APPENDIX B. SIMULATIONS OF TIME AND SPECTRAL CHARACTERISTICS OF ULTRAWIDEBAND SIGNALS AND THEIR EFFECTS ON RECEIVERS

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B.1 Introduction

In this appendix a class of time-dithered, time-hopped UWB systems is modeled and simulated from an analytic description of the system. These simulated time waveforms and Fourier spectrum results are analyzed to show the effect of a receiver's intermediate frequency (IF) bandwidth (BW) on peak and average power. These peak and average power curves provide the basis for establishing a normalized bandwidth correction factor (BWCF) curve and equation. The BWCF is used to estimate peak power over a range of bandwidths from average power measurements made in a 1 MHz BW as prescribed by the FCC for Part 15 devices. Simulation of the UWB devices complements measurements and other analytic model results for these devices.

B.2 UWB Model

The simulated time-dithered ultrawideband system block diagram is shown in Figure B.1. The system transmits a quasi-periodic, very low duty cycle, dithered pulse train *s(t)* where delta functions (narrow pulses in hardware) are pulse position modulated (PPM) and shaped with a Gaussian 2nd derivative filter *w(t)*. The analytic expression for *s(t)* and *w(t)* are provided in (1) and (1a) where d_k is the total dither in time units and N_p is the number of pulses in the pulse train. In the simulation results the number of pulses was set at 100 (10,000 ns). This was estimated to be similar to the observation window of a spectrum analyzer measurement. The model employed here is similar to that used by Win and Scholtz [1] except that their pulse trains were infinite in length, which led to smoothed spectral lines corresponding to this infinite observation window.

$$s(t) = w(t) * \sum_{k=1}^{N_p} \delta\left[t - d_k - (k-1)T\right] \qquad (1)$$

$$w(t) = \left[\ 1 - 2(\pi\ t f_c)^2\ \right] e^{-(\pi\ t f_c)^2} \qquad (1a)$$

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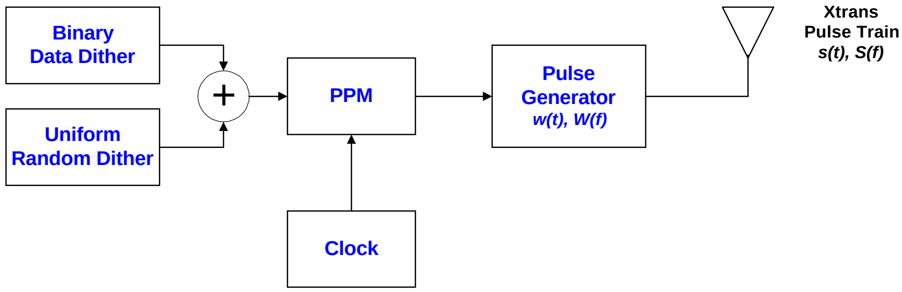

Figure B.1. Time-dithered ultrawideband system model.

The shaping filter for a specific hardware configuration depends on the transmit and receive antennas and may deviate some from this model. The specific pulse shape is probably not as important a factor in determining a receiver's narrow IF BW response as the pulse width and corresponding BW. The receiver IF filtering will remove pulse shape details if the pulse is sufficiently narrow and the corresponding BW sufficiently wide, compared to the receiver IF bandwidth. Shape details are filtered out in these simulations, as will be seen in the IF output pulses. In this system the dither consists of two components: a pseudo-random time-hopping dither and a data dither. Usually the time-hopping dither is large compared to the data dither. In our case the time-hopping dither was uniformly distributed between 0 and 0.5T (50% dither); whereas the data dither represented binary 0s and 1s with 0 or 0.045T (4.5% dither). The time-hopping dither values are commonly generated from a pseudo-noise sequence. An undithered pulse repetition rate (PRR) of 10 MHz was used, which made the nominal pulse train period T= 100 ns. Simulation results were also obtained for the 0 or the non-dithered case where the waveforms are periodic with a period T=100 ns resulting in a line spectra with a fundamental frequency equal to the PRR .

B.3 UWB Simulation

The simulation and power calculation processes are shown in the flow diagram of Figure B.2. A periodic impulse train is dithered by the combined amount of dither and then Fourier transformed using the FFT (Fast Fourier Transform). Then the spectrum is shaped using the Gaussian 2nd derivative filter transfer function *W(f)* described by the analytic expression in (2a). Alternatively, the complex Fourier spectrum, *S(f)*, can be calculated using the analytic expression in (2).

$$S(f) \quad W(f) \sum_{k\;1}^{N_p} e^{-j2\pi f[d_k \;(k-1)T]} \qquad (2)$$

$$W(f) \quad \left(\frac{f}{f_c}\right)^2 e^{\left[1 - \left(\frac{f}{f_c}\right)^2\right]} \qquad (2a)$$

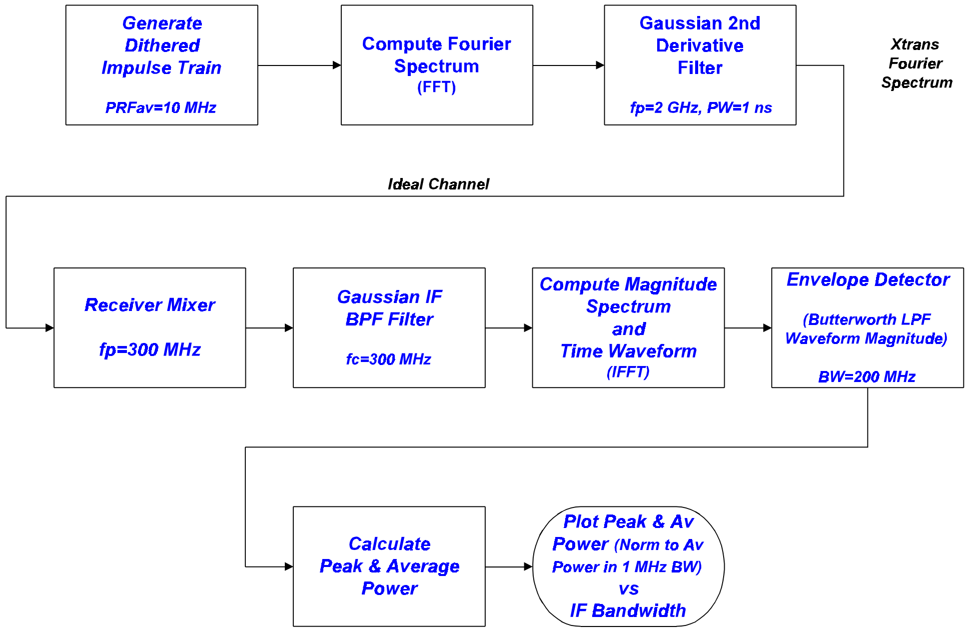

Figure B.2. Simulation and power calculation process.

