1. Introduction

On August 26, 2004, the Multi-band OFDM Alliance Special Interest Group (“MBOA-SIG”) requested a waiver of certain measurement procedures. We at decaWave ask that this request be denied.

decaWave is a semiconductor company designing ultra wideband communications devices and a member of the UWB forum which promotes a direct sequence spread spectrum pulse based approach for ultra wideband communications (DS-UWB).

This document gives an analysis which demonstrates that the MB-OFDM frequency hopping modulation scheme interferes more with existing services than a pulse based system would.

DS-UWB is a pulse based system as originally envisioned by the FCC for UWB devices.

The following analysis gives the probability of error for an interfering DS-UWB signal and an interfering MB-OFDM signal. BPSK was chosen as the victim’s modulation scheme, but the results are extendable to many other types of modulation scheme.

2. Interference caused to an in-band BPSK victim receiver

Let’s say the victim receiver is a digital system using BPSK modulation, say it has a bit duration of less than an MB-OFDM symbol duration. For example, if the bit rate is 10Mbps, the receiver bandwidth is 10MHz.- 20MHz.

Case 1.

AWGN Interference.

If AWGN and attenuation are the only impairments, the receive signal after demodulation will be proportional to **T+n/g** where **T** is the transmit signal before modulation, **n** is the noise, a gaussian random variable with zero mean and variance σ_n and **g** is the gain between transmitter and receiver.

Case 2.

Direct sequence UWB (DS-UWB) + AWGN interference.

An interfering DS-UWB signal is white with a gaussian distribution in any band where it is transmitting (Although the transmit probability distribution is not gaussian, the receive is, especially after filtering by a relatively narrow band receiver, see appendix 1).

Because of this, the interference from a DS-UWB, pulse based device looks just like AWGN to this receiver. So, in the case of an interfering DS-UWB, the receive signal is proportional to **T+n/g+c/g**, where again **T,n** and **g** are as above and **c** is the DS-UWB interference, another gaussian random variable with zero mean and variance σ_c.

Case 3
MB-OFDM + AWGN Interference

At the receiver, before the receive filter, an interfering MB-OFDM signal, with **m** bands, is also approximately white with gaussian distribution in any band, while it is transmitting in that band, and zero while it is not.

The MB-OFDM bursts will have a steep rise and fall time after the receiver filter used in this type of victim receiver. For simplicity we will assume that the filter transforms the ultra wideband MB-OFDM signal into a gated AWGN signal with the same bandwidth as the BPSK receiver.

While transmitting in the victim's band, it also looks just like AWGN to this receiver. During this time, it transmits at **m** times the power of the DS-UWB case and at zero power (in the victim band) for the rest of the time. So, in the case of an interfering MB-OFDM, the receive signal looks is **T+n/g+√m.c/g** for **1/m** of the bits and **T+n/g** for **(m-1)/m** of the bits.

Case 1 AWGN error rate
The probability of error for case 1 is the well known result for BPSK:

$$P_{en} = \frac{1}{2} erfc(\sqrt{\frac{g^2 T}{\sigma_n}})$$

Say that the noise is such that the error rate is quite small, e.g. $1x10^{-6}$

=> $\frac{g^2 T}{\sigma_n} = 3.4$

Case 2 DS-UWB + AWGN error rate
The probability of error for case 2, from the same formula is: (Note that the sum of 2 gaussian random variables is another gaussian random variable whose variance is the sum of the individual variances.)

$$P_{ec} = \frac{1}{2} erfc(\sqrt{\frac{g^2 T}{\sigma_n + \sigma_c}})$$

$$P_{ec} = \frac{1}{2} erfc(\sqrt{\frac{1}{\frac{1}{3.4} + \frac{\sigma_c}{g^2 T}}})$$

Case 3 MB-OFDM + AWGN error rate
The probability of error for case 3, also from the same formula, is as for case 2 while it is interfering, but with a greater interference power and as for case 1, $1x10^{-6}$, while it is not in-band

$$P_{em} = \frac{1}{2m} erfc(\sqrt{\frac{1}{\frac{1}{3.4} + \frac{\sqrt{m}\sigma_c}{g^2 T}}}) + \frac{(m-1)}{m} 1 \times 10^{-6}$$

As we expect, setting m=1 reduces case 3 to case 2.

Lets plot these error rates as a function of $\frac{g^2 T}{\sigma_c}$ i.e. The signal to interference ratio.

