Universidad Politécnica de Madrid

Master Thesis

Wireless Sensor Network for Smart Transportation Systems

César Calvo Ramírez

Master's thesis presented to obtain the Master's Degree in the Internet of Things under the supervision of:
Dr. César Briso
&
Dr. Fernando Pescador

July 7, 2019

Resumen

El objetivo de este proyecto es validar la tecnología de ultra banda ancha (UWB) para aplicaciones en Internet de las Cosas, en concreto para sistemas de transporte inteligentes como los ferroviarios. Para ello se desarrollará unos quipos de medida basados en las tarjetas de desarrollo de Decawave para poder realizar medidas del canal radio en este tipo de entornos. A lo largo de la memoria se detallan los desarrollos teóricos, principios de modelado y sondeo de canal para comunicaciones de banda ultra ancha. Asimismo, se explica la descripción y cálculos necesarios para la implementación de los equipos que permiten modelar el canal.

Para poder realizar medidas de validación y testeo de esta tecnología es necesario realizar un desarrollo software para poder extraer parámetros de calidad propagación y rendimiento general. Este proyecto expone y resuelve los requisitos técnicos necesarios que se tienen que satisfacer para la aplicación demandada. Los software realizados se validan con medidas en entornos reales comparándolo con equipos profesionales de medida.

La tecnología necesaria para la implementación es proporcionada por los transceptores de banda ultra ancha que se programan a bajo nivel para obtener información útil a través de los registros internos. Se desarrollan 3 módulos: 2 programas en C para el transmisor y el receptor y un software para programación y representación basado en Matlab. Adicionalmente se usaran otros equipos como analizadores vectoriales de redes.

Finalmente, se llevan a cabo medidas reales en trenes del Metro de Madrid y en grandes recintos interiores. Con este proyecto se ha reducido el proceso de medida, aligerando el equipo necesario y haciéndolo más versátil para medidas en circunstancias más complejas como en partes de difícil acceso del tren.

Abstract

The aim of this project is to validate ultra Wide Band (UWB) technology for applications on the Internet of Things (IoT), specifically for intelligent transport systems such as railways. For this purpose, some sounding devices based on the Decawave development cards will be developed to be able to carry out measurements of the radio channel in these types of environments. Throughout this report, the theoretical developments, modelling principles and channel sounding for ultra-wide band communications are detailed. Likewise, the description and calculations necessary for the implementation of the equipment that allow modelling the channel are explained.

In order to perform validation and testing of this technology, it is necessary to carry out a software development in order to extract parameters of propagation quality and general performance. This project exposes and resolves the necessary technical requirements that have to be met for the demanded application. The software is validated with measurements in real environments, comparing it with professional measuring equipment.

The necessary technology for implementation is provided by the UWB transceivers that are programmed at a low level to obtain useful information through internal registers. In this project 3 modules are developed: 2 programs in C for the transmitter and receiver and another software for programming and representation based on Matlab. Additionally, other equipment will be used as vector network analysers.

Finally, real measurements are carried out in ”Metro de Madrid” trains and in large indoor environment. With this project, the measurement process has been reduced, lightening the necessary equipment and making it more versatile for measurements in more complex circumstances such as parts of difficult access of the train.

Contents

List of Figures

List of Tables

Acronimos

AGC	Automatic Gain Control
API	Application Programming Interface
ATO	Automatic Train Operation
ATP	Automatic Train Protection
ATS	Automatic Train Supervision
BPM	Burst Position Modulation
BPSK	Binary Phase Shift Keying
BW	Band Widt
CBTC	Communication Based Train Control
CDMA	Code Division Multiple Access
CIR	*Channel Impulse Response*
CRC	Cyclic Redundancy Check
CS	Channel Sounder
DSSS	*Direct-Sequence Spread Spectrum*
FCS	Frame Check Sequence
FSK	Frequency Shift Keying
HRP	High Rate Pulse repetition frequency
IoT	Internet of Things
ISM	Industrial, Scientific and Medical

LAN Local Area Network

LED *light-emitting diode*

LDE Leading Edge Detection

LoS *Line of Sight*

LoRa Low Range

LPWAN Low Power Wireless Area Network

LR-WPAN Low Rang Wireless Personal Area Network

MAC Medium Access Control

MIMO Multiple Input Multiple Output

MPC *Multipath Components*

NB Narrow Band

NLoS *No Line of Sight*

NFC Near Field Communication

OFDM Orthogonal Frequency Division Multiplexing

PDF Probability Density Function

PDP *Power Delay Profile*

PDS Power Spectrum Density

PHY Physical

PL Path Loss

PLC Power Line Communication

PN Pseudo Noise

PRF Pulse Repetition Frequency

PSK Phase Shift Keying

PTC Positive Train Control

RF Radio Frequency

RCC Rail Communication and Control

Rx Receiver

SFD Start of Frame Delimiter

SNR Signal to Noise Ratio

SPI Serial Peripheral Interface

STDCC Swept Time-Delay Cross-Correlation

S-V Saleh-Valenzuela

Tx Transmitter

UAV Unmanned Aerial Vehicle

UWB Ultra Wide Band

V2I Vehicle to Infrastructure

V2V Vehicle to Vehicle

V2X Vehicle to everything

VNA Vectorial Network Analyser

TWR Two Way Ranging

WFAN Wireless Factory Area Network

WHAN Wireless Home Area Network

WLAN Wireless Local Area Network

WNAN Wireless Neighbourhood Area Network

WPAN Wireless Personal Area Network

WWAN Wireless Wide Area Network

WSN Wireless Sensor Network

5G 5th Generation

Chapter 1

Introducción

Internet of Things (IoT) are becoming an essential technology in many verticals. The vertical concept in IoT its refers to all markets applications in which IoT can be deployed as a solution to a problem of the different sectors. IoT solves business problems in vertical markets like Smart City, Industry 4.0, Smart Building, Connected Car, Smart Energy, e-Health, Smart Agriculture, Smart Retail...

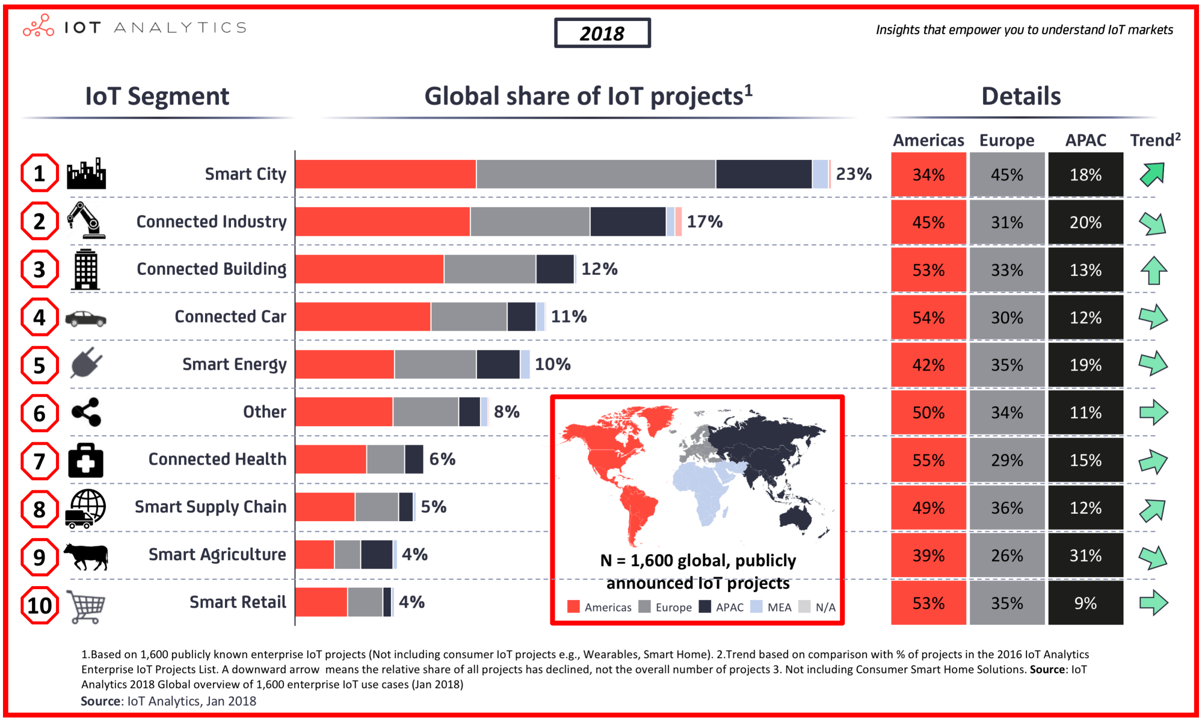


Figure 1.1: Verticals

Indubitably the role of IoT in the next years will be crucial but also challenging since touch and rather many technologies this heterogeneity make to the engineers solve new problems. One of the most important parts is communication, we usually talk about 'connected things' and that connection is refered to wireless communication in most of cases. Although the trends in IoT for wireless long range communication is the use of narrow band signals, in the last years, Ultra-Wide-Band (UWB) technologies have drawn great interest in wireless communications for indoor environments. This technology allows to reuse the actual spectrum without licence. Besides by the physical characteristics of the signals used makes it especially interesting for critical communications given its robustness and reliability in indoor propagation. Moreover, It also supports high precision indoor location features. Thus, has a special interest in Wireless Sensor Network (WSN) applications. [1]. In this field some of the main industrial applications have been carried out in the field of indoor location [2], personal and short distance sensors[3], public transport system[4] and indoor data transmission systems [5].

On the other hand, the railway industry plays a critical role in transportation because of the growing demand of passengers. However, due to many challenges faced by railway stations such as harsh environments, traffic flow, safety and security risks, new and adaptive systems employing new technology are recommended. If where the WSN applications are proposed to enhance security, safety, and decision-making processes to achieve more cost-effective management in railway systems, as well as the development of integrated systems.

This work tries to evaluate the Ultra Wide Band (UWB) radio technology for the implementation of sensor networks in railways environments.

1.1 Structure

This thesis is divided into 5 chapters:

- *Chapter 2* is reviewed the state of art in wireless communication for IoT for industry and home area networks. As well some of the most important challenges in IoT wireless communication. Finally the most relevant radio features of the UWB.

- *Chapter 3* detail the UWB modelling for indoor environments: Channel sounding techniques and the most used model for UWB signals.

- *Chapter 4* includes the development of the tools used for the study of the communications. The technical aspect of the development, characteristics and features.

- *Chapter 5* gather a set of measurements, test and models for WSN in railways and large indoor environment. Evaluate the technology in different scenarios to study weather is suitable for WSN in smart railways systems.

Chapter 2

IoT Wireless Communication

2.1 Technical requirements for IoT Wireless Communications

IoT presents new challenges and requirements with respect to traditional communications. Formerly, the wireless communication protocols were created to solve the divergent needs of the transmission most of the time focused on a big amount of data where the evolved technology has been increasing the quality of service. One of the big efforts has been in the mobile communications industry since the economy is highly linked with the quality of the telecommunication infrastructure of the country. Thus, during more than 40 years new wireless technologies and generations appear to solve the new requirements of the people has each decade. In contrast, with the appear of IoT the communications of the internet of things has an important impact in the future economy [6]. So, now it is a new challenge to consider, as reflected in the new 5th Generation (5G) communication standards. Not only the new challenges of IoT have been introduced in 5G. Also, legacy standard has been recover for the characteristics of IoT and also new research lines in developments are in IoT. The main is in 5G. Nevertheless, international standardization organism and private companies work to develop a more efficient solution for IoT communications.

There is a set of new requirements according with the general IoT specification. However, there is no a general solution for all problem and the diversity of technologies make to the designers choose the best option for each project. IoT applications and verticals are highly diverse in data rate, ranges, power consumption requirements, security and ease of use. So, consequently it is impossible for a single wireless technology to merge all the needs of all the types of applications. Each of the technology standards being developed are trying to address key requirements of different target applications.Despite this, there are some general characteristics that are described below:

Power consideration. The communication system is the most consuming part of an

IoT device [7] especially when the device is transmitting data to the gateway. Therefore, is need to take care of the power consumption in the design of the communication system because the IoT devices are thinking to be feed with a battery and require little maintenance. Thus, the approach is to design low power transmission and efficient communication technologies. This affect to a lot of technical consideration. The trend is going to low-speed communication since the IoT device does not need to send big amount of data. Thanks to this low requirement the band width can be reduced. This simplifies the electronic and power. The bandwidth and the data rate are the key consideration for communication in IoT application and both are involved for the power requirement. Additionally, must consider a good Radio Frequency (RF) design in order to match the impedances and avoid losses of power in the circuit and another critical part is the power amplification that must be optimized because is one of the most inefficient parts of the RF front-end.

Modulation is very important in the technology used. This the way how the information is carried in the electromagnetic wave. There are many modulation options regarding which parameter of the wave modifies. But the trend in IoT is going to the most efficient modulation, from the point of view of power amplification. For example, it used to modulate with constant amplitude like Frequency Shift Keying (FSK), Phase Shift Keying (PSK) and alternatives derived from these. That means that the information usually is in the frequency and phase parameters of the signal. Using constant power ensure that the amplifier works with no dead times. It is important to highlight that a radio technology does not have a single modulation, it uses adaptive modulations that change depending on the quality of the link to get to optimize speed when the propagation conditions are better. That is why it is common to see in the specifications more than one type of modulation.

Cost Saving. When there is a big deployment of IoT devices is important to save each Euro possible per device because it has a big impact on the overall final price. So, the radio can be an expensive part of the IoT device and his price depends mainly on the complexity and the data rate required. Nevertheless, it also can be affected by the frequency, high frequency needs more precise and less tolerant component and increase the price unnecessary. So, the way to reduce the price is again using low data rates, and simple systems.

Bandwidth consideration. Bandwidth is directly linked with the data rate. Higher bandwidth is need when the data speed is higher according to the theory of Nyquist [8]. Thus, the narrow band system sysmplifies the technology, reduce the noise, doppler effect, multipath issues and other propagation problems that appears with broadband signals. However, there is spread spectrum techniques [9] used in IoT like *Direct-Sequence Spread Spectrum* (DSSS) or Low Range (LoRa) (sometimes considered as modulation) that despite being broadband signals exploit some of the advantages they present. The main is the ability to share the medium. That is, the devices are capable of transmitting on the same frequency at the same time without interfering with each other. Moreover, these signals are more robust to the narrowband interferences, more secure and are not affected by the propagation fading phenomena.

Media Access Control. From the physical point of view of the communication media access control lead with the ability of communication to share the channel with other devices. These techniques are required because the resources (time and frequency) are limited and in IoT there is a massive number of elements that want to communicate almost at the same time. According to how these resources are shared can distinguish different multiplexation techniques that are: in time, in frequency, in space and in code. For IoT, time and frequency are the most common media access techniques used, followed by code and the less use is in space due to Multiple Input Multiple Output (MIMO) need a lot of expensive resources to work. Moreover, these techniques are helped with protocols like collision detections and avoidances to share in asynchronous time multiplexing channels.

2.2 Wireless Technologies Classification by Area Range

The need for different solutions in IoT connectivity is clear. However this fragmentation difficult the standardization and interoperability of the IoT devices, that is one of the main challenges of this technology. The diversity of technologies make difficult to classify according to one characteristic because can be applied several classifications. Nevertheless, the most common classification is according to the range of coverage that the technology can provide. And this range makes the area of use. The technologies can be split into a different range of uses. In Figure 2.1 can be shown an example of the coverage range or area range.

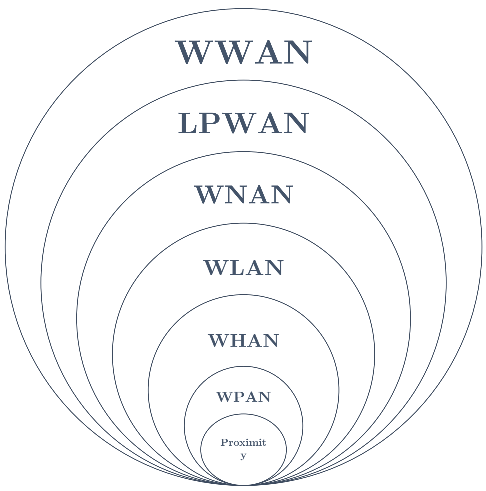


Figure 2.1: Wireless technologies by area range.

