UNDERSTANDING HF CHANNEL SIMULATOR REQUIREMENTS IN ORDER TO REDUCE HF MODEM PERFORMANCE MEASUREMENT VARIABILITY

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SUMMARY

This paper begins with a brief overview of the HF channel and the mechanisms that hinder both analog and digital communications. Next the paper examines the Watterson channel model and describes the constituent parts common to most channel simulator implementations. This is followed by an overview of standards and documents which address various aspects of simulator implementations utilized for HF data modem testing. Variation of modem performance measurement is evaluated for different fading process characteristics, which meet some of the current specifications. It is shown that these current specifications do not enforce a tight enough constraint on implementations with a resulting variation in measured performance. This paper provides sufficient detailed specifications to reduce modem measurement variability between different HF channel simulators.

1 INTRODUCTION

Most HF waveform standards contain minimum Bit Error Rate (BER) performance requirements that modem manufacturers must meet in order to be compliant with these standards. In order to measure performance, HF channel simulators are required. Harris Corporation recently played a major role in defining and standardizing the new high data rate waveforms defined in STANAG 4539 [1]. During the early stages of this process (i.e. STANAG 5066 Annex G development [2]), it became evident that different channel simulators produced slightly different results for the same HF modem and a specified HF channel condition. This paper will address several channel simulator implementation issues and will provide a more complete set of requirements, which should help reduce performance measurement variability.

2 OVERVIEW OF THE HF CHANNEL

The High Frequency (HF) band (2 to 30 MHz) is used primarily for maritime, military and aeronautical systems and long distance (AM) broadcasting [3]. Standard bandwidth allocations are 1.24 kHz and 3 kHz. From a physical point of view, the HF channel is characterized as a multi-path time-varying environment that produces time and frequency dispersion [4]. The sources of multi-path are the reflections of radio signals from different layers in the ionosphere. In addition, multiple reflections can occur between the earth's surface and the ionosphere, giving rise to multi-hop propagation. Thus, the received signal can contain several "echoes" or modes, separated in time by a matter of milliseconds (i.e. time spread). The source of frequency spread is that each mode is itself fading due to the specular nature of the ionospheric reflection.

For mid-latitude HF circuits, the amount of multi-path (often called delay spread) can range up to 6 ms and the fading rate (often called Doppler spread) can be as high as 5 Hz. However, more typical values are 2 ms and 1 Hz, respectively, which are the basic parameters of the standardized CCIR Poor HF channel [5][6]. Northern trans-auroral paths, of great interest to NATO, can be significantly more challenging with up to 10 ms of delay spread and 50 Hz of Doppler spread [7][8][9].

3 THE WATTERSON CHANNEL MODEL

One of the key contributions to HF channel modeling was a paper by Watterson et. al. [10] in 1970. In this paper, a stationary model for the HF channel was proposed and experimentally validated with on-air measurements. Although HF channels are in general non-stationary, this model was shown to be valid for sufficiently short times (≈ 10 minutes) and for band-limited channels (approximately 10 kHz).

The Watterson Model views the HF channel as a transversal filter where the taps are complex and vary with time. This model is expressed by the following equation:

$$y_i = \sum_{j=0}^{L-1} h_j x_{i-j} + n_i \tag{1}$$

where i is the time index, y_i is the complex output of the channel, x_i is the complex input to the channel, h_j is one of the L taps of the time-varying transversal filter, L is the length of the channel and n_i is Additive White Gaussian Noise (AWGN).

The time-varying taps (h_j) are generated by filtering complex WGN through filters whose frequency-domain power spectra have a Gaussian shape (this shape was initially chosen arbitrarily but subsequent measurements and analyses showed that this was a good choice). The desired Doppler spread (d_j) is incorporated into the filter by setting the standard deviation (σ_j) of each Gaussian-shaped power spectrum equal to $d_j/2$. In equation form:

$$\left|H_j(f)\right|^2 = \frac{e^{-2f^2/d_j^2}}{\sqrt{\frac{\pi d_j^2}{2}}}, \ -\infty < f < \infty \tag{2}$$

By computing the Inverse Fourier Transform of the amplitude of equation (2) (i.e. $\left|H_j(f)\right|$) the equation for the time-domain filter taps becomes:

$$f_j(t) = \sqrt{2} e^{-\pi^2 t^2 d_j^2}, \ -\infty < t < \infty \tag{3}$$

Note that the resulting time-domain equation has a Gaussian shape. The taps computed using equation (3) should in addition be normalized to provide a power gain equal to one.

Figures 1 and 2 provide a pictorial view of the Watterson Channel model and of the generation of each time-varying transversal filter tap. If one desired to model the CCIR Poor Channel, only two of the taps in the transversal filter would be non-zero, the two taps would be separated by 2.0 ms, and the Doppler spread of each path (d_j) would be set to 1.0 Hz.

It is important to note three important benefits to having a channel model for HF:

1) Waveforms can be developed and tested in a controlled and repeatable environment using the software model
2) Multiple researchers can work independently but are still be able to compare results
3) Multiple test facilities can compare results

