Modified Adjacent Frequency Coding for Increased Notch Depth in MB-OFDM under DAA/Spectral Sculpting

Conference Paper · July 2006

DOI: 10.1109/CROWNCOM.2006.363478 · Source: IEEE Xplore

Interference Analysis and Sensing Threshold of Detect and Avoid (DAA) for UWB Coexistence with WiMax

Kwan-woo Kim[1], Jongmin Park[1], Jinyoun Cho[1], Kyutae Lim[1], Charles J. Razzell[2], Kihong Kim[3], Chang-ho Lee[4], Haksun Kim[5] and Joy Laskar[1]

[1]Georgia Electronic Design Center (GEDC), Georgia Institute of Technology, Atlanta, GA, USA
[2]NXP Semiconductor, Pleasanton, CA, USA
[3]Samsung Electro-Mechanics Inc., Suwon, Korea
[4]Samsung RFIC Design Center at Georgia Tech., Atlanta, GA, USA
[5]Hanbat National University, Daejeon, Korea

Abstract— **Although Ultra Wideband (UWB) is a promising wireless technology for the future due to its high data rate, low power consumption, and low cost, its worldwide acceptance is conditioned by coexistence issues because of the frequency overlap with other wireless standards such as WiMax. In many countries, a Detect and Avoid (DAA) scheme has been promoted as a means to mitigate interference and it is now regarded as an indispensable solution for commercialization of UWB. A detailed specification for DAA can be determined by analyzing co-channel interference for a victim receiver. This paper presents a quantitative interference analysis using Desired to Undesired (D/U) signal power ratio as well as verification results using an equipment-based WiMax testbed. Finally, the D/U ratio results were used to determine minimum keep-out distance and the sensing threshold level for DAA in a UWB device.**

Index Terms— **Ultra Wideband (UWB), WiMax, Detect and Avoid (DAA), Desired to Undesired (D/U) ratio, spectrum sensing, sensing threshold, Bit Error Rate (BER)**

I. Introduction

Today, wireless technology is used in nearly every form of modern electronic communication. As people have become accustomed to using mobile phones and wireless internet, the demands for wireless services are expanding to every kind of data communications. In particular, wireless technologies must be significantly faster to meet the demands of emerging multimedia applications. Ultra Wideband (UWB) is a technology for transmitting the multimedia information spread over a large bandwidth at a high data rate in a personal-area network (PAN). UWB technology has received great interests from both the research community and industry. The strength of UWB radio technology lies in its use of extremely wide transmission bandwidth, which facilitates accurate position determination and ranging, robust radio links, high multiple access capability, covert communications, and lower attenuation in building materials [1].

Despite its merits, UWB is under substantial debate regarding potential interference with existing or future wideband wireless systems using the same and nearby bands, such as WiMax or 3G/4G cellular networks [2]. For example, although the FCC in the US issued its final ruling on February 14, 2002 [3], allowing UWB systems to operate on an unlicensed basis from 3.1~10.6GHz at a power spectral density of -41.3dBm/MHz, some parts of UWB frequency bands (3~5GHz) in Europe overlap with WiMax bands [4]. It is clear that interference between the two signals must exist, if the two devices are operating simultaneously in proximity. Therefore, in order to mitigate the interference while maintaining a consistent worldwide specification, a detect and avoid (DAA) technology was proposed. DAA can minimize the interference by sensing the spectrum and then abruptly switching to unoccupied frequency bands in case of frequency conflict. It allows UWB devices to reuse the available spectrum when there is no near-by narrow-band system using the spectrum.

Although DAA has also been proposed in UWB draft regulations in Korea and Japan, many DAA implementation issues remain unresolved. Most of all, a UWB device should be able to detect local spectrum usage with adequate sensitivity. In order to protect a victim receiver, its sensing threshold level should become the order of the victim receiver sensitivity. Only by analyzing the effects of UWB on a victim receiver and calculating a permissible interference level, it is possible to estimate the exact sensing requirements for the UWB terminal.

This paper introduces quantitative calculation methods of permissible desired to undesired (D/U) ratio and an equipment-based interference measurement system to protect WiMax from OFDM-UWB. This analysis estimates the allowable UWB interference power for a given WiMax signal, the minimum keep-out distance for a UWB terminal and the threshold level of sensing for DAA. Section II presents a calculation of D/U ratio and applies it to a WiMax system. Section III presents an equipment-based UWB-WiMax interference measurement system to verify the calculated D/U ratio and shows experiment results. Finally, required keep-out distance and DAA sensing threshold are presented and discussed in section IV.