Another gross classification could be in 3 kinds of technologies as is shown in the comparative table in Figure 2.2.

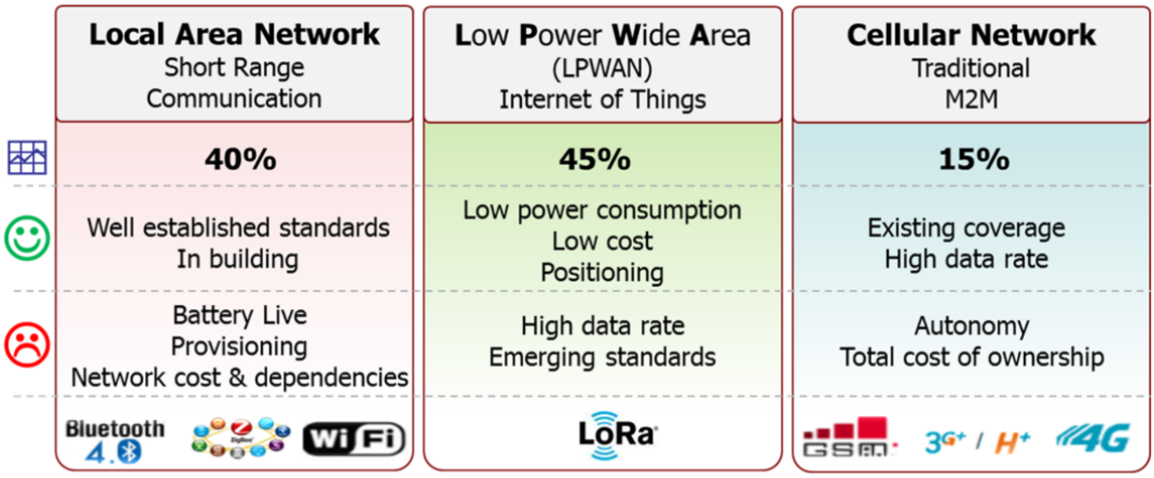


Figure 2.2: Wireless connectivity clasification. Comparative table.

A cellular network or Wireless Wide Area Network (WWAN) are considered the technology that gives more distance coverage. They uses license wireless bands regulated by the governs and exploit by operators. Therefore require pay for the use.

More interesting is the Low Power Wireless Area Network (LPWAN) characterized by kilo-metrics ranges and low power consumptions. The use of no licensed bands in sub GHz frequencies allow them good propagation capabilities inside buildings and indoor areas thanks to the low penetration losses and good propagation by diffraction. However, they have a low bandwidth and data rate.

Finally, when big distances are not required for example in WSN inside buildings or means of transport, there are other technologies more suitable like the technologies gather in Local Area Network (LAN). These technologies will be the study set of this document. Especially the family 802.15.4.

2.3 Technologies based on 802.15.4 PHY

The standard [10] was defined in 2003 by the IEEE 802.15.4 working group and currently, is still active it defines the Physical (PHY) and Medium Access Control (MAC) layers for low rate wireless communication, also known as Low Rang Wireless Personal Area Network (LR-WPAN). It is the base of famous higher layer specifications like *ZigBee*, *Thread*, *Wireless Hart* or *ISA100.11A* as can be shown in Fig. 2.3. The aim of this standard is to define the basic network layers to provide communications in Wireless

Local Area Network (WLAN) prioritizing low-cost and low-speed for limited battery consumption requirements, ideal for IoT devices. Additionally, the standard is able to provide precision ranging capabilities, less than 10 cm when the High Rate Pulse repetition frequency (HRP) UWB PHY is used.

Are defined multiple PHY to support a variety of license-free bands for all countries.

ZigBee

ZigBee is a proprietary specification of high-level communication layers that is based on the IEEE 802.15.4 radio. The aim was to be simple and inexpensive than other standards like Bluetooth. ZigBee is widely used in commercial applications. This standard is able to manage sleep modes and thousands of nodes in a network topology [11].

Wireless HART

WirelessHART is a proprietary specification for a wireless mesh network that sits on top of IEEE 802.15.4 radios. The WirelessHART protocol is based on the original highway addressable remote transducer (HART) wired protocol which superimposes digital signals using FSK on the 4-20mA analog current loop signals. It defines and adds capabilities to the HART protocol while maintaining compatibility with existing HART devices, commands and tools. It is widely used in industrial environments.

ISA100

ISA100 is an acronym for a committee within the international society for automation (ISA). The ISA100 committee develops a family of standards. The ISA100.11a is a standard for wireless field devices in scalable plant-wide systems and is available for purchase. It supports 6LoWPAN over IEEE 802.15.4 radios.

Thread

Thread starts in 2014 is similar to ZigBee; however, it uses the IPv6 over low-power WPAN (6LoWPAN) protocol. It can managed hundreds of sensors with encryption and secure capabilities [12].

6LoWPAN

6LoWPAN has defined encapsulation and header compression mechanisms that allow IPv6 packets to be sent and received over IEEE 802.15.4 based networks. It is implemented in other standards like Thread.

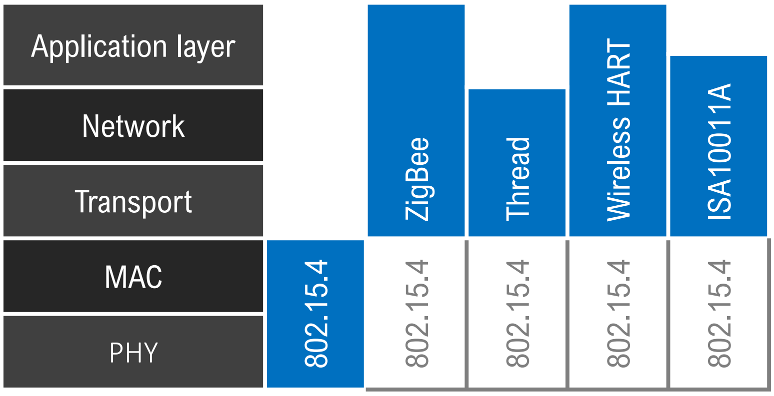


Figure 2.3: IEEE802.15.4 PHY and MAC layers

2.3.1 Application in Railways

According to the application are different groups of works and standard in this subsection have described some application of the Rail Communication and Control (RCC) that belongs to the standard 802.15.4p [13] as part of the Positive Train Control (PTC) that involves different systems, infrastructures and mechanisms that help to provide to the train safety capabilities.

General Description

There in application in smart transport systems like railways where are defined this standard for exchange of information sensing and control. For example in 3 approaches:

- Wireless links between trains or wagons to fixed trackside or network infrastructure is known as Vehicle to Infrastructure (V2I) [14]
- Wireless links between connected fixed, remote trackside infrastructure and fixed network infrastructure.
- A wireless link in the same train or between two or more trains. With application in virtual coupling [15], Communication Based Train Control (CBTC) [16].

RCC devices are intended to support communications at high speeds up to 600km/h with data rates from 9.6 kbps to nearly 1 Mbps that enable connections at distances of over 50 km (subject to the path loss, power, frequency, data rate and antenna placement). The RCC PHYs are designed to take advantage of relatively small amounts of the spectrum where spectrum is costly or scarce with the ability to operate in channel width from 12.5 kHz (licensed spectrum) to nearly 2 MHz.

Communications-based train control (CBTC)

A CBTC system is a contrinuous and automatic train control system defined in the standard IEEE 1474.1-2004 [17] that uses:

- Train location and positioning
- Independent circuits tracks
- High-capacity data communications
- Train-bone and wayside processors to implement:
  - ◇ Automatic Train Protection (ATP) functions
  - ◇ Optional Automatic Train Operation (ATO) functions
  - ◇ Automatic Train Supervision (ATS) functions
- System safety criteria

This system are very used in most of metropolitan railways system of the world. Included two *Metro de Madrid* lines. The standard IEEE 802.15.4p is in charge of the PHY specification for data communication.

2.3.2 HRP UWB PHY specification

The UWB technology is an IEEE project known as 802.15.4a that starts in 2003 and was completely finsished in 2011. The standard ”defines the physical layer (PHY) and medium access control (MAC) sublayer specifications for low-data-rate wireless connectivity with fixed, portable, and moving devices with no battery or very limited battery consumption requirements. In addition, the standard provides modes that allow for precision ranging. PHYs are defined for devices operating various license-free bands in a variety of geographic regions” also provide simultaneous two-way communication — up to 27Mbps. Recently, in 2018, the Task Group 802.15.4z Enhanced Impulse Radio(EiR) was re-opened [18] to add further security for a secure transaction wireless technology by the automotive and mobile industries [19].

In this section is going to be into details of the PHY layer, mainly focused on precision ranging. The waveform uses UWB signal with HRP. Also, will be described some of the main features of this standard in order to provide technical knowledge about the description of this standard.

Table 2.1: PHY UWB band allocation

Channel Number	Center Frequency (MHz)	Bandwidth (MHz)	Channel Number	Center Frequency (MHz)	Bandwidth (MHz)
0	499.2	499.2	8	7488.0	499.2
1	3494.4	499.2	9	7987.2	499.2
2	3993.6	499.2	10	8486.4	499.2
3	4492.8	499.2	11	7987.2	1331.2
4	3993.6	1331.2	12	8985.6	499.2
5	6489.6	499.2	13	9484.8	499.2
6	6988.8	499.2	14	9984.0	499.2
7	6489.6	1081.6	15	9484.8	1354.97

Operating frequency bands

The HRP UWB PHY support 3 different bands of operation:

- **Sub-GHz band** 1 channel from 249.6 GHz to 749.6 GHz
- **Low band** 4 channels from 3.1 GHz to 4.8 GHz
- **High band** 11 channels from 6 GHz to 10.6 GHz

In the Table 2.1 can be shown all description frequency for operation in UWB. The frequencies assigned are in the regulated use although can be used according with the maximum output mask of Power Spectrum Density (PDS).

Modulation

The modulation is a no traditional one. In order to support coherent and no coherent receivers. The standard defines a combination of two types of modulations: Burst Position Modulation (BPM) and BPSK. The symbols are modulated with the combined BPM-BPSK, so each symbol is a burst of RF pulses. The data rate is defined thought with the length of the burst.

Data rates are from 0.1 Mbps to 27.24 Mbps that can be selected with the code rate and mean pulse repetition frequency according to the quality of the channel.

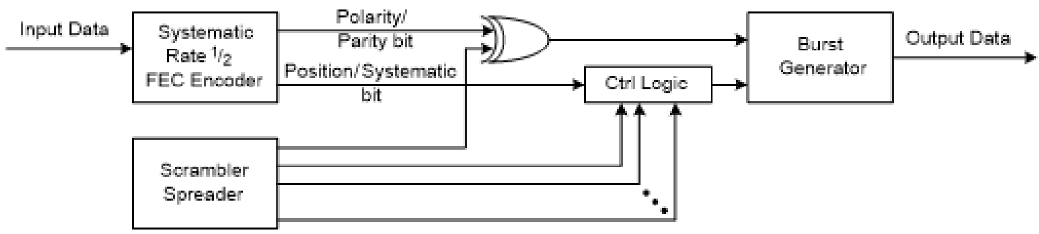


Figure 2.4: Reference symbol modulation.

Ranging

The UWB PHY supports precision ranging and location through the capability of time stamping, using a ranging counter that inserts a timestamp in the precise instant that receive or transmit to the antenna. The most interesting PHY is the UWB capability is the robustness again the multipath fading [20]. Moreover, UWB allows distinguish accurately in multipath environments when the signal was received and reject the multipath. As can be shown in Fig. 2.5 there is represented the baseband waveform. The signal of the direct path (which provide the valuable ranging information) is represented in black; the reflection path is in red and the received signal that is the sum of both is in light blue. Comparing The real direct path with the received signal can be observed that the UWB signal provided a clear reject of the reflection with the direct path. As long as the narrow band signal is non-resolvable and introduce a time error in the detection that leads in a distance error ranging. An that is the problem of the narrow band communication to provide trustworthy ranging capabilities. Furthermore, PHY has the capability to provide communication and precision ranging functions, even where a LoS radio path may not exist.

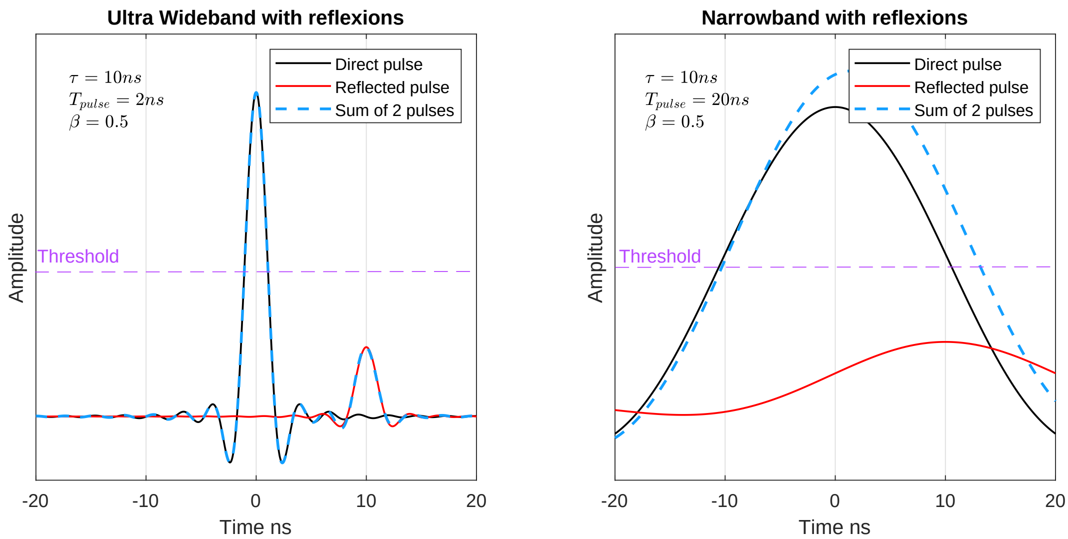


Figure 2.5: Comparison between baseband waveform in NB signal and UWB signal with presence of one reflection path.

Chapter 3

Channel modelling in wideband and UWB communications

3.1 General concepts

Wireless communications are affected by several propagation effects that degrade the signal. Understand and model this distortion helps designers make more reliable and robust communication. The first step to support propagation in a complex environment is to express mathematically how the signal behaves in each environment. However, this is a complex task because even though the propagation is deterministic, the environment is very complex for predicting the propagation. Therefore, usually is model from the statistic point of view in empirical process. So, the different model parameters are considered as random variables and stochastic process.

In a simple communication, the transmitted signal travel through the channel spreading in all directions before reaching the receiver. The signal that is radiated into the environment can experiment reflections, diffractions, o scattering before to reach the receiver but a sort time delayed with respect to the one that arrives directly. This delay is due to the different paths. First, the LoS signal arrives at the Receiver (Rx), afterwards the signal reflected in the environment also known as *Multipath Components* (MPC). Depending on the kind of signal transmitted (wideband or narrow band) the effect is different. In the case of narrow band signal, the MPC are sum in phase and makes that the signal fluctuates the strength. The effect is the fading that can lead to a loss of coverage and loss of communication. The study of fading can be done in different scales. The slowest attenuation is due to the path loss related to the Transmitter (Tx)-Rx separation. Then can observe the shadowing that is due to the momentary hide signal with objects, also effects of the radiation pattern of antennas. And the most faster fading that is provoked by the MPC of the surrounding objects.

In the case of using wide band or UWB signal, the MPC effect manifests itself in the frequency domain as a selective attenuation. Analogously, in time is shown as a time dispersion.

In this chapter, we will study the effect of propagation on ultra-wide band signals as well as its statistical modelling for UWB communications.

