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Matti Hämäläinen

SINGLEBAND UWB SYSTEMS

ANALYSIS AND MEASUREMENTS OF COEXISTENCE WITH SELECTED EXISTING RADIO SYSTEMS

FACULTY OF TECHNOLOGY,
DEPARTMENT OF ELECTRICAL AND INFORMATION ENGINEERING,
UNIVERSITY OF OULU

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MATTI HÄMÄLÄINEN

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Analysis and measurements of coexistence with
selected existing radio systems

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Abstract

An inevitable trend in wireless communications is the requirement for higher and higher data rates. At the same time, location awareness requires high accuracy for positioning ability. One option fulfilling both of these challenges is the use of an ultra wideband (UWB) physical layer technology due to its extremely large inherent bandwidth. From the two possible solutions to generate UWB signals, this thesis is focused on the singleband approach. This technique is closer to the original idea of impulse radio transmission than the other recently proposed multiband UWB approach.

This thesis focuses on UWB coexistence with several selected radio systems; global positioning and cellular systems, and wireless local area networks. The topic was studied analytically and with experimental tests. The analytical part is divided into simulations and theoretical calculations. In the study, two different physical layer concepts, several modulation schemes and pulse waveforms have been used to find the best system performance under interference. From time hopping and direct sequence based approaches (TH and DS, respectively), the latter with binary pulse amplitude modulation was seen to outperform the former one in an interfered multipath channel if compared with bit error rate performance. Therefore, the theoretical calculations are addressed to the DS-UWB approach. The formulation defined makes it possible to rather easily calculate the upper bound for DS-UWB system performance in an AWGN channel and the results can be used to calculate reference bounds, for example, in receiver algorithm studies.

The experimental part of the work focused on link level coexistence measurements between UWB and either IEEE802.11b or 3G networks. UWB can cause harmful performance degradation on the victim system if there are unrealistic numbers of active interferers in close vicinity of the victim receiver. However, increasing the separation between the UWB interferer and victim to 40 cm, or 70 cm, in the case of WLAN and 3G, respectively, the impact is insignificant. It was also shown that the activity factor of the UWB transmitter has a great impact on the victim system's performance degradation. UWB activity factors of less than about 5% can be tolerated by the studied victim systems.

Keywords: bit error rate, cellular, data communications, interference, modulation, spread spectrum, wireless local area network

Preface

The research, on which this doctoral thesis is based on, has been carried out at the Centre for Wireless Communications (CWC), University of Oulu, Finland during the years 1999-2006 as a part of several ultra wideband (UWB) research projects.

I would like to express my deepest gratitude to my supervisor Professor Jari Iinatti, and Dr. Ian Oppermann, ex-director of the CWC, for their encouraging attitude and guidance throughout the whole research project. I would also like to thank Professor Kaveh Pahlavan, Worchester Polytechnic Institute, Worchester, MA, USA, being also partially with the Telecommunication Laboratory, University of Oulu, for the fruitful discussions we have had and the new ideas I have adopted from these meetings. Professor Matti Latva-aho, Director of the CWC, and Professor Pentti Leppänen, Head of the Telecommunication Laboratory, earn the warmest thanks for giving the subject and the possibility to do this work at the CWC.

I am most grateful to my reviewers, Assistant Professor Lorenzo Mucchi from the University of Florence, Italy, and Dr. Ben Allen from the University of Oxford, UK, for their careful examination of the manuscript that helped me to improve the overall quality of the thesis. Mr. Zach Shelby is acknowledged for proofreading the manuscript.

I also greatly appreciate my research team at the CWC, which is working towards common goals in several UWB projects; all of those researchers are doing a great job. I would like to name a few of them: Lic.Tech. Raffaello Tesi, M.Sc. Veikko Hovinen, M.Sc. Niina Laine, M.Sc. (stud.) Jani Saloranta, and M.Sc. (stud.) Ari Isola.

During the thesis preparation, the author has also been the advisor of one Licentiate thesis [1] and four Master theses at the CWC [2-5]. This has given another perspective to research work; the learning process has been two-way. Being also a technical program committee member in ultra wideband conferences, and a reviewer of several conference and journal papers, gave a wider view of the research topics in general.

I would like to thank all the other research colleagues at the CWC and Telecommunication Laboratory. The atmosphere at the CWC has been very encouraging. The proper computer facilities, as well as all the help by the supporting personnel and the administrative group (Elina Komminaho, Laila Kuhalampi, Pirjo Kumpumäki, Pekka Nissinaho, Hanna Saarela, Jari Sillanpää and Timo Äikäs) have left more time to concentrate on the research work.

The project funding provided by Elektrobit Ltd., the Finnish Defense Forces, the Finnish Funding Agency for Technology and Innovation (Tekes) (through the FUBS and CUBS projects), Nokia Oyj (through the FUBS project) and the Finnish Academy (through the CAFU project, project number 104783) are gratefully acknowledged. Their support to UWB research projects, and interest in the topic in general, has made this work possible. PJ Microwave, Oulu (currently Elektrobit Microwave Ltd.) is also acknowledged for the experimental part of the thesis. Without the UWB devices they have designed and built within the FUBS project, the field trial part of this study would have never been completed. This thesis partly relates to the European Commission funded PULSERS and ULTRAWAVES projects (EU-IST-506897 and EU-IST-2001-35189, respectively).

I would also like to thank the Foundation of the University of Oulu (Oulun yliopiston tukisäätiö), Nokia Foundation and HPY Research Foundation for their stimulating financial support. The finalization of the thesis has been done under the Infotech Oulu Graduate School.

Finally, yet importantly, I would like to thank my parents Mirja and Pekka for the support and encourage they have given to me throughout my life and studies, and Kaisu for all the love, joy and stimulation.

Oulu, April 10, 2006 Matti Hämäläinen

List of original papers

The thesis is based on the following nine articles, which are referred to in the text by their Roman numerals. All the listed papers have been conceived and written by the author of this thesis.

I Hämäläinen M, Iinatti J, Hovinen V & Latva-aho M (2001) In-band interference of three kind of UWB signals in GPS L1 band and GSM900 uplink band. Proc. 12th International Symposium on Personal, Indoor and Mobile Radio Communications, San Diego, CA, USA, D: 76 – 80.

II Hämäläinen M, Hovinen V, Tesi R, Iinatti J & Latva-aho M (2002) On the UWB system coexistence with GSM900, UMTS/WCDMA and GPS. IEEE Journal on Selected Areas in Communications 20(9): 1712 – 1721.

III Hämäläinen M, Tesi R, Iinatti J & Hovinen V (2002) On the performance comparison of different UWB data modulation schemes in AWGN channel in the presence of jamming. Proc. 2002 IEEE Radio and Wireless Conference, Boston, MA, USA: 83 – 86.

IV Hämäläinen M, Tesi R, Hovinen V, Laine N & Iinatti J (2003) Ultra wideband system performance studies in AWGN channel with intentional interference. Proc. International Workshop on Ultra Wideband Systems, Oulu, Finland, on CD: 5 p.

V Hämäläinen M, Tesi R & Iinatti J (2004) UWB co-existence with IEEE802.11a and UMTS in modified Saleh-Valenzuela channel. Proc. 2004 International Workshop on Ultra Wideband Systems joint with Conference on Ultra Wideband Systems and Technologies, Kyoto, Japan: 45 – 49.

VI Hämäläinen M & Iinatti J (2005) Interference and distance studies for DS-UWB. Proc. 2005 International Workshop on UWB Technologies, Yokosuka, Japan: 197 – 201.

VII Hämäläinen M & Iinatti J (2005) Analysis of jamming on DS-UWB system. Proc. IEEE Military Communications Conference, Atlantic City, NJ, USA, on CD: 6 p.

VIII Hämäläinen M, Saloranta J, Mäkelä JP, Oppermann I & Patana T (2003) Ultra wideband signal impact on the performances of IEEE802.11b and Bluetooth networks. International Journal of Wireless Information Networks, ©April 2004, Plenum Publishing Corp., USA: 201 – 210.

IX Hämäläinen M, Iinatti J, Oppermann I, Latva-aho M, Saloranta J & Isola A (2006) Co-existence measurements between WCDMA and UWB systems. IEE Proceedings – Communications 153(1): 153 – 158.

The research work included in the listed papers was carried out at the Centre for Wireless Communications in several ultra wideband related basic research projects. The work for Papers I–VIII was carried out within the framework of the Future Ultra Wideband Radio Systems (FUBS) project during 1999 … 2003 and Concepts for Ultra Wideband Radio Systems (CUBS) project during 2004 … 2005. Papers V and I are partly funded also by European Commission through ULTRAWAVES. Papers VI and VII have received partial funding from the Finnish Academy through the Concepts and Algorithms for Ultra Wideband Systems (CAFU) project. Paper IX is an output from CUBS but is partly funded by CAFU and the EU PULSERS project.

All the work has been carried out under the supervision of Prof. Iinatti, except Paper VIII, which was prepared under the supervision of Dr. Oppermann.

In addition to the listed original papers, the UWB research at the CWC was published in book [6] where the author of this thesis is one of the main editors and chapter writers. Numerous other conference papers where the author has been either the first author or co-author have been published. Those papers related to the thesis but not included as an original paper have been referred to within the discussion part.

List of symbols and abbreviations

A, A_j	amplitude
A_max	scaling factor
B_f	fractional bandwidth
B_R	resolution bandwidth
$B_\mathrm{-3dB}$	-3 dB bandwidth
$B_\mathrm{-10dB}$	-10 dB bandwidth
$B_\mathrm{-20dB}$	-20 dB bandwidth
C	channel capacity
c_p	momentary code phase
c_w	momentary code word
d_k	k-th data bit
D_c	duty cycle
d_k	k-th data bit
E_b	energy of bit
E_b/N_0	signal-to-noise ratio
$(E_\mathrm{b}/N_0)_\mathrm{req}$	required signal-to-noise ratio
E_c/N_0	carrier-to-noise-power ratio
f	frequency
f_c	center frequency
f_h	the higher frequency point
f_j	center frequency of the interference (jamming)
f_l	the lower frequency point
f_m	frequency of the modulating signal
G	processing gain
G_DS	processing gain for direct sequence UWB system
G_TH	processing gain for time hopping UWB system
G_rx	receiving antenna gain
G_tx	transmitting antenna gain
J	jamming power
j	index
k	index

L	length of a pseudo random code, number of slots in a frame
L_{imp}	implementation loss
L_{pl}	path loss
M	link margin
n	order of the Gaussian pulse derivative
N	number of pulses used to send one data bit, number of used rake fingers
N_{j}	power spectral density of the interfering signal
N_0	one sided power spectral density of white Gaussian noise process
$NP_{10\mathrm{dB}}$	number of propagation paths whose energy is within 10 dB of the maximum energy
$NP_{85\%}$	number of paths who are conveying 85% of the propagating energy
P	signal power
P_{av}	average equivalent isotropic radiated power
P_{b}	bit error probability
$P_{\mathrm{n}}(f)$	power spectral density
P_{peak}	peak equivalent isotropic radiated power
P_{rx}	received power
P_{tx}	transmitted power
R_{d}	data rate
$S(\cdot)$	power spectral density
$s(t)$	transmitted signal
t	time
T_{c}	chip length
T_{d}	bit length
T_{f}	frame length
T_{p}	pulse width
$V_{\mathrm{p\text{-}p}}$	peak-to-peak voltage
W	bandwidth
W_{NB}	bandwidth of narrowband system
$W(f)$	amplitude spectrum
$w(t)$	pulse waveform
x, x_0	time variables

α	attenuation factor
δ	Dirac's delta function
Δf	frequency deviation
$\Delta\omega$	deviation of the angle frequency
ϕ	modulation index
θ	phase
θ_0	arbitrary but time-independent constant phase
σ	standard deviation
τ_{m}	mean delay
τ_{res}	delay resolution
τ_{rms}	rms delay
ζ	power scaling factor
ω_{m}	angle frequency of the modulating signal

A-rake	all rake receiver
AC	absolute combining
AF	activity factor
AWGN	additive white Gaussian noise
BER	bit error rate
BLER	block error rate
BPM	bit position modulation
BPPM	biorthogonal pulse position modulation
BPSK	binary phase shift keying
BT	Bluetooth
CEPT	European Conference of Postal and Telecommunications Administration
CGN	colored Gaussian noise
DAA	detect and avoid
DARPA	Defense Advanced Research Project Agency
dc	direct current
DH	delay-hopped
DHTR	delay-hopped transmitted-reference
DS	direct sequence
EC	European Commission
ECC	Electronic Communications Committee
EGC	equal gain combining
EIRP	equivalent isotropic radiation power
ERO	European Radiocommunications Office
ETSI	European Telecommunications Standards Institute
EU	European Union
FCC	Federal Communication Commission
FM	frequency modulation
FNPRM	Further Notice of Proposed Rule Making
FWA	fixed wireless access
GPR	ground penetrating radar
GPRS	general packet radio service
GPS	global positioning system
GSM	global system for mobile communications
IEE	Institution of Electrical Engineers
IEEE	the Institute of Electrical and Electronics Engineers, Inc.
ITU	International Telecommunication Union
LDC	low duty cycle
LOS	line-of-sight
MAC	medium access control
MO&O	Memorandum Opinion and Order
MRC	maximum ratio combining
NLOS	non-line-of-sight
NOI	Notice of Inquiry
NPRM	Notice of Proposed Rule Making
NTIA	National Telecommunication and Information Administration
OFDM	orthogonal frequency division multiplexing

OOK	on-off-keying
OSI	open systems interconnection
PAM	pulse amplitude modulation
PE	power estimation
PHY	physical layer
PM	phase modulation
PPAM	pulse position amplitude modulation
PPM	pulse position modulation
P-rake	partial rake receiver
PRF	pulse repetition frequency
PRN	pseudo random noise
RSCP	received signal code power
PSD	power spectral density
PSM	pulse shape modulation
QPSK	quadrature phase shift keying
R&TTE	Radio and Telecommunications Terminal Equipment
RAN	radio access network
RSSI	received signal strength indicator
RF	radio frequency
RMS	root mean square
RO	the First Report and Order
SE	spectrum engineering
SG	study group
SINR	signal-to-interference plus noise ratio
SIR	signal-to-interference ratio
SLC	square-law combining
SNR	signal-to-noise ratio
S-rake	selective rake receiver
SRD	step recovery diode
SS	spread spectrum
SSA	soft-spectrum adaptation
SV	modified Saleh-Valenzuela channel model
TDMA	time division multiple access
TG	task group
TH	time hopping
TR	transmitted-reference
TX	transmitter
UMTS	universal mobile telecommunication systems
USB	universal serial bus
UWB	ultra wideband
UWBFM	ultra wideband frequency modulation
WBAN	wireless body area network
WCDMA	wideband code division multiple access
WG	working group
WLAN	wireless local area network
WPAN	wireless personal area network

Contents

1 Introduction

"Chance of finding something unconventional is increased by studying something that is as different as possible from the conventional."
H.F. Harmuth

1.1 Background

An inevitable trend in wireless communications is the need for higher and higher data rates in upcoming applications. Another trend is the need for ubiquitous access to the backbone network and location based information delivery. All this requires larger bandwidths and higher center frequencies due to the lack of spectrum available in the lower frequency bands. In addition, there is a need for more accurate positioning capabilities. The forthcoming systems should also operate seamlessly with the existing radio systems.

Currently, short-range wireless local area network (WLAN) applications are often based on existing IEEE (the Institute of Electrical and Electronics Engineers, Inc.) standards, like IEEE802.11a,b,g,h [7] or Bluetooth (i.e., IEEE802.15.1) [8]. For data transmission, these systems are exploiting wideband signals whose bandwidth is much wider than that needed by the used data rate and modulation technique. If the signal bandwidth is much smaller than the centre frequency, we are dealing with narrowband signals. In that case, also the modulation does not increase the bandwidth much. However, when we are dealing with wideband signals, the transmitted bandwidth is exceeding the coherence bandwidth of the channel and the channel is frequency-selective. Then the system is capable to distinguish different multipath components. In a frequency-selective channel, the transmitted signal components are affected by different attenuations and phase shifts when passing through the channel. Ultra wideband (UWB) technology is one candidate for a physical layer technique for new wireless standards, such as IEEE802.15.3a (Task Group 3a – WPAN[1] Alternative High Rate PHY[2]) and

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[1] WPAN = Wireless Personal Area Network

[2] PHY = Physical Layer

IEEE802.15.4 (Task Group 4a – WPAN Alternative Low Rate PHY) [8] that could increase the recent data rates or the positioning accuracy in the future.

Time-domain electromagnetic studies have been conducted as early as 1962, when different transient phenomena in microwave networks were solved [9]. In the sixties, so-called ultra wideband technology has been developed for military radar applications [10]. Radars could utilize the technology due to its extremely large inherent bandwidth that makes fine object recognition possible due to the very accurate time and distance resolution provided by the UWB signal. The first commercial ground penetrating radar (GPR) was invented in 1974 [11]. In 1975, a technology named a baseband radar or free space time domain reflectometry was introduced in [12] for applications such as pre-collision sensing, collision avoidance and docking from about 1.5 m to 1.5 km with a pulse having a 200 V amplitude driving an antenna. Obviously, it was not yet time for high volume communications applications due to the high signal strengths. In [9], a proposal for the utilization of baseband pulse techniques for short-range wireless communications was given. Finally, in the late 1970’s, the time had come to exploit the pulse technology in low power applications in addition to the original high power radars. Still, the development of the technology was quite slow.

During the second half of the 1990’s, ultra wideband technology was adopted for civil applications, such as through-material radars. At the end of the 1990’s, the technology was finally recognized as an option for data communications. The term “impulse radio” was raised, and nowadays it is a commonly acknowledged technology amongst the others, for short-range data communications and localization solutions, but it is still without a global standard. UWB systems may use a frequency band of several GHz. It is also possible to operate such systems license-free in the frequency regions allocated to other technologies as an underlay basis. Due to the extremely large inherent bandwidth of the UWB signal, the spectrum is naturally overlapping with other existing radio systems.

Communication systems based on impulse radio and impulse radars both utilize very short pulses in transmission that results in an extremely large spectrum occupation. The pulse width used in these systems is typically less than one nanosecond, currently approximately 200 … 300 ps. For data communication applications, this transmission method was also classified as a pulse modulation technique because the data modulation was originally introduced by pulse position modulation (PPM) [13]. Later, other modulation schemes such as pulse amplitude modulation (PAM) [14,15], on-off keying (OOK) [16] and pulse-shape modulation (PSM) [17] have been applied to UWB. A combination between PPM and PAM is proposed in [18], and the proposed method does not generate a line spectrum. If line spectrum components are arising, the transmitted signal is easier to intercept. Another disadvantage of the line spectrum is that it passes through the bandpass filters if it fits in the same band. The overall effect is stronger performance degradation of the victim receiver when compared to the case where only the continuous spectrum is available.

Typically, a singleband UWB signal is noiselike due to the very large bandwidth and low transmitted power level. This makes its interception and detection quite difficult. This phenomenon could have been utilized in secure military applications. During the years, a transmission technique making use of an extremely large bandwidth has been referred to as “impulse”; “short-pulse”; “non-sinusoidal”; “carrierless”; “time domain”;

"super wideband"; "fast frequency chirp"; "large-relative bandwidth" and "monopulse" [11,19]. For UWB radar terminology, quite extensive lists can be found from [20,21].

Evident spectral overlapping gave the motivation to study UWB coexistence issues, which is the major theme throughout this thesis. The term "coexistence" is used when different types of radio systems can simultaneously operate in the same area and in the same frequency band without causing significant degradation to the other systems' performance. However, if the simultaneous operation causes performance degradation, then one is dealing with an interference problem.

The possibility of utilizing UWB in an underlay manner results from the low power spectral density (PSD) that UWB signals have. Just like in conventional spread-spectrum (SS) systems, the actual bandwidth used to transfer the information through the media is much larger than what is required by the used modulation scheme [22]. In UWB transmission, the spectrum is spread using very narrow pulse waveforms that are lasting less than 1 ns. The conventional direct sequence (DS) SS system is based on the same approach but the spreading codes do not reach as short chip lengths as UWB pulses do. Nowadays DSSS systems, such as the global positioning system or wireless local area network IEEE802.11a, have a bandwidth of tens of megahertz at maximum, which is leading to a chip rate that is half the null-to-null bandwidth of the signal. Typically, the chip waveform also differs from the one used in UWB applications. A SS chip waveform can be, e.g., a raised cosine pulse [23].

For the time being, only the USA has existing regulations and frequency bands allocated for different UWB systems. These regulations are given by the radio frequency regulation authority, the Federal Communications Commission, FCC [24,25]. In addition, inside UWB technology, there are two competing approaches. The original, and the simpler one, is called singleband UWB. This is a carrierless baseband transmission technique, which is based on the transmission of very narrow pulses, thus it is an impulse radio. The spectral properties are related to the transmitted pulse waveform. The other competing technology is multi-band UWB, which utilizes several channels that are wider than 500 MHz and are exploiting sub-carriers. This approach follows the multi-carrier or orthogonal frequency division multiplexing (OFDM) techniques that are used, e.g., in IEEE802.11a wireless local area networks [26] and in digital video broadcasting systems [27].

Based on signal theory, the spectrum is wider, the shorter are the transmitted pulses are [28]. An ideal impulse, like Dirac's delta function, generates a flat frequency spectrum, thus the signal spectrum covers the frequency range from -∞ to +∞. Mathematically, Dirac's delta function $\delta(x)$ is defined by [29]

$$\delta(x - x_0) = \begin{cases} 0 & ,\text{when } x \neq x_0 \\ \infty & ,\text{when } x = x_0 \end{cases} \quad \text{and} \qquad \qquad (1)$$

$$\int_{-\infty}^{\infty} \delta(x)dx = 1.$$

A valuable feature of Dirac's delta function is its shifting property, thus it can be used to select only one sample amongst the mass of samples, as indicated by [29]

$$\int_{-\infty}^{\infty} \delta(x - x_0) f(x) dx = f(x_0), \tag{2}$$

where $f(x)$ and $f(x_0)$ represent the values of function f at time instants x and x_0, respectively.