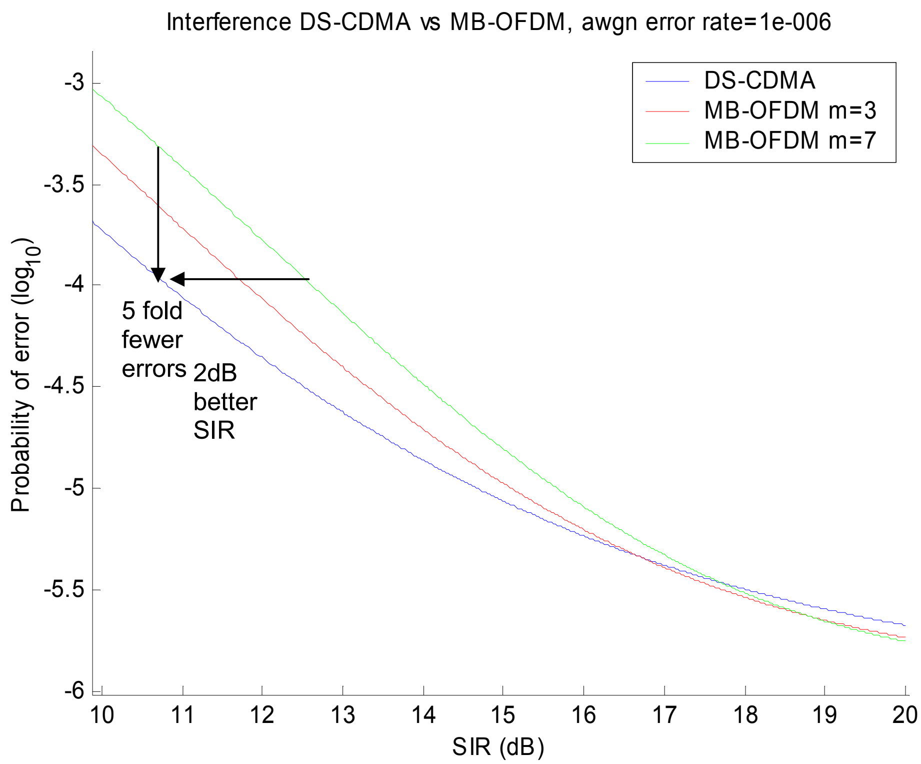

Figure 2.

In both schemes, the interference always increases the error rate, but it can be seen from the graph that, other than at very high SIR, which the receiver should be designed to cope with, this increase is worse for MB-OFDM, especially in the, **m**=7, 7 band case.

This error rate curve demonstrates that MB-OFDM gives greater interference than was anticipated by the FCC when the UWB rules were made.

3. Other modulation schemes

BPSK was chosen as the modulation scheme here for no special reason other than that it is relatively common and easy to analyse. If we had used a different scheme, e.g. FSK, PAM, QAM, we would have got very similar results. The reason for this is that the damage is done because the interferer comes in at a greater power, and the increase in error rate caused by this is greater than the reduction caused by the interferer hopping to other bands for a time.