The transmitted 50% dithered pulse train is shown in the top Figure B.3 plot and an individual pulse is shown in the bottom plot. The transmitted pulse width was approximately 1 ns and the corresponding wideband spectrum peaked at 2 GHz with 40 dB down from the peak occurring at frequencies of 0.25 GHz and 5 GHz. The transmitter spectra are shown in Figure B.4 with dithered pulse train spectrum (before shaping) shown in the top and the shaped transmitter output spectrum shown in the bottom. Note that the spectrum before shaping appears quite noise-like with 50% dither. This random appearance can change significantly with less dither, particularly below 25% dither. With dithers greater than 50% the random appearance does not change significantly. With BWs of 100 MHz or less centered about the peak at 2 GHz, the spectrum still appears quite flat even after shaping.

The transmitter output in Figure B.2 is fed through an ideal channel to a receiver (victim or spectrum analyzer) where the signal is mixed down to a center frequency of 300 MHz. This frequency f_c now is also the peak frequency of the spectrum. That is, the original peak frequency f_p=2 GHz was mixed down to 300 MHz. Next the mixer output is filtered by a Gaussian-shaped filter with an adjustable bandwidth. A Gaussian shape was chosen for three reasons: (1) the spectrum analyzer response, used to make measurements at an IF frequency, resembles a non-symmetric Gaussian; (2) as more stages of IF filtering are employed, their composite response usually tends towards a Gaussian; and (3) simplicity. Bandwidths were employed from 100 MHz down to 0.3 MHz. The IF filter was followed by an envelope detector implemented by computing the waveform magnitude and lowpass filtering it with a 6-pole Butterworth filter using a BW of 200 MHz. Higher bandwidths allowed some ripple through at the IF frequency.

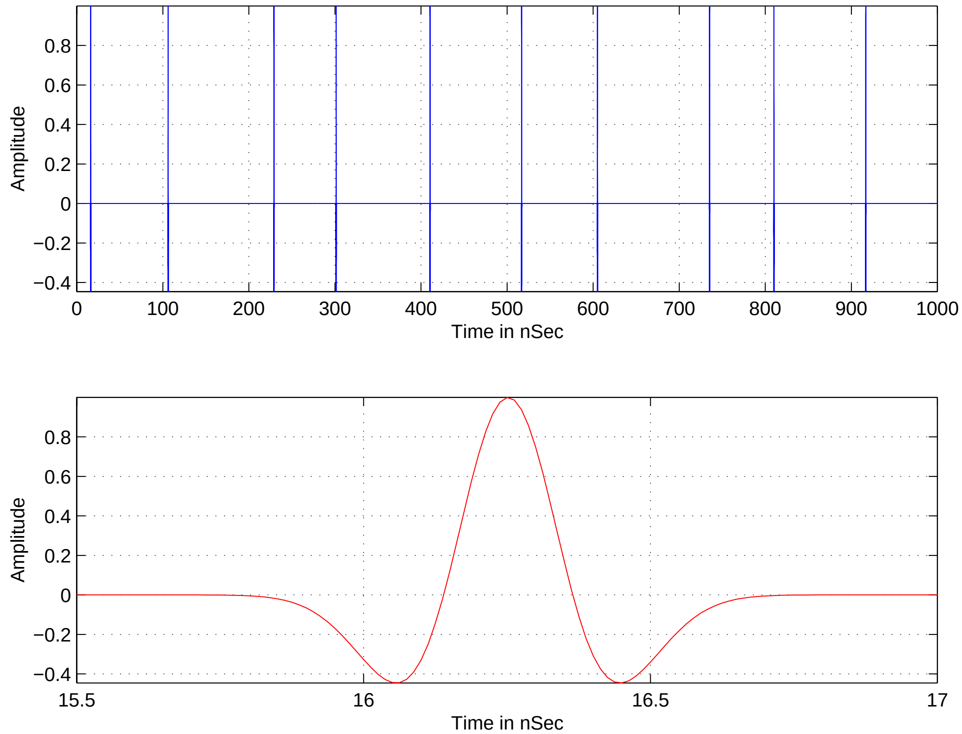

Figure B.3. Normalized 2nd derivative Gaussian dithered pulse train (50% dither); Top: full record, Bottom: exploded view.

