Production Test Methods for Measuring ‘Out-of-band’ Interference of Ultra Wide Band (UWB) Devices

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Abstract

The recent increase in demand within the wireless user community for short-range, very high rate data transmission (data, video) devices has spurred the growth of a new generation of 4G devices, viz. ultra-wideband (UWB). Due to its wide band of operation (3.1-10.6GHz) and non-conventional transmit/receive scheme (using short-duration, narrow baseband pulses), spectral power leakage to outside frequency bands causes interference with other wireless standards. In this paper, we focus on ‘out-of-band’ interference testing of UWB devices during production test. Due to stringent FCC spectrum regulations and very low power spectral density levels of the associated signals (-41.3dBm/MHz), production testing for interference is a big challenge and can incur significant test time, resulting in increased test cost. We propose a simple, low-cost test methodology for testing UWB devices. Simulation results are presented for a typical home environment. The channel model used can be easily modified and incorporated in any production test environment. Results show that using simple tests, estimates of ‘out-of-band’ interference can be obtained easily using the proposed test methodology.

1. Introduction

Ultra-wideband (UWB) technology is a wireless protocol for high-speed data transmission over short distances (IEEE 802.15.3a standard) and has recently received a lot of interest from the wireless manufacturing and user community. UWB has a wide frequency band of operation (3.1 GHz – 10.6 GHz), with very low power spectral density (-41.3 dBm/MHz) and supports simple modulation formats (QPSK etc.). Also, unlike other wireless standards, UWB is not affected significantly by multi-path fading. A wireless signal is defined as UWB if the signal instantaneous bandwidth is > 500 MHz or the fractional bandwidth is > 0.2.

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The fractional bandwidth of a wireless signal, $BW_{frac}$, is defined as:

$$BW_{frac} = 2 \frac{f_H - f_L}{f_H + f_L}$$  \hspace{1cm} \text{(Equation 1)}$$

where, $f_H$ and $f_L$ indicate the upper and lower frequencies that are 10 dB below the maximum radiated emission. Thus, UWB presents a very attractive choice for developing wireless networking products capable of handling very high data rates (up to 500Mbps) for short-distance data or video transfer and is expected to have very high market demand in the near future.

1.1. Motivation

UWB uses short duration, narrow, repetitive pulses to transfer data. The desired UWB spectrum has a flat, ‘brick wall’ response in the passband for increased noise immunity, with little energy spill in the stopband, as shown in Figure 1. The pulses are designed and shaped to obtain the desired spectrum shape in the passband. As per Fourier theory, an ideal ‘brick wall’ shaped spectrum will require a non-causal pulse, which is not possible to generate for all practical purposes. Thus, for any practical transmission, there will always be a certain amount of energy spill outside the UWB frequency band (Figure 1).

Figure 1. UWB Spectrum and interference with other standards

UWB is proposed as an ‘underlay’ technology [1],[2] – it shares the same frequencies with existing wireless standards, without causing interference in their operation. But, as evident from the above figure, UWB can cause some interference, known as ‘out-of-band’ interference with other wireless standards and this needs to be measured during production test to ensure seamless

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integration of the UWB technology with the existing wireless networks operating within the UWB vicinity.

The focus of this paper is to find a method for production test of ‘out-of-band’ interference (which we will call interference from now on) that will:
1. Provide a quick estimate of the interference specification using a standard test setup
2. Produce repeatable results considering channel and environmental effects
3. Incur minimal test cost and test time.

2. Test Setup

In this paper, we study the effect of interference on the GSM900, DCS and PCS bands due to UWB transmission. The presented methodology can be easily extended to other standards (e.g. RAST, UNII). We discuss two setups for measuring the interference caused by the UWB device. The first method is used as a reference test setup, and the second one is the proposed test method. A flowchart outlining the major steps for the proposed method is shown in Figure 2.

Figure 2. Proposed test procedure

The first method is a direct procedure, where two separate tester load boards are used. The first load board contains the UWB transmitter, and the second one contains antenna/multiple antennae for capturing the signal within the band of interest (Figure 3).

There are some issues to consider with this test setup. First, as the test signal propagates through the air medium, the tests may not be perfectly repeatable. Second, the cost associated with this test is larger, as two separate load boards must be used (to test the amount of interference with varying distance between the transmitter and the receiver). The second method uses a different approach and eliminates the above two problems with very little test overhead added. However, additional analysis is required to properly interpret the test results.

