 hours	

Table 1: Project scheduling

A.1.2 PERT Diagram

In Figure A.1 we can see the whole picture of how the project can be realised, taking into account the activities mentioned before in Table 1, which are the same than in the diagram.

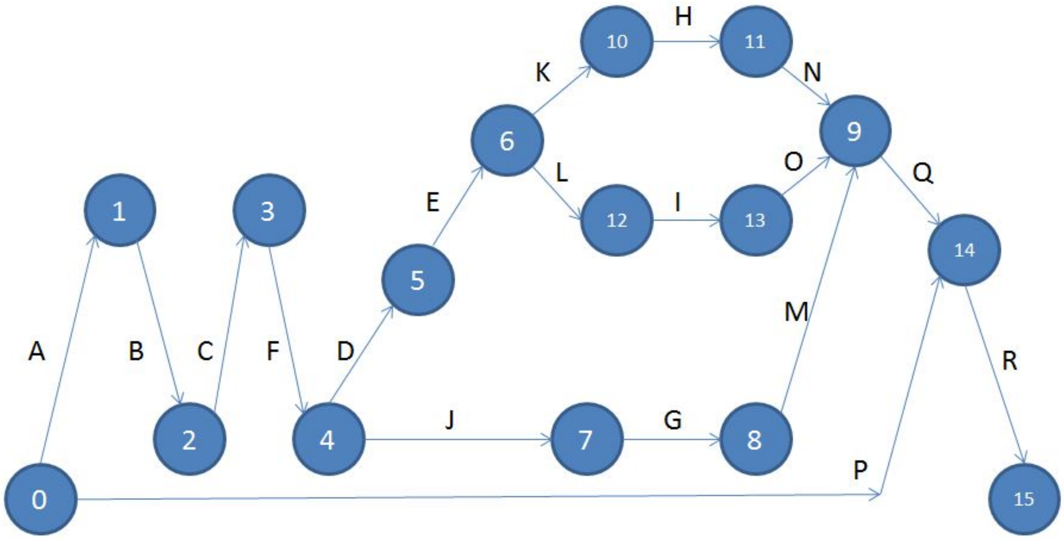


Figure A.1: PERT diagram of the project.

A.1.3 GANTT Diagram

The GANTT diagram seen in Figure A.2 shows how the project was done in time by the student. The diagram matches with a 5 hours shift work schedule from Monday to Friday.

The different activities seen in the GANTT diagram matches with the time table seen in Table 1 and with the PERT diagram seen on Figure A.1.

A.1.4 Description of the Time Table Tasks

- **Documentation read:** Reading about mm-wave communication as well as learning how research centers work and how to interact in them with the different testbeds and results.
- **60GHz equipment preparation:**
  - **Setting up communication:** All the equipment was set up as mentioned on section 4.1.1, installing the WiGig card into the laptop as well as all the necessary drivers to make the wireless docking station working with the laptop.
  - **Capturing the communication:** How to use the Vubiq reception antenna and the oscilloscope as explained in Sections 4.1.2 and 4.1.3 was carried out in this task.
- **Rotatory stage setup:**
  - **Software development:** The program to make the stepper motor work with Arduino together with Matlab through serial communication as explained on Section 4.1.4 was coded in this task.

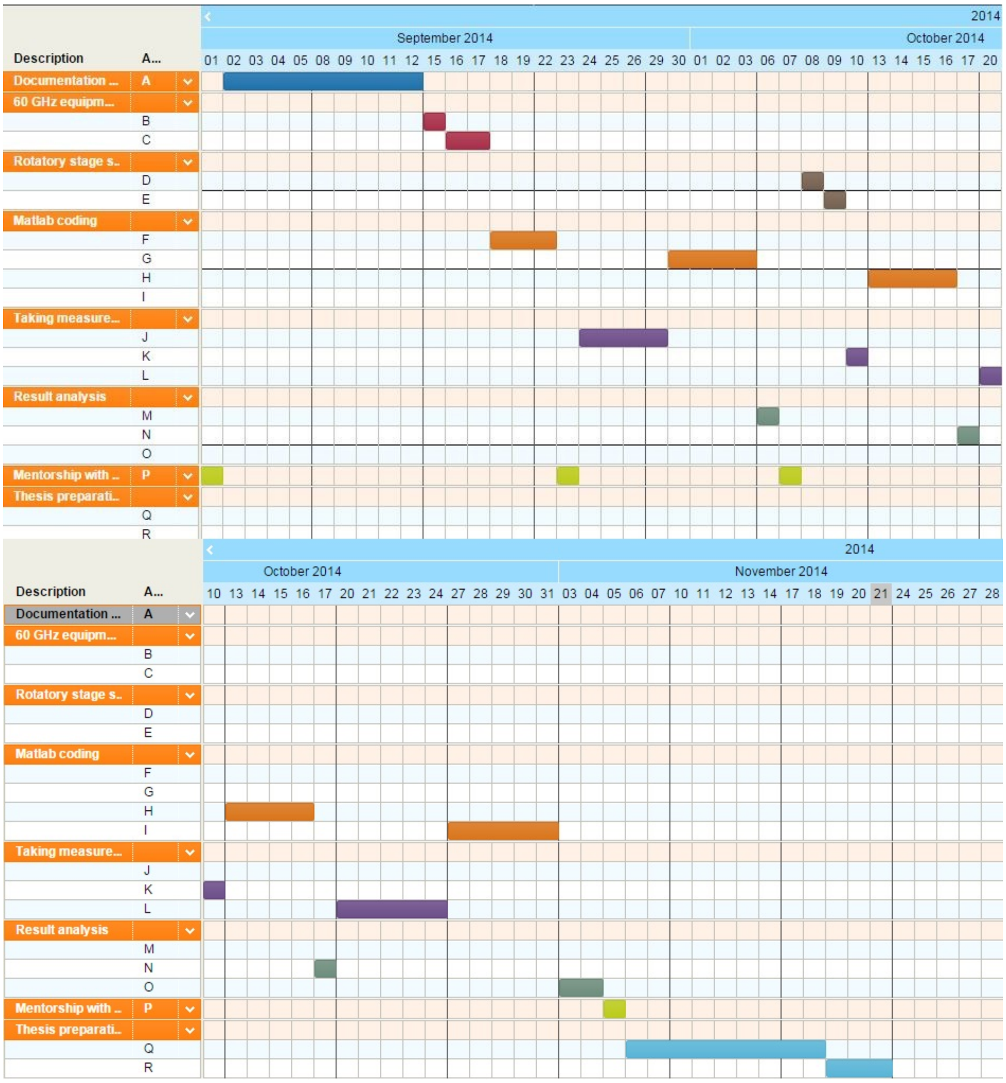


Figure A.2: GANTT diagram of the project.