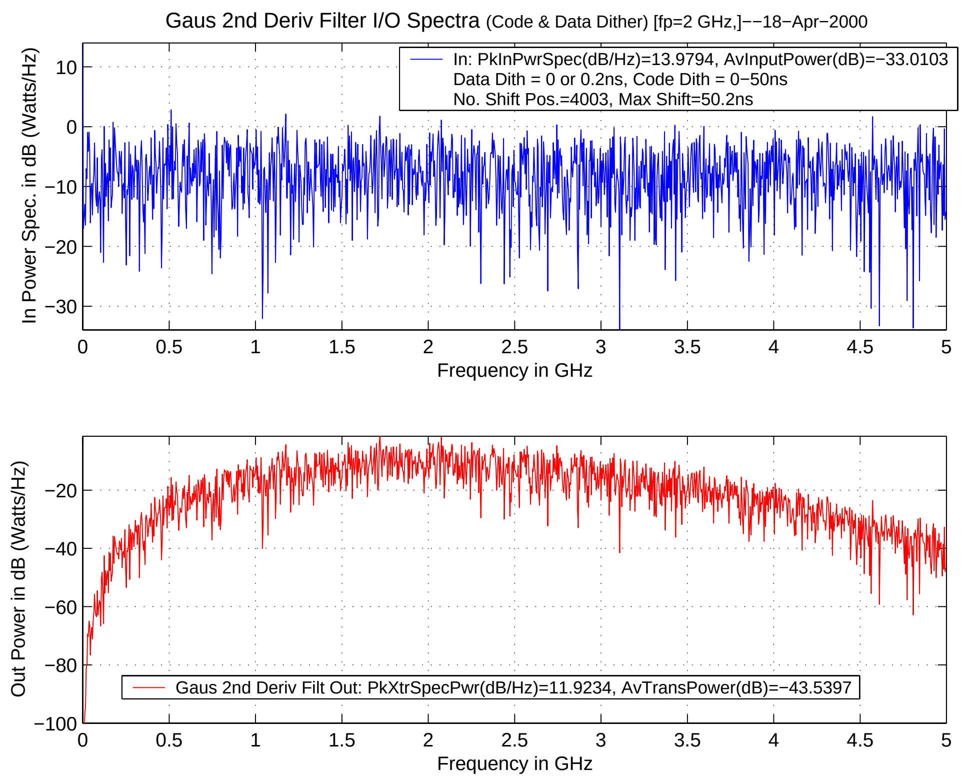

Figure B.4. Transmitter spectra (50% dither); Top: before Gaussian filter, Bottom: after Gaussian filter.

An example output is shown in Figure B.5 employing an IF BW of 30 MHz. The top plot shows the filtered received spectrum centered at 300 MHz, the center plot contains the pulse train out of the IF showing the pulsed RF oscillating at approximately the 300 MHz IF frequency. The bottom plot displays the envelope waveform out of the IF filter. Note the variable spacing of the pulses corresponding to the 50% dither. At a BW of 30 MHz the pulses out of the IF just touch each other. For wider BWs they are completely separated and for narrower BWs they are overlapped, causing peaking in the envelope as observed in Figures B.6 and B.7 for 10 MHz and 3 MHz IF bandwidths respectively. Figures B.8 compare this peaking effect of the detected envelope for these same 3 BWs over a record length of 100 pulses (10,000 ns). It is particularly interesting to compare the 50% and 0 dither cases. With the periodic (no dither) pulse train, the IF filter gets pinged by pulses at a regular interval and just provides periodic pulses out of the detector without peaking. At a BW of 3 MHz the 50% randomly dithered pulse train creates significant peaks and valleys (1 down to 0), whereas the periodic pulse train has a constant envelope coming out of the IF filter.

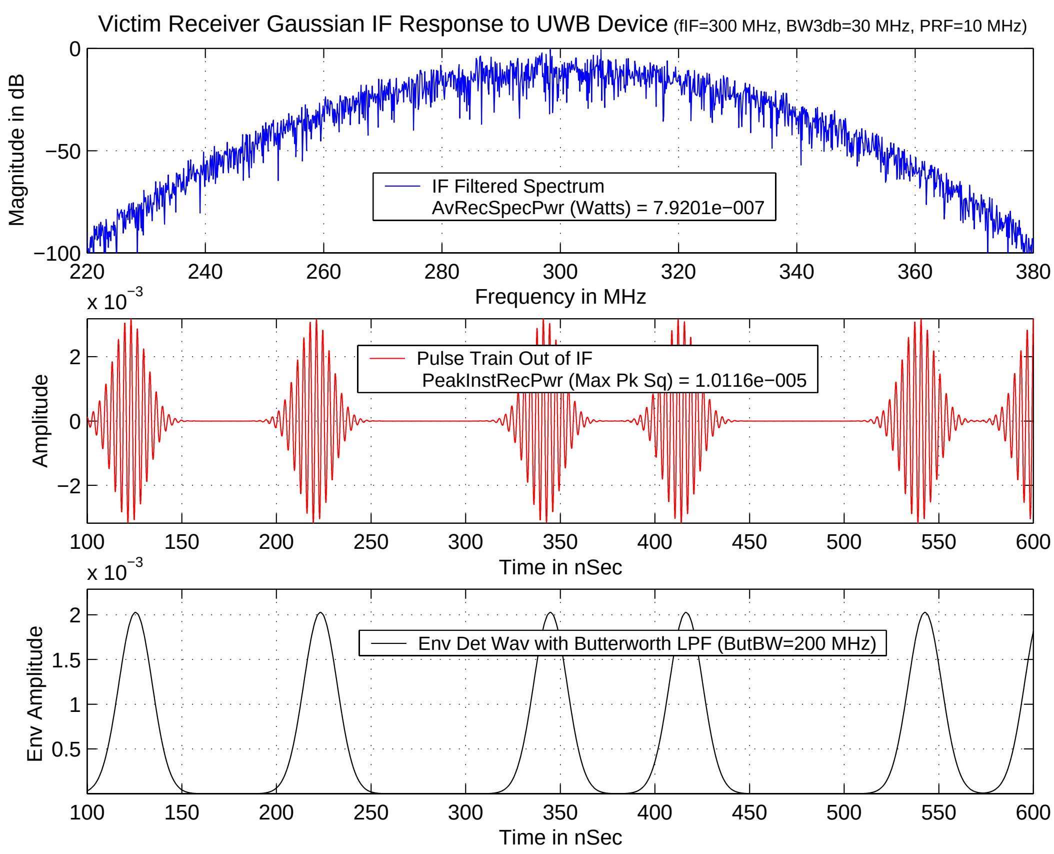

Figure B.5. Receiver 30 MHz IF bandwidth (50% dither); Top: output spectrum, Middle: pulsetrain, and Bottom: envelope detected pulse train.

