A Quantitative Assessment of the Compatibility of Ultra Wideband with Broadband Wireless Access and Radar Services

Final Report of Pilot Phase Agreed with INFSO B4

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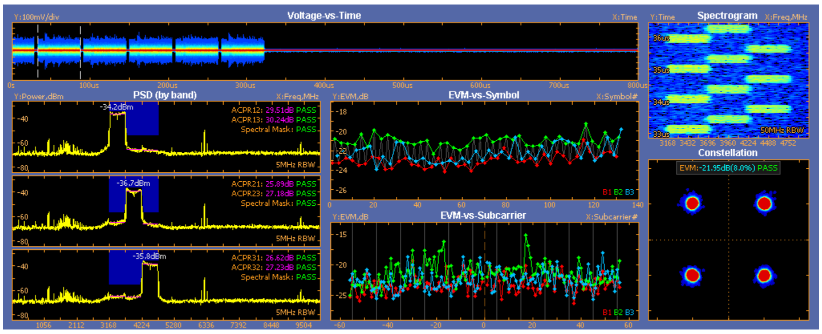

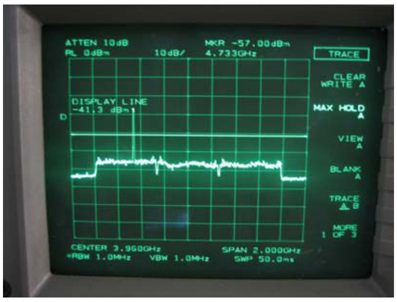

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Executive Summary

In July 2008, following a request made by the Radio Spectrum Policy Unit in DG INFSO (Unit B4), a pilot phase of twelve months was agreed with Member States representatives in the Radio Spectrum Committee. During this time the Institute for the Protection and Security of the Citizen of the EC Joint Research Centre (IPSC-JRC) has been mandated to provide testing facilities to support the development of Community spectrum legal measures under the Radio Spectrum Decision (676/2002/EC). In the frame of this pilot phase, IPSC-JRC has successfully completed the implementation and extensive testing of both a state-of-the-art laboratory test-bed and a simulation tool, which have been specifically designed for two different coexistence studies. Firstly, the coexistence between broadband wireless access (BWA) and ultra wideband (UWB) services in the 3.5 GHz frequency band; and secondly, the coexistence between radiolocation (i.e. radar) and UWB services in the 3.1-3.4 GHz frequency band. The selection of these two coexistence scenarios is not casual and has been made based on the fact that they have been considered highly relevant in the CEPT-ECC studies on UWB mandated by the European Commission.

The main motivation of this particular study was to complement the CEPT work, as reflected in ECC report 120, by lab measurements and simulations in the test facilities of JRC. And this in particular for what regards the Detect and Avoid (DAA) based interference mitigation measures for UWB devices which are meant to protect both BWA and radiolocation (radar) services.

It must be noted that since January 2008, in the frame of the FP7 IST project WALTER, IPSC-JRC has been developing and testing a laboratory test-bed for the certification of the correct implementation of the DAA technique in UWB devices. This test-bed has been the basis to develop those used in this study, which has guaranteed an optimal use of both personnel and laboratory resources at IPSC-JRC, as originally planned when the start of the pilot phase was agreed.

This report summarizes the results obtained in four interference scenarios that have been defined according to ECC Report 120, which defines the mitigation techniques to ensure the protection of radar and BWA services in the bands shared with UWB. All the laboratory measurements reported in this study, have been carried out in the conducted modality. In case of necessity, provided a specific request is made, these could be complemented with additional measurements in the radiated modality.

The main conclusion that can be drawn from this study is that both the protection limits and mitigation measures included in the recent Commission Decision 2009/343/EC are appropriate and ensure the protection of the radar and BWA services. The schedule of this study has not allowed to make the results available sufficiently in time before the publication of this Commission Decision. This was anyway foreseen and it is simply due to the fact that this study has been produced in the frame of a pilot phase. In particular, this study presents a series of laboratory measurements that show the validity of the limits in the coexistence scenarios between BWA and UWB in the 3.5 GHz frequency bands, and that between radar services and UWB in the 3.1 and 3.4 GHz frequency band. This result also confirms the validity and appropriateness of the recommendations made in ECC Report 120.

In July 2009, when the pilot phase is concluded, provided it is positively assessed and there is a continued support of the Member States in the Radio Spectrum Committee, a permanent collaboration on radio spectrum policy between JRC and INFSO can be established. The main focus of this collaboration would be that of providing technical assistance in future coexistence studies in areas where the IPSC-JRC can prove a solid experience and can offer unique experimental facilities. Some possible examples of these areas are the following:

- Coexistence studies where the use of automotive short-range radars (SRR) or UWB systems for sensors and communications is involved. For these measurements, IPSC-JRC can offer an anechoic chamber where full size vehicles can be accommodated during the compatibility tests. This facility has previously been used to assess the compatibility of SRR in the 24 GHz band. Likewise, the present regulation in the Commission Decision 2009/343/EC, which establishes the protection limits for vehicular UWB, is partially based on measurements carried out at IPSC-JRC under an ETSI mandate.

- Coexistence studies where the use of building material analysis (BMA) imaging systems is involved. IPSC-JRC has worked extensively on the testing and algorithm design for both ground-based and through the wall radar imaging systems.

- The assessment of the effectiveness of present and future mitigation measures to be implemented on the UWB transmitters (e.g., DAA and LDC) to ensure the protection of the radio services licensed in the UWB frequency band.

- The assessment of the compatibility between UWB and radar services. This could include radar systems not addressed to date, such as bistatic and passive radar.

- Coexistence studies and interference measurements where the impact of the aggregate effects needs to be assessed. In fact, the issue of aggregate interferences may become very relevant in a near future in case the interference sources are spatially distributed with a high density close to the victim receiver. IPSC-JRC is currently conducting research in this area developing state-of-the-art theoretical models. Provided an specific request is received, this activity could be complemented with experimental work by developing a dedicated test-bed designed to study the impact of the aggregate interference effects.

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Introduction

In July 2008, following a request made by the Radio Spectrum Policy Unit in DG INFSO (Unit B4), a pilot phase of twelve months was agreed with Member States representatives in the Radio Spectrum Committee. During this time the Institute for the Protection and Security of the Citizen of the EC Joint Research Centre (IPSC-JRC) has been mandated to provide testing facilities to support the development of Community spectrum legal measures under the Radio Spectrum Decision (676/2002/EC). This document summarises the results obtained to date and provides recommendations on the possible follow-on activities that could be undertaken.

In this study, the CEPT Electronic Communications Committee (ECC) Report 120 [1] is used as the main reference document for the definition of the tests-beds and interference scenarios.

The work carried out in the frame of the pilot phase can be divided into four main areas:

- Implementation of a laboratory test bed specifically designed to assess quantitatively the impact of an UWB MB-OFDM interference onto a WiMax channel in the 3.5 GHz band.

- Development of a simulation tool based on Matlab specifically designed to study the impact of an UWB MB-OFDM [2] interference onto a WiMax [3] channel in the 3.5 GHz band.

- Analysis of the implications of the results obtained in the numerical simulations using the interference simulation tool and those obtained in the laboratory measurements.

- Implementation of a laboratory test bed specifically designed to assess quantitatively the impact of a UWB MB-OFDM onto a radar receiver in the 3.1-3.4 GHz band.

We firmly believe that the development of both the simulation tool and the test beds are instrumental to complete the coexistence study subject of this pilot phase. After an exhaustive search in the literature, we have concluded that there is an evident lack of reference material. As an example, in the case of the fixed WiMax IEEE standard [3], it is not yet clear what is the precise signal to noise ratio (SNR) measured at the receiver that guarantees the required bit error rate (BER) of 10^{-6} mentioned in the standard. The figures have been corrected in various occasions and they seem to be still under discussion. The availability of reference material based on measurements and extensive simulations could notably contribute to a more coherent definition of the regulations dictating the possible coexistence scenarios.

It should be noted that, at this stage and in order to verify the correct implementation of the selected test beds, all test scenarios have been implemented in the conducted modality. The over the air (OTA) test scenarios are at the moment in a definition phase and could be conducted in case they are requested. Since the OTA tests procedures and the test bed are very much similar to those used in the conducted modality, no major difficulties in completing these tests are expected in case they need to be completed.

The main motivation of this particular study was to complement the CEPT work, as reflected in ECC report 120, by lab measurements and simulations in the test facilities of JRC. And this in particular for what regards the Detect and Avoid (DAA) based interference mitigation measures for UWB devices which are meant to protect both BWA and radiolocation (radar) services.

It must be noted that since January 2008, in the frame of the FP7 IST project WALTER, IPSC-JRC has been developing and testing a laboratory test-bed for the certification of the correct implementation of the DAA technique in UWB devices. This test-bed has been the basis to develop those used in this study, which has guaranteed an optimal use of both personnel and laboratory resources at IPSC-JRC, as originally planned when the start of the pilot phase was agreed. Furthermore, through one of the WALTER partners, the company Wisair, a set of UWB sample devices have been made available and used in the IPSC-JRC test-bed presented in this study. The IPSC-JRC team that has contributed to this activity is formed by five electrical engineers with a sound technical background both in the wireless communications research and industry fields. Three of them hold a PhD degree, respectively, from the Centre for Wireless Technologies in the University of Oulu (Finland), the Wireless Access Research Centre in the University of Limerick (Ireland), and the Institute for High Frequency Technology and Electronics in the Technical University of Karlsruhe (Germany).

This report is organized as follows. At first, the context of the coexistence study and the current regulatory status in Europe, after the completion of the third mandate given to CEPT ECC on the introduction of radio services based on UWB technology, is presented. Then, the laboratory measurements carried out to assess the compatibility between broadband wireless access (BWA) and UWB in the 3.5 GHz band are described. Four different interference scenarios considered those most representative are introduced and analyzed by means of simulations and measurements in the laboratory. Then, a description of the test-bed along with a selection of the results on the coexistence study between radiolocation services (i.e., radar) and UWB in the 3.1-3.4 GHz is provided. In both coexistence studies an extensive series of conducted measurements has been completed. These tests have been designed to assess the impact of the UWB interference, respectively, on the BWA and radar receivers. Finally, the implications of the presented results and the recommendations on the possible follow-on activities that could be carried out are provided.

The document has two annexes with a detailed description of the two laboratory test beds (Annex A) and the simulation tool (Annex B) that has been developed to carry out the two coexistence studies between UWB with BWA and radiolocation services.

CURRENT REGULATORY STATUS

On February 21, 2007 the European Commission issued its Decision 2007/131/EC which regulates the use of the radio spectrum for equipment using ultra-wideband (UWB) technology in a harmonised manner in the European Community. This Decision was based on investigations carried out in the technical groups of ECC-CEPT.

The ECC had previously issued a number of Decisions on UWB, including ECC/DEC/(06)12 and ECC/DEC/(06)04. On October 31, 2008 the ECC amended decision ECC/DEC/(06)12 which had been developed in response to an EC mandate to CEPT to identify the conditions relating to the harmonised introduction in the European Union of radio applications based on UWB technology.

This ECC Decision, which defines conditions of use applicable to UWB devices implementing Low Duty Cycle (LDC) or DAA mitigation techniques, supplemented Decision ECC/DEC/(06)04 amended 6 July 2007 on the harmonised conditions for devices using UWB technology in bands below 10.6 GHz.

The frequency band 6 - 8.5 GHz was identified in Europe for long-term UWB operation with a maximum mean e.i.r.p. spectral density of –41.3 dBm/MHz and a maximum peak e.i.r.p. of 0 dBm measured in a 50MHz bandwidth without the requirement for additional mitigation.

In the frequency band 3.1 - 4.8 GHz and 8.5 – 9 GHz, ECC investigated DAA (Detect And Avoid) and LDC mitigation techniques in order to ensure the protection of Broadband Wireless Access (BWA) terminals and applications in the radiolocation services, with a view of allowing UWB devices in the band 3.1 - 4.8 GHz and 8.5 – 9 GHz with maximum mean e.i.r.p. spectral density of –41.3 dBm/MHz.

Particular attention was paid to DAA mechanisms, which detect the presence of signals from other radio systems (such as fixed broadband wireless access and mobile services) and reduce the transmitted power of the UWB device down to a level where it does not cause interference to indoor reception of these systems.

ECC Reports 94 and 120 that were developed in support of this Decision define the protection requirements for BWA and the LDC and DAA mechanisms and parameters to be implemented in UWB devices.

The DAA mechanism is based on the definition of different zones for which an appropriate UWB emission power level (maximum mean e.i.r.p. spectral density) is authorised. A zone is defined by a range of isolation between a device/system of a victim radio service and the UWB device. Theses zones and associated range of isolation correspond to the maximum mean e.i.r.p. spectral density levels specified in table 1.

A sketch of the associated protection zones in the 3.5 GHz band as defined in the ECC report 120 is shown in figure 1. The UWB device detects the WiMax UL signal radiated by the nearest BWA terminal and sets the transmitted power level accordingly in order to avoid any harmful interference

It is worth noting that the DAA parameters Detect and Avoid Time and Detection Probability are defined differently as a function of the type of service provided via BWA, as shown in table 2.

In addition to BWA, report 120 defines the protection requirements for radiolocation services in the 3.1 to 3.4 GHz and the 8.5 to 9.0 GHz bands. Two protection zones with maximum e.i.r.p. levels of -70 dBm/MHz and -41.3 dBm/MHz are defined by establishing a detection threshold value of -38 dBm, as shown in table 1.

	Frequency Band (GHz)	3.1 - 3.4	3.4 - 3.8	3.8 - 4.8	8.5 – 9
	Minimum initial channel availability check time (sec)	14	5.1		14
Zone 1 for Signal detection level S >A	Maximum mean e.i.r.p. spectral density (dBm/MHz)	-70	-80	-70	-65
	Default Avoidance bandwidth(MHz)	300	200		500
Signal Detection Threshold A (dBm)		-38	-38		-61
Zone 2 for Signal detection level A > S > B	Maximum mean e.i.r.p. spectral density (dBm/MHz)	-41.3	-65		-41.3
	Default Avoidance Bandwidth(MHz)	-	200		-
Signal Detection threshold B(dBm)			-61		
Zone 3 for Signal detection level S < B	Maximum mean e.i.r.p. spectral density (dBm/MHz)	-	-41.3		-

Table 1:
Technical parameters to be used by UWB DAA devices

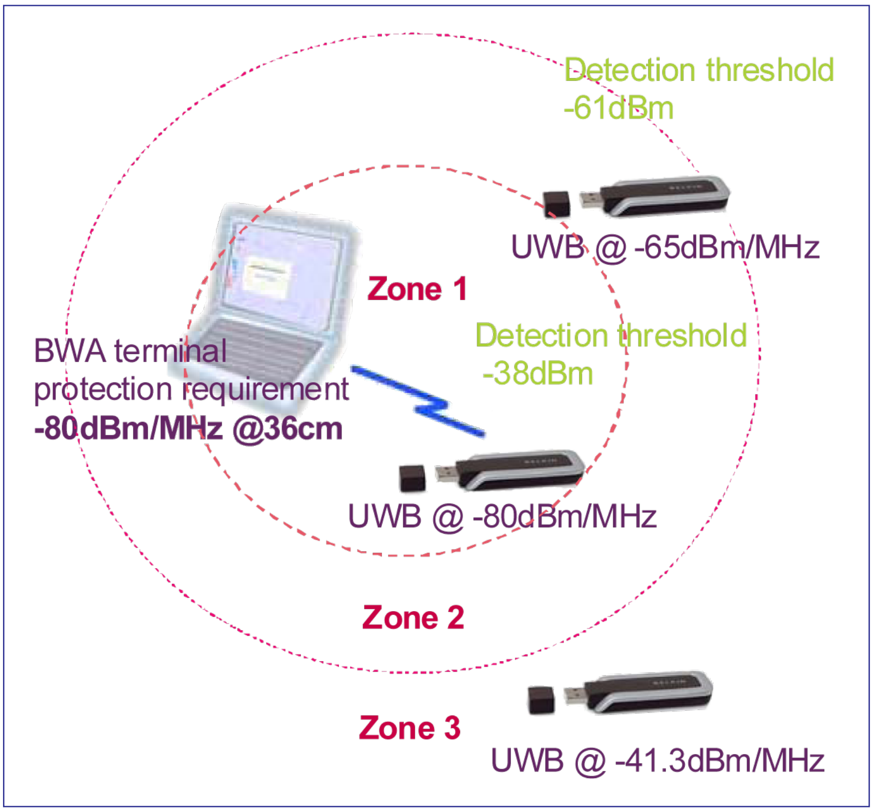


Figure 1:
Protection zones associated with the DAA mitigation technique in the 3.5 GHz band.