- **Hardware building:** In order to make the stepper motor working properly with the Vubiq system there was the need of building a basis for it, so it could stand properly the equipment. There was also the need of building an adapter to attach the antenna and the docking station to the stepper motor axis.

- **Matlab coding:**
  - **Capturing script:** After learning how to use the oscilloscope, the Vubiq antenna and the laptop together, it was time to begin coding the main script that would make the different tools interact between them capturing the frames from the oscilloscope from Matlab saving them into different files.
  - **Beam pattern processing:** After the beam pattern measurements were done, we had to interpret all the saved files programming and running scripts to achieve the different patterns.

  - **Device discovery processing:** After the device discovery measurements were done, we had to interpret all the saved files programming and running scripts to see how the different sub-elements from the device discovery protocol were behaving.
  - **Reflections processing:** After the reflection test measurements were done, we had to interpret all the saved files programming and running scripts to achieve the different reflection patterns from the different positions.

- **Measurements campaign:**
  - **Beam pattern:** The different outdoors measurements for the beam pattern analysis were carried out in this activity.
  - **Device discovery:** The outdoors measurement for the device discovery analysis was carried out in this activity. For this activity the rotating table was used.
  - **Reflections:** The different indoors measurements for reflection test were carried out in this task. For this activity the rotating table was used.

- **Result analysis:**
  - **Beam pattern:** The different theoretical analysis for the beam pattern were carried out in this activity.
  - **Device discovery:** The different theoretical analysis for the device discovery process was carried out in this activity.
  - **Reflections:** The different theoretical analysis for the different reflections setup were carried out in this activity.

- **Mentorship with advisors:** This time was used to have different team meetings to get advised in different fields, as the experimental setups, coding or the written thesis.

- **Thesis preparation:**
  - **Written redaction:** This task was meant to write in a formal way this bachelor thesis. It has been performed using LaTeX, a document preparation system for high-quality typesetting which widely used in technical and scientific documents.
  - **Oral presentation:** This task was meant to prepare a formal oral presentation of this bachelor thesis. It has been performed using PowerPoint, a very extended and powerful tool to make presentations.

A.2 Economic Framework

The measurements done during this research project has been used, or will be used in some scientific publications. Having published works makes it easier to have founding and partners.

A.2.1 Budget of the Project

In order to compute the budget of the project we need to calculate the amortization of the equipment and sum the total cost of it during the three months of use during the study:

The Dell equipment used to create the 60GHz communication is the same equipment that has been used to process and collect all the data during the testbeds. This equipment will be used after this project by other students on different projects.

The mean utilization time of this computer equipment is of four years, so the total price of it needs to be divided by 48 months to know how much is its real cost. This calculation can be seen in Table 2.

Expenditure	Total cost [€]	Monthly cost [€]
Latitude E7450	1550.00	32.30
D5000	246.00	5.13
Dell 1601 WiGig card	29.00	0.60
Screen	150.00	3.12
Sub-TOTAL	1975.00	41.15
TOTAL COST IN 3 MONTHS		123.45€

Table 2: Computer and creation of 60GHz communication equipment budget

The equipment used to capture the 60GHz communication as well as the wireless HDMI will be used after this project for different studies. It is calculated that it will be used for two years, so the amortization of its cost will be calculated for 24 months as seen in Table 3.

Expenditure	Total cost [€]	Monthly cost [€]
Wireless HDMI	180.00	7.5
Vubiq system	9700.00	404.17
Horn antennas	1000.00	41.67
Oscilloscope	8000.00	333.33
10m Ethernet cable	15.00	0.62
Extension cables	100.00	4.16
Sub-TOTAL	18995.00	791.45
TOTAL COST IN 3 MONTHS		2374.38€

Table 3: Capturing 60GHz communication equipment budget

The rest of the equipment, as the rotating table used on the different testbeds or the student software licenses, are not going to be used after the project, so the total cost of them needs to be applied to the total budget.

For the student salary it can be established a salary of 5 € per hour, and for the advisor 20€ per hour. For the Internet, electricity and water connection is calculated a price consumption of 30€ per month of Internet connection, 30€ per month of electricity consumption and 10€ per month of water consumption.

The rental of the building used in this project is free as the building from IMDEA Networks is lent for free by the regional government.

The total budget of this project comes to be 4960.82 euros as we can observe on Table 4. If we divide this amount between the three months, the budget is of 1653.60 € per month.

Expenditure		Sub-Cost [€]	Cost [€]
Creating 60Ghz:			123.45
Capturing 60Ghz & WiHDMI:			2374.38
Rotating Table:			
	Arduino Uno Rev 3	28.00	
	Stepper motor	40.00	
	Wireless module	40.00	
	Other hardware	20.00	
Sub-TOTAL			128.00
Student software licenses:			
	Matlab 2014 & toolboxes	120.00	
	Microsoft Office	80.00	
Sub-TOTAL			200.00
Working place:			
	Internet connection	90.00	
	Electricity consumption	90.00	
	Water consumption	30.00	
	Others	25.00	
Sub-TOTAL			235.00
Student salary			1500.00
Supervisors salary			400.00
TOTAL			4960.82
TOTAL COST PER MONTH			1653.60€

Table 4: Total budget of the project

B Annex 2: IMDEA

This project has been carried out at IMDEA Networks, which is public foundation affiliated to the UC3M, in this section it is going to be explained how IMDEA institutes work as well as how public founding is taken.

B.1 IMDEA Institutes

IMDEA Networks is one of the seven IMDEA institutes inside the Madrid Community. That is why before starting talking about IMDEA Networks there is the need of talking about all the IMDEA institutes in a more general way:

IMDEA institutes were created by the regional government preparing Madrid to solve the challenges of the future through the research in different sciences and technologies areas, 'Making human capital the source of wealth for the nation', as they describe on their webpage [39].

IMDEA is included on the IV regional plan of science and technology 2005-2008 to start with these advanced research centers.

All the seven different IMDEA Institutes are managed by independent foundations focused in one special topic. As the institutes are public foundations, all of them are non-profit associations. The seven different institutes are: Institute IMDEA Water, Institute IMDEA Food, Institute IMDEA Energy, Institute IMDEA Materials, Institute IMDEA Nanoscience, Institute IMDEA Networks and Institute IMDEA Software.

Inside IMDEA there is a big welcome for students from different levels and from different nationalities. As well as training internship students from bachelor or master studies, IMDEA is a place where many researches are working to obtain their PhD titles.

