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Departamento de Engenharia Electrónica, Telecomunicações e Informática

Sérgio Carlos da Conceição Pires

Impacto de Canais não Lineares em Sistemas UWB

Impact of Nonlinear Channels in UWB Systems

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Dissertação apresentada à Universidade de Aveiro para cumprimento dos requisitos necessários à obtenção do grau de Mestre em Engenharia Electrónica e de Telecomunicações, realizada sob a orientação científica do Prof. Doutor Nuno Borges de Carvalho, Professor Associado do Departamento de Electrónica e de Telecomunicações da Universidade de Aveiro

Este trabalho é dedicado à minha noiva.

o júri

presidente	Prof. João Nuno Matos Professor Associado – Universidade de Aveiro
vogal	Prof. Maria João Rosário Professora Auxiliar – Instituto Superior Tecnico
vogal/orientador	Prof. Nuno Borges Carvalho Professor Associado – Universidade de Aveiro

agradecimentos

Todo o trabalho requer a sua dose de esforço e dedicação, mas nas alturas em que as coisas correm menos bem, é necessário apoio técnico, para esclarecer dúvidas e obter orientações. Neste apecto tenho a agradecer ao meu orientador Professor Doutor Nuno Borges de Carvalho pelo apoio prestado.

Este trabalho foi conseguido após longas noites em claro, nas quais a minha noiva sempre me apoiou e ajudou de modo a que conseguisse concluir esta dissertação.

palavras-chave Ultra Wideband, UWB, pulso, sistema não linear, BER

resumo Esta dissertação tem como principal objectivo o estudo da tecnologia Ultra Wideband (UWB). Serão também apresentadas propostas para arquitecturas de transmissores e receptores, baseados na comunicação por pulsos e verificação do impacto, que canais de transmissão não-lineares provocam nas arquitecturas propostas.

Keywords Ultra Wideband, UWB, pulse, nonlinear system, BER

Abstract The main purpose of this MSc thesis is the study of the Ultra Wideband (UWB) technology. Will be also proposed transceiver architectures, based on pulsed communications. The impact of non-linear channels in the quality of communication will be verified.

Index

Figures

Tables

Acronyms List

4BOK	–	Quaternary Bi-Orthogonal Keying
ADC	–	Analog Digital Converter
AES	–	Advanced Encryption Standard
ASK	–	Amplitude Shift Keying
AWGN	–	Additive White Gaussian Channel
BER	–	Bit Error Rate
BJT	–	Bipolar Junction Transistor
BPSK	–	Binary Phase Shift Keying
BW	–	Bandwidth
CEPT	–	European Conference of Postal and Telecommunications
CI-UWB	–	Carrier Interferometry Ultra Wideband
CMOS	–	Complementary Metal Oxide Semiconductor
DC	–	Direct Current
DS-SS	–	Direct Sequence Spread Spectrum
DS-UWB	–	Direct Sequence Ultra Wideband
Eb	–	Bit Energy
ECC	–	Electronic Communications Committee
ETSI	–	European Telecommunications Standard Institute
FCC	–	Federal Communications Commission
FFT	–	Fast Fourier Transform
FH-UWB	–	Frequency Hopped Ultra Wideband
Gbps	–	Gigabits per second
GPR	–	Ground Penetrating Radars
ICS	–	Indoor Communication Systems
IEEE	–	Institute of Electrical and Electronics Engineers
ITU	–	International Telecommunications Unit
LNA	–	Low Noise Amplifier
LOS	–	Line-of-sight
LPF	–	Low-Pass Filter
LTCC	–	Low Temperature Co-fired Ceramic
MAC	–	Media Access Control
MB-OFDM	–	Multi-Band Orthogonal Frequency Division Multiplexing
MIS	–	Medical Information Systems
MMAC	–	Multimedia Mobile Access Communications

MPT	–	Ministry of Post and Telecommunications
NLOS	–	Non-line-of-sight
OFDM	–	Orthogonal Frequency Division Multiplexing
OFDM-UWB	–	Orthogonal Frequency Division Multiplexing Ultra Wideband
OHHCS	–	Outdoor and Handheld Communication Systems
OOK	–	On Off Keying
O-QPSK	–	Offset Quadrature Phase Shift Keying
PAN	–	Personal Area Network
PCB	–	Printed Circuit Board
PG	–	Processing Gain
PHY	–	Physical Layer
PICA	–	Planar Inverted Conic Antenna
PIN	–	P-type Intrinsic N-type
PPM	–	Pulse Position Modulation
PRF	–	Pulse Repetition Frequency
PSD	–	Power Spectral Density
QoS	–	Quality of Service
QPSK	–	Quadrature Phase Shift Keying
RF	–	Radio Frequency
RMS	–	Root Mean Square
RX	–	Reception Chain
RZ	–	Return-to-Zero
SNR	–	Signal Noise Ratio
SRD	–	Step Recovery Diode
SS	–	Surveillance Systems
TEM	–	Transverse Electromagnetic
TG	–	Task Groups
TH-UWB	–	Time-Hopping Ultra Wideband
TH-PPM	–	Time-Hopping Pulse Position Modulation
TH-BPSK	–	Time-Hopping Binary Phase Shift Keying
T-W IS	–	Through Walls Imaging Systems
TX	–	Transmission Chain
USB	–	Universal Serial Bus
UWB	–	Ultra Wideband
VLSI	–	Very Large Scale Integration

VRS	–	Vehicular Radar Systems
WLAN	–	Wireless Local Area Network
WPAN	–	Wireless Personal Area Networks
WPS	–	Wall Penetrating Systems
WUSB	–	Wireless Universal Serial Bus

Chapter 1

1 Introduction

The rapid growth of wireless communications, that in several applications replaced some of the wired communications in the residential and enterprise environments, caused a demand of higher bit rate transmission. Also some new services, like high quality wireless video streaming require a high bit rate, that the current technologies cannot guarantee the quality.

1.1 Thesis organization

This thesis began with a brief history of Ultra Wideband (UWB) communications. The concept is presented after, just to have a better understanding of the technology. The worldwide regulation and efforts for standardization are also introduced. As the technology is under development, the state of the art regarding the different components of a UWB system (transceiver, antennas, propagation channel and modulations) is depicted. Then, a possible implementation for the pulsed UWB system architecture is presented and the non-linear channel effects on it are studied. Finally some conclusions are presented.

Chapter 2

2 Background

2.1 History

Although the ultra wideband technology is relatively recent, voltage arcs were already used for Heinrich Hertz, in his experiments, to generate electromagnetic waves. For some time this arcs generators were the only ones used in communications, until sinusoidal generators appeared.

In the beginning of the 60’s, Gerald F. Ross described the transient behavior of some microwave devices through its impulsive response [4] [5]. Only after the development of the sampling oscilloscope, by Hewlett-Packard in 1962, it was possible to measure the output of pulses generators with duration inferior of 1ns. By this way, the impulsive response of the microwave devices was observed and measured.

Besides sampling oscilloscope, the first applications were also made in the 60’s. They based on the radar and military applications, especially US army.

Systems development that used very short pulses was always degraded due to the lower flexibility of the sampling oscilloscope. However, in the beginning of the 70’s, Robbins developed a pulse receiver, which allowed the speed up of other systems, like short range tracking and detection. [6].

The denomination Ultra-Wideband (UWB) only shows up at the end of the 80’s. Before, it was referred as baseband, carrierless or impulse.

Also in that time, some company’s began their research and development. In the middle of 90’s, some of these companies made some pressure at the USA communications regulatory entity (FCC), to liberalize the technology for commercial use, because, until then it was exclusively to the military.

In parallel, is known that the Soviet Union had also studied the ultra wideband signals, but the information that came to outside was always very rare.

2.2 Concept

The traditional communications usually are based on the transmission of the information on a carrier modulated. The resultant signal bandwidth is relatively narrow and can reach some MHz.

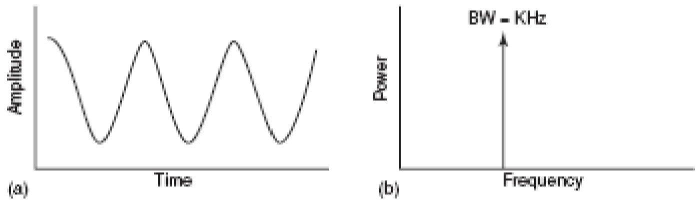

Figure 1 – Narrowband time and spectrum

In the UWB communications, the carrier does not exist but the bandwidth is very high. Consequently, the signal period is inversely proportional to the bandwidth, i.e. very short [8]. This technology is based in the transmission of ultra-short pulses with known intervals.

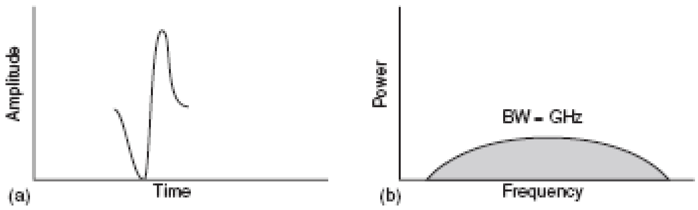

Figure 2 – Ultra Wideband time and spectrum

The information is directly associated to the pulses characteristics (shape, position, polarity), however it is always necessary to fulfill the requirements of the regulation. The most common form is the one that uses the transmission of pulses that can have different characteristics, being able to be of Gaussian form, 2ª derivative of the Gaussian form, etc.

Chapter 3

3 Standardization

The international organization, IEEE, has one working group (802.15 WPAN™) whose major task is to develop standards for wireless personal area networks (WPAN). The intention of these standards is to provide guidelines and recommendations, which allow a pacific coexistence and interoperability with other connectivity systems [43].
In time, as the market needs changes and start being more demanding, the technology needs to follow those requirements and some improvements are needed. Due to these different needs, several task groups (TG) were assigned in order to help defining new standards and recommendations for technologies that can be used in product developments for those new requirements:

802.15.1 → This standard is a formalization of the well known Bluetooth wireless technology, a short-range communications system intended to replace the cable(s) connecting portable and/or fixed electronic devices. Key features are robustness, low power and low cost. Many features of the core specification are optional, allowing product differentiation. The term core system denotes the combination of a radio frequency (RF) transceiver, baseband and protocol stack. The system offers services that enable the connection of devices and the exchange of a variety of classes of data between these devices. This standard also defines services and protocol elements that permit the exchange of management information between stations associated in a personal area network (PAN).

802.15.2 → Because both IEEE Std 802.11b-1999 (WLAN) and IEEE 802.15.1-2002 (WPAN) specify operations in the same 2.4 GHz unlicensed frequency band, there is mutual interference between the two wireless systems that may result in severe performance degradation. There are many factors that affect the level of interference, namely, the separation between the WLAN and WPAN devices, the amount of data traffic flowing over each of the two wireless networks, the power levels of the various devices and the data rate of the WLAN. Also, different types of information being sent over the wireless networks have different levels of sensitivity to the interference. This recommended practice addresses the issue of coexistence of wireless personal area networks (WPAN) and wireless local area networks (WLAN) and describes coexistence mechanisms that can be used to facilitate coexistence of WPANs and WLANs.

802.15.3 → The purpose of this standard is to provide for low complexity, low cost, low power consumption (similar to the goals of 802.15.1) and high data rate wireless connectivity among devices within or entering the personal operating space. This standard also addresses the quality of service capabilities required to support multimedia data types.

IEEE Std 802.15.3-2003 was designed to enable wireless connectivity of high-speed, low-power, low-cost, multimedia-capable portable consumer electronic devices. The intention is to be simple, providing the ability to exchange information and form networks, without the user direct intervention. This standard provides data rates from 11 to 55Mb/s at distances of greater than 70m while maintaining quality of service (QoS) for the data streams. Privacy and integrity are provided for data and commands with 128-bit AES encryption in some operation modes. This standard has also provided a variety of techniques that can be used to enhance the coexistence of 802.15.3 piconets with other wireless networks.

802.15.3a → The IEEE 802.15.3 Task Group (TG3a) for Wireless Personal Area Networks (WPAN) worked to specify an high rate alternative PHY capable of transmitting data as high as 110Mbps at 10m distance and 480Mbps at 2m distance, so that the residential applications of entertainment can be enclosed (mainly the high resolution video). The name of this standard proposal is commonly used as UWB (Ultra Wideband).

Until the moment, two proposals were introduced by two alliances, which are formed by the main world companies of electronic and telecommunications:

- DS-UWB (ultra-short pulses)
- OFDM-UWB (multiple bands)

The consensus was not reached after successive meetings and the work is in a deadlock [44]. In order to unlock the situation, it was decided that the acceptance of the market would define the standard.

The UWB and these two proposals will be described in the following chapters.

802.15.3b → The IEEE 802.15.3 Task Group (TG3b) for Wireless Personal Area Networks (WPAN) worked on an amendment to 802.15.3 to improve implementation and interoperability of the MAC layer. This included minor optimizations while preserving backward compatibility. In addition, this amendment corrected errors, clarified ambiguities and added editorial clarifications.

802.15.4 → The purpose of this standard is to specify guidelines for ultra-low complexity, ultra-low cost, ultra-low power consumption and low data rate wireless connectivity to build inexpensive devices. The data rate supported is scalable from the maximum of 250kb/s, down to 20kb/s or less. This is appropriate to wireless communications of simple devices, such as toys or garage commands.
This standard defines the protocol and interconnection of devices via radio communication in a personal area network (PAN). The standard uses carrier sense multiple access with a collision avoidance medium access mechanism. Also supports peer-to-peer topologies.
Four PHYs are specified:

- 868/915MHz direct sequence spread spectrum (DSSS) (BPSK modulation).
- 868/915MHz direct sequence spread spectrum (DSSS) (O-QPSK modulation).
- 868/915MHz parallel sequence spread spectrum (DSSS) (BPSK and ASK modulation).
- 2450MHz DSSS PHY (O-QPSK modulation).

The 868/915MHz PHYs supports data rates of 20kb/s, 40kb/s, and optionally 100kb/s and 250kb/s.
The 2450MHz PHY supports data rate of 250kb/s.

802.15.4a → The IEEE 802.15 Low Rate Alternative PHY Task Group (TG4a) for Wireless Personal Area Networks (WPANs) works on a project for an amendment to 802.15.4 to achieve an alternative PHY. The final goal is to provide communications and high precision ranging / location capability (1 meter accuracy and better), high aggregate throughput, and ultra low power; as well as adding scalability to data rates, longer range and lower power consumption and cost.
P802.15.4a is complete and the IEEE-SA standards group expects to publish this standard at the end of June 2007.

802.15.4b → The IEEE 802.15 task group 4b was chartered to create a project for specific enhancements and clarifications to the IEEE 802.15.4-2003 standard, such as resolving ambiguities, reducing unnecessary complexity, increasing flexibility in security key usage, considerations for newly available frequency allocations and others.

Chapter 4

4 Regulation

The ITU (International Telecommunications Unit) [7], in agreement with the major communication institutions of the world, defined some rules that characterize an ultra wideband signal:

A → The -10dB bandwidth of the signal must be at least 500MHz

$$\beta_F \rangle 500MHz \quad (1)$$

B → The fractional bandwidth must be higher than 20% during transmission

$$\beta_B = 2 \times \frac{f_H - f_L}{f_H + f_L} \rangle 0,2 \quad (2)$$

Where,

f_M → frequency of maximum UWB transmission

f_H → highest frequency at which the power spectral density is -10dB relative to f_M

f_L → lowest frequency at which the power spectral density is -10dB relative to f_M

There is also a limit for the transmit power, because this technology has the possibility of coexist with others already available, namely WLAN, BLUETOOTH among others. These limits depend on the operation band, the standard proposition and on the globe region. The most advanced are the United States, Europe and Japan [3] [41].

→ **United States**

The FCC (Federal Communications Commission) is in the front line in terms of UWB world regulation. The proposal of any standard is essentially to protect the external and internal devices of the interference caused by the devices in the standard. The works began in 1998 and the first proposal was announced in May 2000. The first version was published in February 2002 and after the manufacturer's opinion, in February 2003, a definitive version of the standard was published [3].