II. Quantitative Analysis of Interference

A. Calculation of required D/U Ratio

In general, in order to analyze the performance of a victim receiver in noisy channels with interference, either SNR or BER of the receiver should be considered, because the interferer would degrade both SNR and BER of the victim. It may be reasonable to say that the interferer does not degrade receiver operation, if the system maintains its communication links in the presence of interference even when operating at a minimum received power level. However, this is not achievable in the presence of interference at the threshold received power level because, at the minimum sensitivity, any interference will degrade the SNR. At a higher signal power, it is possible to calculate the tolerable increment in noise. Therefore, any calculation and measurement of tolerable interference must make an assumption about receiver sensitivity reduction. This also corresponds to both sensitivity decrement of the receiver and permissible interference power of interferer. In this paper, this power increment level will be called ΔP.

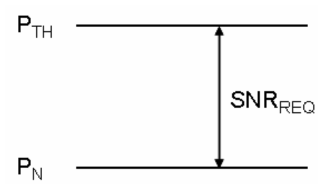

Figure 1. Signal and Noise Power Diagram

The sensitivity decrement level, ΔP, can be easily illustrated with the diagram of signal and noise power levels. Figure 1 shows the required SNR level of common receiver systems without interference. In order to establish transmitter-receiver links, the received signal power from the transmitter must exceed the noise floor level, P_N, by SNR_{REQ}. The P_N is due to thermal noise and can be calculated [5], as shown in (1).

$$P_N\big|_{dBm} = k_B T \Delta f + NF = -174dBm/Hz + 10\log BW + NF \tag{1}$$

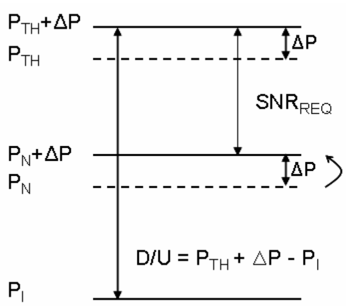

Figure 2. Signal and Noise Power Diagram with Interference

Under the assumption that the received signal power is at a minimum threshold level, P_{TH}, if an in-band interference source is turned on near the receiver, it will interrupt the channel links. As the receiver recognizes the interference as noise, the overall noise level of the receiver will be increased by the power of the interference, which results in insufficient SNR for demodulation. In order to maintain SNR_{REQ}, the receiver needs more signal power, and let the needed signal power increment be ΔP. For each given ΔP, it is possible to set a limit of permissible interference power as a function of ΔP because the overall noise power can also be increased as much as the signal power increment. Figure 2 shows the signal power increment, ΔP, and the allowable overall noise increase due to interference. We can see that both increments are the same (ΔP).

In the figure, ΔP is overall noise floor increment due to interference. Therefore, the power of interference, P_I, can be calculated from ΔP (expressed in *dBm*), as shown in (2).

$$P_I\big|_{dBm} = 10\log_{10}\left(10^{\frac{(P_N+\Delta P)}{10}} - 10^{\frac{P_N}{10}}\right) \tag{2}$$

With the ΔP and P_I, the permissible D/U ratio of the receiver in the presence of interference is as follows.

$$\begin{aligned} D/U &= P_{TH} + \Delta P - P_I \\ &= P_{TH} + \Delta P - 10\log_{10}\left(10^{\frac{(P_N+\Delta P)}{10}} - 10^{\frac{P_N}{10}}\right) \\ &= P_N + SNR_{REQ} + \Delta P - 10\log_{10}\left(10^{\frac{(P_N+\Delta P)}{10}} - 10^{\frac{P_N}{10}}\right) \\ &= P_N + SNR_{REQ} + \Delta P - 10\log_{10}\left(10^{\frac{P_N}{10}}\left(10^{\frac{\Delta P}{10}} - 1\right)\right) \\ &= SNR_{REQ} + \Delta P - 10\log_{10}\left(10^{\frac{\Delta P}{10}} - 1\right) \end{aligned} \tag{3}$$

Therefore, by changing ΔP, it is possible to calculate the required D/U ratio as a function of input signal strength.