3.2 Path loss

All wireless communications are affected by the path loss propagation. It is the effect of power decrease due to the distance between edges of link. In a Narrow Band (NB) system is defined as:

$$PL(d) = \frac{E\{P_{Rx}(d, f_c)\}}{P_{Tx}} \tag{3.1}$$

where P_{Rx} is the power received and P_{Tx} the power transmitted. d is de separation between transmitter and receiver, f_c the centre frequency and $E\{\}$ is the mean of values over a large enough area to ensure the filtering of shadowing and small-scaling fading effect. Nevertheless, in (3.1) are not consider the antenna effect in the channel model and this is frequency dependent, whereas UWB has to consider all range frequency due to the wide contribution. Te anntena effect may not have negligible eeffects in the path loss. Thus, Path Loss (PL) defined in refs [21]:

$$PL(f, d) = E\left\{\int_{f-\Delta f/2}^{f+\Delta f/2} \mid H(\tilde{f}, d) \mid^2 d\tilde{f}\right\} \tag{3.2}$$

where $H(d, f)$ is the antenna frequency response and Δf is de bandwidth signal. To simplify we assume that the PL is the product of frequency and distance term:

$$PL(f, d) = PL(d)PL(f) \tag{3.3}$$

Pathloss frequency term follows the following law [22]:

$$\sqrt{PL(f)} \propto f^{-k} \tag{3.4}$$

Whereas the distance dependence PL in logarithmic units is defined as

$$PL(d) = PL_0 + 10nlog_{10}\left(\frac{d}{d_0}\right) \tag{3.5}$$

where d_0 is the reference distance, typically 1m and PL_0 is the path loss at the reference distance. n is the path loss exponent that depends on the environment, the *Line of Sight* (LoS) or*No Line of Sight* (NLoS) conditions. For example, the free space and LoS conditions $n = 2$.

3.3 Shadowing

Shadowing, or large-scale fading, is the variation around the mean value of the path loss and is similar to the fading in narrow band signal. This effect is produced by objects obstructions between transmitter and receiver. The filter in large scale fading is more than 40λ, consider λ as the wavelength. The change in the environment also is considered as shadowing and it is filtered in tens of hundreds meters. In PL the shadowing in dB is modelled as

$$PL(d) = PL_0 + 10nlog_{10}\left(\frac{d}{d_0}\right) + S \tag{3.6}$$

where S is a Gaussian distributed random variable $S \sim \mathcal{N}(0, \sigma_S)$

3.4 Ultra Wideband modelling

To model the *Channel Impulse Response* (CIR) in UWB is used Saleh-Valenzuela (S-V) model [23] given as

$$h(\tau) = \sum_{l=0}^{L}\sum_{k=0}^{K} a_{k,l}e^{j\phi_{k,l}}\delta(\tau - T_l - \tau_{k,l}) \tag{3.7}$$

the model is compose by L clusters composed with K rays. $a_{k,l}$ is the amplitud of the kth component in the lth cluster. T_l is the delay of the lth cluster. $\tau_{k,l}$ is the delay of the MPC in the lth cluster, relative to the T_l. The phase is represented by $\phi_{k,l}$ and it is model as a random uniform variable from 0 to 2π. The number of clusters L is characterized as a Poisson distribution with $\bar{L}$ parameter.

$$pdf_L(L) = \frac{\bar{L}^L e^{-\bar{L}}}{L!} \tag{3.8}$$

The power of each MPC decays in a exponential way with arrivals times that follows a Poisson process

$$p(\,T_l\,|\,T_{l-1}\,) = \Lambda e^{-\Lambda(T_l - T_{l-1})}, \quad l > 0 \tag{3.9}$$

Λ parameter is the cluster arrival rate. Regarding the arrival time of the rays in the clusters, the S-V model it with the same Poisson process. However, [24] proposed a modified model with a mix of two Poisson process

$$p(\,\tau_{k,l}\,|\,\tau_{(k-1),l}\,) = \beta\lambda_1 e^{-\lambda_1(\tau_{k,l} - \tau_{(k-1),l})} + (\beta - 1)\lambda_2 e^{-\lambda_2(\tau_{k,l} - \tau_{(k-1),l})}, \quad k > 0 \tag{3.10}$$

where β is the probability of mixture and λ_1 and λ_2 the ray arrival rate.

3.4.1 Power Delay Profile

Power Delay Profile (PDP) is defined as the mean of the power distribution in an environment. It can be extracted from the CIR (3.7) and is a useful abstraction of how the power is distributed in time.

$$P(\tau) = E\left\{|h(\tau)|^2\right\} \tag{3.11}$$

The expression 3.11 is averaged in time in order to get the mean value over a place. In the UWB model the PDP is exponential with each cluster.

$$E\left\{|a_{k,l}|^2\right\} = \Omega_l \frac{1}{\gamma_l[(1-\beta)\lambda_1 + \beta\lambda_2 + 1]} e^{-\tau_{k,l}/\gamma_l} \tag{3.12}$$

The expression in (3.12) gives the normalized value of power in each ray. Where Ω_l is the integrated energy in the lth cluster and γ_l is the intra-cluster decay constant. The mean power of the lth cluster follows (generally) an exponential decay.

$$10\log(\Omega_l) = 10\log(\exp(-T_l/\Gamma)) + M_{cluster} \tag{3.13}$$

where $M_{cluster}$ is a random variable with $\sigma_{cluster}$ standard deviation.

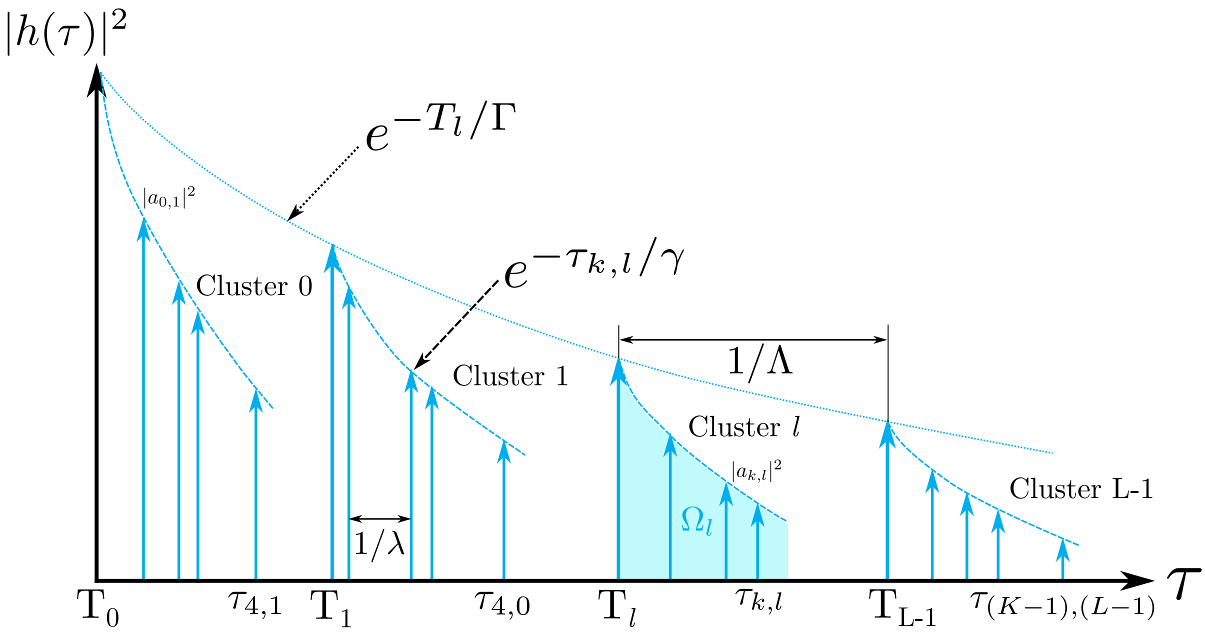


Figure 3.1: Line of Sight Power Delay Profile of Saleh-Valenzuela model.

In case of NLoS conditions the PDP can follows a log-linear scale [24]

$$E\left\{|a_{k,1}|^2\right\} = (1 - \chi \cdot e^{(-\tau_{k,l}/\gamma_{rise})})e^{(-\tau_{k,l}/\gamma_1)} \cdot \frac{\gamma_{rise} + \gamma_1}{\gamma_1} \frac{\Omega_1}{\gamma_1 + \gamma_{rise}(1-\chi)} \tag{3.14}$$

where χ is the attenuation of the first component; γ_{rise} is how fast the power increase to the local maximum and γ_1 is the decay at late time.

Other parameters

Most of the parameters are extract from the PDP function. They provide a general quantification of the channel. Nevertheless, it involves a big abstraction of the channel properties that usually are enough descriptive for most of the communication systems. The most used is the mean excess delay

$$\bar{\tau} = \frac{\int_0^\infty \tau P(\tau) d\tau}{\int_0^\infty P(\tau) d\tau} \tag{3.15}$$

And root mean square (rms-ds). It is the most important parameter to express the time dispersion. It is defined as:

$$\sigma_\tau = \sqrt{\frac{\int_0^\infty (\tau - \bar{\tau})^2 P(\tau) d\tau}{\int_0^\infty P(\tau) d\tau}} \tag{3.16}$$

Finally, can be defined other auxiliary time parameters from the PDP function in (3.11) for example number of MPC that is within xdB of the peak amplitude, or MPC that carries at least $y\%$ of the total energy

3.4.2 Small Scale Fading

In the equation 3.7 the tap weight $a_{k,l}$ is distributed *Nakagami* Probability Density Function (PDF).

$$pdf(x) = \frac{2}{\Gamma(m)} \left(\frac{m}{\Omega}\right)^m x^{2m-1} exp\left(-\frac{m}{\Omega} x^2\right) \tag{3.17}$$

where Ω is the mean square value of the amplitude $a_{k,l}$. $\Gamma(m) = \int_0^\infty t^{m-1} e^{-t} dt$ and $m \geq 1/2$ is the *Nakagami* factor that can be related with the K factor of a Rician distribution that is defined as the relation between LoS power with the sum of NLoS power from the MPC:

$$K = \frac{P_{LoS}}{\sigma P_{NLoS}} = \frac{|a_{0,0}|^2}{\sum_{l=1}^{L} \sum_{k=0}^{K} |a_{k,l}|^2} = \frac{\sqrt{m^2 - m}}{m - \sqrt{m^2 - m}} \tag{3.18}$$

where K factor of a Rician distribution with a PDF

$$pdf(x) = \frac{2(K+1)x}{\Omega} \exp\left(-K - \frac{(K+1)x^2}{\Omega}\right) I_0 \left(2\sqrt{\frac{K(K+1)}{\Omega}} x\right) \tag{3.19}$$

Table 3.1: Summary of UWB modelling parameters

Parameter	Description
PL_0	pathloss at 1m distance
n	pathloss exponent
σ_n	shdowing standard deviation
k	frequency dependence of the pathloss
$\bar{L}$	mean number of clusters
Λ	inter-cluster arrival rate
$\lambda_1, \lambda_2, \beta$	ray arrival rates (mixed Poisson)
Γ	inter-cluster decay constant
$\sigma_{cluster}$	cluster shadowing variance
m_0, k_m	Nakagami m factor mean
$\hat{m_0}, \hat{k_m}$	Nakagami m factor variance
$\gamma_{rise}, \gamma_1, \chi$	parameters for alternative PDP

where I_0 is the 0th order modified Bessel function of the first kind. This distribution is also very used to model the fast fading in narrow and wideband channels. However for in Nakagami distribution the m parameter is model as a log-normal distribution with $\mu_m(\tau)$ and $\sigma_m(\tau)$ and it is possible a dependence with delay τ.

Chapter 4

Develop of Measurements tools. UWB Channel sounder

4.1 General concepts of channel sounding

Channel sounder is the measurement equipment used to characterizing the electromagnetic propagation. It is useful equipment composed by one transmitter that generates the deterministic sounding signal and a receiver that is responsible for interpreting the propagation produced between both meter devices. In the previous chapter have been discussed the propagation models for UWB signals. The statistical model proposed is composed of certain parameters that allow us to describe de channel. The channel sounder is in charge of extract those parameters from the channel in order to compose properly the mathematical expression that characterized the communication channel in terms of quality, performance and limits that can achieve.

4.2 Classification.

The main classification that we should take is according to the bandwidth of the sounding signal.

- **Narrow band**. Is the straightforward implementation of a channel sounder. It implies the transmission of a continuous wave signal in the Tx meanwhile the Rx records the received instantaneous power.
- **Wide band**. This technique employs more sophisticated and complex signal in order to measure a wide range of the spectrum. Regarding the domain measure can be distinguished 2 classifications:
  - ◇ Time. If the sounding signal model the time behaviour of the propagation.

◇ Frequency. Whether it is model the behaviour of the frequency selective fading due to the multipath.

Both of them can be changed the domain by the Bello functions [25]. So, it is indistinct time characterization or frequency characterization and the choice will depend on the type of measure.

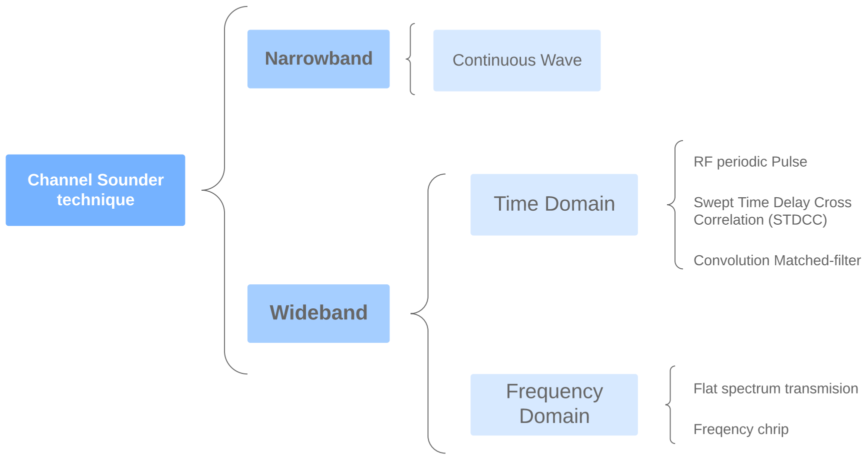


Figure 4.1: Classification of the channel sounding techniques.

In the next subsection will be described 3 sounding techniques that will be used for the UWB channel characterization.

4.2.1 Vector Network Analyser

Also known as frequency chirp technique uses a wideband signal in the frequency domain. The sounding signal consists of a sinusoidal tone sweeping on frequency thought the spectrum. Its performance with a Vectorial Network Analyser (VNA). As advantages of this technique are the optimum power transmission, accurate measurements with high dynamic range and large bandwidths. In contrast, they are expensive, heavy to handle and need synchronization and short distances. Thus, it is suitable mainly for static and short indoor environments.

4.2.2 Swept Time-Delay Cross-Correlation

The pulse compression technique Swept Time-Delay Cross-Correlation (STDCC) employ wideband signal in the time domain. The signal is a deterministic Pseudo Noise (PN) sequence that modulates a carrier frequency. On the receiver side this signal is correlated with the same PN sequence and the autocorrelation function gives the CIR of the channel. These measurements must be implemented with custom equipment. Long range measurements can be carried on thanks to good efficiency modulation. However, can be difficult to synchronize to measure phase information. Anyway, is the most used technique for outdoor environments.

4.2.3 RF periodic pulse

It is the most simple technique to measure wideband channels. Consists in the transmission of a short burst of frequency pulses in a periodic way. This technique uses the principle of characterization of linear systems with a Delta de Dirac signal. So, the sounding signal tries to be similar to this function. The received signal in baseband gives the CIR of the channel. As advantage present a easy implementation and do not need complex synchronization either processing and sampling resources. In contrast, this technique does not use efficiency the power and reduce the maximum dynamic range. Also, need high power to work properly in the detection of weak MPC.

Table 4.1: channel sounder characteristics

	STDCC CS	**UWB CS**	**VNA CS**
Distance	Large	Medium	Short
Precision	High	Medium	Very High
Dynamic Range	Good	Normal	Very Good
Variant Channels	Yes	Yes	No
Max BW/Res	100MHz/20ns	900MHz/1ns	6GHz/166ps
Cable Synchornization	No	No	Yes
Suitable for:	Outdoor, hillary, rural environments	Large indoor time-variant scenarios	Static and indoor scenarios

4.3 Development of RF periodic pulse UWB channel sounder

In this section is described the development of a UWB channel sounder with the narrow RF periodic pulse. The development is based on the radio chip DW1000 [26] of *Decawave* as a wireless UWB chip for ranging and communications proposes. The chip implements the standard 802.15.4-2011 described in section 2.3.2. The modulation used was a narrow pulse (2ns) RF transmission where the information was code in the position and phase of the pulse. The idea is to exploit the debugging properties of the transceiver to program a complete channel sounder using the evaluation boards DWM1001 [27] and 2 custom firmware programmed in C. The advance processing will be done with an external computer with higher computing capabilities using Matlab.

