Models for UWB Pulses and Their Effects on Narrowband Direct Conversion Receivers

Leonard E. Miller
Wireless Communication Technologies Group
National Institute of Standards and Technology
Gaithersburg, Maryland

Abstract

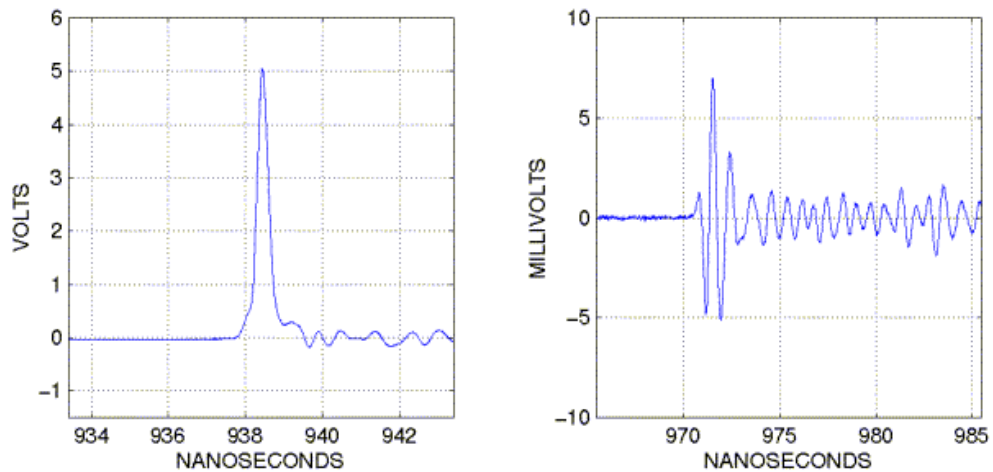
- As interest grows in using UWB pulsed signals for various communication applications, methods are needed for predicting their effects on other systems, as well as predicting system performance.

- Because of the extremely wide bandwidths of UWB pulses, most other systems appear to be narrowband systems.

- This presentation:
  - (1) Models for UWB pulses.
  - (2) Derivation of the received power at baseband of a direct-conversion narrowband receiver that is due to a modulated train of UWB pulses.
  - (3) Example simulation results using equivalent-baseband methodology to characterize receiver response to UWB pulses.

Models for UWB Pulses

•Unlike pulsed CW signals, the differentiation effects of antennas (depending on the antenna transmission method) affect UWB pulse shapes.

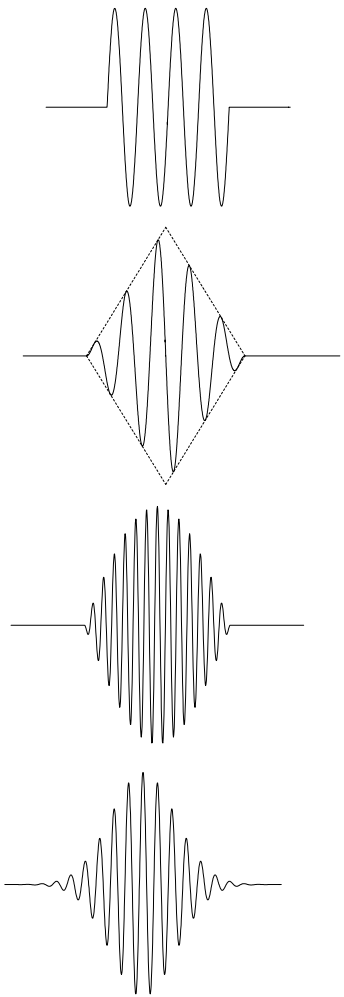


(a) Pulser Output (b) Received Signal

•Various models of UWB pulse waveforms have been used for analytical studies, e.g. (see bibliography at http://www.antd.nist.gov/wctg/manet/)

- •Sinusoidal bursts (polycycles) with various envelope shapes
- •Modified Hermite polynomials

Example Pulse Models



- General form:

$$s(t) = V(t)\cos(\omega_r t + \phi)$$

Coherent case:

