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A Tutorial on Ultrawideband Technology

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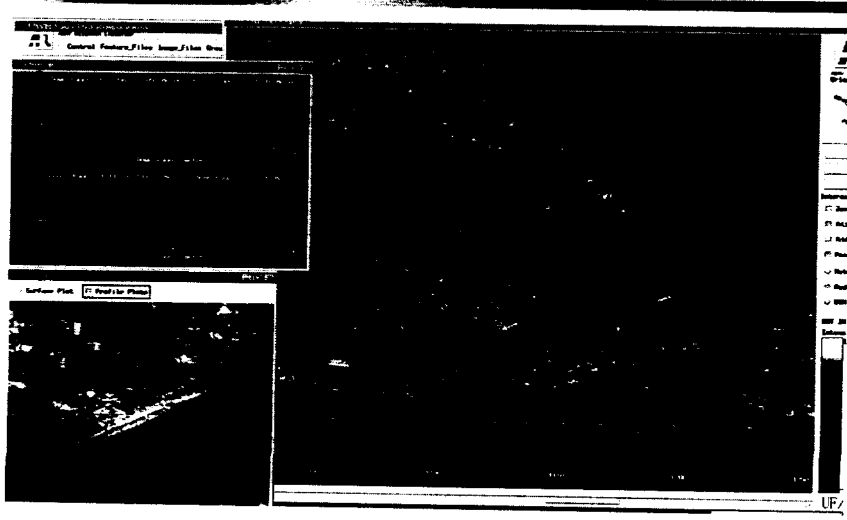
XSI

- Brief Background on Speaker
- Definition of UWB
- Waveforms and Spectrum
- Modulation & Information theory
- Summary of FCC Filings
- Conclusion

XSI

- PI for the Army's UWB radar Programs -- industry, DARPA university, tri-service, efforts
- Designed highest resolution LF SAR
  < 1/2 sq. ft. pixels
  Over 1 GHz bandwidth
- John's patents Include
  - Antennas
  - Baluns
  - RFI extraction
  - Adaptive background subtraction
  - T/R switch
  - Image formation
  - Optimal interleave Processing
  - Jitter code & hardware
- Co-Founder of XtremeSpectrum Inc. To commercialize high performance in-building communications.

XSI



THE WIDEST ULTRA WIDEBAND RADARS ENABLE TARGET IDENTIFICATION BELOW FOLIAGE THAT WAS UNTHINKABLE BEFOR UWB

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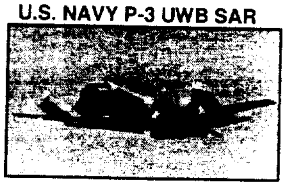
- **The Technology Is Older and More Developed Than Most Are Aware**

U.S. NAVY P-3 UWB SAR

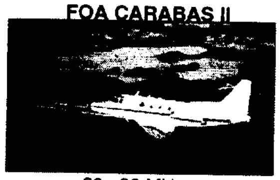


UHF; Polarimetric;
0.3 x 0.7 m Resolution
(X-, C-, L-Bands; Polarimetric;
1.5 x 1.5 m Resolution)

SRI FOLPEN III

100 - 300 MHz, 200 - 400 MHz,
or 300 - 500 MHz;
HH, VV, or HV Polarization;
0.5 x 0.5 m Resolution

FOA CARABAS II



20 - 90 MHz;
HH Polarization;
2 x 2 m Resolution

SANDIA LF SAR TESTBED

125 - 950 MHz; Polarimetric
Resolution: UHR

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- **UWB is a term of art implying wide relative coherent bandwidth**

$$B_f = \frac{B}{f_c} = \frac{(f_h - f_l)}{(f_h + f_l)/2} \approx 1$$

- **Definition is Based on Physics of Wave interaction (i.e. Scattering and Loss Phenomenology)**
- **The interaction of UWB emissions with the environment enables utility that cannot be obtained with narrowband (i.e. $B_f < .25$)**
  - ☐ Minimizing reflections from clutter (objects < ¼ λ)
  - ☐ Capability to penetrate at high data rates and high resolution
  - ☐ Minimize, scintillation, fading, ambiguous multipath

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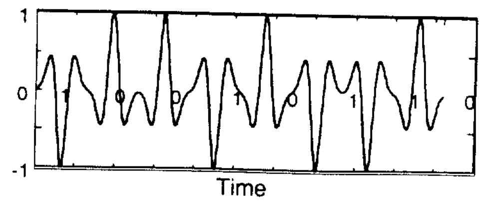
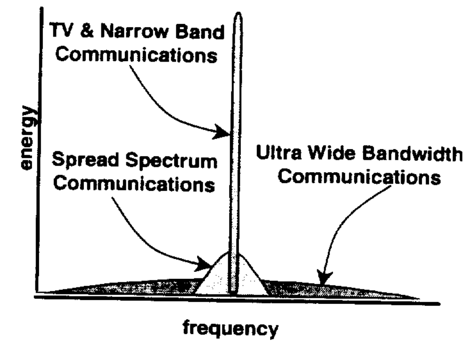
- **Coded short duration pulses spread the signal energy over frequency and time**
- **Can overlay existing FCC frequency assignments**
  - Spread is so broad little energy gets in a narrowband
  - Modulation Prevents Spectral Lines
  - Short range WPAN systems can operate below the detection threshold of conventional receivers
- **Not spikey in time or frequency domains - Low probability of intercept (LPI)**





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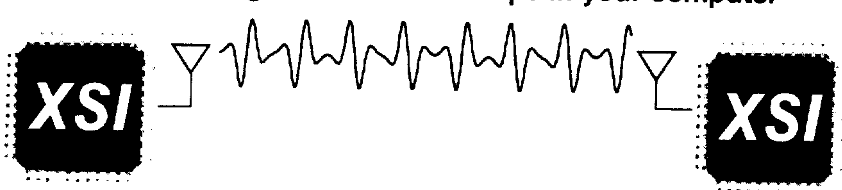
Same low voltage CMOS as the chips in your computer



Computer Chip	XSI Radio Chip
Pins toggle to send bits	Pins toggle to send bits
Antenna is PC board traces	Antenna is etched on PC board
Unintentional UWB radiates	Intentional UWB radiates
	UWB signals are received

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- What do UWB signals look like
- Key is Coherency, Not zero-crossings
- Modulation Decision Tree
- Information Theory – What does Shannon's equation say
- Derivation of PSD
- Waveform Properties, Analytic waveforms
- Practical Outcome