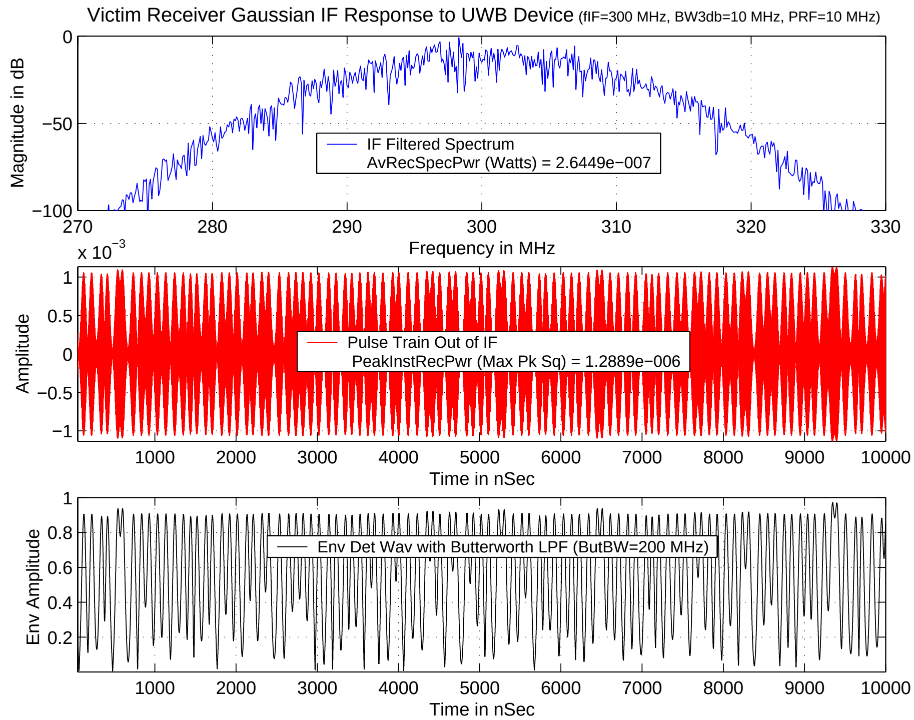

Figure B.6. Receiver 10 MHz IF bandwidth (50% dither); Top: output spectrum, Middle: pulse train, and Bottom: envelope detected pulse train.

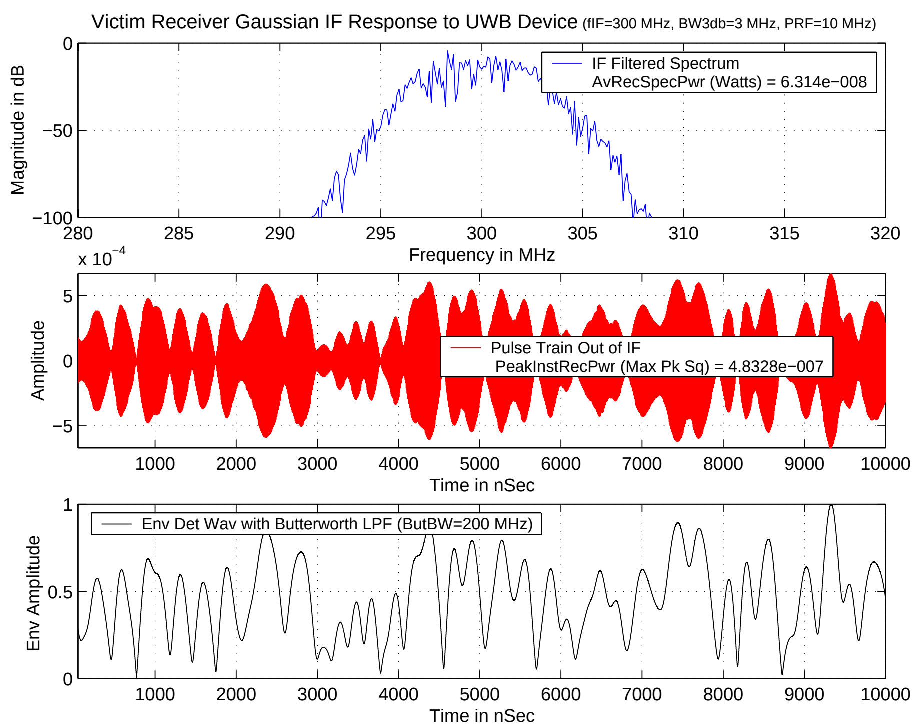

Figure B.7. Receiver 3 MHz IF bandwidth (50% dither); Top: output spectrum, Middle: pulse train, and Bottom: envelope detected pulse train.

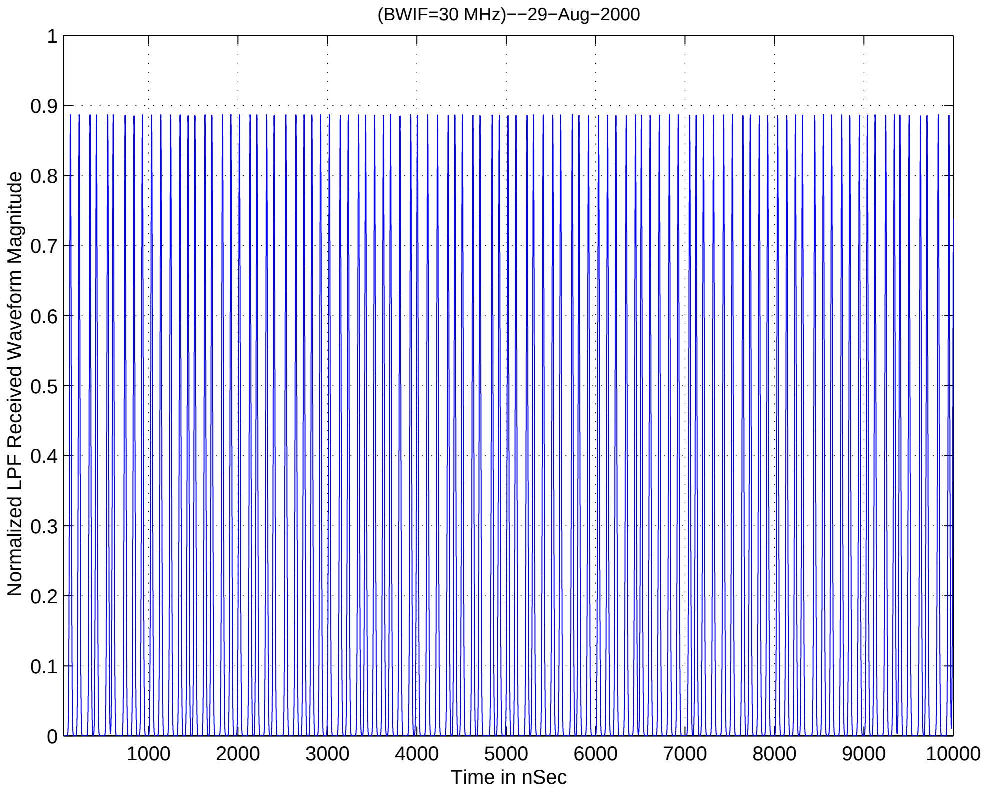

Figure B.8.A. Receiver IF envelope for 30 MHz bandwidth with 50% dither.

