Md. Abdur Rahim

Interference Mitigation Techniques to Support Coexistence of Ultra-WideBand Systems

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Interference Mitigation Techniques to Support Coexistence of Ultra-WideBand Systems

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der Fakultät Elektrotechnik und Informationstechnik
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zur Erlangung des akademischen Grades eines

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Abstract

The current trend in the wireless communications world is to move towards a complex and composite radio environments, where a number of co-located, and potentially, spectrally overlapping radio access technologies may present at the same time. Ultra-wideband (UWB) application scenario is one of such example in which UWB system spectrally overlaps with many existing licensed radio technologies (e.g. WiMax). Consequently, the interference from UWB system on WiMax system is a concern due to high impact on the WiMax services if both systems are co-located. Hence, all regulation authorities except USA proposed extra restriction on use of licensed part of UWB frequency bands or even if these are used, they must be used with very limited transmitting power compared to FCC limit. This restriction will reduce the opportunity for UWB systems to exploit the market. Therefore, a technique called detect and avoid (DAA) is proposed to increase the power emission of UWB device in addition to support coexistence with WiMax system and it is the main research topic of the thesis. The thesis is focused on two main research topics: i) possible interference evaluation between UWB and WiMax systems, and ii) design and evaluation of DAA technique.

The parameters of indoor wireless channels are characterized by the measurement results, which are useful for analyzing the UWB interference impact on the WiMax systems. A SEMCAT simulation tool and additionally a real-time experimental setup with WiMax and UWB systems are used to measure the requirements of UWB coexistence. We found that the interference impact strongly depends on the definition of the interference scenario and on the parameters that are used in model. It was shown, that the interference caused by UWB systems strongly depends on the spatial distribution of the UWB devices. On the other hand, the experimental results suggest that UWB devices might not be able to communicate due to the opposite interference coming from WiMax system. Hence, in general the spatial distribution of the radio devices is of extreme importance and has to be handled with special care.

We proposed a framework of DAA interference mitigation techniques based on the uplink WiMax signal detection. The proposed zone based DAA model is evaluated with appropriate algorithm development and theoretical analysis as well as simulation experiments. In DAA technique, the detection of licensed signal is a challenging task by a single UWB device due to several reasons such as hidden terminal problem, very low power signal detection, dynamic environmental conditions, etc. Therefore cooperative detection techniques namely partial and full cooperative technique are proposed, in which several nodes share the spectrum detection tasks and/or share the acquired knowledge of the licensed systems. These techniques minimize the uncertainty of the detection while maintaining the control over the time and amount of energy spent for spectrum sensing by UWB node. Additionally, the cognitive pilot channel (CPC) concept is developed as an alternative of spectrum sensing so that UWB device receives the primary system information via the cognitive pilot channel.

The thesis results have partially been used by several regulation and standardization bodies,

particularly by CEPT ECC TG3 for UWB regulation in the definition of spectrum mask. Additional contributions are used by ETSI RRS WG3 for the standardization of the cognitive pilot channel.

Zusammenfassung

Die Welt der drahtlosen Kommunikation entwickelt sich hin zu immer komplexeren Szenarien, in denen eine Reihe unterschiedlicher, möglicherweise spektral überlappender Funktechnologien gleichzeitig Verwendung finden können. Ultra-Wideband (UWB) ist eine dieser Funktechnologien, die spektrale Überschneidungen mit vielen bestehenden, teilweise konzessionierten Funktechnologien wie beispielsweise WiMax aufweist. So ist im Falle räumlicher Überlappung beider Systeme die Beeinflussung von WiMax-Systemen durch UWB-Systeme eine sehr bedeutsame Frage. Deshalb haben alle Regulierungsbehörden mit Ausnahme der USA eine Beschränkung der Nutzung der lizenzierten Teile der UWB Frequenzbänder beschlossen oder, wenn diese Frequenzbänder verwendet werden dürfen, dies nur mit einer sehr begrenzten Sendeleistung im Vergleich zur FCC-Grenze gestattet. Diese Einschränkungen verschlechtern die Chance auf eine breite Markteinführung für UWB-Systeme. Aus diesem Grunde werden DAA-Techniken (DAA - detection and avoid) vorgeschlagen, um die Sendeleistung der UWB-Systeme zu erhöhen und gleichzeitig die Koexistenz mit anderen Funksystemen, z.B. WiMax, zu sichern. Dieser Themenkreis wird in der vorliegenden Dissertation bearbeitet. Dabei werden vor allem zwei Aspekte betrachtet: i) Bewertung möglicher Interferenzen zwischen UWB und WiMax-Systemen und ii) die Entwicklung und Evaluierung von DAA-Techniken.