Figure 1 - HF Channel Model

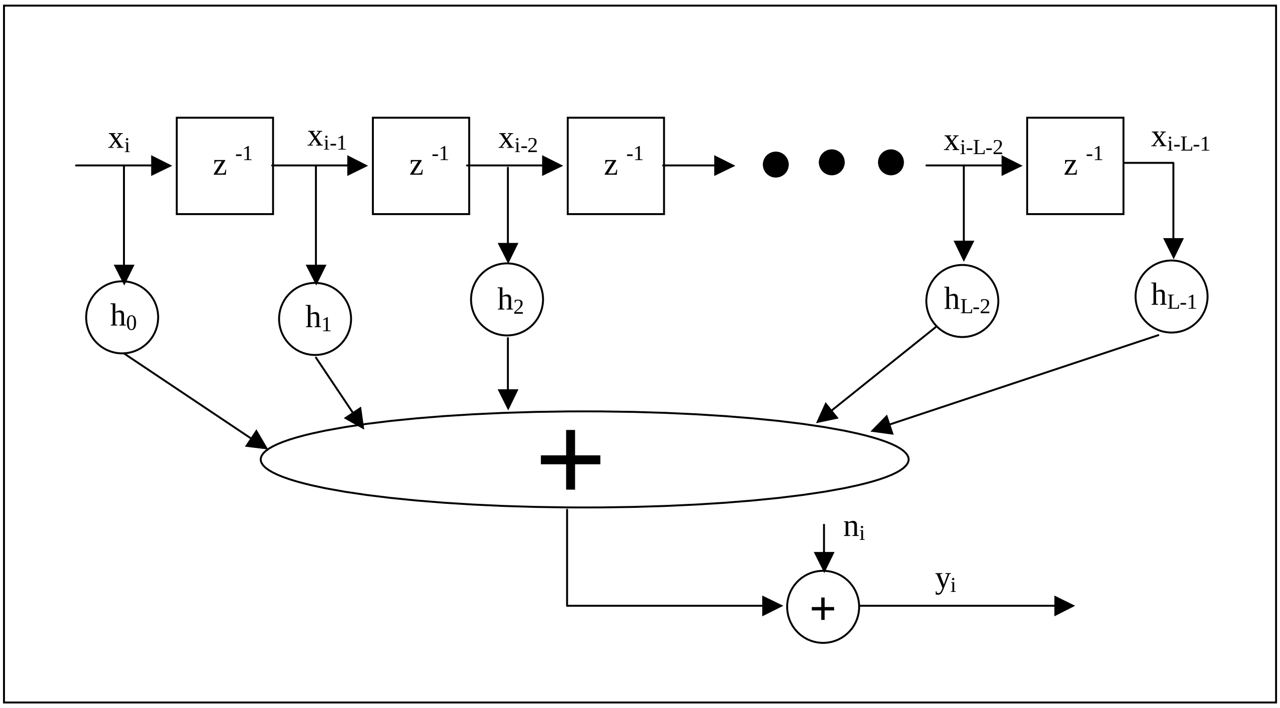
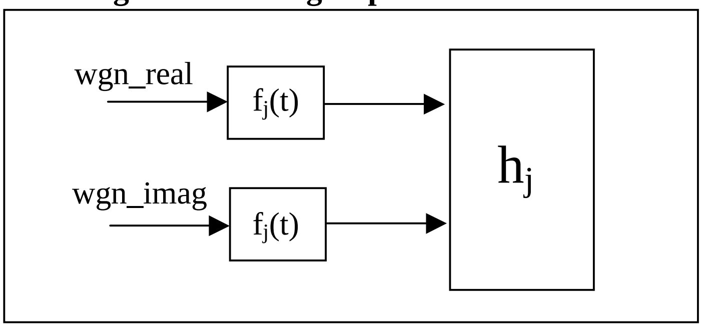


Figure 2 - Fading Tap Generation



4 LITERATURE OVERVIEW

Most HF waveform standards contain minimum BER performance requirements (for a specific set of simulated HF channel conditions) that modem manufacturers must meet in order to be compliant with the standard. These performance requirements are included in order to control the quality of the different modem vendor implementations. Since a modem is now required to meet a performance criterion, it now becomes extremely important to define an HF channel simulator specification that provides enough detail to guarantee that performance measurements made by different organizations provide the same results. In order to accommodate this requirement, many standards included channel simulator guidelines.

Recall from Section 3 that the Watterson model did not provide specific details as to how the model should be implemented. It only described the model in very general terms. For example, no update rate on the fading taps was given, only the shape of the filters was discussed. The equation for computing the filter taps (3) requires an infinite number of taps and no guideline was given as to an acceptable truncation length. This lack of detail can unfortunately lead to significantly different implementations of a “Watterson” model.

The International Radio Consultative Committee (CCIR) Recommendation 520–1 [5] listed a number of HF Channel conditions. It is in this document that the well-known and referenced CCIR Good, Moderate, and Poor channels are defined. It also defines the CCIR Flutter Fading channel, which is defined as a dual path 0.5 ms differential time delay with each path having a Doppler spread of 10 Hz. No mention of HF channel simulator specifics, other than time spread and frequency spread are mentioned in this document.

CCIR Report 549-2 [6] provides a more in depth discussion of HF Ionospheric channel simulators. This document provides some of the propagation theory background to support a multiple propagation mode model. It discusses this Gaussian-scatter HF Channel model, the experimental validation of this model, and an implementation of a channel simulator based on this model. This document defines the well-known relationship between Doppler spread and the standard deviation of the Gaussian filter spectrum. This document also states that the Gaussian spectrum of the fading taps has been validated over other filter spectra. The latest version of this document, ITU-R F.1487 [11], provides some additional channel models for HF based on latitude and presents a technique for comparative testing of HF modems, but does not cover the details of HF Channel simulator implementation.

US MIL-STD-188-110A(B) [12][13] and STANAG 4415 [9] required performance verification utilizing a baseband channel simulator patterned after the Watterson model in accordance with the CCIR 549-3 document [14], an updated version of 549-2.

STANAG 4285 [15] also required performance verification utilizing a base-band channel simulator patterned after the Watterson model. This standard did go a little bit further in that it included a section on HF channel simulation and discussed the fading process generation. STANAG 4285 states that the shape of the low pass filter utilized to generate the fading process is not critical, but should at least be a two-pole filter. STANAG 4285 also states that the update rate of the fading taps should be at least 32 times the Doppler spread.

It is interesting to note that the authors of STANAG 4285 did not believe the shape of the low-pass filter mattered but did feel that the update rate was worth specifying.