The first step involved in the production test plan is to develop an accurate channel model and to characterize the channel in which the UWB device will operate in the field. Once the ‘worst case’ environment (channel model) in which the UWB device will operate is determined, a production test sequence can be designed to ensure that the UWB device will not interfere with other standards during normal operation. With an accurate channel model, the overall channel attenuation and the associated path delay can be estimated for a specific position of the victim receiver with respect to the UWB transmitter. In the proposed approach, using a programmable attenuator and a delay unit, the UWB transmitter and the victim receiver’s input filters (antenna is no longer required, as this uses a wired connection between the transmitter and the receiver) are placed on a single load board (Figure 4). Thus, test reliability and repeatability is highly improved. Also, problems associated with crosstalk and isolation are mitigated due to:
- a) The UWB transmitter being the only active signal source on the load board.
- b) The RF response measurements are targeted at frequency bands outside the UWB frequency band of operation.

Figure 3. UWB production test setup I

2.1. Channel modeling

In this work, the channel is modeled using the Saleh-Valenzuela (S-V) model as proposed in [3]. As proposed in the S-V model, we assume the rays arrive in clusters. The cluster arrival times and ray arrival times within a cluster follow the following exponential distributions:
\[ p(T_1 \mid T_{-1}) = \Lambda e^{-\frac{\Delta T_{1}}{T_{-1}}} \quad \text{(Equation 2)} \]
\[ p(\tau_2 \mid \tau_{-1}) = \lambda e^{-\frac{\Delta \tau_{2}}{\tau_{-1}}} \quad \text{(Equation 3)} \]
where the constants \( \Lambda \) and \( \lambda \) values depend on the room geometry. We assumed these constants to be \( 1/35 \times 10^{-9} \) and \( 1/5 \times 10^{-9} \), respectively. For determining the amplitudes of the rays, the amplitude of the first ray of the first cluster is determined as shown in Equation 4.
\[ \bar{\beta}^2_i = \frac{1}{\gamma^2} G(1m)r^{-\alpha} \quad \text{(Equation 4)} \]
\[ G(1m) \] denotes the loss at a distance of 1m from the source, \( r \) being the actual distance between the transmitter and the receiver, \( \gamma \) is a constant equal to \( 50 \times 10^{-9} \). Using Equation 4, the amplitude of the \( k^{th} \) ray of the \( i^{th} \) cluster is determined using the following equation (\( \Gamma \) is a constant, whose value is \( 100 \times 10^{-9} \)).
\[ \bar{\beta}^2_{i,k} = \bar{\beta}^2_i e^{-\frac{\Gamma_k}{\Gamma_i} e^{-\frac{\bar{\beta}^2}{\gamma^2}}} \quad \text{(Equation 5)} \]
Finally, the amplitudes follow the exponential distribution described in Equation 6.
\[ p\left(\frac{\bar{\beta}_{i,k}}{\bar{\beta}^2_i}\right) = \frac{2\bar{\beta}^2_i}{\bar{\beta}^4_i} e^{-\frac{\bar{\beta}^2}{\bar{\beta}^4_i}} \quad \text{(Equation 6)} \]
It is assumed that production test is used to qualify interference parameters for direct Line of sight (LOS) transmission between the UWB transmitter and the victim receiver and thus, the subsequent clusters after the first cluster have very little effect on the victim. We have studied the effects of interference for two different positions, viz. 1 inch and 3m from the UWB transmitter. Figure 5 shows simulation data for a single pulse transmitted and received by a receiver located 3m from the transmitter. Only the first cluster was considered during analysis. Note the spreading effect due to the channel (input and output data amplitudes were scaled to fit in the same window) and the exponential distribution followed by the amplitudes of the rays in different clusters.

![Figure 5. Waveform of pulse transmitted and received.](image)

### 2.2. Attenuator setting

In the following, we show how the attenuator and delay settings required for different positions of the victim receiver are determined.

First, we notice that most of the wireless standards have a very narrow bandwidth compared to the UWB bandwidth. As an example, the GSM900 bandwidth is 25MHz (935-960 MHz), with 200 KHz channel spacing, while the UWB channel bandwidth is 7500 MHz. Hence, it is possible to model the victim receiver channel by a single pair of tones located at the channel frequency limits. Due to the large differences in the bandwidths of UWB and the victim receiver, this is a fair approximation. Consequently, the attenuator settings are determined for the two frequencies, as discussed above and are assumed to vary linearly within the channel of operation of the victim receiver. Also the amount of attenuation for select frequencies within the UWB band is determined.