Discontinuous transmission in UWB applications using very short pulses can be exploited to reduce the received noise energy at an undesired receiver. This property is behind the term *impulse radio*. The use of discontinuous transmission decreases the average noise at reception but also requires higher pulse energy to be used to maintain reliable detection. However, impulse radio is not just an example of a UWB system but is also a very simple realization of it. The other methods of generating UWB signals will be introduced in Section 2.5.

In addition to the underlay usage with other existing radio systems, time hopping UWB systems can offer good immunity to multipath propagation because of the low duty cycle used in the transmission. In that case, the multipath delay of the channel is shorter than the pulse repetition time, and therefore inter-pulse interference is not introduced. This feature, however, limits the maximum achievable data rate. The UWB signal bandwidth is also higher than the channel coherence bandwidth providing extra frequency diversity for reception. Due to the low duty cycle, the transmission includes silent periods, and therefore, the average power level is decreased. Because of the high signal bandwidth, UWB systems can also be used in high precision ranging, localization and tracking applications, as well as in other location-based services. The wide UWB bandwidth makes it possible to distinguish multipath more accurately than in the other existing systems. Currently, the use of wall and through-wall imaging systems is restricted by the FCC only to law enforcement, fire and rescue organizations, to scientific research institutions, to commercial mining companies and to construction companies [24]. UWB applications can also be found in medicine and the technology has been proposed for wireless monitoring of the human body. In [30], the history of UWB development is also discussed from a communication system point of view. In [24] and [25], the frequency band of around 24 GHz is allowed for UWB vehicular radar applications.

When the interests towards UWB increased, the ideas were first discussed in the regular sessions in the major conferences, including IEEE events. The first open forum dedicated only for short pulse (thus ultra wideband) issues was organized in Los Alamos in 1991 [31] but the presentations were covering only high power radar applications. Since then, the topic has been covered in “High-power, short-pulse electromagnetics” conference series [32-37]. The first UWB conference dedicated to low-power applications was organized in Washington, D.C. in 1999 [38], having continued under the name “IEEE Conference on Ultra Wideband Systems and Technologies (UWBST)” in 2002 and 2003 [39,40]. The first “International Workshop on Ultra Wideband Systems (IWUWBS)” was organized in Oulu, Finland in 2003 [41], and in 2004, these two conferences were jointly organized in Kyoto, Japan [42]. In 2005, the name of the merged event was changed to “2005 IEEE International Conference on Ultra-Wideband”, and the conference took place at Zurich, Switzerland. This conference series will continue on Sep

2006 in the Boston area, USA. In 2004, the “IEE Seminar on Ultra Wideband Communications Technologies and System Design” was organized in London. The forthcoming UWB event by the IEE, “IEE Symposium on Ultra Wideband Systems, Technologies and Applications” will be held in April 2006 [43]. New UWB events, such as the “International Workshop on UWB Technologies”, Yokosuka, Japan, Dec 2005 [44], “Workshop on Ultra Wide Band for Wireless Internet”, Budapest, Hungary, Jul 2005 [45], “International Workshop Networking with Ultra Wide Band”, Rome, Italy, Jul 2005 [46] and the 1st IEEE/CreateNet International Workshop on “Ultrawideband Wireless Networking”, Oct, 2005 [47] have frequently been arising, thus [46] was the second one in order.

In addition to the conferences by the IEEE, IEE and others, there are also dedicated journal issues for UWB. The rising interests towards UWB technology can also be seen from the number of UWB dedicated textbooks that have come out recently, such as [6,48-51]. A good start to seek out information about UWB technology is [52], which includes an extensive list of historical references on the subject.

This thesis does not cover or take stand to the commercial approaches or products available at the time of writing the thesis. The focus is limited only to single band UWB system research.

1.2 Motivation

Recently, ultra wideband research has globally reached a big boost as shown by the conference list shown above. For example, in Europe there are several ongoing UWB related projects funded by the European Commission. The main contribution to this thesis has been completed in the Finnish national UWB projects that were carried out at the Centre for Wireless Communications at the University of Oulu. However, part of the work has also been done under the projects funded by the European Union.

The goal of this thesis is to study coexistence issues of different UWB communication system concepts that can be adopted for indoor, short-range high data rate applications. The thesis is focused on simple UWB transceiver structures that allow the manufacturing of cheap and high volume devices. The demand of inexpensive and disposable devices excludes multiband UWB from the study. The work has been completed both via simulations and theoretically. In addition, during the work, experimental coexistence measurements have been carried out and the results are included in the thesis.

Since the operational environment for UWB is extremely wide, the studied interference scenarios have been limited to reasonable numbers, covering the most relevant systems, which came from the author’s subjective selection. The selected systems include wireless local area networks, cellular mobile phones and the global positioning system. It should be noted, that these systems have also been selected by frequency regulation authorities as potential victim systems, e.g., in [53]. In addition, multiple access interference can be seen as an independent category and has been excluded from the studies.

For the analytical part, the aim was to study UWB system performance in an additive white Gaussian noise (AWGN) channel as well as in a multipath channel by simulation.

The theoretical part of the work focused on the AWGN channel that indicates the upper bound for UWB system performance. In a multipath fading channel, the AWGN performance cannot be achieved without any additional coding methods and therefore AWGN results can be used as a simple performance limit. In addition, the simulator verification is typically done against the theoretical results in AWGN, which are simple to derive and reported in the literature.

The coexistence results are extremely important, e.g., in the ongoing UWB standardization and regulation processes worldwide, and in UWB system development in general. If one could include information about system performance in the presence of interference in the system design, the harmful effects, for example, could be removed or countermeasures could be implemented. The aim of the thesis was to study how different modulation schemes, pulse waveforms, or physical layer concepts affect the coexistence of UWB and other existing radio systems. This thesis omits detailed ultra wideband radio channel measurements and modeling discussion, which the author has also been involved. Neither are the higher open systems interconnection (OSI) layers, like medium access control (MAC), or network layers, nor channel capacity touched within this work. All the listed topics are important but the focus of the thesis is on the coexistence issues for a single-user case, without going into interference mitigation aspects. The single-user case is a simple example of a more complex but realistic multi-user system.

In the multi-user case, the time division multiple access (TDMA) method is used to separate different users. In that case, the transmission instant differs user by user. Multipath propagation and asynchronous transmission decrease the orthogonality between the users, and therefore cause multiuser interference. In a DS-UWB system, all users can transmit at the same time but the user separation is carried out by using different pseudo random codes, like in a conventional spread spectrum system [23,54]. Again, orthogonality between the different users will decrease due to the multipath.

1.3 Author’s contribution

The open literature presents different methods for studying UWB coexistence mechanisms applied to different radio systems. A literature review is given as background for the thesis to point out the current interests on the topic.

The main area of the research discussed in this thesis covers ultra wideband signal coexistence with other radio systems. The study has been carried out by analysis and experimental coexistence measurements. The analytical part is divided between simulations and theoretical calculations.

Comprehensive link level simulations have been performed to discover the impact of several interference sources on the performance of different UWB physical layers. The comparative measure was bit error rate (BER). In addition, the in-band powers caused by several UWB signal structures are calculated for selected victim systems. The Matlab simulator developed in the FUBS project has been used in all the simulations.

The author of the thesis has been involved in the simulator development by specifying its structure, creating blocks for the simulator, defining the scenarios for simulations, carrying out lots of simulations, and analyzing the results. In addition, the author was the main contributor for the conclusions, and wrote and presented the conference publications used as original papers in this thesis. The author has also been the main author of the journal papers included in the thesis as original papers.

Based on the simulations, Papers I – V have been created. Previously, the studied UWB system had, in most of the cases, focused only on one UWB PHY structure at a time. In this study, using similar environmental assumptions, the UWB performance has been studied for different PHY approaches (different multiple access and modulation schemes), which both affect interference tolerance. The interference issues are discussed in both ways: from UWB to other radio system, and vice versa.

The simulated results are verified through theoretical formulation for the singleband UWB case. The fact that, in the presence of interference and a multipath channel a direct sequence UWB system outperforms the corresponding time hopping approach, predefined the analytical study to DS-UWB. The practical formulations are defined to calculate bit error rates in the presence of interference, and the results are shown in Papers VI – VII. The given formulation makes it very convenient to estimate the upper bound performance level for DS-UWB in AWGN and it can be used as a reference limit in system design. The author has derived the formulations and verified them, as well as being the first author of the papers and presenting them in front of the scientific audiences.

The UWB impact on selected victim radio systems has also been studied through measurements, which gave a wider approach to the topic. The author planned the measurement scenarios, analyzed the results and was the first author in the related publications. Coexistence measurement results between UWB, WLAN IEEE802.11b and Bluetooth are presented in Paper I , and between UWB and 3G cellular in Paper IX.

This thesis merges different approaches of interference studies into one report. Nevertheless, the author’s research group has carried out the supporting work and is greatly appreciated for that.

1.4 Outline of the thesis

The focus discussed in this thesis is UWB coexistence with several commercial communication applications. Chapter 2 gives a summary of a literature survey about ultra wideband technologies and the coexistence issues applied to the data communications. In Chapter 2, also an overview of the current UWB standardization process is given. Chapter 3 introduces the framework utilized within the study. Chapter 4 gives a summary of the original papers. Finally, Chapter 6 will conclude the thesis. The original papers are collected in the appendices, and they could be divided into three individual groups; simulation (I – V), theoretical (VI – VII) and experimental approaches (VIII – IX), respectively.

Simulation results give the widest view of different UWB physical layer techniques, theoretical calculations are focused on the technique that was found to outperform the other studied approaches and the experimental work has been carried out using non-commercial UWB interference sources. It should be noted that from the two main UWB categories, the thesis is focused on the single band approach and multiband UWB is only shortly introduced.

2 State of the art of ultra wideband technology

In conventional communication applications, the transmitted information bandwidth is the one provided by the modulation scheme, and we are then talking about narrowband communications. In wideband communications, the information signal is intentionally sent using a larger bandwidth than is required. In wideband applications, the transmitted bandwidth is also larger than the coherence bandwidth of the channel, which allows one to distinguish between multipaths [23]. This kind of transmission is called as spread spectrum communications due to the additional spectrum utilization.

Typically, this spectrum spreading is achieved by modulating the information data bit with a pseudo random code having a higher data (chip) rate, or by using a frequency-hopping approach [22]. These methods could also be merged into a hybrid solution [55]. Ultra wideband techniques allocate an even larger part of the frequency spectrum than conventional spread spectrum systems. In time-hopping impulse radio, the signal energy is spread over the frequency domain using extremely narrow pulses whose waveform can also be used to define the spectrum allocation. Pulse shaping using filters, or passing the signal through an antenna, introduce spreading that can be seen also in the time domain. The peculiarities of UWB signal characteristics compared to narrowband and wideband signals can be seen from Fig. 1. One could imagine the same energy under each semi-ellipse. From this large spectrum utilization, the PSD of the UWB signal is very small and noise-like.

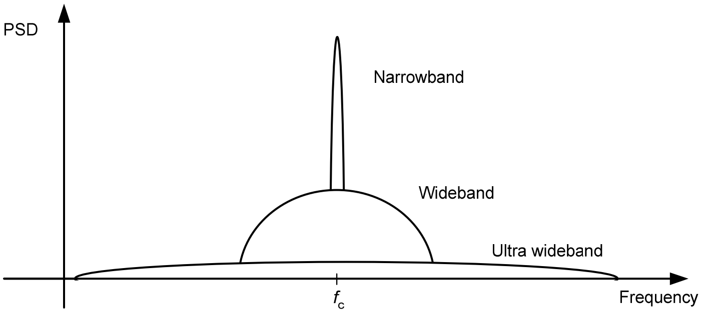

Fig. 1. Power spectral densities of narrowband, wideband and UWB signals.

The first wireless communication link by Hertz in 1887 [56] was actually based on impulse radio technology due to the spark gap transmitters used. The information signal was transmitted using short pulses akin to impulse radio nowadays. The first trans-Atlantic wireless link was established by Marconi on Dec. 12, 1901 [56]. Again, the radio was based on a spark gap transmitter, i.e., impulse radio. Shorter link distances were achieved in previous years. In the late 1960's, Harmuth, Ross and Robbins launched work towards real UWB applications [11]. The first systems utilizing UWB technology were radars. US Patent 3,728,632 by Ross in April 1973 [57] has been seen as a start for the UWB communication era, as stated in [11], which is also an excellent survey of UWB history. In addition, [11] gives an extensive reference list for early UWB publications, especially in the field of high power radars. Reference [58] gives a survey of UWB technology utilization in short-range communications. The future perspectives of UWB technology are discussed in [59].

In this Chapter, the focus of the literature survey carried out in more detail for UWB data communication applications. First, short summaries of the standardization process and the overall UWB technology development are given.

2.1 Status of the standardization process

The term "ultra wideband" was first adopted by DARPA (Defense Advanced Research Project Agency, USA) in 1990 [60]. At the same time, a definition of the UWB technology was first given. Based on DARPA's work, a signal was seen as an UWB signal if its fractional bandwidth, B_f, was greater than 0.25. B_f was defined by [19]

$$B_f = 2\frac{f_h - f_l}{f_h + f_l} \ , \tag{3}$$

where f_h and f_l are the higher and lower -10 dB frequencies, respectively, e.g., the frequencies where the level of the PSD has decreased 10 dB from its maximum value. Based on [19], the signal is classified as narrowband if $B_f < 5\%$ and wideband if $5\% < B_f < 25\%$, where the upper limit came from DARPA's old UWB definition in [60]. Currently, the lower limit for UWB fractional bandwidth is set to 20% [24], as discussed next.

In the USA, the process towards the regulation of civilian UWB applications was started in the late 1990's. The FCC released the *Notice of Inquiry* about UWB technology, NOI, [61] to collect information and background knowledge about UWB technology to help the standardization process. This call was publicly open to all interested parties. Based on the responses to NOI, the FCC prepared the first draft for UWB regulation. This document was called a *Notice of Proposed Rule Making*, NPRM, [62] and it was released in 2000. Again, public comments were requested. The FCC encouraged different parties to submit theoretical and experimental results on UWB technology and, especially, its suitability to be used in the frequency bands allocated to other radio applications. Thus, discussions about coexistence issues arose. After the second public commenting round in February 2002, the FCC finally released the first radiation limits for UWB applications to be used on an unlicensed basis. The complete version of *The first Report and Order*, RO [24] was released in April 2002. The RO gave permission to commercialize the technology if the UWB radiation fits the given radiation mask which was a compromise between the FCC and National Telecommunication and Information Administration, NTIA, and seemed to be more political than technical. There were amendments after the public responses to [24] called *Memorandum Opinion and Order and Further Notice of Proposed Rule Making,* MO&O and FNPRM [63] released on February 2003. At the end of 2004, a revisited version of the RO, *Second Report and Order and Second Memorandum Opinion and Order* was released [25]. One specialty of [25] is that it allows any kind of system, regardless of the bandwidth, to operate under the UWB standards.

The standardization work is globally controlled by the International Telecommunication Union (ITU) [64]. Within its Study Group 1 (SG1) it has set a specific task group (TG), called TG 1/8, to coordinate the UWB activities within the other ITU-R SGs (R stands for radiocommunications). TG 1/8 has four study areas (working groups); WG1 (UWB characteristics), WG2 (compatibility studies), WG3 (frequency management framework) and WG4 (measurement techniques) [65]. The work of TG 1/8 ended in its sixth meeting in Geneva, Switzerland, October 12-20, 2005. The aim of TG 1/8 was not to make changes to ITU's radio regulations but to give recommendations. TG 1/8 output four new draft documents and one new draft report in concensus, e.g., no voting was needed in the document finalization [66].

The European Commission (EC) mandated CEPT (European Conference of Postal and Telecommunications Administration) to identify and develop harmonized standards for UWB applications covering the whole European Union (EU) area. The first mandate was given on April 7, 2004 and the second on June 6, 2005 [67]. The European Communications Committee (ECC) has studied the possibility to allow the use of UWB on an unlicensed basis. The first public inquiry [53] was released in October 2004 with the commenting deadline at the end of the same year. Reference [53] also listed 15 different victim systems in three categories selected for coexistence studies. The general categories are; mobile and portable stations, fixed outdoor stations and satellite/aeronautical on-board receivers. Authorization for the process was given by the European Telecommunications Standards Institute (ETSI). In Europe, the most dangerous threat for UWB market expansion might be that UWB has not been classified as a radio service in the radio regulations. If having this status, the frequency authority should handle the UWB technique differently than as a source of unintentional radiation. The system defined as a radio service has precisely defined system parameters, not only a limiting mask, which under it has to operate. The European standardization organizations and the involved parties are presented in Fig. 2 [49]. The consolidated UWB radiation limits presented in [53] are shown in Fig. 3 together with the FCC indoor mask, which will be described in Section 2.2 in more detail. However, the consolidated mask is not a standard proposal but it collects the interference limits from the existing system's point of view, thus being very complex.

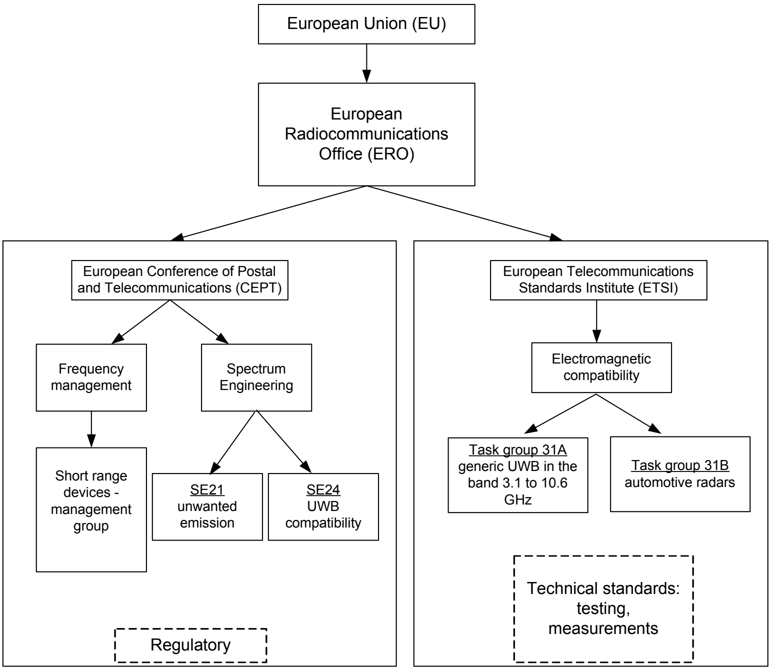

Fig. 2. Structure of the regulation and standardization authorities in Europe.

On September 15, 2005, the ECC introduce a radiation mask proposal [68] that is not as restrictive to UWB than the previous one shown in Fig. 3 [53]. The proposed mask is given in Fig. 4. The report introduced a new feature for UWB devices, the so-called detect and avoid (DAA) mechanism. The spectral mask shown in Fig. 4 assumes that DAA is used. Regulations in [68] allow the use of -41.3 dBm/MHz (or -45 dBm/MHz) within the band 3.1 … 4.95 GHz if the activity factor is 5% or less over one second, or 0.5% over one hour. The activity factor is defined as the ratio the transmitter is active within a certain time frame. The maximum peak equivalent isotropic radiation power (EIRP) is calculated within the 50 MHz band and is 40 dB higher than the mean EIRP shown in the figure. The use of the frequency band 4.2 … 4.8 GHz should be allowed until the end of June 2010 with a -41.3 dBm/MHz limit according to the same proposal. After that, the upcoming 4G systems might create new restrictions.

The use of DAA allows UWB systems to detect if there is other signal energy on the air at the same time and on the same frequency band. If such traffic is detected, the UWB system should decrease its own power level. The proposal also encourages further studies of possible interference mitigation techniques to improve the coexistence ability of UWB systems in respect to other radio systems.

Especially in the United Kingdom, the local regulator Ofcom has released a proposal [69] and a sequel on September 2005 for the European UWB regulation process. The proposed radiation mask is redrawn in Fig. 4 [70]. In their proposal, Ofcom concluded that the DAA mechanism has to be used in the band between 3.1 GHz … 4.2 GHz. If DAA is used, the maximum radiation level could be -41.3 dBm/MHz. Without DAA, the mask is set to -85 dBm/MHz, as shown by *Choice 2*, that determines the radiation limit for the latter case (without DAA). In any case, the maximum acceptable radiation power level with DAA is set to -45 dBm/MHz within a band from 3.1 GHz to 5 GHz that is depicted by *Choice 1*. According to the same proposal, UWB devices should be prohibited on board, aircrafts and outdoor fixed services.

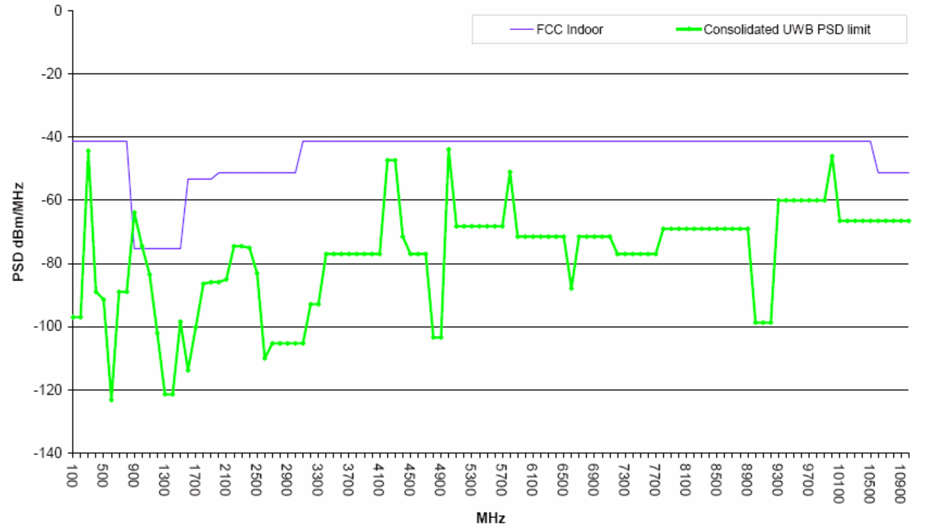

Fig. 3. Consolidated UWB radiation limit by the ECC compared to the FCC indoor mask.