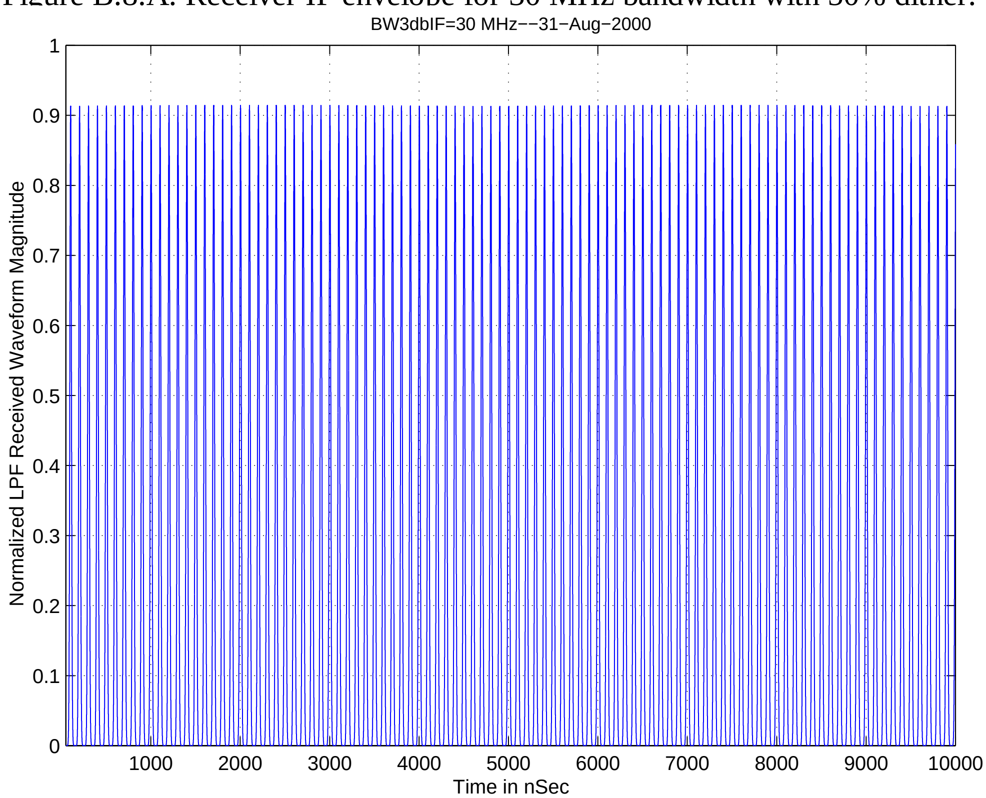

Figure B.8.B. Receiver IF envelope for 30 MHz bandwidth with 0% dither.

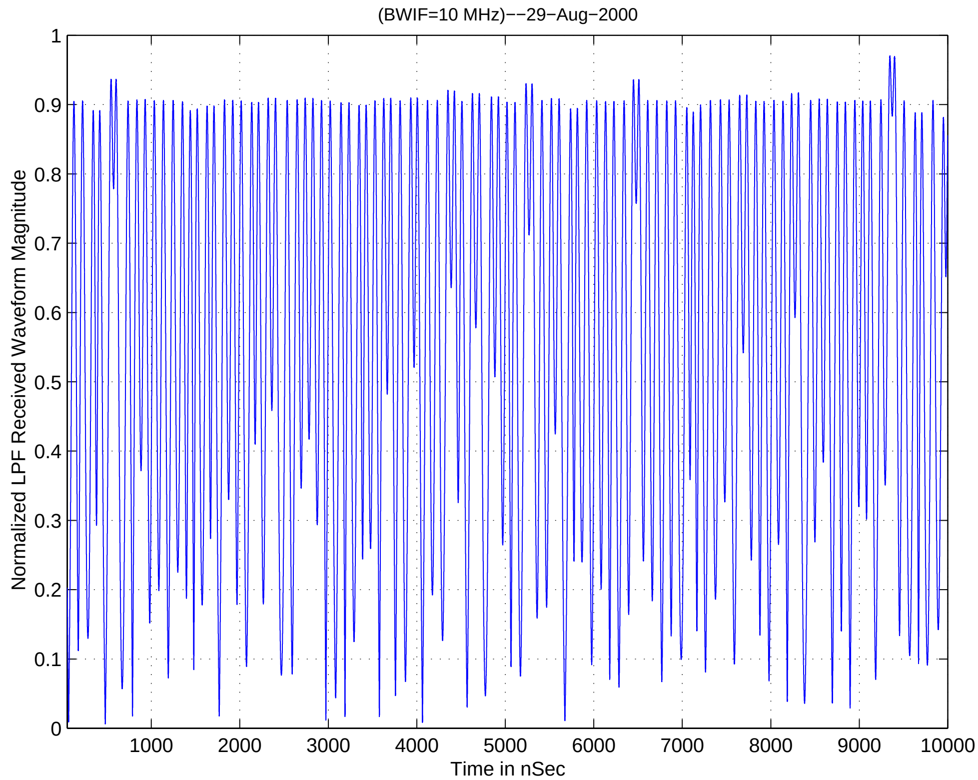

Figure B.8.C. Receiver IF envelope for 10 MHz bandwidth with 50% dither.

