

# Ultra-wideband Technology for Short-Range, High-Rate Wireless Communications

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# Overview of Presentation

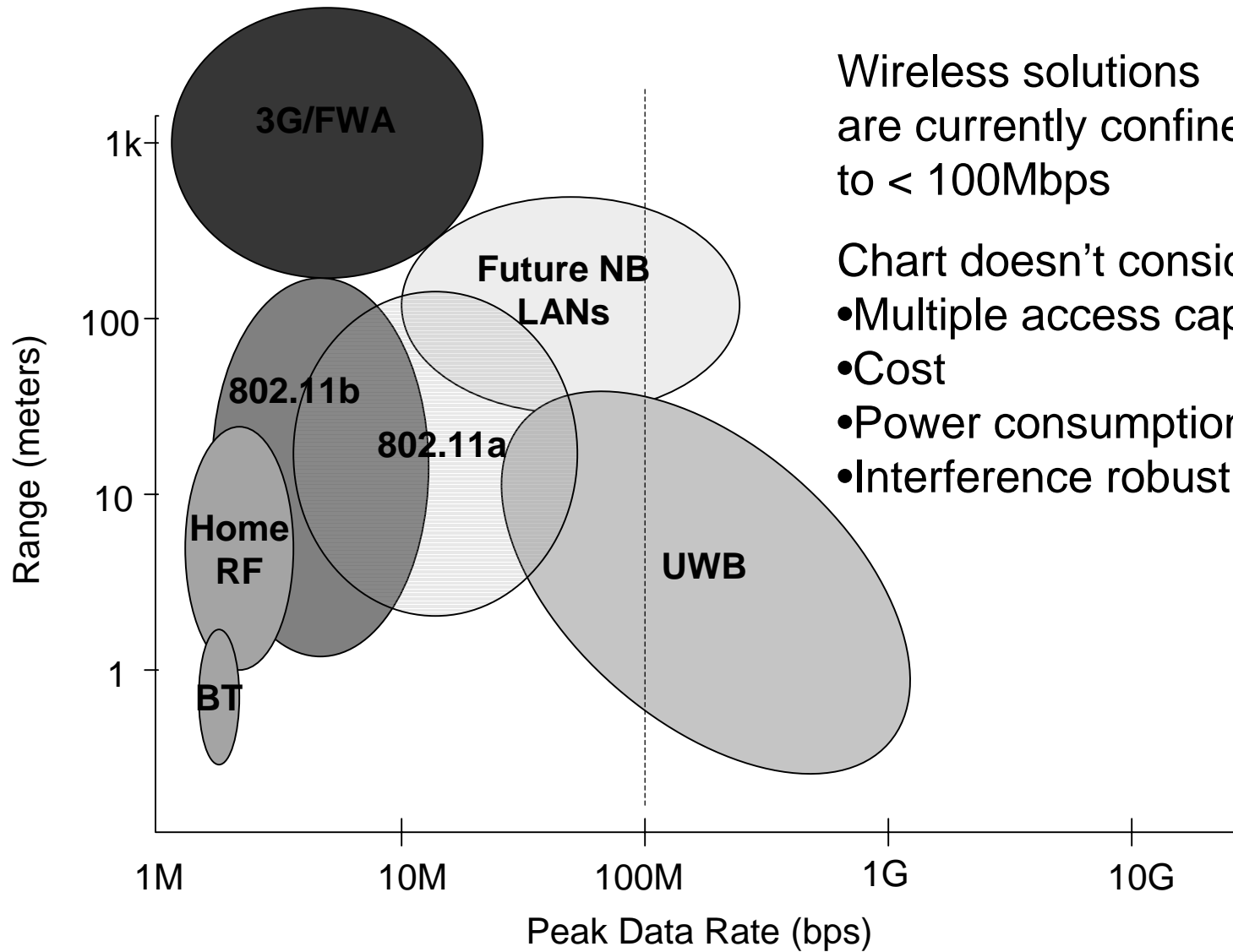
- Review of current short/medium range wireless standards and expected challenges for future systems
- Introduction to Ultra-wideband (UWB) Technology
  - What is it?
  - Possible benefits and challenges
- Performance example of M-PAM and DS-SS UWB systems with various RAKE receiver structures
- Can UWB coexist with other systems?
  - Review of FCC regulatory process and interference studies
  - Other considerations
- Conclusions