United States – FCC	
Frequency Range	Power Spectral Density [dBm/MHz]
Lower than 900MHz	-41,3
0,9 a 1,6 GHz	-75
1,6 a 2 GHz	-53
2 a 3,1 GHz	-51
3,1 a 10,6 GHz	-41,3
Higher than 10,6 GHz	-51

Table 1 – FCC UWB Regulated Spectrum

In the FCC's document, it was contemplated several systems categories with potential to use UWB technology:

- Ground Penetrating Radars (GPR) and Wall Penetrating Systems (WPS)
- Through walls Imaging systems (T-W IS(1), T-W IS(2))
- Surveillance Systems (SS)
- Medical Information Systems (MIS)
- Vehicular Radar Systems (VRS)
- Indoor Communication Systems (ICS)
- Outdoor and Handheld Communication Systems (OHHCS)

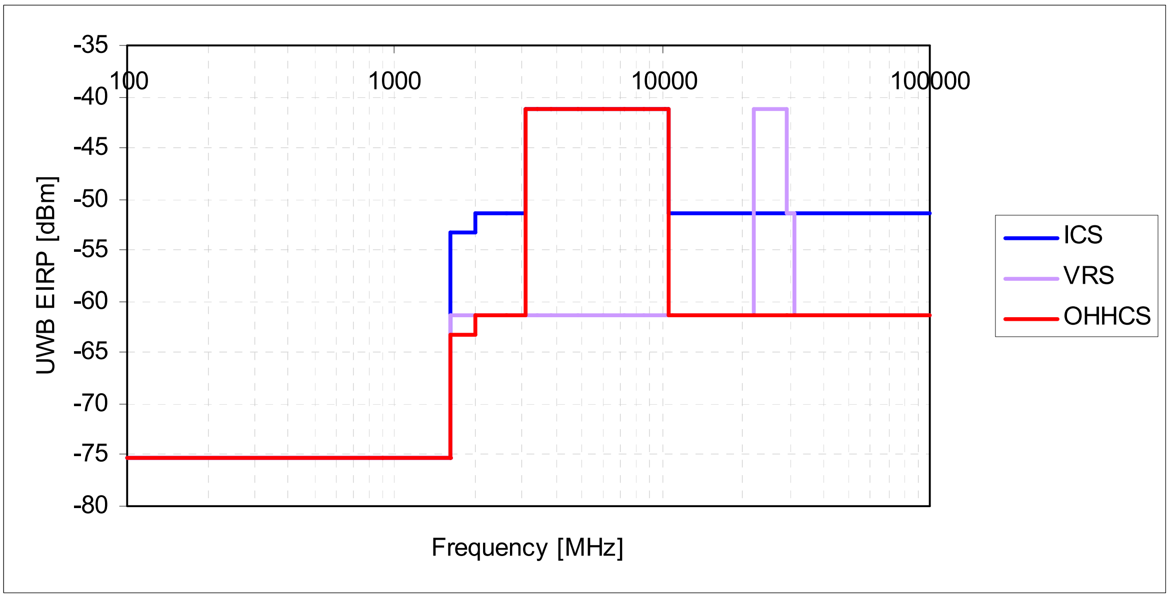

Figure 3 – FCC Application specific spectrum #1

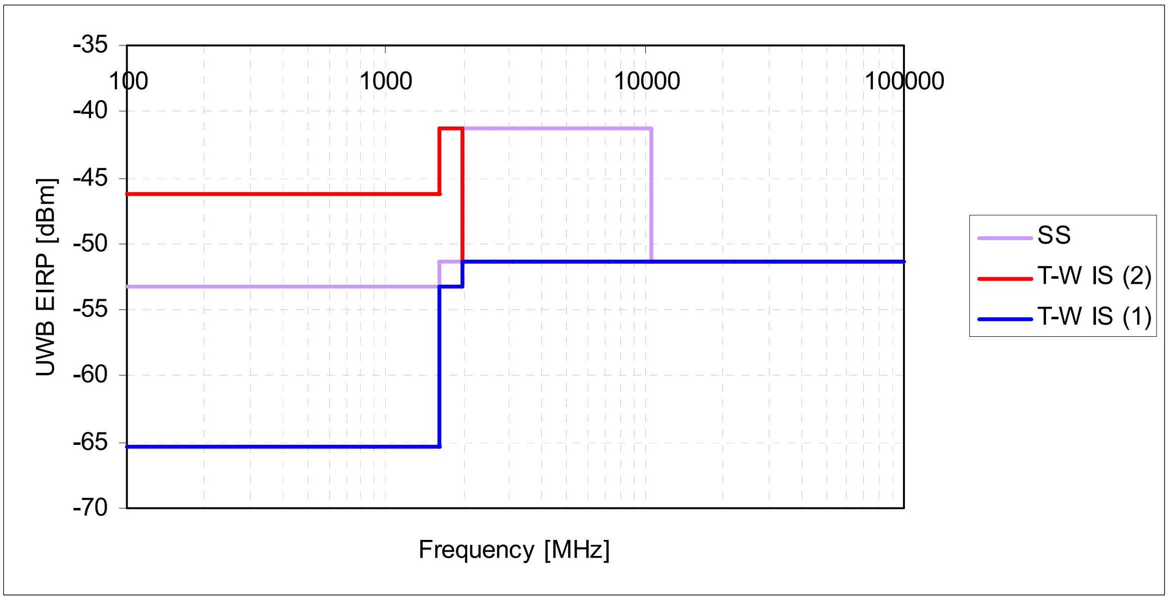

Figure 4 – FCC Application specific spectrum #2

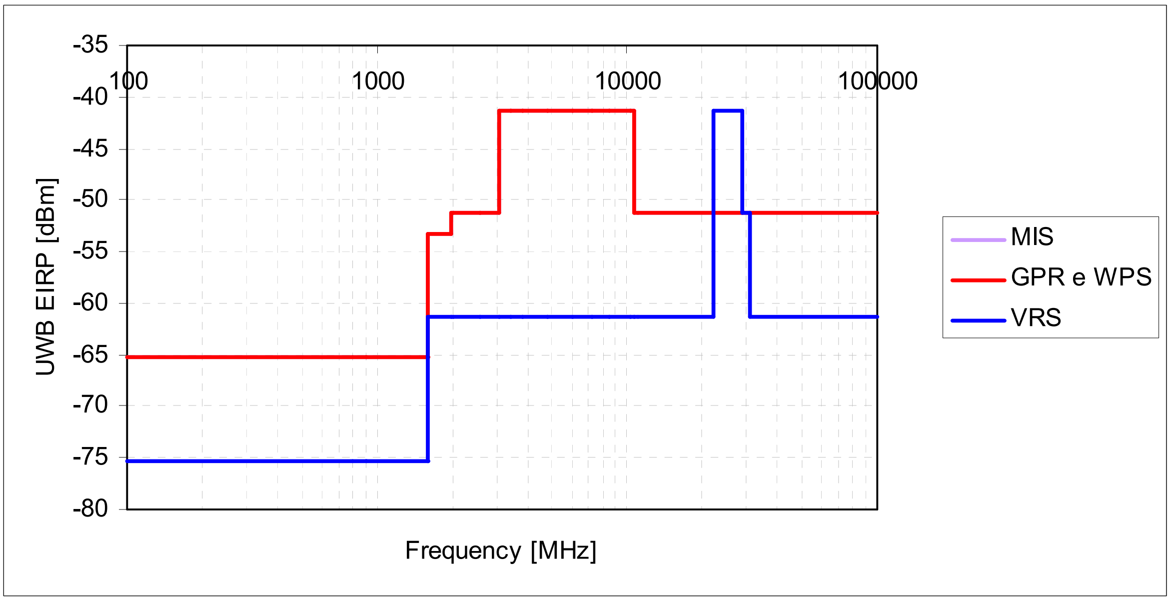

Figure 5 – FCC Application specific spectrum #3

→ Europe

The European Union through the Electronic Communications Committee (ECC) formed the European Conference of Postal and Telecommunications Administrations committee (CEPT) which has been applied two mandates. The purpose was recollect enough information to develop a common standard to the state members related to the use of the non licensed band bellow 10,6GHz, in UWB communications. The European Telecommunications Standard Institute (ETSI) had an important role due to his experience in the technical support dedicated to CEPT.

The CEPT, after his second mandate formalized the proposal [1], where all the state members were invited to comment the proposal [2].

Europe – ECC	
Frequency Range	Power Spectral Density [dBm/MHz]
Lower than 1,6 GHz	-90
1,6 a 3,8 GHz	-85
3,8 a 4,8 GHz	-70
4,8 a 6 GHz	-70
6 a 8,5 GHz	-41,3
8,5 a 10,6 GHz	-65
Higher than 10,6 GHz	-85

Table 2 – ECC Regulated Spectrum

The ECC is still considering if either adopt or not, an alternative decision for the 3,1 – 4,8 GHz range.

→ **Japan**

The Japan in order to have the regulation of UWB communications, through the Ministry of Post and Telecommunications (MPT), ordered that the institute Multimedia Mobile Access Communications (MMAC) to start the work in the standard. The first standard version was approved by the MPT in the second semester of 2005 and the final version at August 1, 2006.

The allocated frequency bands are from 3.4 to 4.8GHz and from 7.25 to 10.25GHz.

As for the 3.4-4.8GHz band, it is required to use a technology to reduce interference with other radio services, although temporary measures are taken until the end of December 2008 to permit the use of the 4.2-4.8GHz band without an interference reduction technology.

The average transmission power is limited to -41.3dBm/MHz or lower (the peak value is set to 0dBm/50MHz or lower) on both bands.

As for the devices without an interference detection technology that uses the 3.4-4.8GHz band, however, the average transmission power is limited to -70dBm/MHz or lower (the peak value is set to -30dBm/50MHz or lower).

Japan – MPT	
Frequency Range	Power Spectral Density [dBm/MHz]
3,4 a 4,8 GHz	-41,3
7,25 a 10,25 GHz	-41,3

Table 3 – MPT Regulated Spectrum for devices with interference detection

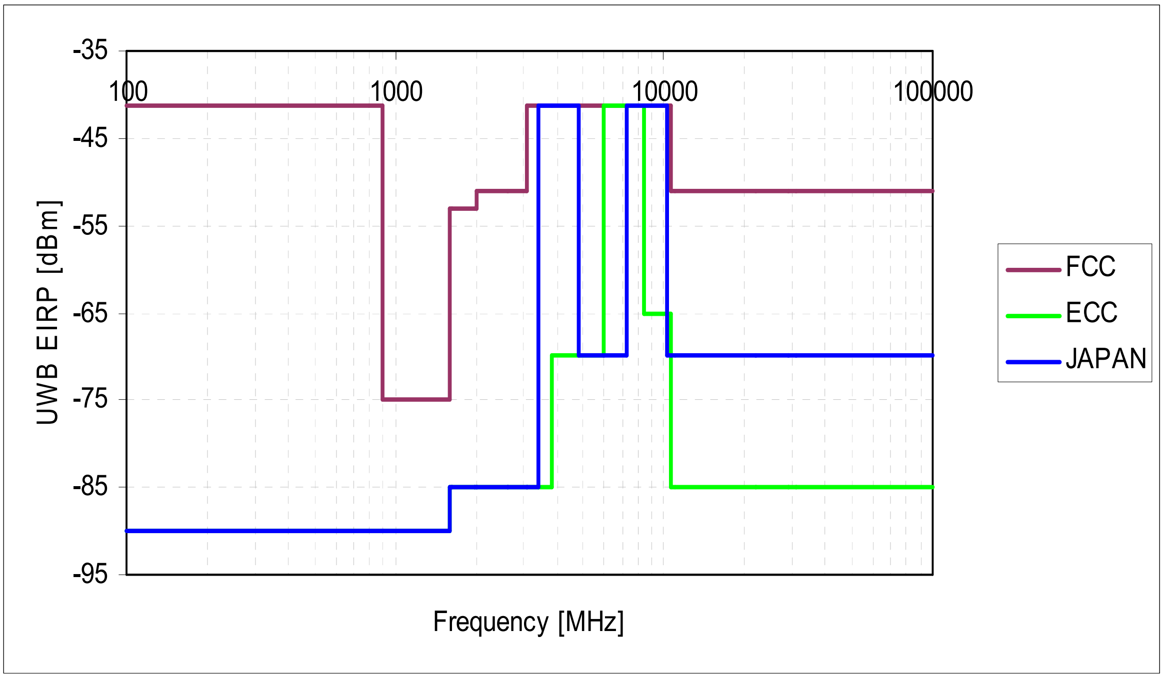

Figure 6 – Regulated Spectrum Overview

As part of the UWB spectrum has been already licensed to other systems and companies, studies are being made to analyse the impact that the possible interferences can caused in the UWB applications and vice versa. These researches are been made together with the FCC and the CEPT.

Chapter 5

5 Innovation

Several specific characteristics of this technology are quite new and very appellative to the recent commercial applications.

5.1 Capacity

According to theory of Shannon, the capacity of a transmission channel is limited to:

$$C = B \times \log_2\left(1 + SNR\right) \quad (3)$$

Increasing the bandwidth (B) the channel capacity increases in direct proportion. With a channel that has a bandwidth of some GHz, we could reach transference rates in order of the Gbps [8].

5.2 Resistance to Interference

The interference can be caused by a very strong signal of narrow band. This interference can be more or less severe depending of the modulation used by the UWB system. The presence of a WLAN net in the proximity of the receiver or transmitter can be sufficiently disturbing therefore the power of the aggressive signal can be very superior to the one of the UWB system. This interference can for example, excessively harm the income of the receiver to the level of the input amplification (saturation), being therefore very important the study of the behavior of the receivers levels most vulnerable to this phenomenon, nominated the input LNA.

The interference can be of broad or narrow band, however the possibility of being narrow band is very high. The UWB signal has a much raised band so, that is very difficult that the interference also has it. Only a part of UWB signal band will interfere.

There are at least three methods that are efficient in the interference attenuation, but it will never be totally eliminated. The decision on which method will be implemented is left to the care of the system architect, which must evaluate the most efficient one [9] [10]:

1. Channel selection

The available band (B) for the use in UWB communications can be divided in sections of lower bandwidth (N), that are not overlapped and that still fulfill with the minimum requirements (500MHz). In such a way, the system will choose the bands whose interference is lower.

2. Removal of the interference (filtering)

This method is based on the detection of the signal interference band and adjusting the central frequency and bandwidth of a notch-filter in order to decrease the related interference. This method requires some care, because the interference is in the band of the desired signal and the filtering will remove some of the UWB signal power.

3. Spectrum spreading

The spectrum interference happens mostly in reception, when the received signal is composed by the desired signal plus the interference. If during the transmission the information is uniformly spread over the spectrum, by multiplying the signal with a pre-defined higher rate sequence, the resulting signal will be the spread signal plus an narrow band interference (when compared with the bandwidth of the transmitted signal).

At the reception, we could recover the desired signal by multiplying again the receiver signal with the same sequence. In this way, the desired signal will be recovered and the interference will be spread over the spectrum, suffering the same operation than the desired signal when the transmission. An important propriety is the processing gain:

$$GP = \frac{Channel\,bandwidth}{Information\,bandwidth} \qquad (4)$$

This relation is very important because as bigger this value is, more immune it will be to the interferences. By other side, if the information transmission is relatively high, the information bandwidth will be approached to the signal bandwidth, the GP will be lower, e.g. how much greater the necessary bandwidth less immunity will have.

5.3 Interception

Due to its characteristics, the UWB communication is very difficult to decipher and intercept because it possess a high bandwidth and a lower power transmission. Beyond these factors, it is virtually impossible to detect pulses with one nanosecond or inferior without knowing it's previously location in time. These factors make this technology very attractive for military ends.

Chapter 6

6 Challenges

Although this is a very innovating technology with lots of potential, there are some technical difficulties that need to be investigated.

6.1 Propagation Channel

The classic propagation models are applicable to narrowband systems, at which the arrival of the multipath components (most due to reflections) occurs within a symbol time. Other reflections could arrive after a symbol time, but its amplitude can be neglected.
Knowing the importance of a good channel model, IEEE formed a special group (802.15.SG3a), that had the task to achieve a suitable channel model to be used in UWB system simulations [11]. The need to develop a new propagation model is due to the fact that the bandwidth of a UWB system could be as large as 7,5GHz and the classic models are not applicable. The multipath components with significant amplitude could arrive several symbols after, for example the first one, because the bandwidth is comparable to the centre frequency of the system.
With the aid of several techniques, many measurements campaigns were performed for this model, in several environments, which the most important ones are the residential and the office. The characteristics of these two are quite different, due to the different construction materials that lead to different RF propagation. Additionally, it was also considered the line-of-sight (LOS) and non-line-of-sight (NLOS) channels.
After the measurements acquisition and analysis, some characteristics were considered more important than other ones, because it was very difficult to match all the channels in a single model:

→ RMS Delay Spread

→ Power Decay Profile

→ Number of multipath components, whose amplitude is up to 10dB below the highest component

The models developed were based in the Saleh and Valenzuela [12] one, which is composed by mathematical equations with adjustable coefficients to different environments. In order to have a better fit between the measurements and the mathematical model, 4 types of channels were defined:

→ CM1 (LOS 0-4m measurements)

→ CM2 (NLOS 0-4m measurements)

→ CM3 (NLOS 4-10m measurements)

→ CM4 (extreme NLOS multipath channel measurements with 25ns delay spread)

These models require four main parameters,

→ Cluster arrival rate

→ Ray arrival rate within a cluster

→ Cluster decay factor (observed from the power decay profile)

→ Ray decay factor (observed from the power decay profile)

Based on these ones was possible to model the above environments.

Due to the different transmission bands that UWB can be used around the world and the flexibility of the system, further investigations are ongoing [42], in order to have a better model of the entire system.

6.2 Receptor digitalization

Due to the great velocity and the pulses shape, the receptor needs to have an ADC with a very high sampling frequency (1-2GHz). These ADC are very difficult to implement namely if the necessary resolution is relatively big. In parallel, the consumption is growing proportionally at the same time that the previous factors increase. In order to obtain a satisfactory behavior, these ADC's need pre-amplification which increase the system complexity.

6.3 Ultra fast pulses transmission

Although the transmitted pulses have a very short duration and short spacing, they need to have a temporal shape that limits the transmitted power in the frequency domain in order not to violate the regulator limits. The conception of a circuit that implements exactly these pulses shape is not trivial.