Die auf Messergebnissen beruhenden Parameter der Indoor-Wireless-Kanäle sind nützlich für die Analyse der UWB-Störungen auf die WiMax-Systeme. Eine SEMCAT-Simulation und zusätzlich ein Echtzeit-Versuchsaufbau mit WiMax- und UWB-Systemen wurden verwendet, um die Anforderungen an UWB-Systeme zu ermitteln, die eine Koexistenz mit WiMax sichern. Es wurde festgestellt, dass die Beeinflussung stark von der Definition der Szenarien und den Parametern des verwendeten Modells abhängt. Es wurde auch gezeigt, dass die UWB-Interferenz stark von der räumlichen Verteilung der UWB-Systeme abhängt. Auf der anderen Seite deuten die experimentellen Ergebnisse darauf hin, dass die Kommunikation der UWB-Systeme durch WiMax-Systeme sehr erschwert werden kann, wenn die räumliche Lage ungünstig ist. Somit kommt der räumlichen Verteilung der beiden Funksysteme eine große Bedeutung zu.

Es wird vorgeschlagen, als Grundlage für DAA-Techniken zur Vermeidung von Interferenz die Messung des WiMax-Uplinks zu nutzen. Für dieses zonen-basierte DAA-Modell wurden theoretische Analysen durchgeführt, Algorithmen entwickelt und deren Implementierung in Simulationen erprobt. Für ein einzelnes UWB-Gerät ist diese Detektion aus mehreren Gründen, z.B. wegen des Hidden-Terminal-Problems, der möglicherweise sehr unterschiedlichen Signalstärke des WiMax-Signals, der sich verändernden Umgebungsbedingungen etc., eine sehr anspruchsvolle Aufgabe. Daher werden kooperative Detektionstechniken vorgeschlagen, bei denen sich mehrere UWB-Geräte an der Detektion beteiligen und/oder die Detektionsergebnisse austauschen. Diese Techniken minimieren zum einen die Unsicherheit der Erkennung des WiMax-Signals und ermöglichen zum anderen die Kontrolle über den Aufwand an Zeit und Energie, den die UWB-Geräte für die Detektion aufbringen müssen. Zusätzlich wird das Konzept

eines Cognitive Pilot Channel (CPC) als Alternative zur spektralen Detektion vorgestellt. Dabei beziehen die UWB-Geräte Informationen zu primären Funksystemen über diesen zusätzlichen Informationskanal.

Die Ergebnisse der hier vorgelegten Dissertation wurden von mehreren Regulierungs- und Standardisierungsgremien genutzt, so beispielsweise während der Regulierung von UWB in Europa von CEPT ECC TG3 für die Festlegung der spektralen Maske oder von ETSI RRS WG3 im Rahmen der Standardisierung eines Cognitive Pilot Channel.

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Contents

List of Abbreviations

3G	*3rd Generation*
4G	*4th Generation*
BER	*Bit Error Rate*
BS	*Base Station*
BSR	*Base Station Receiver*
BWA	*Broadband Wireless Access*
BW	*Bandwidth*
CBS	*Cognitive Base Station*
CER	*Cell Edge Reliability*
CEPT	*European Conference of Postal and Telecommunications Administrations*
CPC	*Cognitive Pilot Channel*
CRN	*Cognitive Radio Network*
CR	*Cognitive Radio*
CSD	*Cyclic Spectral Density*
DAA	*Detect and Avoid*
DL	*Downlink*
DLA	*Dynamic Link Adaptation*
DS	*Direct Sequence*
EC	*European Commission*
ECC	*Electronic Communications Committee*
ECMA	*European Computer Manufacturers Association*
EIRP	*Effective Isotropic Radiated Power*
ETSI	*European Telecommunications Standards Institute*
EVM	*Error Vector Magnitude*
FCC	*Federal Communications Commission*
FDD	*Frequency Division Duplex*
FDMA	*Frequency Division Multiple Access*
FFI	*Fixed Frequency Interleaving*
FFT	*Fast Fourier Transfer*
FM	*Fade Margin*
FN	*Noise Figure*
FWA	*Fixed Wideband Access*
HDR	*High Data Rate*
ImL	*Implementation Loss*
IR	*Impulse Radio*
LAN	*Local Area Network*
LDC	*Low Duty Cycle*