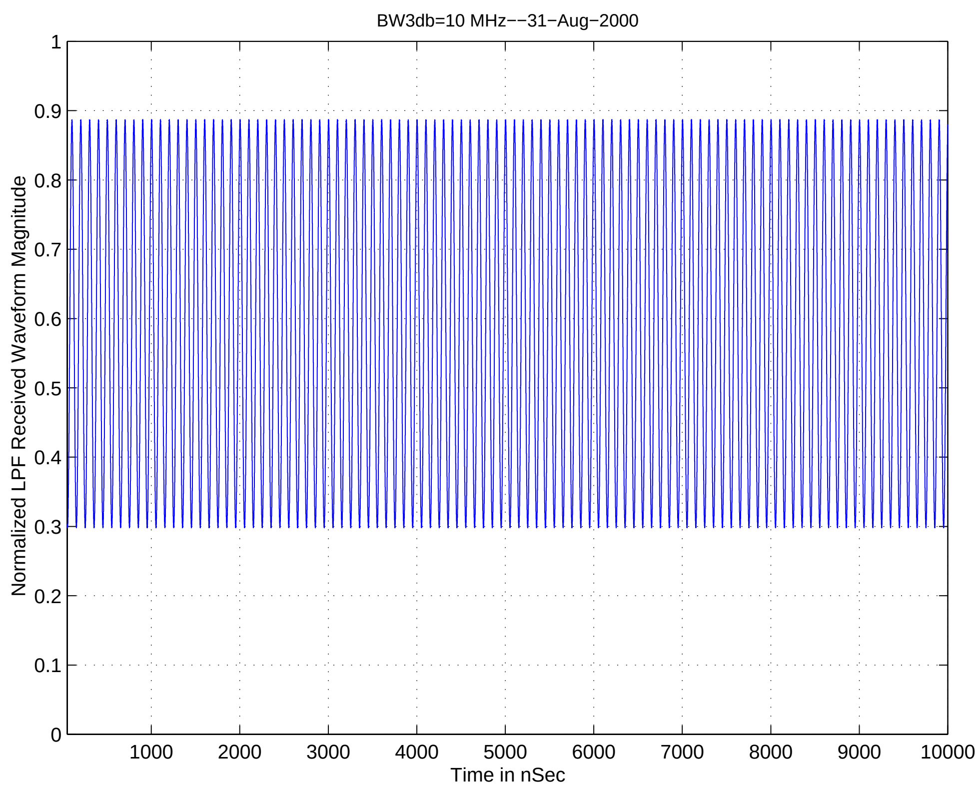

Figure B.8.D. Receiver IF envelope for 10 MHz bandwidth with 0% dither.

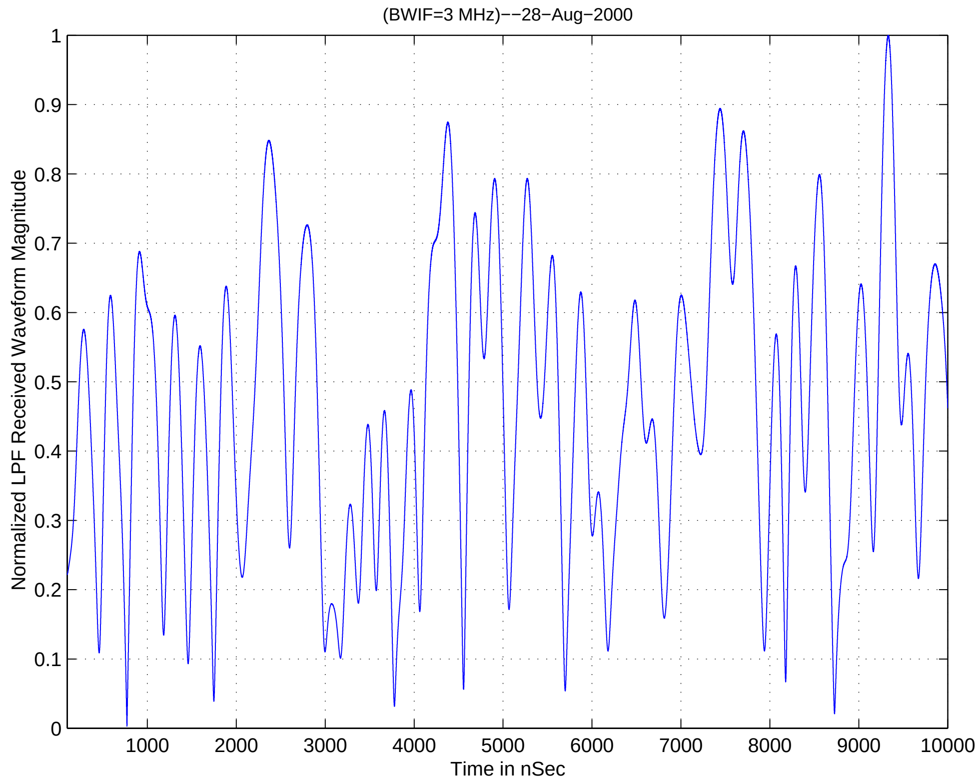

Figure B.8.E. Receiver IF envelope for 3 MHz bandwidth with 50% dither.

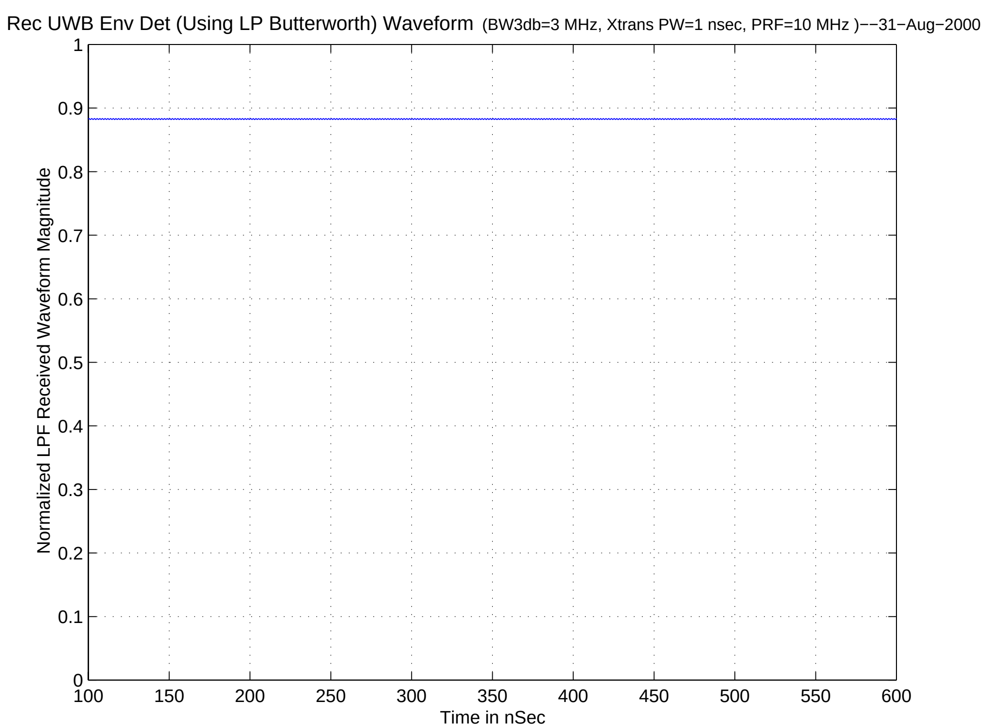

Figure B.8.F. Receiver IF envelope for 3 MHz bandwidth with 0% dither.