B.2 IMDEA Networks

'Developing the Science of Networks' is the slogan of IMDEA Networks, which basically describes the intention of the IMDEA Networks Institute: the research of communication engineering, computer networks and their applications [40].

The research lines adapts to the strength of the research team and collaborators, right now, the three main general areas of research are:

- **Networked Systems and Algorithms:** Design and understand network protocols and architectures from a practical point of view, working with real data when developing to validate the analytical conclusions.
- **Wireless Networking:** With the limited and rising demand of wireless spectrum, the objective is to design optimum and self organized wireless networking, through theoretical and practical results through a range of wireless testbeds.
- **Energy-efficient Networking:** With the greenhouse effect and the climate change, power consumption needs to be also reduced on the computation and communication areas.

B.3 Founding

As the IMDEA Institutes are non-profit organizations, it is important to know how they are founded in order to keep researching.

Two main categories can be distinguished on the external founding:

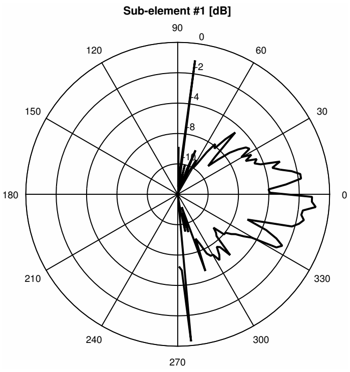
- **Researchers individual founding:** They are based on subsidies and grants addressed directly by the research professors, who choose how to manage with them and how to organize it.
- **Research projects with external founding:** This founding allows to cooperate with public and private organizations. They are awarded after the project is left out to tender.

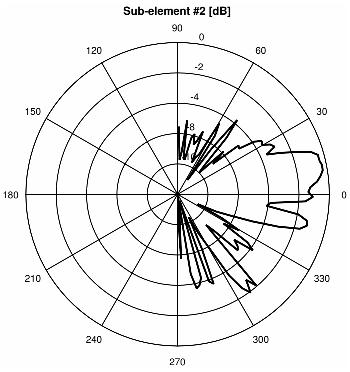
As well as having the different types of founding, the foundations also have different partners which helps with the evolution of the institutes:

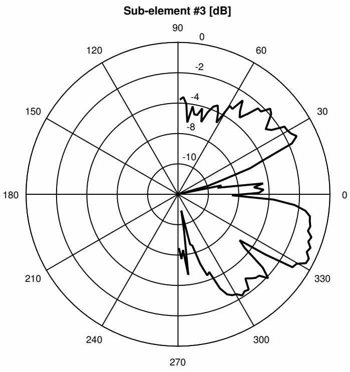
- **Academic partners:** The collaboration criteria depends on the research organisms. It stands out the preparation of researchers through their PhD program as well as the post-doc and other collaborations as sided publications with different organizations.
- **Industrial partners:** The technologies that are developed inside the institutes are focused to make a socioeconomic impact on society. That is why it is needed to transfer those technologies to the industry through different agreements under intellectual property rights with different companies.

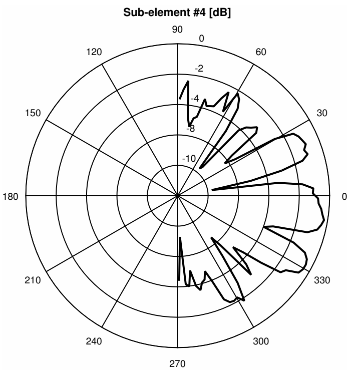
C Device discovery patterns

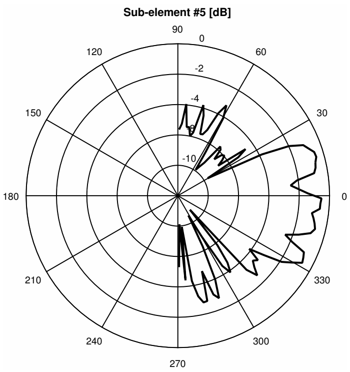
This annex shows the 32 different beampatterns carried by the different sub-elements during the device discovery process of the Dell D5000 Wireless docking station. The test can be seen in Section 5.1.2.