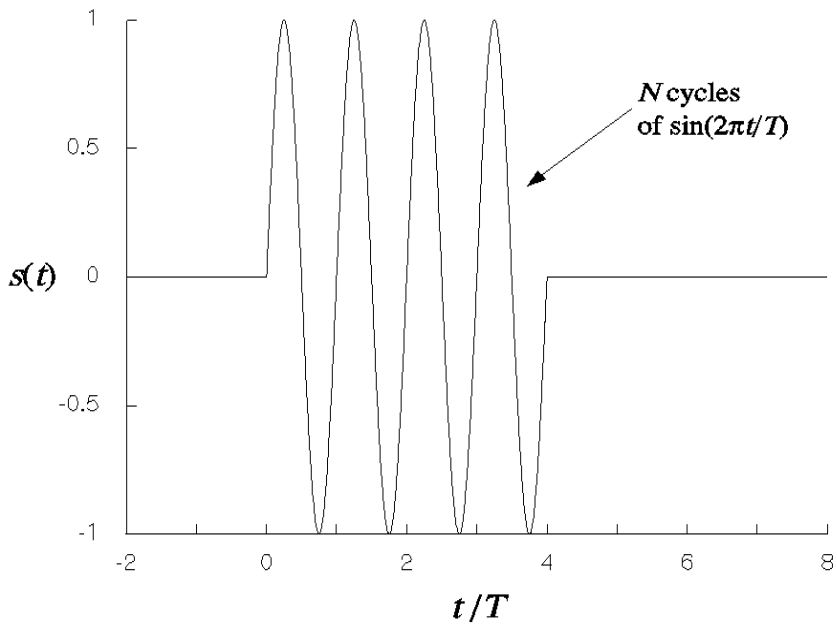
$\phi = 0$ or fixed

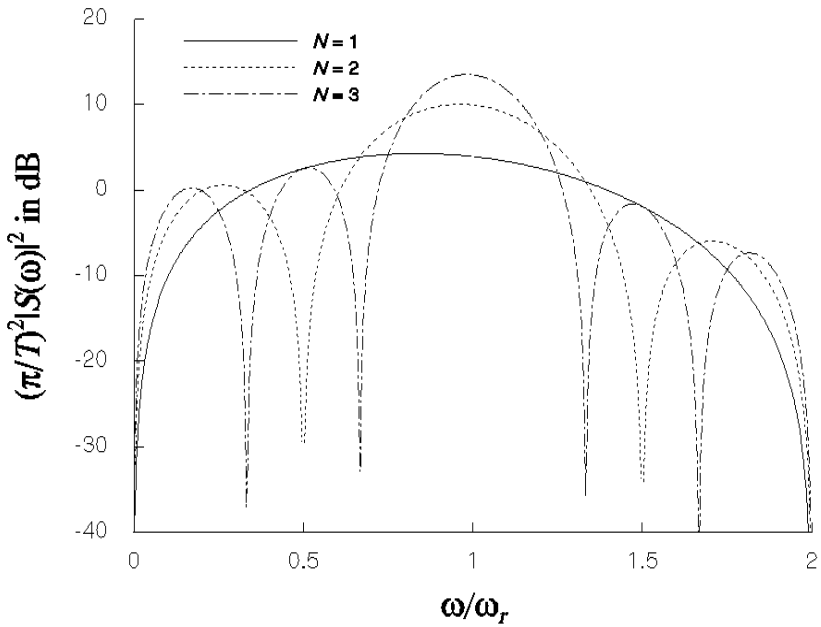
Noncoherent case:

ϕ uniformly distributed

- Center frequency determined by ω_r, bandwidth determined by pulse shape and duration

Example UWB Pulse Spectrum: Polycycle

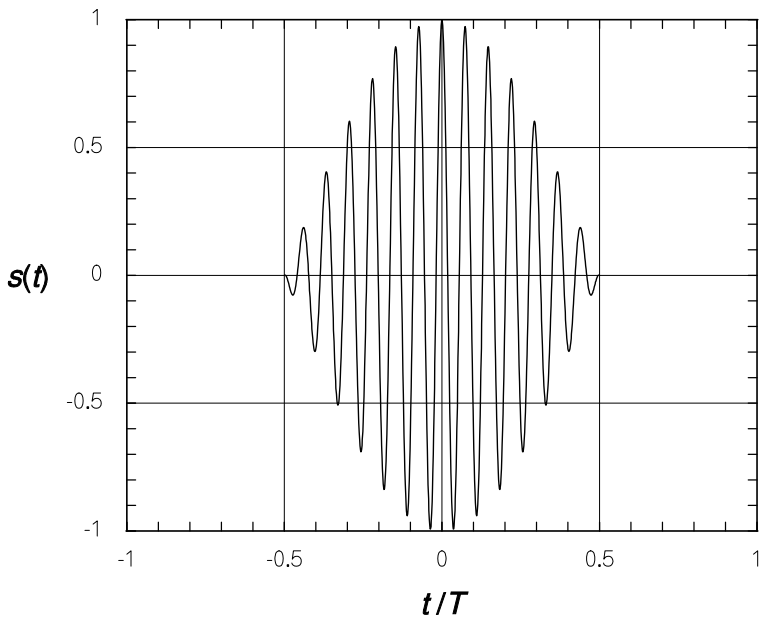


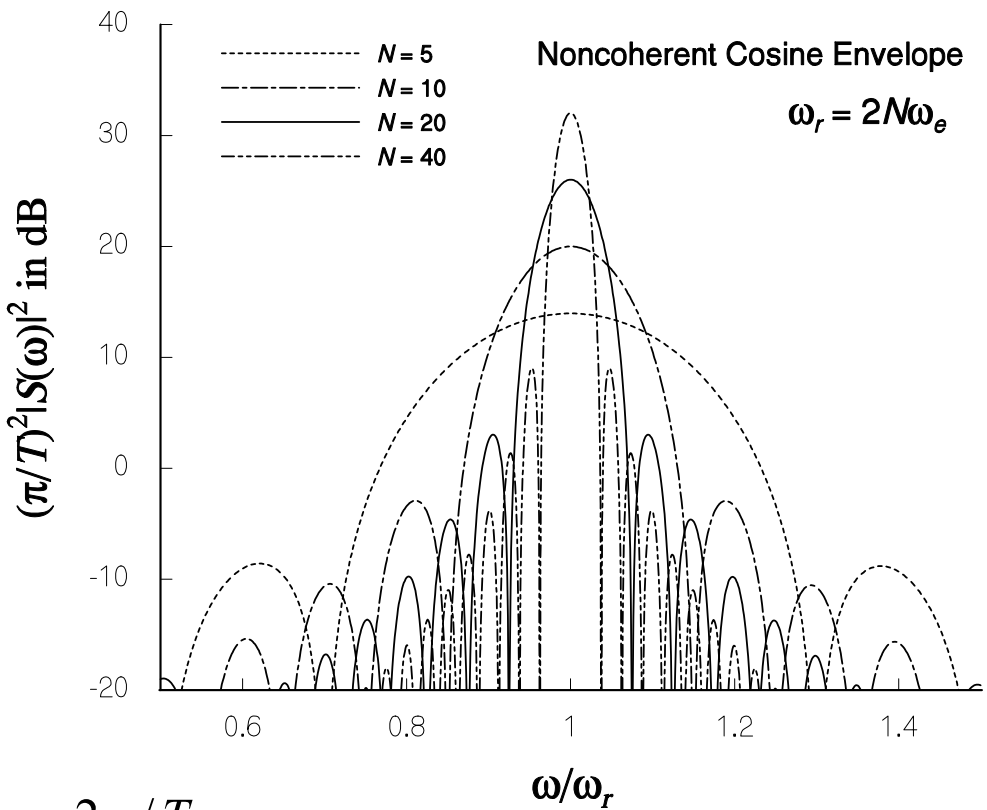


$$\omega_r = 2\pi / T$$

Example UWB Pulse Spectrum: Half-wave cosine envelope

Noncoherent: the phase of the sinusoid is not synchronized with the envelope.