BWA Service / Mode	Detect and Avoid Time	Detection Probability
VoIP	2 s	95%
Web surfing	15 s	95%
Sleep mode	60 s	95%
Multimedia broadcasting	2 s	95%
Radiolocation Services	150 s	97 %

Table 2:
Protection requirements for active BWA and radiolocation terminals

Interference Margins Between WiMax and UWB MB-OFDM: Laboratory Measurements

In the present coexistence study, the victim system is the fixed WiMax system defined by the IEEE 802.16d standard released in 2004 [3]. The interfering service is a UWB MB-OFDM signal defined by the WiMedia standard [2]. The effects of the UWB MB-OFDM interference are evaluated on the downlink of the WiMax system as specified in the ECC report 120. The study considers the interfering signal UWB MB-OFDM both with and without time hopping (i.e., respectively, time frequency codes 1 and 5).

The scope of the study is to quantify the effect of the interference generated by UWB devices on the DL WiMax system performance. The parameters of the WiMax and UWB MB-OFDM system are presented in the tables 3 and 4, respectively.

In the present study, we have identified four interference scenarios that we consider the most representatives to assess the compatibility between WiMax and UWB MB-OFDM. The four scenarios are defined as follows:

Scenario #1: WiMax in a AWGN channel free of interference: Estimation of the receiver sensitivity level (i.e., SNR_{min}).

Scenario #2: WiMax in a AWGN channel with a UWB MB-OFDM interference above the receiver noise level: Estimation of the interference margin (SIR) between WiMax and UWB MB-OFDM with frequency hopping (TFC1).

Scenario #3: WiMax in a AWGN channel with a UWB MB-OFDM interference above receiver's noise level: Estimation of the interference margin (SIR) between WiMax and UWB MB-OFDM with no frequency hopping (TFC5).

Scenario #4: WiMax in a AWGN channel with a UWB MB-OFDM interference below the receiver noise level: Estimation of the interference margin (SIR) between WiMax and UWB MB-OFDM with no frequency hopping (TFC5).

A sketch of the spectra illustrating the selected four interference scenarios is shown in figure 2. A test bed specifically designed to investigate the coexistence between WiMax and UWB MB-OFDM has been implemented in our laboratory. See Annex A.1 for a detailed description of the test bed.

Interference scenario #1

In the first interference scenario, the performance of the WiMax system is evaluated in an additive white Gaussian noise (AWGN) channel in a conducted test without presence of interference in order to obtain a performance benchmark of our measurement setup. The results of this first series of tests are summarized in figure 3. The measurements are carried out with bandwidths of 1.75 MHz and two different modulation and coding schemes: QPSK ½ and 64QAM 3/4. These two schemes are chosen to estimate, respectively, the minimum and maximum sensitivities of the WiMax receiver. An extensive series of 250 measurements with increasing transmit power of the WiMax signal has been conducted. In this series, a total of 25 different power levels ranging from -80 to -25 dBm have been used. For every transmit power level, a total of 10 measurements have been averaged, recording the full set of demodulation results and processing them subsequently.

The results shown in figure 3 illustrate the fact that the minimum SNR that guarantees a WiMax channel free of errors (i.e., sensitivity of the receiver) with the modulation and coding schemes of QPSK ½ and 64-QAM ¾ are, respectively, about 6 and 22 dB. These sensitivity values are in line with those obtained with the interference simulation tool described in the Annex B.

Interference scenario #2

In this case, we address an interference scenario where there is a dominating UWB MB-OFDM interference signal whose power level is significantly above the thermal noise in the WiMax channel. We can see this interference as a "noise" and conduct measurements to estimate the sensitivity of the receiver in this new scenario, which is expected to be higher than that in a AWGN channel. This means that the UWB MB-OFDM interference, from the WiMax receiver viewpoint, behaves as a "noise" that is slightly more harmful than the thermal noise. Along this line, recently, a theoretical study considering the interference from impulse radio systems has proven the Gaussian contribution of the UWB interference to the noise level of a WiMax receiver [6].

The UWB MB-OFDM interference has been generated with an arbitrary waveform generator that is specifically designed to synthesize UWB waveforms up to 7 GHz. Further details about the set up used are given in the Annex A.1. The measurement campaign is made in the worst possible interfering scenario, with a duty cycle of the interference signal of 100% at the highest transfer rate of 480 Mbps. The time-frequency code (TFC) of the UWB MB-OFDM interference is that with frequency hopping (i.e., TFC1). The impact of the UWB MB-OFDM interference has been investigated with two different frequency bandwidths of the WiMax system, 1.75 and 7 MHz. As expected from the theory, no difference has been observed.

WiMax 802.16d (2004)	
Modulation	QPSK , 16 and 64-QAM
# of subcarriers	256
Bandwidth	1.75, 3.5, 7 , 14 and 20
Data Rate	Up to 75 Mbps

Table 3: Fixed WiMax system (IEEE 802.16d)

UWB MB-OFDM	
Modulation	QPSK
# of subcarriers	128
Bandwidth	528 MHz
Data rate	Up to 480 Mbps

Table 4: UWB MB-OFDM system

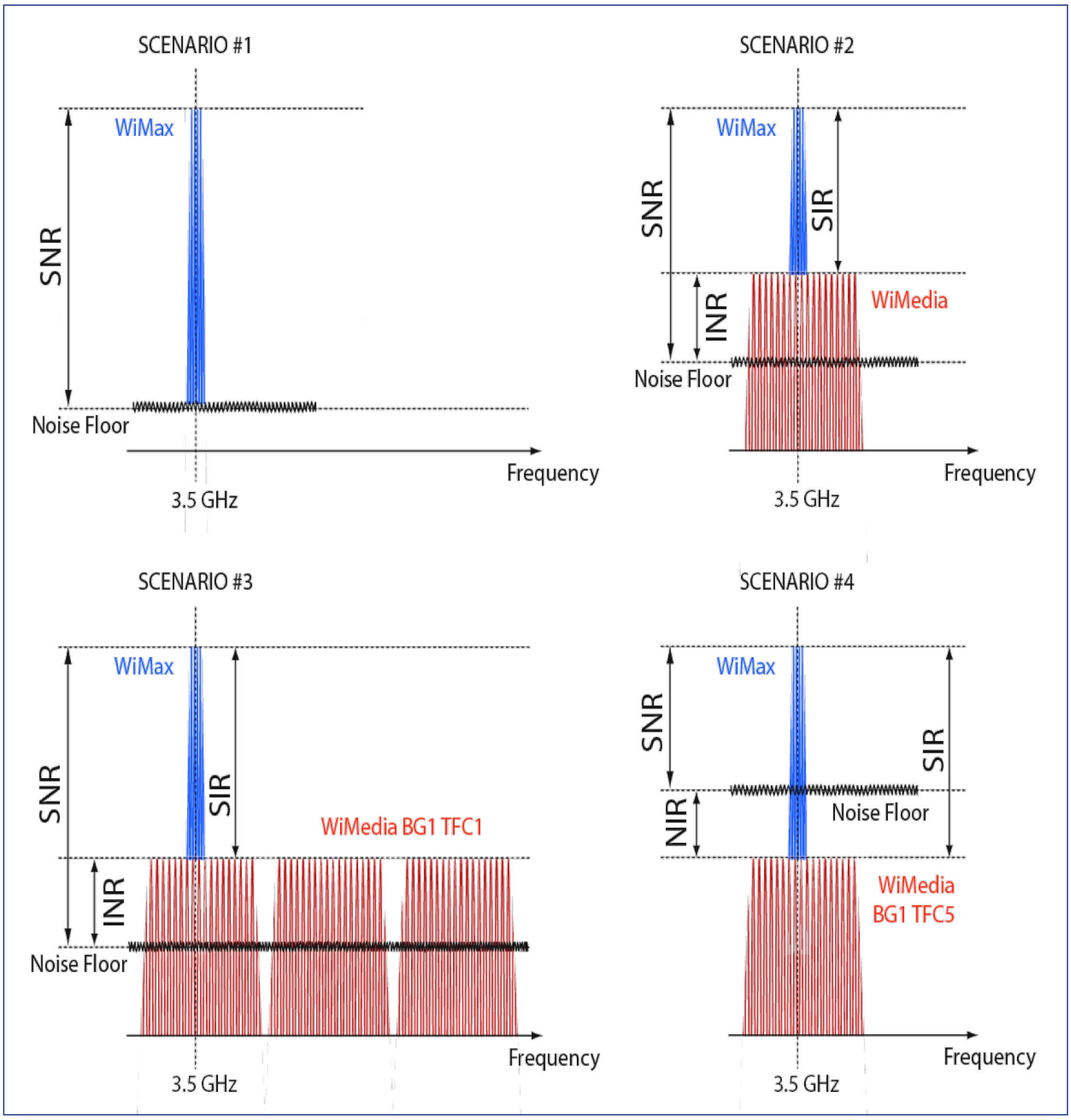


Figure 2: Sketch of the spectra corresponding to the four interference scenarios

Similarly, as in the first interference scenario, a series of conducted measurements are carried out with a UWB MB-OFDM interference power spectral density level (PSD) of -73 dBm/MHz in the WiMax band, which is about 10-12 dB above the noise floor of the receiver (-84 dBm/MHz). Under this condition, the dominant interference is that of the UWB MB-OFDM signal and the effect of the thermal noise on the WiMax channel can be assumed to be negligible. A series of 250 measurements with increasing transmit power of the WiMax signal are then conducted. The performance of the WiMax receiver will, in this case, clearly depend on the signal-to-interference ratio (SIR) defined as $SIR = P_s / P_I$, where P_s is the received power of the WiMax signal and P_I is the interference power. From these measurements, a precise estimate of the threshold SIR value assuring no degradation of the WiMax performance can be found.

Figure 4 shows the results of the minimum sensitivity measurements in the scenario with a WiMax system with 1.75 and 7 MHz bandwidth. The resulting minimum receiver sensitivity values are just the same and both slightly higher than those in the AWGN channel. This proves that the UWB MB-OFDM interference can be seen as a “noise” with a more harmful effect on the WiMax performance.

Interference scenario #3

This interference scenario is about the same as that of the previous scenario with the only difference of having a UWB MB-OFDM interference with no frequency hopping (i.e., TFC5) and occupying the first slot of the WiMedia band group 1.

The results of the measurements in this interference scenario are summarized in figure 5, where the plot of the EVM as a function of the SIR is shown along with a screenshot of the spectrum analyzer. It can be seen that, as expected, the minimum receiver sensitivity with the two modulation and coding schemes (i.e., QPSK ½ and 64-QAM ¾) with no frequency hopping is about 4 dB higher than that with the frequency hopping enabled. The expected difference in SIR should be in the order of 10*log10(3), because the interference is only present in the WiMax band a third of the time. This theoretical estimate is very close to that observed in the measurements.

Interference scenario #4

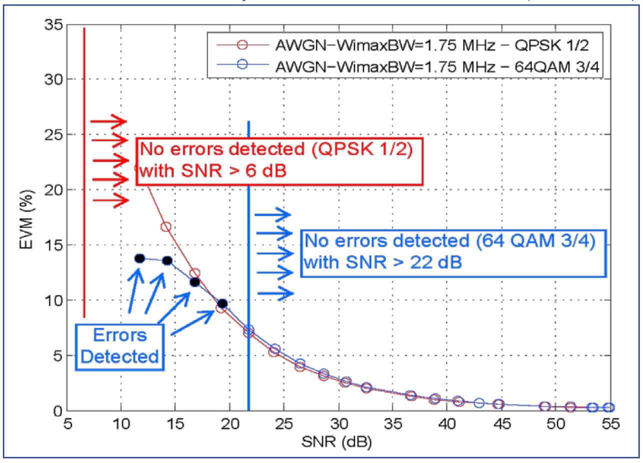
In the fourth interference scenario, we evaluate the impact of the interference generated by the UWB MB-OFDM device on the Wimax downlink. The measurements are made assuming a WiMax receiver working very close to the minimum sensitivity level (i.e., it is located at the edge of the cell). The minimum sensitivity level of the receiver when a 64-QAM 3/4 modulation and coding scheme is used is found at -61.4 dBm/MHz, that corresponds to a SNR of 24.6 dB and guarantees a minimum BER of 10^{-6}. It is worth noting that the minimum sensitivity levels defined in the WiMax standard [3] assume a receiver with a noise figure of 7 dB. The results presented in this report have been obtained with a receiver showing a noise figure larger than those ones defined in the ECC report 120 and, consequently, we have to use higher minimum sensitivity levels. However, this shall not change the conclusions that can be taken from the analysis of this interference scenario.

In this scenario, differently from the last two interference scenarios, the UWB MB-OFDM interference is generated by a commercially available UWB device (i.e., a Wisair DV9110 WiMedia evaluation system operating in the test mode) which is transmitting a UWB signal according to the WiMedia standard [2]. The measurements are made with no frequency hopping (i.e., in TFC5 mode) in the first band of band group 1, which is centered at 3.432 GHz. In order to adjust conveniently the output power of the UWB sample device, a variable attenuator is used. In the test mode, this sample device operates with a fixed duty cycle of 50%, a frame duration of 600 µs, and a constant data rate of 200 Mbit/s. Since we have to estimate precisely the symbol error rate (SER) in the WiMax channel, for every single value of interference to noise ratio (INR), a total of 100 measurements have been averaged. The measured output spectral density power is -44.5 dBm/MHz.

In the measurements, the level of the interfering signal is adjusted in order to have interference-to-noise ratios between 2 dB and -11 dB, which correspond to an attenuation of the WiMedia signal between 33 and 48 dB, respectively. This is an interesting interference scenario where the UWB signal falls below the noise level of the WiMax receiver. We want to estimate the threshold INR margin where the interference becomes harmful and the SER increases drastically. The INR values represented in the two plots of figure 6 are for 100% activity factor. It is noticeable that the presence of the interference signal becomes negligible when the INR is below -10 dB. This is confirmed in the measured EVM versus the INR values too, that are shown in figure 6 (right).

This measurement has also been used to estimate experimentally what is the contribution of the interference to the noise floor. The results are shown in figure 7, where the predicted contribution values from ECC Report 64 are also shown for comparison. It can be noticed that both measured and theoretical results match perfectly. As expected, an INR of 0 dB corresponds to an increase of the noise floor of 3 dB.