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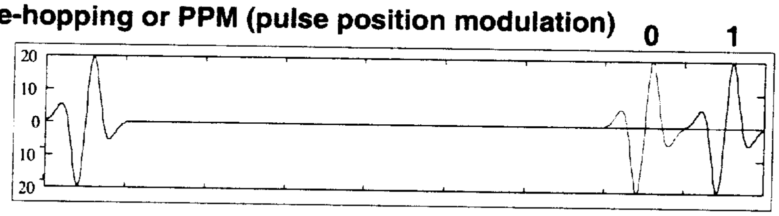
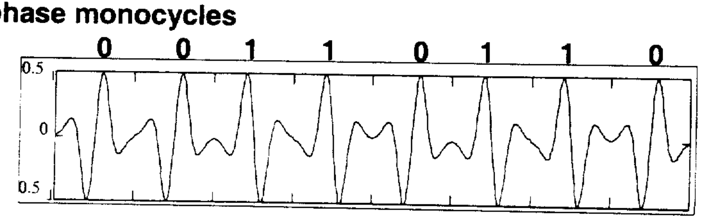
- Time-hopping or PPM (pulse position modulation)



- Bi-phase monocycles



- Positive and negative video pulses (no DC)
- Chirp and step frequency
- Noise

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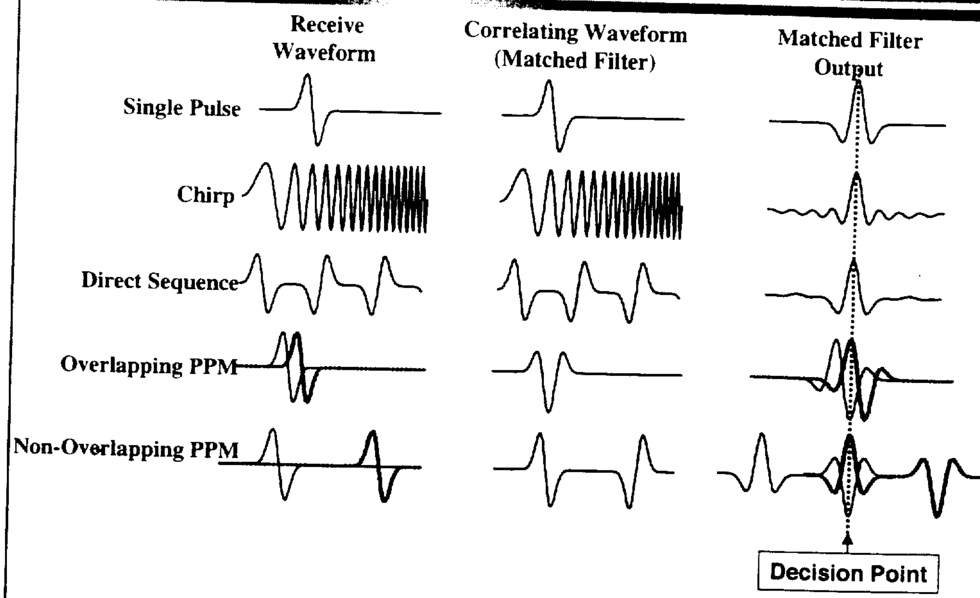
Key Attribute is Wide Coherent Relative Bandwidth
No Zero Crossings



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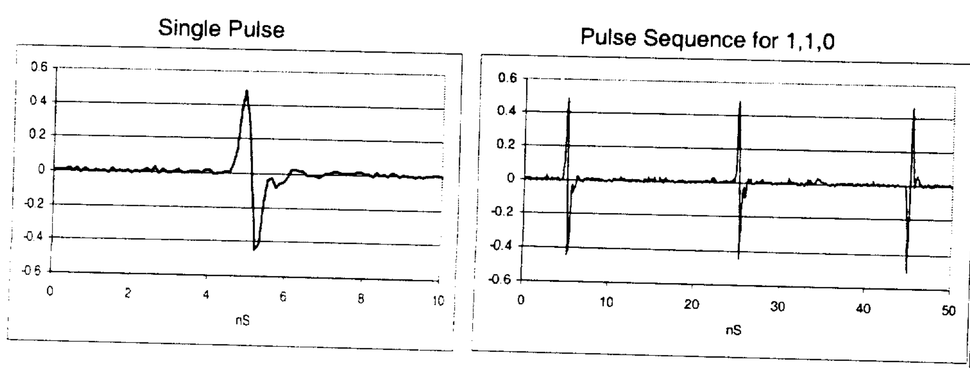
- Real-world outputs are of our laboratory systems closely match theory.



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- Bi-phase modulation yields a 3dB to 6dB advantage over PPM (time-hopping) in multipath-free environments -- greater advantage in multipath since multipath appears as data modulation in PPM
- Bi-phase modulation exhibits a peak-power to average-power ratio of less than 3 (for reference, a sine wave is 2). This leads to efficient transmitters and a natural fit into low cost, low voltage CMOS.

$b \in \{0,1\}$ Bit is either 1 or 0

$s(t,b)$ Energy Normalized Waveform.

t = time, b = bit

$n(t)$ AWGN, zero mean, standard deviation σ

$r(t) = V_t s(t,b) + n(t)$ Received Signal

$\langle s(t,0), s(t,0) \rangle = 1$ Receive 0 and correlate to 0

$\langle s(t,1), s(t,1) \rangle = 1$ Receive 1 and correlate to 1

$\langle s(t,0), s(t,1) \rangle = \rho$ Receive 0 and correlate to 1

$P_e = Q\left(\frac{V_t}{\sigma}\sqrt{\frac{1-\rho}{2}}\right)$ Probability of error

$Q(x) = \int_x^{\infty} \frac{1}{\sqrt{2\pi}} e^{-\frac{y^2}{2}} \partial y$ Error Function, $Q(\cdot)$

For Bi-phase, $s(t,0) = -s(t,1)$, so $\rho = -1$

For PPM, $\rho = 0$

$$P_e^{biphase} = Q\left(\frac{V_t}{\sigma}\sqrt{\frac{1-\rho}{2}}\right) = Q\left(\frac{V_t}{\sigma}\right)$$

$$P_e^{PPM} = Q\left(\frac{V_t}{\sigma}\sqrt{\frac{1-\rho}{2}}\right) = Q\left(\frac{V_t}{\sigma\sqrt{2}}\right)$$

XSI

- **Objective is high data-rate in a high multipath cluttered environment, yet without causing harmful interference**
  - BPSK, PPM, OFDM, UWB, etc.
  - No Spectral Lines
- **For a given range & data-rate**
  - Minimize Average Power of Transmitter – (lowest possible interference)
  - Minimized Peak Power Spectral Density (PSD) – (lowest possible interference)
- **Operate on future generations of CMOS**
  - Operate at 1 volt levels
  - Standard devices (No avalanching)
- **Simple, Small (Low Cost) to Implement**
  - No FFT's, etc