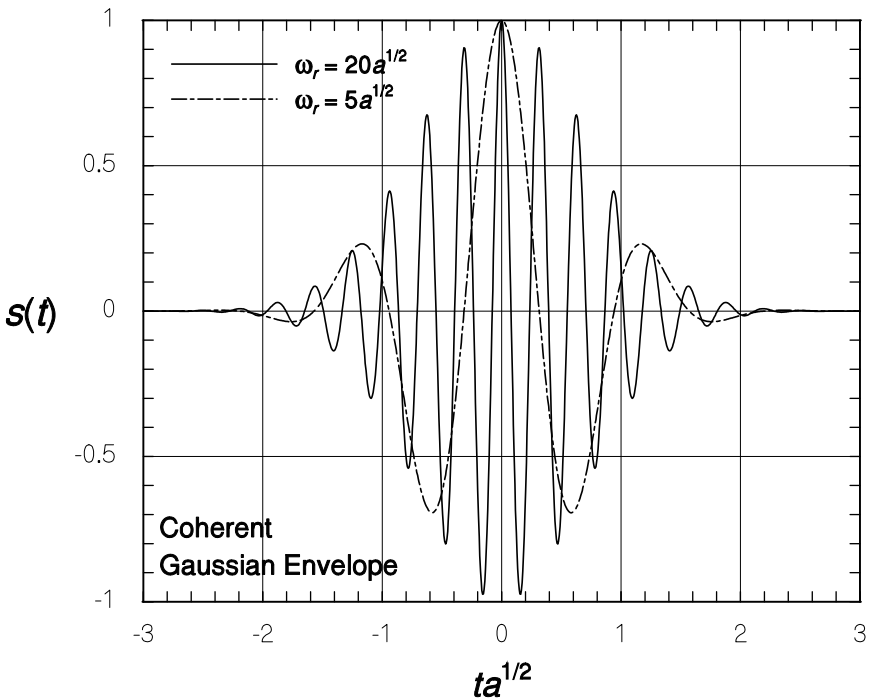


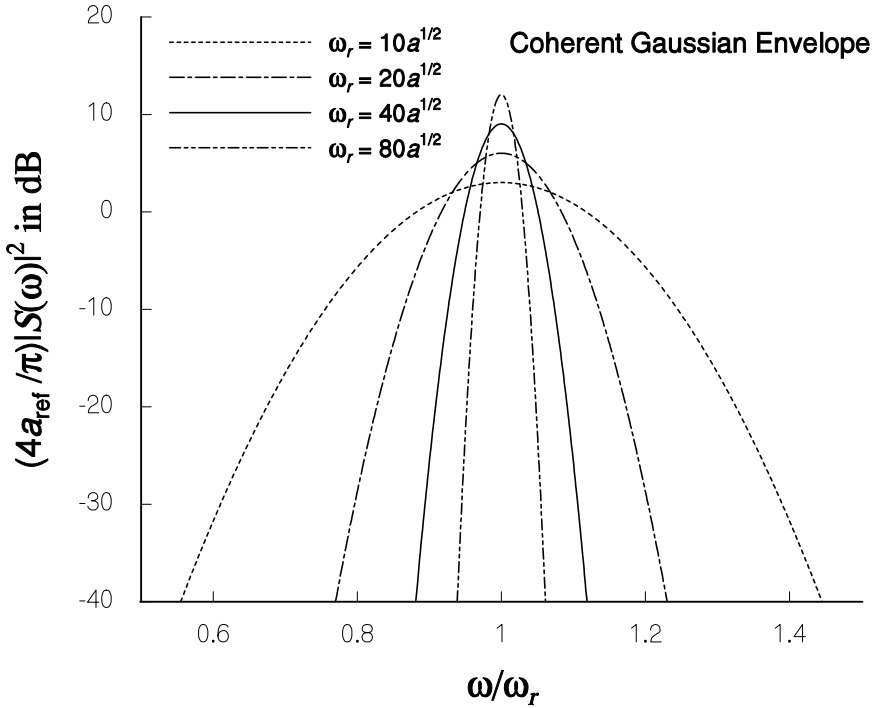
$$\omega_r = 2\pi / T$$

Example UWB Pulse Spectrum: Gaussian envelope

$$s(t) = e^{-at^2}\cos(\omega_r t) \qquad BW = \sqrt{a/2\pi}$$

Spectrum for noncoherent is practically the same





Model of UWB Communications Signal

$$z(t) = A_T \sum_{l=-\infty}^{\infty} u_l \, g(t - lT_u), \;\; \mathrm{E}\{u_l\} = 0, \; \mathrm{E}\{u_k u_l\} = \delta_{kl}$$

Proakis: This is a "cyclostationary" signal, with the time-averaged autocorrelation function and spectrum