Figure 3:
EVM vs. SNR of WiMax in an AWGN channel (BW=7 MHz)



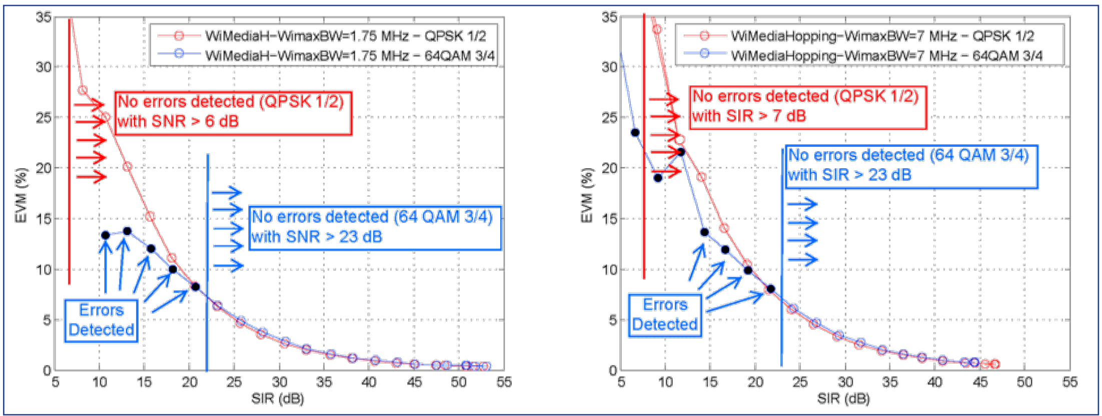


Figure 4:
EVM as a function of the SIR for a WiMax bandwidths of 1.75 MHz (left) and 7 MHz (right)

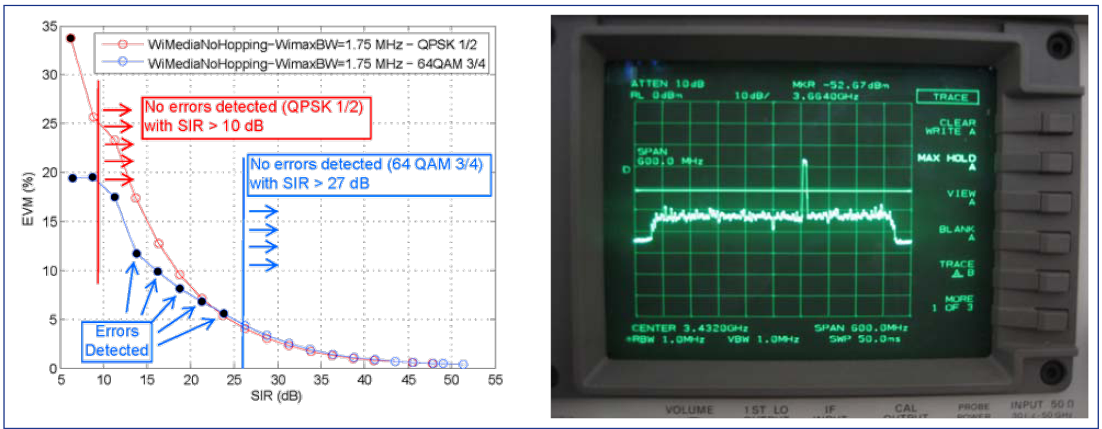


Figure 5:
EVM as a function of the SIR for a WiMax bandwidths of 1.75 MHz (left) and corres-ponding screenshot of the spectrum analyzer captured during the mea-surements (right)

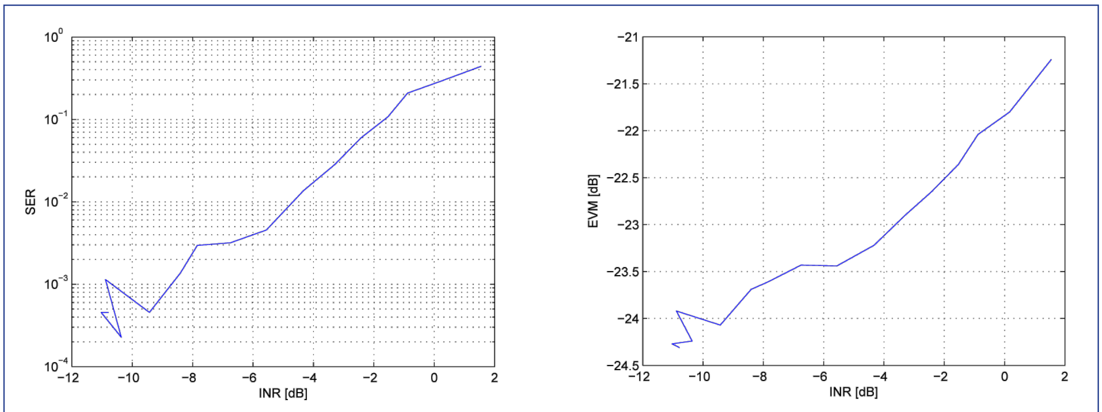


Figure 6:
Symbol Error Rate (left) and EVM (right) as a function of the interference to noise for a fixed SNR of 24.6 dB

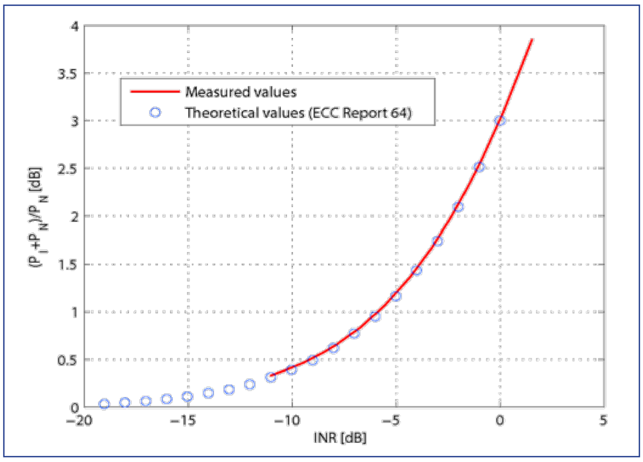


Figure 7:
Contribution of the interference to the noise floor as a function of the INR

Interference Margins Between WiMax and UWB MB-OFDM: Numerical Simulations

A coexistence network composed of WiMax DL transmissions and a UWB MB-OFDM single link is implemented in the simulation tool, as described in Annex B. The WiMax system is modelled according to the IEEE 802.16d standard (section B.1) and the UWB simulated interferer follows the ECMA-368 standard (section B.2).

The parameter employed in the simulation tool that relates the received WiMax signal and the UWB level of interference is the signal-to-interference ratio (SIR). The SIR is defined as $SIR = P_S / P_I$, where P_S is the power of the received WiMax signal and P_I is the power of the UWB interference measured at the output of the WiMax receiver filter. Both P_S and P_I values only account for the power contributions received in the WiMax data subcarriers.

The UWB MB-OFDM signal causes interference to the WiMax system only if it operates in the first sub-band of the Band Group 1 (BG1), since the wimax centre frequency is located at 3.5 GHz. Two interference situations can be clearly distinguished depending on whether the UWB system employs hopping over the sub-bands or transmits information in the first sub-band during all the observation time. As an example of the former, UWB systems with time-frequency code 1 (TFC1) are considered in the simulations. The latter situation of non-hopping interference is modelled using UWB signals with TFC5.

A detailed simulation analysis of the WiMax radio link in AWGN channel is presented in section B.3. In this section, the presence of hopped and non-hopped UWB interference is added to the system. Two modulated and coded systems are considered in this analysis; QPSK with R=1/2 and 64-QAM with R=3/4. The QPSK R=1/2 system is considered here due to its robustness in BER performance as can be seen in figure B5 when AWGN is the only degradation phenomenon. The largest data rate system that uses 64-QAM R=3/4 reflects the worst-case scenario in terms of BER. The simulations in this section are performed by considering a WiMax system with nominal bandwidth BW=7 MHz and no cyclic prefix CP=0, and UWB MB-OFDM interferer transmitting at 53.3 Mbps.

Initially, a very large value of SNR (SNR=100 dB) is considered in this simulation analysis to evaluate the interference effects on the WiMax link caused by the hopping or the non-hopping UWB interference when no other distortion effects are present. This setting corresponds to Scenarios 2 and 3 of figure 2 for TFC 1 and TFC5 respectively, with a very large INR value. The BER performances as a function of the SIR of the two coded systems are plotted in figure 8. The simulation results show that both QPSK R=1/2 and 64-QAM R=3/4 systems with TFC5 present very similar behaviour to the equivalent systems with SNR of figure B5. A comparison of figures 8 and A7 reveals that interference effects are slightly more destructive (1 dB when BER=1e-6) than the Gaussian noise. It is also noticeable, that the BER of the TFC5 systems degrades 4.7 dB with respect to the TFC1 systems. This is due to the fact that only 1/3 of the UWB TFC1 symbols cause interference to the WiMax link.

The other metric employed in the simulator to evaluate the performance of the WiMax link in the presence of UWB interference is the EVM. The percentage of EVM vs SIR curves are plotted in figure 9. The results show that the simulated EVM curves are identical between each pair of modulated systems with the same TFC, indicating the correct performance of the simulator.

In the following simulation analysis, the receiver SNR's that provide a BER of 1e-6 without interference are set to the values of table B5. These SNR values are 6 dB and 21.5 dB for QPSK R=1/2 and 64-QAM R=3/4, respectively.

The BER performances of the four interference systems are plotted in figure 10 under these new conditions. These simulated BER curves allow the values in which the interference effects are negligible (noise floor level) to be estimated. It is not clearly defined in [1] how to set the threshold level that considers the interference as insignificant. Nevertheless, it is mentioned in [14] that the maximum permissible interference level should be set to 1 % of the thermal noise. It can be observed in figure 10 that when approximately SIR=20 dB for TFC1 and SIR= 25 dB for TFC5 in QPSK R=1/2, the BER curves are very close to the asymptotic 1e-6 BER value. In 64-QAM R=3/4, this situation happens when SIR=35 dB and SIR=40 dB.

These SIR values that are compliant with the 1% criterion can be easily and accurately obtained by analysing the EVM performance, as shown in figure 11. The percentage EVM of a QPSK R=1/2 system without interference when SNR=6 dB is 39.15%. Similarly, a Percentage EVM of 6.65% is required for 64-QAM R=3/4 systems with SNR=21.5 dB. These thresholds values have been obtained from figure B7(b) and are plotted in figure 11. The minimum allowed SIR values for non-interference coexistence operability are 19 dB and 23.4 dB for QPSK 1/2 with TFC1 and TFC5, respectively. For 64-QAM 3/4 systems, these SIR values are 31.8 dB and 37.2 dB for TFC1 and TFC5, respectively.

A more realistic channel model is considered in the following simulation analysis. Channel models SUI-1 and SUI-4 with parameters described in table B2 are employed to obtain the BER performances in a multipath fading scenario. The SUI-1 channel model accounts for low delay and low Doppler spread values whereas the SUI-4 channel simulates a low Doppler and high delay spread scenario. Figure 12

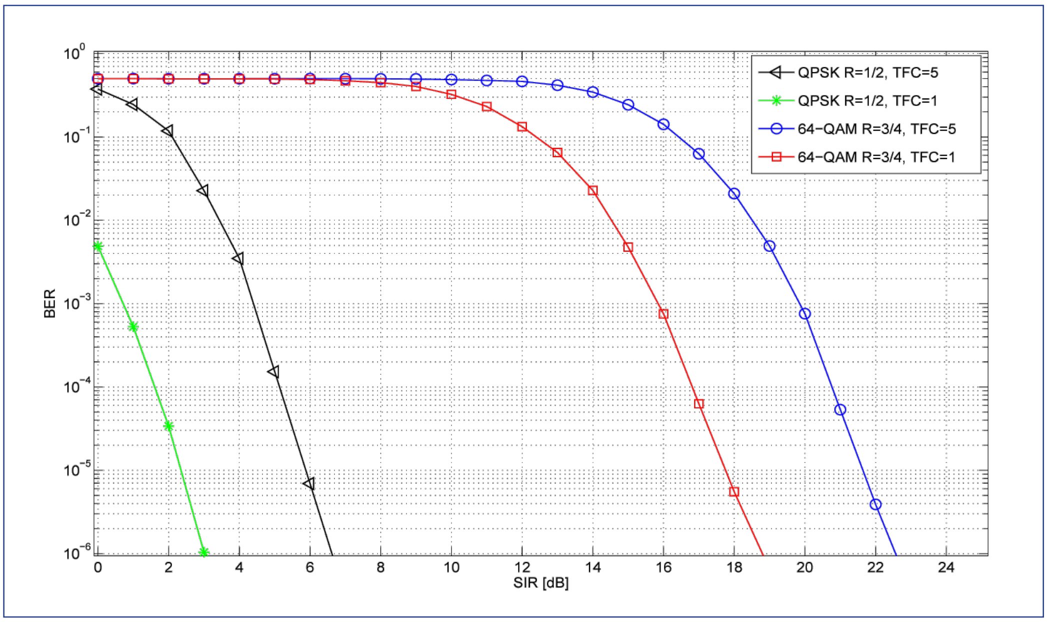


Figure 8:
BER vs SIR Performance of QPSK R=1/2 and 64-QAM R=3/4 WiMax systems with TFC=1 and TFC=5 and SNR=100 dB

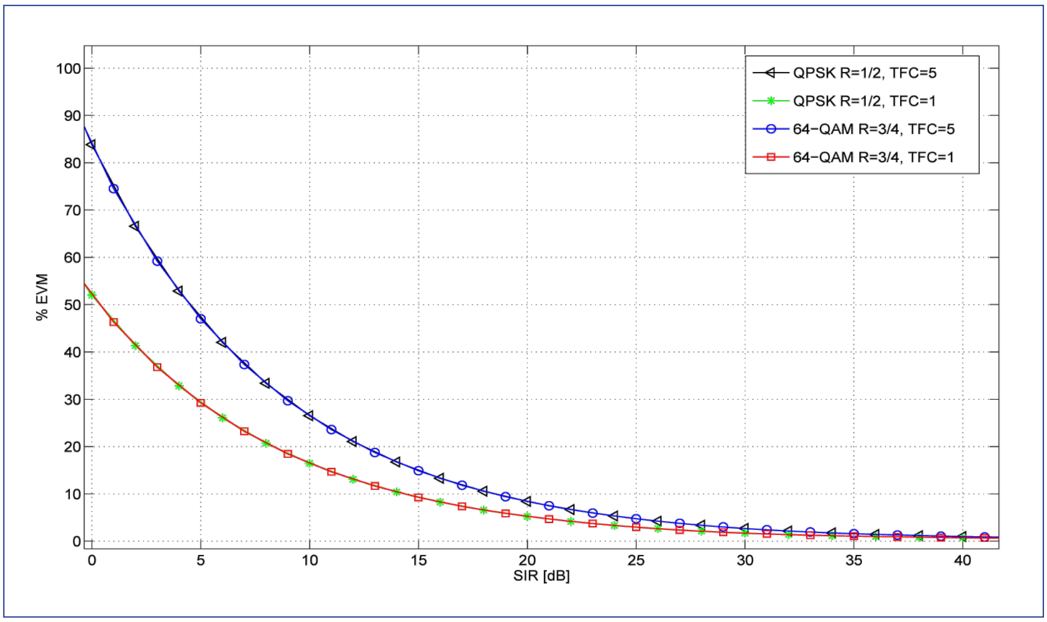


Figure 9:
Percentage EVM vs SIR of QPSK R=1/2 and 64-QAM R=3/4 WiMax systems with TFC=1 and TFC=5 and SNR=100 dB

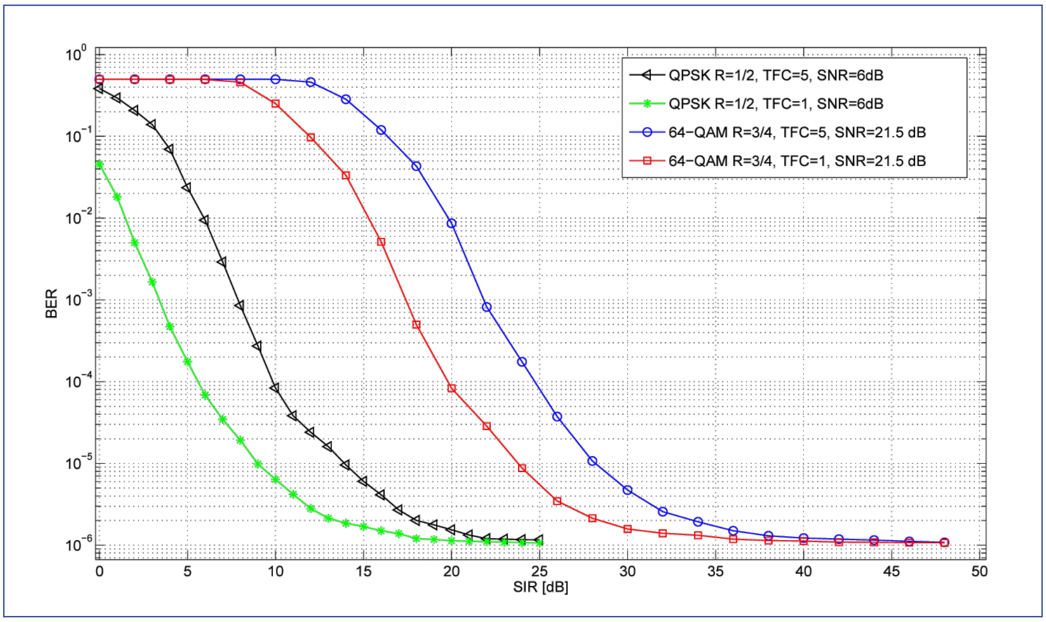


Figure 10:
BER vs SIR Performance of QPSK R=1/2 SNR=6 dB and 64-QAM R=3/4 SNR=21 dB WiMax systems with TFC=1 and TFC=5

illustrates the BER performance of a WiMax system with CP=1/8 as a function of the SNR for both QPSK R=1/2 and 64-QAM R=3/4 signalling and without presence of UWB interference. The effects of the fading are notorious on the BER performance in the situation of SUI-1 with respect to the case of AWGN channel. In this scenario, the minimum SNR required to obtain a BER value of 1e-6 is numerically obtained as approximately 18 dB and 42 dB for QPSK R=1/2 and 64-QAM R=3/4, respectively. The BER performances of both signalling schemes show an error floor in channel SUI-4. This is due to the effects of the Inter-symbol interference. To combat these effects, a larger CP value should be chosen at the expenses of reducing the raw data rate value.