B. Required D/U Ratio of WiMax Receiver

In the scenario of interest, the WiMax terminal is a victim and UWB device is an interferer. The SNR at the WiMax receiver will be degraded by thermal noise and interference from the OFDM-UWB signal, which can also be modeled as additional Gaussian noise because OFDM signal has a random noise-like amplitude in the time domain. Using the above equation of D/U ratio, it is possible to estimate a maximum allowable UWB signal power at each WiMax signal power level by specifying ΔP, after having defined the required WiMax SNR. For example, in the WiMax specification IEEE802.16e-2005 (OFDM), states the required BER of WiMax receiver is 10^{-6} after forward error correction. Based on this BER, the specification also provides the corresponding required SNR values according to various constellations and coding rates. These SNR values are summarized in Table I [6].

Let the assumed noise figure of the receiver be 12*dB*. Then, the noise floor in 1*MHz* of bandwidth at the receiver can be found as

$$P_N = -174dBm/Hz + 10\log(10^6) + 12dB = -102dBm/MHz \tag{4}$$

The sensitivity of the receiver can be calculated as follows:

For BPSK-1/2 case,

$$P_{TH} = P_N + SNR_{REQ} = -102 + 3 = -99dBm/MHz \tag{5}$$

For 64QAM-3/4 case,

$$P_{TH} = P_N + SNR_{REQ} = -102 + 21 = -81dBm/MHz \tag{6}$$

Table I. Receiver SNR Requirement of OFDM WiMax

Modulation	Coding Rate	Receiver SNR [dB]
BPSK	1/2	3.0
QPSK	1/2	6.0
	3/4	18.5
16QAM	1/2	11.5
	3/4	15.0
64QAM	2/3	19.0
	3/4	21.0

For the above power levels, Figure 3 shows calculated D/U ratio with respect to WiMax signal power at the receiver. Two modulation schemes (BPSK, 64QAM) were evaluated to illustrate different power levels. 64QAM has a much larger threshold level due to its modulation complexity. The required D/U ratio for a noise-like UWB interferer asymptotically approaches the required SNR of the given modulation and coding scheme as the input signal strength increases. This is logically the case, since the interference dominates the thermal noise under these conditions. The required D/U ratio approaches infinity as the signal strength approaches threshold sensitivity for a given modulation and coding scheme. It is common practice to define required D/U ratio with desired signal strength 3*dB* higher than the threshold sensitivity. In that case, one can infer the required D/U ratio would be 3*dB* higher than the required SNR for the given modulation and coding scheme because the interference and noise are at equal powers.

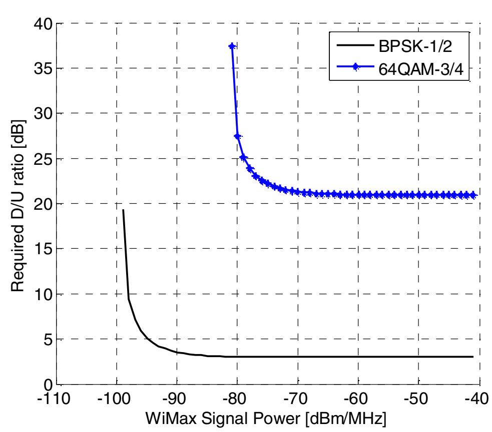

Figure 3. Required D/U Ratio for WiMax with UWB interference

III. System Setup for D/U Ratio Measurement and Test Results

In order to verify the required D/U ratio and to measure the actual effects of UWB on WiMax, an equipment-based testbed, as shown in Figure 4, was developed.

The testbed consists of dual RF-channel vector signal generator (VSG), vector signal analyzer (VSA) and personal computer. The programs for the instrument control and BER measurement of WiMax were developed in MATLAB. Dual RF signals available from the VSG emulated the victim-WiMax signal and interferer-UWB signals. Although omitted from these tests, the VSG's fading and noise options could be used to more accurately represent the channel. Figure 4 and Table II shows the system configuration and specification of the testbed system, respectively.

The WiMax and UWB signals from the VSG were mixed together in an RF combiner, and then fed into the VSA to measure the WiMax signal quality. For WiMax signal generation, mandatory long length test message payload bit patterns, as defined in the WiMax standard for measuring receiver sensitivity, were used. The VSA demodulated the WiMax signal from the combined signals and then provided spectrum, constellation, EVM, demodulated bit streams, and so on. As BER of 10^{-6} after forward error correction coding is a criterion of minimum WiMax sensitivity, the bit stream stored in the VSA must be decoded to determine the BER. A MATLAB program downloaded the bit streams from VSA by Ethernet, then decoded the streams, and finally measured the BER. In accordance with the WiMax standard, the coding consisted of 3 parts as follows:

1. Randomization
2. Concatenated Reed-Solomon-Convolutional Coding
3. Interleaving

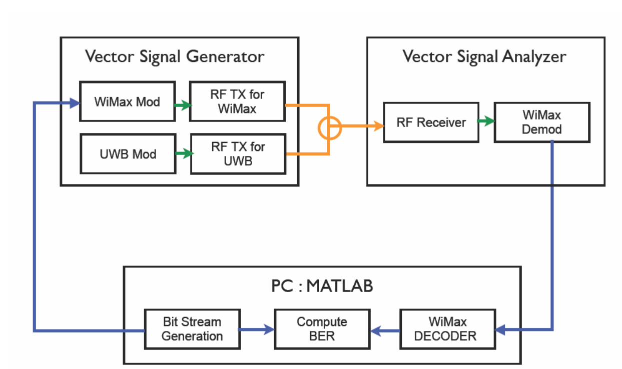

Figure 4. UWB-WiMax Interference Test Setup

Table II. System Specification of Testbed Equipment

Instrument	Specification
VSG	Dual RF-path vector signal generator Two Complete baseband paths Wi-Max : IEEE802.16e-2005 (OFDM, OFDMA)
VSA	Input RF frequency : up to 26 GHz I/Q demodulation bandwidth : 28 MHz Signal analysis for – 3GPP FDD/HSDPA/cdma2000/cdma2000 1xEV-DV, 1xEV-DO – GSM/EDGE/Bluetooth® – WLAN : IEEE802.11a/b/g – Wi-Max : IEEE802.16-2004, IEEE802.16e-2005
H/W Interface	Ethernet 100BASE-T Interface

The procedure for measuring permissible UWB interference starts with finding a minimum sensitivity of WiMax at the VSA without UWB interference. The minimum signal power level that satisfies a BER of 10^{-6} can be found by increasing the WiMax signal power from the lowest value in VSG. After the sensitivity measurement, the permissible UWB interference for a given WiMax power can be measured by finding the level which does not increase WiMax BER above 10^{-6}. The sweeping range of WiMax power starts from the minimum sensitivity. Figure 5 shows the measured WiMax sensitivity, -81*dBm/MHz*, of VSA, and Figure 6 presents UWB signal powers which yield a WiMax BER of 10^{-6}. For the experiments, WiMax, 64QAM-3/4 coding rate, 7*MHz* BW signals were used to compare the results with the D/U ratio calculated in Section II.

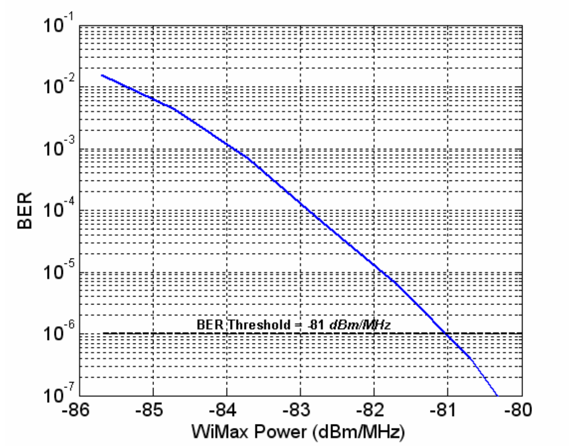

Figure 5. WiMax Receiver Minimum Sensitivity Measurement

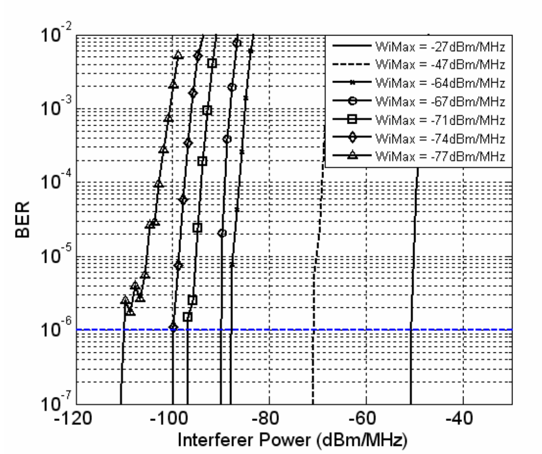

Figure 6. BER with WiMax with UWB Interference

Figure 7 shows the measured D/U ratio results from the experiments and calculated D/U ratio from the preceding section. Although there exist some level offsets between the two, the curves are very similar in shape and tendency. In general, the differences depend on the performance of equipments and channel selection filters. These results verify the proposed D/U ratio analysis approach.