6.3.1 Pulses format

Before the definition of the pulses generator is necessary to verify which of the pulses format is the most appropriate to the system. Some of the most popular formats, due to its known mathematical properties, are the following ones [16]:

Gaussian Pulse:

$$s(t) = A \cdot e^{-\frac{(t-\mu)^2}{\sigma^2}} \quad (5)$$

In which:

A -> Signal amplitude

t -> Time

σ -> Gaussian pulse standard deviation

μ -> Gaussian pulse mean

Having the pulse a very small width in time, the signal will spread in frequency through a big bandwidth:

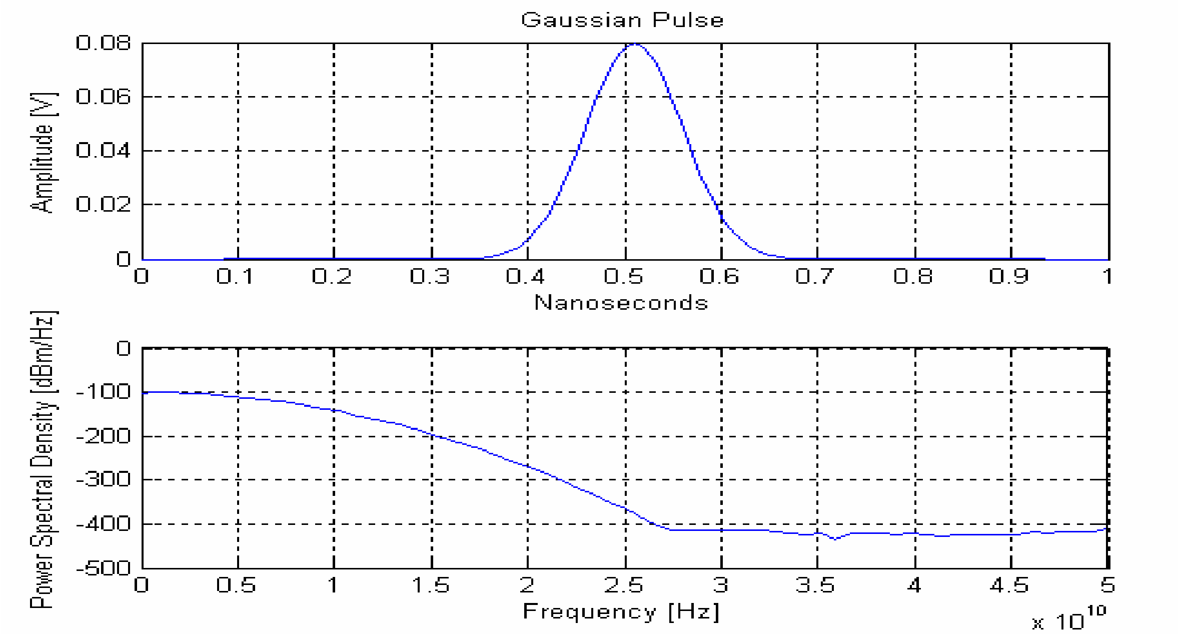

Figure 7 – Gaussian Pulse time and Spectrum

However, this format is not allowed by the regulator, because the transmission power violates the limits. It needs to be formatted, even if the pulse will be distorted.

→ Gaussian Monocycle

This pulse format is the result of the Gaussian pulse first derivative.

$$s(t) = 2\frac{A}{\sigma}\sqrt{e}(t-\mu)e^{-2\left[\frac{(t-\mu)}{\sigma}\right]^2} \tag{6}$$

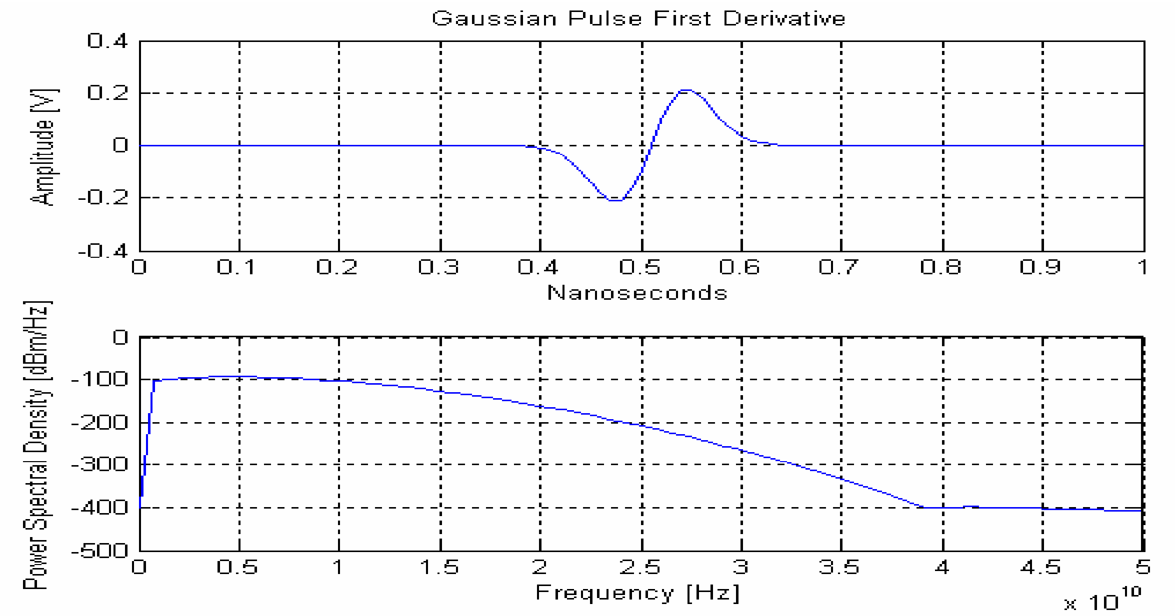

Figure 8 – Gaussian Pulse first derivative time and Spectrum

→ Scholtz monocycle

This name became of the Mr. Scholtz work with this type of pulse and that it is the second derivative of the Gaussian pulse.

$$s(t) = A\left[1-4\pi\left(\frac{t-\mu}{\sigma}\right)^2\right]e^{-2\left[\frac{(t-\mu)}{\sigma}\right]^2} \tag{7}$$

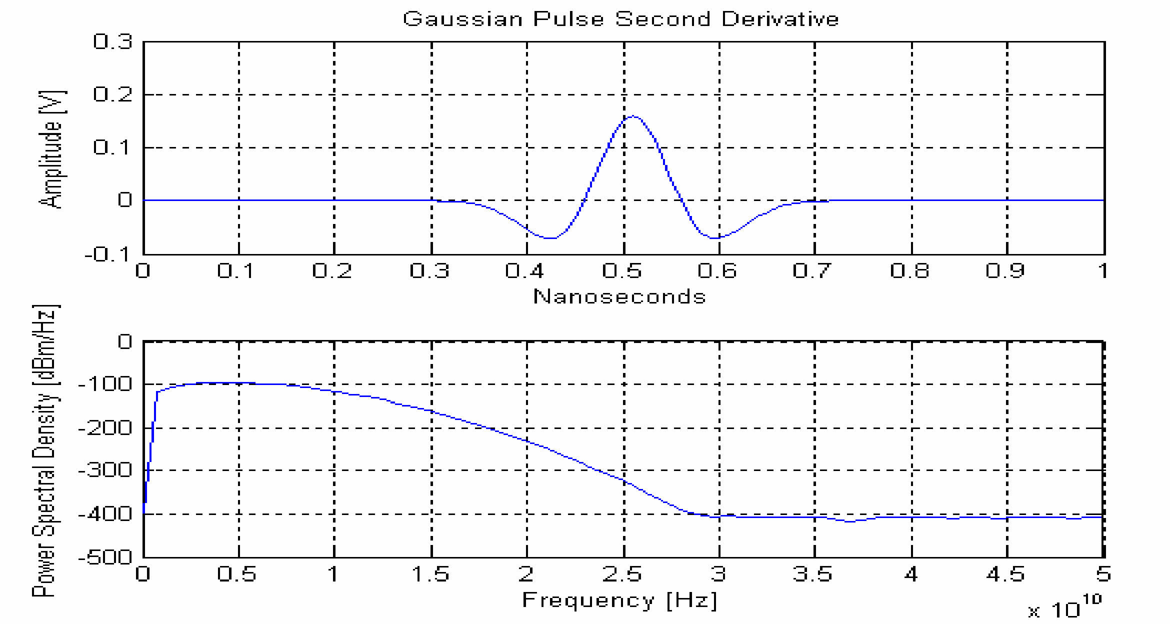

Figure 9 – Gaussian Pulse Second Derivative time and Spectrum

→ **Manchester monocycle**

The Manchester monocycle has A amplitude during half of the monocycle and –A during the second half.

→ **RZ-Manchester monocycle**

In this case, the RZ-Manchester monocycle has A amplitude during only one part of the first half of the monocycle duration. The other part has zero amplitude. The same occurs in the second half. One part has –A amplitude and the other has zero amplitude.

→ **Sine monocycle**

This signal shape is only a very short period of a sinusoidal wave.

→ **Rectangular monocycle**

The rectangular monocycle has A amplitude with all monocycle duration.

6.4 Generator

To produce similar pulses as the ones above, are normally used some devices [14], [15], [17]:

→Tunnel diode

→ Step Recovery Diode (SRD)

The first ones are quite difficult to find because the market existence decreased due to the lack of use in new systems. However, its characteristics are very appreciated for fast transition applications due to his negative resistance in the operation region.

When a quadratic wave is applied to a SRD we could see a ramp wave at its output when a Gaussian pulse was expected. SRD diodes have a PIN type structure, i.e. they have an intrinsic layer between the positive and negative doped silicon. In this layer, when the diode is directly polarized, a certain amount of load Q is stored. At this time, if we invert the diode polarity, he will continue to conduct until the load Q deplete and when that happens, the diode turns off abruptly.

Let i_d as the diode instant current, Q as the stored load and τ as the life time of the carriers:

$$i_d = \frac{dQ}{dt} + \frac{Q}{\tau} \tag{8}$$

When a constant current I_F is applied at the directly polarized junction a certain load is stored, during t_F :

$$Q_f = I_F \tau \left(1 - e^{-\frac{t_F}{\tau}}\right) \tag{9}$$

If t_F is much higher than the life time of the carriers,

$$Q_f \approx I_F \tau \tag{10}$$

The junction is instantaneously inversely polarized with a current I_R and the previously stored load is removed in t_s:

$$\frac{t_s}{\tau} = \ln\left[1 + \frac{I_F\left(1 - e^{-\frac{t_F}{\tau}}\right)}{I_R}\right] \approx \ln\left[1 + \frac{I_F}{I_R}\right] \quad , \quad t_F >> \tau \tag{11}$$

SRD circuits are normally polarized taking into account that:

$$\frac{t_s}{\tau} \approx \frac{I_F}{I_R} \tag{12}$$

However, if we put two transmission lines in the SRD cathode [18],

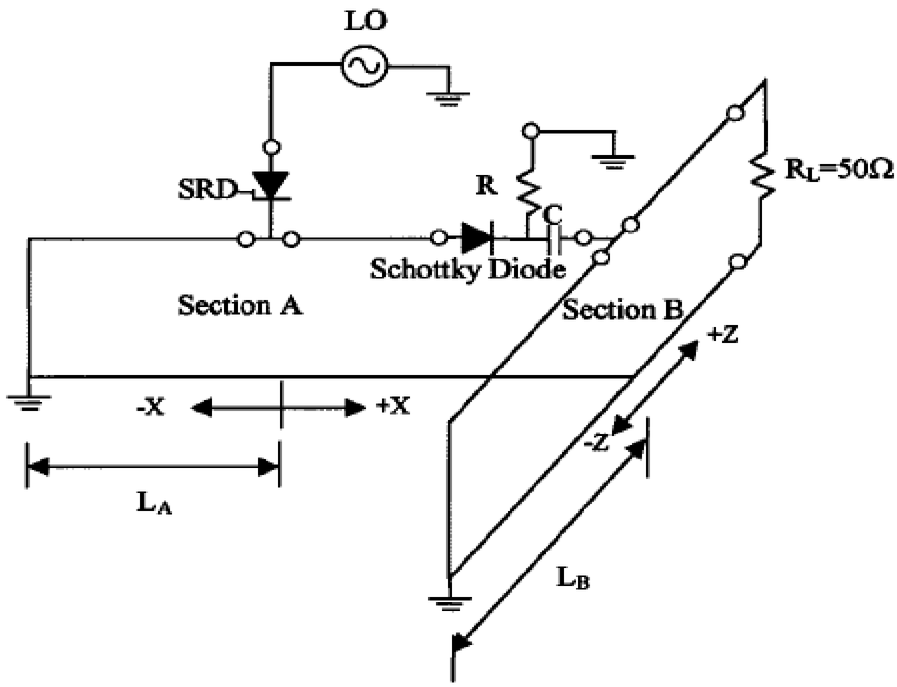

Figure 10 – SRD Pulse Generator circuit

That be, the ramp pulse that appears at the A point propagates in the inverse transmission line, is totally reflected in the short circuit (with negative phase) and it propagate again backwards. At this time, he is added (or multiplied) to the pulse that is constantly leaving the SRD, causing the pretended formatting of the Gaussian pulse at the input of the Schottky diode.

The pulse width is calculated, taking to account the transmission line length:

$$\tau = \frac{2 \cdot L_A}{v_p} \qquad (13)$$

L_A → Transmission line length

v_P → Velocity propagation of the wave in the mean where the transmission line is implemented.

Simplifying the circuit:

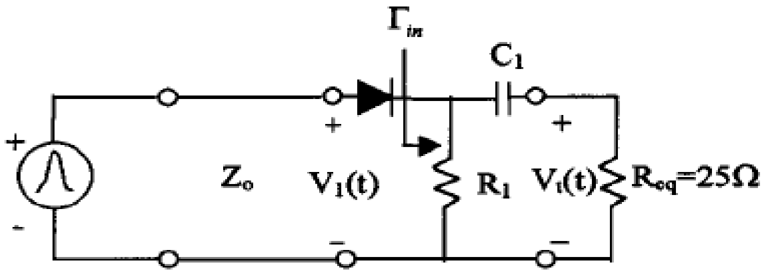

Figure 11 – SRD Pulse Generator simplified circuit

At the time of the transition of the SRD generated pulses that arrive to the Schottky diode (assuming that $V_i(t)$ has a triangular shape), we could simplify the circuit and analyze it more easily. R_{eq} represents the equivalent resistance of the transmission line at the point B, when the pulse transient is present.

Assuming that the Schottky diode behaves as an ideal switch,

$$V_i(t) = R_{eq} C \frac{dV_C(t)}{dt} + V_C(t) \tag{14}$$

Where,

$V_C(t)$ is the voltage at the capacitor terminals and it is:

$$V_C(t) = A\left[\tau \cdot e^{-\frac{t}{\tau}} - \tau + t\right]U(t) - 2A\left[\left(t - \frac{T}{2}\right) - \tau + \tau \cdot e^{-\frac{t-\frac{T}{2}}{\tau}}\right]U\left(t - \frac{T}{2}\right) \tag{15}$$

$\tau = R_{eq}C$ Is the time constant

A is the positive transition of the triangular wave $V_i(t)$

$U(t)$ is the unitary step function

At the time that $V_C(t)$ is equal to $V_i(t)$, the voltage at the R_{eq} terminals can be described, counting the diode voltage drop V_D,

$$V_B(t) = V_i(t) - V_C(t) - V_D \tag{16}$$

Through this point on, the diode starts to become inversely polarized, causing a fast capacitor discharge.

The Gaussian pulse spectrum does not fulfill the legal requisites, mostly due to hits DC component. In order to accomplish the spectrum masks, is convenient in some situations, to avoid that these have to be posteriori shaped. Therefore other kinds of pulse are also frequently used. The most common is known as Scholtz monocycle and like it was previously described, is resultant of the second derivative of the Gaussian pulse. There are several ways of generate it but due to the growing importance of the CMOS technology, one of them use this technology through the vertical BJT structures implementation [18].

Hyperbolic functions are used, in this approach, as approximation to the Gaussian pulses. The Gaussian format can be introduced in the following way:

$$x(t) = e^{-t^2} \tag{17}$$

The series Taylor approach of this function:

$$x(t) \approx 1 - t^2 + \frac{t^4}{2!} - \frac{t^6}{3!} + \cdots \tag{18}$$

The variable secant also can be approached to the series Taylor:

$$\operatorname{sech}(t) \approx 1 - \frac{t^2}{2} + \frac{5t^4}{24} - \frac{61t^6}{720} + \cdots \tag{19}$$

$$\begin{aligned} x_2(t) = \operatorname{sech}^2(t) = (\operatorname{sech}(t))^2 &= \left(1 - \frac{t^2}{2} + \frac{5t^4}{24} - \frac{61t^6}{720} + \cdots\right) \cdot \left(1 - \frac{t^2}{2} + \frac{5t^4}{24} - \frac{61t^6}{720} + \cdots\right) \\ &= \left(1 - t^2 + \frac{16t^4}{24} - \frac{152t^6}{720} + \cdots\right) \end{aligned} \tag{20}$$

With the exception of some minor differences in the coefficients, the $x(t)$ approach to $x_2(t)$ can be considered valid.

It is known that,

$$\tanh^2(t) + \operatorname{sech}^2(t) = 1 \tag{21}$$

It is possible to generate with great facility a similar signal to a $\tanh$ from a sech. Applying this signal to a quadratic circuit it is possible to obtain a desired $\operatorname{sech}^2(t)$.

One of the proposals is described in the circuit bellow,

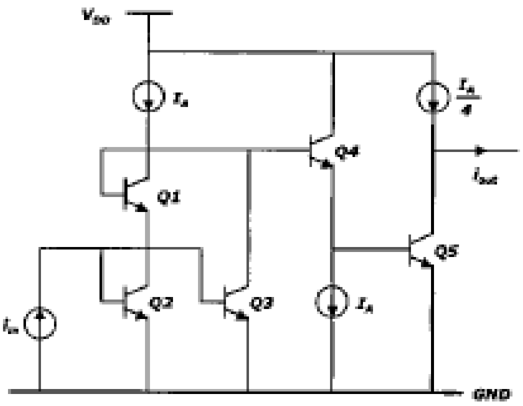

Figure 12 – CMOS with vertical BJT structures pulse generator #1

Analyzing the circuit, we know that,

$$i_{C1} = \frac{I_A - i_{in}}{2} \tag{22}$$

$$i_{C2} = \frac{I_A + i_{in}}{2} \tag{23}$$

$$i_{C5} = \frac{i_{C1} + i_{C2}}{I_A} \tag{24}$$

To the circuit output we have,

$$i_{out} = \frac{I_A}{4} - i_{C5} = \frac{I_A}{4} - \frac{i_{C1} + i_{C2}}{I_A} = \frac{i_{in}^{\ 2}}{4I_A} \tag{25}$$

By this way, if we apply a wave with $\tanh$ shape to the input, in the output we have his square that for the previously equality is equal to the $\mathrm{sech}^2(t)$ and consequently similar to the Gaussian pulse.