Figure 4.2: DWM1001 Development Board used for Tx and Rx equipment.

4.3.1 Requirements

- Acquisition of complex Channel Impulse Response in the baseband. And a representation of the PDP in dB scale with an acquisition rate higher than 1 per second. The dynamic range and maximum excess delay should be maximum as possible.
- Precise range measurements from the transmitter to the receiver in order to relate the channel propagation models with the separation between ends of communications. In order to achieve good results, the measurement distance should be incremented by increasing the transmitter power.
- Total power received first path power and K factor estimation for each measurement.
- Packet Error Rate and event error counter that allows counting the reason for packet loss.
- No synchronization between devices. Both devices must work autonomously.

4.3.2 General Framework

The channel sounder is developed with 2 DWM1001 development board and a PC with Matlab. Thus, achieve a simple and portable development very suitable for difficult to measure scenarios. The board development software is done by low-level radio programming accessing to the device through the Serial Peripheral Interface (SPI) interface register set. The source code is in C programming language through an Application Programming Interface (API) version 2.7 provided by the manufacturer.

The software application is running in an operating system *FreeRTOS* [28] in the microprocessor Nordic nRF52832. The hardware architecture of the system is represented in Figure 4.3. Both modules use the same hardware with a STM32F072 for debugging proposes and the microprocessor and transceiver embedded in the module DWM1001. Meanwhile, the transmitter uses an external connection to upload the data; the transmitter does not have any external connection for communications.

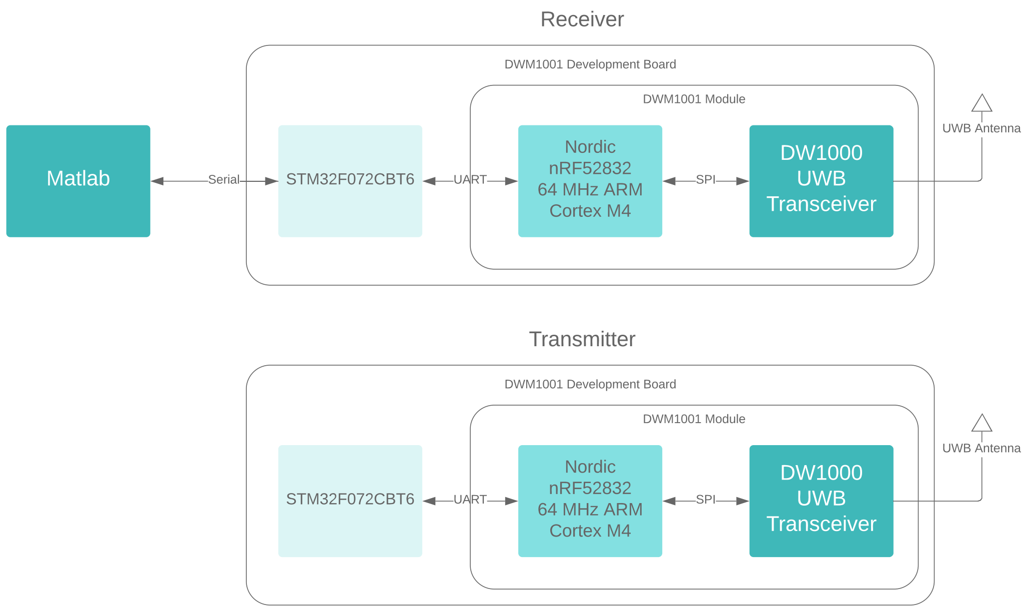


Figure 4.3: Hardware architecture schema.

Segger Embedded Studio is used as Integrated Development Environment with FreeRTOS and *decawave* libraries that provided the API functions. The API allow controlling through the SPI the transceiver register to program low-level operations in the DW1000 radio chip abstracting the target SPI. In Figure 4.4 is represented the software framework with the drivers used.

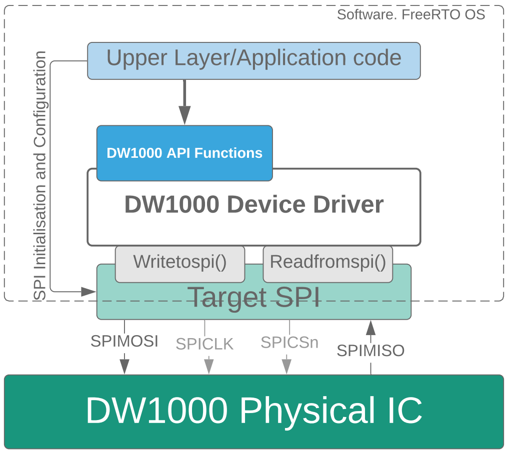


Figure 4.4: General Software Framework of DW1000 device driver.

4.3.3 Measurement Procedure

The software development is based on the code example 6a and 6b: single-sided Two Way Ranging (TWR) (SS TWR). This application sends a poll frame recording the timestamps of the transmission then it waits for the response whit the time stamps of the received frame and the transmission response. In addition to the time stamp of the receive, the response can be calculated the Time of Flight between two devices and consequently the distance range. However, the most recommended implementation for measuring distance is double side TWR to avoid the clock offset errors this protocol gives us accurate enough for the application and does need to use 3 packets for calculating the range.

In figure 4.5 its represented the packet exchange between the 3 devices implied. The first packet is optional and typically is used at the start of the measurement process to set up the radio parameters like channel, bandwidth, preamble... The information is communicated by wireless to the transmitter device. When a measurement procedure starts the receiver sends periodically poll messages to the Tx and wait for the answer. Tx device response the poll message including all timestamps needs for the ranging calculus and when the response message is received can be read in Rx transceiver registers about the response message status. This information includes the CIR in accumulator memory; the events counters, about the header errors, time-outs, checksums; and power estimation. Finally, all these parameters are reported to the Matlab software for store, processing and representation.

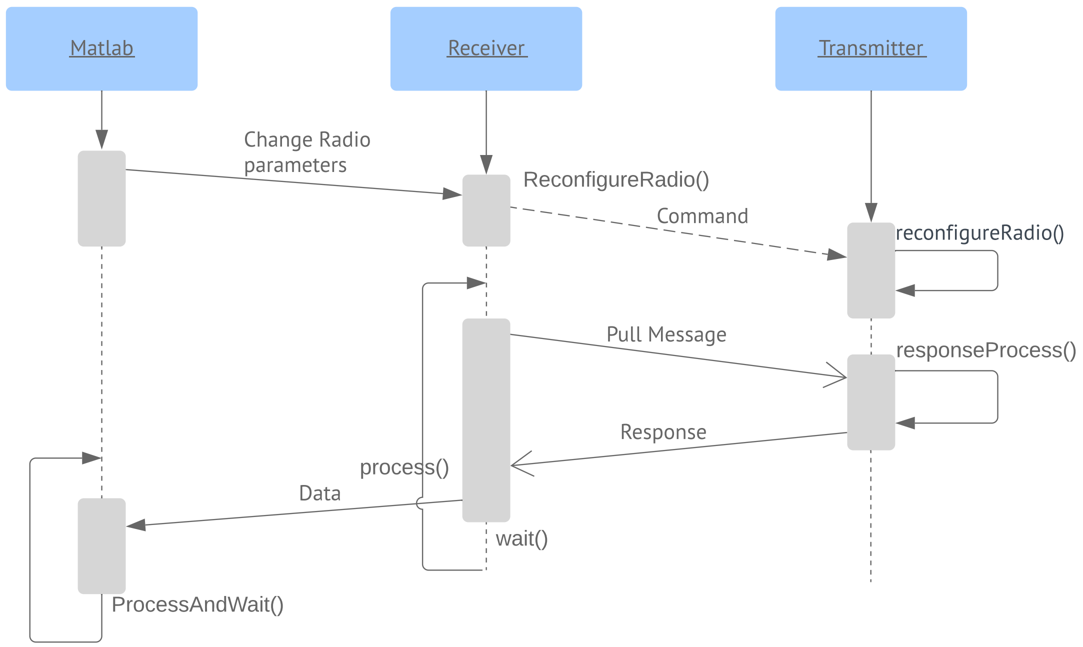


Figure 4.5: Measurement procedure and packets exchange.

4.3.4 Transmitter

The transmitter is an isolated board that only need to connect to a power supply to work. It means that is not any exchange of information by a wired connection. In figure 4.3 and Figure 4.5 is shown how Tx are in charge of answer the pull messages.

The logic processing of the software is model in Figure 4.8 as can be shown there is an initial program that initializes and configure the device and throws 2 tasks: one for a blinking status LED and the other one for the main application function. The main application function is Task 2 that is constantly pulling for new messages and checking the message received. If the message is good and is a command reconfigure the radio if is good and is a poll message then create the response and is sent to the Rx.

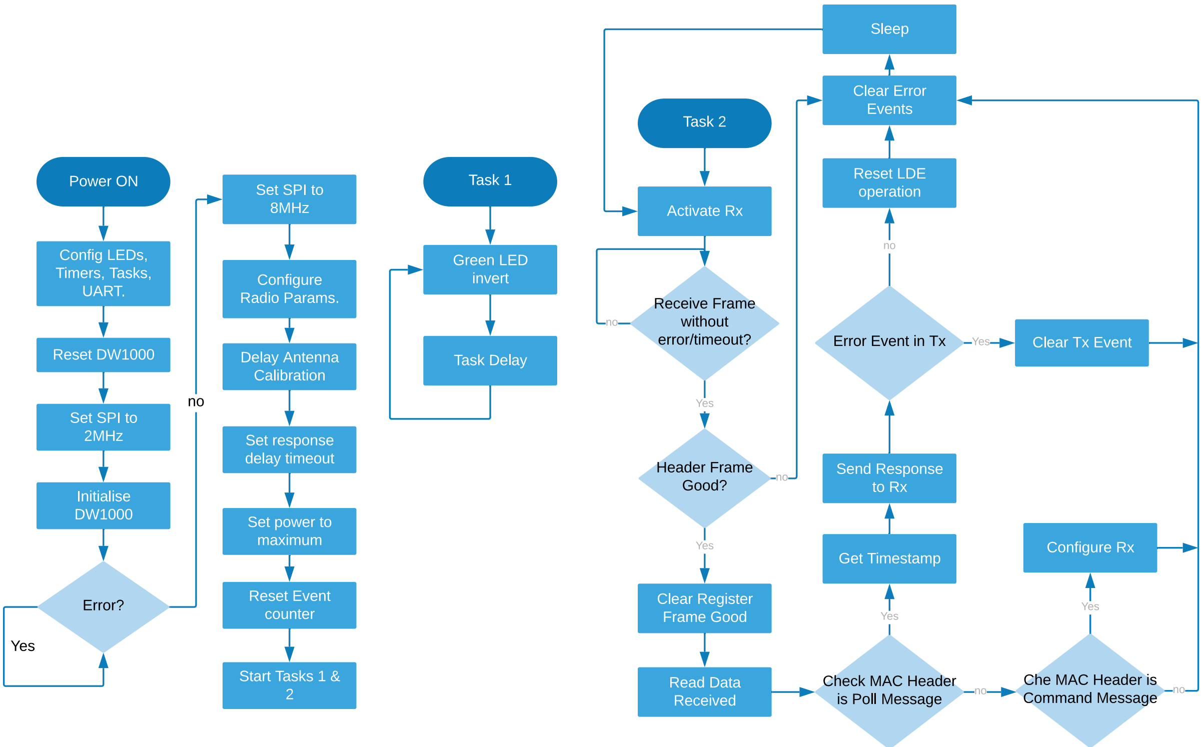


Figure 4.6: Classification of the channel sounding techniques.

4.3.5 Receiver

The Receiver (Rx) is responsible to generate the poll messages and receive the response message. It calculates the ranging measure according to the timestamps and read from the transceiver the quality parameters of the transmission. The information is upload to the external Matlab software.

The logic processing of the software is model in Figure 4.7 as can be shown there is an initial program that initializes and configure the device and throws 2 tasks: one for a blinking status LED and the other one for the main application function. The main application function is Task 2 that is waiting for command in the UART interface. If this command is received the application change the radio parameter. Later, constantly send pull messages to the Tx module and waits for the response. If message is good it extracts the radio information from the registers. Also estimate the distance with the information of the response. Finally all information is sent by the UART interface to the computer. After, Matlab application process and storage the data sent.

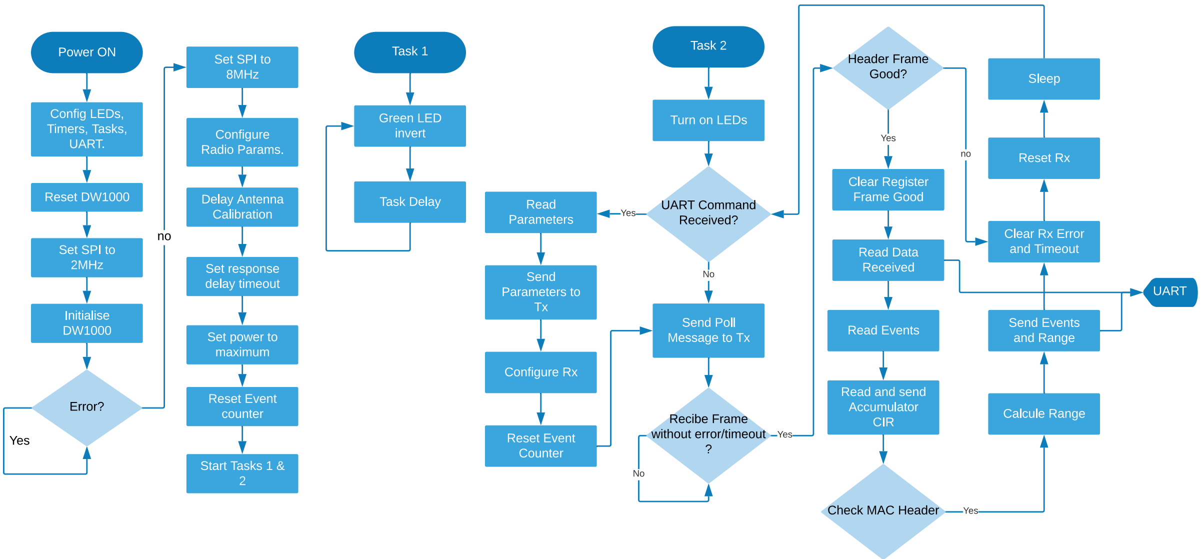


Figure 4.7: Process Diagram of the Receiver software application.

4.3.6 Matlab Software

Matlab software is needed as an external way to show, plot and storage the channel information acquired during the measurement process. Additionally, it will need to reconfigure radio parameters of the boards before measurements. Matlab is used thanks to the fast development process and by the toolbox and functions included.

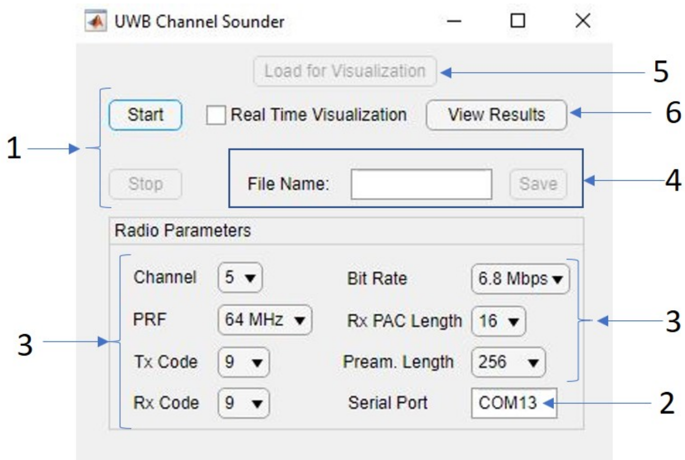


Figure 4.8: Matlab control interface.