5 COMPARISON OF SIMULATOR MODELS

When Harris Corporation began implementing the high data rate waveforms of STANAG 5066 Annex G (the predecessor to US MIL-STD-188-110B and STANAG 4539), two different software channel simulators were available. The first had been developed in the early 90's based on STANAG 4285 guidelines. It utilized a two-pole Butterworth filter for the fading process, updated at a rate of 600 times a second. The second was developed specifically for STANAG 4415 testing since the NATO working group decided to tighten the channel simulator specification so that multiple waveform developers could compare candidate waveforms. This simulator utilized a Gaussian shaped filter, updated at a rate at least 32 times the desired Doppler spread. Unfortunately, the tighter channel simulator specification was not included in the standard for reference purposes.

When Harris Corporation decided to internally standardize its channel simulator to the one developed for STANAG 4415, a significant difference in performance was observed between the two channel simulators when the 9600 bps waveform was tested on a CCIR Poor channel. It was noted that there was close agreement in measured performance under single path, non-fading channel conditions, but not under fading channel conditions. This highlighted the fading tap generation process as the likely culprit responsible for the differences in performance. Further investigation demonstrated that the filter shape, the update rate of the taps, and the interpolation technique, or lack thereof, all contributed to the observed differences in performance. What follows is a series of performance and spectrum plots that highlight modem performance measurement variations as a function of spectral shape, interpolation scheme, and update rate.

Figure 3 is a plot of the measured performance on a CCIR Poor channel for the 110B 2400 bps long interleaver waveform (2400L). Figure 4 is a plot of the measured performance on a CCIR Poor channel for the 110B 9600 bps very long interleaver waveform (9600VL). Measured performance is presented for two different filter implementations, Butterworth and Gaussian, both with and without sample based interpolation. Comparing Figures 3 and 4 reveals that the 9600VL waveform is much more sensitive to variations in the implementation of the HF channel simulator than the 2400L waveform. The 2400L waveform shows a maximum difference in performance of about 1/2 dB at a BER of 10^{-5} compared with a deviation of over 2.3 dB for the 9600VL waveform for the same BER of 10^{-5}.

5.1 Filter Shape

Figures 5 and 6 display the theoretical power spectra of an ideal Gaussian shaped filter and of the two-pole Butterworth filter employed by the recent and earlier Harris Channel simulators, respectively. The plotted spectra are for a Doppler spread of 1.0 Hz. Figure 6 highlights the major differences. The Butterworth spectrum is narrower in the 0 to 1.5 Hz range and wider at deviations greater than 1.5 Hz. Since these two plots are the numerical evaluation of the theoretical Filter spectra, they are centered at 0.0 Hz.