CLEAR WINNER IS UWB USING BPSK

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- Shannon's Equation $$C = B\log_2\left(1+\frac{S}{N}\right)$$
- Data rate capacity (*C*) can only go above the channel bandwidth *B* at an unfavorable *log* function with power.
- Regulatory limits provide Po Watts/Hz

$$C = B\log\left(1+\frac{S}{N}\right) = B\log\left(1+\frac{P_0 B}{KTB}\right) = B\log\left(1+\frac{P_0}{KT}\right)$$

XSI

General Form of constant PRF Amplitude Modulated UWB Signal
(e.g. PAM, BPSK, OOK, etc.)

$$s(t) = p(t) \otimes \sum_{k=-\infty}^{\infty} a_k \delta(t - kT_b) = \sum_{k=-\infty}^{\infty} a_k p(t - kT_b)$$

Here $s(t)$ = transmitted signal, T_b = bit interval and $p(t)$ = basic pulse, and a_k = whitened data sequence

General form for PSD, assuming random data (i.e. a_k)

$$\Phi_{SS}(f) = |P(f)|^2 \Phi_{AA}(f)$$

Here, $P(f)$ is the Fourier transform of $p(t)$, and $\Phi_{AA}(f)$ is the PSD of the data sequence a_k

General form for PSD, assuming i.i.d random data, σ^2 = variance, μ = mean

$$\frac{\sigma_a^2}{T_b}|P(f)|^2 \qquad \frac{\mu_a^2}{T_b^2}|P(f)|^2 \sum_{m=-\infty}^{\infty} \delta\left(f - \frac{m}{T_b}\right)$$

Continuous Part — Line Spectra Part

General form for PSD assuming zero-mean, i.i.d random data, σ^2 = variance

$$\Phi_{SS}(f) = \frac{\sigma_a^2}{T_b}|P(f)|^2$$

Note 1: No Spectral Lines
Note 2: PRF Does Not Matter

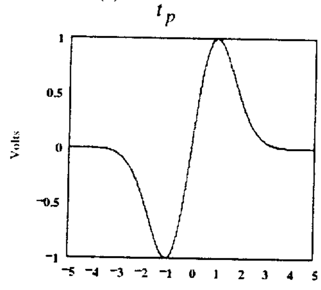
XSI

[illegible]

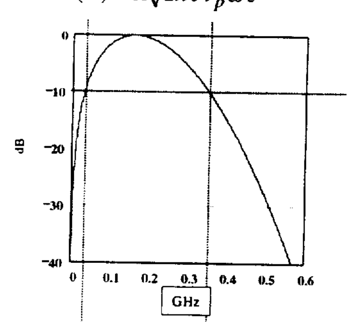
- This result—no spectral lines—is is well known
- Virtually all digital RF communications systems designed today use zero-mean constellations.
- Theorist have also demonstrated that a zero-mean symbol set is often the best choice when the desire is to build a power-efficient communications system.

XSI

$$s(t) = \frac{A\sqrt{e}}{t_p} t e^{-\frac{1}{2}\left(\frac{t}{t_p}\right)^2}$$



$$S(\omega) = A\sqrt{2\pi e}\, t_p \omega e^{\frac{-1}{2}(t_p \omega)^2}$$



$$f_{max} = \pm\frac{1}{2\pi t_p}$$

$$f_c = \frac{f_{lo} + f_{hi}}{2} = 1.12 f_{max}$$

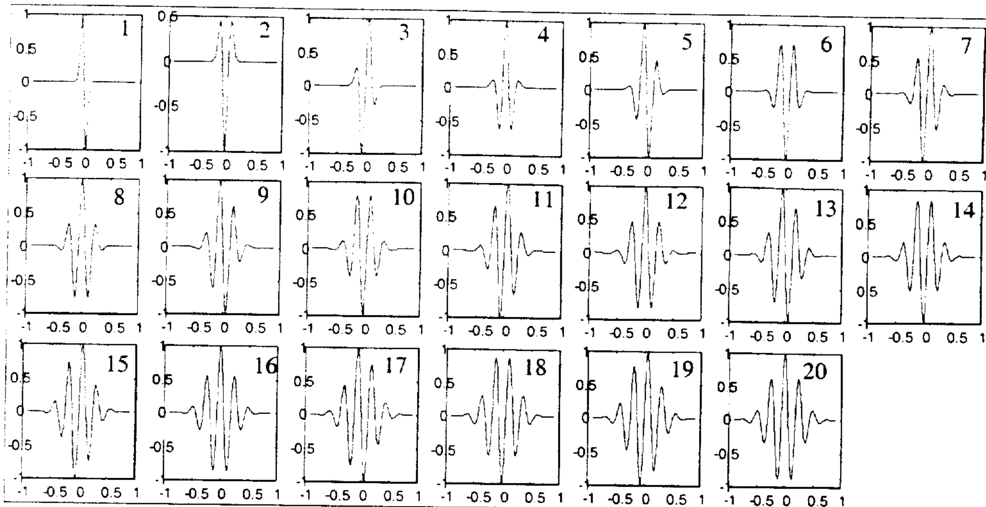
$$f_{lo} = 0.3191057 f_{max}$$

$$f_{hi} = 1.9216229 f_{max},$$

$$p = A^2 t_p \frac{e\sqrt{\pi}}{2}$$

XSI

- Waveform is more like modulated sine wave at higher derivatives (i.e. lower relative bandwidth)



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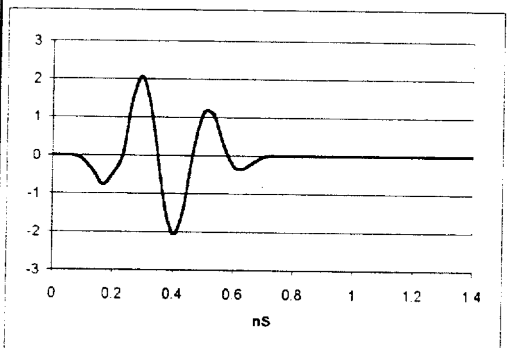
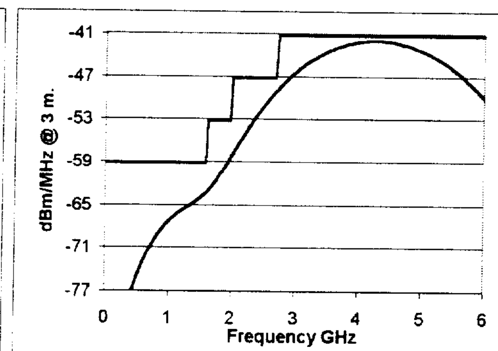