It is used as a script in order to get the fastest performance in the management USB by the operating system. Nevertheless, there is a problem with USB management in

Windows and sometimes data is lost. An increase in the Tx buffer to 4096 improve the performance but still is very related to the computer used. The functionality is split in 3 sections.

1. Control the execution of the program. Reads the serial port to get the Channel Information. The flow process is in the diagram of the figure 4.12. There is a check-box (Real time representation) to show CIR in real time meanwhile is measuring. But, this option can affect to the read serial port and should be OFF for better performance in poor quality computers. The measuring process is interrupted with the "stop" button.

2. Configure the communication port of the computer. This must be configured previous to start a new measure. The port assignment is managed by windows OS independently on each equipment. Thus, should be checked the assignment of the board.

3. Configure the radio parameters in Rx board, then the configuration is transmitted to the Tx board when the user starts a new measurement. The command composition is shown in Table 4.3 and the description and suggest values is in the DW1000 User Manual [29].

4. After a measured process is stopped all parameters can be stored in a `'.mat'` extension file for further representations.

5. Alternatively, storage `'.mat'` files can be load into the program for the standard visualization.

6. Representations. This part is run to show useful channel plots in order to see after measurement a rough result to check the validity of measures. Can be shown the current measures or a storage measures previously load. There are 3 windows that automatically plot:

    - Table with the statistic event counter, like packet error rates or errors in communications and what is the reason that originated it. Could be decodification errors in Reed-Solomon decoding, header errors, Frame Check errors, time-outs errors, etc. That is good to identifier and debug problems in radio configuration.

	1	2	3
1	PHE	0	Physical Header Error
2	RLS	13	Synchonization loss (Red-Solomon)
3	CRCG	627	CRC Good
4	CRCB	0	CRC Bad
5	ARFE	0	Address Filter Rejection
6	OVER	0	Rx Overflow
7	SFDTO	3	SFD Time Out
8	PTO	0	Preamble Timeout
9	RTO	27	Rx Wait Time-Out
10	TXF	670	Number of Transmitted Frames
11	HPW	0	Half Period Warnings
12	PER	6.4179	Packet Error Rate

Figure 4.9: Matlab representation: Table information

- 3 composed graph that relates the measurement time with CIR, distance and power. CIR graph is a 3D representation with more warm colour represents the signal strength. Below this is represented the distance function with the red background if is consider NLoS conditions according to K factor estimation below -6dB. In the last graph is plot 3 functions FPP, PRx and K factor.

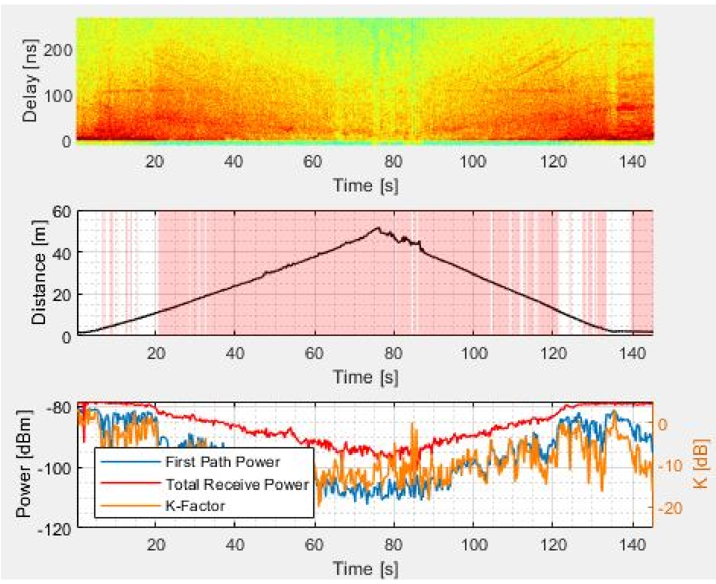


Figure 4.10: Matlab representation: Graphs

- Finally, is plot the PRx with the distance measure to relate the magnitude with the path loss measurements. Nevertheless, this utility is not useful weather is used the AGC in the Rx.

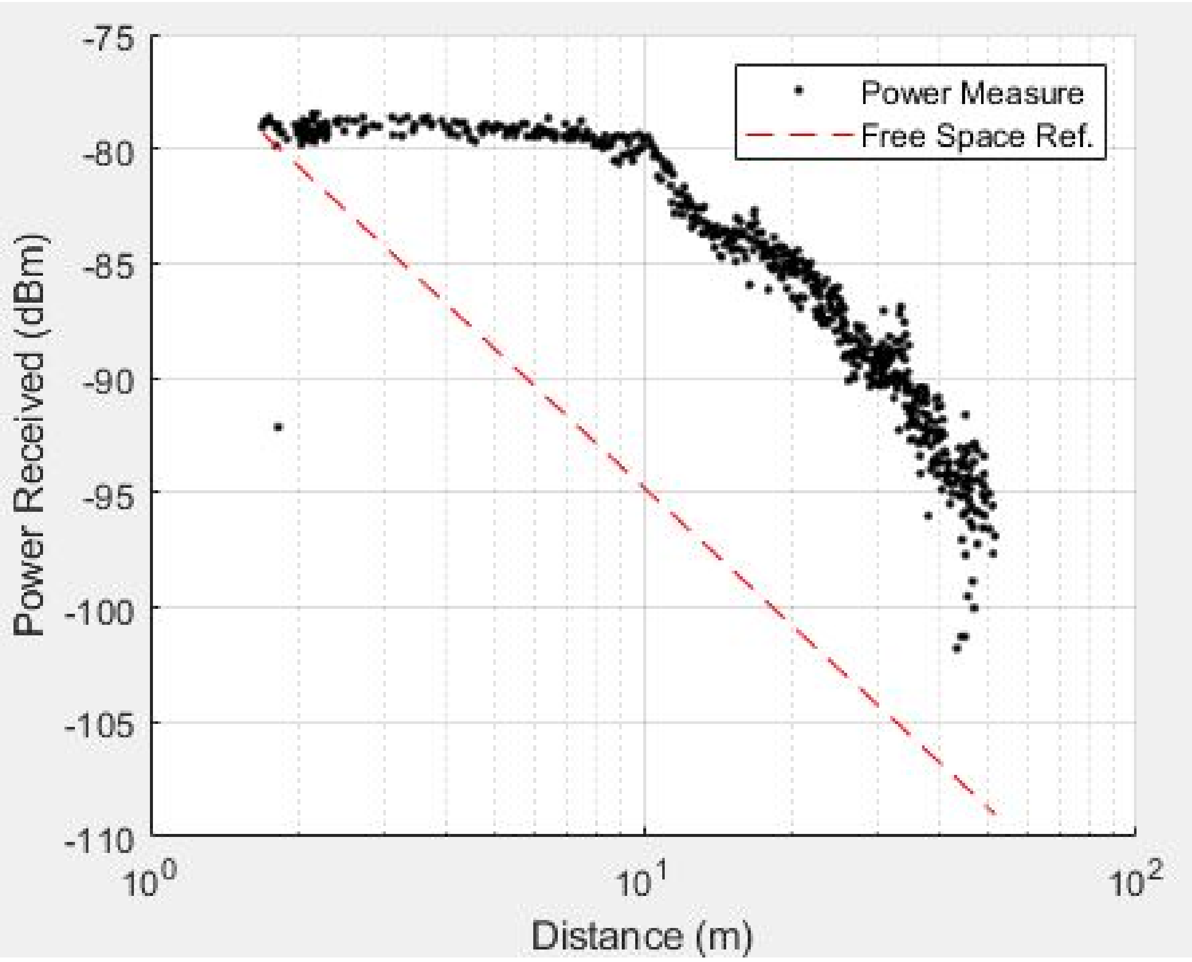


Figure 4.11: Matlab representation: Power vs distance

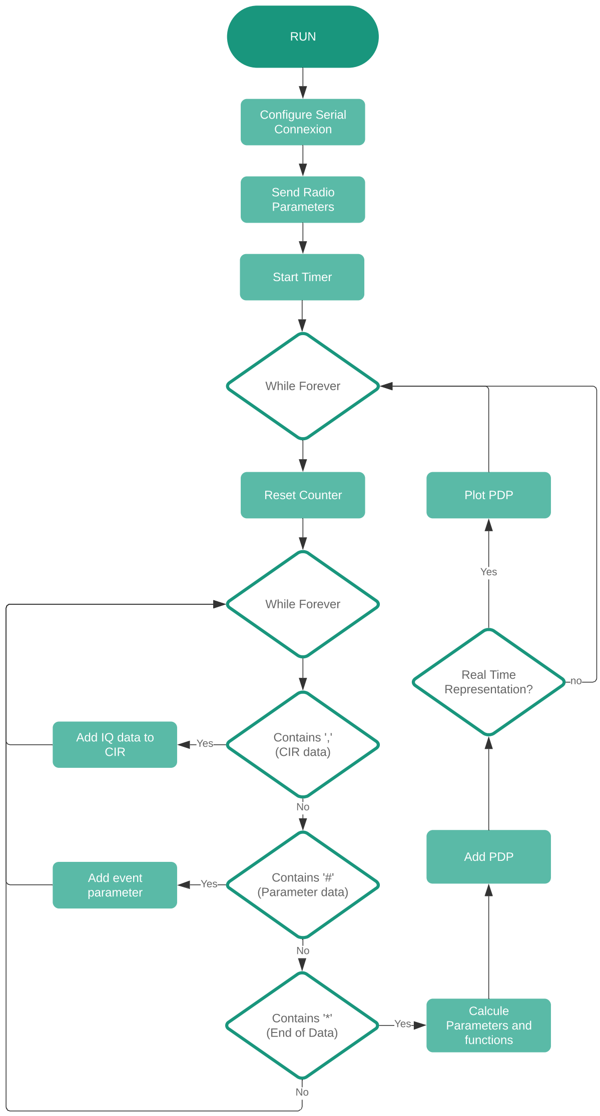


Figure 4.12: Process Diagram of the Receiver software application.

Table 4.2: USB configuration for Matlab controller.

Parameter	**Value**
Speed	1MSa/s
Buffer Rx Size	4096
Data	8 bits
Stop bit	1
Parity	None

Table 4.3: Command composition

	Channel	PRF	Rx Code	Tx Code	Bit Rate	Tx Preamble Length	PAC	SFD mode	PHR Mode
Number of Bytes	1	1	2	2	1	1	1	1	1
Range Values	1,2,3,4,5,7	1, 2	[1-20]	[1-20]	1,2, 3	[1-8]	[1-4]	1, 2	1, 2
Default Value	5	2	9	9	3	2	1	2	1

1. Channel Impulse Response (CIR): Represents the CIR of the channel and this data are store in the accumulator memory. Contains complex values 16-bit real integer and 16-bit imaginary integer each tap represents 1 ns sample interval (or 1 symbol). So, for the 16MHz Pulse Repetition Frequency (PRF) the accumulation length is 992 samples, while for 64MHz PRF is 1016 Samples. Therefore, the most suitable PRF configuration for measurements is 64 MHz in order to get the maximum excess delay possible. An other remark is the index of the first path is around 750 for low multipath effect. Thus, the real maximum excess delay is 266 ns in good conditions. For the real value of the first path detected by Leading Edge Detection (LDE) algorithm must be read the *firstPath* register. To avoid overloading the serial communication only are use from 10 samples before of the *firstPath* to the end of the accumulator.

2. Power estimation: There are two power that can be calculated with the register's value reported after a good received frame. The power received (PRx), is the total power received; First Path Power (FPP) is the sum of the power in LoS condition.

   According to [29] power can be calculated with 16-bit value register as the sum of the squares of the magnitudes of the accumulator, CIR or 3 first reporting rays an using the equations (4.1) (4.2).

$$PRx = 10\log_{10}\left(\frac{C \cdot 2^{17}}{N^2}\right) - A\,dBm \tag{4.1}$$

$$FPP = 10\log_{10}\left(\frac{F_1^2 + F_2^2 + F_3^2}{N^2}\right) - A\,dBm \tag{4.2}$$

   Where C is the Channel Impulse Response Power value of the register `0x12`; A is a constant value of 113.77 for PRF of 16MHz, or 121.74 for 64MHz PRF; F_1, F_2, F_3 is the first path amplitude in 3 consecutive points. And N is the *preamble accumulator count* in the register `0x10`. According to the measures in Fig. 4.13 the trust range for $\pm 5dBm$ is from -75dB to -105dBm (30 dB of dynamic range) in the 64MHz PRF mode, that is the typical operation mode.

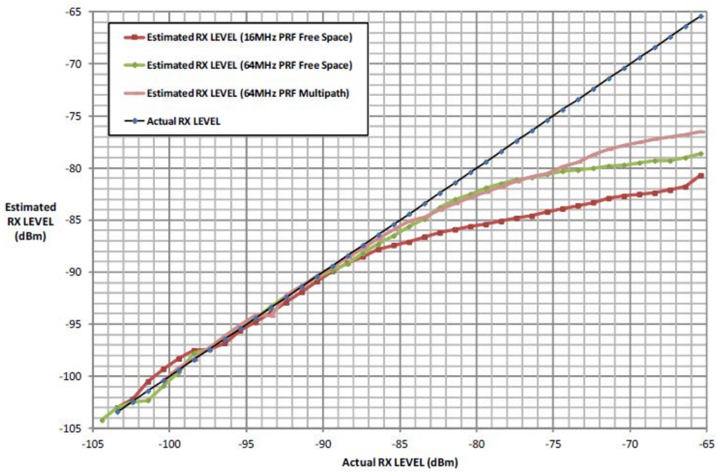


Figure 4.13: Estimated Rx power level.

3. K factor: This parameter can be estimate according the definition in eq. (3.18) that operating in logarithmic units will be

$$K[dB] = FPP[dBm] - 10\log_{10}\left(10^{PRx[dBm]/10} - 10^{FPP[dBm]/10)}\right)$$

4. Distance: For range estimation is used the TWR method with a simple one round message exchange. It is not the most accurate way to take but is enough for the requirements proposed. The package exchange its in figure 4.5.

5. Event counter: These events are generated in Rx during the listening process. And acquire the following information:

   - **PHE** or Physical Header Error indicates the receiver has found a non-correctable error in PHR.
   - **RLS** this counter indicates the number of decoding error of the Reed-Solomon decoder.
   - **CRCG** this counter shows the number of correct receptions of frames with success Frame Check Sequence (FCS) (Cyclic Redundancy Check (CRC) at the end of the frame).
   - **FCE** this is the number of FCS errors accumulated.
   - **OVER** The number of overrun errors occurred in the Rx.
   - **SFDTO** Time out error when a preamble is detected and but not the end of the preamble Start of Frame Delimiter (SFD).
   - **PTO** or Preamble Time Out.

- **RTO** or Rx Time Out. counts when the Rx wait for a frame reception and nothing is detected.
- **TXF** or Number of Transmitted Frames shows the number of transmitted frames in the Rx board. It is used to calculate the packet error rate with the CRCG.

Chapter 5

Real Measurements and Channel Modelling

5.1 Large indoor environment

One of the main advantages of the UWB technology is the propagation in high indoor environment where they become in a robust to multipath effect. Therefore, a good place to test is a large indoor environment in which we can see clearly the multipath components in the CIR function. Moreover, this scenario present the ideal place to use ranging and accurate indoor location capabilities. The last propose is validate the development and accurate of the equipment by comparing with measurement done in the same conditions in [30]. So these measurement are especially interesting for validation, testing and a real and common use case for WSN in industry 4.0.

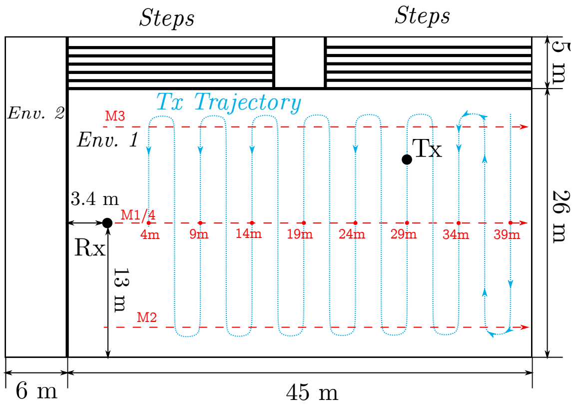
There are some examples of measurements campaign in UWB measurements for industrial applications indoors, such as the cabin of a 737 aircraft [31], indoor parking environment [32], in residential and small indoor environments [33] or between vehicles [34]. In these environments, UWB communications are modelled using both, wideband and narrow band measurements. Using these results, a complete statistical propagation model can be obtained.