Figure 3 - Performance of U.S. MIl-STD-188-110B 2400L bps

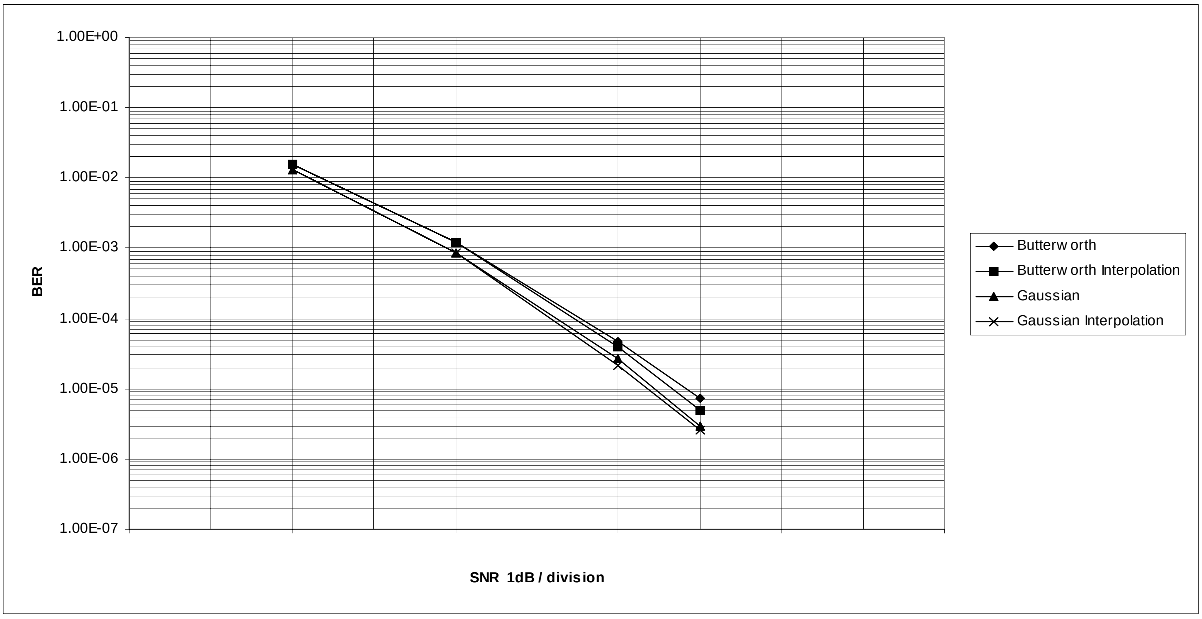
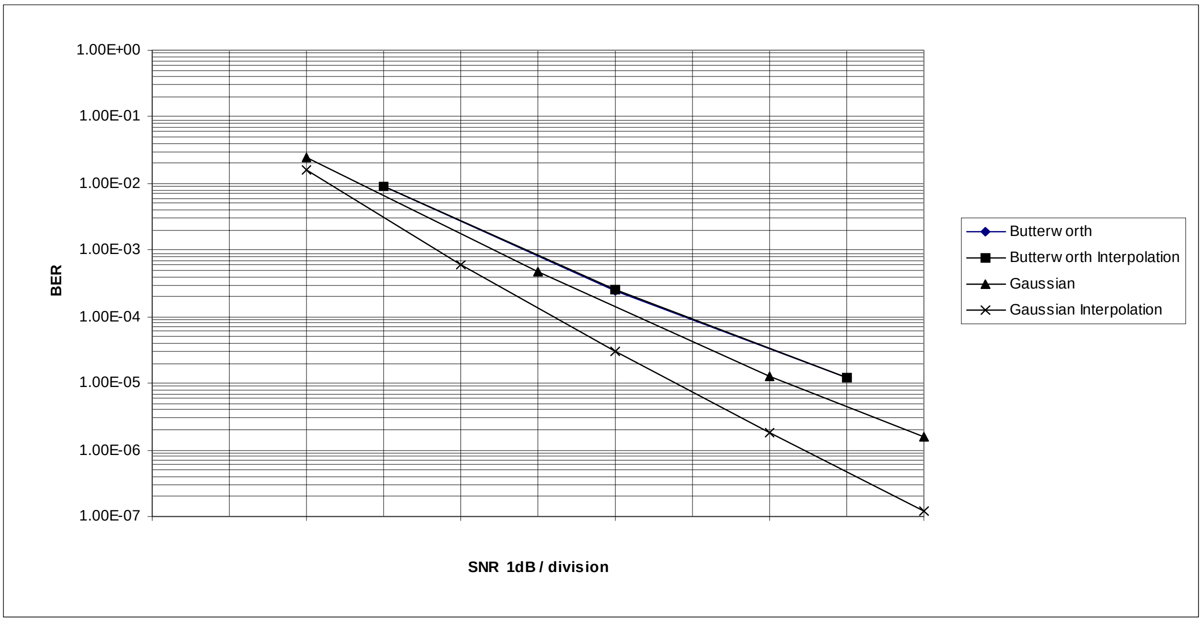
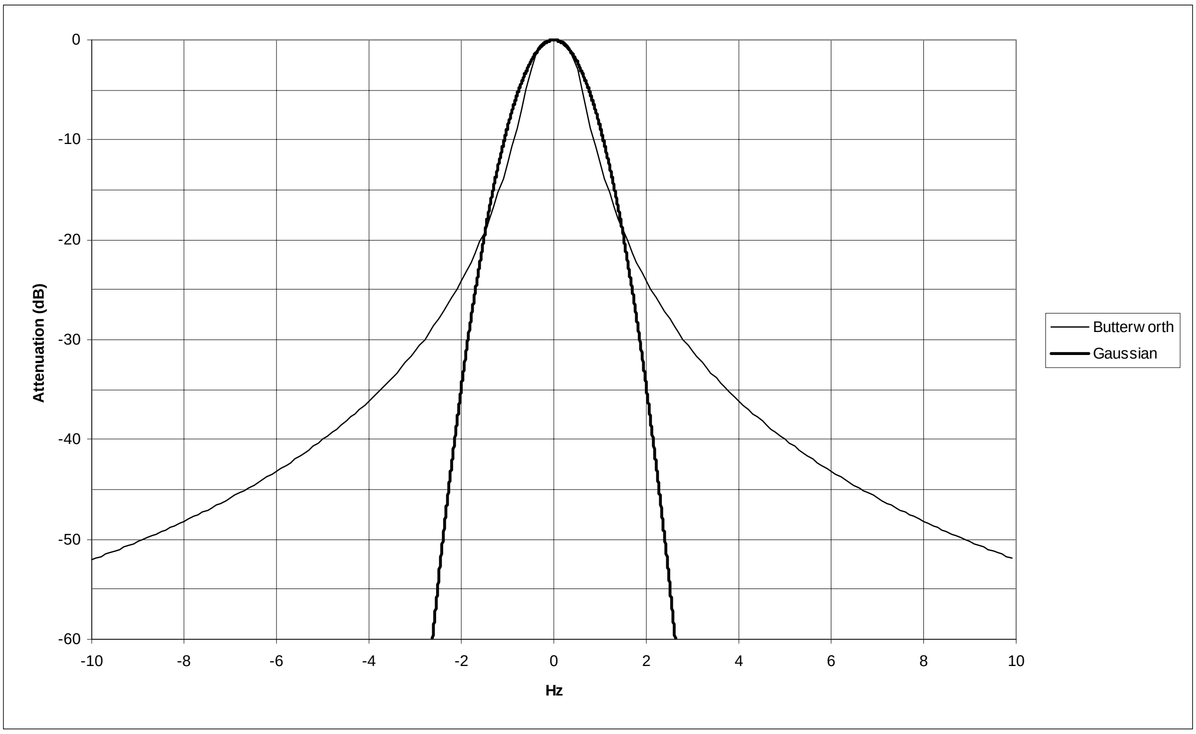


Figure 4 - Performance of U.S. MIL-STD-188-110B 9600VL bps



In order to examine the actual spectra achieved by the software and hardware implementations of the channel simulators, a 1000 Hz tone was input to the channel simulator. The simulator was set to support a single fading path with a Doppler spread of 1.0 Hz. A large number of output samples (representing several hours of real time operation) were then collected and processed to produce the accompanying spectral plots. Taking a 131,072 point FFT of the output samples and then averaging the magnitude-squared of the

Figure 5 - Gaussian and Butterworth Filter Spectra



resulting spectra generated the output plots. This accounts for the next series of plots having their spectra centered at 1000 Hz.