The following regulatory progress in Europe has been reported in [67,71] which are updated versions of [68]. Based on [67], CEPT might not give a restrictive definition for UWB, as is the case in the USA. The goal is to define a generic regulation, which allows the use of devices operating under the EU Radio and Telecommunications Terminal Equipment (R&TTE) directive [72]. Rather than technology or applications, the focus in the regulation should be devices, and a designated frequency band only for UWB will not be admitted. In [73], it is stated that the current draft does not include the requirement for any mitigation technique (DAA or low duty cycle, LDC) due to their immature state. The agreement from the ECC's 12th meeting was that between 4.2 … 4.8 GHz, no interference avoidance mechanism is needed [74] unlike that proposed by the ECC, e.g., in [67]. However, the radiation limits in [71] are more stringent than the corresponding limits by the FCC. The following quotation is the UWB definition by ITU-R TG 1/8 [71]: "*Ultra-wideband technology*: *technology for short-range radiocommunication, involving the intentional generation and transmission of radio-frequency energy that spreads over a very large frequency range, which may overlap several frequency bands allocated to radiocommunication services. Devices using UWB technology typically have intentional radiation from the antenna with either a −10 dB bandwidth of at least 500 MHz or a −10 dB fractional bandwidth greater than 0.2.*" The definition is similar to the prevailing FCC UWB definition to be described in Section 2.2. Public consultation for comments was closed on December 24, 2005. The final ECC decision is expected in March 2006 [66]. The Finnish communications regulatory authority (Ficora) supported the *Temp 12 Rev. 1* mask from Fig. 4 in its comment to the ECC on Dec 23, 2005 [75]. In addition, Ficora proposed that peak EIRP should be calculated using a 3 MHz bandwidth rather than 50 MHz, which is used in the ECC and FCC proposals [75].

Ecma International, an industry association dedicated to the standardization of information and communication systems, accepted its UWB standard that is based on multiband (WiMedia) technology in [76]. As quoted in [76], “*This Ecma specification is not intended to represent the regulatory requirements of any country or region.*” However, Ecma’s support for multiband-based UWB technology instead of the singleband, impulse radio type approach, is very strong while specifying physical and medium access control layers for coming UWB devices. [76] specifies industrial standards for UWB devices obtaining data rates of 53.3 Mb/s, 80 Mb/s, 106.7 Mb/s, 160 Mb/s, 200 Mb/s, 320 Mb/s, 400 Mb/s, and 480 Mb/s. Currently, the Ecma standard applies only to the U.S.

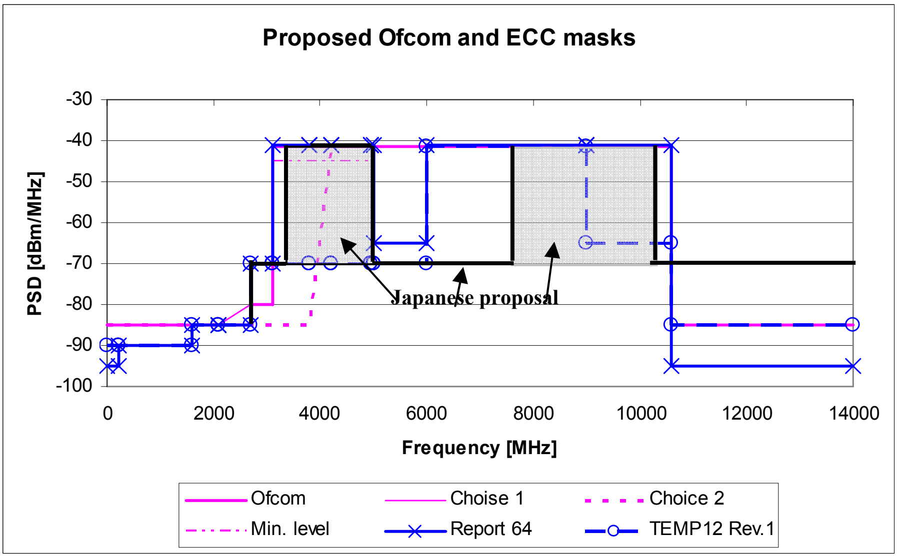

Fig. 4. The UWB mask proposal by the Ofcom and ECC. The Japanese proposal is depicted in black. The left grey box assumes DAA and the left box is without DAA (Japan).

In Japan, the Japanese Radio Administration has been examining the FCC ruling for wireless systems, which are coexisting with UWB. The Modeling Group, which is responsible for making a model of UWB interference, has given a proposal for UWB applications. The limit of the transmission power from 3.1 … 10.6 GHz follows the FCC ruling, and outside that frequency band, it follows the rule of very low power wireless systems. The model has been submitted for review to the other study groups, such as the cellular or satellite groups. Those groups are currently working on the investigation of possible interference sources to their dedicated wireless systems. The updated Japanese proposal is discussed in [77]. The preliminary approval of the FCC limits within the bands of 3.4 ... 4.8 GHz and 7.25 ... 10.25 GHz for indoor devices is given. A detect and avoid mechanism is proposed to be used between 3.4 ... 4.8 GHz. With DAA, the FCC -41.3 dBm/MHz limit could be accepted. Without DAA, or in the presence of other traffic, the limit is set to -70 dBm/MHz. Within the latter band, the FCC mask can be obeyed without DAA. In the frequency band between the listed regions, the maximum average power level is limited to -70 dBm/MHz. These bands are also depicted with grey boxes in Fig. 4. The preliminary approval protects the bands of current services and is prepared for new ones, such as WiMax, 4G and digital broadcast services. It might also be possible to operate UWB devices within a band between 4.2 … 4.8 GHz without DAA until the end of 2008, which makes it possible to fasten the UWB exploitation process and boost DAA development [78]. An UWB band for the quasi-millimeter band of 22 … 29 GHz where coexistence problems would be minimized was proposed in a talk related to [79]. However, at the time of writing this thesis, the Japanese standardization process is still ongoing but, according to [77] and [79], the process is expected to end by the end of 2005 [65] and the final report with the regulations will be expected in March 2006 [66]. The regulation itself is supposed to be finalized during summer 2006 [80].

Reference [64] is used as an opening document for UWB standardization discussions in New Zealand. In September 2005, a report specifying the trial and piloting license requirements in New Zealand was released [66]. In Singapore [81], the UWB radiation mask inside an “Ultra Wideband Friendly Zone” allows a 6 dB higher power spectral density than the one by the FCC. This exception has been carried out under the control of the Infocom Development Authority of Singapore, the local frequency regulator. A web site of UWB activities in Singapore is available in [82]. In China, the FCC regulations will most probably be followed. Again, according to the talk related to [79], Asian countries are trying to harmonize UWB standardization and regulation.

The IEEE established study groups IEEE802.15.3a and IEEE802.15.4a. The former was focused on the physical layer of high data rate applications [8]. The latter is defining a new UWB based physical layer (PHY) concept that can be used in low data rate applications. The main applications within this study group are WPANs (Wireless Personal Area Network), sensor networks etc. that have only a moderate data rate but long battery life is required. In addition, precision ranging and location with less than one-meter accuracy is required [83]. IEEE802.15.3a failed to define a UWB PHY standard, and its work was withdrawn in January 2006 [84]. Both competing camps, DS-UWB and MB-OFDM (WiMedia), already have chipsets available without any standard, so the markets can make the final decision which one is the better approach and lives in future applications.

2.2 Prevailing UWB definition and radiation limits

In February 2003, the FCC adopted a new definition for UWB [24]. This FCC ruling does not limit the UWB only to impulse radio type applications but allows different technologies to be used to generate UWB waveforms [24,25]. When writing the thesis, as mentioned earlier, the FCC regulation is globally the only existing UWB regulation. In

Europe, the first mask proposal was released on March 2006 by the ECC [85], and the comments are expected before the end of May 2006.

2.2.1 In the USA

EXISTING LIMIT BY THE FCC: *The prevailing definition has decreased the limit of* B_f *defined by (3) to a minimum of 20%. According to the same ruling, the signal is also recognized as UWB if the -10 dB signal bandwidth is 500 MHz, or larger.*

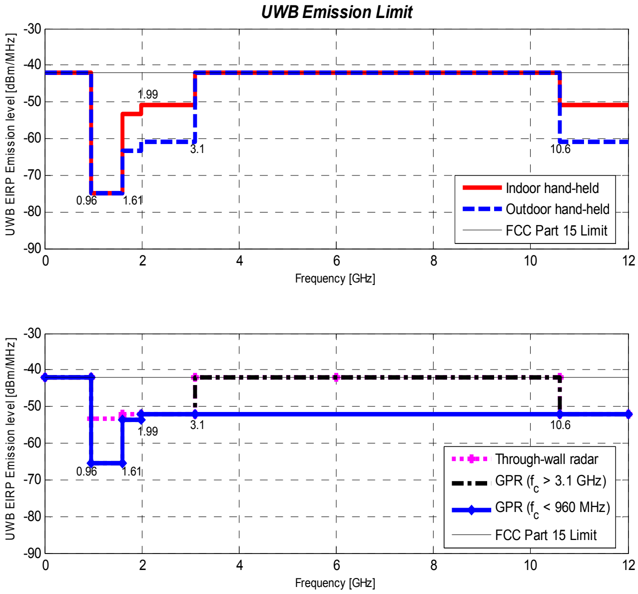

Fig. 5. UWB radiation mask granted by the FCC.

The existing FCC approved radiation limits for different UWB applications are presented in Fig. 5. The upper plot represents the masks for data communications applications for indoor and outdoor use. The lower plot gives the FCC radiation masks for radar and sensing applications. In all cases, the maximum average power spectral density follows the limit of FCC Part 15 regulations, being less than -41.3 dBm/MHz [24]. The averaging time is 1 ms. In the UWB friendly zone in Singapore, the maximum radiation level between 2.2 GHz … 10.6 GHz is 6 dB higher than the FCC's Part 15 level, thus being -35 dBm/MHz [81]. Note, that the lower frequency in Singapore is also lower than in the FCC's mask.

The same FCC regulation limits the peak EIRP in pulsed transmission to

$$P_{\mathrm{peak}} \le \frac{P_{\mathrm{av}}}{0.45}, \qquad (4)$$

where P_{peak} and P_{av} are the peak and average EIRP powers, respectively when the pulse repetition frequency is higher than the resolution bandwidth of the measurement device. In general, the maximum acceptable peak EIRP = 0 dBm, measured over the resolution bandwidth B_{R} = 50 MHz. If 1 MHz < B_{R} < 50 MHz, peak EIRP can be defined by $20\lg(B_{\mathrm{R}}/50)$ dBm [24]. In [25], the FCC defined the peak power measurement to the 50 MHz band centered at the frequency having the highest signal level. The peak power limits have been derived for real-world applications, not only for a fully controllable laboratory environment, and are technology independent [25]. At the same time, [25] also allows higher peak powers for pulsed (or gated) transmission, if the duty cycle is simultaneously decreased.

The use of UWB technology in communication applications is limited to hand-held devices only, and, for example, operation in toys is forbidden [24,25]. In addition, exploiting UWB on board an aircraft or a satellite, or in fixed outdoor links, is prohibited by the same regulations. However, the regulations made it possible to obtain UWB in outdoor long-haul portable links if the maximum radiation power limit is not exceeded. Due to the high processing gain requirements of long-haul applications, the communication link is limited to low data rates only.

2.2.2 A proposal for Europe

On 24 March 2006, the ECC released an explanatory memorandum about UWB regulation for the European Union [85]. The memorandum identifies how UWB devices can be exploited inside the EU. Comments concerning the decision are requested to be filed to the European Radiocommunications Office before 29 May 2006. The ECC's decision is applicable to radio technologies having a bandwidth wider than 50 MHz, and is intended for communication; measurement; location; imaging; surveillance and medical applications. The use of UWB devices is primarily intended for indoor use. According to [85], the use of unlicensed UWB devices is prohibited in aircraft; devices that are installed in road and rail vehicles; and outdoor installations. The frequency range below 5 GHz is reserved for advanced cellular services, which will be discussed in the next World Radio Conference in 2007.

Within the frequency band of 6 – 8.5 GHz a long-term UWB transmission without any mitigation techniques is allowed using the maximum average PSD of -41.3 dBm/MHz. Peak power is calculated over a 50 MHz band. A more detailed view of the preliminary maximum radiation levels by the ECC is presented in Fig. 6. According to [85], the pulse repetition frequency should be higher than 1 MHz.

In [86], which has been developed from [85], detect and avoid, along with a low duty cycle interference mitigation method are proposed for the frequency band of 3.1 – 4.8 GHz. This proposal has been released for statements and comments. Since there is no interference mitigation requirement available for the frequency band of 3.1 – 4.8 GHz, the proposal considers allowing the use of the band between 4.2 – 4.8 GHz without any mitigation technique for a certain time (until either 2010 or 2012). The ECC decision about the proposal from [86] is expected in July 2006.

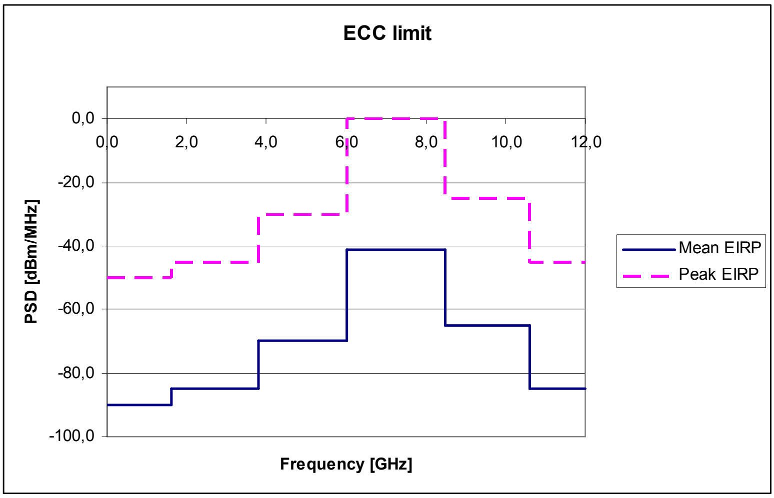

Fig. 6. UWB radiation mask preliminary granted by the ECC.

2.3 Pulse waveforms

To benefit from extremely large bandwidth, narrow pulses need to be used to transfer the signal energy through the media. In the literature, the most common pulses used are based on the Gaussian or Hermitean waveforms [87-89]. The former one can be seen as special cases of the latter one. In [90,91], the so called soft-spectrum adaptation technique (SSA) is proposed to improve the interference avoidance and scalability of the UWB system by pulse shaping. SSA utilized binary phase shift keying (BPSK) data modulation and several multi-band pulse waveforms to adopt the given spectral requirements. By pulse design, it is possible to generate nulls to avoid some victim radio systems. The SSA approach is used in [92] where the pulse generation is based on time-limited B-spline functions. In [93], prolate spheroidal waveforms for *M*-ary PPM were proposed. In that case, a different pulse waveform is associated to the different bit pattern. The generated pulses are orthogonal, and independently of the order of the pulse, they maintain the pulse length and bandwidth. A summary of UWB pulse candidates is also given in [94], where the focus is on Gaussian pulses, modified Hermitean polynomial functions and prolate spheroidal wave functions. Numerical pulse generation based on Gaussian monocycle is presented in [95].

The original pulse waveform adopted for UWB was the first derivative of the Gaussian pulse, called a monocycle [96]. In the frequency domain, this pulse occupies the band from near direct current (dc) to the GHz range, the upper frequency depending on the pulse width. The current FCC UWB regulations [24,25] deny the use of frequencies below 3.1 GHz for communication applications as stated in Fig. 5, which also means that the higher order derivatives of the Gaussian pulse are required to fulfil the spectral requirements. In this thesis, the pulse waveforms used in the further studies are selected amongst the higher order derivatives of the Gaussian pulse set.

The general zero-mean Gaussian pulse $w(t)$ is derived by

$$w(t) = \frac{A}{\sqrt{2\pi}\sigma} \exp\left(-\frac{t^2}{2\sigma^2} \right), \tag{5}$$

where A is the amplitude. The standard deviation, σ, is related to the excited pulse width by the approximation $T_p \approx 7\sigma$. The same T_p definition is also used in [94] as a ratio between standard deviation and pulse width for a non-zero mean Gaussian pulse. When propagating through the antenna, the pulse is differentiated once and the waveform in the channel is therefore the first derivative of the generated one [49,97]. In general, the characteristics of the frequency response are determined by the antenna used, which has more or less a bandpass filtering effect. The filtering can be seen as a change in the pulse shape in the time domain. In addition to shifting the radiated pulse to a higher frequency range, higher order derivatives are needed because the antennas do not radiate at direct current (dc). For example, the basic Gaussian pulse contains a dc term, and therefore, it cannot be used as a UWB pulse.

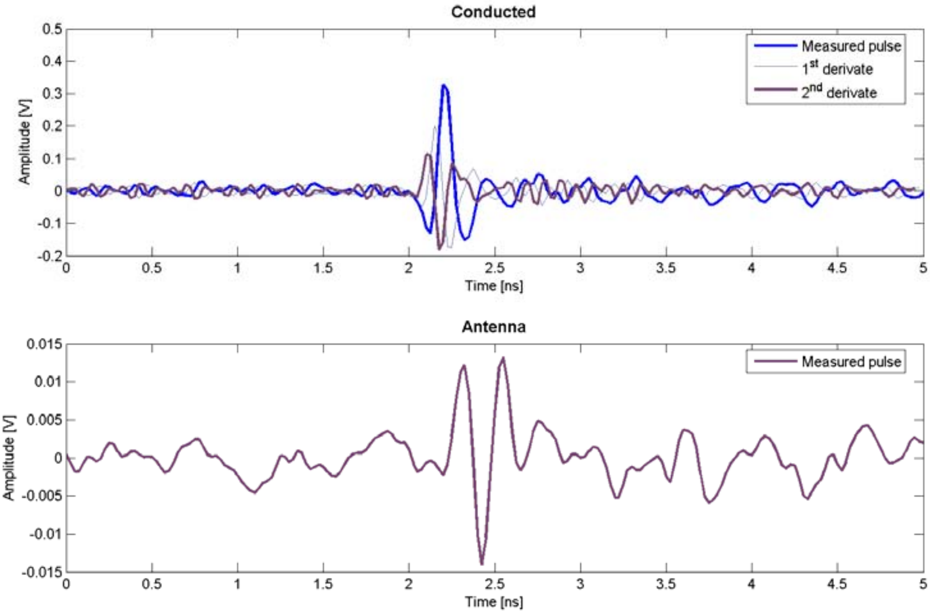

Fig. 7. The received pulse waveform including the antenna effects.

At the receiver side, the pulse waveform is also changed when passing through the antenna. The double derivation of the pulse waveform within the transceiver chain has been recognized when using a pulse generator (described in Section 4.3.2 in more details) and antennas built in the FUBS project. Two similar UWB antennas (see Fig. 3 in Paper I) were used and the pulse waveform was received over the air using a digital sampling oscilloscope. This effect is also depicted in Fig. 7. The reference result was obtained with the conducted measurement, i.e., a cable connection was used between the output of the pulse generator and the input of the oscilloscope, as shown in the upper plot. The measured waveform is numerically differentiated twice and the corresponding waveforms are shown in the plot. The lower plot in Fig. 7 is the result from the radiated measurement at a distance of 10 cm. This simple test proved that the received waveform was the second derivative of the generated one when small dipole type antennas were used. The further assumptions made during the simulations were based on this observation of the double derivation effect.

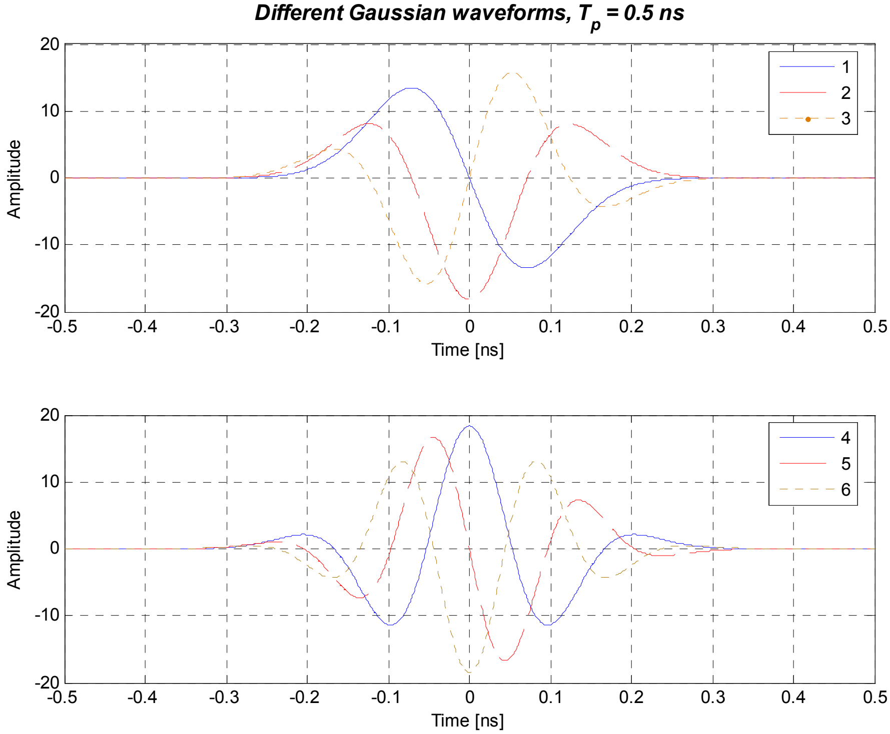

Fig. 8. Gaussian pulse waveforms used in the simulations.

The recursive presentation for the higher order (n-th order) derivatives of the Gaussian pulse depicted in Fig. 8 can be derived by [98]

$$w^{(n)}(t) = -\frac{n-1}{\sigma^2} w^{(n-2)}(t) - \frac{t}{\sigma^2} w^{(n-1)}(t). \tag{6}$$

The amplitude spectrum of the Gaussian pulse, $W(f)$, thus the presentation of $w(t)$ in the frequency domain, can be derived from (6) using the Fourier transform by [98]

$$|W_n(f)| = A(2\pi f)^n \exp\left\{-\frac{(2\pi f\sigma)^2}{2}\right\}. \tag{7}$$

The power spectral density for the n-th order Gaussian pulse is then derived by [98]

$$|P_n(f)| = A_{\max} \frac{(2\pi f\sigma)^{2n} \exp\left\{-(2\pi f\sigma)^2\right\}}{n^n \exp(-n)}, \tag{8}$$

where $A_{\max}$ scales the normalized power spectral density under the radiation regulations and f is frequency.