LDR	*Low Data Rate*
LOS	*Line-of-Sight*
LRT	*Likelihood Ratio Test*
MAC	*Medium Access Control*
MAS	*Medium Allocation Slots*
MAP	*Maximum a Posteriori*
MB-OFDM	*Multiband-OFDM*
MCL	*Minimum Coupling Loss*
MIC	*Ministry of Internal Affairs and Communications*
NF	*Noise Figure*
NLOS	*Non-LOS*
NoF	*Noise Floor*
NoZ	*Non Operating Zone*
OFDM	*Orthogonal Frequency-Division Multiplexing*
OFDMA	*Orthogonal Frequency-Division Multiple Access*
PAN	*Personal Area Network*
PC	*Personal Computer*
PHY	*Physical Layer*
PL	*Path Loss*
PSD	*Power Spectral Density*
PU	*Primary User*
QoS	*Quality of Service*
QPSK	*Quadrature Phase Shift Keying*
RF	*Radio Frequency*
RLAN	*Radio Local Area Network*
ROC	*Receiver Operating Characteristic*
RRS	*Reconfiguration Radio System*
SME	*Medium-sized Enterprises*
SNR	*Signal-to-Noise Ratio*
SS	*Subscriber Station*
SSR	*Subscriber Station Receiver*
TDD	*Time Division Duplex*
TDMA	*Time Division Multiple Access*
TFC	*Time- Frequency Coding*
TFI	*Time-Frequency Interleaving*
TG	*Technical Group*
TH	*Time Hopping*
TN	*Thermal Noise*
TPC	*Transmit Power Control*

UL	*Uplink*
UWB	*Ultra Wide Band*
WiMax	*Worldwide Interoperability for Microwave Access*
WG	*Working Group*
WPAN	*Wireless Personal Area Network*
WLAN	*Wireless Local Area Network*

Chapter 1

Introduction

§ 1 Background

Short range communication systems within 10 meters, IEEE 802.15 wireless personal area network (WPAN), have became the popular choice for replacing the cable communications. It enables seamless wireless connectivity in mobile handsets, desktop peripherals, home entertainment systems and personal devices, etc., for multimedia applications. Bluetooth version 1.2, a member of WPAN that operates in the 2.4 GHz band and consumes less energy (1mW/Mbps) at a limited data rate of 2 Mbps, has penetrated and gained mass market, particularly in mobile multimedia applications. The wireless local area network (WLAN) based on IEEE 802.11 standard has also been gaining popularity in some of those applications though the initial idea was to develop a single worldwide - accepted standard to replace personal computer (PC) wired local area network (LAN). The recent development of WLAN can offer upto 100 Mbps while consuming high energy (15-20 mW/Mbps). However, the requirements of emerging next-generation WPAN are characterized as follows:

- increased data rate (hundreds of Mbps and upto several Gbps) to support high-quality video streaming, faster large file transfer,
- very low power consumption for long battery life (<1mW/Mbps),
- supports cognitive functionalities for interference free communication

Considering the above future requirements, it indicates that neither WLAN nor Bluetooth can not support the requirements of those applications in a great extend. Hence ultra-wideband (UWB) system is seen to be the best candidate to offer a fulfilling solution.