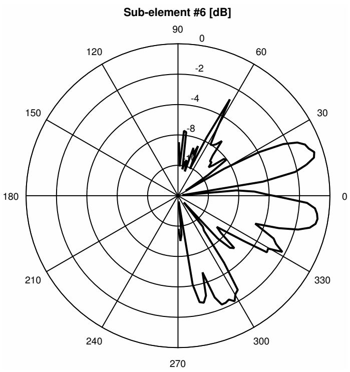


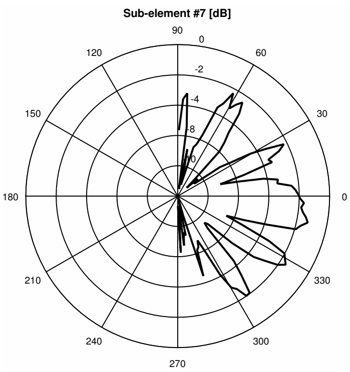


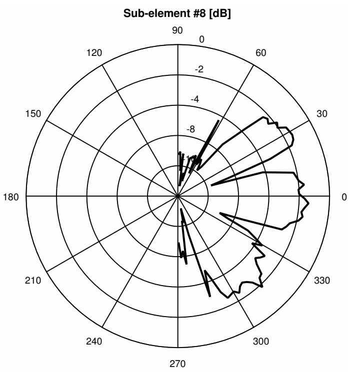


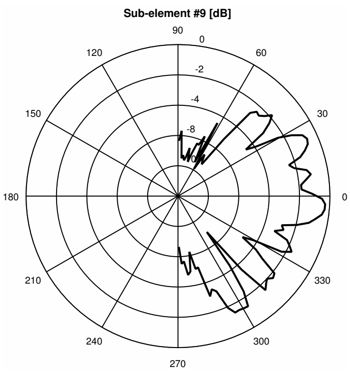


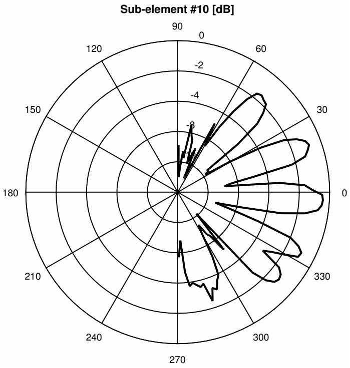








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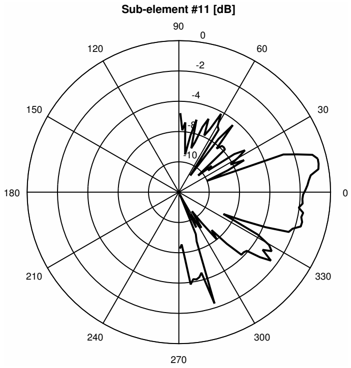
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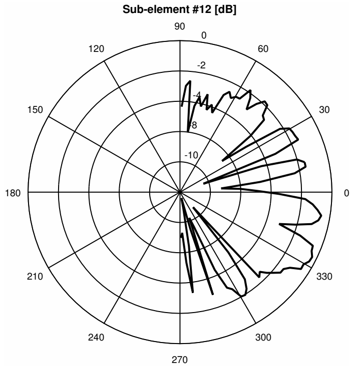
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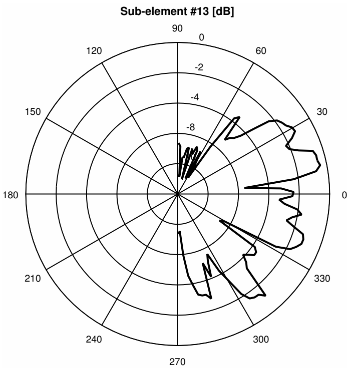
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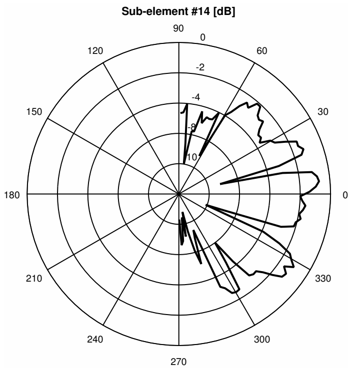
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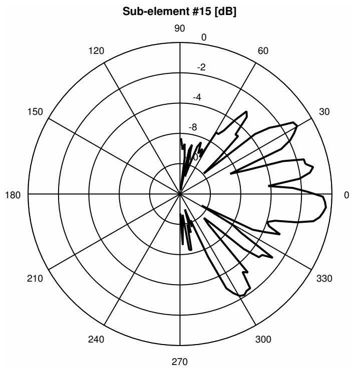
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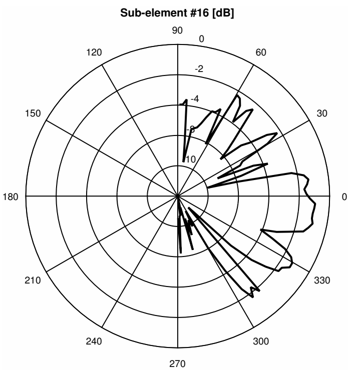
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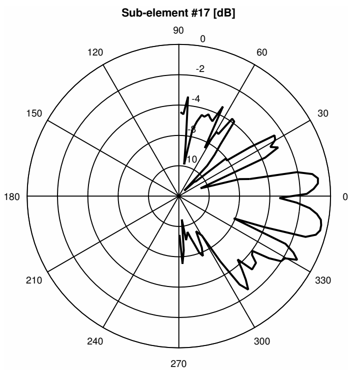
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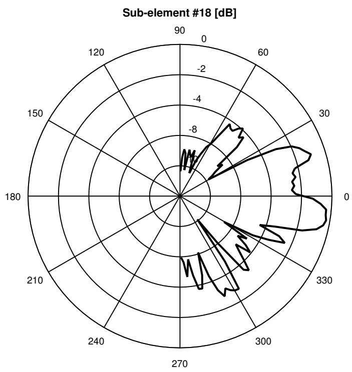
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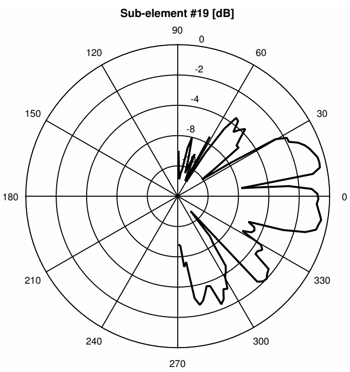
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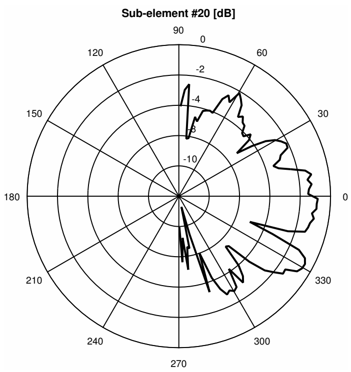
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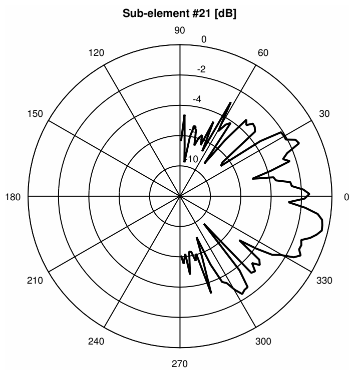
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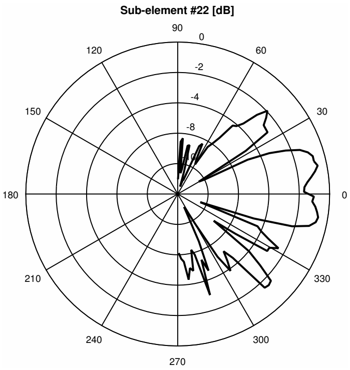
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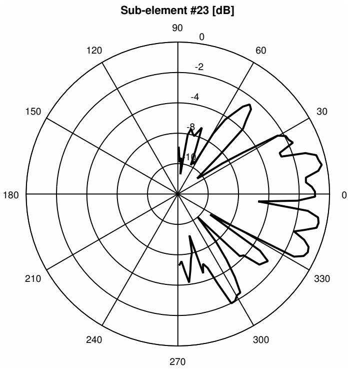
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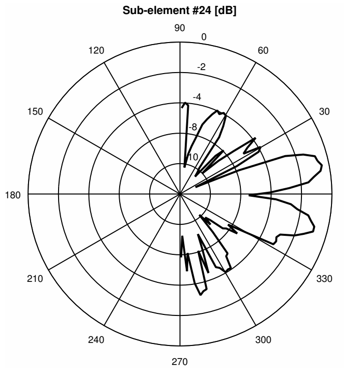
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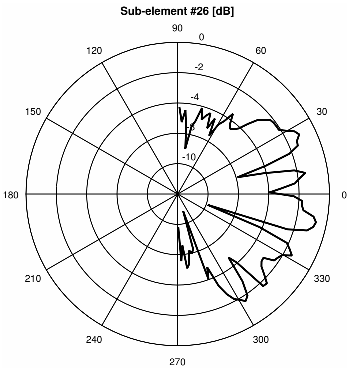
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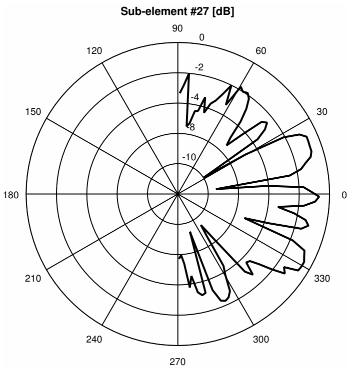
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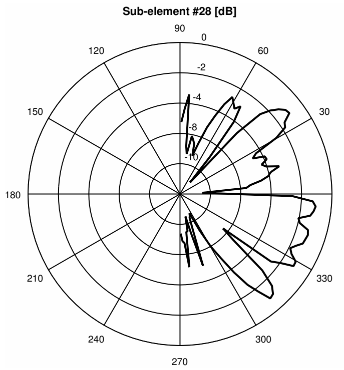
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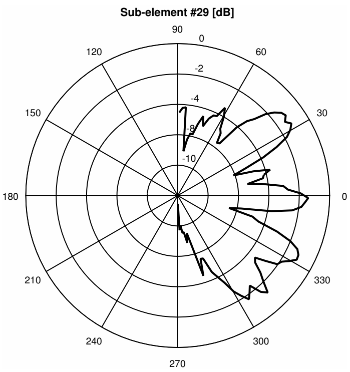
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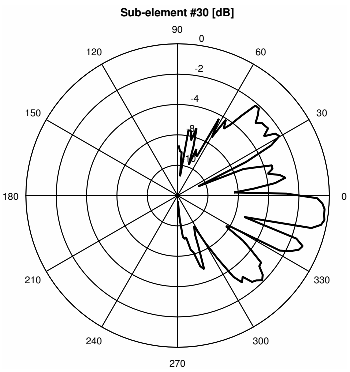
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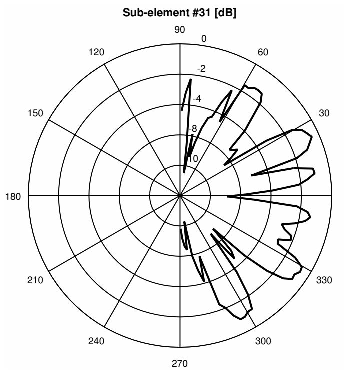
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240
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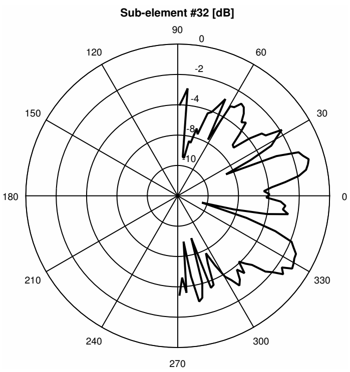
Sub-element #32 [dB]
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D Thesis Summary