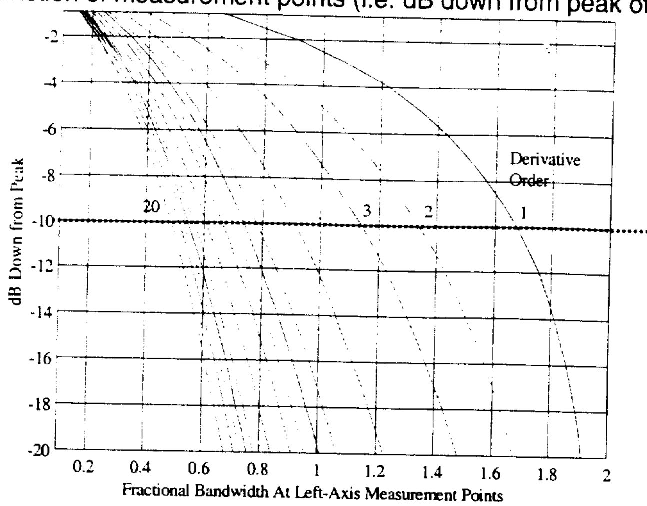
Radiated Single Pulse Waveform



Spectrum and proposed XSI mask

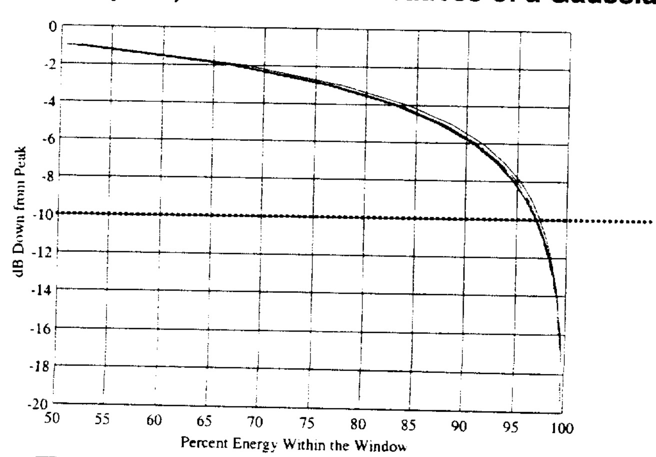
XSI Fractional Bandwidth

- As a function of measurement points (i.e. dB down from peak of spectrum)

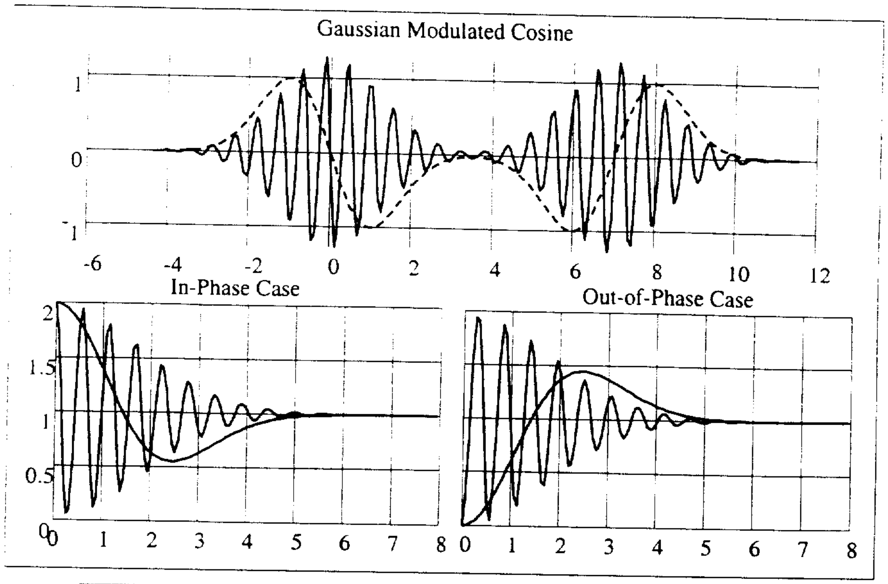


XSI

- **Percent of energy between measurement points (i.e. dB down from peak) for first 20 derivatives of a Gaussian**

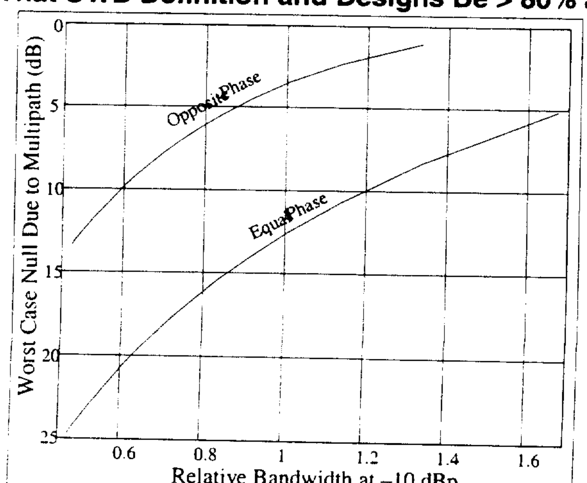


XSI



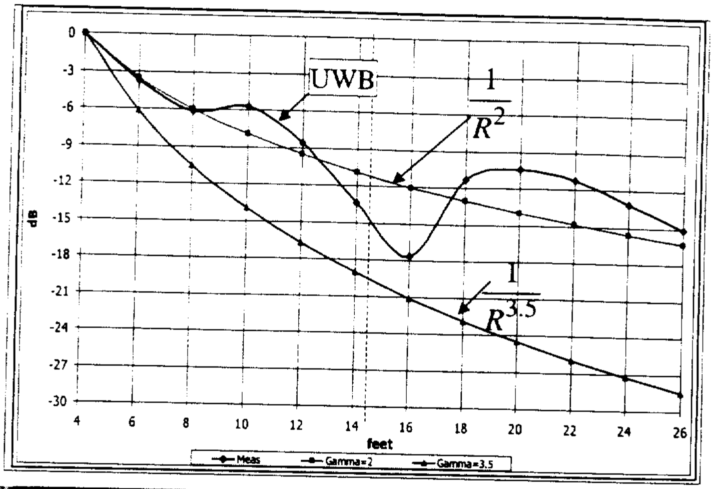
XSI

- Benefits of UWB degrade as Relative Bandwidth drops
- For Sub Optimal Modulation (e.g. PPM) the curves move down
- Argues That UWB Definition and Designs Be > 80% at –10 dB down



XSI

- Real World Measurements Demonstrate UWB Is Not On A $1/R^4$ Curve
- Lower Radiated Power – Minimized Potential for Interference