# Review PAN/LAN Standards

- Personal Area Networking (PAN) Standards typically operate within a “personal operating space” of ~ 10 meters
- Local Area Networking (LAN) Standards typically operate between 50-100 meters

	< 2.0 GHz	2.4 GHz ISM	5 GHz UNII/ISM
<b>PAN</b>	802.15.4 (low rate 915/868 MHz)	Bluetooth (802.15.1)	
		802.15.3 (high rate)	
		802.15.4 (low rate)	
<b>LAN</b>		802.11	802.11a
		802.11b (11 Mbps)	HyperLAN2
		802.11g (high rate)	
		HomeRF	
<b>Other</b>	Cordless phones (900 MHz, DECT @ 1.8 GHz)	ISM devices (Microwave ovens, RF lighting, etc.)	802.16.4 (5.7 GHz)
		Proprietary solutions	Proprietary solutions

# Review PAN/LAN Standards



Wireless solutions are currently confined to < 100Mbps

Chart doesn't consider:

- Multiple access capacity
- Cost
- Power consumption
- Interference robustness

# Review PAN/LAN Standards

- Problems
  - Many devices sharing the same spectrum (both communications and ISM devices)
  - Different applications require different design and optimization requirements (must trade-off power, throughput, distance, cost, etc.)
    - One or even two standards may not be able to address all requirements effectively...spectrum sharing of “uncooperative” devices will continue
  - Difficult to get high rates, high spectral sharing, and good robustness to interference simultaneously
  - Power efficiency continues to be important as capabilities get integrated into smaller, portable devices
    - Difficult to optimize both power efficiency and spectral efficiency simultaneously