Finally, the effects of the UWB MB-OFDM interference on the WiMax signals are simulated in the case of SUI-1 channel environment, as shown in figure 13. A SNR values of 18 dB and 42 dB are set for QPSK R=1/2 and 64-QAM R=3/4, respectively. The numerical results show that, as expected, there is an approximately 4.5 dB difference between the hopping interference (TFC1) and the non-hopping situation (TFC5).

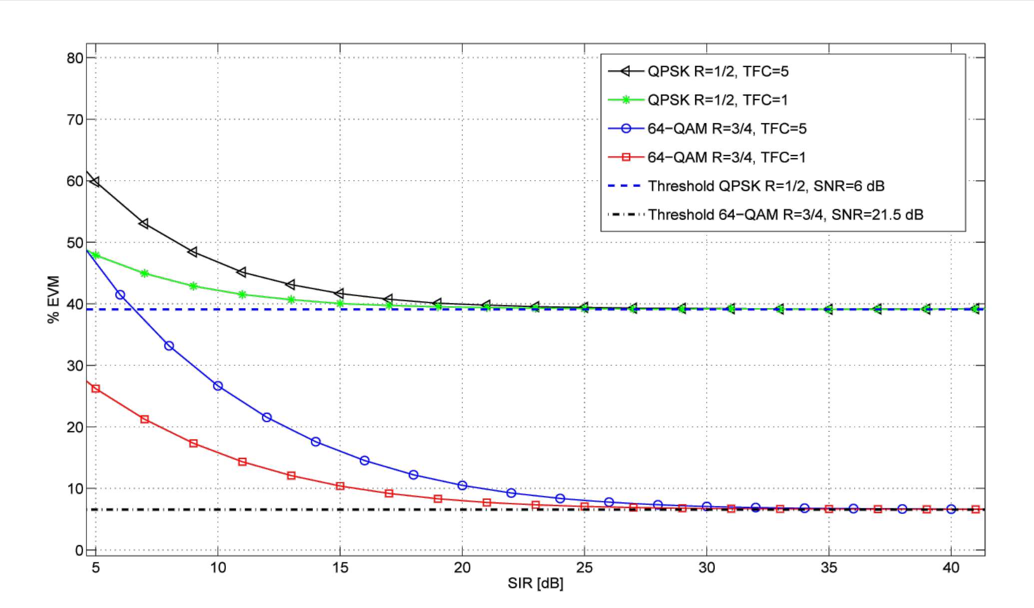


Figure 11: Percentage EVM vs SIR of QPSK R=1/2 SNR=6 dB and 64-QAM R=3/4 SNR=21.5 dB WiMax systems with TFC=1 and TFC=5

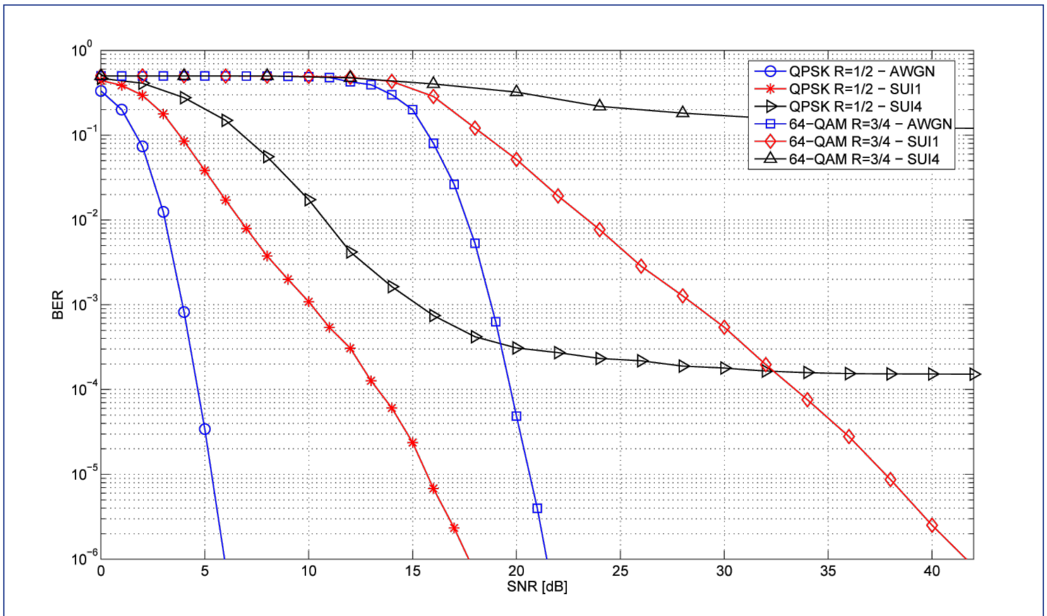


Figure 12: BER vs SNR Performance of QPSK R=1/2 and 64-QAM R=3/4 WiMax systems in different SUI channel environments

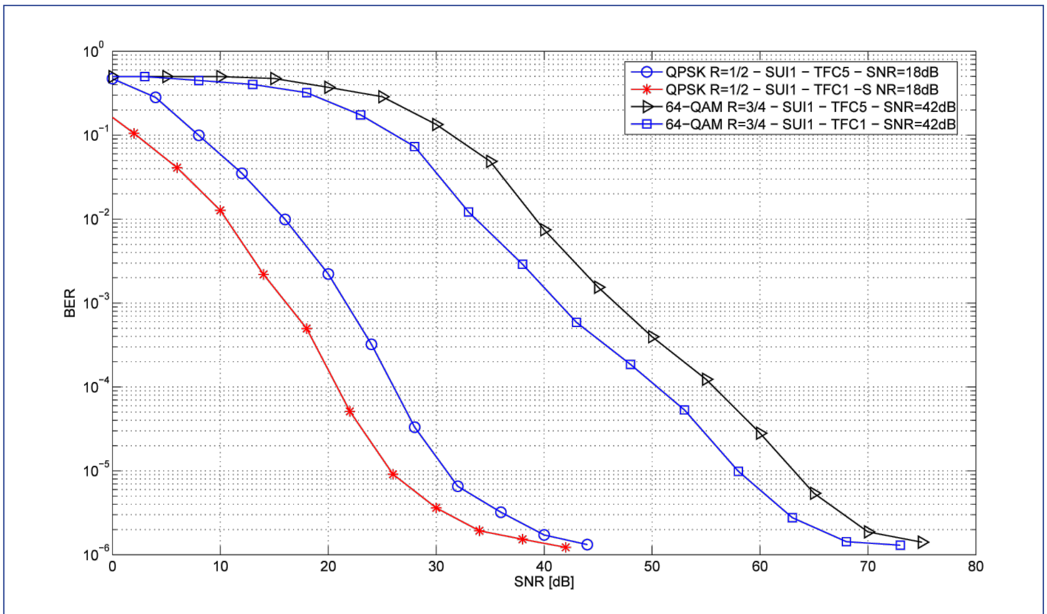


Figure 13: BER vs SIR Performance of QPSK R=1/2 SNR=18 dB and 64-QAM R=3/4 SNR=42 dB WiMax systems with TFC=1 and TFC=5 in SUI-1 Channel

UWB MB-OFDM Interference on Radar systems. Laboratory Measurements

In this coexistence study, the victim system is a Radar device working in the S-band (3.1 GHz to 3.4 GHz). The interfering service is a UWB MB-OFDM signal defined by the WiMedia standard [2]. The effects of RF interference on Radar receivers have been exhaustively studied in [15], where it has been stated that Radar performance starts degrading when the interference-to-noise (I/N) levels are in the range from -10 dB to -6 dB. This means that the interference is below the noise of the system.

The required detection thresholds for the Detection-And-Avoid (DAA) detection mechanism that guarantee an interference free operation of the potential victim Radar device are calculated in the ECC Report 120 [1]. This report also provides the radiolocation system characteristics for the compatibility studies. These characteristics are described in table 5.

Next, a link budget analysis can be performed taking into account the Radar characteristics of ECC Report 120. We consider a Radar system with centre frequency at 3.25 GHz and an antenna gain of 25 dBi, i.e. worst case, and an UWB device with an antenna gain of 0 dBi emitting at the allowed power spectral density (PSD) levels, i.e. -70 dBm/MHz in zone 1 and -41 dBm/MHz in zone 2. The Radar thermal noise at the input of its receiver is -114 dBm/MHz. We can easily obtain the path loss between the Radar system and the UWB device for a certain I/N criteria and a PSD UWB level as

$$PL(dB)=PSD_{UWB}(dBm/MHz)-G_{UWB}(dB)-G_{Radar}(dB)-[Noise_{Radar}(dBm/MHz)+I/N(dB)]$$

If we consider a free-space propagation model [16], the Radar-to-UWB ranges for both PSD UWB levels and several I/N levels can be straightforward calculated. The results for I/N levels of good performance limits stated in [15, i.e. -10 dB and -6 dB, and for more powerful interference signals, i.e. 0 dB and 6 dB, are shown in table 6.

From the results of table 6, it can be observed that the UWB device must be very close to the Radar system to degrade its performance. Moreover, if we had selected a NLOS propagation model with an exponent greater than 2 or an antenna with more gain, the ranges would have been lower.

For further information, the ECC Report 120 refers to the Recommendation ITU-R M.1465-1 [17]. This Recommendation provides technical and operational characteristics, as well as protection criteria, of operational land/ship/air based radars in the 3100-3700 MHz band. These characteristics are summarized in table 7.

The employed modulation schemes are described in the NATO document ACP-131 [18] and listed as follows:

- P0N = (P) sequence of unmodulated pulses / (0) no modulating signal / (N) no information transmitted.
- Q3N = (Q) a sequence of pulses in which the carrier is angle-modulated during the period of the pulse / (3) a single channel containing quantized or digital information with the use of a modulating sub-carrier / (N) no information transmitted.
- Q7N = (Q) a sequence of pulses in which the carrier is angle-modulated during the period of the pulse / (7) two or more channels containing quantized or digital information / (N) no information transmitted.

The Technical Specification ETSI TS 102 754 [19] and the draft of the Technical Report ETSI TR 102 763 [20] provide the technical specifications of DAA mitigations techniques, and the description of the test setups and test procedures for the compliance of DAA in UWB devices. Also, the test patterns for radiolocation services are described in the abovementioned documents. Table 8 illustrates the main parameters of radiolocation test signals in the band 3.1 GHz to 3.4 GHz.

The Radar Test Frequency, i.e. the centre frequency, shall be arbitrarily chosen between 3.1 GHz and 3.4 GHz. The pulse width used in these tests is assumed to be representative of real radar systems with different pulse widths and different modulations. The PRF shall be randomly chosen in the given range. Pulses have instantaneous bandwidth of 0.5, 1, 2 or 5 MHz and modulation types can be CW, LFM or BPSK.

The number of pulses per burst simulates real radar systems and takes into account the effects of pulse repetition and pulse width on the detection probability for a single burst. PPB represents the number of pulses seen at the UWB DAA device per radar scan, given by:

$$N = \frac{antenna\_beamwidth(\deg)\cdot pulse\_repetition\_rate(pps)}{scan\_rate(\deg/s)}$$

$$L = PPB \cdot \frac{1}{f_{PRF}}, \text{ burst length in seconds.}$$

The number of pulses shall be randomly chosen in the given limits.

Figure 12 shows the general bursts structure of this type of radiolocation services.

The parameters of the radar test waveforms used in the experiments are shown in table 9.

The values of the parameters in table 9 have been chosen taken into account the variation limits of pulse width (W),

Radar Systems Deployments in 3100 – 3400 MHz			
System Mobility	Fixed and Mobile systems		
Radar system deployment: One single radar per area	Yes		
Radar Systems Characteristics in 3100 – 3400 MHz			
	Min	Typ	Max
Pe: Radar transmitter emission power Peak power in [dBm]	55	80	95
Ge: Antenna Gain in [dBi] In the antenna main beam (for 0º elevation and azimuth)	25	35	45
Pe + Ge: Peak EIRP according to distance coverage in [dBm]	80	115	140
Radar Receiver bandwidth (Typical) In [MHz]		10	
Radar Signal Characteristics			
	Min	Typ	Max
Pulse duration in [µs]	0.2	10 & 110	110
Pulse repetition frequency in [Hz]	300	4000	7000

Table 5: Radar Characteristics in 3100-3400 MHz

I/N (dB)	Radar-to-UWB ranges (m)	
	A: PSD-UWB = -41 dBm/MHz	B: PSD-UWB = -70 dBm/MHz
-10	5.829	0.206
-6	3.678	0.130
0	1.843	0.065
+3	1.305	0.046

Table 6: Radar-to-UWB ranges for different I/N levels

Parameter	Land -based systems		Ship systems		Airborne system
	A	B	A	B	A
Use	Surface and air search	Surface search	Surface and air search		Surface and air search
Modulation	P0N/Q3N	P0N	P0N	Q7N	Q7N
Tuning range (GHz)	3.1-3.7		3.5-3.7	3.1-3.5	3.1-3.7
Tx power into antenna (kW) Peak	640	1000	1000	4000-6400	1000
Pulse width (µs)	160-1000	1-15	0.25, 0.6	6.4-51.2	1.25
Repetition rate (kHz)	0.020-2	0.536	1.125	0.152-6.0	2
Compression ratio	48000	Not applicable	Not applicable	64-512	250
Type of compression	Not available	Not applicable	Not applicable	CPFSK	Not available
Duty cycle (%)	2-32	0.005-0.8	0.28, 0.67	0.8-2.0	5
Tx bandwidth (MHz) (-3 dB)	25/300	2	4, 16.6	4	>30
Antenna gain (dBi)	39	40	32	42	40
Antenna type	Parabolic		Parabolic	PA	SWA
Beamwidth (H, V) (degrees)	1.72	1.05, 2.2	1.75, 4.4 csc^2 to 30	1.7, 1.7	1.2, 6.0
Vertical scan type	Not available	Not applicable	Not applicable	Random	Not available
Maximum vertical scan (degrees)	93.5	Not applicable	Not applicable	90	±60
Vertical scan rate (degrees/s)	15	Not applicable	Not applicable		Not available
Horizontal scan type	Not available	Rotating	Rotating	Random	Rotating
Maximum horizontal scan (degrees)	360		360		360
Horizontal scan rate (degrees/s)	15	27.7	24	Not available	36
Polarization	RHCP	V	H	V	Not available
Rx sensitivity (dB)	Not available	-112	-112	Not available	Not available
S/N criteria (dB)	Not applicable	0	14	Not available	Not available
Rx noise figure (dB)	3.1	4.0	4.8	5.0	3.0
Rx RF bandwidth (MHz) (-3 dB)	Not available	2.0	Not available		Not available
Rx IF bandwidth (MHz) (-3 dB)	380	0.67	8	10	1
Deployment area	Worlwide	Worlwide	Worlwide	Worlwide	Worlwide

Table 7: Characteristics of radiolocation systems in the band 3100-3700 MHz

pulse repetition frequency (PRF) and bandwidth of the modulated signal (BW) for the two radar test signals of table 8. Thus, the whole set of radar signals in this band can be described by a short number of waveforms.

A laboratory test bed has been specifically designed to study the interference of UWB MB-OFDM on Radar systems. A detailed description of the test bed platform is presented in Annex A.2.

The main parameters of the UWB MB-OFDM interference used in the experiments are: 3.432 GHz centre frequency (band group 1 and sub-band 1 WiMedia), 528 MHz bandwidth, 50% duty cycle, and no frequency hopping, i.e. time-frequency code (TFC) TFC5. This is the UWB MB-OFDM configuration that causes the largest interference on S-band Radar systems working in the range 3.1 to 3.4 GHz.

The settings of the acquisition system, i.e. the RSA 3408A real-time spectrum analyzer, are fixed for all the measurements. The acquisition bandwidth is 10 MHz, which is the typical bandwidth of these Radar receivers, as it can be seen from table 5 of Radar characteristics from the ECC Report 120. The acquisition time of each measurement is 10 ms, so that it can be simulated a single Radar scan for the whole set of waveforms.

In addition, it should be taken into account that the estimated noise floor of the real-time spectrum analyzer is -84 dBm/MHz and the thermal noise of the Radar system is -114 dBm/MHz, therefore the power levels of the Radar system and the UWB MB-OFDM device must be selected according to this 30 dB difference.

An extensive series of 6460 measurements has been conducted. For each one of the 20 Radar waveforms defined in table 9, 19 different Radar power levels, ranging from -70 dBm to -40 dBm, have been employed. Also, for each Radar power level several attenuation values of the UWB MB-OFDM interference have been applied in the measurements.