Figures 7 displays the spectra measured on the Harris DSP based HF Channel simulators by using the above measurement technique. Comparing this plot to the ideal plot shows close agreement. Both spectra deviate from the ideal between 30 and 40 dB below the maximum

Figure 6 - Butterworth and Gaussian Filter Spectra (magnified view)

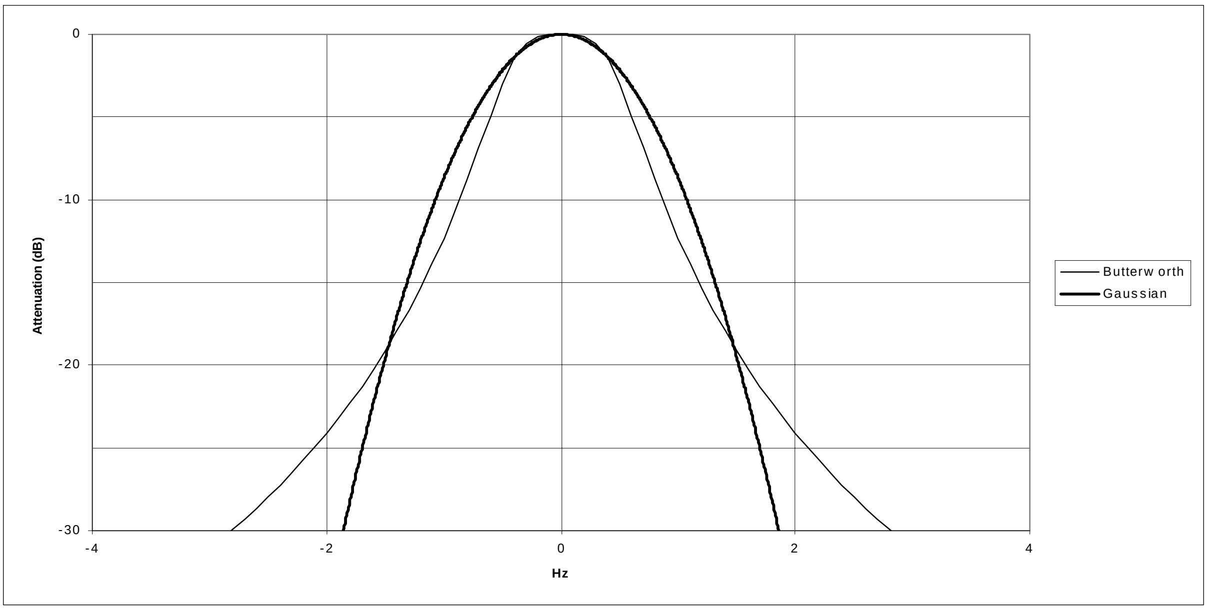
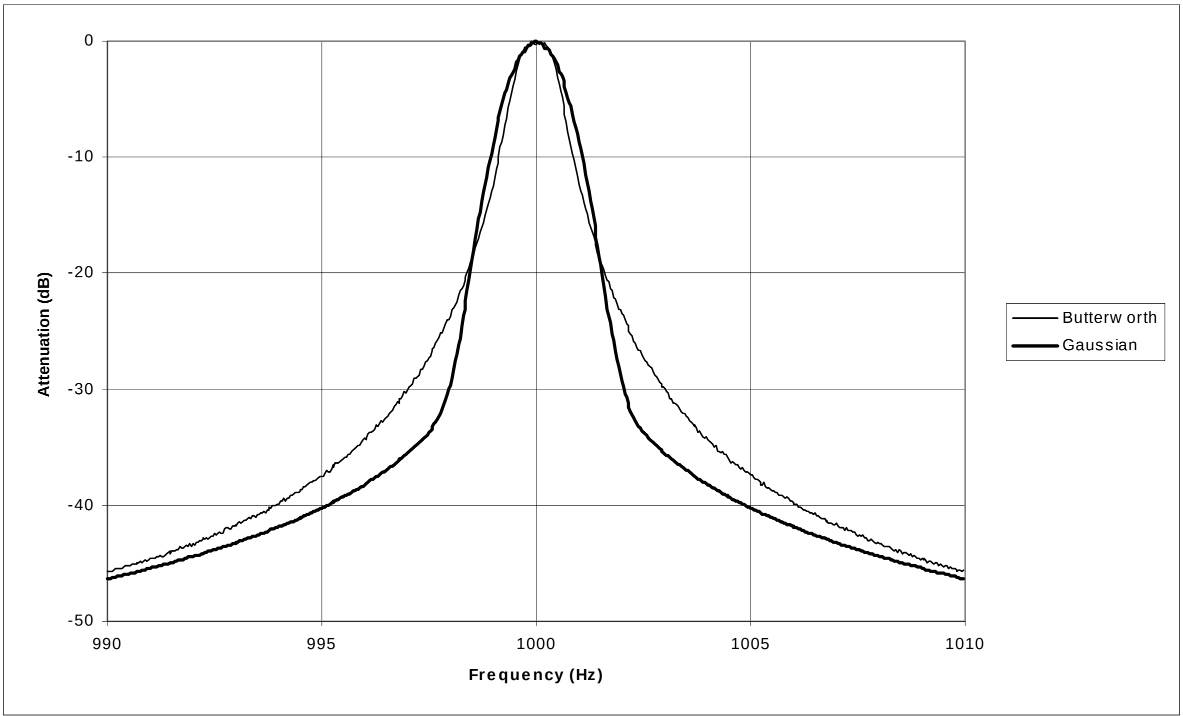


Figure 7 - Measured Spectra, Butterworth and Gaussian



output level. This deviation is likely due to both filter implementation issues as well as the periodogram approach to estimating the spectrum (i.e. the averaging of the FFT output squared-magnitudes). The Gaussian filter is implemented as a FIR filter where its coefficients are obtained from sampling the impulse response of the Gaussian shaped filter, equation (3). The filter coefficients must be truncated at some level to result in a finite length filter. This truncation may also be responsible for some of the spectrum deviation seen below 30 dB.