4. Second crossover point

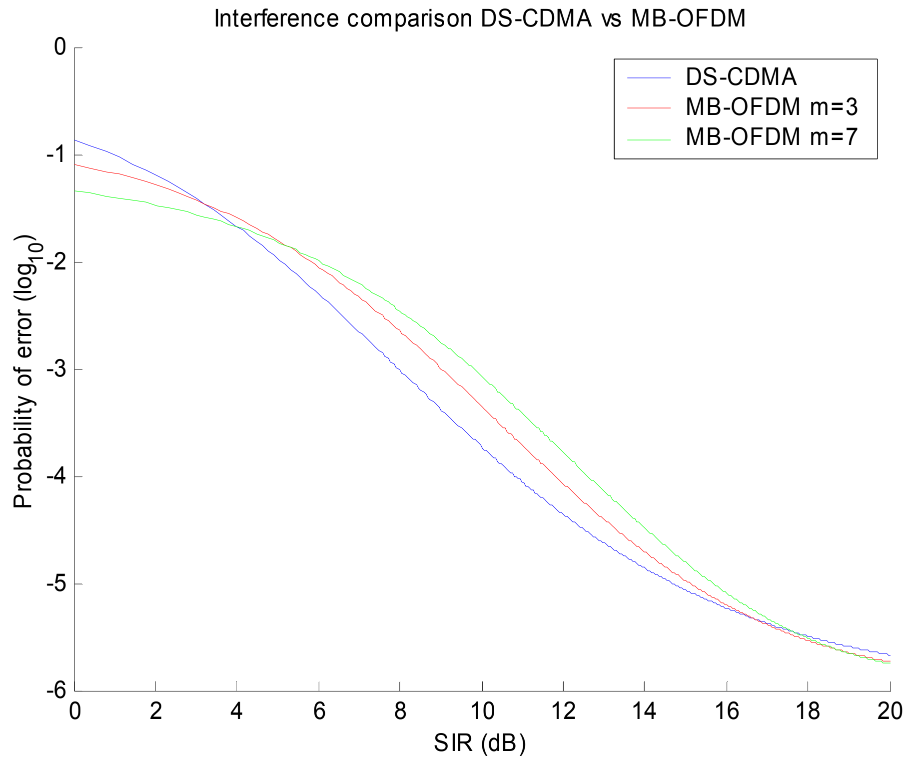

Figure 3.

Note that there is a second crossover point in the error rate curves at very high levels of SIR. This is because the error rate is approaching a maximum of 1/(2m), i.e. 50% probability of a bit error for both DS-UWB and MB-OFDM, but the MB-OFDM interferer is only there for 1/m of the time. This does not help the MB-OFDM case very much because at these error rates the victim receiver is likely to be a long way outside its viable operating error rate range.

5. BPSK operating at Pe ≥ $1x10^{-5}$ in AWGN

What happens if we increase the noise power, i.e. a receiver that can deal with more errors.

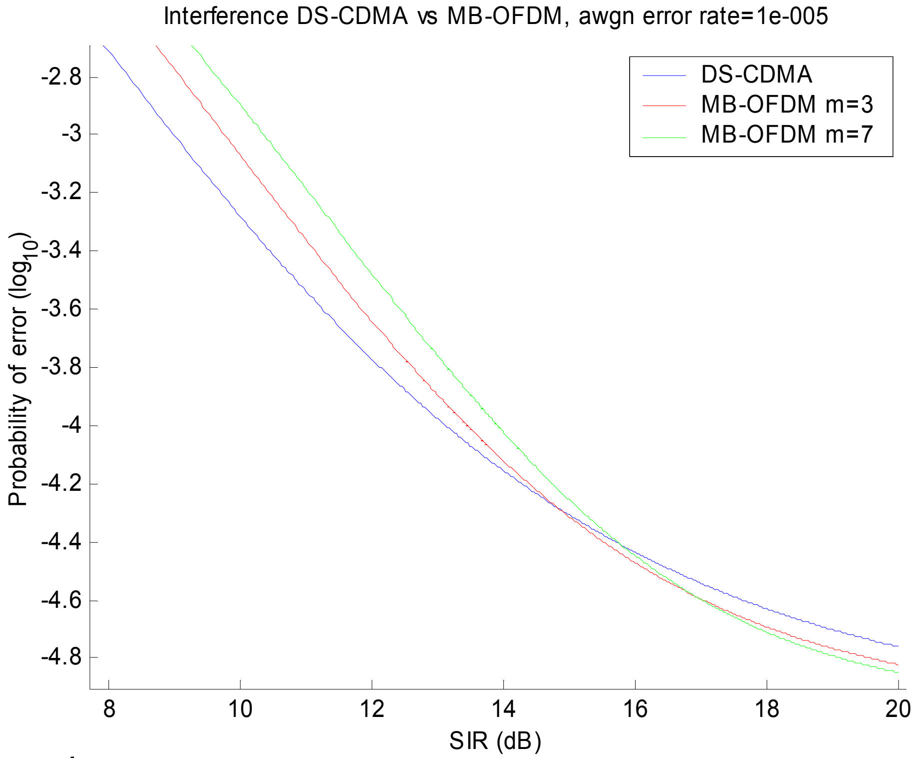

Figure 4.

In this case, the two crossover points move closer to each other. This shows that the detrimental effect of the multiband scheme is lessened if the victim is able to operate at higher error rates.