The channel attenuation is determined by repeating the same measurement 100 times. Each time the received signal is filtered and the RMS value of the signal is determined. The channel attenuation is the ratio of the RMS values of the transmitted and received waveforms. While the transmitted RMS value remains almost the same (except for measurement and instrument inaccuracies), the receiver RMS value follows a Rayleigh distribution. A Rayleigh pdf is fitted to the data and the parameter \( \beta \) for the fitted Rayleigh distribution, normalized with respect to the transmitter RMS value is taken as the attenuation value.

### 2.3. Determining the correct pulse shape for test

Once the attenuation and delay values for the different standards are obtained, the next step is to choose the right pulse shape and pulse duration for transmission. The pulse shapes we considered were the gaussian pulse and its derivatives (up to the 3rd derivative). The initial choice of the pulse shape is guided by the proposed FCC power spectral density (PSD) mask for UWB and the UWB guidelines outlined in Section 1. To do so, first the mode of communication is set to DS-UWB [2],[5]. In this mode, each transmitter/receiver pair is assigned a codeword and each bit in the data, is coded accordingly. Figure 6 shows a description of the DS-UWB procedure. Each pulse (also called a ‘chip’) is a 2nd order gaussian pulse as shown in Figure 6. Also, the amplitude of the pulses is scaled to make the energy of each bit equal to 0.5 mW.

![Figure 6. DS-UWB scheme](image)
Next, the different pulses under consideration are compared. The results are presented in Table 1. The experiments were performed for a fixed codeword \([0 \ 1\ 0\ 0]\), with pulse duration of 1ns, yielding an effective data rate of 250 Mbps. Maximum number of UWB receivers in the vicinity of the transmitter is set to 16, requiring a 4-bit codeword. The chosen codeword has the maximum margin from the FCC PSD limit among all possible code words. Figure 7 shows the spectra for different pulses and the corresponding PSD. As shown in the right hand side figure, except for the gaussian pulse, the other pulses have some margin when compared to the FCC limit and thus can be used for UWB test. We chose the 3rd order derivative of gaussian pulse as it has the maximum margin from the FCC limit.

<table>
<thead>
<tr>
<th></th>
<th>Maximum Emission</th>
<th>BW (MHz)</th>
<th>Fractional Bandwidth</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gaussian Pulse</td>
<td>-7.6 dBm</td>
<td>2000</td>
<td>1.6</td>
</tr>
<tr>
<td>1st Order</td>
<td>-8.87 dBm</td>
<td>3000</td>
<td>1.5</td>
</tr>
<tr>
<td>2nd Order</td>
<td>-8.92 dBm</td>
<td>3000</td>
<td>1.2</td>
</tr>
<tr>
<td>3rd Order</td>
<td>-8.94 dBm</td>
<td>3000</td>
<td>1.0</td>
</tr>
</tbody>
</table>

Figure 7. Spectra and PSD for different pulses

Next, we determine how the amplitudes of the pulses need to be scaled when the UWB device is tested for interference at variable data rates. The data rates supported by UWB span from 100Kbps to 480Mbps. Figure 8 shows how the spectrum and PSD changes as the data rate is changed.

For this analysis, the codeword used is \([0 \ 1\ 0\ 0]\), while the pulse is of a 3rd order gaussian. As the codeword and the order of the pulse remains the same for all the data rates, the plots in Figure 8 show the same shape of the spectrum, only scaled along the frequency axis with varying data rates. As can be seen from the plots, all the different data rates can be tested using the gaussian pulse. Amplitude scaling is required for data rates ranging from ~50-250Mbps (This is in agreement with Figure 7, where the data rate was 250Mbps and the PSD plot for 3rd order waveform shows the need for scaling).

Finally, tests are performed to determine the usable codewords for DS-UWB transmission. Figure 9 shows the spectrum for the allowable codeword(s). All possible combinations are tested. It turns out that all the codewords are suitable for data transmission, with proper scaling. The waveforms used are 3rd order gaussian pulses with a data rate of 250 Mbps.

Thus, the final test waveform selected is a 3rd order derivative of a gaussian pulse, DS-UWB encoded with codeword \([0 \ 1\ 0\ 0]\) and pulse duration of 1 ns (data rate of 250 Mbps).

2.4. Variations at transmitter antenna

While performing tests, we considered parametric variations in the manufactured devices. The variations are modeled as variations in pulse amplitudes, pulse width and timing jitter. The amplitude variation is considered to be ±5%, variations in period to be ±2%, both uniformly distributed within the range of variation. The following figure shows the amount of interference at the transmitter antenna for the different bands (for 100 devices under parametric variations).