5.2 Interpolation

In the original Harris channel simulator utilizing the Butterworth filters, the fading taps were updated at a rate of 600 times per second. There was no interpolation of these taps for the intermediate channel simulator samples. Both Harris channel simulator implementations utilize a waveform sample rate of 9600 samples per second. The newer Harris channel simulator utilizing the Gaussian shaped filters selected the update rate based on the specified Doppler spread. This was done to minimize the number of taps required to sample the impulse response. For the 1.0 Hz Doppler spread case that is being examined in this paper, the update rate of the Gaussian filters was 37.5 times per second. Originally neither simulator interpolated the fading tap gains between the updates. It should be pointed out, however that both implementations met the STANAG 4285 requirement of updating the taps at least 32 times the specified Doppler spread.

Figure 8 displays a wider spectral view of the measured spectrum of the Butterworth filter approach with no interpolation. It can be seen that there are a number of images of the spectrum repeated at different frequency offsets. These images are the result of interpolating to a higher sample rate by simply repeating the sample. In the frequency-domain, repeating the samples creates images of the spectrum at multiples of the original update rate multiplied by a sin(x)/x spectrum (i.e. time-domain rectangular window with width equal to the original update rate). The Gaussian filter approach, as seen in Figure 9, has even more undesired spectral peaks because of the much lower update rate. Figure 10 displays the realized spectra of both the Butterworth and Gaussian filter approach after the fading taps have been linearly interpolated for each simulator sample. The undesirable spectral peaks have been eliminated. Note that in the time-domain, not interpolating the filter taps creates a fading process that changes value instantly and then remains constant until the next update (i.e. behavior that does not model HF channels properly).