# Review PAN/LAN Standards

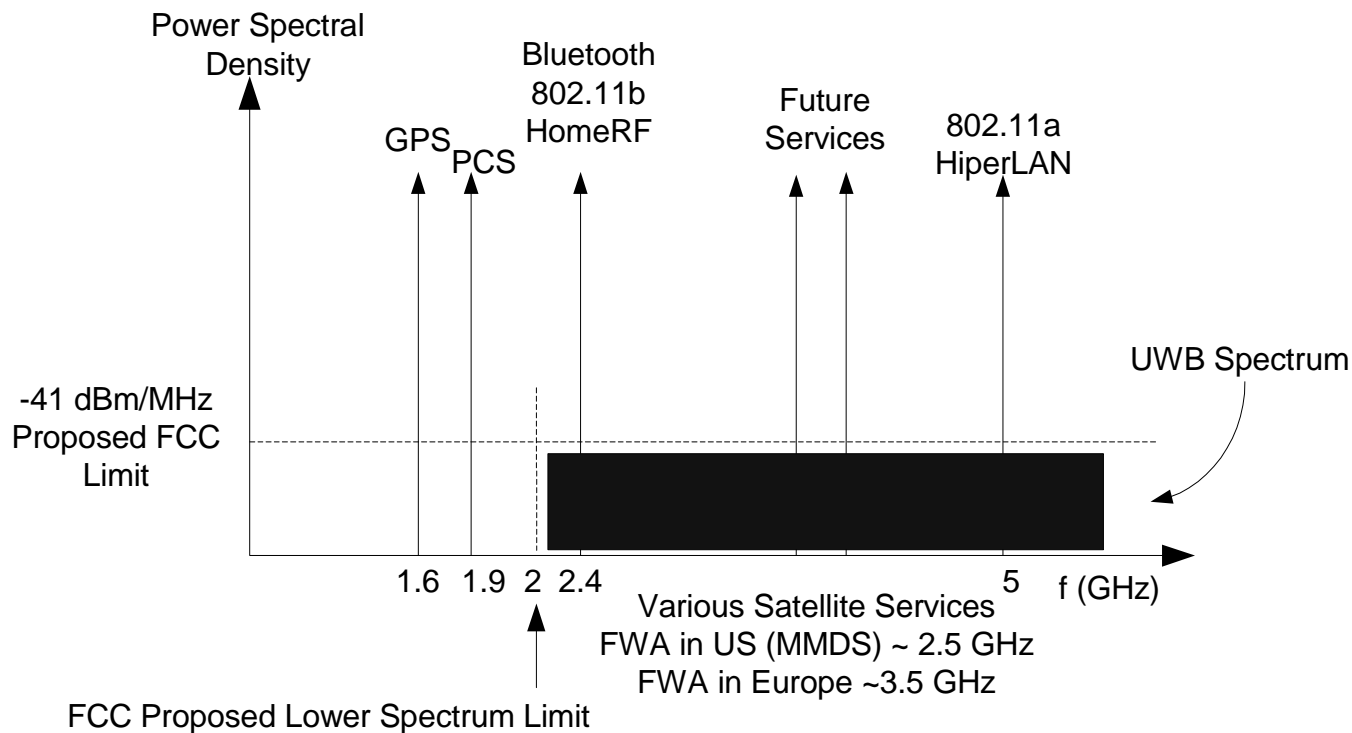
- Expected future needs
  - If short/medium range wireless really takes off, capacity (both in terms of number of users and throughput per user) will be increasingly important
  - New applications are being conceived
    - Wireless kiosk in mall to download pictures
    - Wireless sensor networks to control building heating/energy use
    - Wireless internet connections in coffee shops, airports, and hotels
    - Video distribution within the home (single or multi-hop network)
  - Position location is entering into more applications (< 1 foot accuracy in some cases)
    - Assists ad hoc networking protocols (location based master/slave node determination)
    - Enables new applications (cargo tracking)

# Review PAN/LAN Standards

- Possible solutions
  - More industry cooperation
    - Develop single “unified” standard (very difficult)
    - Push WLAN applications to use IEEE 802.11a at 5 GHz to lessen congestion at 2.4 GHz (Intel is very active here)
    - Agree on coexistence strategies (IEEE 802.15.2, adaptive frequency hopping)
  - Improve current technology
    - Standards are becoming more spectrally efficient (bps/Hz)
    - Higher integration of technologies (PAN/LAN capability in same chip(s), software radio approaches)
  - Look at new technologies
    - Ultra-wideband (UWB) technology
    - Other...