This annex summarizes the bachelor thesis 'Characterization of Wireless Millimeter Wave Systems Considering the Impact of Reflections and Imperfect Beam Pattern', written by *Guillermo Bielsa* and supervised by *Albert Banch*, *Thomas Nitsche* and *Joerg Widmer*.

All the results obtained from this work have been submitted to a peer review conference, as they are unique knowledge that can benefit the scientific community. It has been submitted to the CoNEXT 2015 conference under the title 'Boon and Bane of 60 GHz Networks: Practical Insights into Beamforming, Interference, and Frame Level Operation'

D.1 Introduction

Local area networks are evolving into a more sophisticated 60GHz environment. These millimeter wave communications are directly related to the use of highly directional antenna arrays, meaning free interference and energy efficient environments [1].

In this bachelor thesis the behaviour of first generation off-the-shelf millimeter wave systms is studied through a frame level analysis. We focus on the measurement of beam patterns, the device discovery process and the impact of reflections.

D.2 Background

In this section we give a short description of the basics of our work.

D.2.1 Radiowave Propagation

Transferring information between different points that are not interconnected by a conductor is called wireless communication. Wireless communications are based on the transmission of different forms of energy trough air or vacuum, nowadays the most commonly used one is radiowave communications.

Electromagnetic fields follow the superposition principle; if there exist different charges producing fields at different points, the total electromagnetic field in another point is going to be the sum of all of the different fluxes.

There are different phenomenas which we need to take into account when talking about the electromagnetic waves's properties, those are: reflection, diffraction, dispersion, absorption and attenuation.

To emit and receive these waves, antennas are needed. There are many types of antennas with different properties. The most important antenna parameters are: radiation pattern, bandwidth, directivity, efficiency and gain [8].

D.2.2 Wireless Transceiver Basics

The transmitter is the device which transforms the electric power into a radiofrequency current, a receiver is the device which transforms the radio frequency current into electric power. A transceiver is a combination of both, being able to transmit and receive radio frequency currents.

The most important part of a transmitter is the modulator, which is in charge of inserting the signal with information inside a carrier signal. This carrier signal guides the information with a selected frequency and bandwidth.

There exist a wide diversity of modulations, and depending on the used one the communication can be more robust regarding error corrections or more efficient in the transmission bit-rate.

The WiGig standard, which is analyzed in this work, uses the IQ modulation, which divides the signal in two different components, the I(In-phase component) and the Q (Quadrature component).

The WiGig standard also uses differential signaling, which is a technique that ensures high robustness in the communication sending two symmetrical signals which need to be subtracted at the receiver side, so the errors get cancelled.

At the end, the different operations that we need to do to obtain the final system are the ones seen in Equation D.1, where C is the final signal.

$$\mathrm{I} = \text{Channel 1} - \text{Channel 2} \tag{D.1a}$$

$$\mathrm{Q} = \text{Channel 3} - \text{Channel 4} \tag{D.1b}$$

$$\mathrm{C} = \mathrm{I} + \mathrm{j} \cdot \mathrm{Q} \tag{D.1c}$$

D.2.3 Radioelectric Spectrum

Legislation in the radioelectric spectrum is necessary because when different devices are using the same carrier frequency or when their bandwidths are overlapping in the reception range of a receiver problems arise. When that happens, interferences can be created in the receiver side, as the different signals mix up and become inseparable. This interferences lead to retransmissions whenever there is a collision.

There are different legislation authorities depending on the countries, but the most important one to be mentioned is the ITU: The International Telecommunication Union [13], which was funded in 1865 to be the United Nations specialized agency responsible for the regulation of the radioelectric spectrum and the telecommunication standardization sector.

Inside Spain, the CNAF [15] (Cuadro Nacional de Atribución de Frecuencias/ National Frequency Attribution Regulator) is the national authority, being the regulator of the radio spectrum following the ITU recommendations.