Although the term UWB is not new, the opportunity to deploy it in a high-speed data application is opened after February 14, 2002, when the US Federal Communications Commission (FCC) approved its Part 15 rules to permit UWB devices to operate from 3.1 GHz to 10.6 GHz as a license-exempt technology. According to the FCC definition, any wireless technology that emits signals having fractional bandwidth greater than 20% or with a total bandwidth wider than 500 MHz is called UWB. The fractional bandwidth is defined as the ratio of channel bandwidth to centre frequency of the channel and it is given by

$$B_f = \frac{BW}{f_c} = \frac{(f_H - f_L)}{(f_H + f_L)/2} \tag{1.1}$$

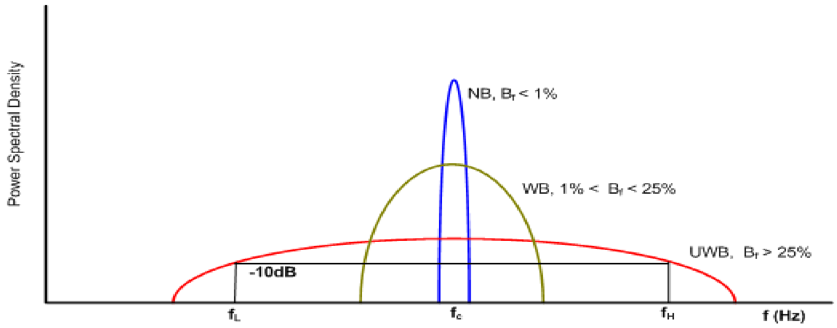

Fig. 1.1: UWB signal definition.

where f_H and f_L are the highest and the lowest transmitted frequencies at -10 dB emission point, respectively, BW is the channel bandwidth and f_c is the centre frequency. Fig. 1.1 compares and defines the conventional radio transmission signals (i.e., narrowband and wideband systems) to/and UWB signals in terms of fractional bandwidth.

Now-a-days, UWB is dominated by two main technologies: one is based on multi-band orthogonal frequency-division multiplexing (MB-OFDM) preferable for high data rate applications and other is based on impulse radio IEEE 802.15.4a to satisfy the need for extended range and location capabilities of the low data rate applications. The IEEE standardization bodies explored two solutions for high data rate UWB applications under IEEE 802.15.3a standard: one using direct-sequence spread spectrum (UWB Forum) and another using MB-OFDM (MB-OFDM alliance). After three years in January 2006, supporters of both proposals decided to discontinue IEEE 802.15.3a task group without any conclusion. However in the mean time, the WiMedia alliance (former called MB-OFDM alliance) submitted a proposal to pursue standardization in an alternative organization called Ecma International. Ecma is an industry association founded in 1961 and dedicated to the standardization of information and communication technology (ICT) and consumer electronics (CE). In December 2005, Ecma International in support of WiMedia alliance released its first version, ECMA 368, for UWB physical (PHY) layer and medium access control (MAC) layer. This WiMedia standard is based on subdivision of the large available bandwidth into several subbands of 528 MHz and each subband use OFDM modulation techniques.

Major players developing UWB technology based on MB-OFDM technique include Freescale Semiconductors, Intel, Texas Instruments, Hewlett Packard, Philips, Samsung, and Sony as well as small and medium-sized enterprises (SME) such as Alerion, Staccato Communications and Wisair. Data rates of 500 Mbit/s and beyond have been announced by UWB developers, mainly in the U.S.A. Both Freescale Semiconductor and Wisair have announced the availability of integrated circuit (IC) solutions for high data rate UWB system above 100 Mbit/s. PulseLink has announced a system capable of 1 Gbit/s.

Besides short range wireless communications with data rates ranging upto Gigabit per second, UWB technology enables precise real-time location tracking inherently due to its unique feature of ultra-wide radio frequency band allocation. Widespread applications of this new wireless technology will facilitate growth of a number of market segments. All applications enabled by the UWB radio being highly scalable with regard to complexity, range, costs and data rate as well as location precision accuracy. UWB system also provides minimum interference to the other electronic equipment compared to existing alternative radio systems. Even if this last statement seems to be not widely accepted by a number of national administrations, several major industry sectors are convinced of this advantage and support fully the introduction of UWB radio services.