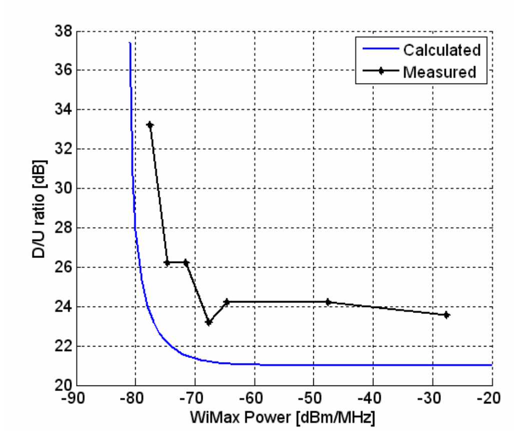

Figure 7. Calculated and Measured D/U Ratio of 64QAM-3/4, 7MHz BW

IV. Minimum Sensing Threshold for UWB-DAA

A co-channel UWB device will interfere with a WiMax terminal unless they are separated by an infinite distance. However, the interference becomes very small and negligible when the separation is sufficiently large. In the preceding sections, a maximum allowable UWB power at the WiMax receiver was calculated by setting a tolerable interference level ΔP. Therefore, ΔP determines permissible UWB power at the receiver, and the amount of attenuation of UWB signal from its transmitter gives a minimum keep-out distance between the UWB device and the WiMax terminal. Then, the minimum threshold level of DAA-UWB is simply the WiMax signal power received at that distance.

Table III shows the link budget analysis example of distance calculation. In the Table, a 0.5*dB* of ΔP is selected and it means that 0.5*dB* increment of overall noise floor is tolerable UWB interference. The D/U ratio is the result from Eq. (3). For the maximum UWB output power is -41.3*dBm/MHz* [4], the minimum distance between UWB and WiMax is calculated from line-of-sight channel attenuation models [7]. Table IV shows the same calculation results for BPSK-1/2 case.

Table III. Minimum Distance for 64QAM -3/4, 7MHz BW, ΔP=0.5*dB*

	Parameters	Value
P_S	WiMax minimum sensitivity	-78.45 *dBm/MHz*
ΔP	Tolerable minimum sensitivity increment	0.5 *dB*
M	Sensitivity margin – D/U Ratio	30.64 *dB*
P_R	Receive power of UWB signal $\left(P_r = P_S + \Delta P - M \quad [dMm/MHz]\right)$	-108.59 *dBm/MHz*
P_T	Maximum UWB power	-41.3 *dBm/MHz*
G_T	Transmitter antenna gain	0 *dBi*
G_R	Receiver antenna gain	0 *dBi*
f_c'	Geometric center frequency of waveform $f_c' = \sqrt{f_{min} f_{max}}$	3882 *MHz*
L_1	Path loss at 1 *m* $\left(L_1 = 20\log_{10}\left(4\pi f_c'/c\right), c = 3\times10^8\,[m/s]\right)$	44.2 *dB*
L_2	Path loss at d *m* $\left(L_2 = 20\log_{10}(d), P_R = P_T + G_T - L_1 - L_2 + G_R\right)$	23.09 *dB*
D_M	Minimum distance $\left(D_M = 10^{L_2/20}\right)$	14.28 *m*

From Tables III and IV, it can be seen that the required minimum distance depends on ΔP, because ΔP is the overall noise increment. Now that the required minimum distance which limits WiMax terminal interference to ΔP is found in this example, the sensing threshold of DAA can be easily calculated from the distance. The sensing threshold is a minimum signal power for detecting WiMax signal at UWB terminal. Therefore, the threshold is an attenuated signal power of WiMax over the required distance.