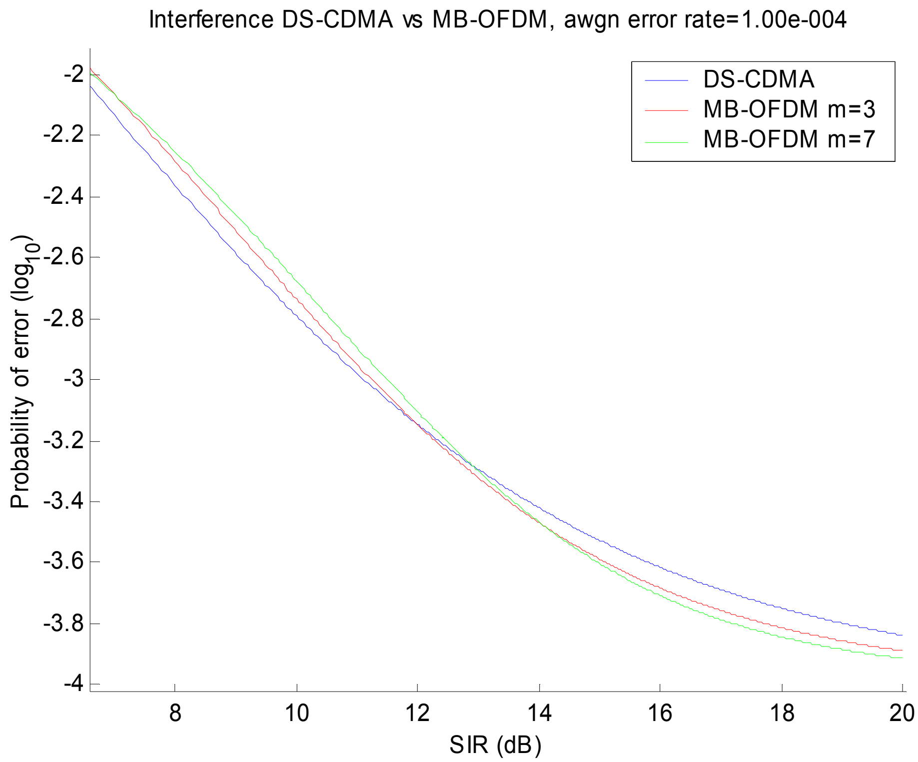
Interference DS-CDMA vs MB-OFDM, awgn error rate=1.00e-004
DS-CDMA
MB-OFDM m=3
MB-OFDM m=7
Probability of error (log10)
-2
-2.2
-2.4
-2.6
-2.8
-3
-3.2
-3.4
-3.6
-3.8
-4
8
10
12
14
16
18
20
SIR (dB)

Figure 5.