Even so we did not obtain the desired Scholtz monocycle. Substituting the current power supply $\frac{I_A}{4}$ for a coil with L value, the voltage at the $Q5$ collector will be the i_{out} derivative, obtaining then the Gaussian monocycle. In order to obtain the Scholtz monocycle it is necessary derive the signal again. That can be made by applying a resistor load (50Ω) in series with a capacitor that will realize the Gaussian monocycle derivative.

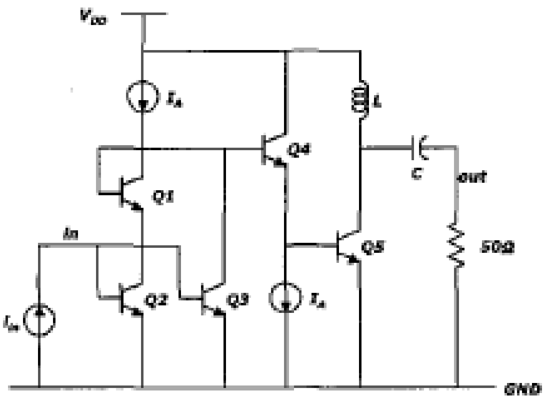

Figure 13 – CMOS with vertical BJT structures pulse generator #2

Normally, the bond wire used in integrated circuits is used to implement the coil in a way to save the area of these integrated circuits. But is always necessary make some adjustments.

6.5 Antennas

Any narrow band antenna (the most common) is characterized for some parameters more or less commons [39]:

- All bandwidth adaptation
- Gain
- Bandwidth

The UWB antennas need other parameters types due to his final application [40]:

- Phase linearity
- Radiation diagram stability
- Group delay variation

The antennas used initially to transmit the UWB pulses have relatively big dimensions that prevented their application in new systems that request some mobility. The following type's stranded out:

- - TEM horn antenna
- - Resonant monopole
- - Bi-conic antennas

In a way to facilitate the UWB antennas integration in new systems, new antenna types will have to be projected. That is why planar monocycle and microstrip antennas were developed and directly implemented in the printed circuit board (PCB). Although this is not

a recent method and the fact that they need to have a greater bandwidth, some adaptation techniques were developed in order to improve them without degrading the radiation diagram.
The last studies had been focalized in the following microstrip antennas types:

→ **Vivaldi**

Technically this antenna has infinite bandwidth but her principal disadvantage is in its dimensions and in the way to adapt her that causes bandwidth diminution.

Figure 14 – Vivaldi UWB antenna

→ **Rectangular patch antenna**

This antenna is composed by a copper rectangle where one of the sides is step adapted to the connection of the rest of the circuit. The frontal and back sides of this antenna could be seen bellow.

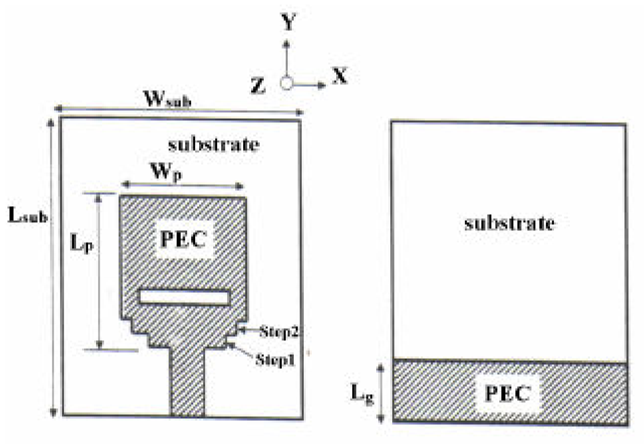

Figure 15 – Rectangular patch UWB antenna

→ **Planar antenna with co-planar waveguide**

Beyond these normal characteristics of a UWB antenna, this one also possesses the propriety of rejection a certain band (small) inside her operation frequencies.

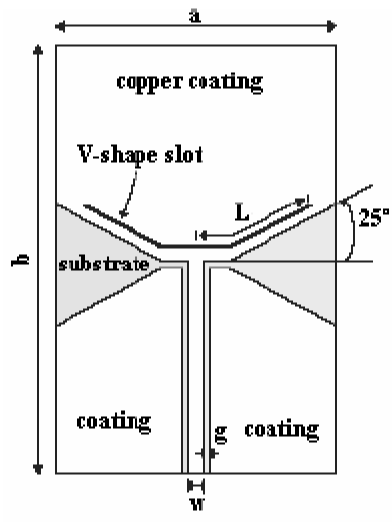

Figure 16 – Planar UWB antenna with co-planar waveguide

→ UWB antenna with LTCC slot

A new material technology appears with the LTCC introduction. This antenna is composed by ceramic material molten at low temperature. In this case the radiant element has elliptic shape.

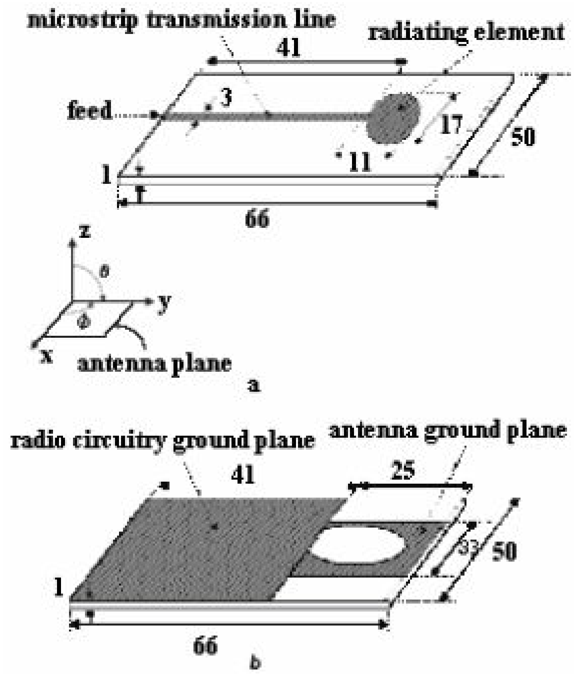

Figure 17 – UWB antenna with LTCC slot #1

But also appears with circular shape:

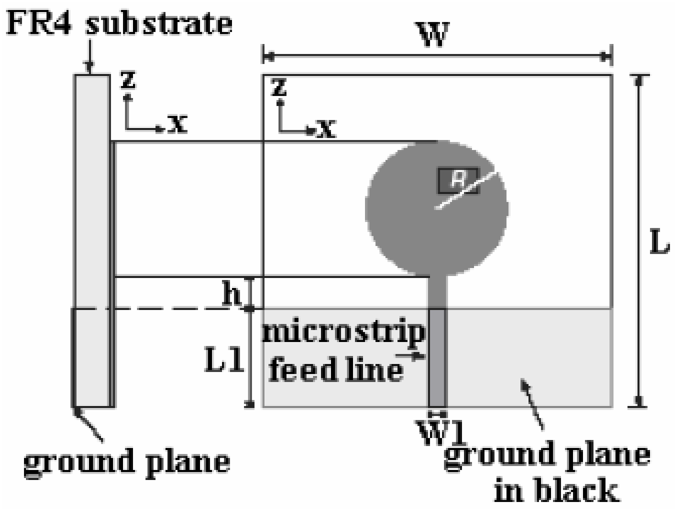

Figure 18 – UWB antenna with LTCC slot #1

→ **Microstrip antenna with adjustable fractal stubs**

The insertion of this antenna represented a progress in the shrinking of the antenna dimensions, relatively to the others that already exist. This antenna also possesses a rejection band.

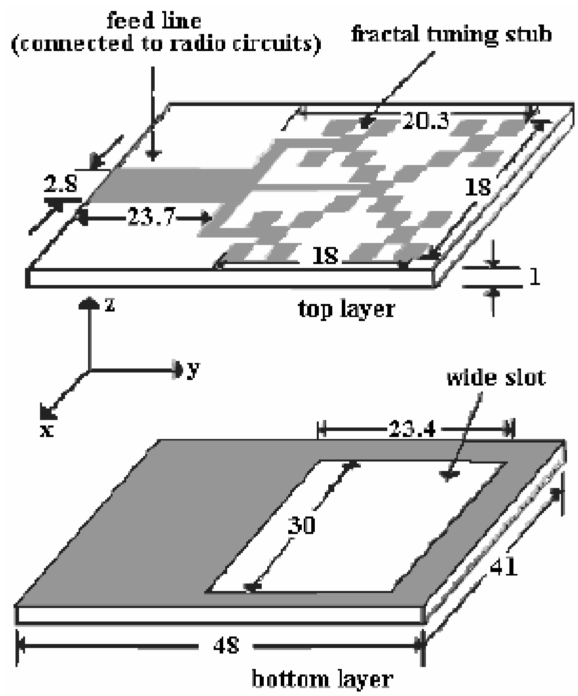

Figure 19 – Microstrip UWB antenna with adjustable fractal stubs

→ **Planar UWB antenna feed by the conic slot**

One of the principle characteristics is its size and that's why it is sometimes called miniature antenna.

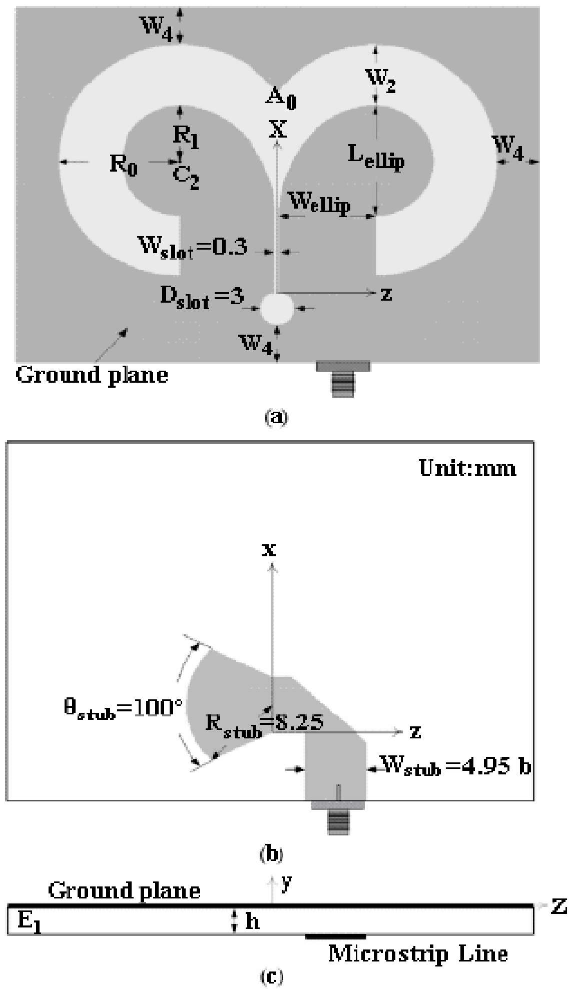

Figure 20 – Planar UWB antenna feed by the conic slot

Recently were developed planar monopole antennas where the most familiar are:

→ **Planar inverted conic antenna (PICA)**

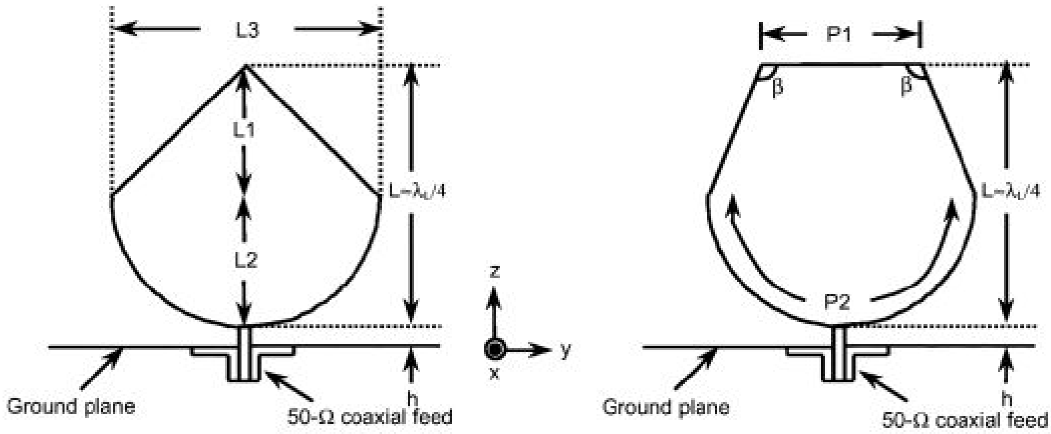

Figure 21 – Planar inverted conic UWB antenna (PICA)

→ UWB monopole antenna with rolled double arm

Made using a UWB monopole antenna, but shaped in a way that it has a cylinder shape.

Figure 22 – UWB monopole antenna with rolled double arm

Whatever is the used antenna, there are always associated problems to each one, but the most common is, without a doubt, the adaptation method at the amplifier output of the transmitter or the receiver input. However, some of these are already balanced, what makes the problem solution easier.

Chapter 7

7 Common modulations

Although the energy sent over the air relies in pulses with at least 500 MHz of bandwidth, those ones are modulated according with the systems used and the data transmission needed.

7.1 Simple Band

7.1.1 TH-UWB

When the existence of multiple users or accesses is needed, the transmission of time hopping sequence is commonly used. A certain amount of time for a data transmission is considered and then it is subdivided in time intervals even more shorts, that are used for each user to access the system. Each user is attributed a time slot within a burst and each one transmits in its time interval. This method is used in order to avoid the collisions.
A TH-UWB non modulated signal can be described as [19], [23]:

$$s^{i}(t) = \sum_{j} p(t - jT_f - C_j^{(i)} T_C) = \sum_{n} a_n^{(i)} p(t - nT_C) \quad (26)$$

- The time is divided in T_C fractions where each fraction is used by one user
- N_C fractions are grouped in a frame with $T_f = N_C T_C$ duration that corresponds to the one bit duration
- $0 \leq C_j^{(i)} < N_C$ is a integer with N_f period that adds an additional deviation to the pulse in order to avoid collisions when there are multiple accesses.
- $a_n^{(i)} = \begin{cases} 1, & if\ an\ \mathrm{int}eger\ j\ exists\ where\ n = jN_C + c_j^{(i)} \\ 0, & in\ the\ other\ cases. \end{cases}$

This technique can be combined in, at least, three modulations:

A – Pulse position modulation (PPM)

B – Phase variations (BPSK)

C – Amplitude variations (OOK)

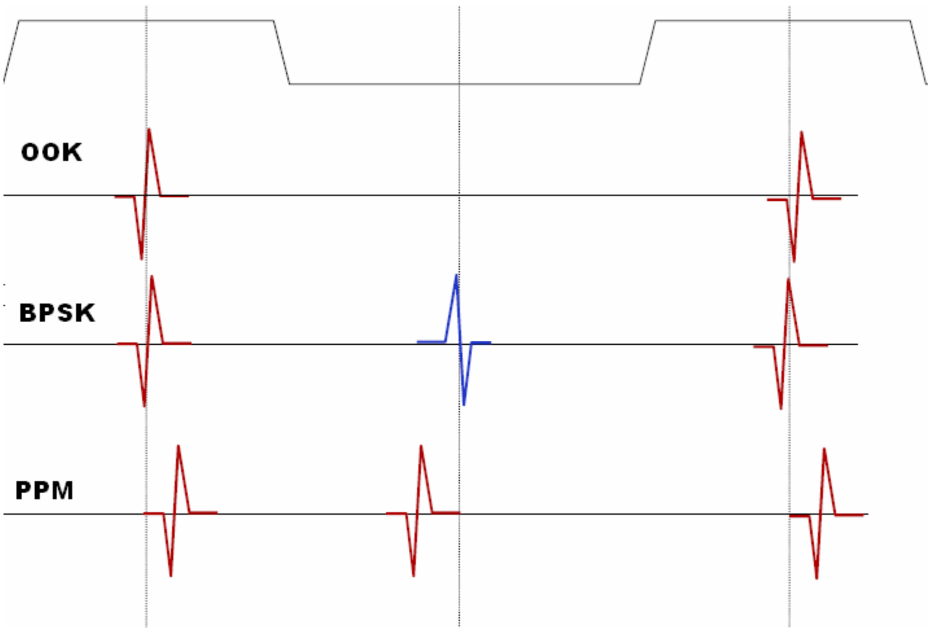

Figure 23 – OOK, BPSK and PPM modulations

A – A TH-PPM signal format is [20]:

$$s^{(k)}(t) = \sum_{j} p(t - jT_f - c_j^{(k)}T_C - \delta d_{[j/N_s]}^{(k)}) \tag{27}$$

$p(t) \rightarrow$ represent the transmitted monocycle that normally starts at the zero instant of the transmitter clock

$^{(k)} \rightarrow$ parameter that depend of the k transmitter (user)

In this way, the transmitted signal by the $^{(k)}$ transmitter is composed by a large number of pulses spaced in time. Therefore, the j monocycle starts at:

$$jT_f + c_j^{(k)}T_C + \delta d_{[j/N_s]}^{(k)}. \tag{28}$$

There are however several ways of positioning the pulses in the time slots:

$jT_f \rightarrow$ Uniform spacing

Being T_f the monocycle spacing in seconds, we obtain a pulse sequence of:

$$\sum_{j=-\infty}^{+\infty} p(t - jT_f) \tag{29}$$

Usually, T_f can be hundred times superior to the duration of the pulses, resulting in a very low duty-cycle signal.

When it is used in multi-user systems, catastrophic collisions can occur. These are the result of a high number of pulses received in the same instant, which were transmitted from several different users.

$c_j^{(k)} T_C \rightarrow$ Pseudo-random spacing

In order to eliminate or minimize the catastrophic collisions, a unique standard shift $\left\{c_j^{(k)}\right\}$ denominated as "jump code" is attributed to each user. These $\left\{c_j^{(k)}\right\}$ codes have a N_p period, that is, $c_{j+iN_p}^{(k)} = c_j^{(k)}$ for all i and j integers.