XSI

- **Free-space $1/R^2$ propagation losses and shallow multipath dips allow small worst-case link margin (LOW RF POWER)**
- **There exist many resolvable path-lengths between a transmitter and receiver. Each of these path lengths can be used to communicate. (ROBUST)**
  - There is a low likelihood that multipath meets the unique conditions to cancel a UWB signal (or cause a fade) on all path lengths available between a transmitter and receiver simultaneously.
  - On the contrary, there is a high likelihood that there are multiple path-lengths that provide a strong signal.
- **Because they are resolvable in time, they can be combined for better SNR.**
  - RAKE that is useless in short range applications with narrowband, can be applied with UWB.
  - Implementing RAKE is simple - no deconvolution, no phase **(SIMPLE)**
    - Since a bit is represented by a pulse that does not have multiple cycles, nothing is required to derive the "phase" of any particular multipath term. Once the peak is found, the phase is also found.
- **Result is that the high data-rate short range UWB radio design is smaller, lower cost, and lower power than a narrowband radio for the same application.**

XSI

- **COMMUNICATIONS**
  - ☐ Radio's with a few dB fading margin & $1/R^2$ propagation
  - ☐ High speed radio's with low SNR (Shannon) and low prime power
  - ☐ Radio's that are scaleable from kbps to 100's Mbps - under software control
  - ☐ Reuse of crowded frequency spectrum
  - ☐ Reliable in-building links at high data rates

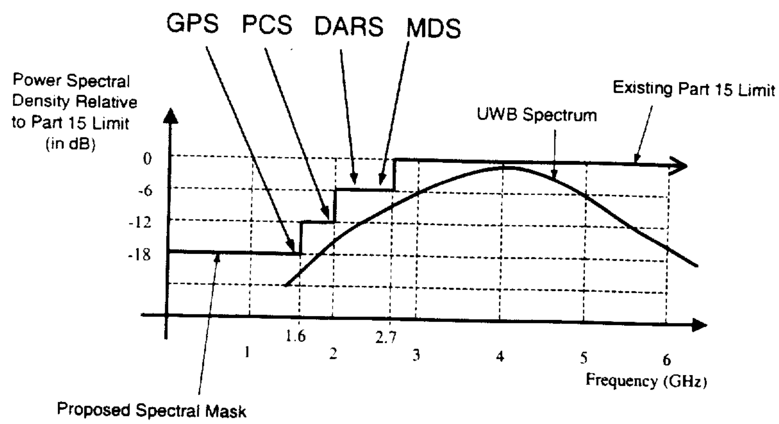
- **SAFETY**
  - ☐ Extremely low total RF power
  - ☐ Extremely low power in any band that resonates with a human organ
  - ☐ Indoor usage restrictions provide building shielding to outdoor systems
  - ☐ Activity factor, since all units share a single channel, maintains low power

[redacted]

XSI

- **Summary of XSI Proposed Changes to NPRM**
  - ☐ Emission mask
  - ☐ Indoor Usage
  - ☐ Test for spectral lines in GPS band
  - ☐ Peak to Average Test
- **Summary of results on Aggregation**
- **Discussion of how proposed changes solve issues raised by:**
  - ☐ GPS
  - ☐ PCS
  - ☐ DARS
  - ☐ NTIA
    - Radar
    - Satellite
    - Airborne
- **Q & A Discussion of items of interest to FCC.**

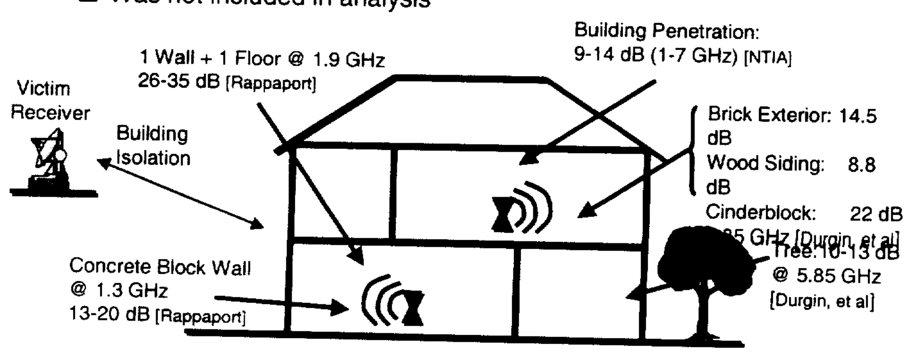
XSI



- **Establish interim rules**
- **Establish technology-neutral rules**

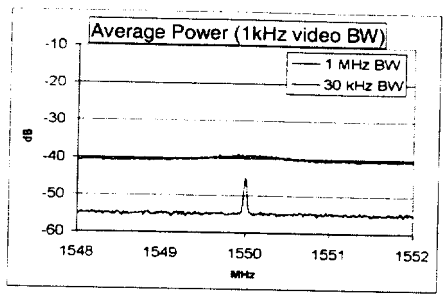
XSI

- **Restriction to indoors provides isolation from victim systems**
  - ☐ No systems with a UWB device on every other telephone pole.
- **NTIA estimated through-the-wall loss of 9-14 dB but**
  - ☐ Estimate is low based on measurements reported in literature.
  - ☐ Was not included in analysis



XSI

- XSI proposes an 30 kHz RBW (resolution bandwidth) test to prevent interference to particular GPS receivers
- This test is 15 dB more sensitive to spectral lines than to noise-like interference.
- This test effectively provides a total of 33 dB extra (over Class-B) protection for GPS against signals with spectral lines at critical frequencies in the GPS L1 band.



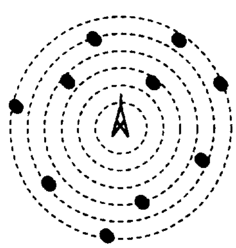
XSI

- The proposed test to limit the ratio of peak power to average power in paragraphs 42 and 43 of the NPRM does not completely accomplish this purpose.
  - Used ratio of power at two different bandwidths
  - fooled by a tone since a tone looks the same in either bandwidth
- We suggest, as per the NPRM (¶44), that the FCC consider requirements that use time domain and frequency domain measurements of UWB signals to measure the ratio of peak power to average power.
  - Use a spectrum analyzer to find the upper and lower –10dB frequencies and spectral peaks
  - Use a high bandwidth sampling oscilloscope to find the true peak-to-peak signal voltage (taking into account the o'scope rise time given the signal bandwidth)
  - Use a power meter to measure the total average power
  - Ratio the Power in peak-to-peak to the average power