Table IV. Minimum Distance for BPSK -1/2, 7MHz, ΔP=0.5*dB*

	Parameters	Value
P_S	WiMax minimum sensitivity	-96.45 *dBm/MHz*
ΔP	Tolerable minimum sensitivity increment	0.5 *dB*
M	Sensitivity margin – D/U Ratio	12.64 *dB*
P_R	Receive power $\left(P_r = P_S + \Delta P - M \quad [dMm / MHz]\right)$	-108.59 *dBm/MHz*
P_T	Maximum UWB power	-41.3 *dBm/MHz*
G_T	Transmitter antenna gain	0 *dBi*
G_R	Receiver antenna gain	0 *dBi*
$f_c{}'$	Geometric center frequency of waveform $f_c{}' = \sqrt{f_{min} f_{max}}$	3882 *MHz*
L_1	Path loss at 1 *m* $\left(L_1 = 20\log_{10}(4\pi f_c{}'/c), c = 3\times 10^8 [m/s]\right)$	44.2 *dB*
L_2	Path loss at d *m* $\left(L_2 = 20\log_{10}(d), P_R = P_T + G_T - L_1 - L_2 + G_R\right)$	23.09 *dB*
D_M	Minimum distances $\left(D_M = 10^{L_2/20}\right)$	14.28 *m*

Table V shows the calculation results of the sensing threshold, *S*. For the calculation, the minimum transmit power of WiMax, BPSK-1/2 is used because it has the minimum required transmit signal power among all modulation schemes. It follows that the maximum noise floor increment due to UWB is ΔP, when DAA determines frequency occupancy based on this sensing threshold level.

Table V. Sensing Threshold Level for the Case of BPSK -1/2, ΔP=0.5*dB*

	Parameters	Value
P_T	WiMax transmit power requirement $\left(P_T = 14dBm - 10\log_{10}(7MHz)\right)$	5.55 *dBm/MHz*
G_T	Transmit antenna gain	0 *dBi*
$f_c{}'$	Geometric center frequency of waveform $f_c{}' = \sqrt{f_{min} f_{max}}$	3882 *MHz*
L_1	Path loss at 1 *m* $\left(L_1 = 20\log_{10}(4\pi f_c{}'/c), c = 3\times 10^8 [m/s]\right)$	44.2 *dB*
L_2	Path loss at d *m* $\left(L_2 = 20\log_{10}(d), P_R = P_T + G_T - L_1 - L_2 + G_R\right)$	23.10 *dB*
G_R	Receiver antenna gain	0 *dBi*
S	Sensing Threshold at UWB $\left(S = P_T + G_T - L_1 - L_2 + G_R\right)$	-61.75 *dBm/MHz*

V. CONCLUSION

This paper has presented a quantified interference analysis method to determine minimum keep-out distance between WiMax and OFDM-UWB, and sensing threshold levels for UWB-DAA. For this analysis, tolerable overall noise floor increment is defined and several other parameters were derived, such as minimum distance and sensing threshold, based on the effective noise power increment. Hence, the threshold level calculated from the proposed methods guarantee that the maximum interference to WiMax from UWB is less than ΔP. Furthermore, an equipment-based testbed system was used to verify the D/U ratio analysis and the experimental data showed the similar results with those of the analysis.

DAA is a critical issue for worldwide UWB authorization and its implementation should be as simple as possible to reduce hardware burden. This analysis and its experimental confirmation are presented in an effort to help establish a simple, accurate and globally consistent DAA specification.

REFERENCES

[1] A. F. Molisch, J. R. Foerster, M. Pendergrass, "Channel Models for Ultrawideband Personal Area Networks", in IEEE Wireless Communications, pp. 14-21, December 2003.

[2] "Detect and Avoid Technology for Ultra Wideband (UWB) Spectrum Usage" in a Wisair White Paper, http://www.wisair.com

[3] Federal Communications Commission (FCC), "Revision of Part 15 of the Commissions Rules Regarding Ultra-Wideband Transmission Systems", First Report and Order, ET Docket 98-153, FCC 02-48; Adopted: February 14, 2002; Released: April 22,2002

[4] V. S. Somayazulu, J.R. Foerster, R.D. Roberts, "Detect and Avoid (DAA) Mechanisms for UWB Interference Mitigation", in Ultra-Wideband, The 2006 IEEE International Conference , pp. 513-518 on September 2006

[5] B. Razavi, "RF Microelectronics, 1st edition", pp. 48-49 in Prentice Hall

[6] IEEE Std 802.16e-2005 and IEEE Std 802.16-2004 Cor1-2005, "IEEE Standard for Local and metropolitan are networks Part 16: Air Interface for Fixed and Mobile Broadband Wireless Access Systems, Amendment 2: Physical and Medium Access Control Layers for Combined Fixed and Mobile Operation in Licensed Bands", pp. 352, February 28, 2006

[7] IEEE P802.15 Working Group for Wireless personal area Networks (WPANs), "Multi-band OFDM Physical Layer Proposal for IEEE802.15 Task Group 3a", pp. 64, March, 2004