Figure 8 - Butterworth Spectrum - No Interpolation

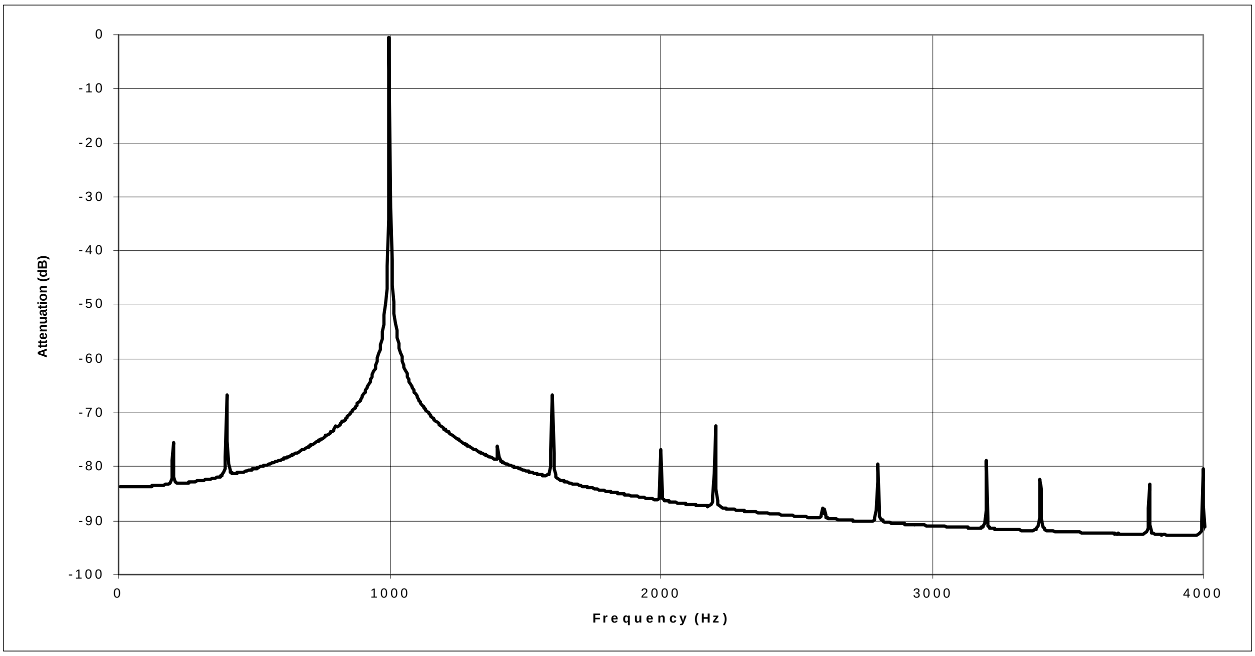


Figure 9 - Gaussian Spectrum - No Interpolation

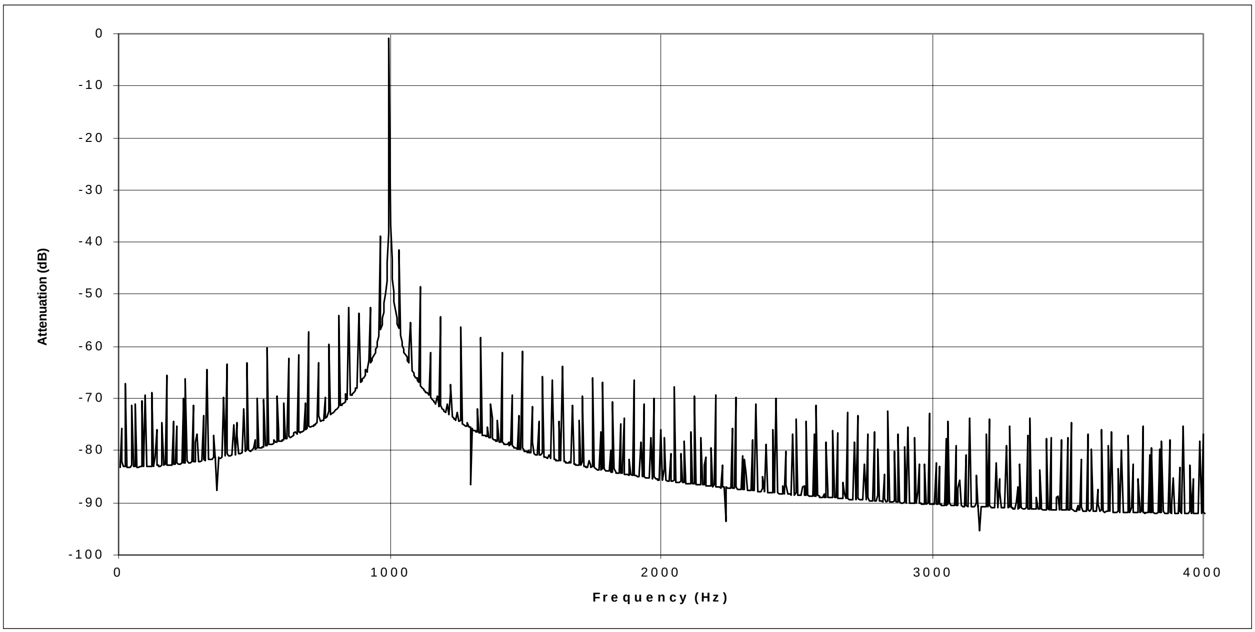
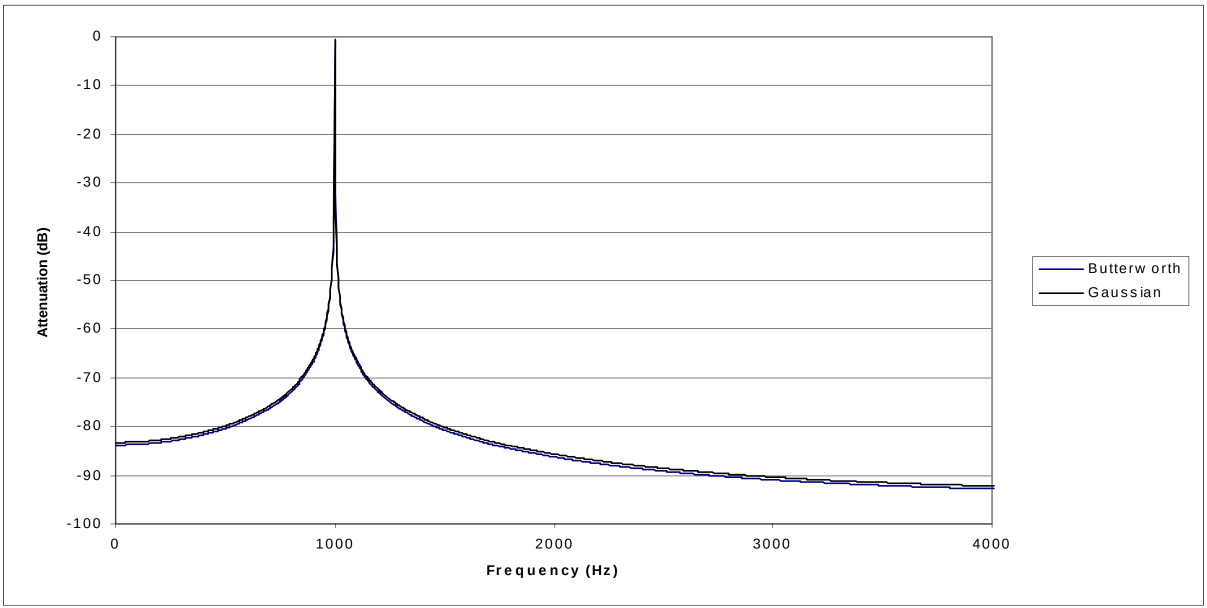


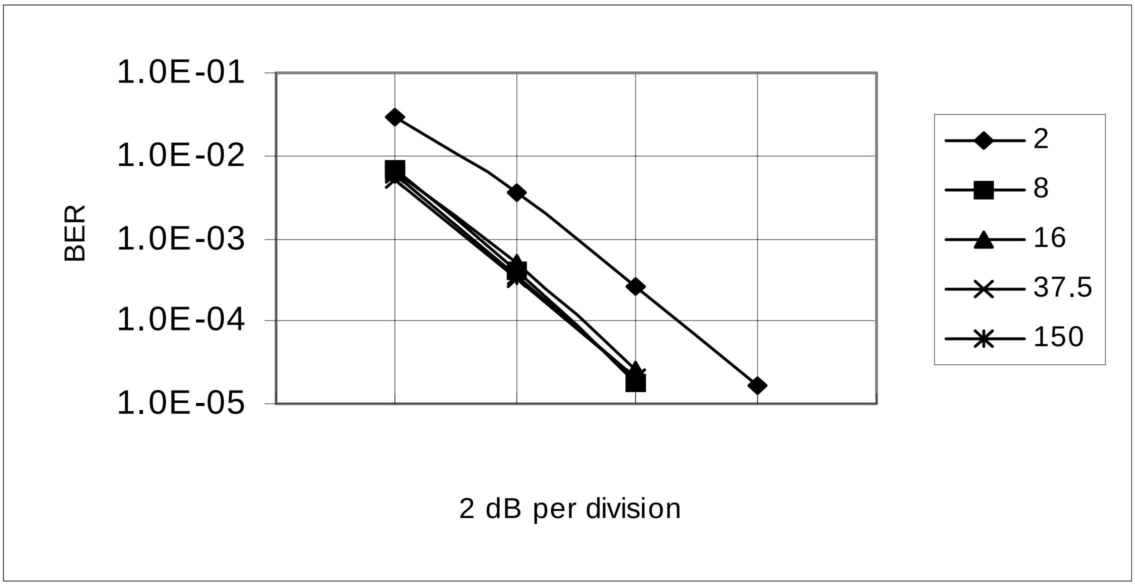
Figure 10 - Butterworth and Gaussian Spectra - Interpolation



5.3 Tap Update Rate

The final fading process issue examined was that of the update rate. As mentioned earlier in this paper STANAG 4285 specifies that the fading taps should be updated at a rate at least 32 times the desired Doppler spread. Figure 11 displays U.S. MIL-STD-188-110B modem performance for the CCIR POOR channel as a function of update rate, specified in Hz. This data was measured with the Gaussian filter process and with interpolation on.