The UWB system based on MB-OFDM technology is more appropriate in terms of coexistence because of its unique feature that it can easily turn off some subcarrier frequencies which may interfere, or to be interfered, with other systems. 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 that means one is suffering with an interference problem.

Like for any other radios, the use of UWB frequency is subject to national regulation; generally the administrations shall monitor and allocate the spectrum for national use in accordance with their international commitments. This regulatory specification defines a "spectrum mask" in a radio to set the maximum mean power spectral density across the relative wide frequency ranges. Regulation is evolving and adapting to the needs of the expanding global market for UWB wireless devices. The major regulatory bodies of interest are those that control the mass market of UWB exploitation and are given follow:

- Federal Communications Commission (FCC) in the United States,
- Electronics Communication Committee (ECC) in European Union
- Ministry of Internal Affairs and Communications (MIC) in Japan
- Ministry of Information and Communication (MIC) in Korea
- Ministry of Information and Industry (MII) in China

At the time of the writing this thesis, UWB regulatory approval already exists in the US, Europe, Japan, Korea, China; however worldwide adoptions are being made, often with some local limitations and extra requirements. The regulatory bodies in Canada, Asia Pacific, etc., are still working with a view to obtain a harmonizing regulatory approval in the near future.

§2 Motivation/Scope of Research

Since UWB covers such a large bandwidth, it is therefore obvious that it will overlap with several frequency bands allocated to various radio communication services with different technical and operation characteristics, depending on the geographical locations. These worldwide incumbent technologies includes RLANs, WLAN, WiMax, 3G and 4G mobile communication, satellite communications, radars, digital broadcasting receivers, radio astronomy stations, etc.

By knowing such consequence, UWB frequencies are purposefully defined by FCC to radiate at a power spectral density of -41.3 dBm/MHz over the total bandwidth, from 3.1 GHz to 10.6 GHz, with a concept of underlay or noise like signal. UWB signal can co-exist with other licensed or unlicensed narrow/broadband communication signals due to its own nature of being detected as noise to other signals so that the efforts of UWB transmission on other systems are negligible. But this concept is seen in different way by the license spectrum holders in the shared bands by UWB system around the world. They concluded that UWB emissions can not be assimilated to radio noise, spurious or unwanted emissions from a regulatory perspective. Their concern is that the interference coming from UWB radio can increase the noise floor by an amount sufficient to cause performance degradation to the license receiver.

Those spectrum holders have little incentive to allow other users to share their licensed spectrum even when in a give set of circumstances there is a small chance of interference. It is in the license holder's business interest to resist and to avoid risks of their licensed frequency bands. Hence, UWB industry has decided for working closely with regulation bodies around the world to finalize the regulation process. The main debate in regulation bodies is to define the conditions in which the interference impact is severe. Such debate was seen more in Europe. The systems and bands that concern for the regulation bodies in Europe are the following:

- military radars, in 3.1 -3.4 GHz, and in 8.5 -9 GHz,
- broadband wireless access services in the band 3.4 -4.2 GHz (including WiMax based on IEEE 802.16e operates from 3.4 to 3.8 GHz)

The interference scenarios for military radars and WiMax system are different; in the first case, the interference can be due to the UWB system installation in road and rail vehicles. But in the second case, it is due to the UWB system installation in office and home environment. The first version of WiMax standard has focused merely on the fixed subscriber installation in outdoor environment. But in 2005, IEEE ratified IEEE 802.16e amendment includes several features and attributes to support mobile subscribers with various form factors such as: personal digital assistance, notebook PCs, handsets, and consumer electronics. That means, the UWB system will be operating in very close proximity to WiMax systems or co-located with WiMax system in the desktop PC/laptop and/or handset scenario. Therefore the possible interference is natural in that scenario and it is the main topic of this thesis. The lack of consistent, conclusion studies of UWB interference impact on WiMax bands, interference mitigation techniques, is the main motivation of further evaluation and analysis of the topic.