# Introduction to UWB

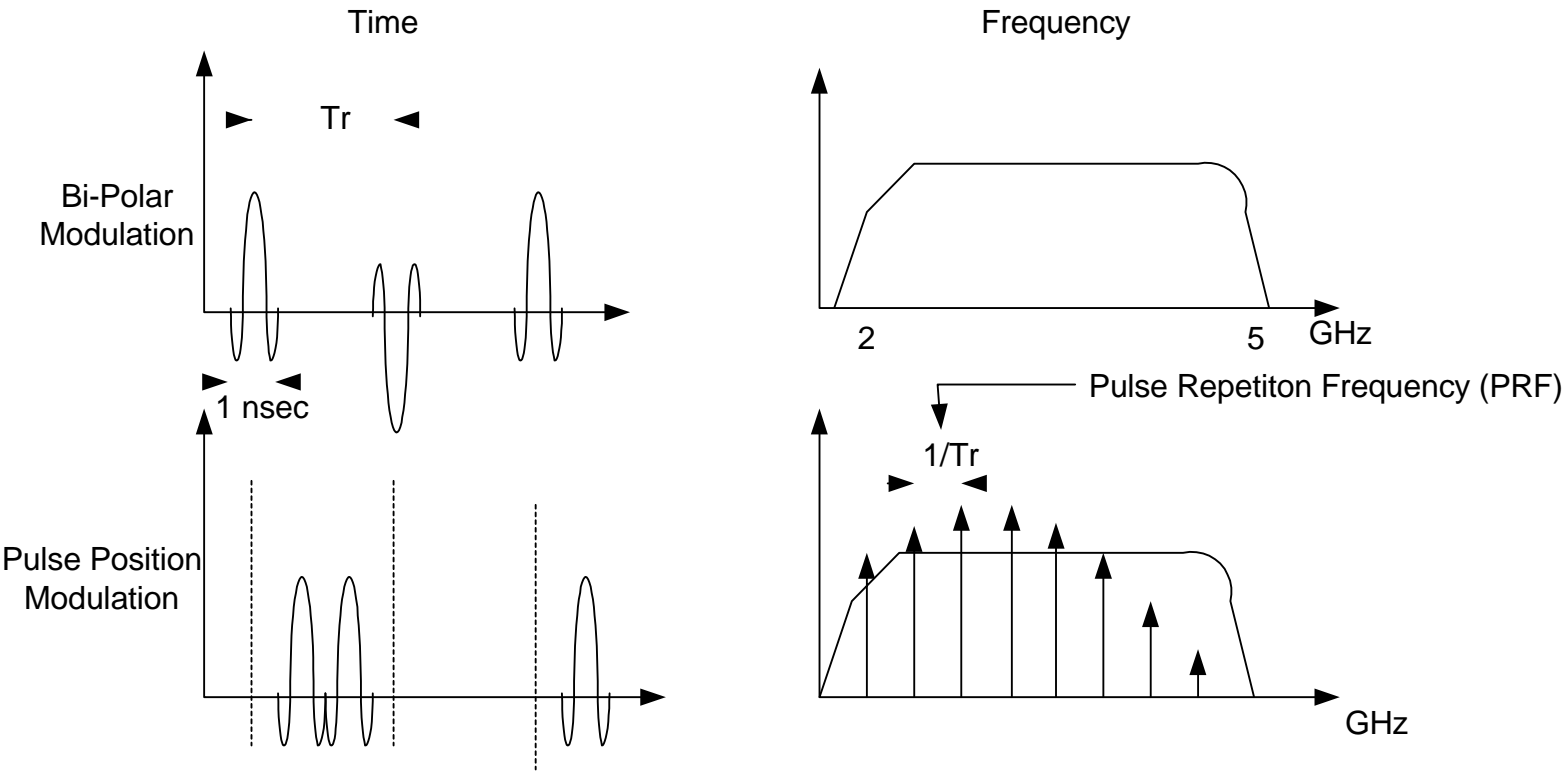
- What is it?
  - Any technology having a spectrum that occupies  $BW > 1/4 f_c$  or  $> 1.5$  GHz (proposed FCC definition).
  - History – started with radar applications for military use – recent advances in silicon process and switching speeds is moving it into the commercial domain