B.4 Power Calculations in Receiver IF Bandwidths

Figures B.9 show the received instantaneous peak and average power computed from the simulated time waveforms for receiver IF bandwidths ranging from 0.3 MHz to 100 MHz. These powers were normalized to the average power in a BW of 1 MHz (a 1-MHz BW is specified by the FCC for Part 15 average measurements). Consequently, the average power curves all go through 0 dB at 1 MHz. These curves provide the basis to develop bandwidth correction factors (BWCF). The BWCFs are used to estimate the amount of peak power at a given BW, starting with measuring the average power in this 1-MHz BW.

In addition to peak and average power curves, another guideline is provided. This straight line on a log-log plot is the 10 $\log_{10}$(BW) average power trend line. It follows the average power quite well for 50% dither (both pre-detection and post-detection); however, for the non-dithered case it follows the average power only for BWs greater than or equal to 10 MHz where the pulses are separated. As pulses overlap for narrower BWs of this non-dithered case, the envelope is constant and the peak and average power are constant as expected. Consequently the power does not change as a function of BW. Another way to look at this is in the frequency domain. An undithered PRR of 10 MHz results in a spectral line at 10 MHz and its harmonics. There is therefore a line at 2 GHz which is down converted to 300 MHz, the center frequency of the IF filter. As the BW increases above 10 MHz, more lines are included in the passband and the power increases linearly with BW. At 10 MHz and below there is a single line in the passband so that the power remains constant. This is in contrast to the 50% dithered case for narrow BWs where the peak and average powers change according to a 10 $\log_{10}$BW rule.

For both the 50% dithered and non-dithered cases, the peak power for BWs greater than or equal to 10 MHz (also the PRR) increases as 20 $\log_{10}$(BW). This is the BW where pulses become distinct in the pulsetrain at the output of the IF, as can be seen in the envelopes shown in Figure B.8.C through Figure B.8.F.

B.5 Reference

[1] M.Z. Win and R.B. Scholtz, “Impulse radio: How it works,” *IEEE Communications Letters*, pp. 10-12, Jan. 1998.

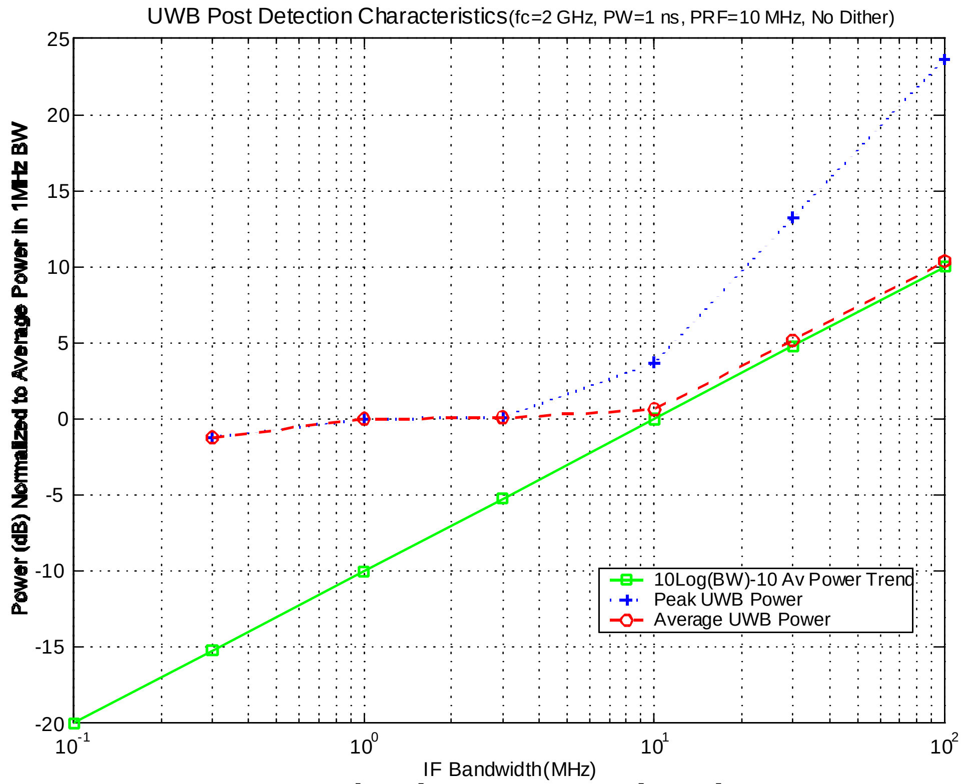

Figure B.9.A. Receiver peak and average power dependence on IF bandwidth (post detection, no dither).