This legislation authorities divide the radioelectric spectrum in three different classes: unlicensed, licensed and governmental. The unlicensed frequencies are the ones that every user can use without paying any fee, as WiFi or Bluethooth technologies. The licensed frequencies are the ones that companies have to pay in order to use, as television or radio broadcasting companies. The governmental frequencies are the ones owned by the government, as the ones used for military purposes.

There are different reasons to state that the available spectrum should increase for future technologies, as the increase in number of devices, the increase of the device's bitrates or the robustness of the communications.

D.2.4 Evolution of IEEE 802.11

The most spread wireless local area networks protocols are the different ratifications under the IEEE 802.11 standard. The most important changes on the different versions according to their web site [19] are the use of different frequencies between 2.4GHz and 5GHz, and the exploit of higher bitrates.

In 2012, the WiGig alliance [6] merged with the IEEE 802.11ad amendment, which will bring us in the near future the first 60GHz wireless network area to connect multiple devices promising a throughput of 7Gbps.

D.2.5 60 GHz Communications

Since several years ago from now, millimeter wave communications have only been used for static applications like backhaul links, but recently, with the formation of the WiGig Alliance [6], several mm-wave devices have been created for home applications as wireless docking stations and laptops. This bachelor thesis is centered on the analysis of this off-the-shelf 60GHz devices.

Transmission characteristics change in this new domain, leading to an increase of 20dB of attenuation with respect to a 6GHz transmitter under the same conditions, making the use of highly directional antennas necessary. Very high bitrates can be achieved under this domain as there is a big amount of unlicensed spectrum on the mm-wave range, going from 6GHz to 9GHz of bandwidth depending on the country.

The use of phased antenna arrays is feasible under these frequencies due to their small size, as each component only needs to be quarter wavelength long. With the use of antenna arrays comes the need of changing the device discovery protocol in order to find devices as well on training the beam when the connected devices move during a transmission, as omnidirectional patterns are not feasible in antenna arrays [22].

D.3 Objectives of the Project

With this project, we are going to present an in-depth beamforming and reflection analysis of the first off-the-shelf mm-wave devices from the Dell family, which consists on a wireless docking station (D5000) with its corresponding notebook (E7540).

This study will provide first insights into what performance is to expect from IEEE 802.11ad devices once they appear on the market. The different objectives are:

- **Beam pattern measurement.** Measurement of the 8x2 antenna array beam pattern and it's changes for an unaligned receiver. It is compared with the ones described in theoretical reports [23, 24, 25], which stand highly directional patterns.
- **Device discovery.** We analyze if our WiGig devices behave in the same way for device discovery as IEEE 802.11ad, which divides the transmitting area into several virtual sectors [20].

- **Reflections.** 60GHz communication has been studied in terms of reflections [2] with the use of directional horn antennas. In this work we are going to study reflections and their interference impact from real antenna arrays.

D.4 Experimental Methodology

In this section we will explain the equipment used for the measurement campaign, as well as the data and device discovery protocol.

D.4.1 Equipment

- **Creating 60GHz communications**

  In order to setup the studied 60GHz communication we used the Dell 'Latitude E7450' laptop together with its wireless dock 'D5000'.

  To have a constant flow of data traffic between the stations we played a random noise video through the HDMI of the dock.

  Both systems use an 8x2 antenna array and the WiGig protocol [26], which has four available channels with 2.16GHz bandwidth each. We fixed the channel to 61.56GHz so we do not observe changes on the medium.

  For the interference study, we used a second device to create 60GHz communications under a different protocol in order to create inter-system interferences. We used the HDMI DVDO Air [27], which is a low latency non compressed video transmitter working under the WiHD protocol [28] which uses very wide radiation patterns under a robust modulation.

- **Capturing 60GHz communication**

  In order to capture the frames we have used an oscilloscope together with a 60GHz reception system:

  The reception system is a Vubiq 60GHz development system [29], which captures the WiGig signals in differential mode. A directional horn antenna is attached to the Vubiq receiver.

  The oscilloscope used is an Agilent MSO-3034A, which includes a LAN TCP/IP module so it can be easily attached to a computer in order to save the data.

  We obtain traces with analog differential I/Q modulation at the output of the Vubiq receiver where frame timing and amplitude can be extracted.

- **Measurement data management**

  All the measurement setups are controlled, measured and processed through Matlab [30] and different toolboxes.

  In order to store the data received from the oscilloscope, we have used its LAN TCP/IP module connected to the laptop. To set up the communication between the computer and the oscilloscope, a VISA instrument object is created with the Keysigh IO libraries Suite from Agilent [31] together with the Matlab's Instrument control toolbox [32].

- **Rotatory stage**

  For the reflection measurements we need a rotatory stage for the receiver. Also, to study the device discovery mechanism, a rotatory stage for the docking station is very serviceable so we can measure it faster and in a more precise way.

  In order to build it, we have used an Arduino [33] as microcontroller and a stepper motor. An H-Bridge was needed to feed the motor with enough power to move the system and a RF system to control the stage in a more flexible way.

  The motor was controlled from Matlab through serial communication with the RF interface.

D.5 Measurement Results

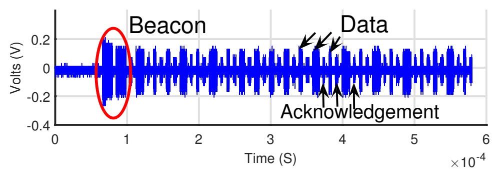
The different measurement campaigns are described in this section. A brief explanation of the setup, result and conclusions are included for every experiment.

D.5.1 Frame Format Analysis

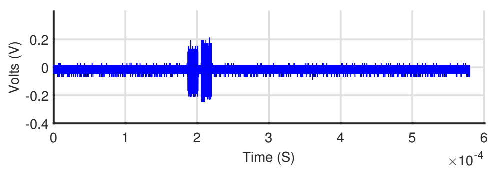
In order to obtain conclusions from the different measurement campaigns, we first investigate the behaviour of the frame format of the systems.

The data is transmitted through frame bursts with a clear structure of data and acknowledgement frames. These bursts have one beacon frame from each device at the beginning and at the end of it. This beacon frames are transmitted with more power than data-ack frames.

Figure D.1a shows the typical frame format for a data transmission from the notebook to the docking station. Figure D.1b shows the keep alive frames, which are transmitted periodically every 1.1 millisecond when there is no data transmission between the stations.



(a) Dell D5000 frame flow.