6. BPSK operating at Pe ≤ $1x10^{-7}$ in AWGN

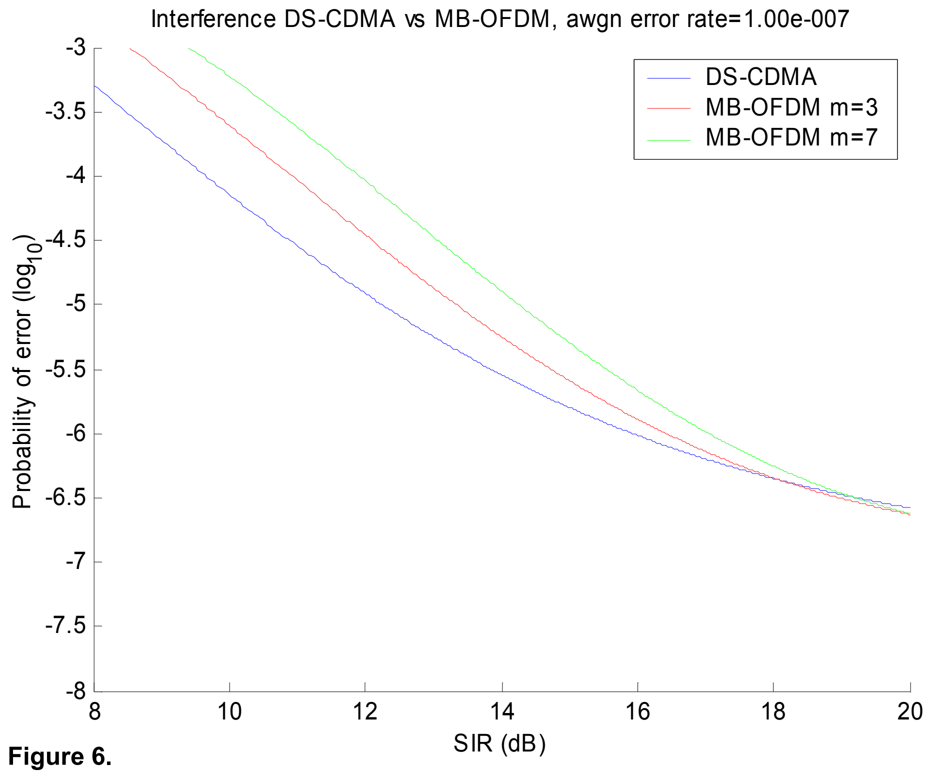

Figure 6.

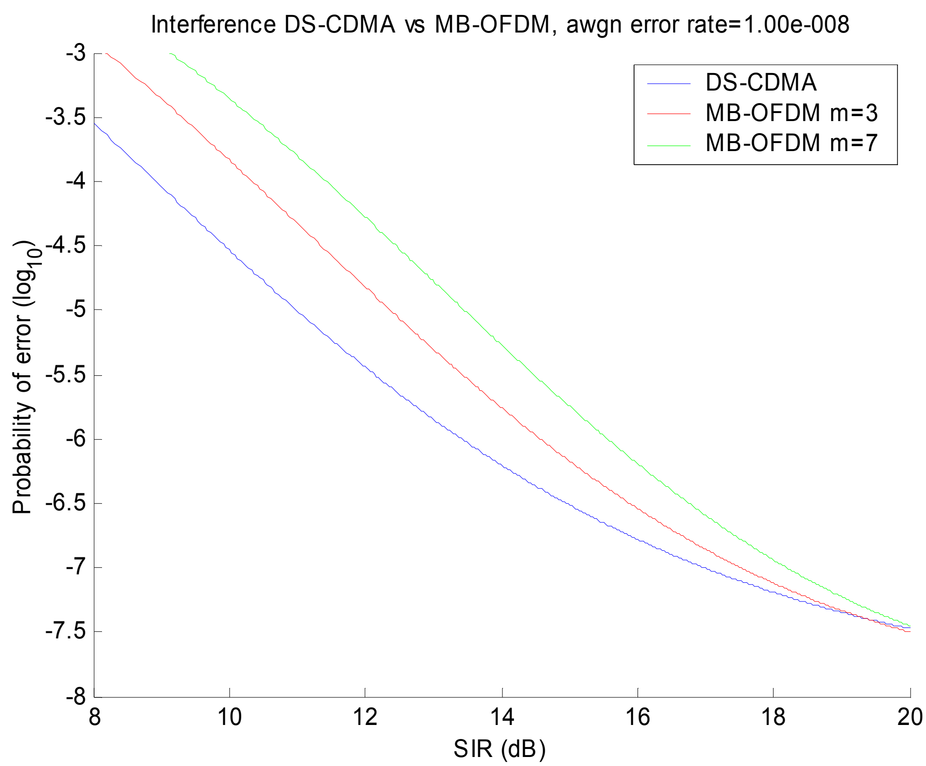

Figure 7.

7. Conclusion

Clearly the MB-OFDM system causes more errors than a spread spectrum DS-UWB system. This means that the interference is worse than anticipated by the FCC when it set out the rules. This was a very good reason for framing the rules in such a way as to discourage frequency hopping modulation schemes.

The preceding analysis does not take into account other factors which may make interference with victim receivers worse. Some of these include

Noise floor measurements. Many receivers measure the noise floor in the absence of a receive signal. This noise floor is then used for in its receiver algorithms. There are many reasons for this but one example is to predict error rates at different receive levels. Another would be to set convergence factors for adaptive equaliser training. These receivers will usually be expecting the noise floor to be relatively constant. With OFDM interference, the interference is coming and going, so unless the receiver measures for more than a certain number of carrier cycles (e.g. 10 frequency hopping groups or 40,000 cycles of a 4GHz carrier), it will not get a true noise floor estimate. This will adversely affect its algorithms.

Burst error sensitivity. The analysis above calculates the average bit error rate. It does not take into account that the errors will be worse for bursts which are the duration of the symbols and better again while the other bands are being used. Many receivers and applications are not able to cope when lots of errors all come together in a train.