5.1.1 Environment Description

The measurements have been carried out in a large sports centre, see Figure 5.1 with similar conditions as measured previously in [30] but with the new equipment developed. In this environment, we have carefully measured the propagation and path losses of the channel and statistically modelled the propagation. The results can be applied for the deployment of sensors networks in environments with similar characteristics.

The UWB propagation measurements were performed in an indoor scenario place on Technical University of Madrid (UPM). The scenario is a sport centre, mostly empty without walls or intermediate objects, as can be seen in Figure 5.1.

(a)



(b)

Figure 5.1: (a) Picture of the measurement environment. (b) Top view of the transmitter trajectory and dimensions of the measurement scenario.

External walls are made of concrete with a steel structure and the roof is made of fibreglass sheet with wavy shape and covered with plasterboards. The building is surrounded by small windows on the top part of the lateral walls. The most remarkable objects are the stands of the public that are made in a staggered way built with bricks and concrete. There are some additional small size elements such as goals and baskets inside the soccer field.

The dimensions of the scenario are some tens of meters. The interior is divided into two environments:

1. Soccer field is a rectangular 45×31 m ($1395m^2$) flat area with 6 steps for the audience along the field with 50cm high and 80cm width. The high roof in this area is 7.4m.

2. Annexed area is an auxiliary area adjacent that is communicated through a window to the field. The dimensions is 6×26m size ($156m^2$) but with a smaller high of 3 m. in figure 5.1a it can be seen a photo made in this environment.

5.1.2 General Setup

The measurement equipment was placed on the field, environment. The receiver side was located on a fix position with an antenna on the top of a mast of 1.7m high. On the other hand, the transmitter was mobile equipment at the same height than receiver by describing a zig-zag trajectory around the environment 1. The Rx device was moving by a person who carried walking with a constant speed. Figure 5.1b shows a graphical representation of the trajectory made and the dimensions of the sports centre scenario. This trajectory allows us to characterize all sports centre with an average PDP to see the dependence with distance.

Table 5.1: Large indoor configuration

Parameter	**Value**
Carrier Frequency	6489.6 MHz
Bandwidth	449.2 MHz
PRF	64 MHz
Bit Rate	6.8 Mbps
Tx Code	9
Rx Code	9
Preamble Length	256
Rx PAC	16
PHR Mode	Standard
SFD Mode	Decawave

5.1.3 Results

The raw measurements acquired were post-processed on Matlab and represented in Figure 5.2 to provide a qualitative representation of multipath in this environment. The figure shows the 3 dimensional PDP function over the trajectory followed by the Tx. The Y-axis represents excess delay and the X-axis represents the relative time of measurement. In the bottom graph is represented the separation between devices, shows on the left axis. And the K factor estimated on the right axis. A coloured pink background in the plot indicates when the $K < -6dB$ and therefore is consider NLoS conditions even knowing that there was a direct vision throughout the trajectory.

It can be observed in Figure 5.2 some clustering behaviours with the multipath components. We can explain this effect as follows:

- There are some strong cluster reflections bounded in delay from 0 to 80 ns created by the lateral walls separated 26m. Both lateral reflections measured cross each other because of the path described. One is more strong than the other due to different geometry, while one had steps, the other did not. So, the lateral steps scatter the multipath the received power is smaller.

- Two weak and long reflections bounded in delay from 0 to more than 250ns that are due to the front and rear walls. Although, geometrically should be 2 crossing diagonals component in the measurement of Figure 5.2 only can be seen one, which corresponds to the front wall furthest from Rx. The other wall is not a flat wall because has a corridor that connects the environment 1 with the environment 2 (Figure 5.1) and the reflection it is weaker and is outside the dynamic range of measurement.

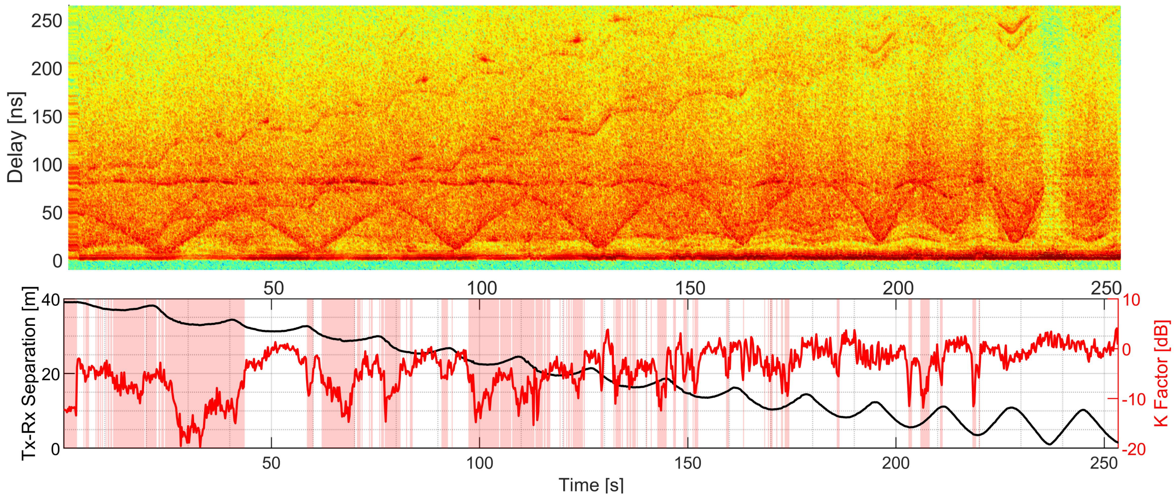


Figure 5.2: 3D representation of the Power Delay Profile received and delay of multipath components while the channel sounder transmitter is moving following a Zig-Zag trajectory. X axis is the measured time; distance and K-factor estimation.

The ground and ceil reflections are no resolvable multipath component then they are mixed with LoS component. These lead in a small fading over the LoS component but is compensated with the Automatic Gain Control (AGC).

To see more clearly the behaviour of the environment analysed it is taken the overall PDP in Figure 5.4 where can be distinguished cluster of lateral reflection and further cluster of the longitudinal reflection.

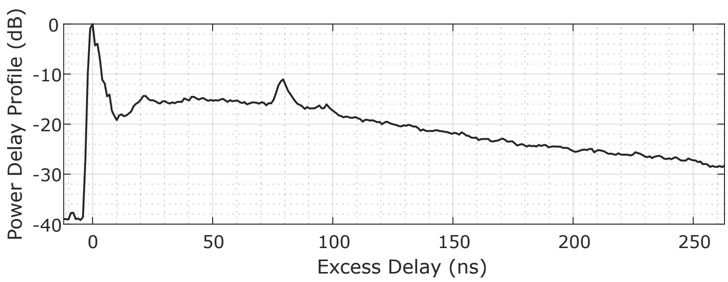


Figure 5.3: Averaged Power Delay Profile of all indoor environment

5.1.4 Discussion

Results match well with [30] in PDP and behaviour studied with a narrow pulse sounding technique. The K-factor studied in narrow band differ from the estimation taken from the channel sounder developed and is mainly because the effect of the AGC and the dynamic range alter the results in short range.

Packets error events are 0% during all test. Thus, coverage can be provided to an enclosure such as the one studied. For location and ranging application in an industry or warehouse distance estimation does not produce any incoherent measure even in $K < -6dB$ areas. In spite of the ground and ceil reflection are no resolvable MPC and the wall reflection are fairly strong the LDE algorithm works rather good in this environment and involve a suitable and accurate application with UWB radios.

5.2 Railways

These measurements are focused to verify the viability of the UWB communication to provide a sensor network in the train. There is a high interest in cheap fast and trustworthy deployment for the communication of different sensor throughout the train without expensive wired infrastructure. Actually, cable in trains is expensive to maintain and heavy. As estimation for each meter of train length, there is one km of cable and connectors that cause problems. Therefore, wireless solution in legacy trains upgrades and modernize into the smart railways without a high cost.

The propose of this section test whether this technology is valid to provide reliable communication under the cabin of the train in order to communicate several sensors in parts of difficult access. Metro trains have moving parts liable to failure that can lead to high cost, and services delay in case of failure. To prevent it can deploy a sensor network in this part to collect information of sensor and predict and anticipate to imminent failures. This has an especial interest in the bogies and mechanisms under the cabin of cars where is difficult to access to these pieces. As well for communication inside cabin like passenger information systems, acclimatization equipment, automatic door control, public address system... Thus, WSN play a very important role in the enhancement of the passenger experience and maintenance costs.

5.2.1 Environment Description

The measurements were carried out in Metro de Madrid garages located near Ventas station. The train hangar has 9 parallel tracks in a sailcloth cover area of $3770m^2$ (94x40m). The train measured has 2 trains in the contiguous tracks. The train model is the 3000 series narrow gauge of 2.3m and 60m meter of total length divided into 4 cars: M1, S1, R2, M2. More information about the Serie 3000 train can be found in the Appendix A and B.

Figure 5.4: Averaged Power Delay Profile of all indoor environment

5.2.2 General Set-up

The measurements were conduct with a typical configuration summarized in the table **??** that are the most optimal parameters checked on laboratory.

Parameter	**Value**
Carrier Frequency	6489.6 MHz
Bandwidth	449.2 MHz
PRF	64 MHz
Bit Rate	6.8 Mbps
Tx Code	9
Rx Code	9
Preamble Length	256
Rx PAC	16
PHR Mode	Standard
SFD Mode	Decawave

(a) UWB Channel Sounder Set-up

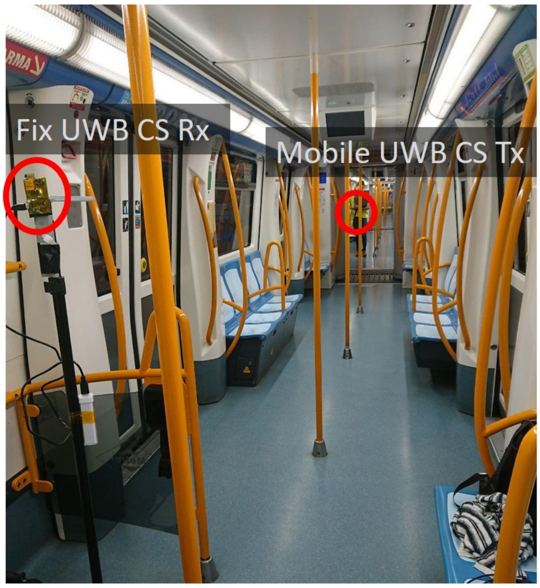
Parameter	**Value**
VNA Model	R&S ZVL
Start Frequency	5 GHz
Stop Frequency	6 GHz
Bandwidth	1 GHz
Power Tx	20 dBm
points	667 points
Average	10
Antenna Model	MGRM-WHF
Antenna Gain	3 dBi

(b) VNA Set-up parameters

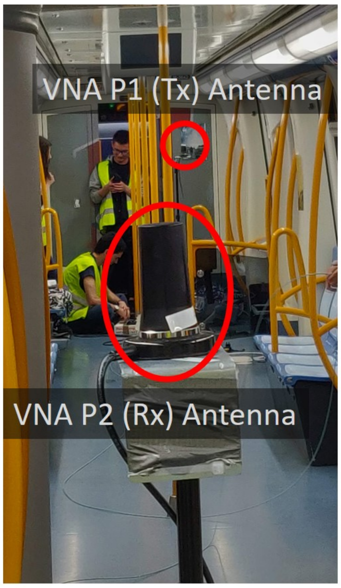
Table 5.2: Train measurement configuration

5.2.3 Scenario 1: Intra-train

For these measurements are used the channel sounder developed and VNA. When UWB Channel Sounder (CS) is used, Tx is moving since it only requires a battery. Rx is connected to the computer with the Matlab software. In case of VNA port 1 (Tx) is in place of Rx and Port 2 in some discrete points according to the Appendix A.



(a)



(b)

Figure 5.5: Scenario 1. Intra-train measurements (a) UWB Channel Sounder setup. (b) VNA setup.

Rx is fixed in 1.4m mast at the beginning of the train and Tx is moving in a 1.4m mast from the back of the train to forward with a constant speed. The initial separation is 50m and the final 0.6m.

For this test there are LoS conditions in mainly all trajectory. However, sometimes the signal was hidden with the handholds in some points.

Besides, in order to validate the results some measurements were made with the VNA in discrete points.

Results

The data measured were processing in Matlab as PDP function in logarithmic units for each of the Tx and Rx separation data as can be shown in figure 5.6. In the results of PDP along the train can be observed that the power is attenuated progressively and cannot distinguishes a clear cluster or reflector in the measurements done. Even though when the separation change within the train, power decay keep almost constant. This effect is because the cabin train is made of metal and works as a reverberation chamber where only a small part of the energy are scape thought the windows. That can be explained with the reverberation theory C.

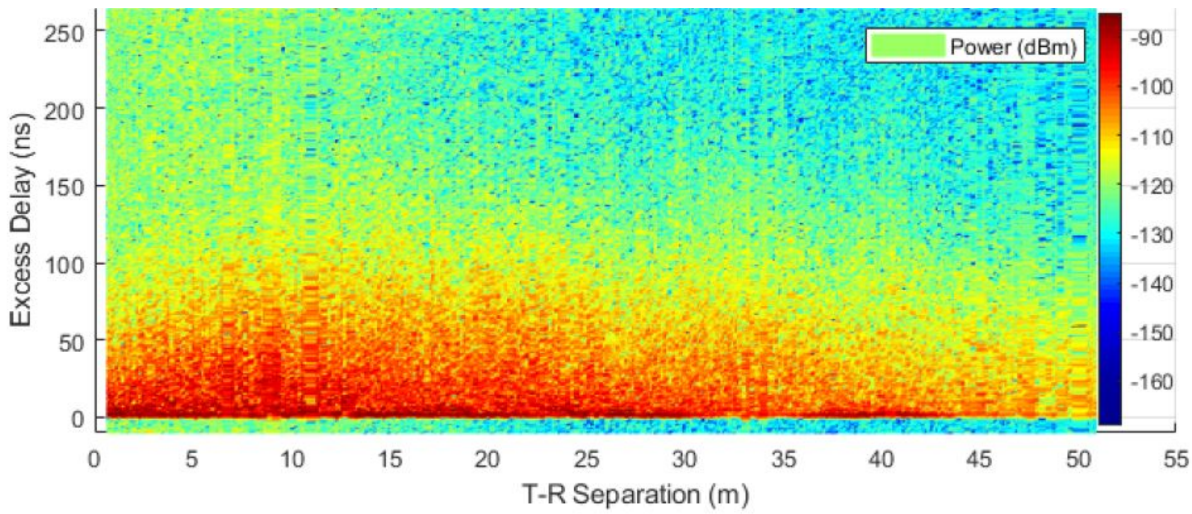


Figure 5.6: Power Delay Profile in Scenario 1.

Despite the predictable results the PDP where measure was compared with a calibrate and trustworthy VNA equipment. The procedure where take 10-averaged PDP's measurement points in 2m, 7.5m, 11.5m and 15m and averaged among them in one PDP that model the intra-train communication. On the other hand, the same PDP points were measured with the UWB CS and subsequently averaged between them. The results are in Figure 5.8. The raw data from VNA were filtered with a hamming window and then compute the Inverse Fast Fourier Transform. The slope in both cases is fairly similar. Nevertheless, there is a big difference in the dynamic range that can be affected to the slope. For instance in the measurement with the UWB CS the dynamic range is 30dB, for this reason, the measurement shows a noise floor. Thus, the error is only 0,354dB/ns.

According to the UWB modelling, the scenario can be modelled with a one cluster S-V model

Other remarks in the transmission quality are the packet error rate value that was measured in 3.38% at the end of the train mainly. It is caused by the loss of coverage and directly links with it the decoding errors.