Figure 9. Spectrum and PSD for selected codeword

Figure 10. Variations in interference PSD for different bands at the transmitter antenna
As evident from the figure, the variation is uniform with very little spread. Thus the channel is the major factor affecting the variations of the receiver performance. Consequently, the next step is to use the attenuator and delay units to obtain the interference at the victim receivers antenna and compare with the first method described in Section 2.

3. Production test setup and use

The delays and attenuators that characterize the channel are determined as described in Section 2.2. Next, a time domain simulation for the channel is performed for each victim receiver. In Figure 5 shown in Section 2.1, the individual rays for the single pulse can be easily distinguished. However, when a train of narrow pulses is transmitted, the received signal is a superposition of all the received rays for each pulse.

Thus, even after the transmitter has ceased to send the signal, signals continue to arrive at the receiver antenna. This is evident in Figure 11, where the transmission stops after ~35ns, the multi-path components keep arriving at the victim receiver well beyond 70ns. Also, for a distant victim, the actual signal is embedded in the noise generated by the MPCs, which is evident from Figure 11. In the center figure of Figure 11, from the received signal for victim1, the transmitted signal can be distinguished from the noise. For victim 2, this is not the case. The victim receivers are separated by a distance of 1 inch and 3m from the UWB transmitter. As evident from Figure 11, the multi-path components affect the distant receiver more compared to the one located closer to the UWB transmitter. Thus, the overall attenuation and the SNR are worse for the distant receiver. Figure 12 (i) and (ii) show the transmitted and the received signal spectra. Also shown is the spectrum obtained after passing through the attenuator and delay units.

Now, using the proposed test setup shown in Figure 4, the interference PSD is measured at each of the victim receiver’s antenna and compared to the actual interference PSD value obtained by performing a complete channel simulation. Table 2 shows the interference PSD values for the victim receivers.

<table>
<thead>
<tr>
<th>Victim I (1 inch)</th>
<th>Interference PSD (dBm/MHz)</th>
<th>Victim II (3m)</th>
<th>Interference PSD (dBm/MHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>GSM</td>
<td>DCS</td>
<td>PCS</td>
</tr>
<tr>
<td>Proposed approach</td>
<td>-109.45</td>
<td>-100.61</td>
<td>-100.15</td>
</tr>
<tr>
<td>Channel simulation</td>
<td>-105.17</td>
<td>-99.53</td>
<td>-98.93</td>
</tr>
<tr>
<td>Error</td>
<td>4.28</td>
<td>1.08</td>
<td>1.22</td>
</tr>
</tbody>
</table>

3.1. Production test repeatability

The final step of the analysis is to perform a repeatability test for the victim’s receiver antenna. For each band of interest, using the obtained attenuator and delay settings, the test is repeated 100 times, under parametric variations. The variations in PSD for both the victim receivers are shown for the different bands considered, viz. GSM900, DCS and PCS. The dotted lines show the actual interference PSD values obtained from channel simulations. We set this as the specification limit. The difference between the spectral responses from channel simulation and the attenuator settings obtained
for different frequencies introduces a level of uncertainty on the results obtained using the proposed approach. We denote the maximum deviation between the channel simulation and the response obtained from attenuator as ‘d’. Thus the test limit is set at ‘d’ units away from the specification limit. The thick line in the receiver PSD diagrams shows the test limit.

The UWB transmitter repeatability results are in accordance with Figure 10, which all follow a uniform distribution. From the receiver PSD, all devices having PSD more than the test limit can be considered bad (devices lying on the right side of the test limit). The devices within the specification limit and the test limit need to be re-tested to determine pass/fail. Such devices are less than 12% of the total number of devices.

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**Figure 13** Repeatability test for victim I at UWB transmitter and victim receiver

**Figure 14** Repeatability test for victim II at UWB transmitter and victim receiver

4. **Conclusions**

In this paper, a production test method for measuring ‘out-of-band’ interference caused by UWB transmitters is presented. Usually, testing for the amount of interference at the antenna of a different wireless device operating at a different standard, a pair of antennae is required, separated by a specific distance (referred as the reference test setup). Factors, e.g. environment, affect such measurement and may not produce highly repeatable results. Using a single load board and a set of programmable attenuators and delay units, highly repeatable results can be obtained under parametric variations present in manufactured UWB transmitters. Also, misclassification ratio is less than 0.12 for all the bands considered. Finally, the error in estimating interference PSD is less than 5dBm/MHz. (4.2%). Final test is highly repeatable and can be programmed to use with any other band.

**References**