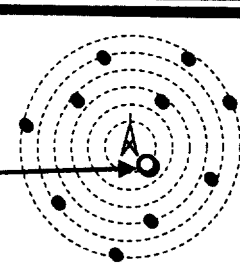
XSI

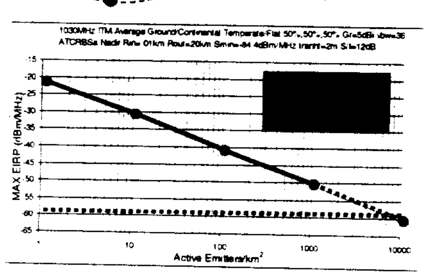
- **For all practical purposes, only the closest transmitters affect the received signal level. So single-emitter analysis can be used to understand interference potential.**
  - Analysis in the NTIA reports, along with XSI's and others, resolve concerns about cumulative interference effects.
- **UWB does not raise the noise floor as some have claimed**
- **Thousands of UWB devices can exist in a small area because**
  - Self limiting:
    - Power and duty cycle must go down as physical densities go up.
  - Only a few will actually transmit simultaneously
    - Single shared channel – TDD/TDMA
  - Real-world attenuation and random reflections cause energy to dissipate
- **Next slide illustrates NTIA's model**

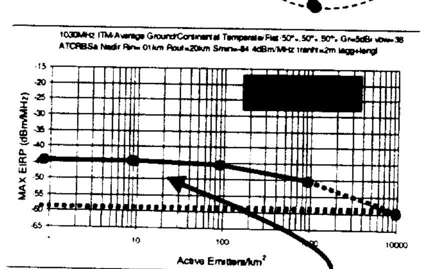
XSI



- NTIA's UWBRings Model is based on uniformly distributed UWB emitters.
- Additional whole emitter added to first ring to force results to match with single-emitter analysis at reasonable densities







Forcing whole emitter on closest ring flattens curve
(only 2 dB rise in interference power for 100x increase in UWB density)

XSI

GPS Interference Testing

[illegible] harmful interference to GPS

- **7 Reports issued on UWB/GPS testing and analysis**
  - Even the most severe test possible shows no harmful interference with the changes proposed by XSI
    - Testing used worst-case UWB signaling with large spectral lines.
    - The UWB device parameters were adjusted to find modes that interfered the most.
    - GPS devices were selected that were most sensitive to the interference.
    - UWB antenna pattern was not factored into analysis, but was always assumed to be pointing at the victim receiver, even for moving receivers.
- **Key Discoveries**
  - C/A code-tracking GPS receivers are particularly vulnerable to critical tones that are associated with spectral lines in the C/A codes.
  - Sensitivity to tones was found to be 15 dB greater than to noise.
- **Impact**
  - XSI proposed a measurement procedure to detect and limit spectral lines in the GPS [illegible]

XSI

- **There were 74 cases in the NTIA GPS study**
- **Results imply 88% of GPS systems experienced interference.**
- **Results imply 93% of airborne systems experienced interference.**

- **Signals used had:**
  - 12 dB more power than proposed in the NPRM
  - 18 dB more that in XSI's proposed limit to make early rules easier.
- **XSI proposed outdoor usage restrictions.**
  - 66% of studied cases were outdoor emitters and 82% had multiple emitters
  - 73% of aircraft studied cases were outdoor emitters and all had multiple emitter cases
- **With the proposed limitations, for <u>airborne</u> cases:**
  - NO cases were affected, At the NPRM level
- **With the proposed limitations, for <u>all</u> cases:**
  - 15% are affected at NPRM levels
  - 4% are affected at XSI's proposed levels without spectral-line test
    - All of these cases produce line spectra that XSI's proposed test detects.
  - **<u>0 % with XSI proposed changes</u>**
    - **<u>Even with multiple emitters</u>**

XSI

■ Key points on Qualcomm tests and analysis

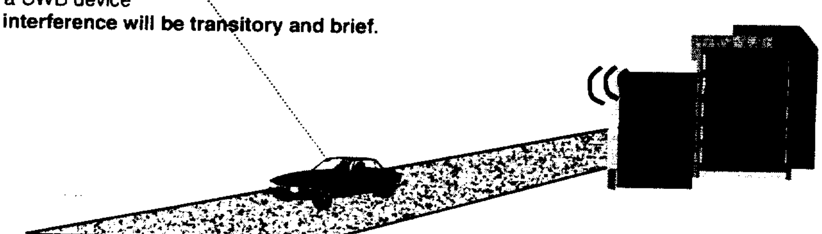
- ☐ The analysis did not include 12 dB reduction below 2 GHz proposed by the NPRM.
- ☐ The analysis assumes an unrealistic threshold for harmful interference (6 dB below the thermal noise).
- ☐ Laboratory results presented by Qualcomm show that this threshold is too conservative by 6 to 16 dB.
- ☐ The analysis assumes a perfectly quiet radio environment (disregards adjacent PCS cells, multipath, etc.).

■ Conclusions

- ☐ When Qualcomm results are re-examined in light of these specific points, the distance to potentially cause harmful interference drops to less than 2m.
- ☐ This result is validated by the Sprint/TDS live tests where < 1.5 ft separation was required to observe any change in performance of a PCS radio.

XSI

- **The DARS proponents have suggested that a level of 18μV/m @ 3 m be the limit of UWB below 3 GHz (28.8 dB below current Part 15 limits) in order to operate 1m from a UWB device.**
- **XSI's proposed changes provide >18 dB reduction to provide <4m separation distance**
  - ☐ XSI's spectral mask provides 6 dB of protection.
  - ☐ Linear to circular polarization loss is 3 dB
  - ☐ Building loss is >9 dB
  - ☐ Total of 18 dB additional loss or –59 dBm/MHz
- **Usage Factors add even more protection**
  - ☐ Excess power to operate through fades means interfering at the thermal noise floor is rare—only in deep fades and quiet areas
  - ☐ Coincidence of a deep fade, the DARS mobile being < 4 m to building, and the activity factor of a UWB device
- **Any interference will be transitory and brief.**



XSI

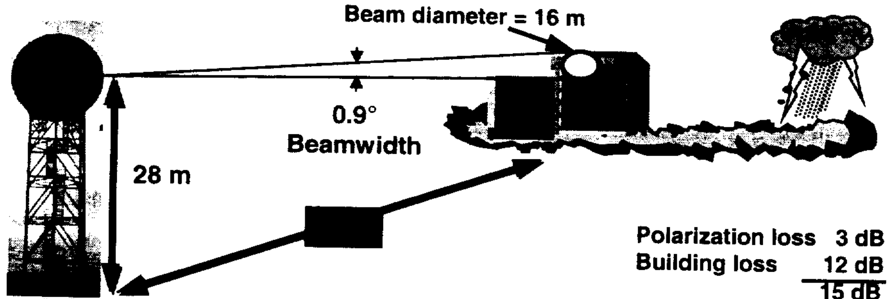
- **The NTIA reports provided a good analytical framework but omitted many items to keep the analysis simple**
  - ☐ Older simple theoretical models of propagation instead of modern measurements-based models
  - ☐ Specific details concerning how victim systems operate, and how they are used and sited, for example:
    - o Impossible geometries
    - o Unrealistic interference thresholds
  - ☐ Effect of indoor usage restrictions on the UWB device's field propagation
  - ☐ Effect of spectral mask (NPRM or XSI's modification)
- **In its comment on the NTIA study, XSI incorporated the above items into the NTIA's analytical framework, and applied its proposed spectral mask**
  - ☐ Showed that the recommendations in the NTIA report were far too restrictive due to the simplifications used in the analysis,