The spectral properties of the first ten derivatives of Gaussian pulses are presented in Fig. 9. In the figure legend $B_{-3\mathrm{dB}}$, $B_{-10\mathrm{dB}}$, $B_{-20\mathrm{dB}}$ and f_c represent -3 dB, -10 dB, -20 dB bandwidths and the corresponding nominal center frequency, respectively. Curves are given for pulse widths of 0.5 ns, 0.75 ns, and 1.0 ns. The center frequency increases monotonically when the order of the derivative of the Gaussian pulse increases, and the shorter the pulse, the higher the center frequency is. The effect of the derivative order on the signal bandwidth is not big and the bandwidth saturates at a specific level for fixed T_p. Within this study, pulses up to the 7th derivative of the Gaussian pulse have been used in the simulations.

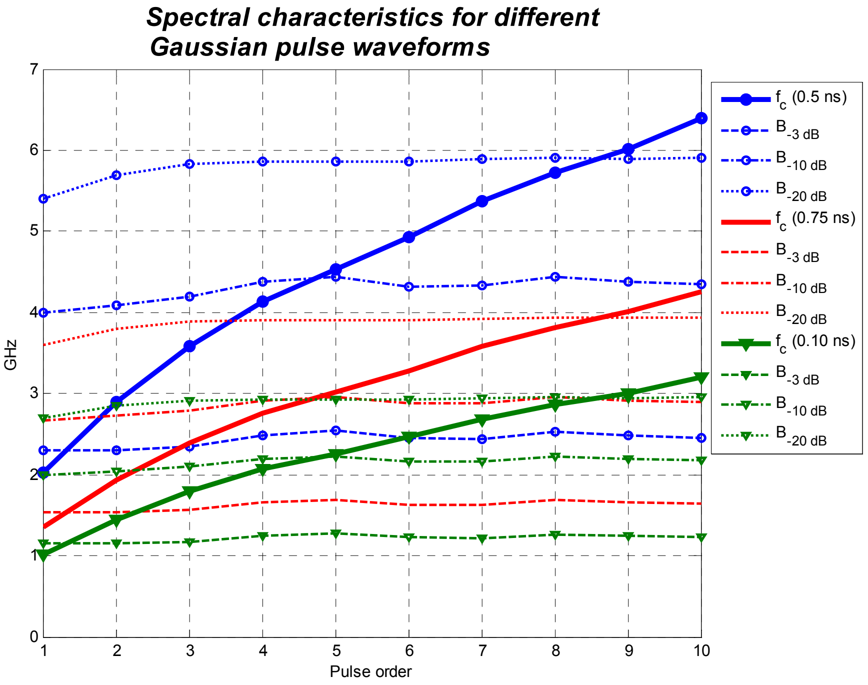

Fig. 9. Spectral characteristics for the first ten Gaussian derivative pulses. The x-axis defines the order of the derivative of the Gaussian pulse.

2.4 Propagation aspects

All radio systems are affected by the propagation medium. The environment causes multipath propagation, and the distance dependent attenuation between the transceivers is also impairing the propagating signal energy. The latter phenomenon is called path loss and it is based on physics. Movement of the active transceiver or environmental motion will cause velocity dependent Doppler shift, i.e., the received frequency is different from the transmitted one. During this work, different UWB concepts are studied in static environment, so the Doppler shift has been ignored. The next sections will shortly discuss the propagation media from a UWB point of view.

2.4.1 Multipath propagation

Due to the extremely wide bandwidth of the UWB signal, the multipath resolution of the system is very high. One can distinguish more paths than if using some conventional radio system, even more than a typical spread spectrum system that might have bandwidth of tens of MHz. Wideband channel models for an urban environment could consist of about twelve significant paths, like the COST 207 model presented in [99, Appendix E]. In general, the number of propagation paths is environment, center frequency and bandwidth dependent. In wideband channel modeling, the bandwidth is relatively narrow and the electrical modeling of the reflecting materials (attenuation, reflection coefficient etc.) could be assumed flat within the band of interest. In the case of UWB, these assumptions are not necessarily valid anymore.

Before UWB channel model definition, there was an open call for contribution by the IEEE802.15.3a, and it resulted in numerous proposals. Because the main goal of this thesis is not in UWB radio channel modeling, a comprehensive literature review has not been included. For example, references [100-108] are dealing with UWB multipath channels, and could therefore be used as a reference for the subject. Due to the very fine delay resolution the UWB signal provides, the number of distinguished paths in the UWB context could be hundreds. Of course, in a realistic implementation, only a fraction of the possible paths will be exploited. The strongest paths are the desirable ones.

To create fair comparison conditions for all the proposed UWB technologies, IEEE802.15.3a and IEEE802.15.4 have defined standard radio channel models to be used in high and low data rate UWB system analysis, respectively. The IEEE802.15.3a models [109,110] used in this work will be described in Section 4.1.2 in more detail. The latter model for low data rate applications is described in [113]. UWB radio channel modeling has also been carried out at the CWC, and the author of this thesis has been involved in these studies. The results from the CWC's radio channel studies are reported in [2,3,111,112].

2.4.2 Path loss

Path loss is defined as a ratio between the transmitted and received power, and typically, it is given in decibels [dB]. Path loss is expressed through attenuation factor α, which gives the slope of the regression line that is fitted to the measured received power plotted as a function of distance ($d^{1/\alpha}$). In free space, $\alpha = 2$ and, e.g., in cellular systems, α gets a value between 2 … 4 [54]. In non line-of-sight urban links, the attenuation factor can be even more. Any obstacle, wall etc. in a propagation link causes additional attenuation to the received signal level.

In many cases, a dual-slope path loss model is more accurate to describe the attenuation of the UWB signal than a linear regression line. The dual-slope model consists of two linear regression lines that both have a different slope. After the environment dependent breakpoint, the attenuation will be deeper than in the closer distances from the transmitter. In long distance narrowband or wideband links, the dual slope model can also be applied. The breakpoint is based on the obstruction that ground will cause in the link.

In [105,114], both line-of-sight (LOS) and non-LOS measurement based statistical channel models for commercial (the latter reference) and residential (both references) indoor environments were derived. In the conclusions, the authors stated that in statistical means, the propagation characteristics in these two environments are similar. The dual-slope model, with a breakpoint derivation, is discussed in [115,116]. The authors stated that in short range UWB links, the attenuation modeling is different from the one that long haul models predict for narrowband radio links. Therefore, the single slope model is not accurate enough for UWB link budget calculations. In [98], *M*-ary PAM using the 5th derivative of the Gaussian pulse as a transmitted waveform is studied, and the results include coverage analysis and link budget calculations.

Due to the high frequency diversity that a UWB signal has, α could be less than 2. E.g., in [117], the measurements carried out in a corridor showed that within a band of 2 – 8 GHz, the path loss is inversely proportional to the distance by a factor of 1.9, or even less. In [108], α was noticed to be between 1.58 and 1.96 in LOS and NLOS cases, respectively. In [117], both one slope and dual-slope models were derived for the studied cases, as shown in Fig. 10 for antenna heights of 110 cm. The same measurements indicated that in the case of through-wall propagation, α was about 3.2 … 3.8.

The knowledge of path loss makes it possible to connect the simulated bit error rates given in the original papers to the achievable link distances through the backward link budget calculations. In general, the link budget can be presented as [23]

$$P_{\mathrm{rx}} = P_{\mathrm{tx}} + G_{\mathrm{rx}} + G_{\mathrm{tx}} - L_{\mathrm{pl}} - L_{\mathrm{imp}} - \left(\frac{E_{\mathrm{b}}}{N_0}\right)_{\mathrm{req}} - M \quad , \tag{9}$$

where P_{rx} and P_{tx} are received and transmitted powers, G_{rx} and G_{tx} are the antenna gains of the receiving and transmitting antennas. L_{pl} and L_{imp} are path loss and implementation loss, respectively. In addition to the physical parameters, a link margin M can be taken into account in the link budget calculation. $(E_{\mathrm{b}}/N_0)_{\mathrm{req}}$ is the required signal-to-noise ratio for the used modulation method that fulfils the specific bit error rate requirement. The required $(E_b/N_0)_{req}$ value for different situations can be found from the results that are given, e.g., in the original papers (bit error rate versus signal-to-noise curves). E_b and N_0 denote the energy of a bit and the one-sided power spectral density of white Gaussian noise, respectively.

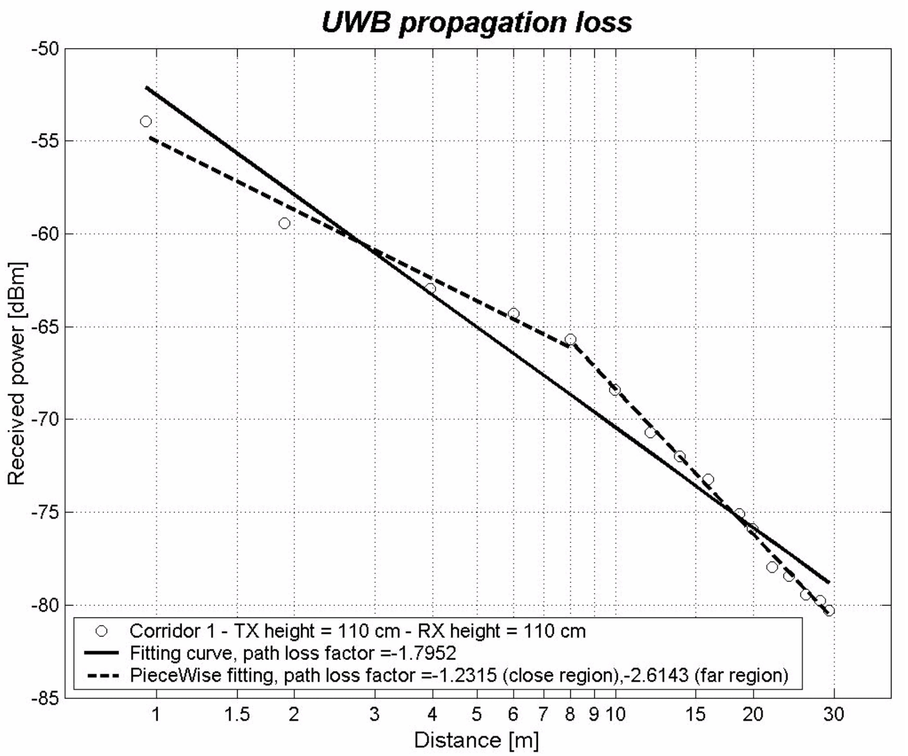

Fig. 10. Example of the UWB path loss model.

It should be noted that also the interfering signal is attenuated when passing through the channel. The existing radio systems, i.e., the possible interfering systems, can also be both narrowband or wideband systems and thus their attenuation differs from UWB attenuation. The wideband radio channel has been extensively studied during the previous years and there are many references available. This thesis is beyond the wideband path loss and channel modeling so the reader is encouraged to find detailed information from the public literature, e.g., [99,118,119]. There are also numerous of conference and journal papers about wideband radio channel measurements and modeling available but not listed in this context.

It is also well known that α depends on the frequency. For the UWB signal, this means that the lower and higher parts of the allocated frequency band have different α. This causes distortion to the pulse shape at the reception because different frequency components will arrive at different times and differently distorted [51].

2.5 Existing UWB technologies

This section discusses the technologies that can be used to generate UWB signals suitable for communication applications. Both single and multiband approaches are introduced, although the focus of this thesis is on singleband systems.

UWB technology can be utilized both in high data rate applications with short distances (link of 10 m or less), as well as in low data rate applications having moderate or long link distances (up to 100 m, or even longer). However, the level of required transmitted power to achieve high data rates over long link distances would exceed the current radiation limits.

2.5.1 Singleband UWB

Singleband UWB is the simplest UWB technology due to its carrier-free nature. The singleband UWB approach can be seen as the original ultra wideband technology because the data flow is conveyed via baseband, low energy pulses rather than modulating it to some higher carrier frequency. Therefore, the up-conversion and down-conversion blocks from the transceiver chain can be avoided. Singleband UWB is a candidate in the IEEE 802.15.4 study group for the physical layer concept for low data rate location and tracking based applications [83], and it is also worthy of consideration, e.g., for data links in sensor networks [120,121] or low to medium data rate communication applications [83,121].

The original papers of the thesis cover both time hopping and direct sequence based UWB concepts. The other approaches are presented to give the reader a wider view on the topic. For detailed information about the other possibilities, a reference list is provided.

2.5.1.1 Time hopping UWB

The original UWB technique proposed for data communication utilized a time hopping (TH) spread spectrum technique combined with a pulse position data modulation scheme. This concept was referred to as impulse radio due to the transmission of short pulses. Because of the very narrow transmitted pulses, the inherent spectrum is very wide. These basic impulse radio systems are covered in, e.g., [96,100,122,123]. In TH-PPM, the nominal pulse transmission instant is defined by a pseudo random noise code (PRN). The PRN code is user dependent, and thus, it does the user separation (channelisation) in a multi-user system. The transmitted data is organized to maintain a certain frame structure during transmission. A unique feature of UWB systems is their low average transmitted power. To make signal detection reliable, one data bit is spread over N multiple low energy pulses in order to increase the total signal energy at the detector. Thus, a data bit includes N frames in the simplest TH-PPM version, where only one pulse per frame is transmitted. Each frame is divided into L slots, where L is defined by the length of the PRN code. The time difference between the pulse transmission and the reference time instant defines if the data bit is “1” or “0”. The changes in pulse polarities in antipodal modulated systems (PAM), or time variation due to PPM, break the regular intervals in the transmission, and therefore smooth the spectrum by diminishing the line spectrum components. The idea of the TH-PPM frame structure (as well as DS-UWB) is graphically presented in Fig. 11 [Paper II].

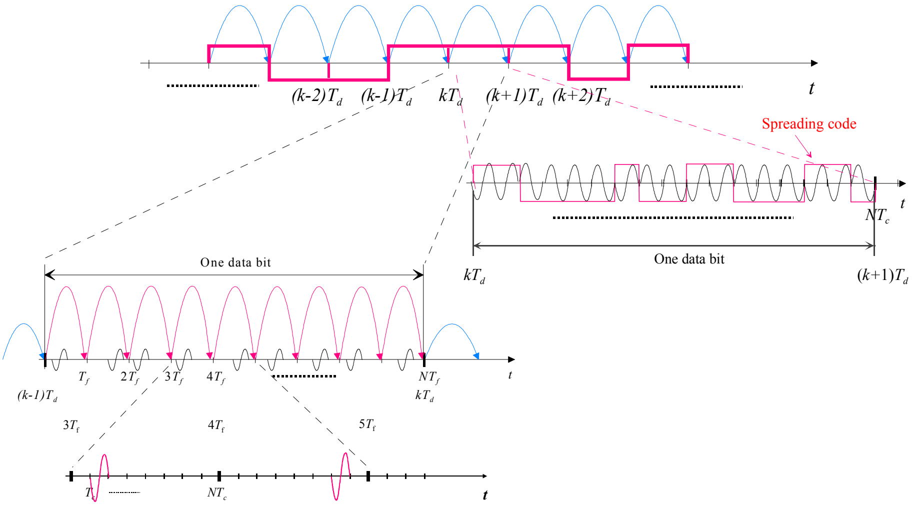

Fig. 11. Models for TH-UWB and DS-UWB concepts.

Due to the time hopping feature, the duty cycle D_c of the transmission is small and silent periods are introduced inside a radiated pulse train. Using the UWB system parameters, D_c can be presented as

$$D_c = \frac{T_p}{T_f} < 100\% , \tag{10}$$

where T_p and T_f are pulse width and pulse repetition period (frame length), respectively. T_f is inversely proportional to the pulse repetition frequency (PRF) which defines the pulse transmission rate.

Modulated data in TH-PPM is conveyed with the time difference between the nominal and actual transmission times. A frame structure organized as described above allows L simultaneous non-overlapping users. The singleband UWB receiver is a homodyne cross-correlator receiver that utilizes a direct RF-to-baseband conversion. Intermediate frequency conversion is not needed which makes the implementation easier than in conventional (super-)heterodyne systems, like cellular phones or radio broadcasting.

Pulse amplitude modulation can also be used in the UWB context as is stated, e.g., in [14,15]. In this case, the data modulation comes with the polarity of the transmitted pulses, and the transmission instant is the one defined by the PRN code. PAM is also considered in the original papers. The processing gain G_{TH} for TH-UWB can be defined using the amount of pulse repetition coding and the duty cycle as

$$G_{\mathrm{TH}} = 10\lg N + 10\lg D_{\mathrm{c}}, \tag{11}$$

where N is the number of pulses used to send one data bit and can be referred to as repetition coding.

Of course, there is a possibility for M-ary PPM where more than one slot per frame is used in a transmission, as presented in [124]. The combination of PPM and PAM, so called pulse position amplitude modulation (PPAM) is also possible, as presented in [125,126]. The latter one extends the basic results from the previous one by adopting rake reception. In biorthogonal PPM (BPPM) [127], the modulated signal is composed of 2^N orthogonal PPM signals in conjunction with its corresponding antipodal PPM signal forming a complete set of 2^{N+1} BPPM signals. Using these multilevel modulation schemes, the system capacity could be increased.

2.5.1.2 Direct sequence UWB

In direct sequence UWB, the pulse repetition is applied using a pseudo random noise code, like in conventional direct sequence spread spectrum systems [22], but having a chip waveform producing the ultra wideband spectrum. Pulse polarity is defined by the chip polarity. In the extreme case, DS-UWB transmission is continuous, i.e., the duty cycle is 100%. If the duty cycle is less than 100%, the method can be classified as hybrid TH/DS-UWB.

The used PRN code can be a maximum length code (m-sequence) or any other code having suitable correlation or other pre-specified properties, like spectral smoothing. Other suitable PRN codes for multi-access and spectral spreading purposes are, e.g., Walsh codes [128] or orthogonal variable spreading factor code sequences [129]. These techniques are naturally suitable for M-ary modulation to be applied also in time hopping systems. The length of the code can easily be associated with the modulation level. The main idea for DS-UWB has also been introduced in Fig. 11. Processing gain, G_{DS}, for pure DS-UWB systems is defined by

$$G_{\mathrm{DS}} = 10\lg(N)\,. \tag{12}$$

DS-UWB was the other candidate in IEEE802.15.3a for high data rate PHY enhancement for applications, which include multimedia and imaging, but was not selected for the final voting. The targeted data rates for the systems under IEEE802.15.3a are 110 Mbps and 200 Mbps with the option of 480 Mbps at distances less than 10 m [130]. In addition, to fulfil the total available spectrum, two operational bands are defined. The lower and upper bands occupy the spectrum between 3.1 … 4.85 GHz and 6.2 … 9.7 GHz, respectively. The proposal supports data rates of 28, 55, 110, 220, 500, 660 and 1320 Mbps, which are achieved by using spreading codes of different lengths [131].

As stated in [84], neither a DS-UWB nor multiband-OFDM (see Section 2.5.2) based system was selected for the standard by IEEE802.15.3a, and the work of the study group has now been stopped.

2.5.1.3 Transmitted reference

The third option that can be used in ultra wideband communications is the delay-hopped (DH) transmitted-reference (TR) method presented, e.g., in [132-134]. DHTR technology is usable for both narrowband and wideband systems, not only for pulsed systems (like UWB). Recently, the technology has been proposed for short-range, highly multipath rich environments to improve the spectral efficiency. The TR technique was proposed already in 1964 [135] due to its capability to carry channel information to the receiver. At an early stage, the technology was also discussed in [136-139].

Narrowband and wideband TR techniques utilize two carrier signals; one to convey channel state information (reference) without any data, and the other to carry the modulated data. The carrier signals can be separated either in the time or frequency domain. In DHTR, the signal separation is done in the delay domain [132]. Multiple access capabilities are taken into account by introducing individual delay hopping codes for different users. The DHTR receiver is a correlator receiver who studies the received energies after the correlation. Because the signal structure is combined from two components, the reference part can be used for channel estimation. To get the same SNR at the receiver as in the concepts presented in 0and 0the total transmission power in a DHTR system is twice as high due to the reference part, which does not convey information. If the transmission power is fixed to be the same, DHTR suffers a 3 dB loss in the information stream energy. The combination of traditional and differential TR systems is proposed in [140] to be used in M-ary systems, using block codes instead of repetition codes to improve the received BER.

Similar performance to what TR systems can offer could be achieved using a simple non-coherent energy collector [141-144]. In this approach, e.g., bit position modulation (BPM) could be used. BPM follows the idea of PPM but instead of using one pulse, a short burst of pulses will be sent. The receiver structure is much easier than in a TR system and no correlator is needed.

2.5.1.4 *Frequency chirp*

One possible technique to generate an ultra wideband spectrum is the use of fast frequency chirps. This method is commonly used in impulse radars. One can generate a wideband transmission by quickly sweeping the transmitter's oscillator in the frequency domain. A bandwidth of 10 MHz … 620 MHz can be achieved with about a 10 ns sweep time [145]. A wider bandwidth can also be used, e.g., ground-penetrating radar with a 50 MHz … 1200 MHz bandwidth is documented in [146].

Ground penetrating radars that are based on UWB technology are suitable for object detection in, e.g., landmine sweeping, avalanche rescue operations, etc. due to the good signal penetration ability and fine spatial resolution they have. The former property is based on the low frequency band the GPR can use, and the latter one is based on the wide spectrum allocation. Because the volume markets of GPR are rather small, and the radiation is very focused, FCC allows the use of UWB radars also below 960 MHz [24].