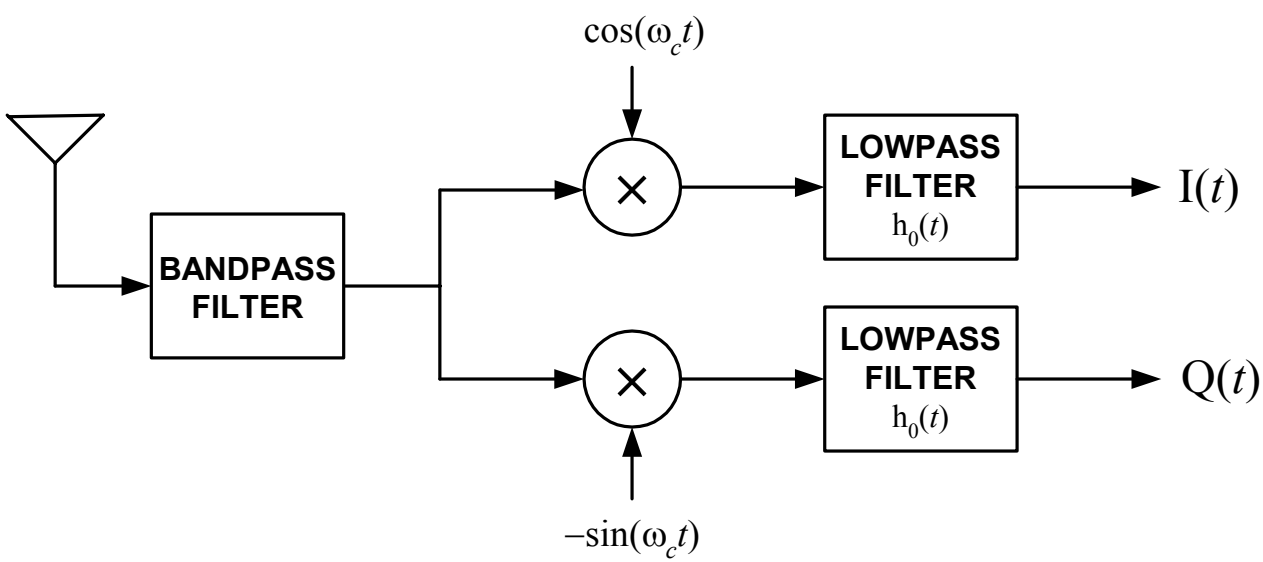
$$R_z(\tau) = A_T^2 \cdot \sum_{l=-\infty}^{\infty} \frac{1}{T_u} \int_{-T_u/2}^{T_u/2} g(t - lT_u)\, g(t + \tau - lT_u)\, dt$$

$$= A_T^2 \cdot \frac{1}{T_u} \int_{-\infty}^{\infty} g(t)\, g(t+\tau)\, dt = A_T^2 \cdot \frac{1}{T_u} \cdot R_g(\tau)$$

$$S_z(f) = A_T^2 \cdot \frac{1}{T_u} \cdot \left| G(f) \right|^2$$

Response of Direct-Conversion Receiver

• For an I/Q receiver, the incoming pulse $g(t)$ is subject to zonal bandpass filtering, then quadrature heterodyning to baseband using lowpass filters with impulse response $h_0(t)$ to extract the I and Q components of the signal, respectively.



- Ignoring the zonal filtering and using an asterisk (*) to denote convolution, the receiver outputs are

$$\mathrm{I}(t) = \mathrm{p}_I(t) = \left[g(t) \times \cos(\omega_c t + \varphi) \right] * \mathrm{h}_0(t)$$

$$\mathrm{Q}(t) = \mathrm{p}_Q(t) = \left[g(t) \times \left(-\sin(\omega_c t + \varphi) \right) \right] * \mathrm{h}_0(t)$$

where φ is an oscillator random initial phase. The Fourier transforms of the quadrature components are

$$I(\omega) = \frac{1}{2}\left[e^{j\varphi} G(\omega - \omega_c) + e^{-j\varphi} G(\omega + \omega_c) \right] H_0(\omega)$$

$$Q(\omega) = \frac{j}{2}\left[e^{j\varphi} G(\omega - \omega_c) - e^{-j\varphi} G(\omega + \omega_c) \right] H_0(\omega)$$

Time-Domain Approximation to Receiver Response

Because the baseband filter response is very slow compared to the UWB pulse duration,

$$= \left[e^{j(\omega_c t+\varphi)} + e^{-j(\omega_c t+\varphi)} \right] / 2$$

$$\mathrm{p}_I(t) = \int_{-\infty}^{\infty} d\tau\, \mathrm{h}_0(t-\tau) g(\tau) \cos(\omega_c \tau + \varphi) \approx \mathrm{h}_0(t) \int_{-\infty}^{\infty} d\tau\; g(\tau) \cos(\omega_c \tau + \varphi)$$

$$= \mathrm{h}_0(t) \cdot \frac{1}{2} \left\{ e^{j\varphi} G(-\omega_c) + e^{-j\varphi} G(\omega_c) \right\} = \mathrm{h}_0(t) \cdot \mathrm{Re}\left\{ e^{-j\varphi} G(\omega_c) \right\}$$

$$\mathrm{p}_Q(t) = -\int_{-\infty}^{\infty} d\tau\, \mathrm{h}_0(t-\tau) g(\tau) \sin(\omega_c \tau + \varphi) \approx -\mathrm{h}_0(t) \int_{-\infty}^{\infty} d\tau\; g(\tau) \sin(\omega_c \tau + \varphi)$$

$$= \mathrm{h}_0(t) \cdot \frac{j}{2} \left\{ e^{j\varphi} G(-\omega_c) - e^{-j\varphi} G(\omega_c) \right\} = \mathrm{h}_0(t) \cdot \mathrm{Im}\left\{ e^{-j\varphi} G(\omega_c) \right\}$$

The effect of the UWB pulse is to generate weighted impulse responses in the baseband filters.