Figure 13 shows the measurements results of one of the waveforms in table 9 (waveform number 20) for one pulse repetition period. The Radar power level used in these measurements is -65 dBm, which means that a target near to the limit of the Radar range is being analyzed. The SNR measured is approximately 12 dB. The attenuation levels of the UWB MB-OFDM interference have been selected to perform four different I/N ratios: -10 dB, -6 dB, 0 dB, and +3 dB. As it can be seen from the results, the received Radar signal can be clearly distinguished from the distortion phenomena, i.e. interference and noise.

Once the received Radar signal is acquired in the stand-alone PC, a post-processing analysis can be applied. Different post-processing techniques will be carried out depending on the type of the selected Radar receiver structure. A probability of detection study in presence of UWB MB-OFDM interference could be performed in the next phase.

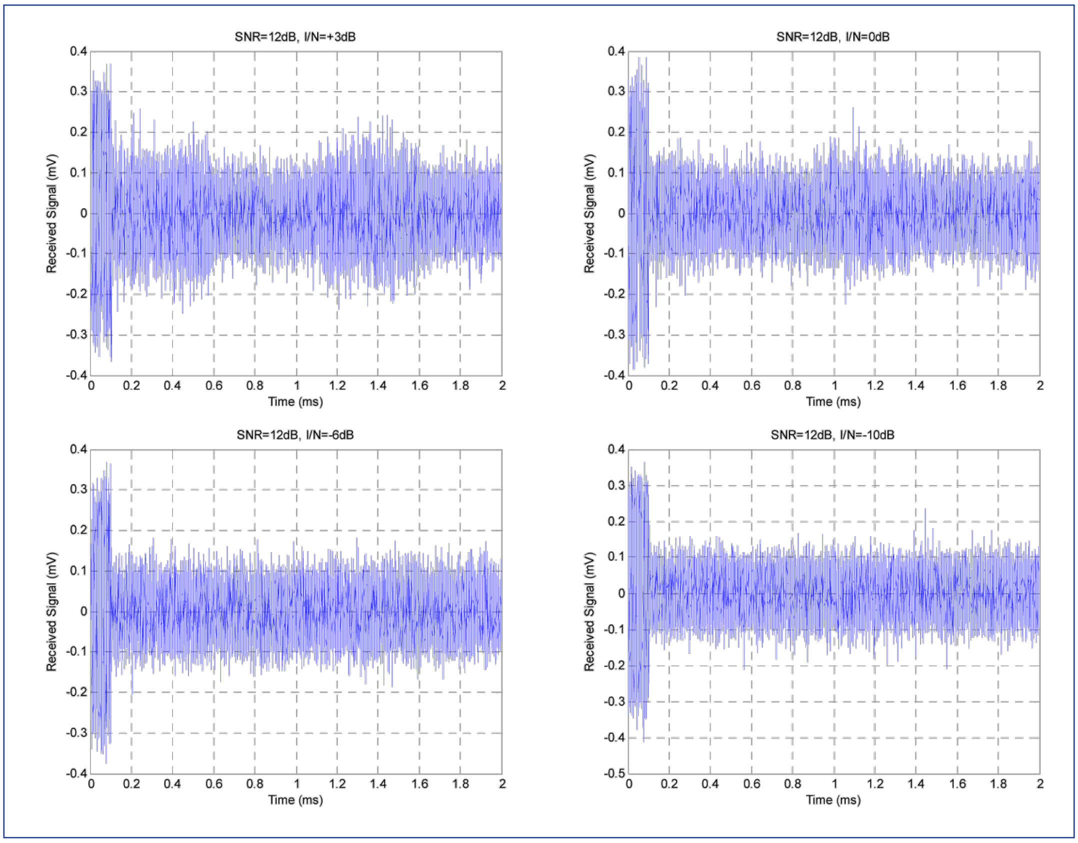


Figure 13: Received signal of the measurements: Radar echo and UWB-OFDM interference, for I/N=+3dB (up-left), I/N=0dB (up-right), I/N=-6dB (down-left), I/N=-12dB (down-right)

Table 8: Parameters of radiolocation test signals

Radar test signal	Pulse width W(µs)	Pulse repetition frequency f_{PRF} (pps)	Pulses per burst (PPB)	Burst repetition frequency f_{BRF} (bps)	Detection probability with 50% channel load
1	20, 30,40	400 – 1400	10 – 60	0.2 – 0.08	$P_d > 90\%$
2	10, 20, 40, 60, 100	100 – 500	2 – 5	0.2 – 0.08	$P_d > 90\%$

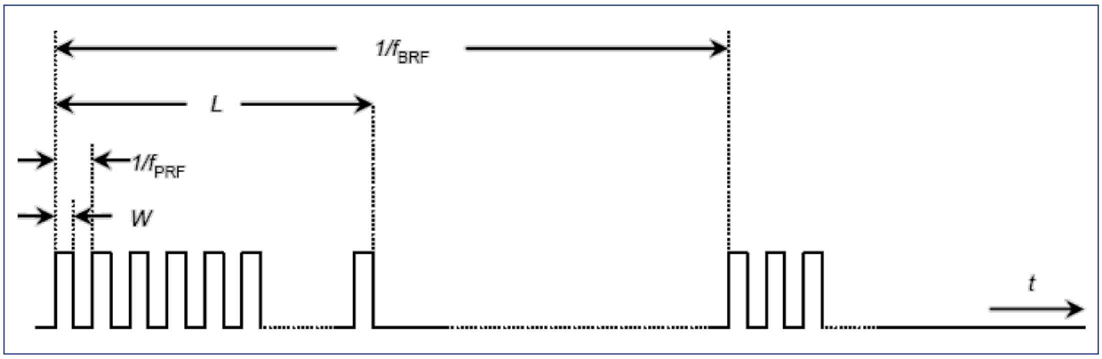


Figure 12: General structure of the bursts

Table 9: Parameters of the radar test waveforms

Waveform number (#)	**Pulse width W(µs)**	**Pulse repetition frequency f_{PRF} (Hz)**	**Bandwidth BW (MHz)**
1	20	400	1
2	20	400	5
3	20	1400	1
4	20	1400	5
5	40	400	1
6	40	400	5
7	40	1400	1
8	40	1400	5
9	10	100	1
10	10	100	5
11	10	500	1
12	10	500	5
13	40	100	1
14	40	100	5
15	40	500	1
16	40	500	5
17	100	100	1
18	100	100	5
19	100	500	1
20	100	500	5

Recommendations and Possible Follow-on Activities

The main conclusions that can be drawn from this study is that both the protection limits and mitigation measures included in the recent Commission Decision 2009/343/EC are appropriate and ensure the protection of the radiolocation and broadband wireless access (BWA) services. The schedule of this study has not allowed to make the results available sufficiently in time before the publication of this Commission Decision. This was anyway foreseen and it is simply due to the fact that this study has been produced in the frame of a pilot phase. In particular, this study presents a series of laboratory measurements that show the validity of the limits in the coexistence scenarios between BWA and UWB in the 3.5 GHz frequency bands, and that between radiolocation services and UWB in the 3.1 and 3.4 GHz frequency band. This result also confirms the validity and appropriateness of the recommendations made in ECC Report 120 [1].

More specifically, on the coexistence between UWB and BWA in the 3.5 GHz band. The main result to date is that both a laboratory test bed and a simulation tool specifically designed to study the coexistence of WiMax and UWB MB-OFDM have been successfully developed and extensively tested. The measurements presented in this report have been obtained with a laboratory test bed in the conducted modality. However, it should be remarked that the same test bed can be used in the radiated modality with minor changes. The control software and the instrumentation required for both conducted and radiated tests are just the same, with the only difference that in the radiated tests we will need the antennas and an appropriate test environment. From the simulation analysis viewpoint, these radiated scenarios can be modelled by using multipath fading channels for both line-of-sight (LOS) and non-line-of-sight (NLOS) environments.

Regarding the coexistence between UWB and radiolocation services in the 3.1-3.4 GHz band, an extensive series of compatibility measurements in the conducted modality has been completed. These tests have been carried out using a set of twenty different radar waveforms with varying duration, frequency bandwidth, and pulse repetition frequency. Results show that with the defined emission masks for UWB and the interference to receiver's noise ratios (i.e,. I/N <-6dB), the performance of the radar is not degraded.

In July 2009, when the pilot phase is concluded, provided it is positively assessed and there is a continued support of the Member States in the Radio Spectrum Committee, a permanent collaboration on radio spectrum policy between JRC and INFSO will be established. The main focus of this collaboration would be that of providing technical assistance in future coexistence studies in areas where the IPSC-JRC can prove a solid experience and can offer unique experimental facilities. Some possible examples of these areas are the following:

- Coexistence studies where the use of automotive short-range radars (SRR) or UWB systems for sensors and communications is involved. For these measurements, IPSC-JRC can offer an anechoic chamber where full size vehicles can be accommodated during the compatibility tests. This facility has previously been used to assess the compatibility of SRR in the 24 GHz band [21]. Likewise, the present regulation in the Commission Decision 2009/343/EC, which establishes the protection limits for vehicular UWB is partially based on measurements carried out at IPSC-JRC under an ETSI mandate [22].[23].
- Coexistence studies where the use of building material analysis (BMA) imaging systems is involved. IPSC-JRC has worked extensively on the testing and algorithm design for both ground-based and through the wall radar imaging systems.
- The assessment of the effectiveness of present and future mitigation measures to be implemented on the UWB transmitters (e.g., DAA and LDC) to ensure the protection of the radio services licensed in the UWB frequency band.
- The assessment of the compatibility between UWB and radiolocation services. This could include radiolocation systems not addressed to date, such as bistatic and passive radar [24].
- Coexistence studies and interference measurements where the impact of the aggregate effects needs to be assessed. In fact, the issue of aggregate interferences may become very relevant in a near future in case the interference sources are spatially distributed with a high density close to the victim receiver. IPSC-JRC is currently conducting research in this area developing state-of-the-art theoretical models. Provided an specific request is received, this activity could be complemented with experimental work by developing a dedicated test-bed designed to study the impact of the aggregate interference effects [25],[26].

Annex A: Description of Laboratory Test Bed

A.1 WiMax and UWB MB-OFDM Test Bed

The laboratory test bed used in the measurements carried out in the coexistence study between WiMax and UWB MB-OFDM is depicted in figure A1.

The employed instruments are listed as follows:

- WiMax baseband vector signal generator (Rohde Schwarz SMBV100A). Upconverter: Agilent Technologies PSG E8267D
- WiMax Receiver: Tektronix Spectrum Analyzer RS-A3408B
- WiMax Demodulator: WiMax IQSignal software application running on a stand alone pc.
- Two UWB MB-OFDM Sources:
    - Tektronix AWG7000B UWB Signal Generator
    - Wisair DV9110 WiMedia evaluation system operating in the test mode
- Signal combiner

This test bed has been specifically designed to carry out both conducted and radiated controlled measurements of the actual impact of the UWB MB-OFDM interference onto a WiMax channel in the 3.5 GHz band. An implementation of a similar test bed at Georgia Tech University (US) is reported in [4]. The main characteristic of these two test beds is that we use a real time spectrum analyzer as a programmable WiMax receiver. This has the advantage of giving us the possibility to fully control important receiver parameters such as the center frequency, bandwidth, sampling frequency, external triggering and, more important, using a WiMax demodulator software that gives a quantitative estimate of the impact of the interference at the WiMax receiver. A spectrum analyzer has typically a noise figure that is poorer than that of a state of the art WiMax receiver. This is a limitation of the proposed test bed and the interference scenarios will have to be designed taking into account the poorer receiver sensitivity associated with the use of a spectrum analyzer. In our test bed, we have estimated a noise floor of the spectrum analyzer of -84 dBm/MHz, which is about 20 dB poorer than a state of the art WiMax receiver. Last but not least, the analog-to-digital conversion in the spectrum analyzer is made with 16-bits and therefore our receiver has a dynamic above 90 dB. This can be significantly increased using the auto range functionality that sets an adaptive level of the reference signal.

A stand-alone PC remotely controls the settings of the WiMax baseband signal generator, the WiMax up-converter, the UWB MB-OFDM RF generator, and the WiMax receiver. The WiMax receiver (RSA Tektronix 3804A) delivers in real time the I and Q time domain waveforms after the down-conversion to baseband. The demodulation of the WiMax waveform is made offline using a dedicated software tool that runs on the stand alone pc. In our case, we have used a fixed/mobile WiMax demodulation software commercialized by the company Litepoint (IQSignal WiMax Demodulator).

Figure A2 shows the configuration of the test bed when a UWB MB-OFDM sample device operating in the test mode is used.

The proposed test bed has been tested extensively with sequences of several hundred measurements showing an extremely high reliability and robustness.

This WiMax demodulation software has a graphical user interface where the following results are shown:

- Packet EVM of the pilots and the data
- Peak and average power for the preamble and the symbols
- Constellation of the received data
- I and Q waveforms in the time domain
- Power spectral density and mask
- Symbol Error Rate
- Ancillary data such as frequency errors, DC leakage, and IQ imbalance

A snapshot of the GUI of the WiMax demodulation software is shown in figure A3. This tool gives the possibility of a remote access to the whole set of demodulation data through a TCP/IP based command server.

A control software tool written in LabView that programs a sequence of measurements with increasing WiMax transmit power and registers the complete set of demodulation results has been developed. This test bed has been designed to monitor the errors in the WiMax channel for any arbitrary values of the SNR and SIR.

Finally, figure A4 shows a photograph of the laboratory test bed with the two arbitrary waveform generators for the WiMax and UWB MB-OFDM systems, the frequency up-converter, and the WiMax receiver (i.e., the spectrum analyzer).

A.2 Radar and UWB MB-OFDM Test Bed

The laboratory test bed used in the measurements to study the coexistence between Radar and UWB MB-OFDM is shown in figure A5.

The employed instruments are listed as follows:

- Radar Signals Baseband Generation: programmed in MATLAB. Up-Converter: Agilent Technologies PSG E8267D.
- Radar Receiver: Tektronix RSA 3408A Real-Time Spectrum Analyzer.
- Radar Acquisition: software application running on a stand-alone PC.
- UWB MB-OFDM Source: Wisair DV9110 WiMedia evaluation system operating in the test mode. Attenuation: Agilent Technologies 11713B/LXI Attenuator.
- Signal combiner.

The test bed has been specifically designed to carry out both conducted and radiated controlled measurements to evaluate the impact of the UWB MB-OFDM interferences onto a Radar device working in the S-band (3.1 GHz to 3.4 GHz).

The radar waveforms in baseband are programmed with MATLAB and uploaded to the Agilent Technologies PSG E8267D from the stand-alone PC. Then, the baseband generated signal is up-converted in the PSG to the centre frequency in S-band.

The UWB MB-OFDM signal is generated with a WiMedia sample device, Wisair DV9110, which is an evaluation system operating in the test mode. Its power level is set by means of the Agilent Technologies 1173B/LXI Attenuator, which controls the attenuation level of two cascade attenuators: Agilent 84907K (70 dB attenuator) and Agilent 84904K (11 dB attenuator).

The main characteristic of this test bed is that we use a real-time spectrum analyzer as a programmable receiver. This presents the advantage of giving us the possibility to fully control important receiver parameters, such as the centre frequency, bandwidth, sampling frequency, acquisition time or external triggering. However, a spectrum analyzer has typically a high noise figure which leads to poor noise floor. We have estimated a noise floor of the real-time spectrum analyzer of -84 dBm/MHz, which is 30 dB higher than the noise floor at the input of the Radar receiver. Moreover, the analog-to-digital converter of the spectrum analyzer uses 16-bits, so the dynamic range of this receiver is around 90 dB, but this fact can be enhanced using the auto-range function that sets an adaptive level connected to the reference signal.

A stand-alone PC controls the settings of the UWB MB-OFDM generation, the attenuation level of the UWB MB-OFDM signal, the Radar baseband waveforms generation, the Radar up-conversion, and the Radar receiver.

The Radar receiver (Tektronix RSA 3804A) delivers in real-time the in-phase and quadrature time-domain waveforms after the down-conversion to baseband. The post-processing of the received Radar signals can be performed offline in the stand-alone PC using a dedicated software tool.

The set of measurements is performed in the stand-alone PC by means of a sequence of settings in a LabVIEW script. The script is arranged in three nested loops. In the first loop, the Radar waveform is uploaded and up-converted in the PSG E8267D. The second loop sets the power level of the RF Radar signal. Finally, the third loop sets the attenuation level of the UWB MB-OFDM interference signal. Once the settings of each step are ready, the RSA 3804A carries out the measurement of the received signal, which is saved as a separated file in the stand-alone PC. By employing this technique, a large set of measurements with different Radar waveforms, different Radar power levels in the receiver that emulate close or remote targets, and different UWB received power levels that allow choosing the interference-to-noise ratio can be obtained in a relatively short time.