2.5.1.5 *UWB frequency modulation*

The latest innovation in the low or medium data rate (< 1 Mbps) singleband UWB era is ultra wideband frequency modulation (UWBFM). Like frequency chirp modulation, UWBFM is generated in the frequency domain. This technique is introduced in [147], and further discussed in [148-152]. UWBFM is based on double frequency modulation (FM), where digital frequency shift keying (FSK) with a low modulation index is followed by a high modulation index frequency modulation in the analogue domain. As presented in [150], the transmitted FM signal can be presented as

$$V(t) = A\sin\left(\omega_\mathrm{c}t - \phi\cos\left(\omega_\mathrm{m}t\right) + \theta_0\right), \tag{13}$$

where A, ϕ, ω_c and ω_m are amplitude, modulation index and angle frequencies of the carrier and modulating signal, respectively. Angle frequency is related to the actual frequency as $\omega = 2\pi f$ and θ_0 is arbitrary but time-independent constant phase. The derivation of (13) is shown in [150]. FM modulation index ϕ is defined by the frequency deviation Δf and the frequency of the modulating signal f_m, or corresponding angle frequency deviation $\Delta\omega$ and angle frequency ω_m, as [150]

$$\phi = \frac{\Delta f}{f_\mathrm{m}} = \frac{\Delta\omega}{\omega_\mathrm{m}}. \tag{14}$$

The output is a constant enveloped UWB signal whose bandwidth is [150]

$$W \approx 2\left(\phi + 1\right)f_\mathrm{m} = 2\left(\Delta f + f_\mathrm{m}\right). \tag{15}$$

UWBFM uses frequency division multiple access to separate different users to different sub-carriers. The spectrum of UWBFM also has steep roll-off, which makes it a spectrally efficient technique. Using band-pass filtering or triangular sub-carriers, the spectrum of the UWBFM signal can be made flat [150]. FM demodulation is done with a delay-line that performs the FM-to-PM[3] conversion. This is followed by a phase detector. Next, for each sub-carrier, FSK demodulation is carried out by a phase-locked loop. Frequency conversion states are not needed at the receiver side, which simplifies the implementation [150].

2.5.2 Multiband UWB

A competing UWB technology corresponding to the traditional multi-carrier or orthogonal frequency division multiplexing system has been proposed to be a physical layer technique for short-range, high data rate applications by the study group the IEEE802.15.3 [153]. Multiband-OFDM based technology was actually the only survivor in a vote in IEEE802.15.3 meeting at Albuquerque, NM, USA at Nov 9-14, 2003 but did not get the required 75% approval in the final vote to be a UWB standard [154]. This decision lets the markets define the *de facto* standard to be used in high data rate, short link UWB applications. The forthcoming applications could be based on either a direct sequence or multiband approach. Like earlier stated, Ecma International in [76] is also giving strong support to the MB-OFDM approach. However, because both camps, DS-UWB and MB-OFDM, have started the manufacturing phase, the work of IEEE802.15.3a has been cancelled, as pointed out in [84].

Multiband-UWB utilizes a set of carriers with a data signal spread over 500 MHz around each carrier. The used frequency allocation needs to follow the FCC radiation mask defined in Section 2.2 if the product is targeting to American markets. Frequency hopping between the bands is used to decrease the average transmitted power within victim bands. The advantage of multiband UWB compared to singleband UWB is that, if required by the radio regulations, the sub-blocks (or sub-carriers) can be suppressed individually to avoid intentional interference against other services. Of course, the performance of an MB-OFDM based system can be improved by selecting the subbands, which are interference free. The spectral efficiency is also improved, the higher the data rate a multiband system can offer. MB-UWB makes it possible to use the same system globally, still adopting the local radiation regulations, by proper selection of the used sub-bands.

The weakness of the MB-UWB approach is a more complex transceiver structure if compared to the original impulse radio working at the baseband. New functional blocks are needed for the up-converter and down-converter; mixers and amplifiers that are excluded from the simplest impulse radio concept. This also means that the basic idea of cheap, low power consumption UWB devices is lost. On the other hand, the technique can offer higher data rates for medium distances than the single-band approach, and commercial OFDM technology nowadays is quite mature, with components available on

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[3] PM = phase modulation

the shelf. However, the aim of this thesis is not to make a hardware complexity analysis between different proposals or technologies.

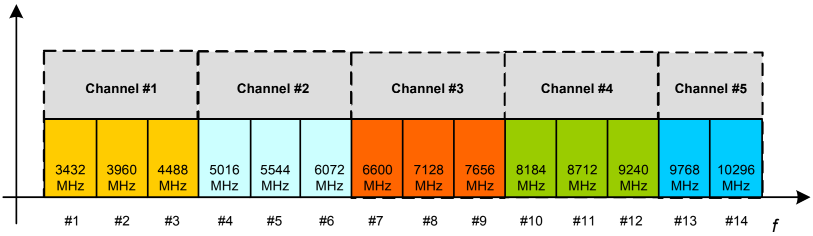

Fig. 12. Multiband-OFDM proposal.

The current proposal has 14 non-overlapping OFDM modulated channels each having a bandwidth of 528 MHz, as presented in Fig. 12 (redrawn from [153]). The center frequencies for each sub-group are depicted in the figure. The data rates aimed at for MBOA are 55 Mbps … 480 Mbps using quadrature phase shift keying (QPSK) data modulation. Currently, multiband-OFDM technology is driven by the WiMedia Alliance [155]. Based on [156], the first plans for multiband-UWB technology utilization are spread into four phases:

- Group A: first generation devices operating at 3.1 … 4.9 GHz,
- Group B: frequency band 4.9 … 6.0 GHz is reserved for future generations,
- Group C: intended for devices with improved simultaneously operating piconet performance, operating at 6.0 … 8.1 GHz and
- Group D: frequency band 8.1 … 10.6 GHz is reserved for future generations.

In MB-OFDM, 110 sub-carriers (100 data carriers and 10 guard carriers) per band are used to transmit the information signal. Coherent detection can be made because of the 12 pilot sub-carriers. Variable data rates are achieved by using different frequency-domain spreading, time-domain spreading, and forward error correction coding, which is carried out by a convolutional code with coding rates of 1/3, 1/2, 5/8 and 3/4 [76,153]. The coded data can be spread over the frequencies using two types of time-frequency codes: by interleaving the information over three bands. This is referred to as time-frequency interleaving. Another way is to transmit the signal using only a single band. This one is referred to as fixed frequency interleaving. Reference [153] specifies a total of 18 logical channels or independent piconets, while [76] gives support for seven channels per band, and specifying a total of 30 independent channels. When a DS-UWB based system always occupies the frequency range defined by the pulse shape and pulse width, the spectrum allocation of a multiband system is possible to do more freely by utilizing a selected set of subcarriers. This feature provided by MB-OFDM is useful when avoiding certain frequency bands in terms of interference; either minimizing the interference to be caused to some other system, or by escaping the interference. Of course, the radiated frequency band can be limited by using additional filtering also in singleband systems, and so certain bands can be avoided.

2.6 UWB channel capacity

The extremely wide bandwidth of an UWB signal linearly increases the theoretical channel capacity. That is one reason the technology has gained a big boost recently in applications requiring high data rates. Based on the classical definition by Shannon [157], the channel capacity, C, depends linearly on the signal bandwidth, W, and logarithmically on the signal-to-noise ratio, E_b/N_0, (or SNR in other words) as given by

$$C = W \log_2\left(1 + \frac{P}{WN_0}\right) = W \log_2\left(1 + \frac{E_\mathrm{b}}{N_0}\right), \tag{16}$$

where P denotes the power of the desired signal.

In UWB systems, the bandwidth is greatly increased which means that the channel capacity should be linearly increased, not logarithmically as in the case of increasing E_b/N_0. This is depicted in Fig. 13 using different bandwidths; 500, 750, 1000, 2000 and 3500 MHz, which are all possible UWB bandwidths. The curves in Fig. 13 implicitly show how the channel capacity increases with the increasing signal bandwidth. If comparing UWB bandwidths to bandwidths of other existing radio systems, the difference is huge; the occupied bandwidths are, e.g., 200 kHz in the global system for mobile communications (GSM) [158], 3.8 MHz in universal mobile telecommunication systems (UMTS) [158] and 16.6 MHz in IEEE802.11a (WLAN) [26].

In real life cases, if possible, the effects of interference should be taken into account in the system performance calculations. The impact of interference on channel capacity can be calculated with [159]

$$C = W \log_2\left(1 + \frac{P}{WN_0 + N_\mathrm{j}}\right) = W \log_2\left(1 + \frac{E_b}{N_0 + N_\mathrm{j}/W}\right), \tag{17}$$

where N_j denotes the one sided power spectral density of the interfering signal. The non-desired signal will increase the portion of the noise part and thus decreasing the signal-to-noise ratio as can be seen from (17).

Channel capacity for the second derivative of a Gaussian pulse based M-ary PPM signal in an AWGN channel is presented, e.g., in [160]. In [161] and [162], the capacity for M-ary PPM and M-ary PAM, respectively, for impulse radio are given as a function of Gaussian pulse derivative order. By taking into account the delay spread and inter-pulse interference, the capacity for PPM-UWB systems is studied in [163]. The capacity for PPM-UWB signals in a multipath channel is studied, e.g., in [164,165]. In addition, PPAM and BPPM capacities in AWGN and multipath channels are discussed in [125] and [127], respectively. Thought there are papers available on multiuser capacity and capacity in a multipath channel, after the literature survey, no published papers on UWB capacity calculations under (un)intentional interference were found.

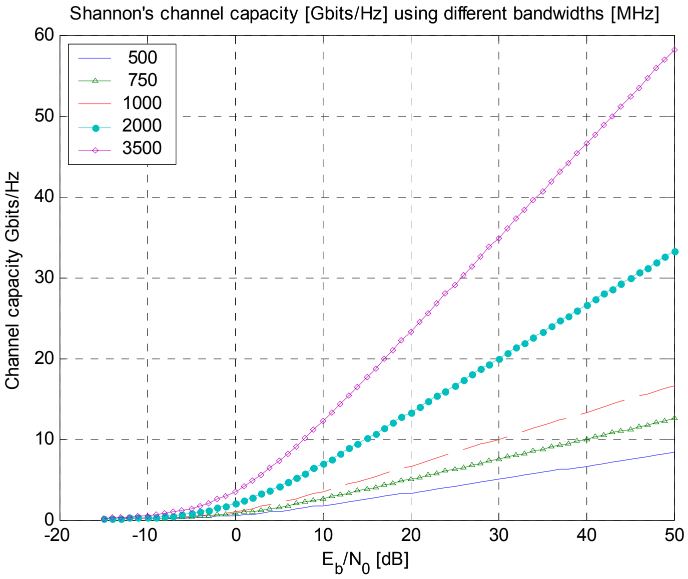

Fig. 13. Shannon's channel capacity for different bandwidths as a function of E_b/N_0.

2.7 Applications

Due to a good resistance against severe multipath fading, TH-UWB can be used in wireless local area networks (WLAN) and in-building communications as a wireless cable replacement to compensate, e.g., IEEE1394 (which is also known as FireWire® (Apple) and i.LINK® (Sony) [166] with data rates of 400 Mbps [167]). UWB technology, due to its capability for high data rate transmission, is an option to link a mobile terminal, laptop etc. to data storage (hard disk) or some other peripherals (printer, screen etc.). For high data rate communications, wireless USB (Universal Serial Bus) having a data rate of 480 Mbps is one of the first applications that will come out on the market [167]. At the end of March, WiMedia Alliance and Bluetooth Special Interest Group announced that multiband-OFDM technology was selected as a common radio platform for the next generation high speed Bluetooth that will operate in a band of 6 – 9 GHz [168].

UWB localization/positioning can be used in places where the global positioning system (GPS) does not work, like indoors, in mines etc. UWB localization can give fine relative position instead of absolute position as GPS does. The UWB range (or position) resolution of tens of centimeters is more accurate than what can be gotten from GPS. Estimated UWB idle power can be as low as 30 μW [169]. If the UWB devices, or at least one of them in the network, knows the exact position (being an anchor node), also absolute position could be calculated. A comprehensive overview of UWB localization techniques is given, e.g., in [120].

The high target resolution of time modulated UWB systems can be used in geolocation, ranging, tracking, navigation, and security systems. Good penetration properties can be utilized in surveillance systems [25], through-wall radars [170,171] and 'through material radars', like ground penetrating radars [12,145,172]. For example, in law enforcement applications, the lower frequency part of the spectrum can be utilized, which improves the signal propagation properties. GPR applications can be found, e.g., from landmine or buried obstacle detection. The first commercial ground penetrating radar was developed in 1974 and commercialized by Geophysical Survey Systems, Inc [11]. Different kinds of GPR applications are listed in [172]. The radar applications benefit from the penetration properties provided by singleband UWB, which operates in lower frequencies, with a center frequency being less than 1 GHz. If higher frequency band is used, the capabilities of radio signal penetration decreases. Good spatial resolution can be utilized, e.g., in a reverse driving aid in cars [173]. In addition, low transmission power guides the technology towards very short-range and low data rate applications, like electric door openers etc. where the generated interference against other systems is minimized.

UWB radars can also be used in medical applications. The following paragraph discusses a little bit on that subject to show the multipurpose use of UWB technology. The applications where UWB can be utilized in medicine are, e.g., in the field of breath, heart and speech research. Actually, the first UWB radar application in medicine was a cardiovascular monitor in 1994 [174]. In a scientific journal, a medical UWB radar application was first introduced in the *Journal on Acoust. Soc. Am.* 103(1), Jan 1998, as was pointed out in [174]. An educational radio stethoscope link project was launched at the Massachusetts Institute of Technology (MIT) in 1995 [174] but the author does not have any further information about the progress of this trial. As UWB technology introduces new problems in communication applications, e.g., in radio channel modeling, similar problems in medicine will arise; models for UWB dielectric properties are missing, as pointed out in [174]. Other medical applications for UWB can be, e.g., vocal cord monitors or devices seeking for sleep apnea [174,175]. References [174,175] nicely summarize the exploitation of UWB technology in medicine. In addition to the previous references, non-invasive human body measurements are discussed in [176,177]. In [178,179], the measurements of breast cancer and cardiac activity using a UWB signal are studied, respectively. In [180], the utilization of a UWB data link in a hearing aid is proposed. Wireless body area networks (WBAN) can also support medical aims through intelligent clothing. Several human body parameters could be measured by the sensors installed in cloth material. [181,183] report the results from WBAN channel measurements, which also indicates that WBAN applications are interesting for future technology deployment.

Not only for communication or through-material type radar applications, UWB can be exploited also in sensors or sensors networks. One can use intelligent UWB sensors in airbag control, collision warning, parking and reversing aids and other applications in the vehicular environment. In sensor networks, the UWB signal can be used in an invisible data link to transfer control and data information inside a network in addition to only being the active monitoring signal. Unmanned aerial vehicles applying UWB sensors for surveillance and reconnaissance, as well as different kind of radars, are discussed in [184]. Paper [53] estimates that 88% of the UWB volume markets will cover indoor communications and measurements systems, 10% covers the corresponding outdoor systems, and the last 2% will be allocated to imaging systems (in- and though-wall, medical and ground penetrating radars, surveillance devices and liquid level detectors).

3 Summary of the coexistence review

Digital cameras, for example, have been very popular and cameras are recently embedded even into cellular phones and personal digital assistants (PDA). For example, in cellular phones, there could be picture uploading and a voice call ongoing at the same time. This requires that these two operating communication systems have to interoperate simultaneously without any effect on link quality. The size of the mobile terminal also limits the maximum distance between the antennas of these two active links, if not even being embedded into the same antenna. After this simple example, the interoperability problem is set. In this section, a summary of the literature study of UWB impact on other radio systems is given.

3.1 UWB and GPS

For the FCC's NPRM responses, several federal organizations in the USA carried out UWB coexistence studies. Early work by the NTIA on temporal and spectral UWB characteristics has been published in 2001 [185]. In [186-188], the experimental coexistence study results between UWB and GPS are introduced. An obvious observation was that the line spectrum appears when the transmitted pulses are uniformly spaced. By changing the pulse repetition frequency, the line spectrum can be shifted and the impact on GPS can therefore be decreased. Using some dithering technique (such as pseudo random coding or pulse position modulation), the line spectrum can be diminished, and the UWB impact could then be insignificant on the specific narrowband victim receiver. A high PRF will cause more interference to GPS due to the higher aggregate energy. A low duty cycle of the UWB signal further degrades the interference caused to the victim due to the smaller amount of received average energy. In [186], 245 ps and 500 ps UWB pulses were used as interference sources, and the signal was sent using OOK or uniformly spaced pulses. In addition to that, absolute and relative referenced dithering was utilized. Studies were based on simulations, and both radiated and conducted tests. In the measurements, the victim system was a GPS simulator whose signal acquisition and tracking features were monitored in the presence of UWB interference. The concluding remarks in [187], which is an addendum to [186], noted that if the PRF is significantly less than the bandwidth of the victim receiver, UWB interference is impulsive (i.e., the pulse width is much smaller than the integration time of the receiver/detector). This rarely causes satellite lock loss. UWB signals with a high PRF and no dithering have strong spectral line components, and therefore they are the most invasive to GPS receivers. When a high PRF UWB system is used, dithering is required to minimize the effect on GPS (or some other victim system). In addition to that, PPM or bipolar data modulation schemes will improve the dithering effect by randomizing the transmission structure. Reference [188] did not give any recommendations for the standardization process but the document lists the measured and analyzed results for UWB and GPS coexistence. In [189], the victim receivers were selected amongst federal telecommunication systems, including different types of radar and satellite systems. In the conclusions, it was stated that UWB operation in the band of 3.1 … 5.65 GHz, at antenna height of less than two meters, are feasible but the frequency band below 3.1 GHz needs more studies.

Previous documents were prepared for NMPR by the NTIA. The following results are gathered from other sources. [190] discusses the aggregate UWB interference on GPS. [191,192] and its summary in [193] reported the interference caused by multiple UWB transmitters to a GPS receiver, and the conclusions pointed out that the multipath propagation and difference in the interference distance have a great impact on GPS performance. In [194], it was stated that the UWB signal structure could be designed to have the characteristics of white noise within the GPS frequency bands. This enables the modeling of aggregate UWB interference using the white noise approximation. However, the spectral characteristics depend on the used modulation scheme, and on the multiple access model. Based on the experimental tests, distances between the GPS receiver and UWB devices that are longer than 3 m did not cause any degradation in GPS performance. According to [194], the results depend still more on the GPS receiver used than the UWB signal itself. However, reference [194] does not give any general conclusion or recommendation on the subject. In [195], the aggregate UWB interference on different victim system bandwidths is simulated. The discussion is similar to the one earlier presented in Paper I, which utilizes both TH and DS UWB systems with binary PAM and three different pulse waveforms. In addition to the GPS system, also radio communication systems like UMTS, fixed wireless access (FWA) and DCS1800 are dealt with as victim systems in [195]. In [196], the software approach to measure the UWB impact on a GPS receiver is presented. The proposed method makes the tests repeatable because the air link effects can be removed from the results. In addition, Papers I and II have also touched on the coexistence problem between UWB and GPS. Because the GPS signal at ground level is very weak, any increase in the noise floor has made the GPS community very anxious about UWB.

3.2 UWB and cellular systems

UWB coexistence with cellular systems is studied in [197-199], as well as in Papers I – V and Paper IX. The results of the original papers are summarized in Chapter 1. Paper [197] discusses UWB in-band interference in the UMTS band, and the key observations were included in Paper II. The results of [198] and [199] created a background for further

UWB system performance simulations in the presence of jamming, and their observations have been taken into account in Papers II – V.

Based on the analytical derivations, [200] suggested that the FCC mask does not give sufficient protection for UMTS against the noise increase based on multiple UWB transmitters if the target outage probability is 1%. GSM900 is reasonably protected but GSM1800 is affected by UWB. In [195], which is an extended version of [201] and [202], the coexistence between cellular, GPS and FWA were discussed. The authors do not see significant performance degradation in victim systems due to the interference based on UWB with a center frequency above 3.5 GHz.

In [203], both the link and network level simulations for a UMTS system have been carried out in the presence of bursty UWB interference. In the conclusions, the authors propose for Europe tighter radiation masks than adopted by the FCC. [204] reports bit and block error rate results (BER and BLER, respectively) that are based on real UWB coexistence measurements with GPS/GPRS (general packet radio systems) and wideband code division multiple access (WCDMA). The measurements were carried out using both radiated and conducted tests. The corresponding coexistence measurements carried out by the CWC, and included as original papers in this thesis (Papers I for WLAN and Bluetooth, and Paper IX for UMTS), are based only on radiated measurements. Reference [205] reports the maximum tolerable UWB power levels within a UMTS band. The results are based on the empirical tests and the authors suggested more restrictive radiation limits for Europe than those accepted by the FCC. For example, in the UMTS band, the maximum acceptable UWB power level should be around -110 … -95 dBm to achieve a 10^{-3} BER. The authors of [195] have concluded the opposite opinion. Based on their studies, UWB systems operating under the FCC limits do not cause any performance degradation to the analyzed power controlled radio systems, such as UMTS, FWA, GSM and GPS.

A different aspect to UWB and UMTS coexistence is given in [206], where a 0.7% – 2.5% decrease in UMTS cell area, and therefore a 0.1% - 0.4% decrease in the UMTS quality of service were estimated because of the aggregate UWB interference. The study was based on different environment models, and £44 million costs for the operators during 2004 – 2010 were approximated due to the cell area reduction. However, this kind of cost effect calculation depends highly on the assumptions used, and therefore is quite inaccurate.

3.3 UWB and WLAN

In [207], the UWB impact on an IEEE802.11a wireless local area network, and vice versa, is reported. Based on the simulations carried out in the paper, the UWB impact on 802.11a has been seen as insignificant if the WLAN has a LOS link. However, if the WLAN SNR decreases, e.g., through a NLOS link, the UWB interference will degrade the achieved WLAN throughput. In general, the UWB impact on the victim receiver's SNR is worse than the impact on throughput, which does not drop so much when the UWB interference is involved. All the system (simulation) parameters in [207] are taken from WLAN [26] and UWB [24] standards. On the other hand, the paper also predicts

UWB system performance degradation in the presence of a WLAN signal for varying link distances.