Each $c_j^{(k)}$ code is an integer from $\left[0..N_h\right[$.

This way, inside the pulse sequence, the j monocycle has an additional shift of $c_j^{(k)} T_C$, that is, this additional time, stands between 0 and $N_h T_C$ seconds.

Assuming that:

$$N_h T_C \leq T_f \tag{30}$$

$\dfrac{N_h T_C}{T_f}$ is the time fraction in which the pulse jumps are allowed.

Some attention is necessary in the $N_h T_C$ dimensioning, because if this value is very small, the possibility of having collisions increases significantly.

$\delta d^{(k)}_{[j/N_s]} \rightarrow$ Data modulation

The data sequence $\{d_i^{(k)}\}$ of the $^{(k)}$transmitter is composed by binary symbols.

Since this system uses an over sampled modulation with N_s monocycles transmitted for symbol, this one changes each N_s time jumps. Assuming that it starts when the pulse index $j = 0$.

In this kind of modulation when:

→ Data symbol $='0' \Rightarrow$ is not added any time shift to the monocycle

→ Data symbol $='1' \Rightarrow \delta$ seconds are added to pulse deviation

Adding the $c_j^{(k)} T_C$ and $\delta d^{(k)}_{[j/N_s]}$ characteristics, the synchronization efficiency of the resultant signal increases and the interference decreases.

A possible architecture for this kind of system is [27],

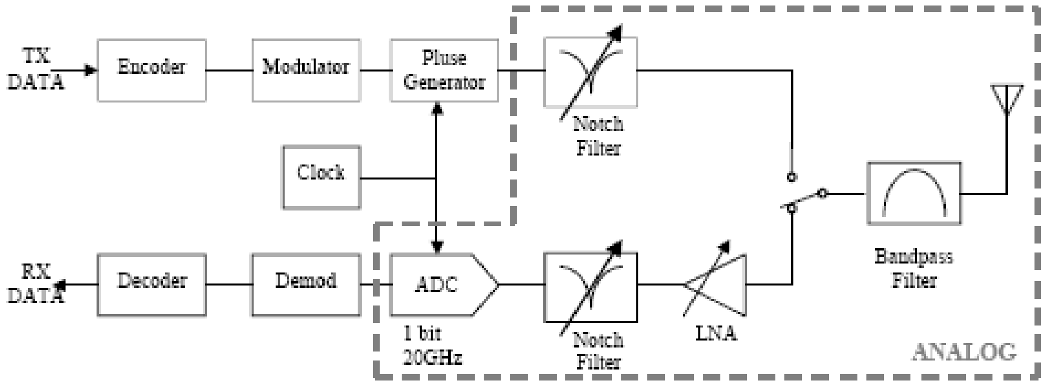

Figure 24 – TH-PPM Transceiver architecture

B – In this case, the TH-BPSK signal is [21]:

$$s^{(k)}(t) = \sum_{j=-\infty}^{+\infty} \sqrt{E_x} \cdot \beta^{(k)}_{[j/N_s]} \cdot p(t - jT_f - c_j^{(k)} T_C) \qquad (31)$$

So, as the previous case, the pulses have a combined spacing

$jT_f \rightarrow$ Uniform

$c_j^{(k)} T_C \rightarrow$ Pseudo-random

The phase bipolarization signal guaranteed is given by:

$$\beta^{(k)}_{[j/N_s]} \rightarrow \beta^{(k)}_{j} = 1 - 2d^{(k)}_{j} \tag{32}$$

$\beta^{(k)}_{j}$ takes the ± 1 value when the data to transmit $d^{(k)}_{j}$ is '0' or '1' respectively.

C – The amplitude variation modulation (OOK) is relatively similar to the BPSK because the pulse is multiplied by a factor that directly depends of the transmitted data.

$$s^{(k)}(t) = \sum_{j=-\infty}^{+\infty} \sqrt{E_x} \cdot \beta^{(k)}_{[j/N_s]} \cdot p(t - jT_f - c^{(k)}_{j} T_C) \tag{33}$$

The phase bipolarization guarantee is given for:

$$\beta^{(k)}_{[j/N_s]} \rightarrow \beta^{(k)}_{j} = d^{(k)}_{j} \tag{34}$$

$\beta^{(k)}_{j}$ → takes the values '0' or '1' when the transmitting data $d^{(k)}_{j}$ is '0' or '1' respectively.

7.1.2 DS-UWB

Since the pulses can be transmitted in different time shifts, the system can support several users at the same time. One of the ways to separate them consists in the already known spectral spreading technique where the user separation is made with orthogonal codes [24], [25], [28], [29], and [30].

A DS-UWB signal consists in the codification of the transmitted binary sequence with other pseudo-random binary sequence of the BPSK type (Binary Phase Shift Keying) or 4BOK (quaternary bi-orthogonal keying) with higher rate. The last one also modulates the sequence to transmit in frequency. Additionally, in order to increase the transmission rate, the spreading code used can have variable length. As bigger the velocity, lower the code length.

The BPSK signal can be described as:

$$s^{(k)}{}_{DS}(t) = \sqrt{\frac{E_b}{N_c}} \sum_{j=-\infty}^{+\infty} \sum_{n=0}^{N_c - 1} c^{k}{}_{n} \cdot p(t - j \cdot T_f - nT_c) \tag{35}$$

Where:

$p(t)$ → Normalized power wave form

N_C → Number of chips for bit information

$c^k{}_n$ → Pseudo-random sequence spreading with values between [-1 ; +1]

T_C → Chip duration when the bit duration is $T_b = T_C \cdot N_C$

T_f → Information frame duration

In this modulation, the transmission band is divided in two. The first one goes from 3.1GHz up to 4.85GHz (low band with 1.75GHz BW) while the second goes from 6.2GHz to 9.7GHz (high band with 3.5GHz BW).

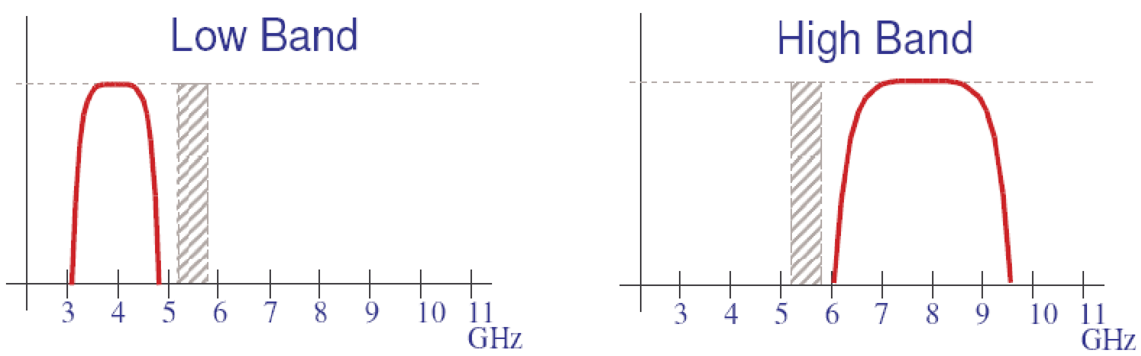

Figure 25 – DS-UWB Spectrum bands

The separation between users (channels) is made through spectrum spreading technique by direct sequence (DS-SS).

The bands can have up to six channels (the so called piconets) with frequencies and independent operations codes. The BPSK and 4-BOK modulations are used to modulate the data symbols where each one of them is composed by a sequence of UWB pulses.

The transmission rate can reach and overcome 1Gbps but in relatively short distances (2-4m). Due to its large bandwidth it is resistant enough to the propagation problems, namely to the Rayleigh fading.

The several transmission rates are obtained with the spreading sequences of variable length between 1 and 24 symbols.

This modulation is one of the two proposals for the specification and normalization of the 802.15.3a system in IEEE.

The picture bellow represents a possible architecture for the transmitter and receiver [10] [27]:

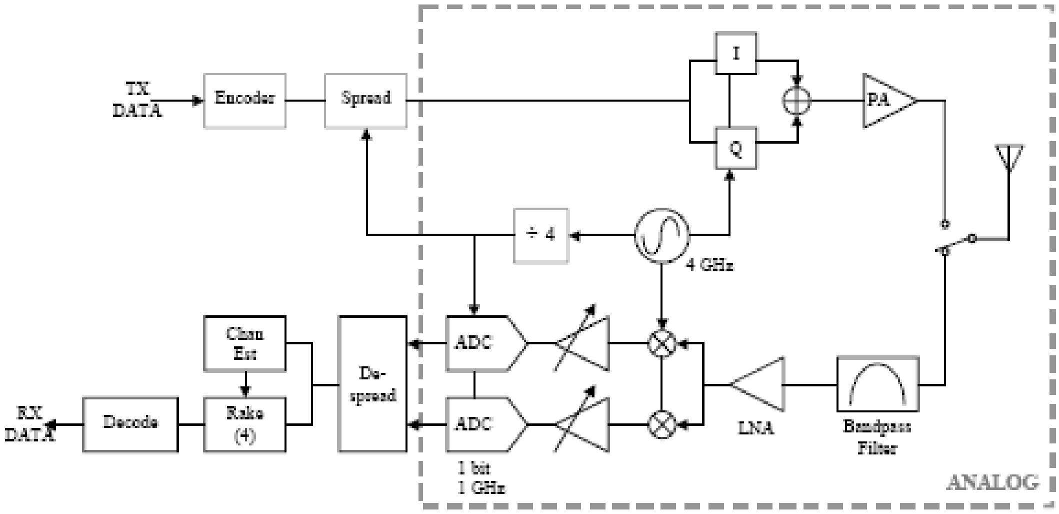

Figure 26 – DS-UWB Transceiver architecture

The transmitter has a very simple architecture where the data to transmit is almost directly connected to the antenna. Since the communication range is very short (due to the power limit settled by the regulator) the output stage does not need to be high power. Nevertheless, it needs to have ultra wideband, which is very challenging.

On the contrary, the receiver has some difficulties in the digitalization of this high bandwidth. Normally, the ADC need to have a very high frequency but the resolution is low (3 or 4 bits maximum).

The interference due to the other systems that can be operating at the same place and that partially hold the same band could be worrying. Usually those systems power is very superior to the UWB signal and that can saturate very easily the input amplification stage [26]. That is why it's necessary some attention in the design of this stage and a more detailed study, which will be presented ahead in this dissertation.

7.2 Multiple Bands

7.2.1 CI-UWB

In this type of modulation, the pulses are generated through the multiple carrier over-positions by [31], [32], [33]:

$$\Delta f = \frac{1}{T_S} \tag{36}$$

Using IFFT, we could calculate:

$$h(t)=\sum_{i=1}^{N} A\cdot\cos(i\cdot 2\cdot\pi\cdot\Delta f) \tag{37}$$

Where:

$A=\sqrt{\frac{1}{N}}\cdot\sqrt{\frac{2}{T_s}}$ so that the pulse has a unitary energy.

In this way, the pulse duration is limited to T_s .

These systems, when using all these carriers assures that those are orthogonal, allowing the improvement of the system efficiency in the following aspects:

→ Error probability

→ Power consumption

To transmit a bit sequence the user k creates the following signal to transmit:

$$s(t)=\sum_{k=1}^{K} a_k\cdot h(t-\tau_k)\cdot g(t) \tag{38}$$

Where:

$a_k = k^{th}$ binary data symbol

7.2.2 OFDM-UWB

The OFDM-UWB or MB-OFDM modulation is characterized by the attributed band division for the UWB communications in smaller sub-bands of 528MHz but still fulfill with the specification [34], [35], [36]. These bands are used individually during the communications with band hopping or using only one. That depend of other factors where among them are the external interferences of other systems that overlap to some individual bands.

The 7.5GHz (3.1GHz to 10.6GHz) spectrum was divided in 14 bands of 528MHz and grouped in 5 groups whose central frequencies are:

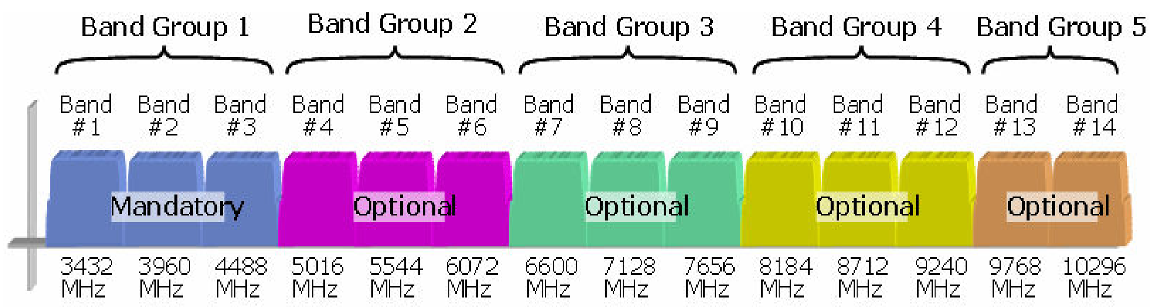

Figure 27 – OFDM-UWB working frequency bands

Additionally, the Band Group 6 was defined and it includes band 9, band 10 and band 11.

At this moment only the first band group is mandatory and is used with major emphasis in the already implemented prototypes, in order to decrease the time to market time. Like this, the wave's codification in the 3 bands of this group is made in the following way:

1) Use of the variable frequency codification
   - Frequency interleaving along the time
2) Data codification in the three bands of the group according to the pre-defined standard.
   - Fixed frequency interleaving
   - The information is codified in only one band.

In the first case, a guard time of 9.5ns is inserted at the end of each symbol in order to the transmitter or the receiver could change the band. Additionally and for the two cases, a prefix is added at the beginning of each symbol to make easier the bits reception due to the problems that the multipath can cause.

Relatively to the OFDM codification, this use:

- 128 sub-carriers for band
  → 100 transmit modulated information in QPSK
  → 10 guard carriers (among the 100 that transmit information)
  → 12 pilot carriers (among the 100 that transmit information)
  → 6 remaining, including DC are nulls to prevent some cross-talk and leakages from the local oscillator of the receivers.

Based in previous experiences (WLAN), it was proven that this technology (OFDM) behaves well in places were the propagation conditions are adverse and suffer from multipath problems, due to multiple reflections.

The fact of using multiple bands makes that we could turn off or changes if some aggressive interference is present.

→ **Transmitter:**

Pulse train frequency coded:

$$p(t) = \sum_{n=0}^{N-1} s(t - nT) e^{-j\frac{2\pi c(n)t}{T_C}} \quad (39)$$

Where:

$s(t)$ → Elementary pulse

N → Number of pulses for frequency

T → Pulses repetition period

$\frac{c(n)}{T_C}$ → Modulation frequency

$c(n)$ → Interval integer permutation $[0,1....N-1]$

$\frac{1}{T_C}$ → Frequency hopping resolution

A UWB-OFDM signal composed by a multiple carrier system use this pulse sequence for modulate them.

$$x(t) = \beta \sum_{r} \sum_{k=1}^{n} b_k^r p(t - rT_p) e^{j2\pi k f_o (t - rT_p)} \quad (40)$$

Where:

b_k^r → Information symbol transmitted during r interval over k carrier

β → Transmitted bit energy and the power spectral density level.

This proposal is similar to a narrowband system since the transmission band was divided in fractions slightly bigger than 500MHz. These bands establish the transmission channels. The system can be configured to work frequency hopping technique between bands, becoming even more immune to interferences and to the interception. Its also able not to transmit in some particular band that might be used by others systems.

On the contrary, the receivers and transmitters complexity is very high due to complex FFT's needed.

This type of modulation is one of the two proposals for the specification and normalization of the 802.15.3a IEEE system.

The picture bellow represents a possible architecture of the transmitter and receiver [10] [27]:

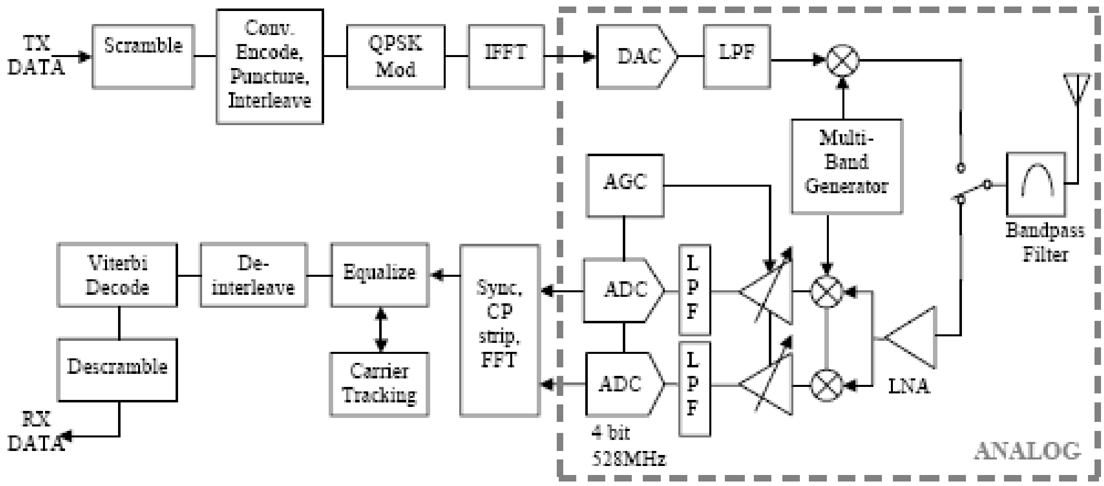

Figure 28 – OFDM-UWB Transceiver architecture

7.2.3 FH-UWB

Not always an UWB system can be composed by short duration pulses whose transmission is timely controlled using ultra-wide band techniques. Another possibility is the use of frequency hops in a similar way to some narrowband systems [37], [38].