XSI

- **The following slides point out key items added to analysis for each of the systems addressed in the report:**
  - ☐ **Ground-based Radar:**
    - o **ARSR-4, ASR-9, NEXRAD, TDWR**
  - ☐ **Mobile Radar**
    - o **Maritime Navigation Radar**
  - ☐ **Satellite Receivers:**
    - o **FSS, SARSAT**
  - ☐ **Airborne Receivers:**
    - o **ATCRBS, MLS, DME**

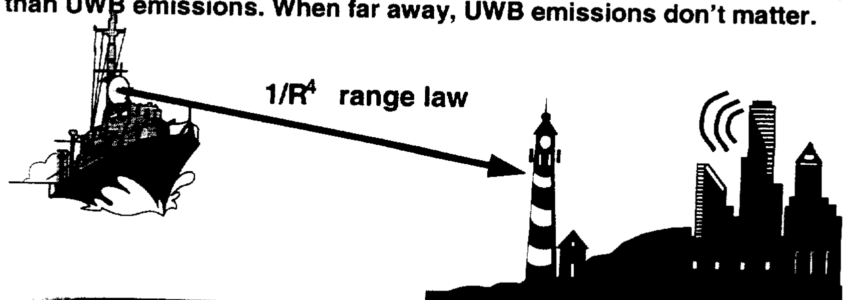
XSI

- **NTIA analysis showed 1 km was required separation distance**
- **BUT**
  - Geometry is unlikely due to site planning of radar system
  - The building itself is the reason for the degraded performance. The Radar cannot see an aircraft or weather behind the obstruction.
  - Ground radar beam width is only 0.9 degrees – 16m dia. at 1 km.
  - Unshielded UWB at 30 m height is unrealistic.
    Building loss (12 dB) must be in model since UWB device would be inside.
  - Polarization loss 3dB



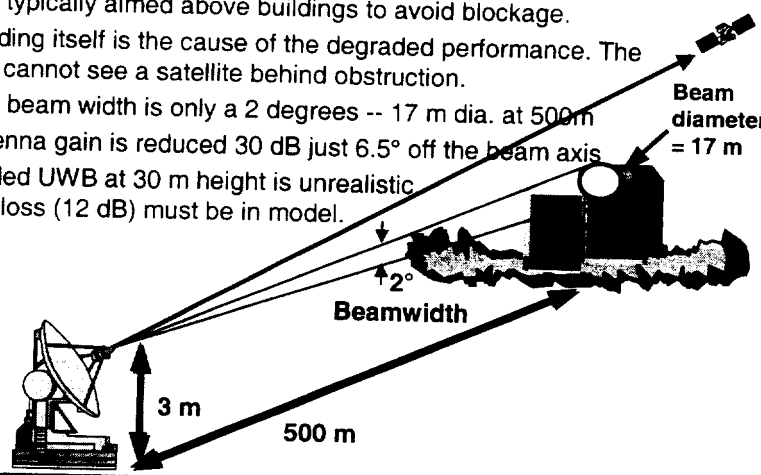
XSI

- **NTIA showed that 1.2 km separation was required as antenna scanned toward land**
- **BUT -**
  - the analysis assumed that the radar was operating at maximum sensitivity in a clutter free environment
  - however, by 1.2km the radar return from the land is 84 dB stronger than the radar's noise floor (the radar is designed to pick up land mass at 160 km range)
  - When the antenna beam scans away from shore, the gain is reduced 25dB, placing UWB devices 10-16 dB below protection criterion.
- **BOTTOM LINE: When the ship is close, radar returns are much stronger than UWB emissions. When far away, UWB emissions don't matter.**



XSI

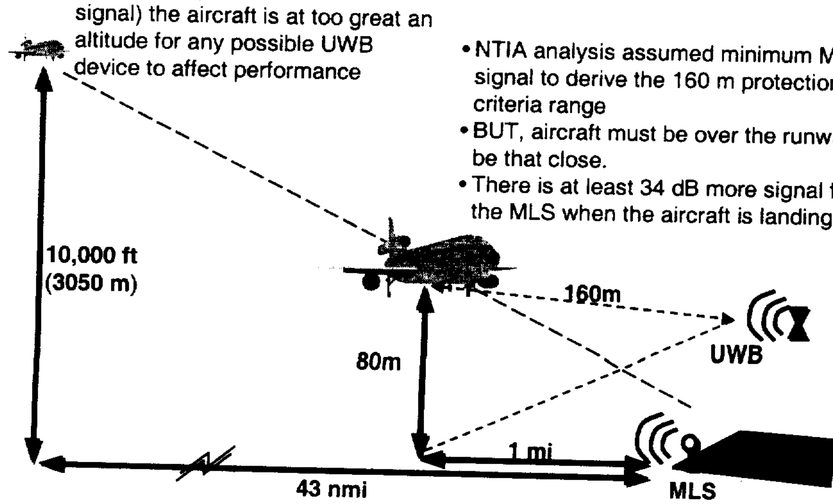
- **NTIA analysis showed that 500 m separation was required**
- **BUT**
  - ☐ Geometry is unlikely due to site planning of satellite ground station Beam is typically aimed above buildings to avoid blockage.
  - ☐ The building itself is the cause of the degraded performance. The receiver cannot see a satellite behind obstruction.
  - ☐ Antenna beam width is only a 2 degrees -- 17 m dia. at 500m
  - ☐ The antenna gain is reduced 30 dB just 6.5° off the beam axis
  - ☐ Unshielded UWB at 30 m height is unrealistic Building loss (12 dB) must be in model.