Papers [208,209] also discuss UWB and IEEE802.11a coexistence. A similar type of coexistence study to those carried out at the CWC with measurements, is reported in [210] where the results are based on simulations. However, the victim system in [210] was IEEE802.11a and, e.g., in Paper I the victim system was IEEE802.11b. In [210], the negative UWB impact on the IEEE802.11a downlink was seen as small, except if the devices are in very close proximity to each other. The conclusion in [210] was similar than ours but due to the better spectral overlapping between the two systems, the results in [210] were worse; the minimum required distance between the transceivers that does not cause interference was longer than in our case. [210] also showed that the throughput of the victim system decreases when the number of UWB users increases. The coexistence between IEEE802.15.1 (Bluetooth) and IEEE802.11b has been studied, e.g., in [211-213]. The papers report insignificant WLAN performance degradation due to the UWB interference if the separation between the devices is more than 40 cm. The UWB influence on WLAN and Bluetooth networks is reported in [214,215], and their main results are merged into Paper I.

3.4 UWB and FWA

Fixed wireless access (FWA) services are operating at 3.5 GHz, 3.6 ... 4.2 GHz and 4.4 ... 5.0 GHz [216]. The results presented in [217] show that by introducing a few simple elements of the UWB system (such as activity factor, power control or realistic propagation models) in the simulation scenarios, even in the extreme UWB densities proposed (over 67.000 devices per km^2) there is no risk to FWA operations. The margins found in the 'hot spot' scenario are exceeding the margin currently used for safety-of-life systems. However, further operational margins not considered in [217] still exist; e.g., outdoor propagation, attenuation, admission control techniques, antenna polarization mismatches, deep NLOS (non line-of-sight) and multiple trough-wall indoor losses. Reference [53] proposed a 5% UWB activity factor to be used in the studies. In addition, a speculation of realistic UWB densities (total and active) and indoor/outdoor ratio were given in the same source. UWB impact on FWA is studied also in [195]. The FWA part of [195] is covered in [218,219] in more detail. The hotspot analysis in [220] showed that the UWB activity factor, and the channel model for UWB, affect the FWA performance. The paper concluded that those two systems could peacefully coexist. A similar conclusion was drawn in [221].

3.5 Generic coexistence

In [222], and in its extended version [223], the TH-PPM and DSSS signal ability to tolerate wideband and narrowband interference were analytically studied. The authors concluded that if the interference is wideband, i.e., a spread spectrum signal, the interference suppression capability in both systems is similar. However, if we are dealing with narrowband interference, the UWB system outperforms the DSSS system. The impact of narrowband interference on a UWB receiver in general is studied also in [143] using continuous wave interferers; both single tone and multi-tone. The channel was AWGN and the desired system was utilizing either a hybrid DS/TH-UWB or DS-UWB approach. An analytical study on the impact of narrowband interference in a multipath fading channel on TH-UWB that is based on PPM is given in [224]. The authors concluded that the UWB performance could be degraded most if the interference is overlapping with the nominal center frequency of the UWB signal. The impact is possible to mitigate by proper selection of the modulation index or using notch filters. Using minimum mean square error combining, similar improvement in the UWB system performance is achieved, but without the need to estimate the frequency of the interfering signal. What interference suppression method should be used is a compromise between complexity and system performance requirements.

In [225], the impact of a Gaussian pulse based UWB system on a narrowband BPSK system is studied through analysis and simulations in an AWGN channel. The studies were carried out with multiple interference sources; either one or ten interfering UWB signals were used. The interference based on UWB was seen as harmful only with large power UWB pulses because only a fraction of the energy will pass through the narrowband front-end filters. In general, due to the assumption of flat PSD in the victim receiver's band, the UWB signal is assumed to raise the noise floor approximately by $P_{\mathrm{rx}}W_{\mathrm{NB}}/2f_{\mathrm{c}}$, where P_{rx} is the total received UWB power, W_{NB} is the bandwidth of the NB system and f_{c} is the UWB center frequency [225].

In [226], the closed-form presentations for bit error probability of a TH-PPM system in AWGN and flat fading channels in the presence of narrowband interference are given. Papers VI and VII extended the study on binary DS-PAM (DS-BPSK). On the other hand, in [227], the formulation to calculate the bit error rate of a generic narrowband receiver in the presence of UWB interference is given. Interference modeled as white Gaussian noise was seen to be a sufficient approximation to illustrate UWB. Earlier than [227], in-band powers were studied in Papers I – II. In [228], the victim system is a DSSS receiver, and the UWB transmissions were based either on binary TH-PPM or on TH-PAM. Based on the given results, a DSSS receiver can tolerate UWB interference with up to -30 dB signal-to-interference ratio (SIR) values. The conclusion in [229] stated that UWB system parameters have a key role in anti-jamming tolerance. The paper studies binary TH-PPM, TH-PAM and DS-PAM theoretically and through simulations. TH-PPM UWB system impact on DSSS systems, and vice versa, have been studied in [230] where it was shown that UWB is less sensitive to DSSS interference than DSSS is to UWB interference. Paper [231] analytically shows the impact of the spreading code and code length on the DS-UWB system performance in the presence of multipath propagation and narrowband interference. The proper selection of the code improves the resistance against multiuser interference but multipath propagation and NB interference can be better tolerated if a non-DS system is used. The gain of the PRN code depends on its auto- and cross-correlation properties so that the sequence autocorrelation function and cross correlations among the code families should be minimized.

Papers VI and VII deal with the analytical coexistence studies and their results are discussed later on in Chapter 4. The presented theoretical approach is very simple if compared to the other existing formulations and therefore the results are quick to calculate.

The comparative study between the performance of DS-UWB and MB-OFDM systems in AWGN and multipath channels has been carried out in [5]. The results showed that a coded MB-OFDM system can perform better than uncoded DS-UWB if the signal-to-interference ratio is very small, being less than -15 dB and -22 dB in an AWGN and multipath channel, respectively. However, the achievable BER level in the MB-OFDM case is higher with small interference-to-signal ratios if compared to the DS-UWB system. The results shown in [5] also indicate that multiband UWB requires channel coding but reasonable good results are possible using uncoded DS-UWB.

As shown in [232], the UWB out-of-band interference testing in production indicates the increasing interest in UWB also on the manufacturers' side. As far as the author of this thesis knows, this is the first paper touching on testing in an UWB production line.

3.6 Summary

As shown by the previous sub-sections, the impact of UWB on other radio systems has globally been a very popular topic in the research field. The importance of the subject arises because some operators have been very concerned about the possible harmful effects that UWB signals can generate. In general, the interference studies have been carried out analytically and by measurements. The victim system is typically selected by the involvement of the corresponding research institute or organization.

The comparative study between different UWB physical layers has not widely been reported and the goal of this thesis, and the original publications, was to fill this gap. Using similar system assumptions for different UWB PHY realizations, the differences between them could be found. The experimental work completed these coexistence studies.

As a summary of the literature survey, UWB has been seen as a threat by the operators of GPS and existing cellular systems. Most threats concern the aggregate increase in the noise level due to the large population of possible UWB devices. The increase in the aggregate noise level could decrease the cellular network capacity, or the accuracy of the positioning system. However, it was also shown that UWB can coexist with the existing systems, and the interference distance (i.e., the minimum distance where different systems do not interfere with each other), for example, between UWB and WLAN it is less than half a meter. Typically, theoretical calculations in the published work also use unrealistic numbers of active UWB transmitters in a space, which makes their result rather pessimistic for UWB exploitation.

4 Framework of the research

The driving force throughout this thesis is UWB impact on other radio systems, and vice versa. The performance of different UWB physical layer structures has been studied, mostly via simulations in an AWGN channel, but also using the modified Saleh-Valenzuela [109,110] channel models. In addition, the studies have been performed with interference that is based on the selected existing radio systems, such as UMTS, GSM or GPS. During the simulations, the interference is introduced at the physical layer, thus in the radio channel. The higher layer interference interaction is not taken into account (e.g., those in the MAC or higher OSI-layers). In addition, UWB impact on the victim system is presented analytically, by simulations and theoretical calculations.

The other part of the study relates to the experimental work where simple UWB prototype transmitters were used to generate intentional interference to existing wireless local area networks and UMTS. In the WLAN case, the victim systems considered were IEEE802.15.1 (Bluetooth) and IEEE802.11b.

4.1 Simulation approach

This study has been carried out using a link level simulator programmed in Matlab®. In this section, the simulator structure is briefly described. Simulations are used to study how much interference UWB signals generate in selected application bands, and what is the impact of external interference on UWB system performance. Especially, the impact of the interference on the DS-UWB signal is studied analytically, and the results are verified with the simulated ones. System performance simulations other than from the UWB viewpoint have not been carried out within this study. Thereby, the UWB impact on the other systems is presented through in-band interference calculations and experimental measurements.

Several pulse waveforms can be used in single-band UWB communications. The most common waveforms are based on Gaussian [51] or Hermitean pulses [233-235]. Section 2.3 introduced also the idea of soft-spectrum adaptation that could be utilized in pulse design. Throughout the analytical part of the thesis, Gaussian pulses were obtained. It was assumed that the pulse waveform in the channel is the first derivative of the generated pulse. The derivation is based on the antenna characteristics, as pointed out also in [49,97]. In this study, the modulation schemes used are PPM, PAM, OOK and PSM. The system concept performances are studied in different kinds of interference scenarios. Both AWGN and the multipath channels that are based on the IEEE802.15.3a recommendation [109] are used. Reference results from an AWGN channel are always given.

The block diagram for link level simulations is presented in Fig. 14. The pulse train is generated in the transmitter block (TX). Pulse shape filtering, as well as modulation and the adopted multiple access technique, being either TH or DS, are also introduced in the same block. A jamming/interference block is used to create an interfering signal, and it can be either narrowband or wideband. In addition, multiple interferers are supported. The UWB signal level in a victim receiver's band can be calculated at point A marked in the picture. Later on, in Papers I and II , the signal level at this point is called in-band interference.

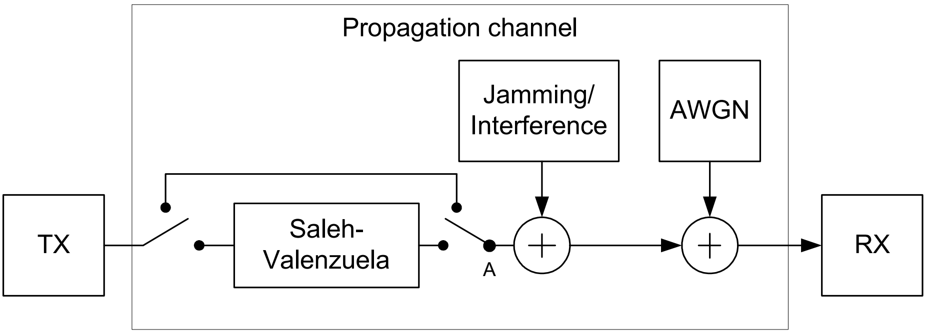

Fig. 14. Studied link level block diagram for UWB system simulations.

4.1.1 Signal model

Analytically, the different transmitted signals can be defined using the following representations:
The analytical form for TH-PPM is

$$s(t) = \sum_{k=-\infty}^{\infty} \sum_{j=1}^{N} w\left(t - kT_{\mathrm{d}} - jT_{\mathrm{f}} - (c_{\mathrm{w}})_j T_{\mathrm{c}} - \phi d_k\right), \tag{18}$$

for TH-PAM

$$s(t) = \sum_{k=-\infty}^{\infty} \sum_{j=1}^{N} w\left(t - kT_{\mathrm{d}} - jT_{\mathrm{f}} - (c_{\mathrm{w}})_j T_{\mathrm{c}}\right) d_k \ , \tag{19}$$

for DS-PAM

$$s(t) = \sum_{k=-\infty}^{\infty} \sum_{j=1}^{N} w\left(t - kT_{\mathrm{d}} - jT_{\mathrm{f}}\right)\left(c_{\mathrm{p}}\right)_j d_k \ , \tag{20}$$

for TH-PSM

$$s(t) = \sum_{k=-\infty}^{\infty} \sum_{j=1}^{N} w_k\left(t - kT_{\mathrm{d}} - jT_{\mathrm{f}} - \left(c_{\mathrm{w}}\right)_j T_{\mathrm{c}}\right) d_k \ , \tag{21}$$

and for DS-PSM and DS-OOK

$$s(t) = \sum_{k=-\infty}^{\infty} \sum_{j=1}^{N} w_k\left(t - kT_{\mathrm{d}} - jT_{\mathrm{f}}\right)\left(c_{\mathrm{p}}\right)_j d_k \ , \tag{22}$$

where T_{d}, T_{f} and T_{c} are data, frame and chip lengths, respectively. C_{w} and c_{p} represent the momentary code word and the user dependent pseudo random code phase, respectively. W_k represents the used pulse waveform which, in the case of PSM and OOK, is defined by the polarity of the data bit d_k. In PPM, ϕ is the modulation index, e.g., time difference between the pulses depicting data bits “0” and “1”. The function of the studied UWB system concepts can be seen from Fig. 15, where one data bit is spread over multiple pulses utilizing both DS and TH methods. A time hopping frame structure is also depicted.

In the example shown in Fig. 15, one data bit is divided into ten frames ($T_{\mathrm{d}} = 10 \cdot T_{\mathrm{f}}$). The processing gain is set to 20 dB, which means that in the DS-concept 100 consecutive pulses have been used to transmit the data bit. In the corresponding TH-concept, ten pulses are sent, and the duty cycle is set to 10%, i.e., $T_f = 10 \cdot T_p$. The energy calculated over the data bit is the same in both approaches but the peak power level is higher in TH due to the smaller amount of transmitted pulses. This causes higher impulsive interference to other radio systems.

Though the modulation levels studied in the thesis are all binary, also M-ary modulation schemes can be used to increase the data rate and spectral efficiency. A drawback of M-ary modulation is the need for higher SNR to maintain a specified BER level. The selection of a proper modulation method affects the whole UWB system performance, and it is therefore an important issue. To fight against interference that is based on multipath propagation or intentional interference (or jamming), the selection of pulse waveform and pulse width gives tools to improve the overall system performance. By changing only one of these parameters, the spectrum allocation could be done, and in the best case, the spectral overlapping with other radio systems could be avoided. As pointed out in the original papers II – V, the UWB performance is also affected by the multiple access scheme used being either DS or TH. The more advanced methods, thus different interference suppression and mitigation methods, are left to the other studies. In addition, these additional features also make the receiver more complex, and therefore they are excluded from this study.

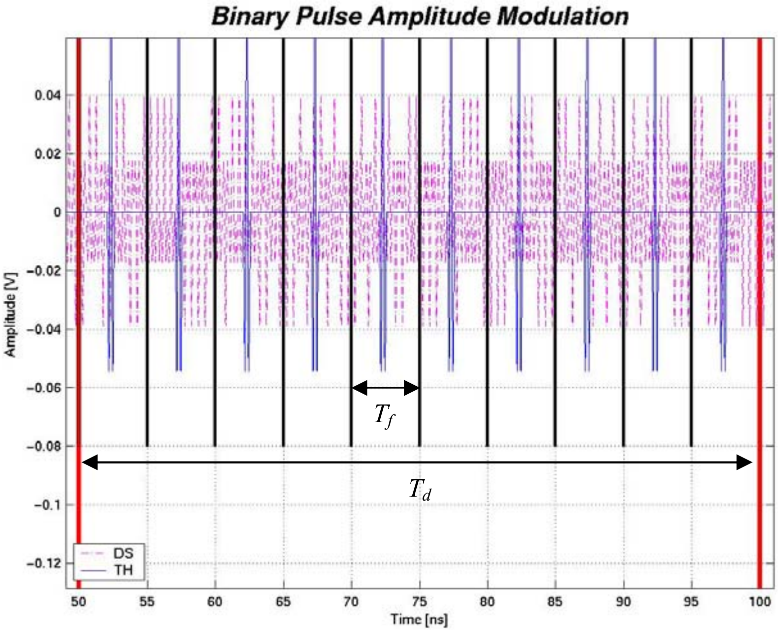

Fig. 15. DS and TH UWB physical layer concepts utilizing BPAM modulation.

4.1.2 Channel model

The propagation media for high data rate UWB applications is modeled using a channel model derived by the IEEE802.15.3a study group [109,110,236]. The multipath channel is a so-called modified Saleh-Valenzuela model, which consists of four different models characterizing clustered indoor channel impulse responses. The models are defined for LOS link for distances between 0 … 4 m, and NLOS for both 0 … 4 m and 4 … 10 m links. The fourth model describes the worst-case NLOS scenario for links between 4 … 10 m. In [109], the minimum number of simulated channel realizations is defined as 100 per calculated BER value, at minimum. The average delay profile for each model is given in Fig. 16. The number of most significant paths, thus those whose level is less than 10 dB below the strongest path, is presented in Fig. 17.

Table 1. Channel characteristics for different Saleh-Valenzuela models.

Model characteristics	SV1	SV2	SV3	SV4
τ_m, mean excess delay [ns]	5.0	9.9	15.9	30.1
τ_{rms}, RMS delay [ns]	5.0	8.0	15.0	25.0
NP_{10dB}, number of paths within 10 dB	12.5	15.3	24.9	41.2
$NP_{85\%}$, number of paths containing 85% of energy	20.8	33.9	64.7	123.3

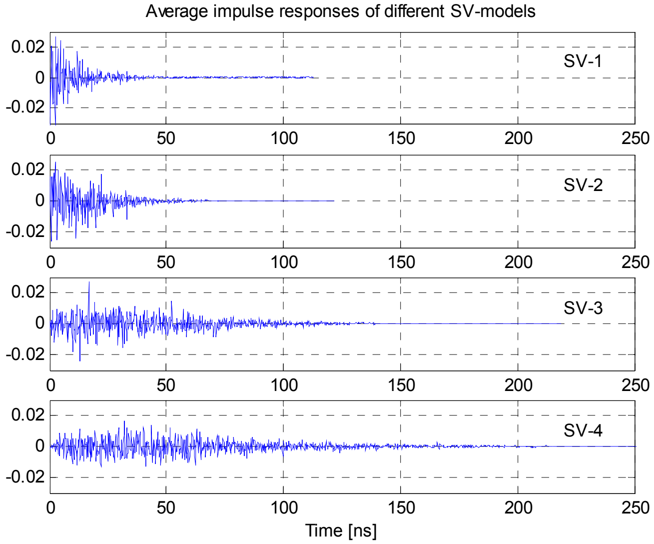

Fig. 16. Average delay spreads for the four modified Saleh-Valenzuela models. Each profile is averaged over 100 realizations.

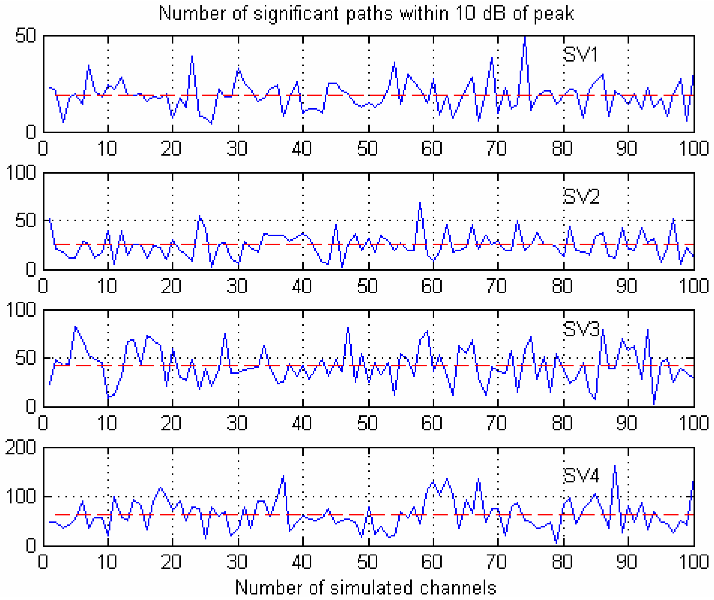

Fig. 17. Number of paths within 10 dB of the peak. Dashed lines depict the average value.

Table 1 summaries the channel characterization for different modified Saleh-Valenzuela models (SV) [109]. The mean and root mean square (RMS) delay terms are giving the length of the channel impulse response, i.e., the delay of the longest detectable multipath component if compared to the first arrived path. NP_{10dB} and $NP_{85\%}$ define the number of distinguishable propagation paths whose energy is within 10 dB if compared to the strongest path, and the number of paths which convey 85% of the entire energy, respectively.

The study group IEEE802.15.4a has also defined a channel models for low data rate UWB applications [113]. The covered frequency range in this recommendation is 2 … 10 GHz. The models are for indoors (office, industrial and residential) and outdoors. In addition, models for body area networks within the band of 2 … 6 GHz with a 1 MHz carrier are discussed. Because the research work included in this thesis has not utilized these models, they are not discussed here in more detail. If the reader is interested in those models, [113] is available from the Internet.

Typically, the system performance results, such as bit error rate, are presented as a function of the signal-to-noise ratio, or E_b/N_0, at the receiver. This presentation excludes, e.g., the impact of path loss from the explicit results. However, based on the SNR, or E_b/N_0, values, as well as the knowledge of the receiver sensitivity and gains in the receiver chain, the transmission power can be estimated if the path loss is known. Link budget calculations will decrease the emitted power by the value that is proportional to the link distance, antenna characteristics and propagation environment, as noted by (9). In BER results presented in the original papers, the impact of path loss is embedded in the E_b/N_0. The use of (9) is encouraged if one likes to reflect the results to the transmission power requirements.

4.1.3 Interference model

The simulations cover three kinds of interference models: multiple tones, and both pulsed and colored Gaussian noise, which are wideband in nature.

Tone interference consisted of multiple narrowband tones whose power and frequency could be set. This model reflects the coexistence between UWB and GSM. Due to the extremely large ratio between the bandwidths of these two systems, tone interference is well justified for this purpose (200 kHz/500 MHz $\hat{=}$0.04%). Typically in simulations, 10 tones are spread over the entire 25 MHz GSM band; either in the uplink or downlink band. The GSM system's physical channel numbers 0 and 124 were always occupied. The rest of the tones were randomly accommodated within the band of interest. During the simulations, tones were reallocated when the simulated SNR value was changed. For each bit, arbitrary phases for each tone were independently updated. The total power allocated to the interfered band was always evenly distributed over the tones. This procedure was selected to maximize the spectral occupation of the tones while still keeping the simulation time reasonable. Analytically, ten interfering tones can be modeled as

$$J(t) = \sum_{i=1}^{10} A_i \sin(2\pi f_i t + \theta_i), \tag{23}$$

where A_i, f_i and θ_i are the amplitude, center frequency and arbitrary phase of the i^{th} interfering tone, respectively.