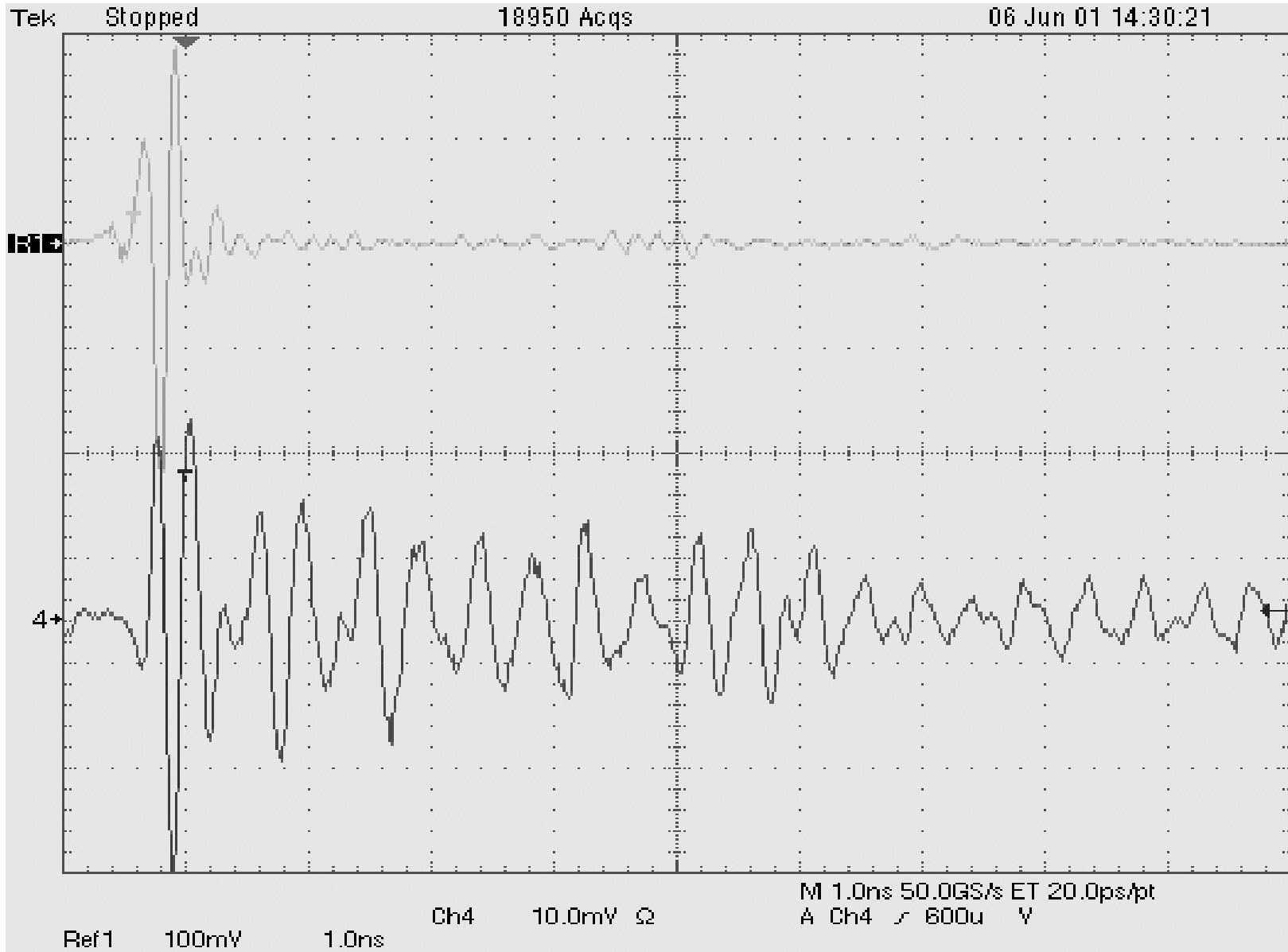


# Introduction to UWB

- UWB usually refers to “impulse” based waveforms which be used with different modulation techniques.