XSI

When the aircraft is at the maximum range (43 nautical mi) of the MLS (e.g. minimum MLS signal) the aircraft is at too great an altitude for any possible UWB device to affect performance

- NTIA analysis assumed minimum MLS signal to derive the 160 m protection criteria range
- BUT, aircraft must be over the runway to be that close.
- There is at least 34 dB more signal from the MLS when the aircraft is landing



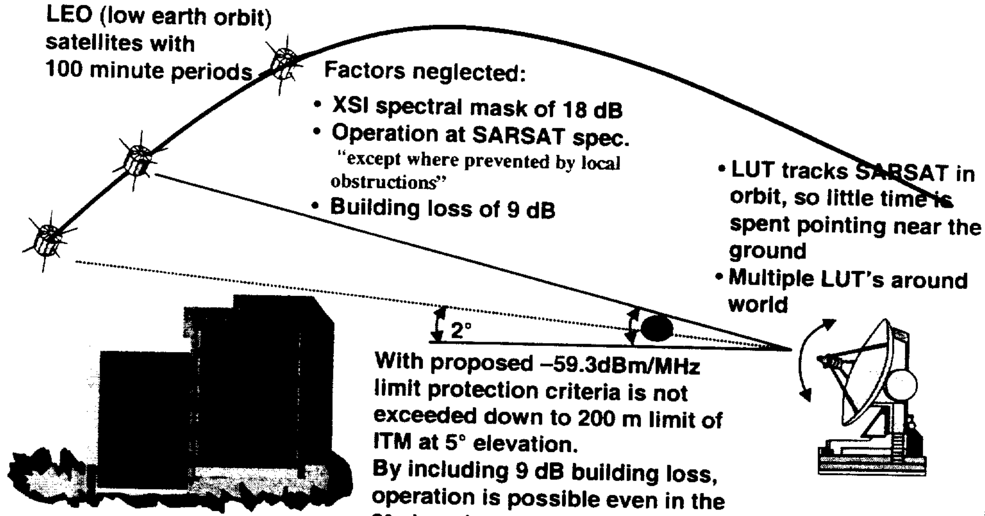
XSI

LEO (low earth orbit) satellites with 100 minute periods

Factors neglected:

- XSI spectral mask of 18 dB
- Operation at SARSAT spec.
  "except where prevented by local obstructions"
- Building loss of 9 dB

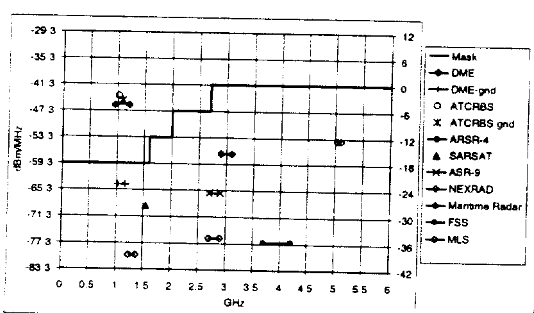
- LUT tracks SARSAT in orbit, so little time is spent pointing near the ground
- Multiple LUT's around world



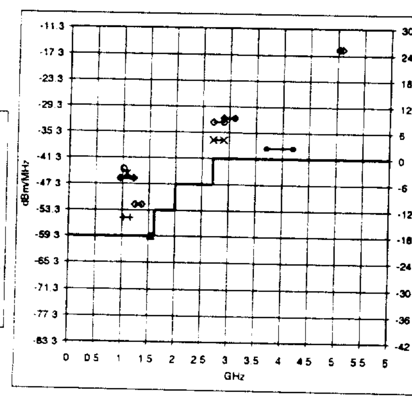
With proposed –59.3dBm/MHz limit protection criteria is not exceeded down to 200 m limit of ITM at 5° elevation.
By including 9 dB building loss, operation is possible even in the 2° elevation case.

XSI

- Simplified NTIA analysis versus XSI's proposed mask



- Same Analysis After including items omitted



- Factors included in extended analysis:
  - Realistic propagation losses, building penetration, antenna polarization, system usage.

XSI

Summary

- Analytical procedures used are accepted by the scientific community.
- Key commercial and government systems were tested and/or analyzed.
- In *all* cases, by applying the changes to the NPRM proposed by XSI, NO harmful interference was found.

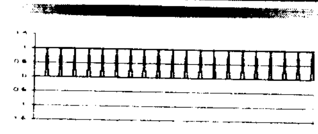
XSI

- UWB solves problems that are otherwise intractable
- It uniquely enables high speed wireless communications in high clutter (in-building) areas at wireline costs, and with long battery life.
- It provides a compelling new technology impacting both communications and remote sensing applications
- UWB can drastically impact the way people use and access information (e.g. WPAN, Residential Gateway)
- UWB chips can resemble the chips in Part 15 devices and generate similar emissions.

- These benefits can be realized without radiation of spectral lines, or high peak signals, and without harm to existing radio services.

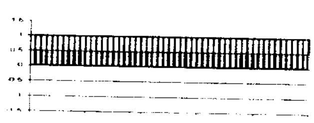
XSI

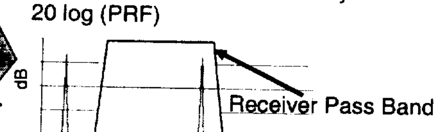
XSI



If each pulse has *n* joules, then increasing the number of pulses per second (i.e. PRF) will increase the average power by 10 log(PRF) (Power Grows Without Limit)

As the PRF is increased, the density of spectral lines decreases, so the power in each line increases by 20 log (PRF)





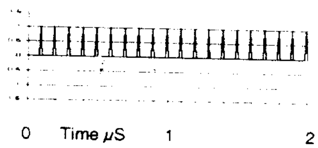
As the number of spectral lines decreases, fewer fall into the victim receiver passband, so the power in receiver passband increases by 10 log (PRF)....

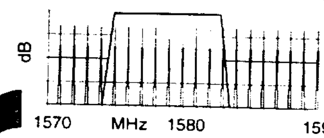
Until PRF > Rec_BW

- i.e. Until only one spectral lines falls into the victim receiver passband, then the power in receiver passband increases by 20 log (PRF)
- But only at the lines, there is no interference between the lines.

XSI

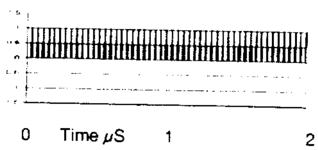
PRF and Spectrum For Pulse Streams

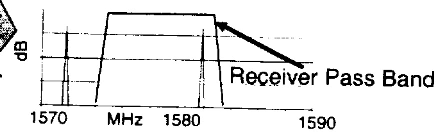




If each pulse has *n/PRF* joules, then increasing the number of pulses per second (i.e. PRF) will not change the average power, but ***decreases the peak-to-average***

As the PRF is increased, the density of spectral lines decreases, so the power in each line increases by 10 log (PRF)





As the number of spectral lines decreases, fewer fall into the victim receiver passband, so the power in receiver passband does not change....

Until PRF > Rec_BW

- i.e. Until only one spectral lines falls into the victim receiver passband, then the power in receiver passband increases by 10 log (PRF)
- But only at the lines, there is no interference between the lines.

XSI

- **Example Measurement of a 220 kHz bandwidth receiver**