The pulsed interference is generated using a sinc-pulse in the time domain. This approach was our first approach to model wider band interference using the time-domain UWB simulator. When implementing the pulsed interference model in the simulator, the FCC radiation mask was not yet defined. The UMTS system was selected to be the interferer due to the evident spectral overlapping between these two radio systems. The assumption was highly valid at the beginning of the 2000’s. The spectrum of the pulsed interference occupies 60 MHz in total of the UMTS band, and its roll-off is steep, i.e., the transition band between the passband and stop band is narrow. Again, the uplink or downlink bands were separately studied. The interference power is also selectable. This interference model can be seen as a pulsed transmission due to its impulsive feature in the time domain. The pulsed signal, having a bandwidth W_j, can be presented as

$$J(t) = A_\mathrm{j} \sin(2\pi f_\mathrm{j} t)\,\mathrm{sinc}(W_\mathrm{j} t), \tag{24}$$

where A_j and f_j depict the amplitude and the center frequency of the pulsed signal, respectively. F_j was selected from the center frequency of the UMTS uplink or downlink band. In the end, the interference power level was the only parameter that could be freely selected with this model.

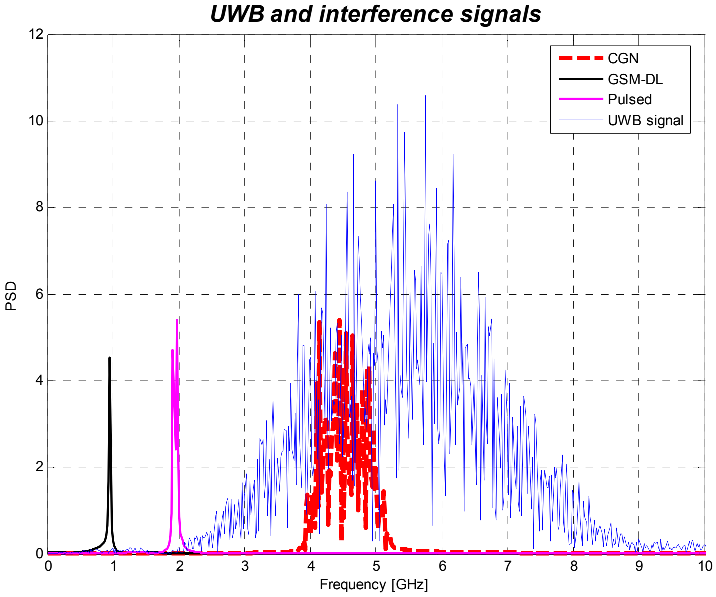

Fig. 18. Interference models used in the simulations presented with the UWB spectrum.

The third interference model used in the studies was more generic than the previous ones. If using the colored Gaussian noise (CGN) interference approach, the spectral allocation and the power level for the interference could independently be selected. Based on the central limit theorem, the sum of statistically independent and identically distributed variables that have zero mean and variance has a Gaussian cumulative distribution function [23]. This is why a band-limited CGN model was selected as the general interference model. For the spectrum allocation, both the center frequency and bandwidth can be defined. In this case, the white Gaussian noise signal is passed through a raised cosine filter. The output, after the filtering, has colored PSD, as the name obviously indicates. The formulation for band limited (colored) Gaussian noise can be found, e.g., from [23]. In our simulator, it is possible to allocate multiple CGN interferers independently to build a multiband interference scenario. Due to the used filtering, the spectrum of the interference has a gently sloping roll-off and the passband is not as flat as in the pulsed noise case.

In all the cases, the interfering signal is added to the desired signal in the channel, so the interference is also passing through the blocks modeling the front-end of the UWB receiver. All interference models that are used in the simulations are summarized in Fig. 18. The UWB spectrum in the figure is calculated for the 6th derivative of the Gaussian pulse having $T_p = 0.5$ ns.

4.1.4 Receiver structure

During the simulations, in addition to the AWGN channel, a multipath channel is also considered. In that case, different rake receiver types have been used to gain the diversity that is provided by the channel. The ideal diversity receiver captures all the signal energy available on the channel. In a rake type receiver, this is done by introducing as many rake fingers as there are distinguishable multipath components. The so-called all-rake (A-rake), whose idea is presented in Fig. 19, is such a receiver. The A-rake receiver collects all the signal energy from every resolvable multipath component [237-239]. The delay resolution τ_{res}, i.e., the finger spacing in rake, is inversely proportional to the used signal bandwidth. If the multipath separation in time is less than the delay resolution, the received signals are merged into one tap (finger) following the superposition principle. If the system bandwidth is infinite, all the energy could be captured.

The problem with the A-rake approach is the need for a very large number of rake branches, thus a huge correlator bank. The number of needed correlators is a ratio between the maximum detectable delay and the delay resolution of the system. Consequently, the implementation of an A-rake is not possible but it can be used as a reference (upper bound for the system performance) in system performance analysis.

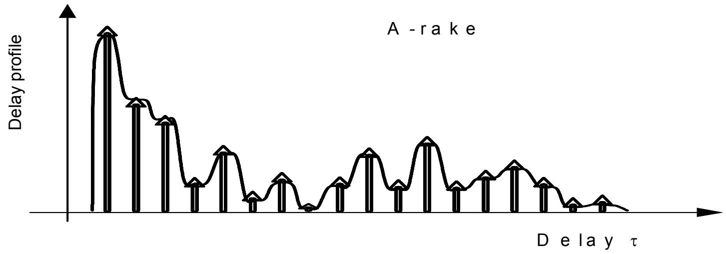

Fig. 19. Rake finger allocation for the all-rake receiver.

A practical rake receiver implementation is a selective rake receiver, S-rake [237,239], which is presented in Fig. 20. S-rake utilizes only *N* of the strongest propagation paths instead of all the distinguishable paths. *A-priori* information of the channel impulse response is required in order to maximize the performance of S-rake. This requires that channel estimation must be performed at the receiver. The SNR is maximized when the strongest paths are detected and their energy is coherently combined. The link performance will be improved relative to the single path receiver. The complexity of the S-rake receiver is much simpler if compared to A-rake because only those multipath components that have significant magnitude have been exploited.

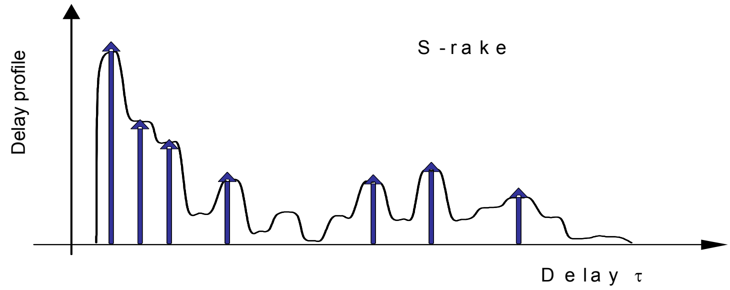

Fig. 20. Rake finger allocation for the selective-rake receiver.

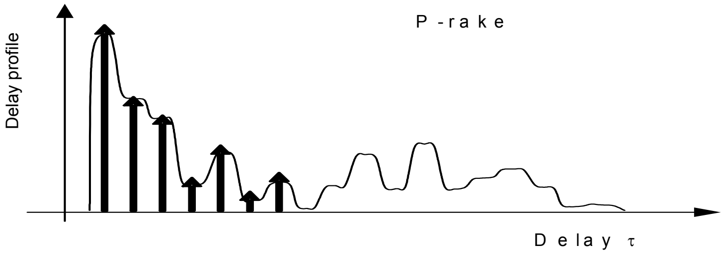

Fig. 21. Rake finger allocation for the partial-rake receiver.

The partial rake receiver, P-rake, represented in Fig 21, is the simplest rake receiver [240]. P-rake combines the *N* first propagation paths regardless of their magnitudes. The idea behind this approach is that the first multipath components will typically be the strongest ones, and they are conveying the majority of the received signal energy. There is no need for comprehensive channel delay estimation with the P-rake receiver except the delay of the first path, which has to be known. However, depending on the used combining method, there might be a need to estimate phases and amplitudes for the delayed multipath. The disadvantage of this structure is that the multipath components that the P-rake receiver combines are not necessarily the strongest ones, so the optimum performance might not be achieved, and therefore, the overall system performance is smaller than in S-rake.

Performance close to the performance of the AWGN channel can be met by using a maximum ratio combining (MRC) technique. MRC involves coherently combining and weighting of all the signal components to achieve optimal performance [23]. In a multipath AWGN channel, thus in noise limited environments, the MRC receiver is the optimal receiver to maximize the signal-to-noise ratio [241]. In interference limited environments (that might also include fading), other receiver structures could give better performance if they can maximize the received signal-to-interference plus noise ratio (SINR). Using the optimal combining strategy, the channel capacity is possible to maximize [241]. If different rake branches are weighted equally and only the phases are estimated, we are dealing with the equal gain combining (EGC), which is a sub-optimal method but is easier to implement [241]. However, this approach is limited to the modulation methods having a constant envelope and the performance is not as good as if using MRC.

In the simulator used, non-coherent detection algorithms were also embedded. In this study, square-law combining (SLC) with power estimation (PE) is utilized. Other non-coherent combining techniques, such as absolute combining (AC), do not reach similar performance in a multipath channel, as stated in [242]. However, if the power estimation is also utilized in AC, the difference between the performances of AC+PE and SLC+PE is negligible [242].

In all the studied cases, a correlator receiver is used. A template waveform is matched to the second derivative of the generated pulse, and the correlation between the received signal and template is calculated. It is also possible to use different template waveforms, but the optimal result will be achieved if the template is as close to the received waveform as possible. This means that also the distortions originating from the channel should be included. To make simulations and the comparison between the receiver architectures easier, perfect channel estimation and synchronization were assumed during the studies reported later on in Chapter 1.

4.2 Theoretical approach

Recently, the presented theoretical formulations to calculate the bit error rates of UWB systems in the presence of interference have been very scenario specific. Typically, one specific case has been defined and the closed form formulation has then been derived for that case. Most of the existing theoretical approaches are also quite complicated and their generic use is almost impossible.

The simulations carried out by the author of the thesis to find the UWB system performance in the presence of interference have shown that the direct sequence based UWB concept that utilizes binary (bipolar) pulse amplitude modulation gives the best performance from the studied PHY schemes (TH-PAM, TH-PPM, TH-PSM, DS-PAM, DS-PSM and DS-OOK, all binary). To make it faster to estimate the upper bound of UWB system performance, a simple theoretical method to calculate the bit error rate in an AWGN channel has been derived for DS-UWB. This result can be used as a maximum performance limit in the system and receiver algorithm design.

The idea for the analytical approach is adopted from [54] where the performance of a DS spread spectrum system is studied under interference (or jamming if dealing with a hostile environment). The assumptions in [54] were that the interference and thermal noise at the receiver are narrowband if compared to the carrier frequency of the desired signal. The original formula from [54] can be presented as

$$P_{\mathrm{b}} = Q\left(\sqrt{\frac{E_{\mathrm{b}}}{\left(N_0/2\right)+S\left(f_{\mathrm{j}}\right)}}\right), \tag{25}$$

where $S(f_{\mathrm{j}})$ is the despreader output PSD, which is a convolution of the PSDs' of the jammer and reference despreader waveform, i.e., the PSD of the affecting interference. Equation (25) is derived for heterodyne receivers, i.e., the signal is transmitted with a carrier after the frequency up-conversion stage. The impact of interference on the DSSS system is then calculated at the intermediate frequency.

By taking into account the effect of the power spectral density of the desired UWB signal, the impact of the interference on the UWB BER could be estimated better. As shown, e.g., by Torrieri in [55], the spread spectrum system's performance can be decreased most by jamming the carrier frequency. If the jammer (interference) is located in some other part of the UWB spectrum than its nominal center frequency, the performance degradation is smaller. Keeping this in mind, the approximation of (25) could be improved for interfered UWB systems by introducing a weighting factor ζ that takes into account the spectral properties of the UWB and interference better. As shown, e.g., in equations (4) and (6) in Paper VI, (25) can be re-written as

$$P_{\mathrm{b}} = Q\left(\sqrt{\frac{E_{\mathrm{b}}}{\left(N_0/2\right)+\zeta\cdot S\left(f_{\mathrm{j}}\right)}}\right) \tag{26}$$

and

$$P_\mathrm{b} = Q\left(\sqrt{\frac{2}{(N_0/2)+\zeta\frac{J}{P}\frac{R_\mathrm{d}}{W}}}\right) \tag{27}$$

for partial band and narrowband interference scenarios, respectively. Parameter ζ is the ratio between the PSDs at the center frequency of the interference and nominal center frequency of the UWB signal [Papers VI ,VII]. The accuracy of the analytical form from (25) is greatly improved if ζ is used, as proved in Papers VI – VII. In addition to ζ, $S(f_\mathrm{j})$ as presented in (25) is replaced with the PSD of the desired UWB signal to improve the accuracy of the formulations more. It was also shown that the calculation of the convolution between the jammer and reference waveform power spectral densities is not needed, which simplifies the calculations from (25). The modified approach was proven to fit also baseband UWB systems analysis with wideband interference. The most valuable feature is that it allows the use of real system parameters very easily, and the interference could be allocated independently of the UWB signal.

4.3 Measurement approach

The experimental part of the research was carried out by using UWB transmitters designed by the CWC and PJ Microwave, currently Elektrobit Microwave, Oulu, Finland [243] and built by the same company. Totally, two sets of different kinds of UWB transmitters have been built in a couple of projects. Both transmitters are shortly introduced in the following sub-sections.

The setups for the measurement were more or less similar although the victim systems differ. Both IEEE802.11b and Bluetooth links were interfered using the first generation UWB transmitters. The parameters measured from the victim systems were throughput and SNR. The improved version of the UWB devices use a higher frequency band and they were used in the coexistence measurements with UMTS. Now, the studied parameters affected by the UWB interference were received signal strength indicator (RSSI), carrier-to-noise ratio (E_c/N_0) and received signal code power (RSCP) measured at the UMTS pilot channel.

Because the empirical coexistence studies were carried out using radiated measurements, the results are not 100% repeatable. The medium (radio channel) affects the system performance due to the multipath propagation and unintentional interference that is not under control during the measurements. Reference measurements in an anechoic chamber were carried out to minimize the uncertainty.

4.3.1 First-generation UWB transmitter

The first UWB transmitter development within the FUBS project was based on a free running oscillator and a step recovery diode (SRD) to generate narrow pulses. In the transmitters, no data modulation was embedded. The centre frequency of the UWB signal is about 1.8 GHz, and the -10 dB bandwidth is about 1 GHz. The free running oscillator operates at an 83 MHz frequency, which means that the pulse repetition frequency is also 83 MHz. One UWB pulse is generated for each oscillator cycle and the pulse width is about 500 ps. The peak-to-peak voltage of the generated pulse is $V_{\text{p-p}} = 0.05$ mV and the average total transmitted power $P_{\text{av}} = 250$ mW. It should be noted that these transmitters do not meet the FCC radiation limit. The pulse waveform and the corresponding spectrum are presented in Paper I , Figures 1 and 2, respectively.

Totally, twenty pieces of the first generation high power UWB transmitters were used in the experiments. Because there is no common clock, the UWB transmission is asynchronous. The spectrum of the first-generation UWB transmitter is presented in Fig. 22 with the FCC mask. In addition, the IEE802.11b WLAN band, which was used as a victim system in Paper I , is depicted. Note that PSD in the figure is given in dBm/Hz.

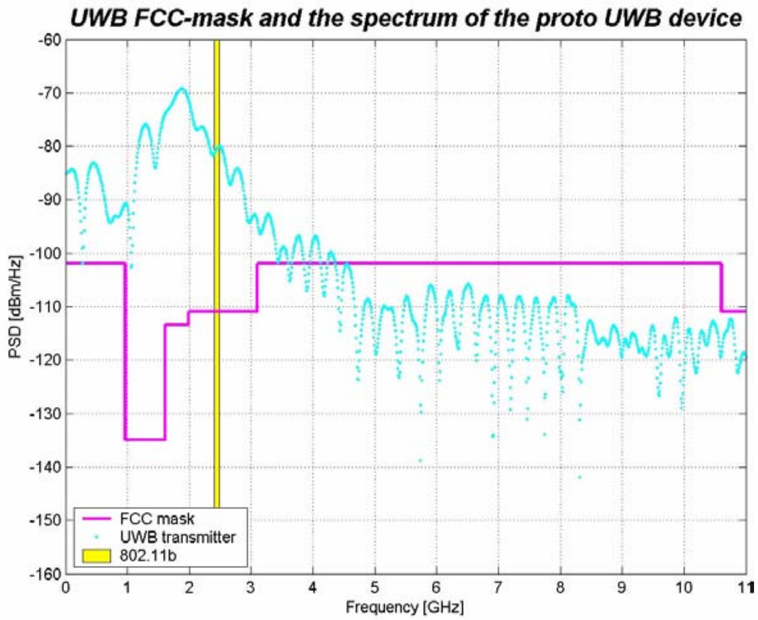

Fig. 22. Spectrum of the first-generation UWB transmitter.

4.3.2 Second-generation UWB transmitter

The second-generation transmitter follows the FCC radiation regulations. The center frequency of the UWB transmission is around 3.5 GHz and the power measured at the output port of the transmitter is about -11.8 dBm (0.0661 mW) within 10 MHz … 10 GHz. Again, the pulses are generated using step recovery diodes.

The second-generation UWB transmitters have external control boards. In these devices, the polarities of the radiated pulses are based on the sign of the maximum length code, i.e., the chip polarity defines the direction of the first slope of the pulse. Due to the adjustable control, there is a possibility to select several system parameters for the transmitter. The length of the code could be as long as $2^{20} - 1 = 1048575$. The activity factor (AF) of the transmission could be selected between 0 … 100% and the frame length between 10 μs … 1 ms. In addition, the pulse repetition frequency can be either 100 MHz or 200 MHz. Again, a common clock between the UWB transmitters was not used, and the generated interference was therefore asynchronous. The spectrum of the generated UWB pulse train is presented in Fig. 23. The pulse waveform's corresponding data bits "0" and "1" are presented in Fig. 24. As shown, the polarity of the pulse is different; representing a BPAM (equivalent to BPSK) modulated waveform.

In the experimental measurements, as much combination as possible during the limited time was tried to get a widespread view of the co-existence problematic.

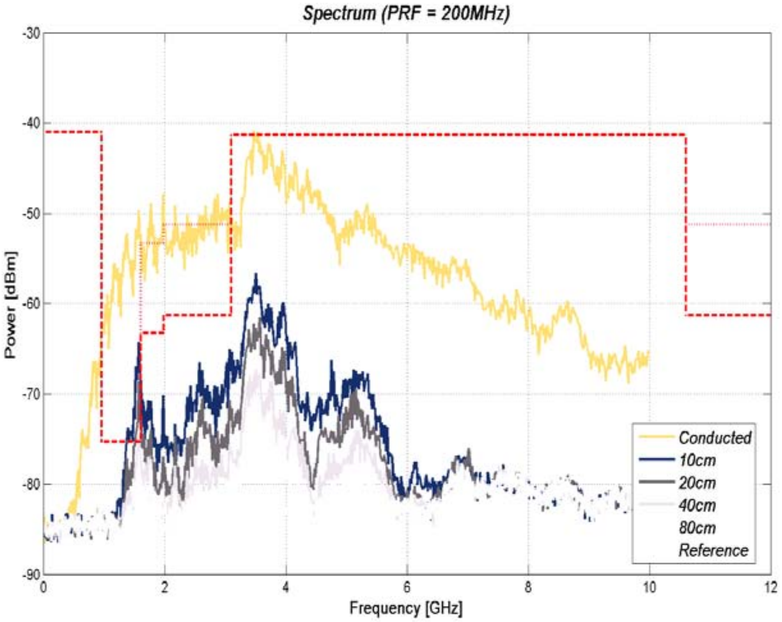

Fig. 23. Spectrum of the second-generation UWB transmitter.

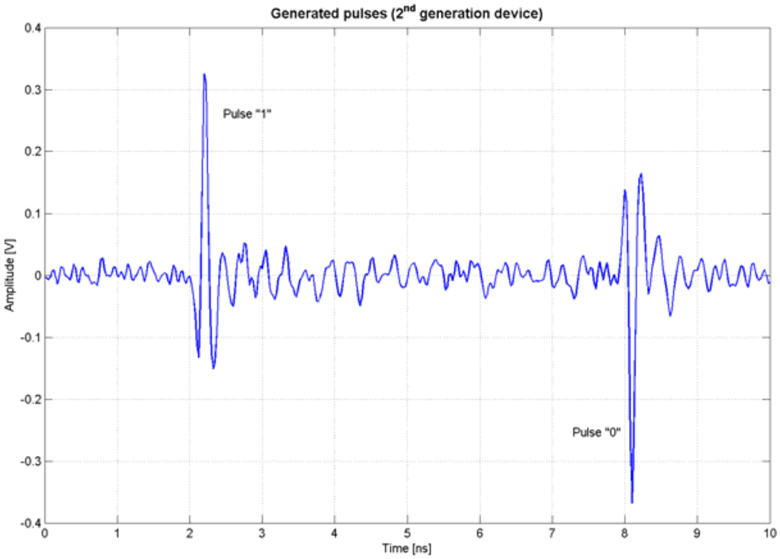

Fig. 24. Generated bipolar pulses.

In Fig. 23, the uppermost spectrum is measured from the output port of the UWB transmitter using a direct cable connection to the spectrum analyzer. The other spectra are based on the radiated measurements, i.e., the small dipole antennas that are designed in the FUBS project by [243] were connected to the UWB device and spectrum analyzer, respectively. The distances between the devices were 10, 20, 40 and 80 cm as pointed out in the legend. The background noise level and FCC radiation masks for indoors and outdoors are also depicted. The spectra are measured using a maximum pulse repetition frequency of 200 MHz and activity factor of 100%. The average level of the PSD is decreased if any of these system parameters is decreased. Thus, the spectra represent the worst-case scenario that can be achieved with the UWB transmitters available at the CWC.