Frequency-Domain Approximation to Receiver Response

Because the baseband filter bandwidth B is very narrow compared to the UWB pulse spectrum,

$$\mathrm{p}_I(t) = F^{-1}\{I(\omega)\} = \frac{1}{2\pi}\int_{-\pi B}^{\pi B} d\omega\, e^{j\omega t}\left\{\frac{1}{2}\left[e^{j\varphi}G(\omega-\omega_c)+e^{-j\varphi}G(\omega+\omega_c)\right]H_0(\omega)\right\}$$

$$\approx \frac{1}{2}\left[e^{j\varphi}G(-\omega_c)+e^{-j\varphi}G(\omega_c)\right]\cdot\frac{1}{2\pi}\int_{-\pi B}^{\pi B} d\omega\, e^{j\omega t}H_0(\omega) = \mathrm{h}_0(t)\cdot\mathrm{Re}\left\{e^{-j\varphi}G(\omega_c)\right\}$$

$$\mathrm{p}_Q(t) = F^{-1}\{Q(\omega)\} = \frac{1}{2\pi}\int_{-\pi B}^{\pi B} d\omega\, e^{j\omega t}\left\{\frac{j}{2}\left[e^{j\varphi}G(\omega-\omega_c)-e^{-j\varphi}G(\omega+\omega_c)\right]H_0(\omega)\right\}$$

$$\approx \frac{j}{2}\left[e^{j\varphi}G(-\omega_c)-e^{-j\varphi}G(\omega_c)\right]\cdot\frac{1}{2\pi}\int_{-\pi B}^{\pi B} d\omega\, e^{j\omega t}H_0(\omega) = \mathrm{h}_0(t)\cdot\mathrm{Im}\left\{e^{-j\varphi}G(\omega_c)\right\}$$

The effect of the UWB pulse is to generate weighted impulse responses in the baseband filters.

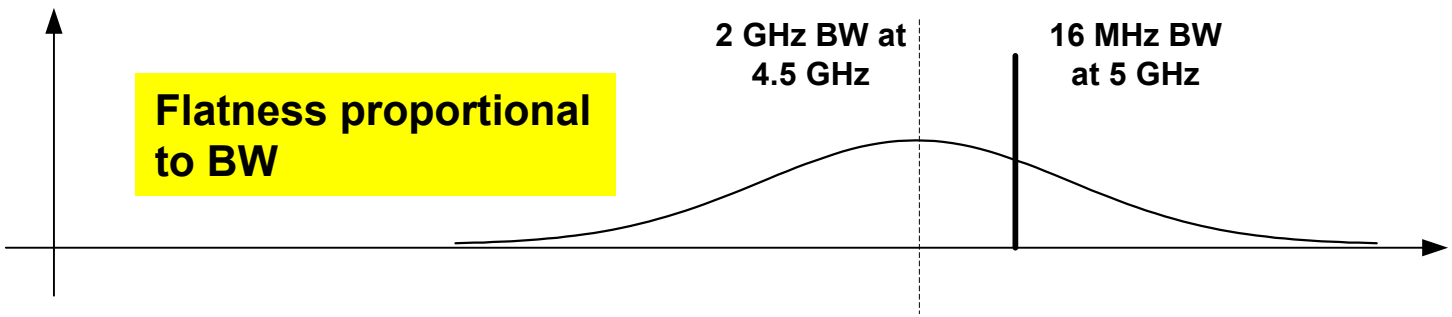
Effective Receiver Outputs Due to UWB Signal

$$A_T \sum_{l=-\infty}^{\infty} u_l \, g\left(t - lT_u\right) \Rightarrow \begin{array}{l} A_R \sum_{l=-\infty}^{\infty} u_l \, \mathrm{p}_I\left(t - lT_u\right) = A_R \, \mathrm{Re}\left\{e^{-j\varphi} G\left(\omega_c\right)\right\} \sum_{l=-\infty}^{\infty} u_l \, \mathrm{h}_0\left(t - lT_u\right) \\ A_R \sum_{l=-\infty}^{\infty} u_l \, \mathrm{p}_Q\left(t - lT_u\right) = A_R \, \mathrm{Im}\left\{e^{-j\varphi} G\left(\omega_c\right)\right\} \sum_{l=-\infty}^{\infty} u_l \, \mathrm{h}_0\left(t - lT_u\right) \end{array}$$

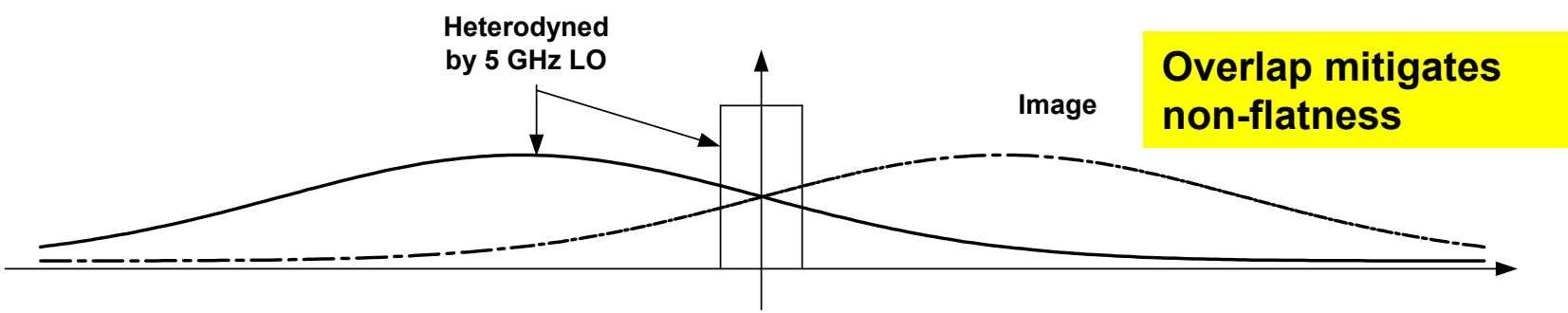
- The effective receiver baseband outputs due to the UWB signal are series of overlapping baseband impulse responses.
- Implication: Simulation of UWB effects on receivers can be done with the usual complex envelope representation, using a sampling rate equal to the receiver bandwidth, NOT the UWB signal bandwidth.