AGC algorithm works up to 20m. Then, from 20m to 50m the PL exponent its around 5 according with the equation (3.5)

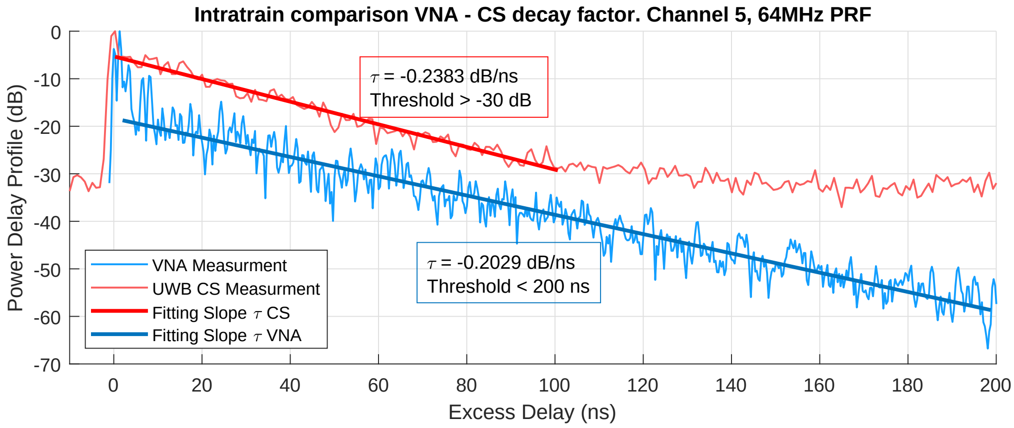


Figure 5.7: Scenario 1: PDP intra train comparison with VNA from 5GHz to 6GHz with respect to the UWB channel sounder in channel 5, 64MHz of PRF.

Discussion

The radio parameters are well chosen but the power to provided coverage to the whole train is not enough and should be incremented. Nevertheless, with the current regulation it is not possible. The most suitable distribution is 2 gateways per train in the cabin that can provide 4 cars coverage.

Distance estimation keeps good in these measurements since are under LoS condition. Even when is NLoS the MPC are rather weak to affect in the detection algorithm because the intra-train scenario isolates the effect of the outside environment. Thus, TWR is a good method to use even when is in NLoS.

5.2.4 Scenario 2: Under-train

This scenario is under the cabin of the train where the rolling part and mechanism of the train place. The measurement where performance with the UWB CS. The Rx sounder was fixed in the end/head of the train meanwhile the Tx was positioning in key parts of the train's underside. In this measurement setup, the train was elevated 1.5m of the ground.

Points of measurement are referenced according to the number in table 5.3 that are located in the position draw in the Appendix B.

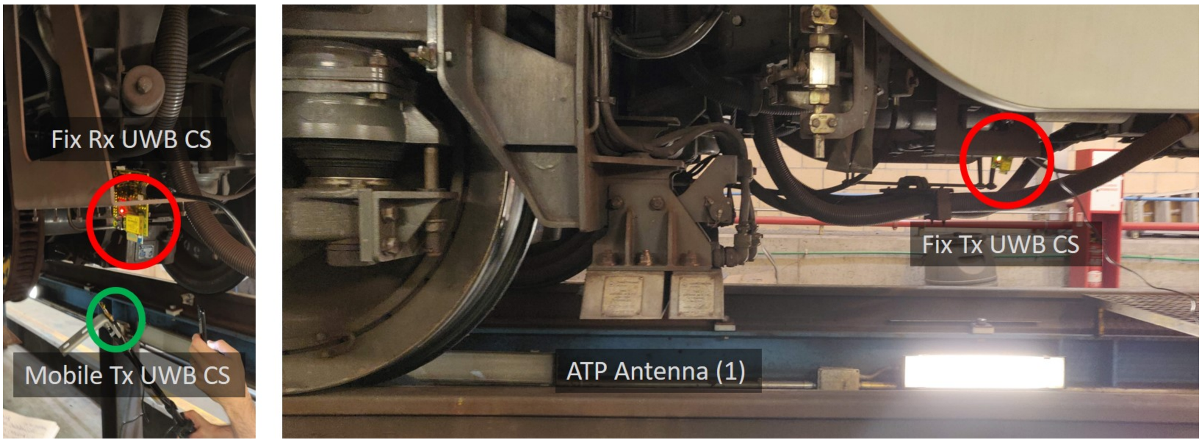


Figure 5.8: Scenario 2: Channel Sounder location.

Table 5.3: Measurement positions under train and K factor estimated

Ref	Postition Description	Car	Bogie	K factor (dB)
1	ATP Antenna	M1	1	0
2	Above the gearbox	M1	1	-3
3	Above Breaks	M1	1	-1
4	Axle box	M1	1	-4.7
5	Above middle of the bogie	M1	1	-10
6	Above boiler	M1		-10
7	Above middle of car	M1		-11
8	First wheel axis above 2nd bogie	M1	2	-19
9	First wheel axis 1m back than ref. 8.	M1	2	-12
10	Gearbox	M1	2	-23
11	Axle box	M1	2	-15
12	End of car. Connectors	M1-S1		-11
13	Suspension system	M1		-19
14	Back of the gear box	M1	1	-13
15	Middle of the 3rd car.	R2		-7

Results

Surprisingly the range achieves with the two UWB cards was rather acceptable even with NLoS and sensor in very hide parts. This configuration has worked well for 2 cars maximum without retransmission, 0% packet error rate. In contrast, for the 3rd car, the signal starts to lost and was necessary retransmission.

For each one of the measurements done in table 5.3 was calculated the K factor on that point that gives us a good abstraction about the quality of the signal. Of course, this configuration does not allow good ranging applications but for the propose tested the positioning does not sense, only communication capabilities.

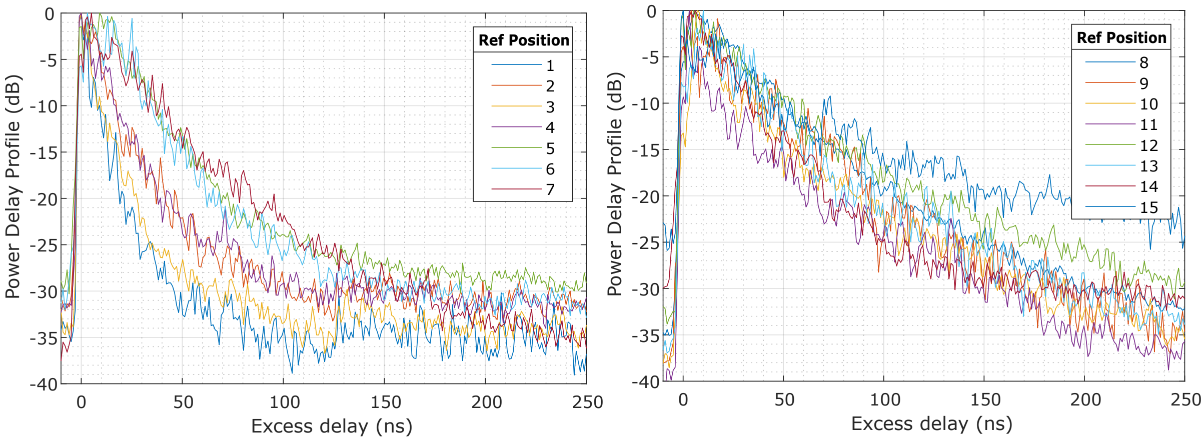


Figure 5.9: Scenario 2: PDPs of the reference positions of the table .

In Figure 5.9 can be shown the PDP of the 15 reference points. Differences start to appear when distance increase and the first ray is the most attenuated. Its important to highlight that probably the first ray consider is the ground reflection and subsequently, some close delay reflections appear and are more remarkable when distance increase. That means that a high number of MPC are present and behaves as a resonant cavity.

Discussion

The first point to discuss is about whether communication is suitable for WSN to deploy in the bottom part of the train. Regarding the results, measure is measure a high multipath environment. Here is where UWB technology is more efficient and gets the full potential to ensure robust and reliable communications. Nevertheless is important to remark one aspect regarding the measuring conditions. Since the train was placed in a 1.5 meter rail above the ground the signal the communication bounced the ground reflection is much better than the direct communication throughout metal parts and mechanisms of the train. In a real track probably the effect will be the same ensuring a channel of communication that can reach parts that are difficult to access. In contrast, narrow band wireless systems are more sensitive to theses multipath and for fix communication can happen that there are parts where is not possible the communication.

An additional remark is about interference. Although it is assumed that UWB technology is a robust communication to narrow band interference. We have observed that is sensible to high power interferences. That was observed when a wireless video transmitter was working on the 5.6 GHz band the communication in channel 5 gave problems. When theses narrow band interferences ceased, communication recovered.

Chapter 6

Budget

In this chapter will be detailing the budget of the project. The budget is spit in different parts: material costs human costs and equipments costs.

The material costs and human costs have been financial by GRC group.

The material costs need for the development of this project are shown in the tab 6.1 and the total amount is TWO HUNDRED NINETY NINE WITH TEN CENTS.

Table 6.1: Partial Budget: Material costs

Ref	**Concept**	**Units**	**Unit Price**	**Total**
1	DWM1001 UWB Development Board	2	34.90 €/u	69.80 €
2	Tripod 2m	2	29.95 €/u	59.90 €
3	MGRM-WHF	2	84.70 €/u	169.4 €
Subtotal				299.10 €

The human resources cost have been much lower than the shown in this budget due to the development of this work have been taken into account in the 300 hours of the development of this master thesis. The extra time have been paid by the GRC group. Regarding the labour costs is establish a general price of a engineer of 25€/hour. The salary estimation have been done with a low experience and general profile of engineers.

The labour cost and human resources needs for running this project are shown in the table 6.2 and the total amount rise to NINE THOUSAND EURO.

Table 6.2: Partial Budget: labour hour cost of the project

Ref	**Details**	**Hours**	**Price per hour**	**Total**
1	Previous studies	100	25 €/h	2500 €
2	Coding and development	100	25 €/h	2500 €
3	Validation and Measurements	100	25 €/h	2500 €
4	Documentation	60	25 €/h	1500 €
Subtotal				9000 €

The partial budget of conditioning laboratory cost, tools and measurement equipment is an auxiliary budget that are correct with a deprecating factor of 20%. The table collect the main elements needs to carry out the project but they have not been elements that have had to be acquired but they already had them and they have been used. The estimate budget is shown in the table 6.3 with a value of FOUR THOUSAND SEVEN HUNDRED SEVEN POINT EIGHTY CENTS.

Table 6.3: Partial Budget: Costs for laboratory conditioning tools and measuring equipment.

Ref	**Details**	**Quantity**	**Unitary Price**	**Total**
1	Coaxial cable 50Ω 1 m	3	3 €/u	9 €
2	Coaxial cable 50Ω 2 m	2	5 €/u	10 €
3	Matlab License	1	2,000 €/u	2,000 €
4	Laptop	1	1,000 €/u	1,000 €
5	Laboratory tools	S/C	500 €	500 €
6	VNA R&S	1	20,000 €/u	20,000 €
Subtotal				23,539 €
			Depreciate factor	0.2
Total				4,707.80 €

The general budget for the execution of the project amounts to the expressed quantity of FOURTEEN THOUSAND SIX DOT NINE EURO

Table 6.4: General Budget.

Concept. Partial Budget	**Total**
Materials [Tabla: 6.1]	299.10 €
Human Costs [Tabla: 6.2]	9,000.00 €
Laboratory equipment [Tabla: 6.3]	4,707.80 €
Total	**14,006.90 €**

Chapter 7

Conclusion and Future Work

7.1 Conclusions

With this project, a low-cost develop measurement equipment has been possible for the research of wireless communications for sensor networks in rail applications and intelligent transport environments. UWB technology has also been proven that is suitable for communication in indoor environments with much more interesting capabilities than narrowband or spread spectrum communications. The results have shown capabilities for precision positioning in interiors as well as a good coverage in areas of difficult communication without interference to other systems so that the validated of this technology has been satisfactorily verified for the proposed application. In addition, some of the advantages presented by the robustness and reliability have been corroborated and other alleged advantages have been hunted as it was found that it does not work very well in the face of strong interference from narrow band systems.

The thesis has been quite satisfactory and has managed to show the potential of a technology not very well known and used in the IoT but, quite competent compared to other solutions for local area networks.

7.2 Future Work

This project has successfully finished however there are some improvements and future lines of work that could be interesting to mention.

Will be necessary more measurements with different conditions and other set-ups and environments. Due to the limitation of the report, they could not be included. But would be interesting comparison with different radio configuration in order to test in more detail the optimum configuration.

The possibility of modifying the radio hardware, specifically the RF front end, has also been valued to provide more power and more adequate antennas for the measurements in all the bands. Even with frequency conversion functions to explore other channels not allows by the hardware limitation.

Create and validate a high precision position measurement application. Currently, a simple method known as SS-TWR has been implemented but it can be improved using other techniques to reduce the error in the estimation of the measurement.

Accurately obtain all the parameters of the S-V model for its statistical simulation in Matlab

Control the AGC and the transmitted power to carry out path loss measurements in the same equipment. Increase functionality and versatility with a low increase in the complexity of the firmware.

Bibliography

[1] J. Zhang, P. V. Orlik, Z. Sahinoglu, A. F. Molisch, and P. Kinney, "UWB systems for wireless sensor networks," *Proceedings of the IEEE*, vol. 97, pp. 313–331, feb 2009.

[2] G. Schroeer, "A real-time UWB multi-channel indoor positioning system for industrial scenarios," in *2018 International Conference on Indoor Positioning and Indoor Navigation (IPIN)*, IEEE, sep 2018.

[3] M. Hernandez and R. Kohno, "UWB systems for body area networks in IEEE 802.15.6," in *2011 IEEE International Conference on Ultra-Wideband (ICUWB)*, IEEE, sep 2011.

[4] A. Skrebtsov, A. Burnic, D. Xu, A. Waadt, and P. Jung, "UWB applications in public transport," in *2011 International Conference on Communications, Computing and Control Applications (CCCA)*, IEEE, mar 2011.

[5] W. Tang and E. Culurciello, "A low-power high-speed ultra-wideband pulse radio transmission system," *IEEE Transactions on Biomedical Circuits and Systems*, vol. 3, pp. 286–292, oct 2009.

[6] C. Saidu, A. Usman, and P. Ogedebe, "Internet of things: Impact on economy," *British Journal of Mathematics & Computer Science*, vol. 7, pp. 241–251, 01 2015.

[7] Farnell, "Calculating battery life in iot applications [online]." [Accessed: 8 May 2019]. Availalble at: `https://uk.farnell.com/calculating-battery-life-in-iot-applications`.

[8] H. Nyquist, "Certain topics in telegraph transmission theory," *Transactions of the American Institute of Electrical Engineers*, vol. 47, pp. 617–644, apr 1928.

[9] L. J. S. and L. E. Miller, *CDMA Systems Engineering Handbook*. Artech House, 1998.

[10] I. Standards, "802.15.4-2015 IEEE Standard for Low-Rate Wireless Networks." [online], 2015.

[11] Decawave, "APS010 Wireless Sensor Networks and the DW1000." [Online], 2014. v0.1.

[12] Keysighth, "5992-1175EN - The Internet of Things: Enabling Techonologies and Solutions for Design and Test." [online], 2018.

[13] "IEEE standard for local and metropolitan area networks - part 15.4: Low-rate wireless personal area networks (LR-WPANs) - amendment 7: Physical layer for rail communications and control (RCC)."

[14] I. Kabashkin, "Reliable v2x communications for safety-critical intelligent transport systems," in *2017 Advances in Wireless and Optical Communications (RTUWO)*, p. 5, IEEE, nov 2017.

[15] F. Gao, S. Li, T. Chen, K. Li, and F. Xie, "A decoupling method for distributed control of vehicular platoons with v2v," in *IET International Conference on Intelligent and Connected Vehicles (ICV 2016)*, Institution of Engineering and Technology, 2016.

[16] R. Pascoe and T. Eichorn, "What is communication-based train control?," *IEEE Vehicular Technology Magazine*, vol. 4, pp. 16–21, dec 2009.

[17] "IEEE standard for communications-based train control (CBTC) performance and functional requirements."

[18] I. Standard, "P802.15.4z - Standard for Low-Rate Wireless Networks Amendment: Enhanced High Rate Pulse (HRP) and Low Rate Pulse (LRP) Ultra Wide-Band (UWB) Physical Layers (PHYs) and Associated Ranging Techniques." [online].