After several years of continuous efforts from the UWB industries, the regulation process is almost finished in the most part around the world. However, the authorities given a restriction not to use some licensed frequency bands or even if some licensed bands are used, they must be used with very limited transmitting power compared to FCC limit. In this context, the regulation bodies proposed a detect and avoid (DAA) mitigation technique to apply in the licensed part of the UWB frequency band in order to protect the licensed wireless systems as well as to increase the power emission of the UWB system. Fig. 1.2 shows the status of UWB spectrum regulation in worldwide and it also depicts the bands that are available for WiMedia applications. In the bands from 4.2 GHz to 4.8 GHz, the "phase approach" is applicable that means after 2010 the DAA technique will be applied in this frequency bands. In the bands from 7.25 GHz to 8.5 GHz (bandwidth of 1.25 GHz), this is the only portion of the UWB frequency band that is currently available for using without any mitigation technique. It seems that there is no much room for

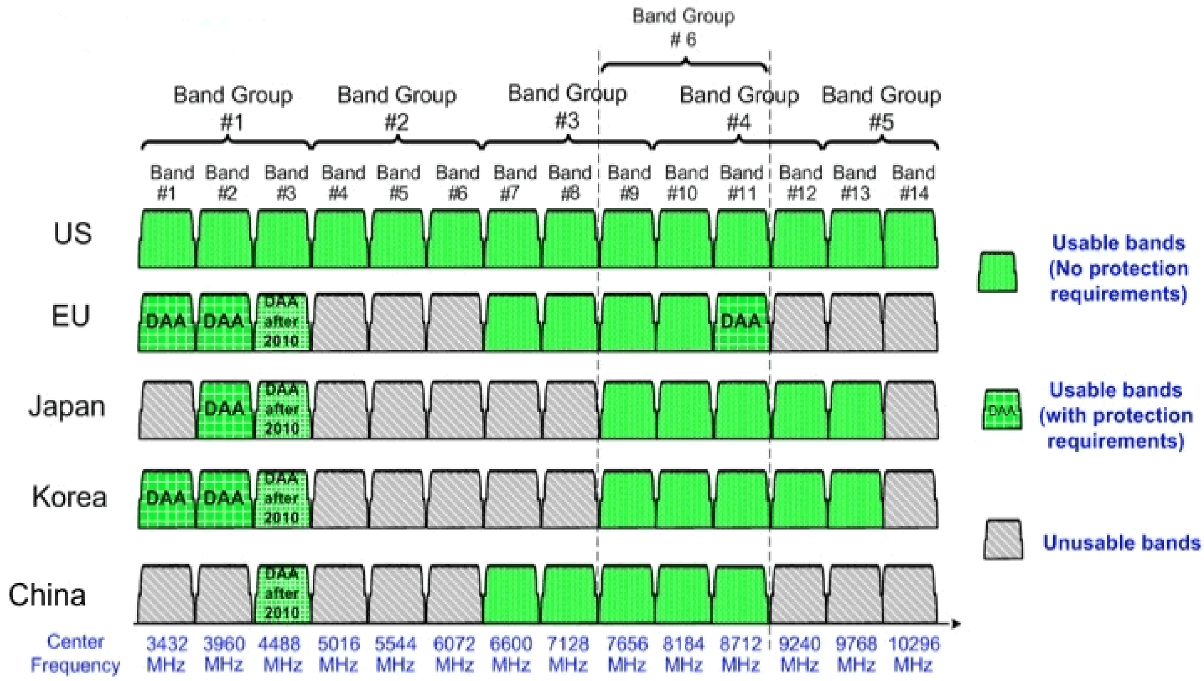

Fig. 1.2: Worldwide regulatory status-January, 2009 [WiMedia Forum].

WiMedia commercialization without applying DAA technique, because in WiMedia at least 1.5 GHz bands (500 MHz multiple 3) is required. Therefore, the DAA technique is very important for commercialization of UWB products.