Figure A6 shows several snapshots of the acquisition system, i.e. the real-time spectrum analyzer, for different signal-to-interference ratios (S/I) and different interference-to-noise ratios (I/N).

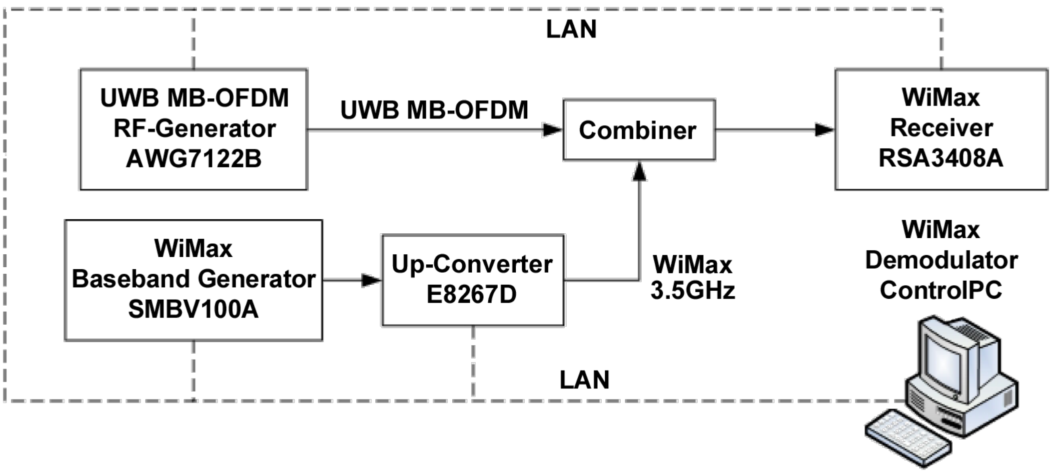


Figure A1:
Sketch of the laboratory set-up for conducted tests

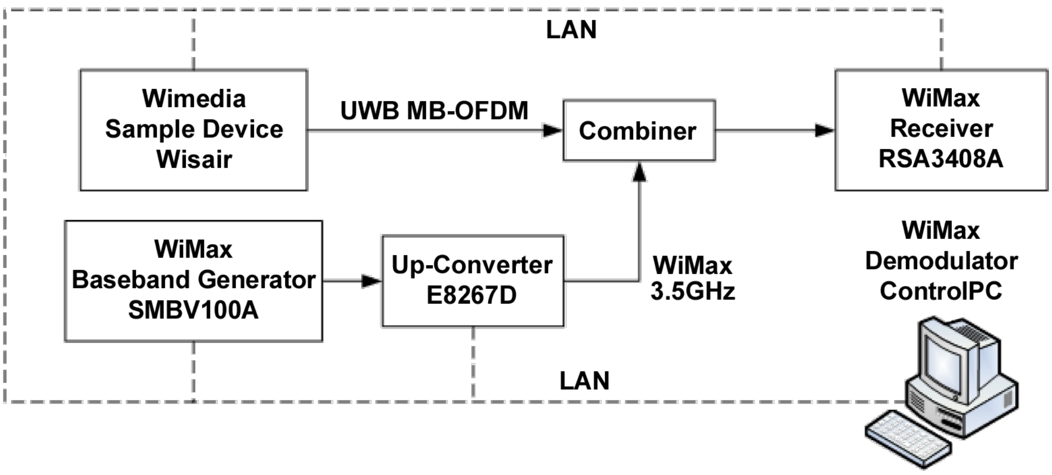


Figure A2:
Sketch of the laboratory set-up for conducted tests

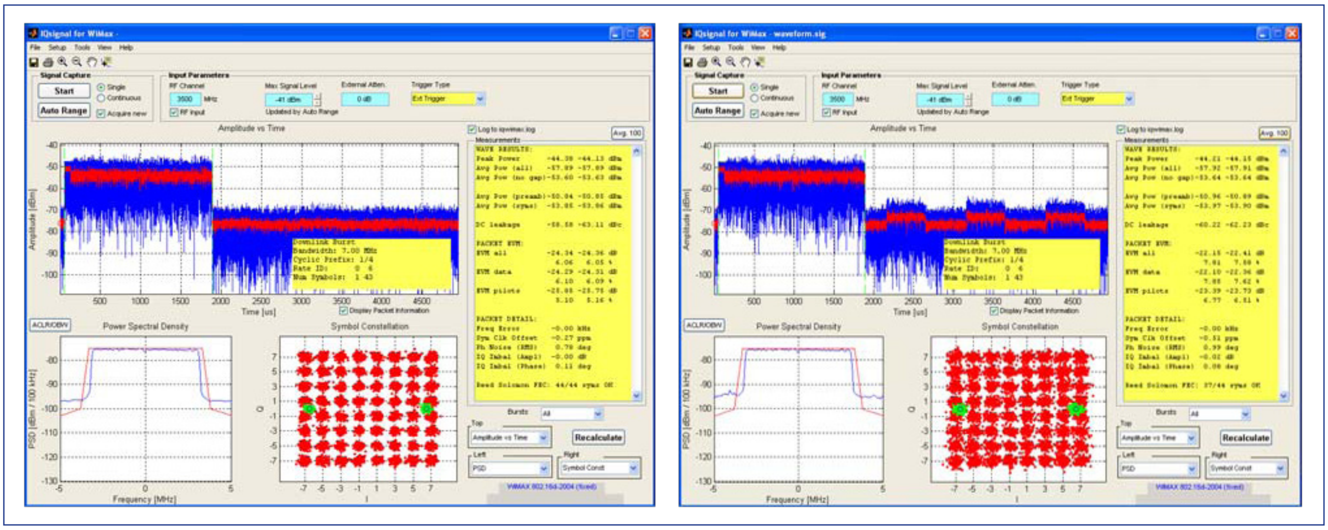


Figure A3:
Snapshot of the GUI of the WiMax Demodulator Software showing the time domain I and Q waveforms without (left) and with (right) an UWB MB-OFDM interference present

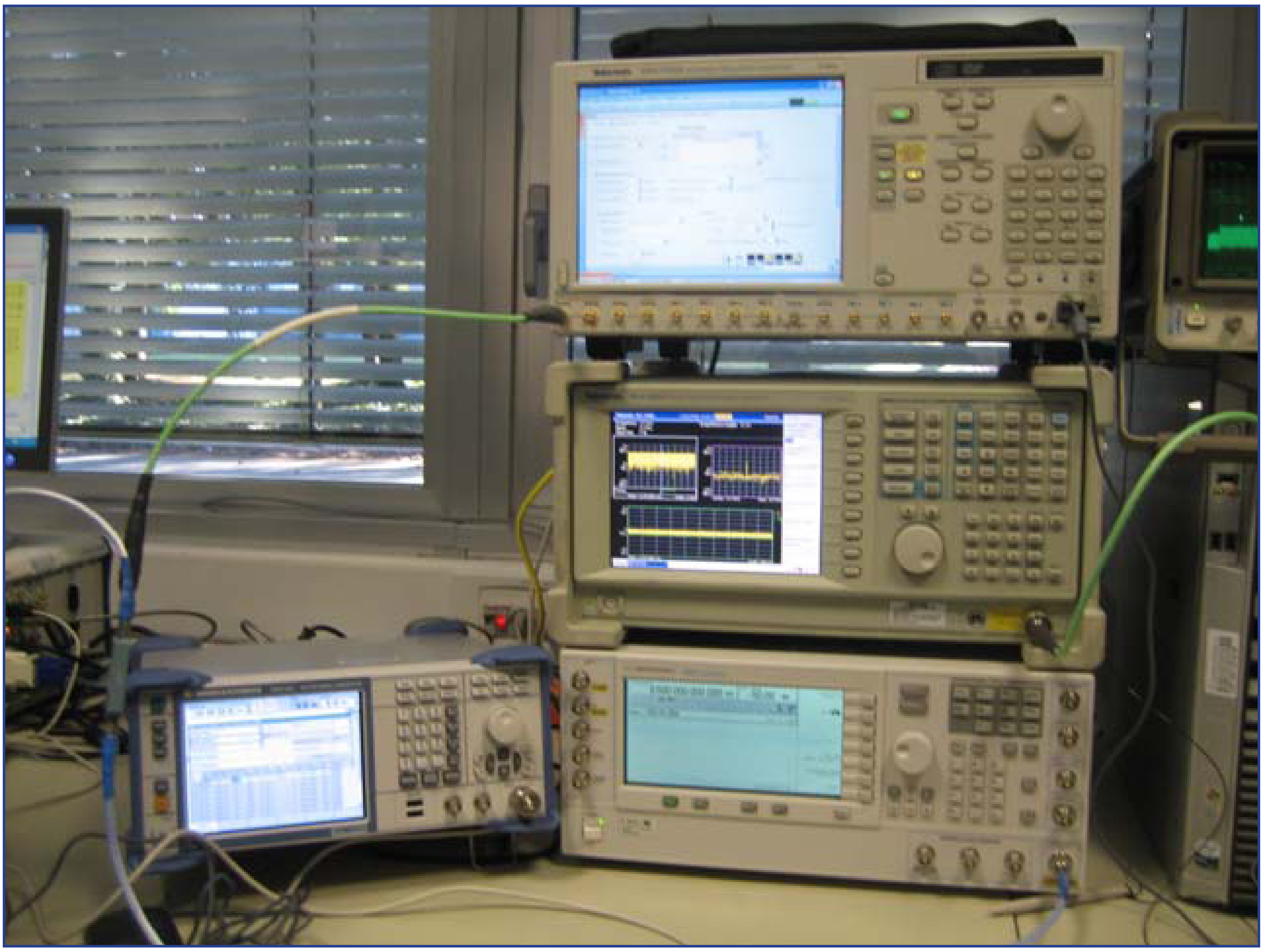


Figure A4:
Photograph of the laboratory test bed for the WiMax UWB MB-OFDM coexistence measurements in the conducted modality

Figure A5:
Sketch of the laboratory set-up for conducted tests

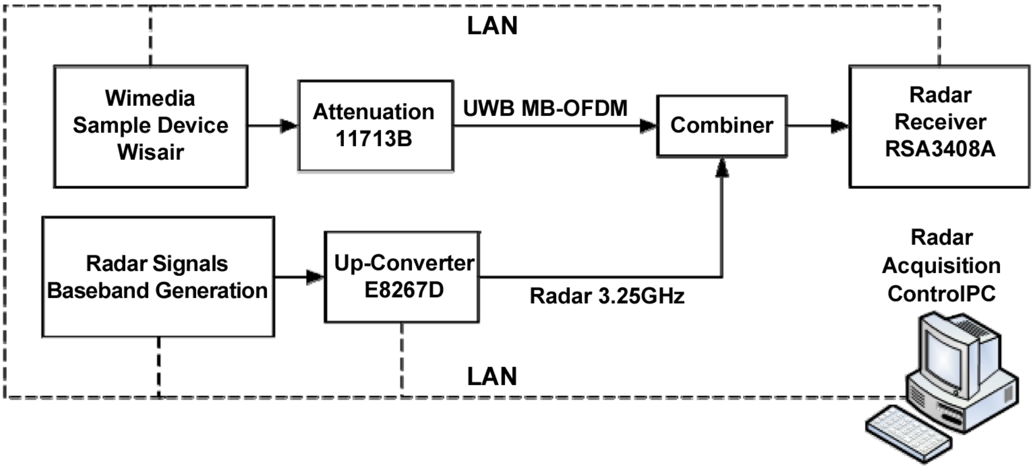


Figure A6:
Snapshots of the acquisition system for different S/I and I/N

Annex B: Description of the Interference Simulation Tool

The main parameters and functionality of the WiMax/WiMedia simulation tool are described in this section. The simulator, which is implemented in Matlab™ software, allows computation of the quality of the radio link, measured in terms of Bit Error Rate (BER) and Error Vector Magnitude (EVM), for different types of interference scenarios. A detailed description of the main blocks that constitute the WiMax/WiMedia network and the most significant numerical results are presented here.

B.1 WiMax system

The WiMax system implemented in this simulation tool follows the specifications of the IEEE 802.16d standard for fixed wireless access networks [3]. The IEEE 802.16d standard is based on orthogonal frequency division multiplexing (OFDM) with 256 subcarriers to accommodate multiple subscriber stations (SS) in the 2-11 GHz frequency band that access the system following a TDMA scheme. The WiMax system presents multiple attractive properties for both line-of sight (LOS) and non line of sight (NLOS) communications scenarios. Among all of these properties, flexible nominal bandwidth, robust error control mechanisms and adaptive modulation and coding schemes are analysed in the implemented simulator.

The IEEE 802.16d system employs 256 subcarriers, of which 192 are used for data, 56 are nulled for guard band protection and 8 are designated to pilot subcarriers for channel estimation purposes. A cyclic prefix (CP) of variable length is appended to the resulting 256 symbol samples to combat the inter-symbol interference (ISI). The stipulated length values of the CP are 1/4, 1/8, 1/16 and 1/32 the length of a symbol.

The nominal bandwidth (BW) is an integer multiple of 1.25 MHz, 1.5 MHz, 1.75 MHz, 2 MHz and 2.75MHz, with a maximum value of 20 MHz. The sampling rate of the WiMax signal is given by $f_S = 8000 \times \lfloor n \times BW/8000 \rfloor$ with n being a sampling factor whose value depends on the selected BW as defined in table 213 of [3].

A robust Forward Error Control (FEC) technique is implemented in the simulation tool based on a two-phase process. This concatenated code is constructed by using an outer Reed-Solomon (RS) code and an inner punctured convolutional code (CC). The CC encoder corrects independent bit errors, while the RS code corrects burst errors at the byte level. The puncturing process allows the concatenated FEC rates to be compatible with the specifications of the standard [3].

Four modulation schemes are specified in the IEEE 802.16d standard for both downlink (DL) and uplink (UL) transmissions. These modulation schemes are binary phase shift keying (BPSK), quaternary phase shift keying (QPSK) and M-ary quadrature amplitude modulation (QAM) with modulation orders M=16 and M=64. The PHY specifies seven burst profiles as a result of combining modulations and FEC rates that can be assigned to both SS and base station (BS). The combined modulation and coding profiles are illustrated in table B1. The selection of an appropriate combination depends on the required performance considering trade-offs between data rate and system robustness.

The block diagram structures of the WiMax transmitter and receiver that are implemented in the simulation tool are shown in figure B1. A brief description of the blocks that constitute the transmitter and receiver is provided next.

The generated random data is initially scrambled to prevent long sequences of ones and zeros by using a pseudo-random binary sequence generator with 15-stage shift registers and a generator polynomial $g(x) = 1 + x^{14} + x^{15}$.

The scrambled bit sequence is initially grouped into blocks of fixed bit length and sent through a shortened Reed-Solomon encoder which is derived from a systematic RS code (N=255, K=238, T=8) within a Galois Field GF (2^8). The shortened RS encoder employs puncturing techniques to achieve variable block sizes as defined in table B1 and variable error correcting capabilities at its output for each modulation-coding paired burst. A tail byte of zeros is appended at the output of each encoded block. The RS encoded block of bits feed an inner convolutional encoder of rate 1/2. Punturing techniques are employed in the convolutional encoder to obtain the variable code rates.

The resulting sequence of bits from the concatenated RS-CC encoder is interleaved by a two-process block interleaver. The size of the block depends on the modulation order. The first permutation step of the interleaver is implemented to ensure that adjacent coded bits are mapped onto adjacent subcarriers. The second permutation step avoids two consecutive encoded bits being mapped onto the same constellation symbol.

The bit interleaved data is sent to the modulation mapping unit in order to obtain a Gray-mapped complex constellation for all the four modulation schemes as specified in figure 203 of the IEEE 802.16d standard [3]. Each complex constellation point is then assigned to individual data subcarriers of the OFDM symbol.