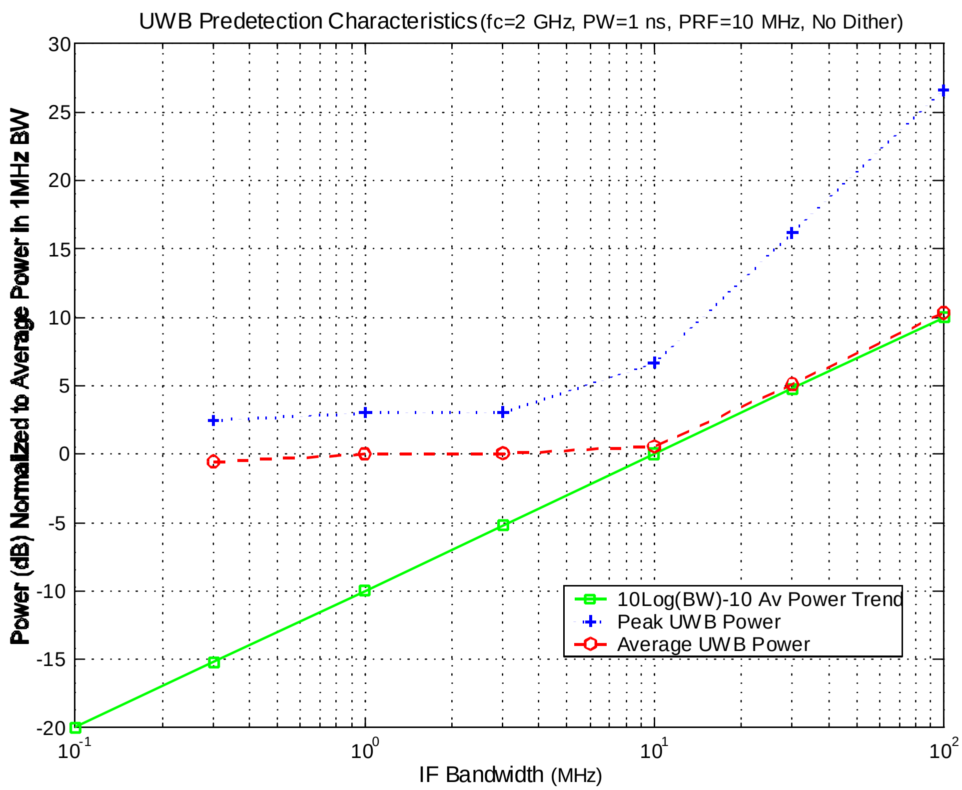

Figure B.9.B. Receiver peak and average power dependence on IF bandwidth (predetection, no dither).

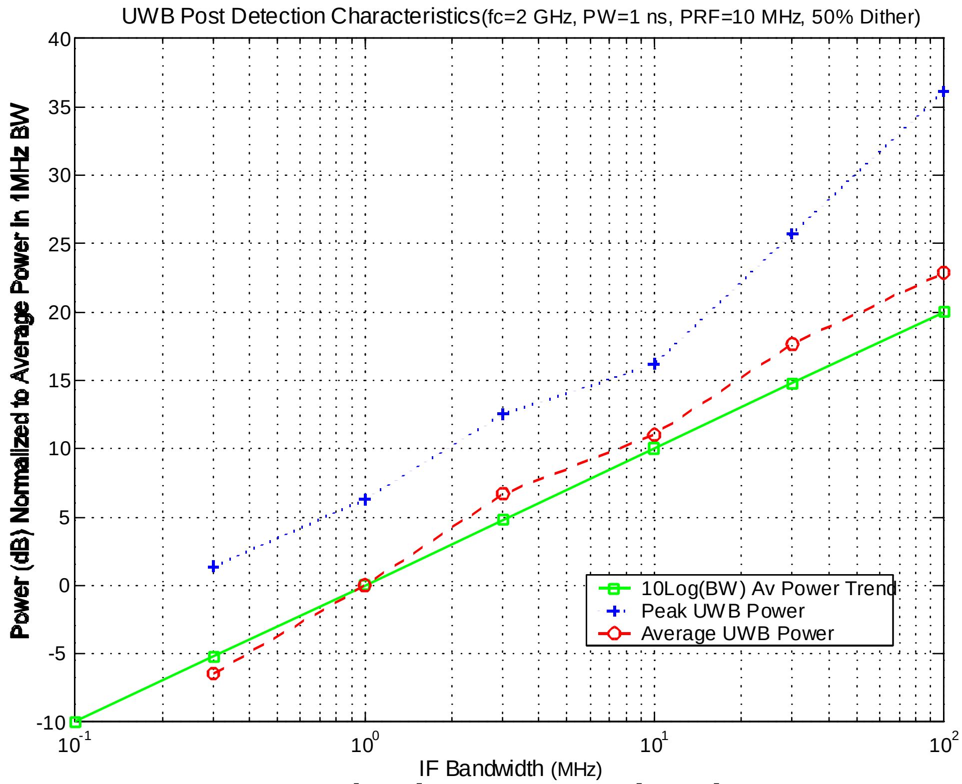

Figure B.9.C. Receiver peak and average power dependence on IF bandwidth (post-detection, 50% dither).

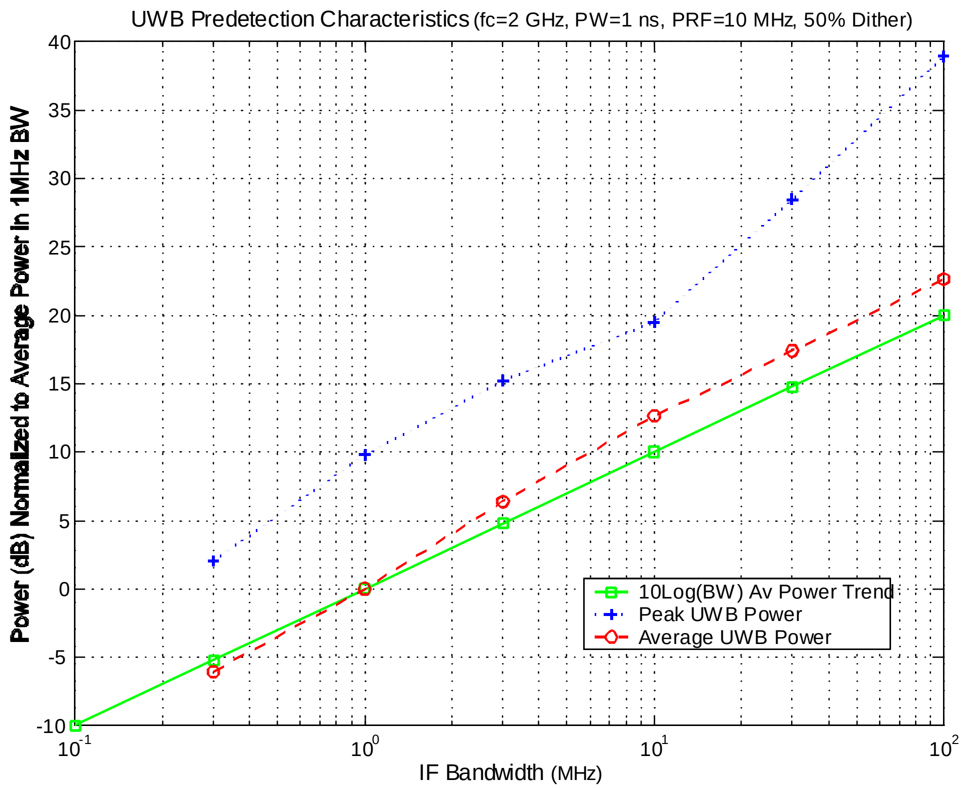

Figure B.9.D. Receiver peak and average power dependence on IF bandwidth (pre-detection, 50% dither).