In order to obtain the capacity to support multi-users in an efficient way, the QPSK modulation is used (this is one of the examples). The available spectrum is divided in several groups in each several users are allocated. If by chance, typical interferences of the high load appears (more users means more traffic transmitted), these are only felt inside the group. But, if on the contrary, the interference is caused by the exterior, this group is instantaneously eliminated and the users are moved to other group. The fact that each resultant group of the spectrum division contains only one carrier is the major difference of this type of multi band system from the OFDM that use sub-carriers inside each group.

The use of this type of systems has some advantages:

→ Some narrow band systems had been widely debated and studied and the acquired knowledge could be an advantage.

→ Since that the chip concept is not used, but the frequency hops, the last ones are much less demanding in terms of processing capacity. This factor will allow saving in the consumptions, if this technology is implemented in VLSI.

→ Is less susceptible to the near and far fields problem.

→ More immune to the exterior interferences as previously described.

On the contrary, one big disadvantage of this system exist in the possible limitation of the data transference rate due to the bandwidth limitation since each user can only use one of the sub-bands.

A possible architecture can be [27]:

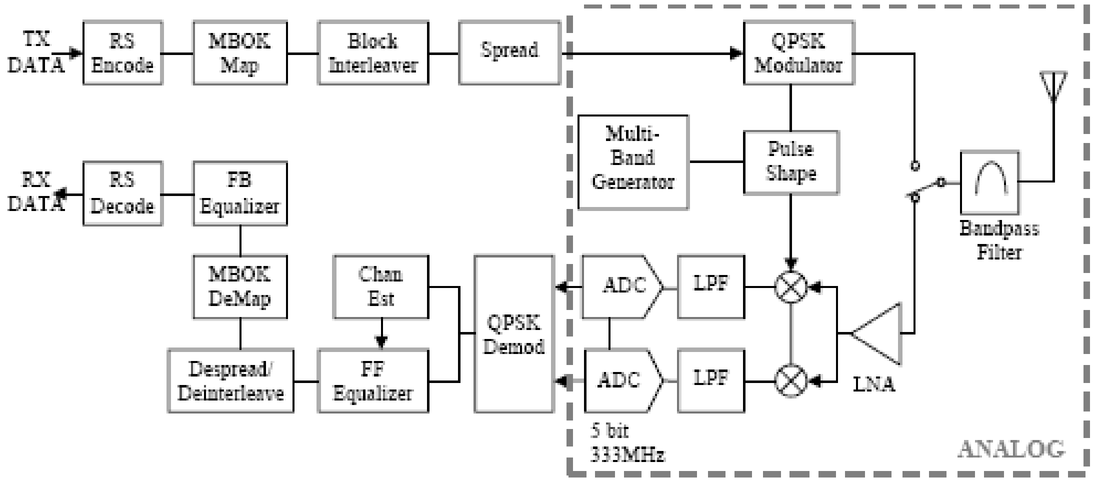

Figure 29 – FH-UWB Transceiver architecture

Another very important characteristic in this type of system consists in the diminution of the computational complexity needed, since that is not necessary the direct and inverse FFT's.

Chapter 8

8 Applications

This technology can be used in distinct ways, but since the distance of the communication can be short due to the low powers used.

→ Positioning systems

If the lower bands of the spectrum are used, the penetration capacity is very high, therefore objects that are out of our sight can be detected with great precision.

→ Ultra wide band communications (WPAN)

The very high bandwidth allows transmission rates also very high in short distances. It can be particularly useful in residential applications, such as:

→ High resolution video transmission in televisions and video cameras.

→ Construction of extreme fast residential wireless nets.

→ Almost direct conversion of the fiber optics communications in wireless communications.

→ A specific application that is the Wireless USB (WUSB) developed to replace the cable connection in the very wide used USB2.0 computer serial communications.

There's a big range of applications at which this technology can be applied, but the development it's still in the beginning and there is also a lot to investigate, in order to overcome some known technical problems.

Chapter 9

9 System Simulation

As stated before, the first objective of this thesis is to study the impact of a nonlinear channel in the pulsed communication, namely in UWB, and how it will affect one of the most important parameters of the system, the Bit Error Rate (BER). In order to have a deeper understanding of the phenomenon, a Simulink® model was developed to simulate the system. Before its description, let's focus on some characteristics that will be useful to model some parameters and to have a better accuracy of the global model.

The Scholtz pulse is the one with best spectral characteristics, regarding the FCC mask, so it will be used throughout our analysis. The FCC mask was used, because it allows a very wide bandwidth pulse. Also the DS-UWB standard proposal spectrum is not strictly used, because the second band allows the maximum of 3,5GHz of bandwidth, while the FCC mask could have 7,5GHz. This is very important, because this study could be applied not just for UWB, but also for other systems that might use such large bandwidth and, or very high transmission rates.

The allowed PSD in the main band of the allowed spectrum, is,

$$PSD = -41{,}3 - 10 \times \log(1e6) = -101{,}3 \ dBm/Hz \qquad (41)$$

Considering that the pulse will generate a flat energy in that band, the bit energy could be approximated as,

$$Eb = -101{,}3 + 10 \times \log(7{,}5e9) = -2{,}55 \ dBm \qquad (42)$$

Below is presented the pulse format as it will be used in the model.

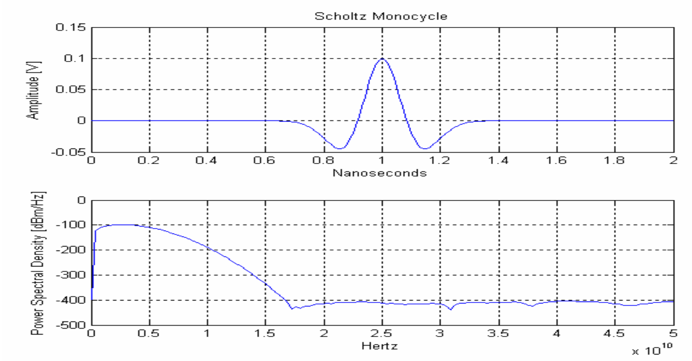

Figure 30 – Scholtz pulse, time domain and spectrum domain waveform

The pulse duration inversely defines the bandwidth occupied (shorter pulse, bigger spectrum). From the beginning to the end, the pulse has around 0,5ns duration and the spectrum generated with significant power goes from a few MHz, up to 10GHz. The power is a bit higher than the limit in the low side (3,1GHz down to DC), but a pass-band filter will correct this. In the high side, the power is a bit inferior to the limit, but this will not conflicts with the regulation.

In order to transmit information, or to have multiple user's access, the pulses are additionally modulated. Some of the modulation schemes, as presented in [19], are the On Off Keying (OOK), Pulse Position Modulation (PPM), and Binary Phase Shift Keying (BPSK).

The pulse to be transmitted can be defined as:

$$s(t) = \sum_j A \times p(t - jT_f) \tag{43}$$

Where,

$p(t) \rightarrow$ Pulse being transmitted

$jT_f \rightarrow$ Pulse position for PPM modulation (null value for OOK and BPSK)

$A \rightarrow$ Amplitude of the pulse. {A, 0} for OOK modulation, {-A, A} for BPSK and {A} for PPM

All the three schemes will be considered in the analysis and using Simulink® three models will be presented.

Figure 31 presents the architecture used to implement OOK and BPSK architectures, while Figure 32 presents the architecture for PPM modulation.

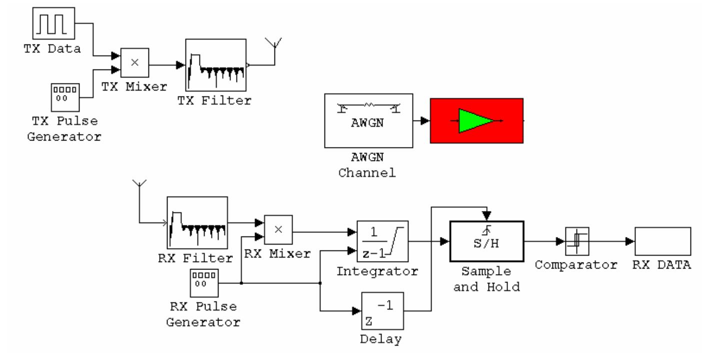

Figure 31 – BPSK and OOK Transceiver architecture

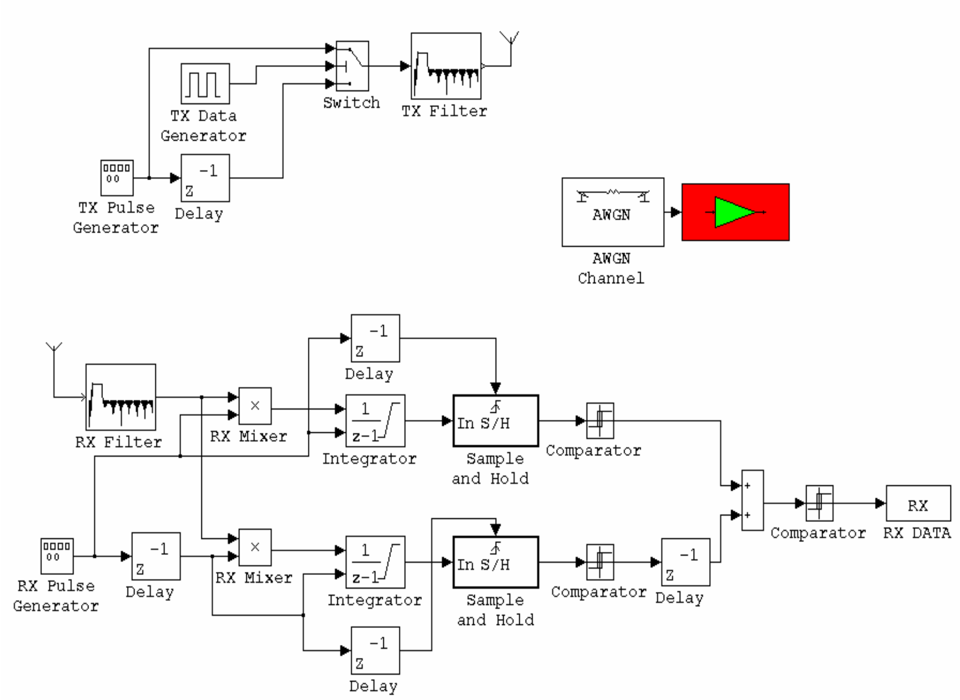

Figure 32 – PPM Transceiver architecture

Next, a brief description of the system will be presented. To better explain the model, it was divided in three different parts:

1. **Transmitter**

- **TX Data**

This is the digital data that should be received by the receiver. In the model is just a bit generator, which is continuously sending random bits with equal probability of ones and zeros. The output level is then formatted to implement the required modulation:

{1,0} → for OOK and PPM

{1,-1} → for BPSK

- **TX Pulse generator**

Implements a mathematical pulse generator with the same shape as showed in Figure 30. The rate adopted was 1Gbps, so the pulse generator needs to have a rate also of 1G pulses per second.

- **TX Mixer**

This mixer is just a simple multiplier block with two inputs, being the output the product of those input signals.

- **TX Filter**

The output transmitter filter is also a spectrum shape filter, in order that the output spectrum of the transmitted pulse fulfils the regulation imposed. This filter is a pass-band with:

Pass-band (3dB) → from 3.1GHz to 10.6GHz with 0,5dB of ripple

Low stop-band → 1.6GHz with 35dB of attenuation

High stop-band → 11.6GHz with 15dB of attenuation

In the PPM modulation, the transmitter will send pulses at two positions to distinguish the transmitted data (zeros and ones) which caused a duplication of the transmitter path and also added the following components:

- **Switch**

In a PPM modulation, the pulse is in a different position, if the transmitted data is a zero or a one. This switch has two inputs and the output will have the value of the TX Pulse Generator or its delayed version, if the TX Data is zero or one respectively.

- **Delay**

This delay is applied to the TX Pulse Generator output, to implement the pulse position modulation. Its value is tuned, in order not to have an overlap in two consecutive transmitted pulses.

2. **Receiver**

- **RX Filter**

This filter has the same spectrum characteristics as the TX Filter, but the purpose is slightly different. The intention is to not let enter the unwanted band in to the receiver.

- **RX Pulse generator**

In the receiver, the same data rate is used as in the transmitter so, a pulse generator with the same characteristics is needed. It also implements a mathematical pulse generator with the same shape as showed in figure 30. The rate is also 1Gbps, so the pulse generator has 1G pulse per second.

- **RX Mixer**

It's also a simple multiplier block, with two inputs.

- **Integrator**

In order to have a better knowledge of the energy present at a certain moment in time, the energy is integrated between two periods (duration of a bit time) and the value is reset at the beginning of each period.

- **Sample & Hold**

This block samples the energy value, which comes from the integrator output, at a certain time and holds it, until the next sampling trigger. The rate of sampling is the same as the data rate used in the system (1G in this case). The clock used for this trigger is a delayed version of the RX Pulse generator.

- **Delay**

The sample and hold block trigger should be efficient and capture the correct value. In order to achieve the best performance, the clock for the sample and hold should be delayed, for it to capture the most representative value at the integrator output.

- **Comparator**

The comparator output represents the data received, so its output has the following value:

{0} → if the input if below of the threshold

{1} → if the input if above of the threshold

The threshold is defined taking in account the output level of the sample and hold.

- **Received bits**

After all the reception chain, the data received is compared with the transmitted one, bit by bit, and the bit error rate (BER) is calculated.

Additionally to those components, in the PPM modulation (Figure 32), the receiver path is duplicated, to decode the position of the pulses and after that, decide if they are {0,1}.

- **Delay**

This is the delay at the output of the RX Pulse generator and it has the same value of the delay in the transmitter. It's essential that both have the same value to achieve the best performance.

- **Adder**

The two paths are then added (before one of them is delayed to decode the position of one of the transmitted pulses) and then again the signal is passed through a comparator.

- **Comparator (last one)**

This comparator is the last one in the chain, and it will decide if the data received is a one or a zero for the BER calculation.

3. Transmission channel

In all cases, the transmission channel is composed by:

- **Additive White Gaussian Noise Channel (AWGN)**

In this part of the channel model, the bit energy is calculated and some noise power is added in a certain amount such that the quantity bit energy over noise has some different controlled values.

As stated before (42), the total power of the pulse is,

$$Ps = -2{,}55\ dBm \tag{44}$$

Assuming that,

$$SNR = \frac{Eb}{N0}\cdot\frac{Rb}{B} \Leftrightarrow \frac{Ps}{P_N} = \frac{Eb}{N0}\cdot\frac{Rb}{B} \Leftrightarrow P_N = \frac{Ps}{\frac{Eb}{N0}\cdot\frac{Rb}{B}} \tag{45}$$

Being,

Rb → Bit Rate (in this system is considered to be 1Gbps)

B → Bandwidth of the system (7,5GHz)

P_S → Signal power over all B (-2,55dBm)

P_N → is the noise power (variance)

The value of the noise power will vary accordingly with the change of Eb/N0 required in simulations.

- **Non-linear component**

As this is the core block of this thesis, the next chapters will have a more detailed description of these block models but, as introduction, this non-linear component can be of two types,

→ BANG-BANG

This component is described by a Wiener-Hammerstein model, based in the pre-distorter power amplifier model.

→ Memory-effects

The memory effects can be of two types [46]:

- Short term, caused by both the reactive components of the active device and matching networks at the RF band
- Long term, usually attributed to the active device's dynamic thermal effects

9.1 Linear channel

The first approach was to verify the robustness of the system in the presence of just noise of the type Additive White Gaussian (AWGN), considering that the channel is linear.

The system end to end was simulated and the transmitted bits compared with the ones received, when the noise in the channel was increased (Figure 33).

As can be seen from the next Figure modulations OOK and PPM have a similar behavior, while BPSK presents better results.

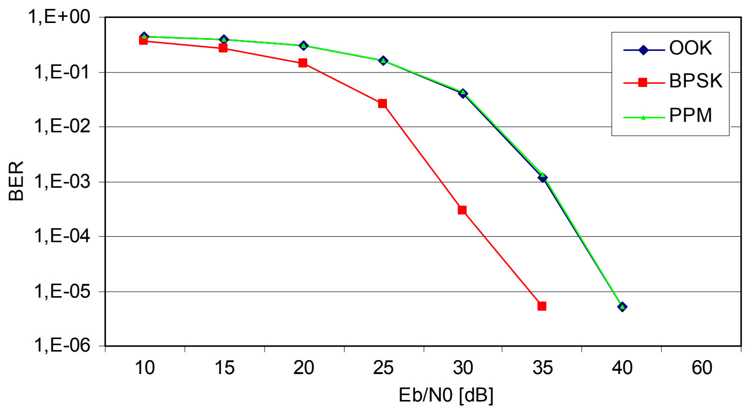

Figure 33 – BER vs Eb/N0 for the three considered modulations

In order to understand better the system behavior and to understand the results, let's probe some internal points in the system, after a simulation with Eb/N0 equal to 60dB.