Once the eight BPSK-modulated pilot subcarriers are assigned according to the normalized pattern for DL and UL emissions [3], and the 56 remaining tones are nulled for

Modulation	Block Size (Uncoded Bytes)	Block Size (Coded Bytes)	CC Rate	RS Code Rate	Overall Coding Rate
BPSK	12	24	1/2	(12,12,0)	½
QPSK	24	48	2/3	(32,24,4)	½
QPSK	36	48	5/6	(40,36,8)	¾
16-QAM	48	96	2/3	(64,48,8)	½
16-QAM	72	96	5/6	(80,72,4)	¾
16-QAM	96	144	3/4	(108,96,6)	2/3
16-QAM	108	144	5/6	(120,108,6)	¾

Table B1: Mandatory channel coding per modulation as defined in Table 215 of [1]

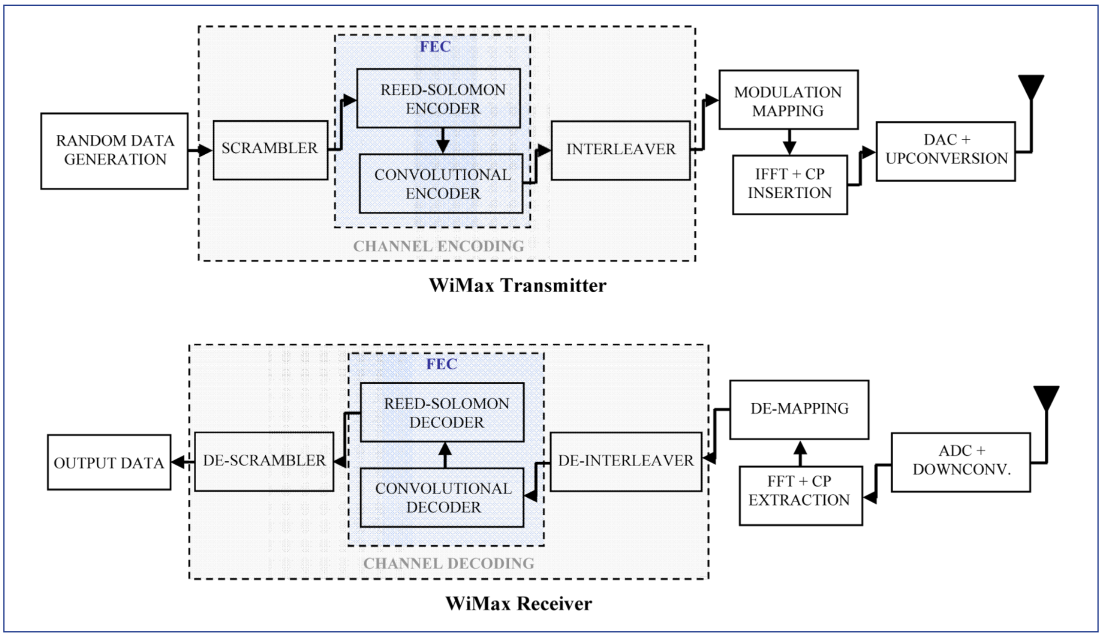


Figure B1: Simulation block diagrams for the WiMax transmitter and WiMax receiver

Channel Model	Tap 1			Tap 2			Tap 3		
	DS (us)	P (dB)	K	DS (us)	P (dB)	K	DS (us)	P(dB)	K
SUI -1	0	0	4	0.4	-15	0	0.9	-20	0
SUI -2	0	0	2	0.4	-12	0	1.1	-15	0
SUI -3	0	0	1	0.4	-5	0	0.9	-10	1
SUI -4	0	0	0	1.5	-4	0	4	-8	0
SUI -5	0	0	0	4	-5	0	10	-10	0
SUI -6	0	0	0	14	-10	0	20	-14	0

Table B2: Parameter values of the SUI channel models guard band protection, the OFDM symbol is constructed by applying the IFFT function [8]. The resulting 256 symbol samples are concatenated with the CP samples to combat the ISI effects caused by the multipath channel.

Finally, the concatenated discrete symbols are passed through a Digital to Analog Converter (DAC) and then, the resulting continuous signal is up-converted to the centre frequency $f_c = 3.5 GHz$. At the receiver front-end, the baseband signal is filtered with a low-pass butterworth filter of order four to eliminate the out-band interference effects.

The rest of the receiver blocks have the reverse functionality of the transmitter modules. For clarity reasons, these are not described in this document.

The simulation tool allows evaluation of the WiMax radio link performance considering additive white Gaussian noise (AWGN) or multipath propagation channels. The simulated multipath channels employed in this work are the Stanford University Interim (SUI) channel models [9]. The SUI model is a set of six channels that characterise the channel impulse response for three different types of terrain types and also considering the mobility of the SS by means of the Doppler spread parameter. Each SUI multipath channel is obtained by defining three taps with the corresponding power, delay spread and K-factor. The values of these parameters are summarized in table B2 considering the following parameters: cell size of 7Km, a base station antenna at 30m with 120º beamwidth, an omnidirectional receiver antenna located at 6m, and 90% cell coverage with 99.9% reliability at each location covered [9].

B.2 WiMedia Ultra Wideband interference

The interferer system implemented in the simulation tool is modelled as WiMedia Ultra Wideband (UWB) devices which follow the Multi-Band OFDM approach [10]. In Multi-Band OFDM systems, the available 7.5 GHz bandwidth (from 3.5 GHz to 10.6 GHz) is divided into fourteen sub-bands, each having a bandwidth of 528 MHz. These sub-bands are grouped into six band groups (BG1-BG6) of three sub-bands each, except BG5 which has two sub-bands. The centre frequency of the $n\text{-}th$ sub-band is defined as $f_{c,n} = 2904 + n \times 528$ MHz.

The transmitted UWB signal is power limited by the regulatory organizations of each respective country in order to protect and coexist with other primary services, also called victim services. In February 2002, the Federal Communications Commission (FCC) in the US released power spectrum masks to regulate UWB emissions for both indoor and outdoor environments [11]. As a result of this, a maximum Effective Isotropic Radiated Power (EIRP) value of -41.3 dBm/MHz was imposed over all the 7.5 GHz operation bandwidth. These FCC masks have been initially adopted in Europe with a considerable restriction of the EIRP levels in specific bands to protect incumbent wireless standards, such as WiMax [6]. Detect and Avoid (DAA) mitigation techniques have been imposed in certain bands to eliminate interference effects caused by UWB devices on victim systems. In this interference scenario, UWB devices operating in Europe must reduce their EIRP levels to -65 dBm/MHz or even -80 dBm/MHz depending on the detected power levels of the WiMax system. The simulator allows transmitted power levels of each sub-band to adapt dynamical to be compliant with the regularity masked proposed in [12].

The WiMedia interferer signal implemented in this simulation tool is based on the ECMA-368 Standard for high rate Ultra Wideband Systems [2]. The transmitted baseband signal can be expressed as

$$s_T(t) = \sum_{m=0}^{N_{pk}-1} \sum_{n=0}^{N_{pack}-1} s_{m,n}\left(t - mT_p - nT_{sym}\right) \qquad (1)$$

where N_{pk} is the total number of packets, each one of duration T_p, N_{pack} is the number of transmitted symbols in one packet, N_{sym} is the total number of samples per symbol, and T_{sym} is the duration of one symbol. The signal $s_{m,n}(t)$ in (1) represents the continuous baseband signal for the n^{th} symbol in the m^{th} packet that is obtained after the equivalent discrete signal $s_{m,n}[k]$ with $k = 0, 1, .., N_{sym}$ passes through a DAC and an antialiasing filter. This discrete signal is defined as

$$s_{m,n}[k] = \begin{cases} p_{m,n}[k] & 0 \le n < N_{sync} \\ h_{m,n-N_{sync}}[k] & N_{sync} \le n < N_{sync} + N_h \\ d_{m,n-N_{sync}-N_h}[k] & N_{sync} + N_h \le n < N_{sync} + N_h + N_f \end{cases} \qquad (2)$$

where $p_{m,n}[k]$ is the preamble of the n^{th} symbol, $h_{m,n}[k]$ is the header of the n^{th} symbol, and $d_{m,n}[k]$ represents the payload for the n^{th} symbol. The parameters N_{sync}, N_h and N_f in (2) correspond to the total number of symbols in the preamble, header and payload, respectively. The relationship $N_{pack} = N_{sync} + N_h + N_f$ must be preserved.

First, the sequence of preamble symbols is generated for different estimation purposes. The preamble is composed of packet/frame synchronization symbols followed by channel estimation symbols. After the preamble, the header and the payload data symbols are generated by using an OFDM technique with $N_{FFT} = 128$ subcarriers. The main timing-related and frame-related parameters defined by the ECMA-368 standard are summarized in table B3.

The block diagram structure of the WiMedia interference signal implemented in the simulation tool is represented in figure B2. A brief description of the functionality and parameters employed for each module is provided below.

B.2.1 PLCP Preamble

The preamble is a real baseband signal generated to aid the receiver in timing synchronization, carrier-offset

Table B3:
Time-related and frame-related main parameters

Parameter	Description	Value
f_s	Sampling frequency	528 MHz
N_{FFT}	Total number of subcarriers (NFFT size)	128
N_d	Number of data subcarriers	100
N_p	Number of pilot subcarriers	12
N_g	Number of guard subcarriers	10
N_T	Total number of used subcarriers	122
D_f	Subcarrier frequency spacing	4.125 MHz (f_s / N_{FFT})
N_{zps}	Number of samples in the zero-padded suffix	37
N_{sym}	Total number of samples per symbol	165
N_{pf}	Number of symbols in the packet/frame synchronization sequence	Standard: 24 Burst: 12
N_{ce}	Number of symbols in the channel estimation sequence	6
N_{sync}	Number of symbols in the PLCP preamble	Standard: 30 Burst: 18
N_h	Number of symbols in the PLCP header	12
N_f	Number of symbols in the PSDU	$6 \times \left\lceil \frac{8 \times L + 38}{N_{IBP6S}} \right\rceil$
N_{pack}	Total number of symbols in the packet	$N_{sync} + N_h + N_f$

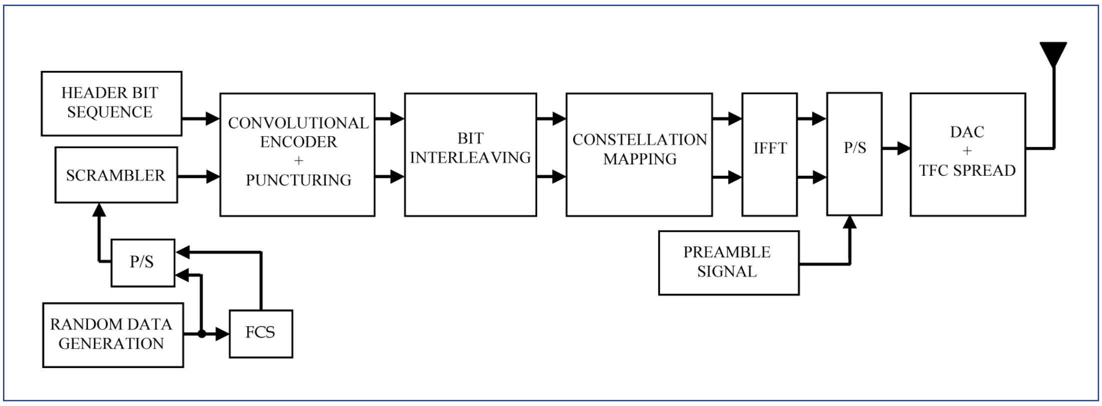


Figure B2:
Simulation block diagram of the WiMedia transmitter

recovery and channel estimation. There are two different types of preambles depending on the selected transmitted data rate. The Standard preamble is applied for data rate values of 200 Mbps or inferior, whereas an optional Burst preamble of shorter duration could be employed for higher data rates.

The PLCP preamble is structured in two portions: a time-domain part for frame/packet synchronization followed by a frequency-domain interval used for channel estimation purposes. A total number of N_{pf} packet/frame synchronization symbols are obtained by multiplying a cover sequence, which is unique for each time-frequency code (TFC), by an extended base sequence. The values of these sequences are defined in table 4 – table 10 and table 21 of the ECMA-368 standard [2]. An identical number, N_{ce} of channel estimation symbols are created by applying the IFFT of the frequency-domain sequence defined in table 23 of the ECMA-368 standard. The results of the IFFT are appended with N_{zps} zeros.

B.2.2 PLCP Header

The PLCP header is added after the PLCP preamble to transmit the required information about the PHY and MAC layers in order to successfully decode the PSDU at the receiver. The Header Bit Sequence of length 200 bits in figure B2 is generated by successively adding 40 PHY header bits, 6 tail bits, 80 MAC header bits, 16 header check sequence (HCS) bits, 6 tail bits, 48 Reed-Solomon parity bits and 4 tail bits.

The Header Bit Sequence is encoded using a convolutional encoder of rate 1/3 and $K=7$ with generator polynomials $g_0=133_8$, $g_1=165_8$ and $g_2=171_8$. The bit sequence at the output of the convolutional encoder is not punctured to keep the coding rate at 1/3.

The encoded sequence of bits is sent through a bit interleaving unit. The bit interleaving is applied to avoid two consecutive bits being modulated within the same frequency tone in order to combat the errors introduced by the frequency-selective channel. The bit interleaving process is performed in three steps; symbol interleaver, tone interleaver and cyclic shifter.

The interleaved bits are grouped in pairs and then modulated using a QPSK scheme with Gray mapping before being loaded onto the data, pilot and guard subcarriers for the IFFT. The modulated complex values are mapped onto the data subcarriers prior the IFFT by grouping them onto sets of 50 consecutive complex numbers in order to achieve both time and frequency spreading. More detailed information about the mapping of the header modulated sequence onto the subcarriers can be found in the Clause 10.10 of the ECMA-368 standard [2].

B.2.3 PSDU

The data information bits are randomly generated and appended with four octet frame check sequence (FCS) bits, 6 tail bits, and a sufficient number of pad bits, N_{pad} to ensure that the PSDU is aligned on the interleaver boundary. The required number of pad bits can be calculated from

$$N_{pad} = N_{IBP6S} \times \lceil (8 \times L + 38) / N_{IBP6S} \rceil - (8 \times L + 38)$$

where N_{IBPS} is the number of information bits per 6 OFDM symbols, and L is the length measured in octets of the data in the PSDU. In the simulation tool, L is set to 1024 bits.

The appended data bit sequence is scrambled using a 15-stage shift registers and a generator polynomial $g(x) = 1+x^{14}+x^{15}$.

After the scrambling process, the randomized data is sent through the chain composed of convolutional encoding and puncturing, bit interleaving and constellation mapping as described in section B.2.2 for the PLCP header. In contrast to the PLCP header, the PSDU can be transmitted at different data rates. The data rate values fixed by the ECMA-368 standard are 53.3, 80, 106.7, 160, 200, 320, 400 and 480 Mbps. These data rate values are obtained by selecting different combinations of modulation scheme and coding rates as shown in table B4. The coding rate value is obtained at the output of the puncturing block with values $R= 1/2,\ 1/3,\ 3/4\ and\ 5/8$. Two different modulation schemes are implemented for the PSDU. The QPSK scheme is employed for data rates of 200 Mbps and below, whereas Dual Carrier Modulation (DCM) scheme is used for higher data rate values. More information about the DCM constellation mapping can be found at section 10.9.2 of the ECMA-368 standard [2].

Finally, the time-domain samples of the PLCP preamble, PLCP header and PSDU are concatenated to generate the baseband discrete packet and then passed through the DAC as shown in figure B2. The continuous signal is up-converted to the RF frequencies by using a TFC pattern that allows frequency-hopping capabilities over the different bands that integrate a band group. There are 10 different TFC codes. Among all of them, TFC1 and TFC5 applied in BG1 are of particular interest in this work, since they reflect the effects of the hopping and non-hopping WiMedia interference signal respectively on the WiMax band.

B.3 Simulation analysis

A brief description of the coexistence issues between WiMax and WiMedia systems is provided in this section in order to identify and set the main parameters of the simulator. The interference scenario that is modelled in the simulation tool is displayed in figure B3. These wireless standards present completely different network topologies. While WiMax devices operate in a cellular communications network with typical values of cell radius of the order of 1-5 km, UWB systems communicate with each other in an ad-hoc manner within 1-10 meter range.