Numerical Example

- Gaussian-envelope sinusoidal burst



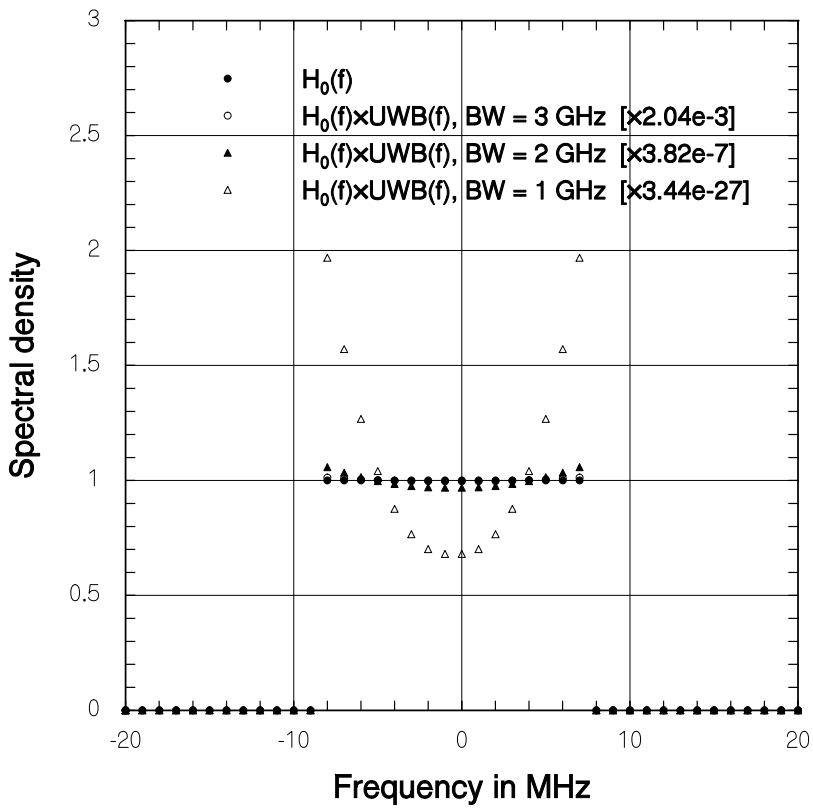
- After heterodyning, the UWB interference spectrum is even

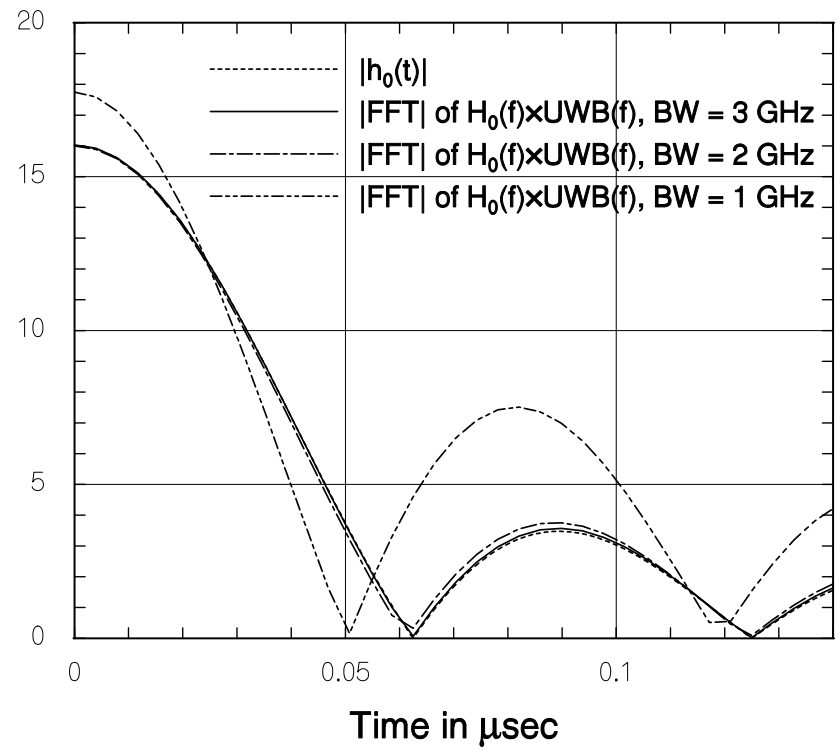


Numerical Example (continued)