In the following two figures (Figure 34 and Figure 35), the output of the selected components are presented for OOK and BPSK, since the PPM and OOK have similar results,

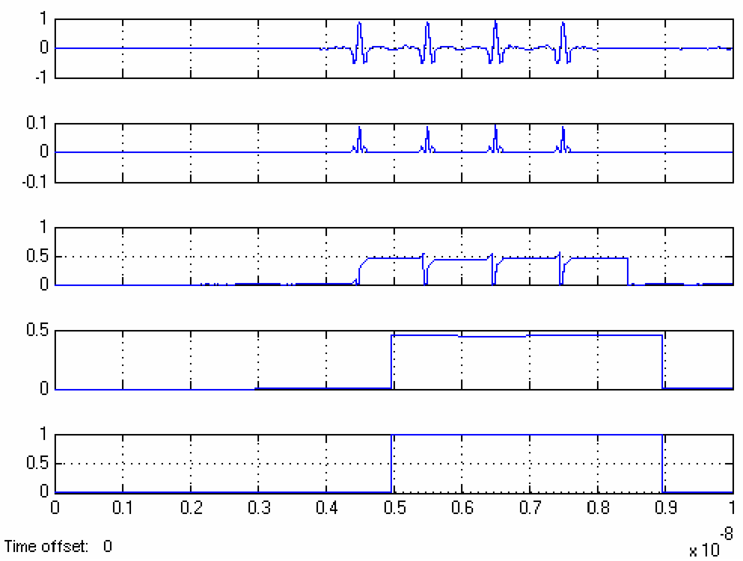

Figure 34 – OOK waveforms at receiver components

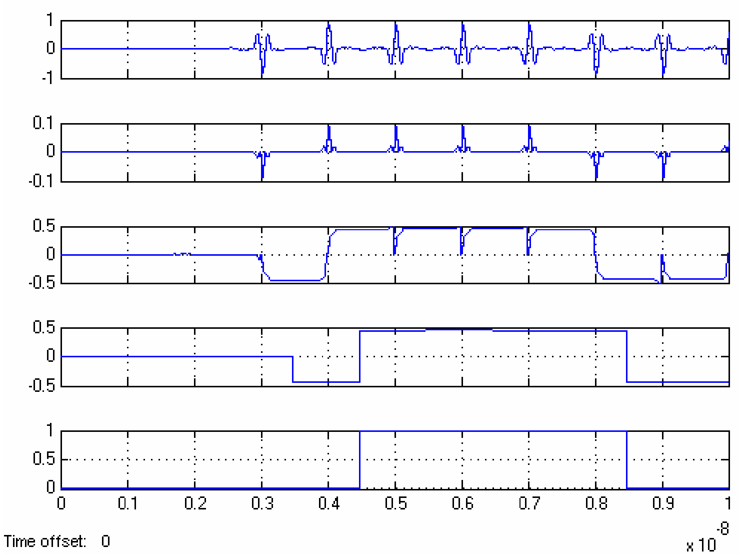

Figure 35 – BPSK waveforms at receiver components

In Figure 34 and 35,

→ **first row**

Output of the RX Filter. This is the format of the received signal. With Eb/N0 equal to 60dB, the shape of the pulses is well defined.

→ **second row**

Output of the RX Mixer. After the multiplication of the RX Pulse Generator pulses with the received ones, a very good detection is achieved.

→ **third row**

Output of the Integrator. The detected pulses are integrated, which lead to a fine voltages steps ready for sampling.

→ **fourth row**

Output of the Sample and Hold triggered by a delayed version of the RX Pulse Generator, in order to sample in the middle of the output step of the Integrator.

→ **fifth row**

Output of the comparator. In the case of the BPSK the threshold is set to 0V, while in OOK it's in the middle Sample and Hold output voltage.

Focusing in the OOK system, when the noise increases, a noise peak can be confused by a received pulse, leading to an erroneous received bit.

In BPSK there are always received pulses, but with different polarity. In this case, only when the noise is very high, the received data is corrupted. This justifies the better results in BPSK related to OOK.

9.2 Polynomial nonlinear channel

One of the simplest nonlinear channel types can be described as:

$$y(t) = a1 \cdot t + a2 \cdot t^2 \tag{46}$$

The coefficients $a1$ and $a2$ play a different role in the model ($a1$ is the linear gain and $a2$ the gain of the quadratic component) and will be changed to reflect how nonlinear the channel is. As higher $\frac{a2}{a1}$, more nonlinear is the channel. In order to keep the simulation simple, $a1$ will be kept with unitary value, while $a2$ will vary between 0.001 and 100.

Below the simulation results for the three modulations,

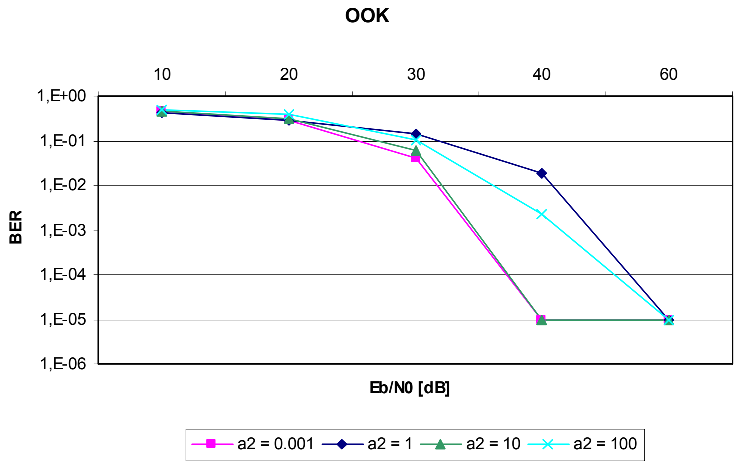

Figure 36 – OOK BER vs Eb/N0 for a2 change

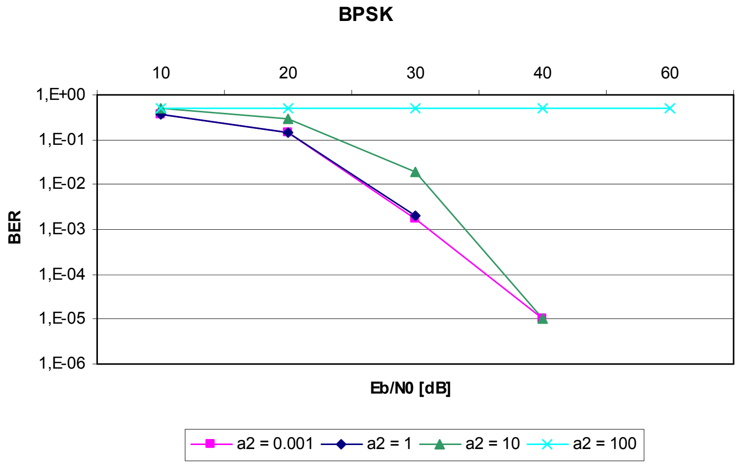

Figure 37 – BPSK BER vs Eb/N0 for a2 change

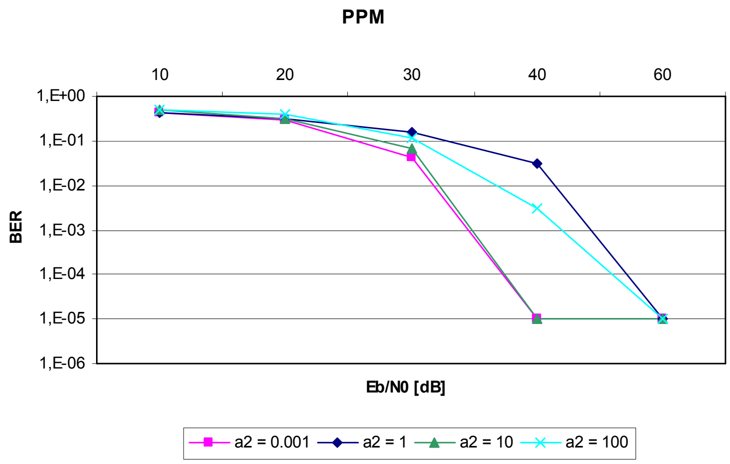

Figure 38 – PPM BER vs Eb/N0 for a2 change

By observing the results, it can be seen that the OOK and PPM modulations have a similar behavior, while BPSK is different. Comparing with the linear case of the previous sub-chapter, there's performance degradation in all modulations. The presence of this type of nonlinearity is quite dramatic and will not be possible to the system recover from the errors.

Focusing in BPSK, when $a2$ is high (100), the system will not work at all, due to the high BER. As the pulse is negative, when the transmitted bit is a zero, the quadratic parcel will invert that polarization, causing a wrong detection.

9.3 BANG-BANG

The transmission channel is a non-linear channel described by a Wiener-Hammerstein model, composed by a filter followed by a nonlinear behavior model and a 2nd filter. Additive White Gaussian Noise is also added to the signal transmitted.

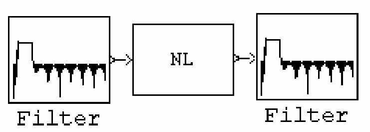

Figure 39 – Wiener-Hammerstein Non-linear model

The nonlinear block is described by a strong nonlinearity that cut the signal for a large value of input signal.

$$y(t) = \tanh\left[Gx(t)\right] \tag{47}$$

This model behaves as a linear gain for small values of the amplitude of the signal but as a strong nonlinearity for higher values of the amplitude of the pulse, so somehow it is describing the behavior of any nonlinearity that is presented in the channel path, as for instance an amplifier.

In the nonlinear channel it is also added AWGN as described in the previous chapter (45).

Now let's see the impact of the transmission channel non-linearity in the performance of the system.

Together with the non-linear part of the transmission channel the AWGN noise was also added, as described previously, creating a two variable function, with one dimension been the input power, the other the Eb/N0.

The Eb/N0 was changed from 5dB up to 60dB, while the input voltage of the pulse has a variation from -60dBV up to -6dBV.

In this case, for OOK and PPM, the comparators threshold of the receiver was dynamically adjusted for every change in the amplitude pulse.

Also the total power of the pulse in all bandwidth was also recalculated, in order that the parameters matched the current conditions.

In the following three figures, the BER results are presented for the three modulations used.

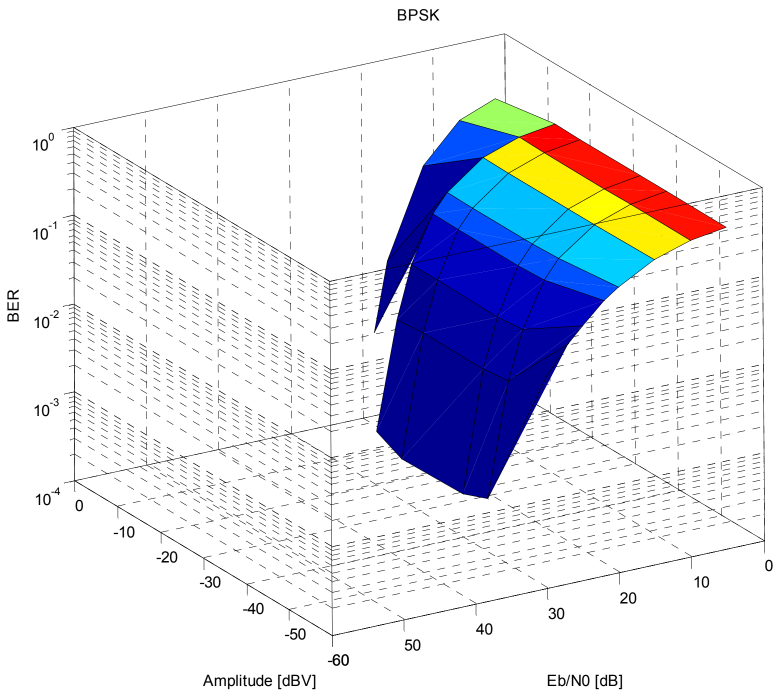

Figure 40 – BPSK behavior in presence of Noise and Power change

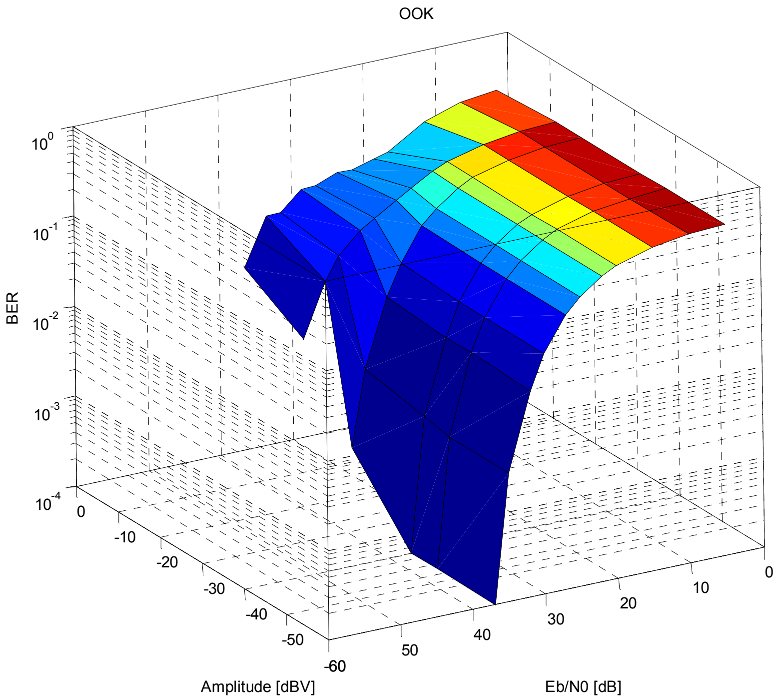

Figure 41 – OOK behavior in presence of Noise and Power change

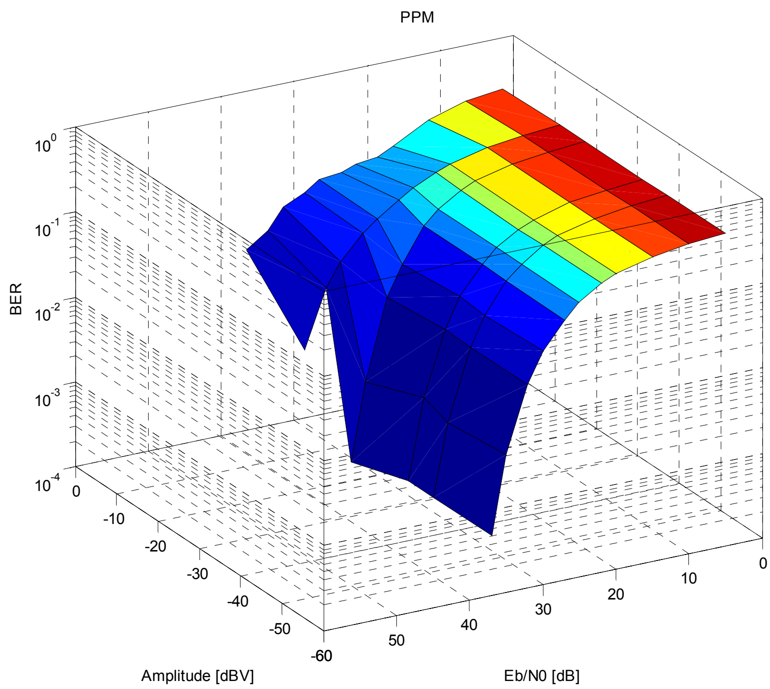

Figure 42 – PPM behavior in presence of Noise and Power Change

As before (in the linear channel), the modulations OOK and PPM have a similar behavior and BPSK is the best modulation for this architectures. It is also visible that the noise is the main cause of the errors in the system, while the non-linearity has a minimal impact.

9.4 Memory effects

The effect of the memory is know in narrowband systems, while it's effect in ultra wideband signals is not so familiar so far. A study of the impact of this type of perturbation was performed with the help of the following model (Figure 43) based on the parallel Wiener model. The long term effect model will be used.

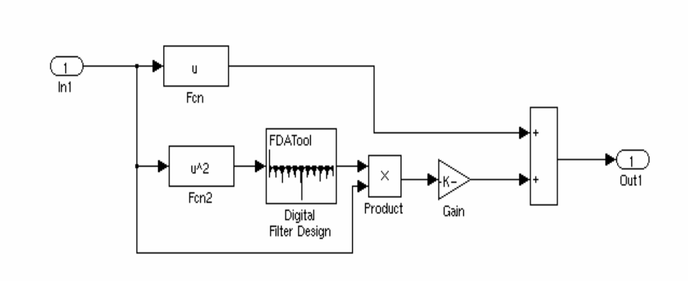

Figure 43 – Non Linear Channel with memory effects

The output signal of this channel is composed by the sum of the direct linear path with a nonlinear path (quadratic direct signal filtered by a low-pass filter) multiplied by the direct path. The gain after the product was inserted, in order that the nonlinear path has a magnitude close to the direct path (extremely non-linear channel).

Taking this in account, the following low pass filters were used in simulations,

- 20M → Pass band = 20MHz, Stop band = 80MHz, 50dB attenuation
- 100M → Pass band = 100MHz, Stop band = 200MHz, 50dB attenuation
- 500M → Pass band = 500MHz, Stop band = 1GHz, 50dB attenuation
- 1G → Pass band = 1 GHz, Stop band = 2GHz, 50dB attenuation
- 2G → Pass band = 2 GHz, Stop band = 4GHz, 50dB attenuation

The filters are low-pass, defined by a pass-band at 3dB and a stop-band defined at the attenuation level. The name of the filter has the indication of the respective pass-band. The wide values of the pass-band were chosen, in order to see the impact in the system's performance.