The objective of this work is to analyse the effects on the radio link performance of the WiMax system when the

Data Rate (Mbps)	Modulation	Coding Rate (R)	Coded bits / 6 OFDM Symbols ($N_{CBP\ 6S}$)	Info Bits / 6 OFDM Symbols ($N_{IBP\ 6S}$)
53.3	QPSK	1/3	300	100
80	QPSK	1/2	300	150
106.7	QPSK	1/3	600	200
160	QPSK	1/2	600	300
200	QPSK	5/8	600	375
320	DCM	1/2	1200	600
400	DCM	5/8	1200	750
480	DCM	3/4	1200	900

Table B4: PSDU rate-dependant parameters

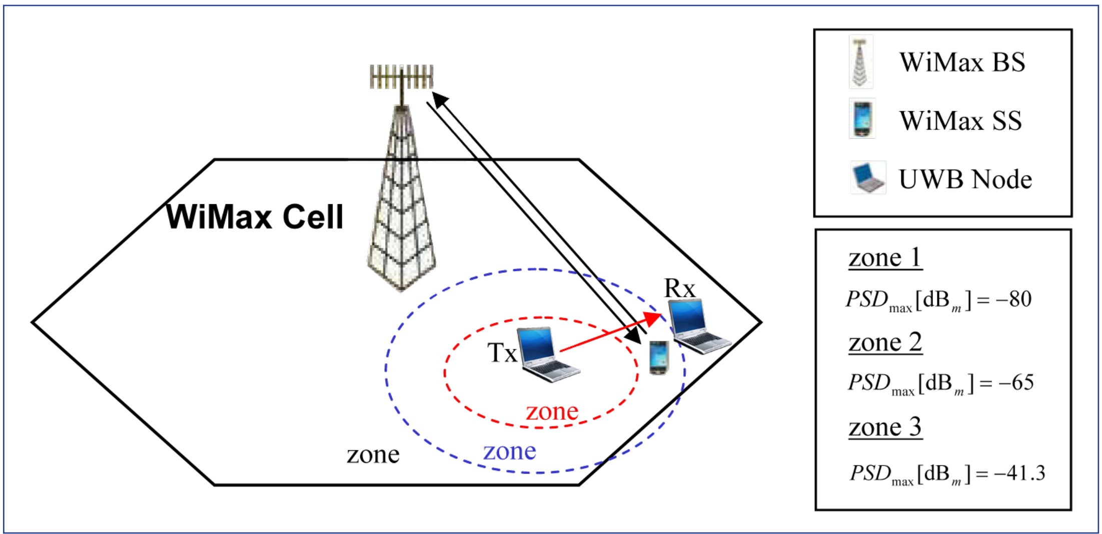


Figure B3: Simulated Interference scenario between WiMax and WiMedia networks

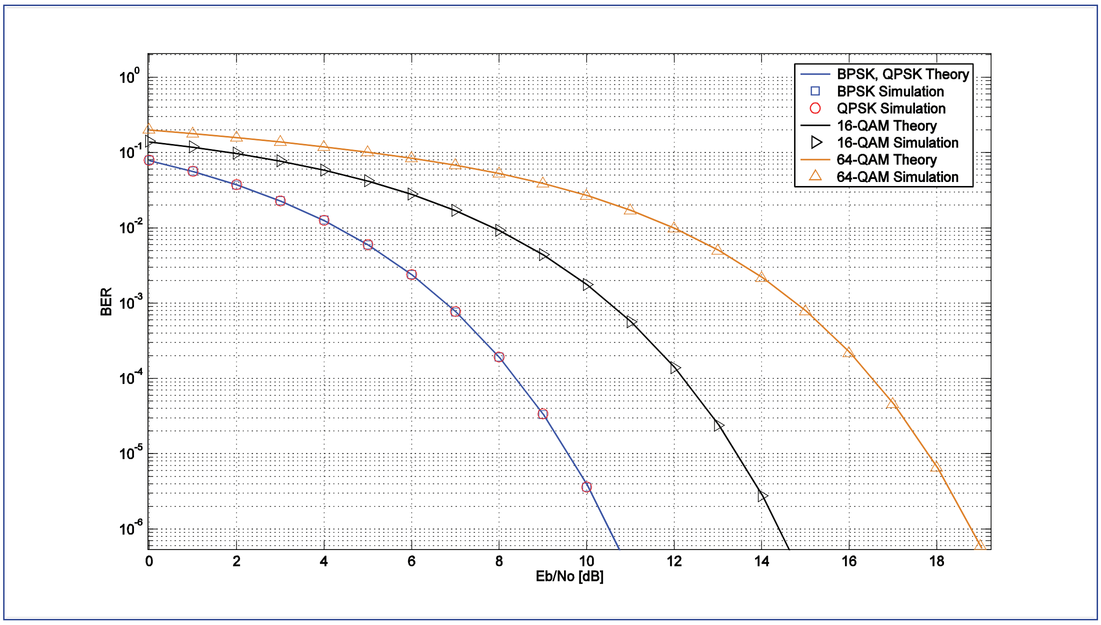


Figure B4: BER Performance for BPSK, QPSK, 16-QAM and 64-QAM uncoded systems

WiMedia interference signal is set to different power levels. Therefore, these interference effects are evaluated in the downlink (DL) when the WiMax receiver is located at the edge of the cell (i.e. weaker received signal). In this situation, the WiMax base station transmits at $P_{t,W}=35dBm$, while the WiMedia transmitted power is set to one of the three different PSD levels (see figure B3) according to the DAA location zones.

A link budget analysis can be established for both systems in order to determine the value of the Wimax received power P_s and the interference power P_I captured by the WiMax receiver. The parameter employed to measure the interference effects is the signal-to-interference ratio (SIR), $SIR=P_s/P_s$, which is measured at the output of the WiMax receiver. Thus, the power of the interference is measured in the WiMax operation band, BW.

The BER and the EVM are the metrics employed in the simulator to evaluate the performance of the WiMax radio link at the physical layer.

B.3.1 Bit Error Rate Performance

Simulation results are presented in this section for a WiMax single link without the presence of the interference. The main objective here is to demonstrate the correct behavior of the simulation tool for a WiMax network in AWGN channel. In this situation, the measured parameter at the receiver is the signal-to-noise ratio (SNR), defined as $SNR=P_s/P_N$, where P_N is the power of the complex white Guassian noise signal.

First, the BER performance as a function of the EbNo (also called SNR per bit) of the IEEE 802.16d link is obtained for an AWGN channel. The simulated results exactly match the theoretical values as shown in figure B4. The theoretical BER curves are obtained as

$$BER=\begin{cases}\frac{1}{2}\mathrm{erfc}\left(\sqrt{\frac{\mathrm{E_b}}{\mathrm{N_0}}}\right) & \text{BPSK/QPSK}\\ \frac{3}{2M}\mathrm{erfc}\left(\sqrt{\frac{ME_b}{10N_0}}\right) & \text{M - QAM}\end{cases} \quad (3)$$

where $erfc(x)$ is the complementary error function [8]. The BER vs SNR curves are obtained in figure B5 for the seven burst profiles defined in section B.1. In this simulation campaign, CP=0 and is the received power of the data subcarriers. Therefore, a correction factor of 192/256 is taken into account in the SNR calculation.

The obtained results meet the expected values of received SNR for BER= 1e-6 given by table 266 of the amendment standard [4], except for the cases of 64-QAM with R=2/3 and R=3/4. In this situation, the simulated SNR values are approximately 0.5 dB larger than the proposed values. The receiver SNR values that guarantees a BER=1e-6 for the seven simulated burst profiles systems are given in table B5

B.3.2 Error Vector Magnitude Evaluation

The EVM is a system-level specification measured at the baseband that describes the quality of the modulation and allows identifying any non-idealities within the system.To measure the EVM, a comparison between the received demodulated symbols and the ideal values in the constellation map is established. This relationship, which quantifies the difference between modulated and demodulated symbols, is expressed as

$$EVM=\left(\frac{1}{N}\sum_{m=1}^{N}\left|V_{id,m}-V_{meas,i}\right|^2\right)\Big/\left(\frac{1}{N}\sum_{m=1}^{N}\left|V_{id,m}\right|^2\right) \quad (4)$$

where $V_{id,m}$ is the m-th transmitted modulated complex symbol, $V_{meas,m}$ is the m-th measured received symbol after the demodulation block and N is the total number of transmitted symbols.

An example of constellation diagrams for QPSK R=1/2 and 64-QAM R=3/4 obtained in the simulator are represented in figure B6 for different values of SNR. The EVM represents the distance magnitude between the modulated points (red dots) and the received demodulated symbols (blue dots).

The EVM values decrease as the SNR increases. This relationship between EVM and SNR is linear as shown in figure B7(a), and it can be computed as $EVM\approx1/SNR$. As expected, the results also show that the simulated EVM curves are identical between the two modulated systems, indicating the correct performance of the simulator. Finally, the percentage of errors (% EVM) curves are plotted in figure B7(b) showing that the typical values when the SNR is large range from 3% to 15% [13].

Table B5: Receiver SNR for simulated BER=1e-6

Modulation + Coding	Receiver SNR [dB]
BPSK 1/2	3.0
QPSK 1/2	6.0
QPSK 3/4	8.5
16-QAM 1/2	11.5
16-QAM 3/4	15.0
64-QAM 2/3	19.8
64-QAM 3/4	21.5

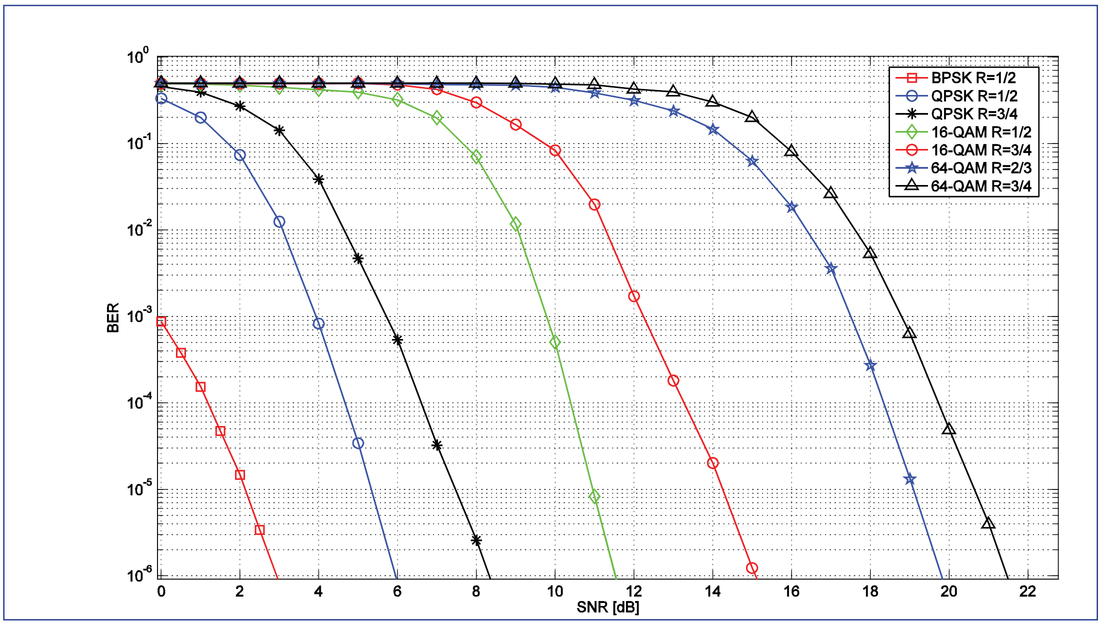


Figure B5: BER performance vs received SNR for a WiMax single link in AWGN channel

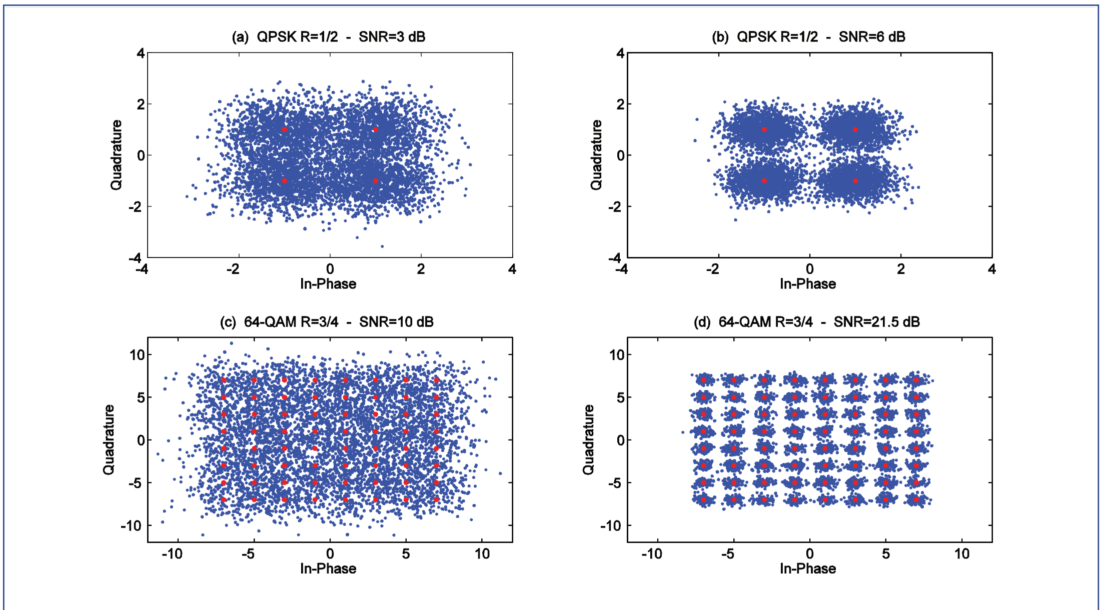


Figure B6: Constellation diagram for WiMax systems: (a) QPSK ½ with SNR=3 dB, (b) QPSK ½ with SNR=6.5 dB, (c) 64-QAM ¾ with SNR=10 dB and 64-QAM ¾ with SNR=22.5 dB

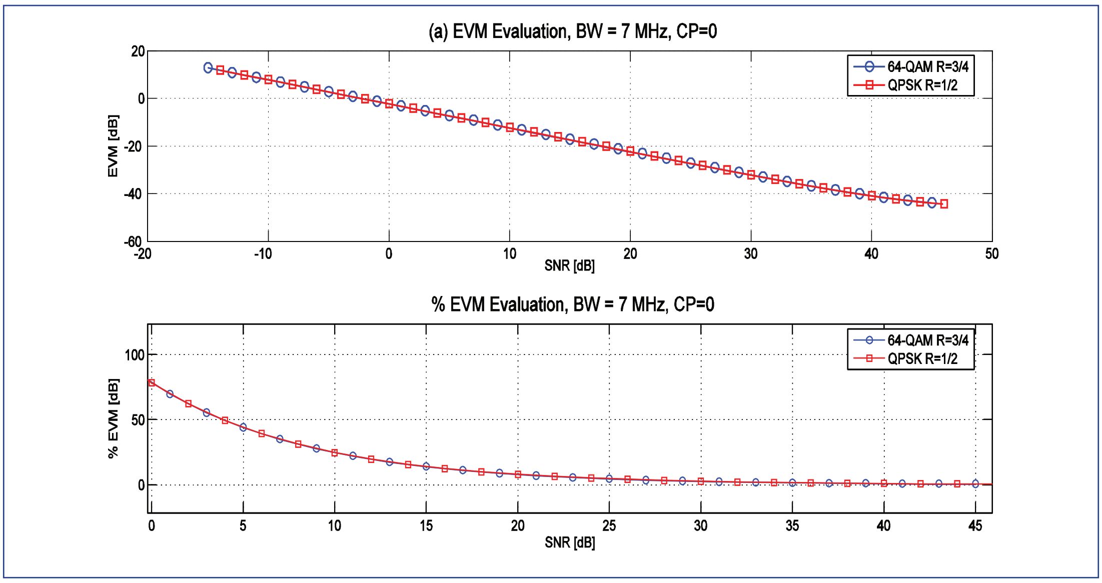


Figure B7: EVM Evaluation for WiMax QPSK 1/2 and 64-QAM 3/4 in AWGN channel

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Abstract

In July 2008, following a request made by the Radio Spectrum Policy Unit in DG INFSO (Unit B4), a pilot phase of twelve months was agreed with Member States representatives in the Radio Spectrum Committee. During this time the Institute for the Protection and Security of the Citizen of the EC Joint Research Centre (IPSC-JRC) has been mandated to provide testing facilities to support the development of Community spectrum legal measures under the Radio Spectrum Decision (676/2002/EC). In the frame of this pilot phase, IPSC-JRC has successfully completed the implementation and extensive testing of both a state-of-the-art laboratory test-bed and a simulation tool, which have been specifically designed for two different coexistence studies. Firstly, the coexistence between broadband wireless access (BWA) and ultra wideband (UWB) services in the 3.5 GHz frequency band; and secondly, the coexistence between radiolocation (i.e. radar) and UWB services in the 3.1-3.4 GHz frequency band. The selection of these two coexistence scenarios is not casual and has been made based on the fact that they have been considered highly relevant in the CEPT-ECC studies on UWB mandated by the European Commission.

The mission of the JRC is to provide customer-driven scientific and technical support for the conception, development, implementation and monitoring of EU policies. As a service of the European Commission, the JRC functions as a reference centre of science and technology for the Union. Close to the policy-making process, it serves the common interest of the Member States, while being independent of special interests, whether private or national.

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