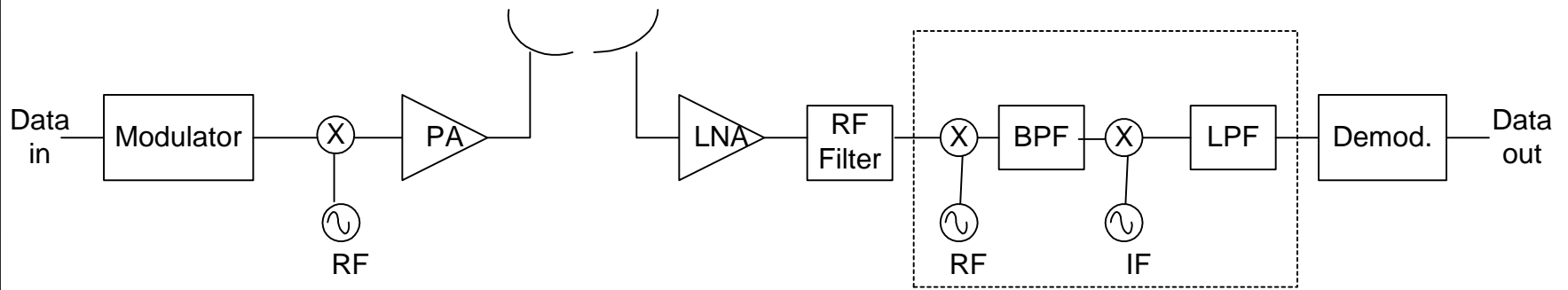


# Introduction to UWB

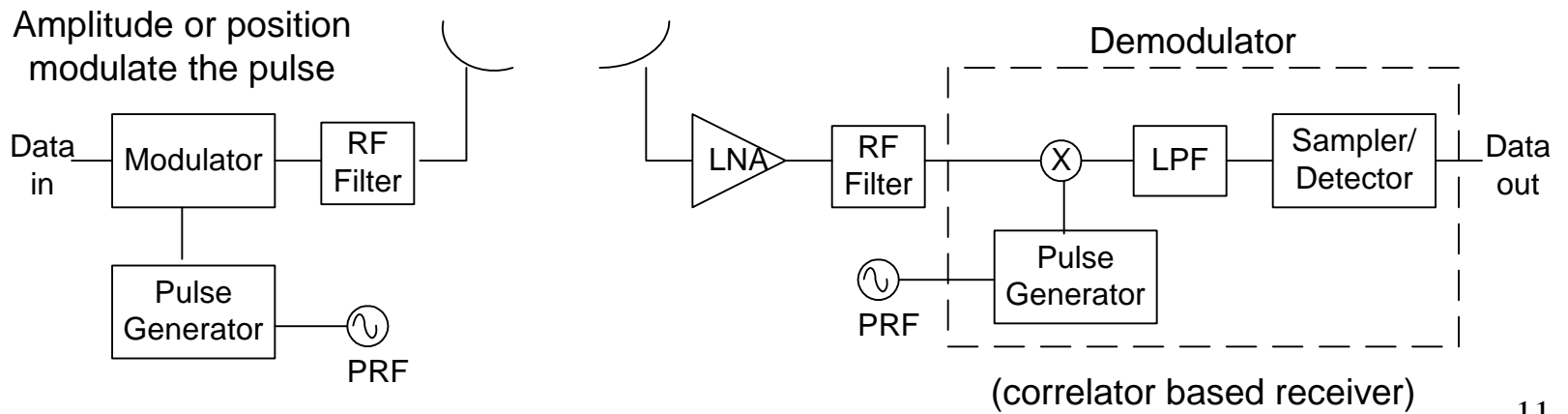


# Introduction to UWB

## Example "narrowband" Transceiver Architecture



## Example UWB Transceiver Architecture



# Introduction to UWB

- Theoretical motivation: consider Shannon's capacity equation, which shows capacity increases faster as a function of BW than a function of power.
- Useful to compare capacity of Tx power limited "narrowband" systems operating in dedicated bands with Tx power spectral density limited overlay system (UWB)
  - Derive  $P$  based on Tx constraints, propagation environment, and operational scenarios

$$C = B \log_2 \left( 1 + \frac{P}{BN_0} \right)$$

Where:

$C$  = Channel Capacity (bits/sec)

$B$  = Channel Bandwidth (Hz)