Next, the simulation results for the five filters are presented and compared with the linear channel condition for the three modulations,

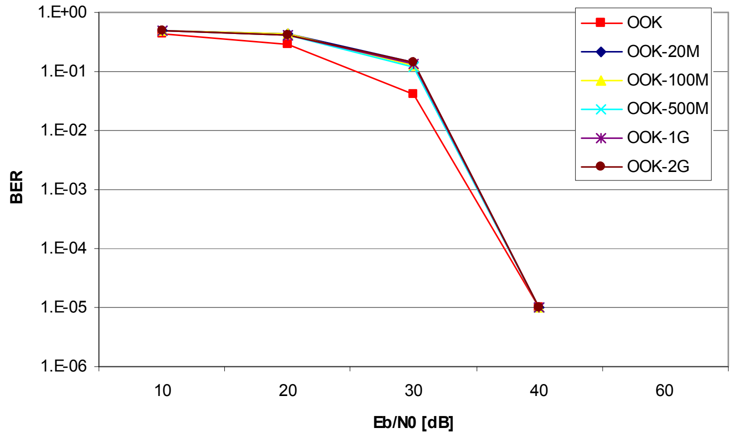

Figure 44 – Memory effects in OOK

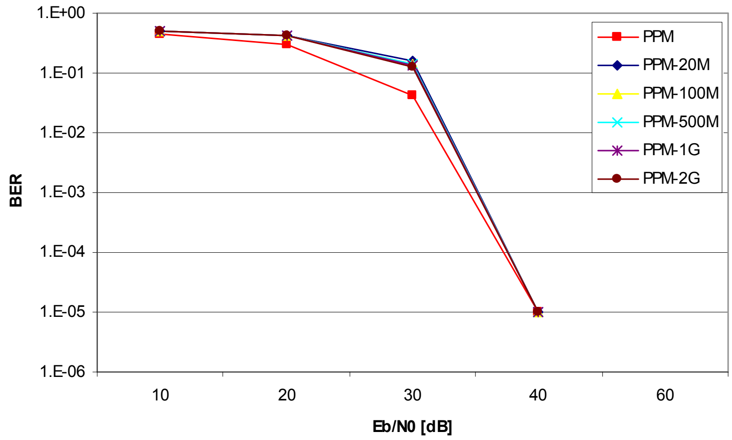

Figure 45 – Memory effects in PPM

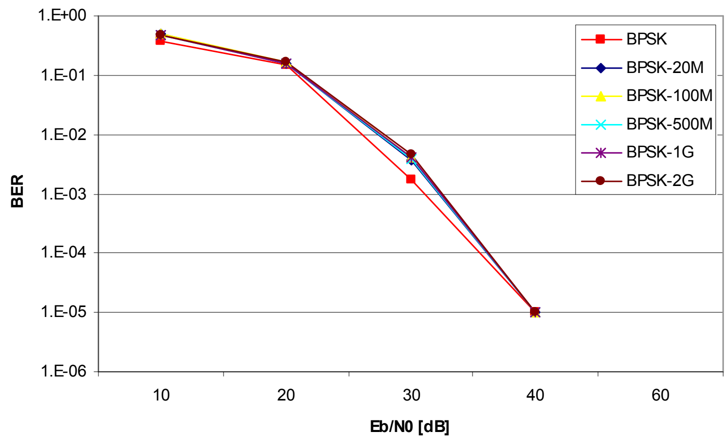

Figure 46 – Memory effects in BPSK

As it can be seen, the non-linear channel as some impact in the system performance, but the principal parameter that affects it is still the noise. It is also visible that the OOK and PPM modulations share similar behavior as before. The impact is small, but it is possible to see, that again BPSK is the modulation that least suffers due to the non-linearity.
In the middle range of noise (around 30dB of Eb/N0) is when the impact is most visible.

In the next figures, is shown the impact of the non-linear channel in the received pulses.
In Fig. 47 to 56 (left figure is from OOK and the right one from BPSK),

→ **first row**

Output of the RX Filter. This is the format of the received signal. With Eb/N0 equal to 60dB, the shape of the pulses is well defined (the same as in the linear channel).

→ **second row**

Output of the Non-Linear Channel. After the channel, the pulses are quite distorted. The impact is more visible in the LPF below than 500MHz (100M and 20M). In the higher band-pass frequencies the deformation is more visible just in the amplitude of the main peak value.

→ **third row**

Output of the RX Mixer. The received distorted pulses multiplied by the pulses from the RX Pulse Generator.

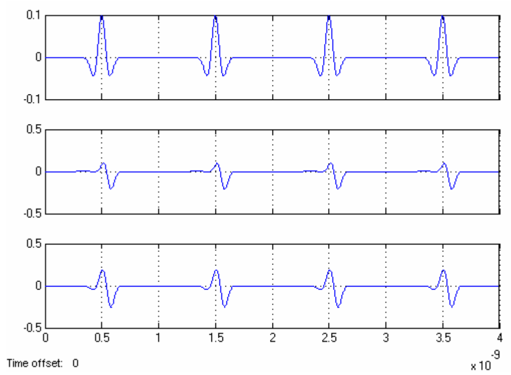

Figure 47 – LPF 20M – OOK

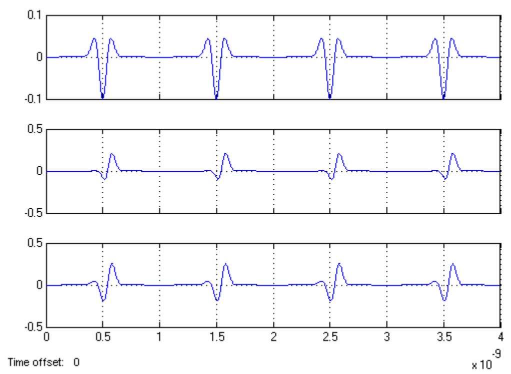

Figure 48 – LPF 20M - BPSK

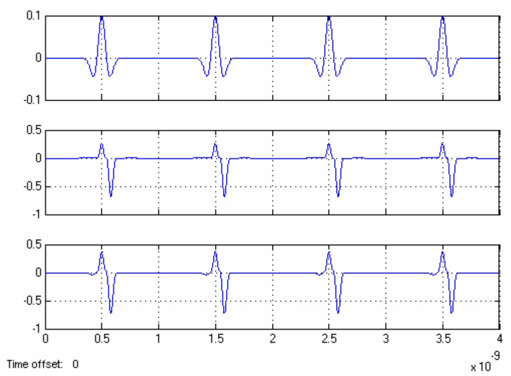

Figure 49 – LPF 100M – OOK

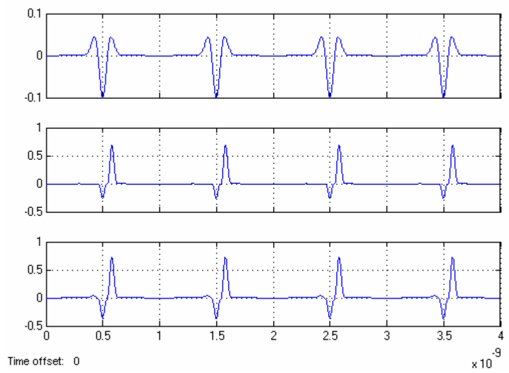

Figure 50 – LPF 100M - BPSK

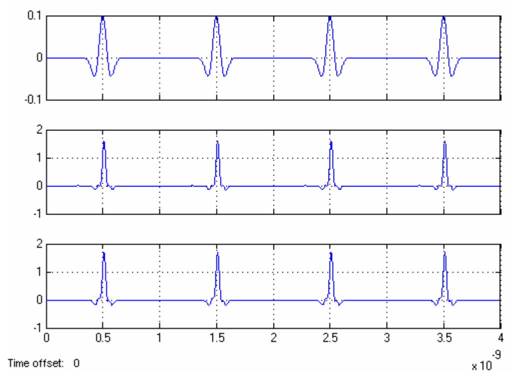

Figure 51 – LPF 500M – OOK

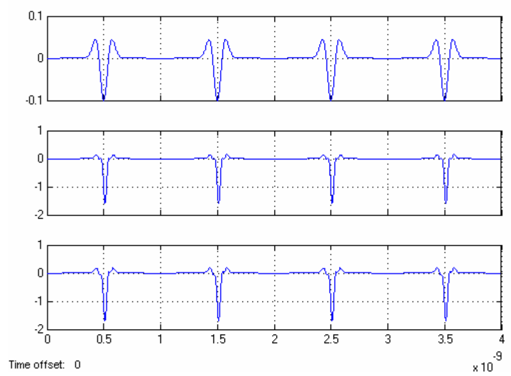

Figure 52 – LPF 500M - BPSK

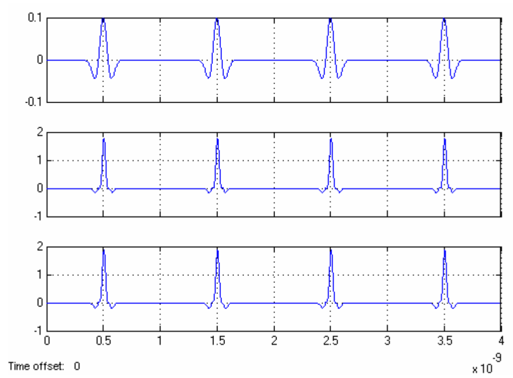

Figure 53 – LPF 1G - OOK

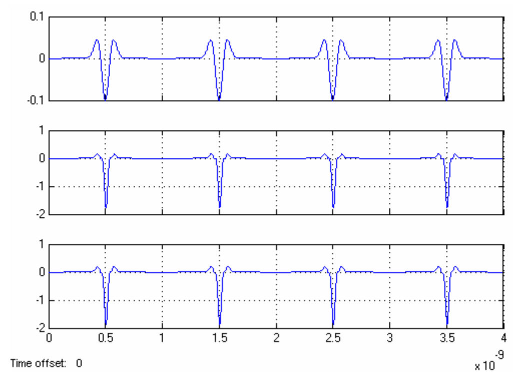

Figure 54 – LPF 1G - BPSK

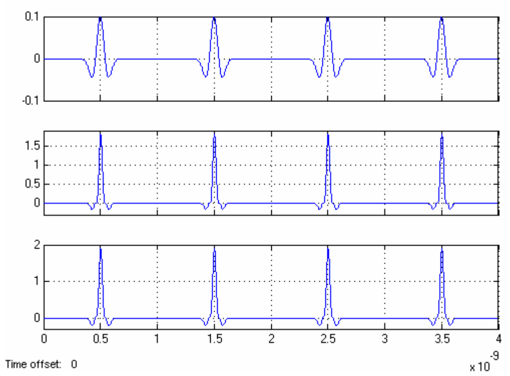

Figure 55 – LPF 2G - OOK

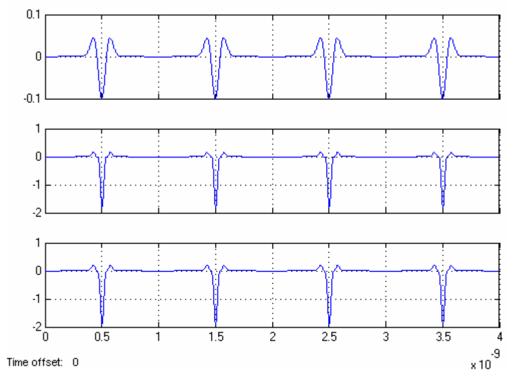

Figure 56 – LPF 2G - BPSK

After these results it would be expected, that the BER of the system would be strongly degraded mainly with the LPF with lowest frequencies (below 500MHz), but taking again a look on the results (Figures 44 to 46), that did not happen. There was a degradation, mainly at Eb/N0 equal to 30dB, but it was almost equal to all filters. The differences are minimal and all the modulations have similar behavior. Let's have a look again on the outputs of the receiver components, to see what really happened.

Regarding the Figures 57 to 64,

→ **first row**

Output of the RX Filter. This is the format of the received signal. With Eb/N0 indicated in the figure legend.

→ **second row**

Output of the RX Mixer.

→ **third row**

Output of the Integrator.

→ **fourth row**

Output of the Sample and Hold triggered by a delayed version of the RX Pulse Generator, in order to sample in the middle of the output step of the Integrator.

→ **fifth row**

Output of the comparator. Once again, in the case of the BPSK the threshold is set to 0V, while in OOK it's in the middle Sample and Hold output voltage.

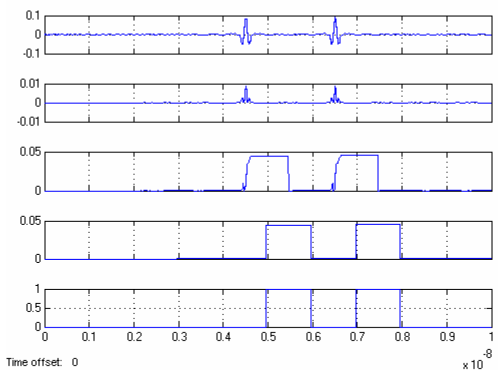

Figure 57 – LPF 20M – OOK receiver waveforms at Eb/N0 = 60dB

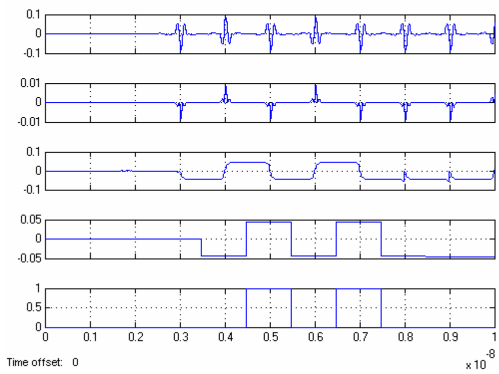

Figure 58 – LPF 20M – BPSK receiver waveforms at Eb/N0 = 60dB

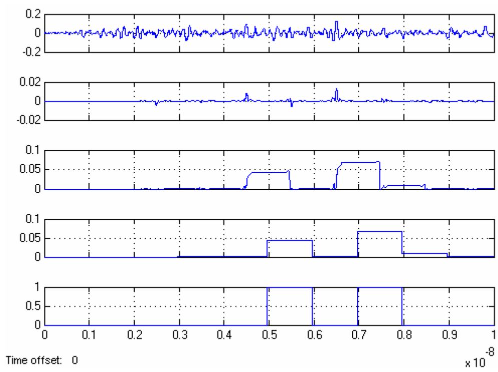

Figure 59 – LPF 20M – OOK receiver waveforms at Eb/N0 = 30dB

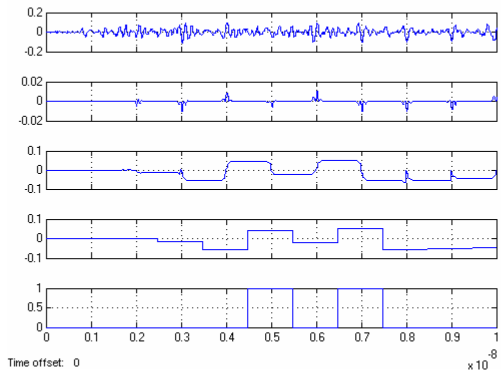

Figure 60 – LPF 20M – BPSK receiver waveforms at Eb/N0 = 30dB

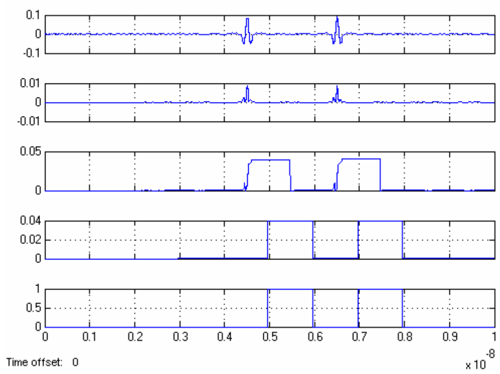

Figure 61 – LPF 2G – OOK receiver waveforms at Eb/N0 = 60dB

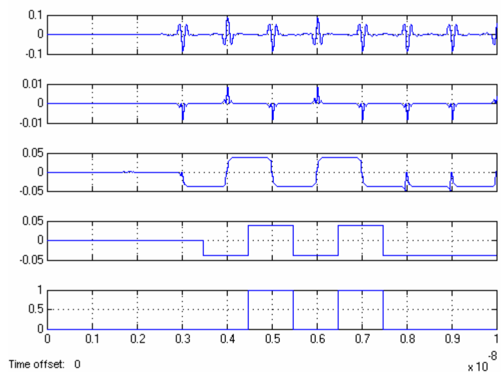

Figure 62 – LPF 2G – BPSK receiver waveforms at Eb/N0 = 60dB

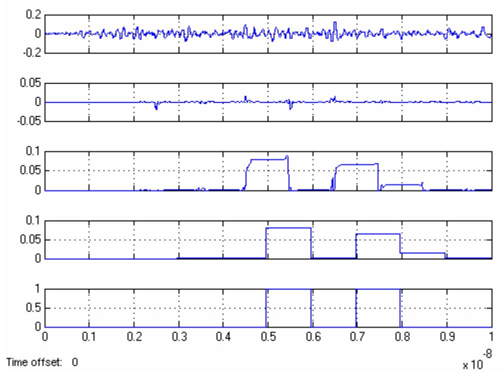

Figure 63 – LPF 2G – OOK receiver waveforms at Eb/N0 = 30dB

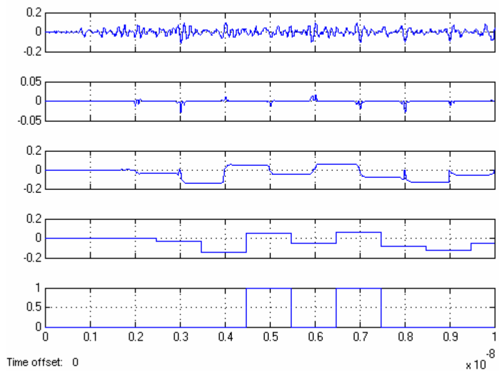

Figure 64 – LPF 2G – BPSK receiver waveforms at Eb/N0 = 30dB

Chapter 10

10 Conclusions

In this thesis, three architectures for UWB communications were proposed, OOK, BPSK and PPM. For all of them the BER was verified regarding the transmission channel noise and non-linear behavior. Some important conclusions can be made, but the most important ones are,

→ the analysis of UWB pulsed systems should be done in the time domain

→ the main source of errors is the noise

Other conclusions are related to the modulations used. The BPSK modulation is the modulation that presents better performance, since it is more immune to noise, OOK and PPM have similar performance, but the complexity of PPM is higher, mainly in the receiver part.

There are always improvements that could be done in the architecture and to improve the quality of the communications.

In [45], an algorithm to predict the Eb/N0 of the bits being received is proposed, by just looking at the output. This prediction is helpful to increase the pulse repetition frequency (PRF), which increases the bit energy (Eb) and subsequently the BER decreases. Although, this new possible feature will cause a decrease of the transmission rate, but could be important when the propagation and interference conditions are bad.

In a future work, the practical implementation is a very good challenge, because there are some difficulties focused here (mainly in the receiver), that would require some attention.

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