With decreasing BW, interference spectrum becomes weaker and less flat

Approximation of interference pulse by $h_0(t)$ is relatively robust





Calculation of Effective UWB Interference Power

Given the phase φ, the average power (variance) of the I-component of the UWB interference is

$$\sigma_I^2(\varphi) = A_R^2 \operatorname{Re}^2\left\{e^{-j\varphi} G(\omega_c)\right\} \sigma_u^2 \cdot \frac{1}{T_u} \int_{-T_u/2}^{T_u/2} \sum_{l=-\infty}^{\infty} \mathrm{h}_0^2(t - lT_u)\, dt$$

$$= \frac{1}{T_u} A_R^2 \operatorname{Re}^2\left\{e^{-j\varphi} G(\omega_c)\right\} \int_{-\infty}^{\infty} \mathrm{h}_0^2(t)\, dt = \frac{1}{T_u} A_R^2 \operatorname{Re}^2\left\{e^{-j\varphi} G(\omega_c)\right\} \boxed{\int_{-\infty}^{\infty} \left|H_0(f)\right|^2 df}$$

by definition, $\left|H_0(0)\right|^2 B_N$

Averaged over φ, the average power (variance) of the UWB interference components is

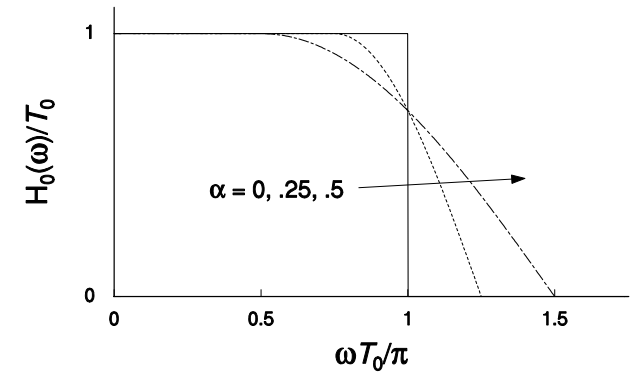
$$\sigma_I^2 = \sigma_Q^2 = \frac{A_R^2}{2T_u} \left|G(\omega_c)\right|^2 \left|H_0(0)\right|^2 B_N$$

Example: Square-root Raised-cosine (Nyquist) Filter

- Frequency domain:

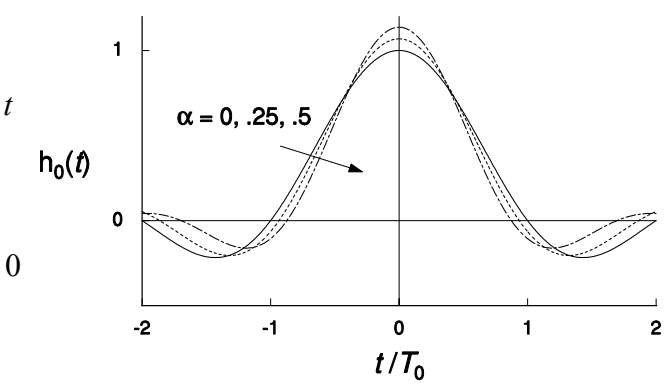
α = excess BW

$$H_0(\omega) = T_0 \begin{cases} 1, & |\omega T_0| \le \pi(1-\alpha) \\ \cos\left[\dfrac{|\omega T_0| - \pi(1-\alpha)}{4\alpha}\right], & \pi(1-\alpha) < |\omega T_0| \le \pi(1+\alpha) \\ 0, & |\omega T_0| > \pi(1+\alpha) \end{cases}$$



- Time domain (≈ unit amplitude):

$$h_0(t) = F^{-1}\{H_0(\omega)\} = \begin{cases} \dfrac{\sin\left[(1-\alpha)\dfrac{\pi t}{T_0}\right] + \dfrac{4\alpha t}{T_0}\cos\left[(1+\alpha)\dfrac{\pi t}{T_0}\right]}{\dfrac{\pi t}{T_0}\left[1-\left(\dfrac{4\alpha t}{T_0}\right)^2\right]}, & \text{all } t \\ 1-\alpha+\dfrac{4\alpha}{\pi}, & t=0 \end{cases}$$



- Noise bandwidth $= 1/T_0$

Example: Square-root Raised-cosine (Nyquist) Filter

$$\sigma_I^2 = \sigma_Q^2 = \frac{A_R^2}{2T_u}\left|G(\omega_c)\right|^2 \left|H_0(0)\right|^2 B_N$$

$$= \frac{A_R^2}{2T_u}\left|G(\omega_c)\right|^2 \times (T_0)^2 \times (1/T_0)$$

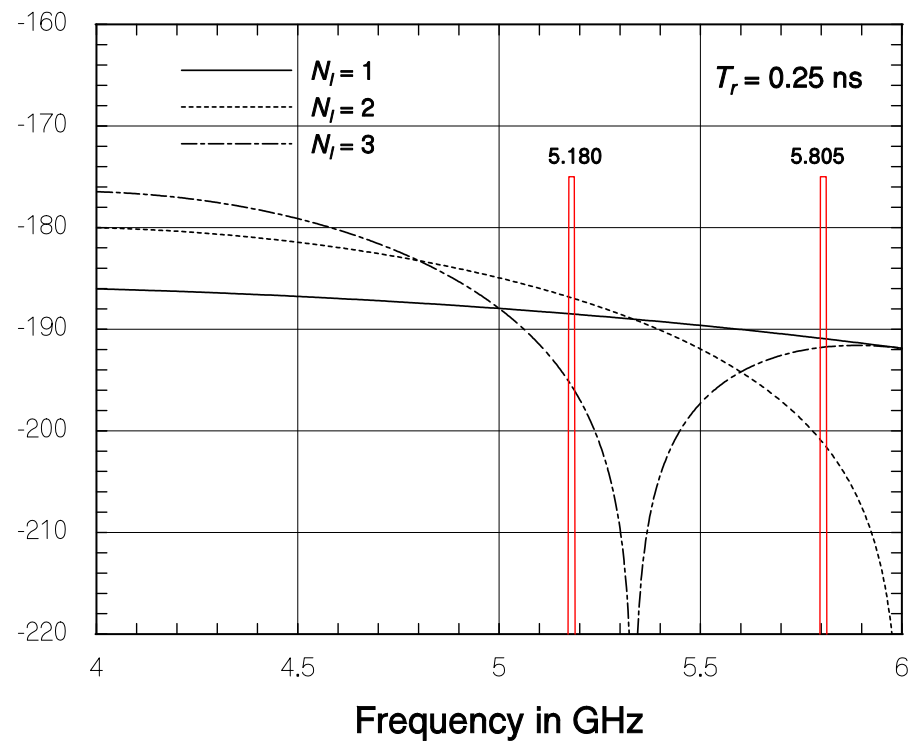
$$= \frac{A_R^2}{2}\left|G(\omega_c)\right|^2 \times \frac{T_0}{T_u}$$