[19] IEEE, "IEEE 802.15 WPAN Task Group 4z Enhanced Impulse Radio." [Accessed: 15 May 2019]. Availalble at: `http://www.ieee802.org/15/pub/TG4z.html`.

[20] M. Win and R. Scholtz, "On the robustness of ultra-wide bandwidth signals in dense multipath environments," *IEEE Communications Letters*, vol. 2, pp. 51–53, feb 1998.

[21] G. Kadel and R. Lorenz, "Impact of the radio channel on the performance of digital mobile communication systems," in *Proceedings of 6th International Symposium on Personal, Indoor and Mobile Radio Communications*, IEEE, 1995.

[22] T. S. Rappaport, *Wireless communications: principles and practice*. Upper Saddle River (New Jersey): Prentice-Hall PTR, 2nd ed., 2002.

[23] A. Saleh and R. Valenzuela, "A statistical model for indoor multipath propagation," *IEEE Journal on Selected Areas in Communications*, vol. 5, pp. 128–137, feb 1987.

[24] A. F. Molisch, K. Balakrishnan, D. Cassioli, C.-C. Chong, S. Emami, A. Fort, J. Karedal, J. Kunisch, H. Schantz, U. Schuster, and K. Siwiak, "Ieee 802.15.4a channel model," tech. rep., IEEE, 2005.

[25] P. Bello, "Characterization of randomly time-variant linear channels," *IEEE Transactions on Communications*, vol. 11, pp. 360–393, dec 1963.

[26] Decawave, "DW1000 Radio IC." [Accessed: 30 May 2019]. Availalble at: `https://www.decawave.com/product/dw1000-radio-ic/`.

[27] Decawave, "DWM1001 Development Board." [Accessed: 30 May 2019]. Availalble at: `https://www.decawave.com/product/dwm1001-development-board/`.

[28] FreeRTOS, "freeRTOS web Page." [Accessed: 30 May 2019], May 2019. Availalble at: `https://www.freertos.org`.

[29] Decawave, "DW1000 User Manual." [Accessed: Jun 2019]. Availalble at: `https://www.decawave.com/dw1000/usermanual/`.

[30] C. Briso, C. Calvo, and Y. Xu, "UWB propagation measurements and modelling in large indoor environments," *IEEE Access*, vol. 7, pp. 41913–41920, 2019.

[31] S. Chiu, J. Chuang, and D. Michelson, "Characterization of UWB channel impulse responses within the passenger cabin of a boeing 737-200 aircraft," *IEEE Transactions on Antennas and Propagation*, vol. 58, pp. 935–945, mar 2010.

[32] J.-Y. Lee, "UWB channel modeling in roadway and indoor parking environments," *IEEE Transactions on Vehicular Technology*, vol. 59, pp. 3171–3180, sep 2010.

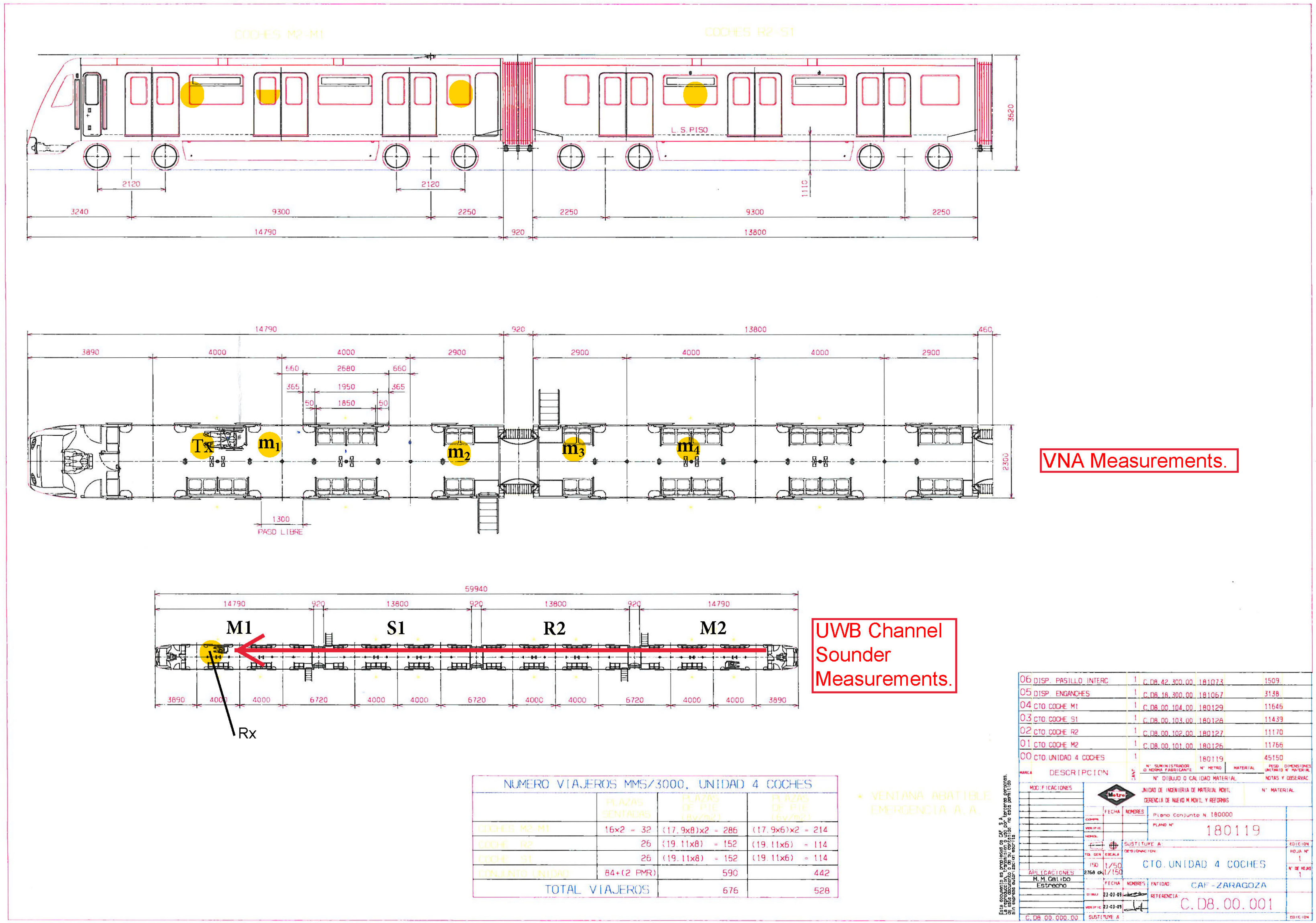
[33] S. Ghassemzadeh, L. Greenstein, T. Sveinsson, A. Kavcic, and V. Tarokh, "UWB delay profile models for residential and commercial indoor environments," *IEEE Transactions on Vehicular Technology*, vol. 54, pp. 1235–1244, jul 2005.

[34] R. He, A. F. Molisch, F. Tufvesson, Z. Zhong, B. Ai, and T. Zhang, "Vehicle-to-vehicle propagation models with large vehicle obstructions," *IEEE Transactions on Intelligent Transportation Systems*, vol. 15, pp. 2237–2248, oct 2014.

Annexes

Appendix A

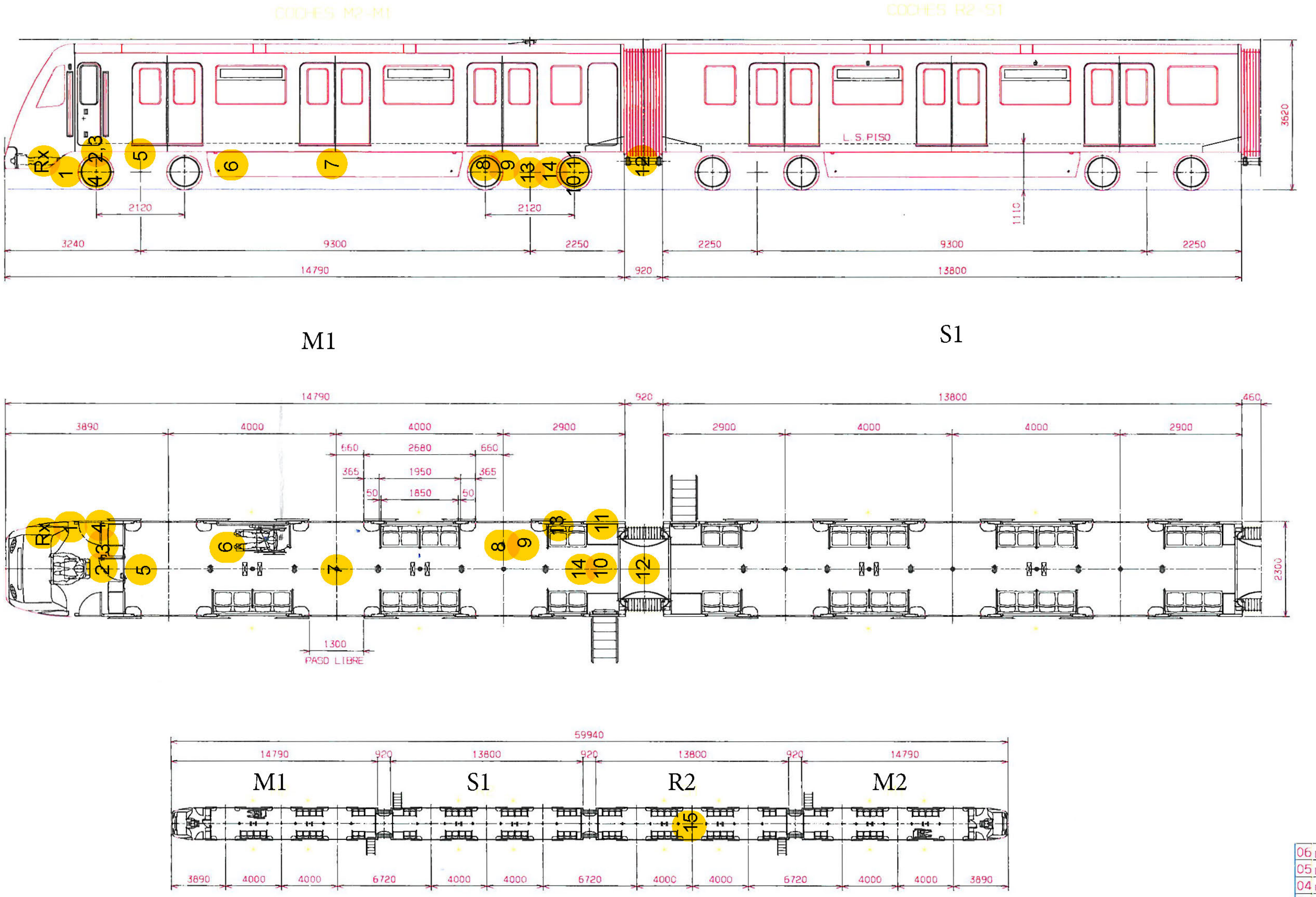
Train measurement position in Scenario 1



COCHES M2-M1
COCHES R2-S1
L.S. PISO
VNA Measurements.
Tx
m1
m2
m3
m4
PASO LIBRE
UWB Channel Sounder Measurements.
M1
S1
R2
M2
Rx
NUMERO VIAJEROS MMS/3000. UNIDAD 4 COCHES
16x2 = 32 | (17.9x8)x2 = 286 | (17.9x6)x2 = 214
26 | (19.11x8) = 152 | (19.11x6) = 114
26 | (19.11x8) = 152 | (19.11x6) = 114
84+(2 PMR) | 590 | 442
TOTAL VIAJEROS | 676 | 528
06 DISP. PASILLO INTERC. 1 C.D8.42.300.00 181073 1509
05 DISP. ENGANCHES 1 C.D8.18.300.00 181067 3138
04 CTO. COCHE M1 1 C.D8.00.104.00 180129 11646
03 CTO. COCHE S1 1 C.D8.00.103.00 180128 11439
02 CTO. COCHE R2 1 C.D8.00.102.00 180127 11170
01 CTO. COCHE M2 1 C.D8.00.101.00 180126 11766
00 CTO. UNIDAD 4 COCHES 1 180119 45150
DESCRIPCION
Plano Conjunto N. 180000
180119
CTO. UNIDAD 4 COCHES
CAF - ZARAGOZA
C.D8.00.001

Appendix B

Train measurement position in Scenario 2



NUMERO VIAJEROS MMS/3000, UNIDAD 4 COCHES			
	PLAZAS SENTADAS	PLAZAS DE PIE (8v/m2)	PLAZAS DE PIE (6v/m2)
COCHES M2-M1	16x2 = 32	(17.9x8)x2 = 286	(17.9x6)x2 = 214
COCHE R2	26	(19.11x8) = 152	(19.11x6) = 114
COCHE S1	26	(19.11x8) = 152	(19.11x6) = 114
CONJUNTO UNIDAD	84+(2 PMR)	590	442
TOTAL VIAJEROS		676	528

* VENTANA ABATIBLE EMERGENCIA A.A.

MARCA	DESCRIPCION	CANT.	Nº SUMINISTRADOR O NORMA FABRICANTE / Nº DIBUJO O CALIDAD MATERIAL	Nº METRO	MATERIAL	PESO UNITARIO / NOTAS Y OBSERVAC.	DIMENSIONES Nº MATERIAL
06	DISP. PASILLO INTERC	1	C.D8.42.300.00	181073		1509	
05	DISP. ENGANCHES	1	C.D8.18.300.00	181067		3138	
04	CTO. COCHE M1	1	C.D8.00.104.00	180129		11646	
03	CTO. COCHE S1	1	C.D8.00.103.00	180128		11439	
02	CTO. COCHE R2	1	C.D8.00.102.00	180127		11170	
01	CTO. COCHE M2	1	C.D8.00.101.00	180126		11766	
00	CTO. UNIDAD 4 COCHES	1		180119		45150	

MODIFICACIONES

Metro

UNIDAD DE INGENIERIA DE MATERIAL MOVIL
GERENCIA DE NUEVO M.MOVIL Y REFORMAS

Nº MATERIAL

Plano Conjunto N. 180000

PLANO Nº 180119

SUSTITUYE A:

EDICION

DESIGNACION: CTO. UNIDAD 4 COCHES

HOJA Nº 1

Nº DE HOJAS 1

TOL. GEN: 150 2768 ck

ESCALA: 1/50 1/150

APLICACIONES: M.M. Galibo Estrecho

	FECHA	NOMBRES
COMPR		
VERIFIC		
HOMOL		
DIBUJ	23-03-09	
VERIFIC	23-03-09	

ENTIDAD: CAF-ZARAGOZA

REFERENCIA: C.D8.00.001

C.D8.00.000.00

SUSTITUYE A

EDICION

Appendix C

Reverberation Theory

The aim of this annexe is to give a general idea of the reverberation theory that rise from the results of the measurements done in the train scenario. The study is specially relevant for UWB signal in close-room spaces with high reflectivity coefficient.

The model of the reverberation time provide a simple characterization of how much time and quantify the decreasing of the power regarding the time. This is a specific case of the S-V model with the parameter γ in the particular case of only one cluster. In this model, we going to call τ also known as **reverberation time**. That for the initial energy of the room SW_0 the following expression gives, in time, the energy W.

$$W = W_0 \cdot e^{-t/\tau} \tag{C.1}$$

Reverberation occurs due to the diffuse scattering. Looking at the Channel Impulse Response, first arrives the LoS component and later the multiple reflections and scattering creating a tail decay that follows an exponential law. The effect is similar to occur in acoustic and much aspect are analogous. Even the model theory that mainly depends on the size of the cabin as the following expression call Sabine's equation:

$$\tau = \frac{4V}{cA} = \frac{4V}{cA'\eta} \tag{C.2}$$

where V is the volume of the cabin, c is the constant speed of light, A is the area of the cabin; η is the absorption coefficient of the wall and A' is the effective area.

Reverberation time can be calculated measuring the slope s of the tail in the PDP function and the relation with τ is given by:

$$\tau = -\frac{10\log_{10} e}{s} \tag{C.3}$$

with dB/ns as units. For practical measurements, the results of the reverberation time should be kept constant along with all the cabin.