Non-linear factors: An FCC approved UWB signal is at a very high frequency so should not interfere with lower frequency bands, but with receiver non-linearities there is often a crystal radio effect where the signal gets rectified and enveloped. This gives rise to energy at the frequency of the bursts. This is the reason for the phenomenon whereby it is possible to know when a GSM mobile phone is going to ring, before it actually does, when listening to the radio.

Although the frequencies used for GSM are in the GHz region and way above the commercial radio spectrum, it uses frequency hopping at audio spectrum frequencies which get unintentionally rectified and envelope detected somewhere in the audio amplifier of the AM/FM radio.

In the MB-OFDM case the energy would be in the 100kHz - 3 MHz band, depending on the hopping patterns. For a DS-UWB signal, the energy envelope is constant in all bands.

Appendix 1. How gaussian is the distribution of samples of a DS-UWB receive signal ?

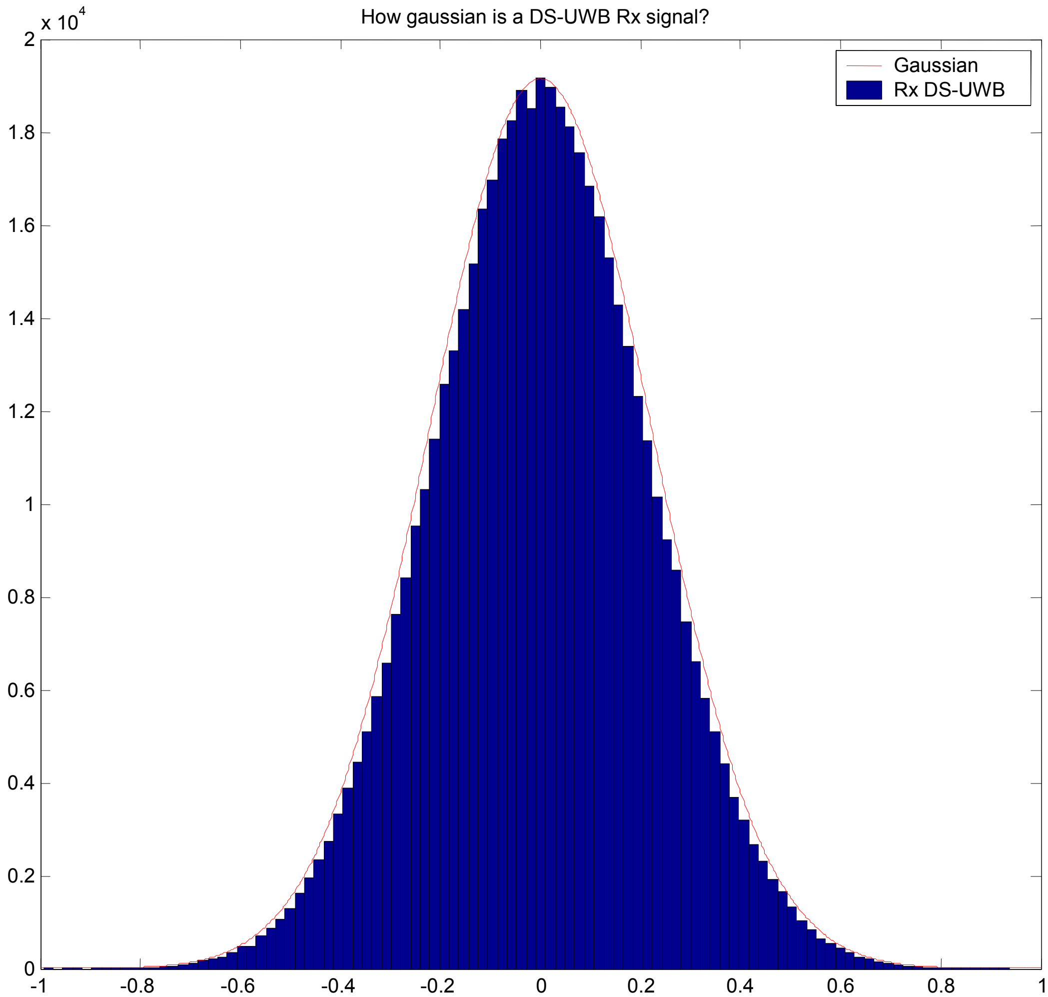

Figure 8.

Figure 8 here is a histogram of 525,000 receive samples of a DS-UWB signal after passing through channel 1 of model 1 of the IEEE channel model.