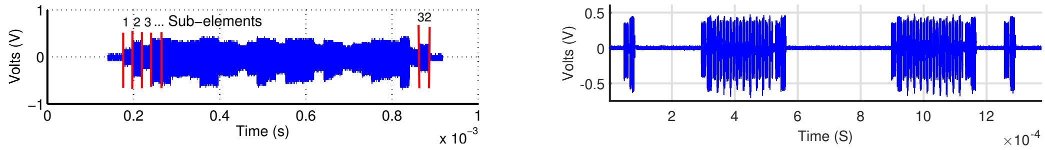
(b) Dell D5000 keep alive frame.

Figure D.1: Protocol analysis.

In order to find the signal strength received by the Vubiq system what we need to obtain is the amplitude of the signal, which is computed knowing the amplitude of the I and Q components with the use of Equation D.2

$$Amplitude = \sqrt{(I^2 + Q^2)} \tag{D.2}$$

During the device discovery process we have distinguished two different processes, first, the docking station searches for devices with 32 different beam patterns and once it finds the notebook, they proceed to establish their connection.



(a) Beam training: Device discovery.

(b) Beam training: Handshake.

Figure D.2: Beam training protocol analysis.

Figure D.2a shows a device discovery frame which has a constant pattern where 32 different sub-elements change on amplitude when the relative angular position of the observer changes. In Section D.5.3 we analyze the beam pattern of the different sub-elements independently.

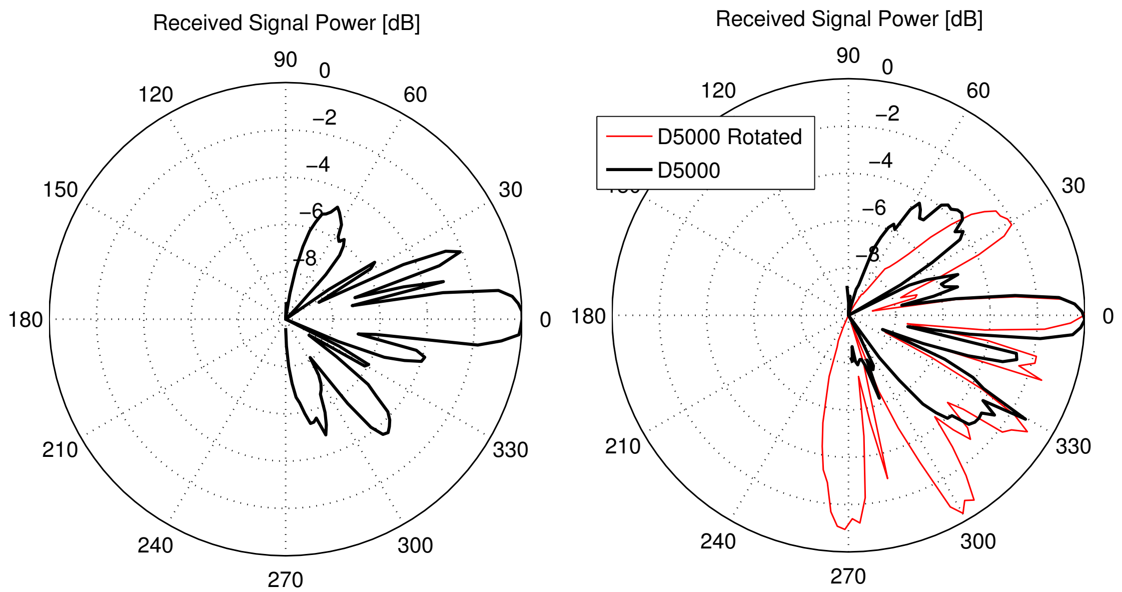
Figure D.2b shows the handshake between the devices that are pairing.

D.5.2 Radiation Pattern

To measure the beam pattern of the systems we drew a circle around the measured transmitter where we obtain the received power from the different angular positions with the Vubiq receiving system.

For this measurement we made a 3.2m radius circle and 100 measured locations to obtain the pattern. We analyzed the laptop as an aligned system and the dock as aligned and unaligned, with an angular shift of 30º.

We can see the obtained beam patterns in Figure D.3.



(a) Notebook pattern.

(b) Dock pattern.

Figure D.3: Measured radiation pattern.

From this measurements, we find that these 60GHz antenna arrays are very directional, but they have big enough sidelobes to produce interferences contradicting what theoretical reports state.

We found both systems having different beam patterns as their cases are build from different materials having different characteristics. We can also see that for an unaligned receiver the beam pattern changes into a less directional pattern having much bigger sidelobes, but still being very directional having its main beam pointing to the receiver.

D.5.3 Device Discovery

As we have seen in Section D.5.1, the device discovery protocol shows a 32 sub-element frame which changes on amplitude depending on the angular position. With this measurement campaign we measure how this sub-elements behave.

We used the same setup as in the beam pattern measurement test, but in this case the docking station is not paired with the notebook. Therefore we can use the rotation stage to turn the docking station while we capture the angular amplitude variation of the frames.

In Figure D.4 we can observe 4 out of the 32 different patterns, in Annex C can be observed the 32 different patterns radiated by the dock.

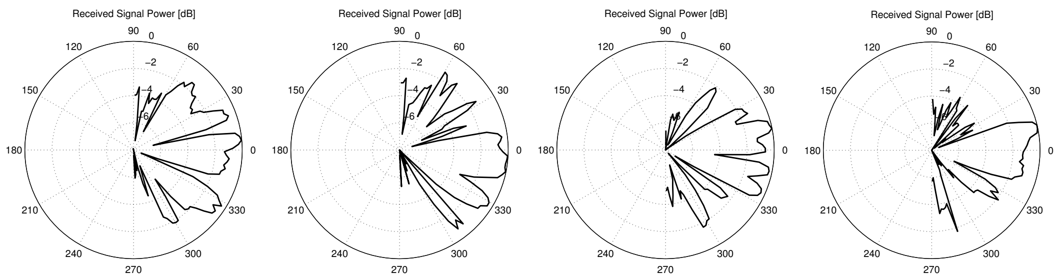


Figure D.4: Quasi omnidirectional beam patterns swept by the D5000.

From these results we can see that our WiGig devices do not perform a beam sweep through different virtual sectors as the IEEE 802.11ad does, but instead sweeps different quasi omnidirectional beam patterns searching for devices. Once the laptop receives the device discovery information from one of the frame sub-elements, the beamforming training is started, optimizing the radiation patterns of both devices to achieve optimum link conditions.