DAA technique is based on the detection of the presence of the licensed signals; once the signal is detected then UWB devices need to avoid the interference impact to the licensed signals. If a radio enables DAA technique then it can also be called as a cognitive radio since the functionalities of cognitive radio comply with DAA technique. The detection of licensed signals or licensed users is one of the most important and critical task in DAA technique. Therefore UWB needs to cope with many challenges during detection of the licensed systems such as hidden problem, very low licensed signal power detection, identifying spectrum and users conditions in dynamic environment. However, continuous and large spectrum scanning is time consuming and not very efficient for UWB system. Hence, detection with several nodes instead of single node can increase the probability of detection in UWB system. Therefore cooperative detection techniques is necessary in which several nodes share the spectrum detection tasks and/or share the acquired knowledge of the licensed systems. In line with the above description, the thesis addresses the following specific problems:

- the potential interference analysis between WiMax and MB-OFDM based WiMedia system; prerequisite of interference studies such as wireless channel characterization,

- study and analyze of UWB interference mitigation techniques based on detect and avoid (DAA) technique

- improve the performance of licensed users detection by using cooperative techniques

§ 3 Research Contributions

The research contributions of the thesis can be divided into two groups: interference evaluation and interference mitigation.

For interference evaluation, the characterization of wireless channel parameters such as path loss, signal attenuation in building materials, signal fading margin due to temporal variations, etc., are important that has been performed with appropriate measurement setups. The interference impact has been evaluated with theoretical as well as simulation results. Hence, a more realistic and complementary interference scenario is presented and implemented in Monte-Carlo based SEMCAT tool. The tool also uses to calculate the maximum distance in where the interference from UWB device may still concern. Another contribution is to analyze the interference impact on the WiMax services to evaluate the reduction of cell size as well as outage of active users. The reverse interference from WiMax to UWB communication links is also demonstrated with measurement setup.

On the other hand, the interference mitigation technique, DAA, has been discussed by algorithm development, theoretical analysis and performance evaluation through simulation experiments. The DAA interference mitigation techniques are not technology dependent and can be used to enable in any wireless technologies with suitable modifications. The proposed zone model DAA interference mitigation technique is based on the definition of different zones in which an appropriate UWB power emission level is authorized. The proposed cooperative mitigation techniques increase the detection reliability and performance. To overcome the spectrum sensing or detection tasks within DAA a cognitive pilot channel concept is developed, so that UWB device receives the primary system information via such channel.

The proposed methodology and obtained results are very useful for UWB products development and it opens the door for the market. The research has been used by several regulation and standardization bodies to finalize the process. All of those include

- Contribution to generic UWB regulation under the CEPT ECC TG3 group to define the maximum emitted power spectral density in the WiMax frequency band
- Contribution to CEPT ECC report 120 and WiMedia standard in the definition of DAA mitigation techniques and its detection parameters
- Contribution to ETSI RRS WG3 (reconfiguration radio system) in working group 3 by the concept of cognitive pilot channel for coexistence and mitigation techniques of UWB systems
- The research will help UWB industry to design a radio that can operate efficiently without interfering with coexisting users in a heterogeneous network

The relevant literature review for each chapter is given; the literature present different methods for interference studies applied to different radio systems. The literature also present the cognitive radio based mitigation techniques and its spectrum detection techniques.

§4 Thesis Outline

The rest of the thesis is structured into several parts:

Part I- Introduction of terms relevant to thesis: This part includes Chapter 2 that presets basic and state of the art of UWB technologies covering regulation and standardization aspect as well as the development of UWB systems. The cognitive radio as means of DAA mitigation technique is also introduced with several functionalities and related mechanisms.

Part II- Interference evaluation and its prerequisite : Chapter 3, as a part of the prerequisite of the interference evaluation, the characterization of the wireless indoor channel is done by taking three sets of measurements: path loss, temporal variation and attenuation. Chapter 4 investigates the interference impact from UWB device to existing radio systems particularly to WiMax system. A SEAMCAT tool is used to investigate the possible power spectral density for UWB systems in 3.5 GHz frequency band. A theoretical analysis and simulation results are presented to study how severe the UWB interference to WiMax system. At the end, a measurement setup is used when WiMax signal interference to UWB communications.

Part III- Interference mitigation techniques : Chapter 5 studies the DAA mitigation techniques with definition and estimation of several detection parameters such as threshold level, channel availability check time, etc. In there, the concept of cognitive pilot channel also introduces. Chapter 6 presents framework and performance simulation results of cooperative detection techniques, partial cooperative and full cooperative, followed by the conclusion of the thesis in Chapter 7.