5 Summary of the original publications

This section summarizes the research results and contributions from the work included in the thesis as original publications. Topics are divided into two sub-categories: analysis and measurements. Both of these categories are individually discussed and concluded in the following sections. The common theme throughout the original papers is the interference and coexistence framework. Table 1 summarizes the different scenarios discussed in the original papers. The research methods in the different papers are shown, as well as the used pulse waveforms, which are given in the Pulse column. The doublet waveform consists of two Gaussian monocycles that equal the first derivative of the Gaussian pulse. Real pulse stands for the pulse transmitted in the experimental work. The interference sources related to each original paper are also depicted. In the table, 11b and BT stand for IEEE802.11b and Bluetooth, respectively. The last two columns in Table 1 indicate which direction the interference is studied. In the simulations, both direct sequence and time hopping systems were always studied. The theoretical analysis is focused on DS systems.

Table 1. Studied scenarios investigated in the original papers. N in the Pulse column indicates that the approach is general.

	Research method				Interference					
	Sim.	Anal.	Meas.	Pulse	GPS	GSM	UMTS	WLAN	From UWB	To UWB
Paper I	x			1-3, doublet	x	x			x	
Paper II	x			1-3, doublet	x	x	x		x	x
Paper III	x			1-4			x			x
Paper IV	x			1-4		x	x			x
Paper V	x			5-6			x	x		x
Paper VI		x		*N*		general interference				x
Paper VII		x		*N*		general interference				x
Paper VIII			x	real				11b, BT	x	
Paper IX			x	real			x		x	

5.1 Analysis

This section gives a summary of the original papers included in the thesis. The discussion is divided into three parts; Section 5.1.1 studies the in-band interference that UWB generates in the selected victim systems' frequency bands; Section 5.1.2 where UWB system performance is simulated in the presence of interference; and the theoretical approach to calculate the bit error rate for UWB systems in the presence of interference, which is discussed in 5.1.3.

5.1.1 In-band interference

The first two original papers included in the thesis discuss how different UWB system parameters affect the spectral properties of UWB transmission, and therefore, on the increasing interference levels for several victim systems. At the time when Paper I was published, interference issues were not publicly reported much in academic venues. In addition, the physical layer concept in the reported studies available was almost only time hopping pulse position modulated UWB (TH-PPM). For example, in appendix A of [144], where the Gaussian monocycle that corresponds to the first derivative of the Gaussian pulse used in the thesis is analyzed. Papers I and II expand the reported studies, during the time when they were published, so that they consider different UWB PHY structures using similar general assumptions for the UWB system. The key idea was that both the spectra (TH-UWB and DS-UWB) allocate the same frequency band.

In Paper I, the simulated interference power levels calculated within the bands that GSM 900 and GPS systems occupy were discussed. Further on, the fraction of the UWB energy within a victim receiver's band is called in-band interference. Comparative results are presented for four different pulse waveforms as a function of UWB pulse width. Three of the waveforms were single pulses, being the first three derivatives of the Gaussian pulse. The fourth one was a doublet consisting of two Gaussian pulses. In addition, both time hopping and direct sequence concepts were considered.

Path loss or antenna losses were not taken into account in the calculations so the results presented radiated power that is comparable. However, these loss effects can easily be included into similar considerations. The effect of DS spreading on line spectrum appearance is also depicted in Paper I, Figure 7. The in-band interference study on GPS and GSM900 bands from Paper I was extended to cover UMTS in Paper II and [197]. The main results from the latter paper were merged into the former one.

It was shown that from the in-band interference point-of-view, that there was no significant difference which UWB PHY is used if the impact is studied only through in-band interference. In the simulations, the energy of the UWB data bit and the processing gain were fixed. Therefore, individual pulse energy depends on the UWB PHY. Because the TH approach is conveying the information with fewer pulses than the corresponding DS system, the individual pulse energy in the TH approach has to be stronger to maintain the same bit energy. On the contrary, if the pulse energy would have been fixed, the average transmission power would differ between TH and DS concepts having the same processing gain due to the different amount of transmitted pulses needed per data bit. In

Papers I – II, it was shown that the selection of the pulse waveform and pulse width strongly influences the in-band power. By selecting the pulse waveform and pulse width properly, the UWB spectrum is possible to locate in the frequency band where it overlaps as little as possible with the other radio systems. Relating results have later been published by other researchers, like [195], where Paper II is used as a reference.

The generated interference (noise rise from the victim system's viewpoint) could also be decreased if a doublet type waveform is used. This approach, however, limits the maximum attainable data rate due to the longer cumulative pulse width. The effect of the degradation of in-band interference is based on the silent gap between the individual pulses forming the used doublet waveform. In the frequency domain, the gaps create regularly appearing notches. However, singleband UWB is not so flexible to avoid multiple frequency bands, in general, due to its rather flat spectrum. One should also keep in mind that the frequency allocation affects also the propagation properties due to the path loss that is frequency dependent. In addition, the fabrication techniques and processes are affected by the frequency band, which is reflected in implementation costs.

As a common conclusion, DS-UWB was found to be slightly better from the coexistence point of view when compared to TH-UWB and thus it is causing less in-band interference for the selected victim receivers. However, as a summary, it has to be stated that if the strong line spectrum component lies within the victim receiver's band, the in-band interference effect is maximized, and this effect depends on the complete system parameters used.

5.1.2 Performance simulations

The other approach for studying coexistence issues is to calculate the bit error rate of the UWB system under jamming or interference. In addition to external interference and noise, the system performance is also affected by the channel model due to the possible multipath propagation. In every simulated case, the reference performance is calculated in an AWGN channel, i.e., the multipath propagation and interference were neglected. The simulations performed also assume perfect synchronization between the transmitter and receiver. Raw BER without channel coding was always studied though the coding gives one extra dimension to fight against multipath and interference.

UWB system performance results that are based on the computer simulations are included in Paper II , as well as in Papers III , IV, and V. In addition, papers [198,199] and [242] cover the same topic. Typically, these papers give a comparative performance analysis between the different UWB physical layer structures; using a different spreading concept, modulation scheme and pulse waveform. The impact of the different interference models has also been studied. The used channel model was AWGN in Papers II - IV and in Paper V, the IEEE802.15.3a [109,110,236] model was used. Throughout the work, simulations were carried out until one million data bits were transmitted or one hundred errors were detected at the reception, which one came first. The performance of the UWB link level simulator was verified in AWGN and Rayleigh fading channels before the comprehensive coexistence simulations were carried out.

In addition to the in-band interference discussions, Paper II covers UWB system performance studies under multitone and pulsed jamming. The modeled interference sources were GSM900 and UMTS. In the paper, the simulations were focused on the low derivatives of the Gaussian pulse because of the simple, impulse radio type approach. The signal-to-interference ratio was fixed to -15 dB and processing G = 20 dB. The paper differs from the other papers available in those days by examining two different concepts under similar spectral and jamming (interference) assumptions. Paper III extends the used modulation schemes from PAM also to PPM and OOK, all being binary. When using PPM, the modulation index was always selected to minimize the cross-correlation between the pulses depicting the two bits, as presented in Paper III. In addition to the used modulation schemes, the study covered the first four Gaussian pulses as transmitted waveforms. Paper IV also takes into account the PSM modulation, and the interference is simultaneously located in both the uplink and downlink band of the interfering system. The jamming in Papers III and IV is assumed to be based on either GSM900 or UMTS, and UMTS only, respectively. For UMTS interference, the former paper uses a pulsed approach and the latter one utilized the colored Gaussian noise approach.

Though DS-UWB with binary PAM causes less in-band interference than the corresponding TH-system the latter one however seems to tolerate single interference slightly better in an AWGN channel. The evident result is that by changing the parameters of the UWB pulse (pulse waveform and pulse width) the spectrum allocation differs and therefore different interferers do not have a similar impact on the UWB system performance. From the studied modulation schemes, PAM outperforms the others in every studied case. The performance of PPM and PSM depended on the used modulation index and designated pulse waveforms, respectively. The worst performance is obtained with OOK, which looses 3 dB of the total energy because only the other bit is transmitted. In simulations, the transmitted power for data bit “1” is the same as is used with the other modulation schemes. Based on the results from Paper IV , in the dual band interference case, there is no significant difference between TH-UWB and DS-UWB when UMTS is the interfering system.

Paper V makes the performance comparison between different UWB PHY in the presence of simultaneous IEEE802.11a and UMTS interference. Channel models were modified Saleh-Valenzuela models 1 and 3, as defined by IEEE802.15.3a [109]. Because the channel model used was a multipath model, different receiver algorithms and rake reception techniques were applied to improve the UWB system performance. Otherwise, the paper follows a similar comparative approach than that used in Papers I – IV. By exploiting the earlier results, the data modulation schemes selected for the study in more details in Paper V were binary PAM and PSM. The receiver utilizes both coherent algorithms (maximum ratio and equal gain combining), non-coherent (square law combining) algorithms, and rake reception. The optimum number of rake fingers for different UWB PHY in the IEEE802.15.3a channel is defined in [242] and the performances of the different detection algorithms under pulsed and colored jamming in [199]. Those two papers were used as background information in Paper V when selecting the algorithms and the amount of rake fingers used in the simulations. The desired UWB link utilizes the 5th and 6th Gaussian pulses to fulfill the FCC requirements. A ten finger rake at the receiver was used. At the same time, the data rate was increased from the 20 Mbps used in the previous cases to 100 Mbps.

Unlike in the AWGN channel, the multipath channel favors DS-UWB instead of TH-UWB. The difference between these two methods is at least 3.5 dB when using antipodal signaling. Orthogonal modulation makes the difference even bigger, at least 6 dB. As a reminder, in AWGN the difference is almost insignificant.

5.1.3 Theoretical performance calculations

Theoretical approaches to easily calculate DS-UWB system upper bound performance in an AWGN channel in the presence of interference are given in Papers VI - VII, as well as in [244]. The earlier simulation results carried out, e.g., by the author [V, 6] have shown that DS-UWB, with binary PAM modulation, gave the best performance from the studied PHY structures in a realistic multipath channel in the presence of interference, if compared to the corresponding TH system. Based on this observation, it was reasonable to first focus the theoretical study on the DS-UWB concept. However, instead of a complicated multipath channel, an AWGN is typically used as a reference channel model in the new receiver algorithm studies. This observation is behind the theoretical calculations first done in an AWGN channel. The system performance upper bound that can be achieved in AWGN is essential to make a fair comparison between the different system approaches.

In Paper II , it was already proposed that the estimation of the needed jamming margin could be based on the spectrum properties. Papers VI - VII define the simple formulas that allow one to calculate theoretically BER bounds in an AWGN channel for DS-UWB with BPAM in the presence of interference. The approach shown uses real system parameters as inputs, and the formulation is very generic.

In Paper VI , the verifications of the modified BER formulas are given using simulated results as a reference. It was shown that the theoretical approach and the corresponding simulations give BER results that are very close to each other, and therefore the proposed formulation can be exploited. Paper VI gives simple examples for the calculation of the minimum tolerable separations between the interfering and desired transceivers. However, from the thesis' point of view, the interference distance calculation does not give any new formulations, but creates a link between the BER versus E_b/N_0 analysis and the minimum distance studies. In both cases, the effects of the interference can be easily taken into account.

Paper VII extended the analytical study to calculate the exploitation range of the formulas. By giving the difference between the simulated and theoretical results, it was shown that the modified formulas have smaller deviation to the simulated results than the original BER formulas from [54] have in the UWB context. The accuracy of the formulation improves when the higher order derivatives of the Gaussian pulse are used. The difference between the simulated and calculated results is also based on the generation of the sidelobes through filtering in the simulations. However, this effect is excluded from the theoretical analysis.

The difference between the proposed formulation and the existing closed-form derivations is that the upper bound calculations of the DS-UWB system performance can be performed using only data rate, SNR and interference power values as input parameters without any complicated mathematics. This simple assumption came from the fact that the existing radio systems are very narrowband if compared to the UWB bandwidth. The accuracy of the BER calculation when the effect of the UWB spectrum is taken into account and the partial band approach is utilized. However, in both approaches, the effect of the interference is weighted by the factor that relates the power spectral densities at the jamming band. This leads to the result where the impact of interference on UWB is higher if the center frequencies of the desired UWB signal and interference are overlapping. Therefore, the UWB system can tolerate stronger interference if the jamming signal is located in the slope of the desired UWB spectrum. Paper VII and [244] discuss also the exploitation range of the proposed simple formulas and show the improvement to the original formulas from [54]. The new derivations are more accurate the higher the used Gaussian pulses' derivative order is.

5.2 Measurements

The UWB transmitters introduced in Chapter 0were designed and built in the FUBS and CUBS projects in co-operation with the subcontractor [243], and were used in the experimental coexistence tests reported in Papers I - IX, as well as in [214,215,245].

Paper I, and supporting papers [214,215], discuss the UWB impact on the performance of IEEE802.11b and Bluetooth networks. The victim systems were selected because they are widely used global standards in wireless short-range data communications. The given results are based on the real coexistence measurements using instant throughput and SNR as a measure of the victim system's performance. It was shown that UWB has significant impact on the victim system if the amount of simultaneously active UWB devices is high and the UWB transmitters are locating in close vicinity of the victim receiver. The 1st generation UWB device used in the study has 30 dB higher transmission power in the 802.11b band than the FCC regulations [24] permit. Therefore, the effective impact of one UWB device used in the experiment corresponds to a very unrealistic amount of active UWB devices that are fulfilling the FCC radiation limits; corresponding to hundreds of FCC compatible devices. However, the distance that after the impact of UWB interference on the studied WLAN systems throughput is insignificant is about 40 cm, even if using these high power UWB transmitters. Of course, the magnitude of the impact of the interference on the victim system depends on the interfered link distance. The increase in the link distance means that the received desired signal strength is smaller due to the higher propagation loss, which besides means smaller SNR and worse performance. It is obvious that the interference has then higher impact on the victim system performance.

In additions to WLANs, the UWB impact on cellular networks, and especially the UMTS network, was studied through experimental coexistence measurements in Paper IX and [245]. Second-generation UWB transmitters whose center frequency was higher than that of the first generation devices were used in the experimental tests. In addition, the 2nd generation devices have more parameters to be selected, as Chapter 4.3 stated. The results reported in Paper IX are based on the measurements carried out inside an anechoic chamber, as well as using an operational UMTS network as a victim system. The results cover the range from realistic UWB usage to the worst case, extremely highly overloaded interference scenarios. The activity factor of the UWB devices was seen to have significant impact on the victim systems' performance. Reducing the activity factor led to disproportionately less interference for the victim system. Packet based transmission in high speed UWB systems can utilize discontinuous transmission allowing in a reduction of the activity factor, and therefore, the unfavorable interference effect can be decreased.

Though the UMTS link seems to coexist with the UWB devices, the study does not cover the impact of UWB on the radio access network (RAN). Maintaining the quality of one UMTS link might cause an increase in UMTS uplink and downlink power levels due to power control. If one mobile link increases its transmission power, adjacent and co-channel interference in the terminals connected to the network increases as well. Beyond a certain level, the entire network capacity will decrease. Therefore, further studies for the impact of UWB on cellular network capacity are definitely needed.

6 Conclusions and future work

6.1 Summary and conclusions

During the last years, the discussion on whether ultra wideband (UWB) technology should be released for unlicensed use has been very active. Combinations of low transmission power and extremely large bandwidth (larger than 500 MHz) create low power spectral density for UWB signals. That makes it possible to use the technology on an underlay basis on the same frequency bands with the other, existing radio systems because the UWB transmission is noise-like from a victim receiver's viewpoint. The existing wireless short-range devices could support data rates of up to 54 Mbps (IEEE802.11a) but the future demands are much higher. For example, wireless USB, which is based on multiband-OFDM, supports 480 Mbps but the overall goals are set to 1 Gbps, or even higher. The forthcoming applications are also requesting support for location awareness and precise positioning. Due to the very fine positioning accuracy, the UWB signal can also fulfill these needs for low data rate applications.

Currently, only the USA has prevailing regulations for UWB technology. The FCC (Federal Communications Commission) has permitted the commercial use of UWB devices without license but the radiation conditions are strictly defined. For communication applications, the allowed frequency band is limited to 3.1 … 10.6 GHz, and the maximum average power spectral density should be less than -41.3 dBm/MHz. For imaging systems, there is a band allocated below 960 MHz with the same maximum EIRP level. The rest of the world has not finalized UWB regulation, yet, even the regulation processes have been ongoing for a long time. At the time of writing this thesis, it seems that Europe and Japan might soon be close to the end of the process. The current deadlines for the decision-making were set to March 2006 in both areas. At least in Europe, the ECC released its proposal [85] for comments at the end of March 2006.

One important topic in the regulation process is the interoperability between different radio systems who are sharing the common frequency band. The main goal for the radio regulators is to maintain the existing systems' ability to operate on the predefined quality level when new technologies are appearing. This is the reason for a rather long regulation processes that needs deep knowledge about the coexistence problem before the final decision-making. Regardless of the status of standardization processes, the knowledge of which technology gives the best performance with less interference is needed.

Within this thesis, the coexistence issue between UWB and other radio systems has been touched in detail. The results based on the physical link level simulations, analytical calculations and experimental tests have been given from the physical layer point of view. The higher OSI-layers, such as data link or network layers, that are also very important in the whole system context, are ignored. This thesis pointed out some singleband UWB system designing aspects that could be taken into account when assembling a UWB system. Therefore, it makes it possible to take into account the coexistence issues in advance.

The impact of UWB transmission on other systems can be decreased by properly selecting the used pulse waveform. Both the shape and pulse width directly affect the spectrum allocation of the transmitted UWB signal. On the contrary, external interference affects UWB system performance, and the degradation of the desired link could be limited by the same parameters. The data modulation scheme affects the UWB system performance (in the presence of interference or without it). Other system parameters, such as pulse repetition frequency or activity factor, influence the generated interference seen by other radio systems.

Though TH-UWB seems to outperform the corresponding DS-UWB in an AWGN channel, the situation is contrary if the channel is a multipath channel, such as the IEEE802.15.3a standard UWB channel. Direct sequence UWB with bipolar amplitude modulation has been seen to outperform the corresponding time hopping system performance in multipath propagation environment. The other studied modulation schemes, such as pulse position and pulse shape modulation, and on-off keying gave worse performance both in TH and DS cases. Based on this observation, the upper bound limit for the UWB system performance is analytically derived for DS-UWB that is operating under interference. The theoretical results are verified with the corresponding simulated results. The benefit of the proposed theoretical approach is that it is very simple to use, and the main UWB and jamming parameters can directly be applied. The theoretical model proves that the formulas originally defined for a wideband signal in the presence of narrowband interference could be utilized in the UWB context with an arbitrary interference signal when slight modifications are obtained. In addition, the in-band interference studies showed that DS-UWB generates less additional interference in the victim system's bandwidth. These are the reasons why DS-UWB was selected for the theoretical study. It has to be admitting that the current theoretical study does not cover multiple interference sources as was studied in Paper V via simulations.

The experimental results included in the thesis showed that UWB has significant impact on the performance of wireless local area networks or cellular systems if the interference distance is short, and the number of active UWB devices is large. However, if the interference is generated using realistic assumptions, those systems can definitely coexist in the same area. The realistic scenario utilizes an activity factor less than 10%, and the number of active UWB devices in the very near vicinity from the victim receiver is reasonable, less than five. The larger amount of active devices typically exceeds also the spatial volume available around the victim receiver. Based on the measurements, a maximum AF about 5% could be tolerated without any performance degradation on a victim system.

6.2 Future work

This thesis discussed coexistence between a singleband UWB system and specified victim system in the single-user case using analysis, simulations and measurements as research tools. Later on, the study should also be focused on multiband-OFDM type (WiMedia) UWB applications. In the CUBS-project, a Master of Science thesis work has already been started by simulating a WiMedia system under interference. This work is advised by the author of this thesis, and the goal is to create comparable results with the existing singleband results. In further studies, the analytical part presented here should include multiple users, multiple interferers and also take into account a more complicated, fading multipath channel. The AWGN channel that was firstly selected can only be used as a reference and it does not relate to real world applications.

After publishing Paper IX, additional coexistence measurements between UWB and UMTS have already been carried out with a UMTS radio communication analyzer. Supplementary measurements were performed in a classroom so that the user case reflects the real interference situation; each supposed student has a UWB device in front of them and the teacher is connected to the UMTS network. The position of the UMTS terminal was moved inside the classroom. A similar case with an IEEE802.11a WLAN has also been measured and a paper from the latter case has been submitted for a conference.

The CWC has recently been granted an UMTS base station, which makes it possible to extend the measurement based coexistence research. Using the UMTS frequency allocated only for research purposes, different environmental layouts can be covered. The system will include a network simulator, which extends the research possibilities even more. Instead of measuring only the performance of a single UMTS link, as has been carried out in the previous measurements, the UWB impact on the radio access network is also possible to measure. This would give important information about the operation of the RAN. If the quality of a single cellular link could be maintained under the interference, it typically means that the uplink or downlink powers of the mobile link are increased. This has an effect on the entire network capacity due to the increase in in-band and adjacent band interference levels. This is the most crucial issue from the cellular network operator point of view.

Coexistence tests are also planned to be carried out using commercial UWB transceivers. Until now, the lack of the study has been that only the impact of UWB on victim system performance has been able to be measured under UWB interference. Later, similar UWB interference, as well as other interference/jamming will be directed to the UWB link whose performance can then be monitored. One major concern is how the UWB link can tolerate intentional interference and this thesis could answer this question only through simulations and analysis, but not by giving experimental results. Using the theoretical approach, the overall UWB impact on the UMTS radio access network can be evaluated. Later on, these analytical results should be verified by measurements. The coexistence measurements between UMTS and UWB will offer results that can be applied also in system or network capacity studies. A new approach that UWB standardization process has introduced is the use of detect and avoid, or some other interference mitigation technique. This feature will also be included in the future studies.

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