D.5.4 Reflection Test

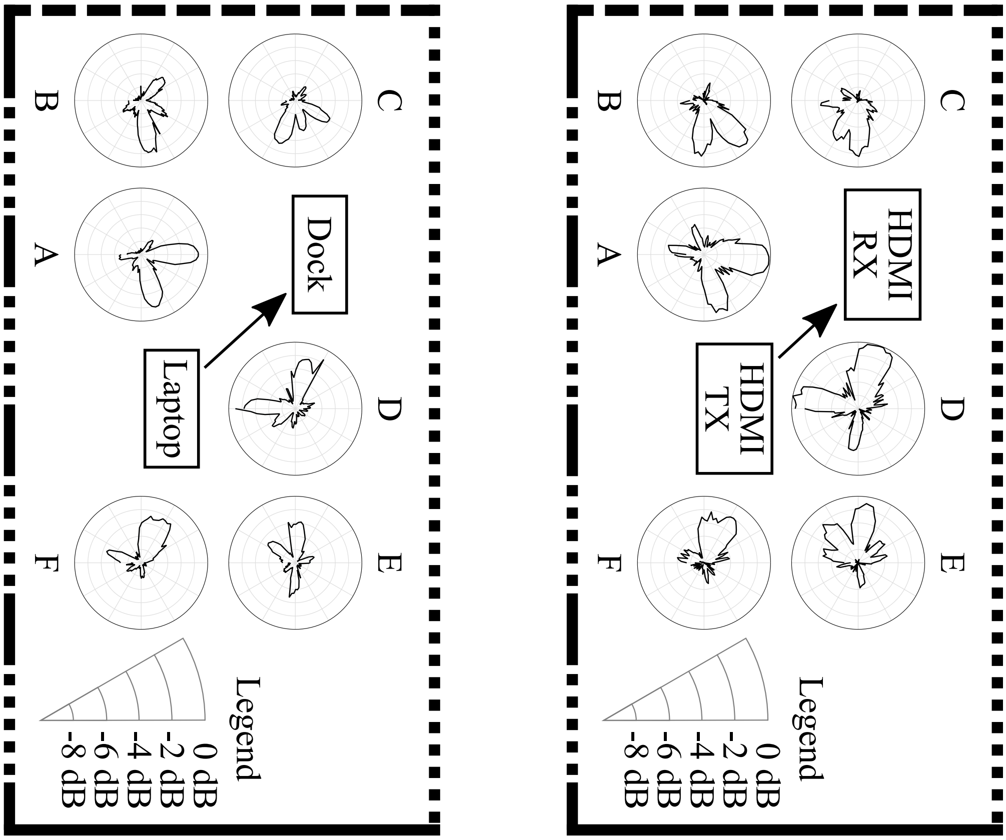
In this experiment we measure how mm-wave signals reflect in an office room watching how reflections could affect in terms of interference to other devices.

To do so, we setup the mm-wave communication and took different measurements with the rotatory stage to see how much power was received from every direction in the azimuthal plane.

We did this measurement campaign for the WiGig devices and for the wireless HDMI to see how reflections behaved for both systems, in order to study how inter-system interferences could arise through reflections.

The measurement results for both reflection tests are shown in Figure D.5, where the dots are glass, the dotted lines wood and the straight lines brick wall.

From this results we can see that reflections can have a big impact for mm-wave communications. We see in some positions that the reflected beams are as



(a) WiGig reflection test.

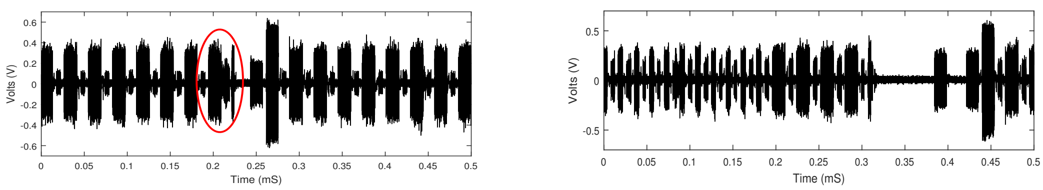
(b) WiHD reflection test.

Figure D.5: Measured reflection tests.

powerful as the direct path from the transmitters. We can also clearly see that as both devices have different beam patterns, they also have different reflections.

To see how this reflections damage other communications in the same room we left the Wireless HDMI on the same position and placed the wireless docking station and the notebook on position E and F. The direct path between the two different systems was blocked so only the reflections could collide the communications.

In Figure D.6 we can see two different retransmissions from the WiGig system due to interferences caused by the reflections. In D.6a we can see how the burst is finished without any ack and then a new burst begins. In D.6b we can see that the same happens but also the begining of the burst fails leading to a retransmission of the beaconing frame.



(a) Retransmission I.

(b) Retransmission II.

Figure D.6: Interference impact.

On the other hand, having this reflections can be also something positive for the user, as even if the direct path is blocked, they could communicate through reflections and establish a link.

D.6 Conclusions, Future Work and Alternatives

With this work we have analyzed the behaviour of the first generation millimeter wave off-the-shelf systems. To do so we carried out different measurement campaigns which gave us different insights about how this equipment behaves.

We have seen that these first devices are equipped with a 16 element antenna array. This array, being the first of its class to be in the market, is not as effective as theoretical reports [23, 24, 25] claim:

We found very strong sidelobes for the Dell D5000 docking station as well as for the connecting notebook, the Dell Latitude 7540 for aligned transmissions. For unaligned transmissions, even stronger sidelobes were measured. This shows that antenna arrays are directional, but still need to improve to achieve their theoretical targets for next generation mm-wave systems.

With the analysis of the Dell D5000 device discovery process we have seen that even if it is not possible to achieve true omnidirectional patterns in mm-wave antenna arrays [22], the station can change through different quasi-omnidirectional antenna patterns to be able to search for devices. This device discovery has been found to be different from the device discovery established by the incoming IEEE 802.11ad standard which is described in [20].

Further, with a mm-wave reflection measurement setup we found strong reflections in many different positions from an habitual office environment, making the connection of devices possible even if there is some blockage between them.

But we have also seen a drawback of these reflections. They can cause interferences implying packet losses and retransmissions to other devices working at the same frequency with a different protocol, even if their direct path is blocked.

To sum up the results of our measurement campaign, we found that this first generation 60GHz equipment is working correctly, but still needs to keep evolving. While this is not surprising, as the mm-wave technology is still in an early phase, the results point out important facts for further system development and protocol design.

Also, with deeper understanding on the analyzed systems, ideas for future research lines arise, as for example an extensive interference and packet collision study, as well as analyzing other 60GHz transceivers with different protocol or with more antenna array elements.

Several alternatives to the performed measurements were considered, as analysing individually components from a transceiver, using signal generators for the different measurement campaigns or the use of software to go through different simulations. Those methods were however rejected, as they would not analyze the real performance of an off-the-shelf system in realistic environment.

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