Figure 11 - BER vs SNR for Different Tap Update Rates (2400L)



As can be seen, updating the taps at the rate that is twice the Doppler spread results in close to a 2 dB deviation in measured performance. This deviation decreases as the update rate is increased. There is very little performance measurement difference between update rates of 37.5 Hz and 150 Hz. In summary, the STANG 4285 recommendation of 32 times the Doppler spread appears to be reasonable. Figure 11 data is for the 2400L bps waveform, similar results were measured for the 9600VL bps waveform.

6 AN IMPROVED HF CHANNEL SIMULATOR SPECIFICATION

Figure 12 compares the ideal Gaussian filter spectrum with that achieved by the new Harris HF channel simulator utilizing the following specifications. It should be noted that the deviation of the spectrum starting at –30 dB is likely due to the spectrum estimation technique employed. These specifications are an attempt to provide a tighter definition of a Watterson model based channel simulator that will result in much less implementation-to-implementation performance deviations.

1) Multipath modelled by tap-delay line as shown in Figure 1.

2) All paths should be normalized by summing the desired powers for each path and setting total power equal to 1.0 (for proper SNR value).

3) Fading taps (for tap-delay line) obtained by filtering complex white Gaussian noise samples. Readers unfamiliar with WGN can find an excellent description in [16].

4) Filters used for fading process should have a Gaussian shaped power spectrum (frequency-domain) with Doppler spread of power spectrum equal to twice the standard deviation (2σ). Equation (3) should be used to compute the filter taps based on the sampling rate of the channel simulator. The length of the filter should be set to at least the length where the computed tap is 0.01 smaller than the max tap. Filter should be symmetrical about max tap (tap for time 0). Filter should then be power normalized to 1.0 and scaled by gain computed in 2) above for given path.

5) Fading taps must be computed at least 32 times faster than the desired fade rate.

6) Fading taps must be interpolated to at least the symbol rate of the waveform (2400 samples a second) to avoid introducing large discontinuities in the output of the simulator. (Harris channel simulator interpolates to 9600 samples per second). Ideally, the fading taps should be interpolated to the sample rate of the channel simulator.

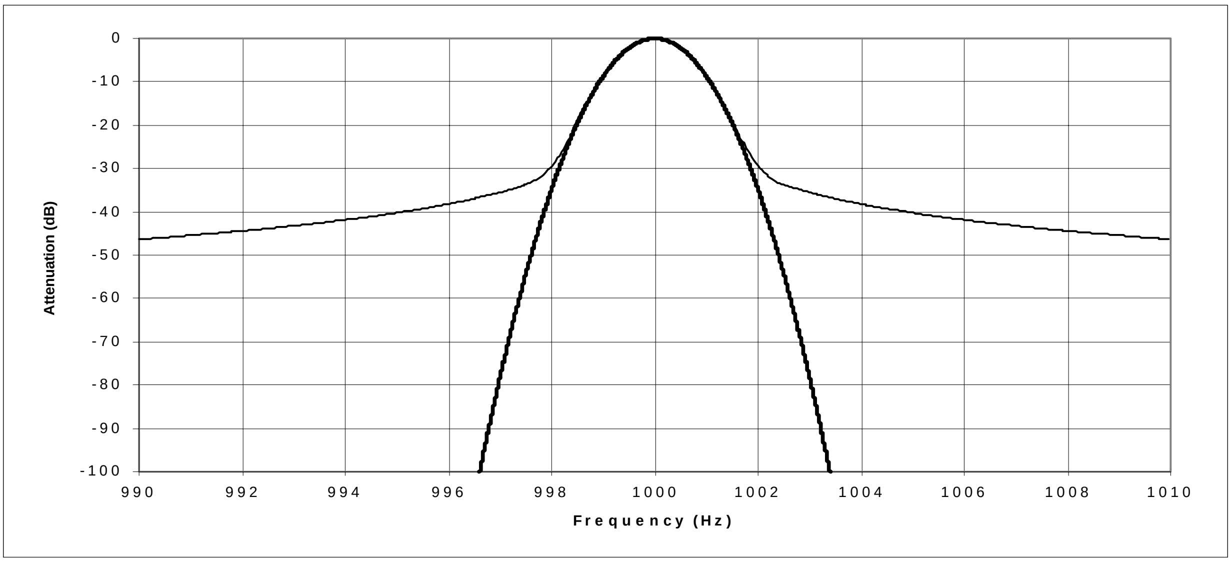
7) No simulated radio filters or AGC should be used. Also, since input to channel simulator is a real audio signal, a Hilbert transform [16] should be used to create a complex signal.

8) SNR should be the average signal to noise ratio of a waveform measured in a 3 kHz bandwidth. Care should be taken to insure enough time has been allowed to measure the average signal power of the input waveform (i.e. average power measurement for higher data rate waveforms should be measured over several minutes)

9) Additive White Gaussian Noise [16] should be used as noise source

10) In order to generate a fading process that is within 0.1% of the desired Doppler spread, the crystal used to generate the sample rate for the channel simulator should not exceed 500 Parts Per Million (PPM).

Figure 12 - Achieved Gaussian Filter Spectrum vs. Ideal



7 CONCLUSIONS

The presented data shows that Watterson model HF channel simulators that meet the specification of the existing set of standards, reports and recommendations can introduce measurement performance deviations. These deviations can be measurable with 2400 bps HF modem waveforms and can be significant with the newer High Data Rate waveforms, employing higher order QAM constellations, which are defined in U.S. MIL-STD-188-110B and STANAG 4539. Further, it has been shown that one of the main areas of concern is in the generation of the fading channel taps. This paper has concluded with a set of guidelines, which should result in less measurement deviation from channel simulator to channel simulator.

8 ACKNOWLEDGEMENTS

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