Number of UWB pulses in one baud

Application of Technique to Simulation

- Effect of hypothetical UWB signal on 802.11a OFDM signal.

- The 802.11a channels are very narrow compared to the UWB spectrum, so the approximation technique can be applied.
- The interference simulation is of overlapping baseband pulses in addition to the noise, prior to the receiver FFT.



Calibration of Simulation

- The average channel SNR at the output of the OFDM receiver is

$$\frac{\overline{P_{Rc}}}{\sigma_{ni}^2} = F \cdot Kr \cdot \frac{E_b}{N_0}, \quad F = \frac{3.2\mu s \text{ symbol}}{4\mu s \text{ period}} \cdot \frac{48 \text{ data tones}}{52 \text{ total tones}} = 0.7385$$

where r is the code rate and $K = \log_2 M$.

- A target value of E_b/N_0 was simulated for unit average channel amplitude by making the sample noise variance equal to

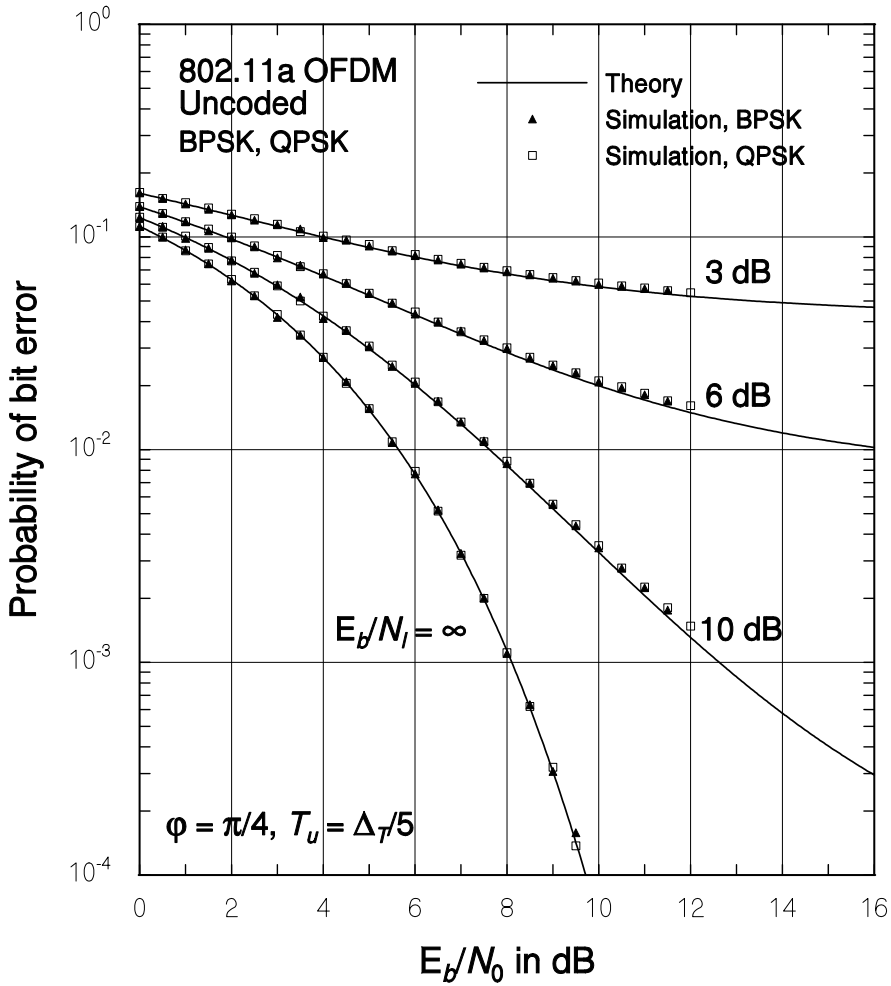
$$\sigma_v^2 = \left(\frac{E_b}{N_0}\right)_{\text{target}}^{-1} \frac{\overline{P_{Rc}}}{KrF} \cdot \frac{1}{N_{FFT}} = \left(\frac{E_b}{N_0}\right)_{\text{target}}^{-1} \frac{1/2}{KrF} \cdot \frac{1}{N_{FFT}}$$

- Similarly, a target value of E_b/N_I was simulated for an OFDM symbol time of T_s by deriving the effective UWB pulse amplitude from

$$\sigma_{Ui}^2 = \left(\frac{E_b}{N_I}\right)_{\text{target}}^{-1} \frac{1/2}{KrF} \approx \frac{A_{R1}^2}{2} \cdot \frac{T_s}{T_u}$$

#UWB pulses per OFDM symbol

Example Simulation Result



Further Work

- Statistical characterization of effective UWB interference
- Modeling approach that includes UWB multipath effects