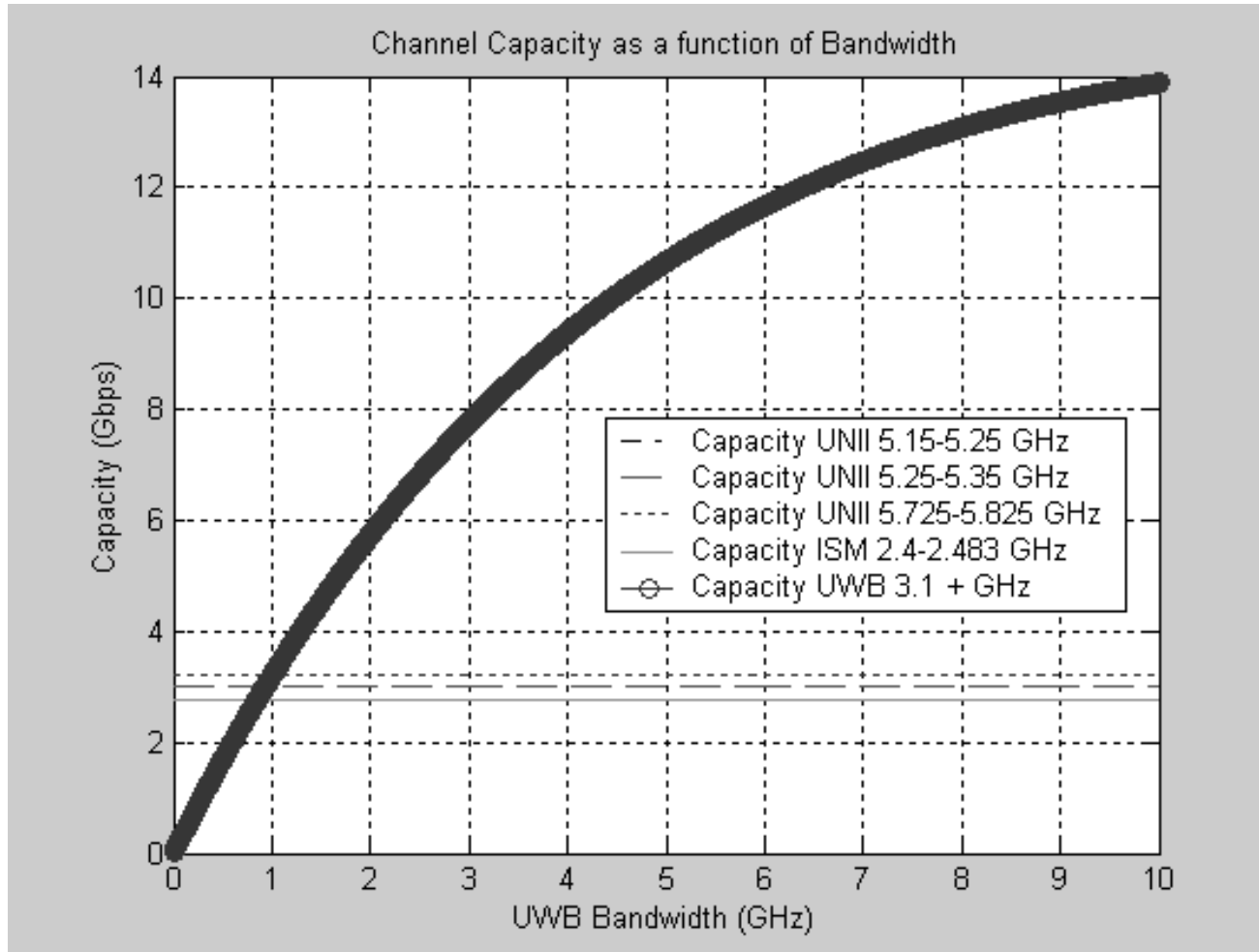
$P$  = Received Signal Power (watts)

$N_0$  = Noise Power Spectral Density (watts/Hz)

**$C$  is an increasing function of  $B$**

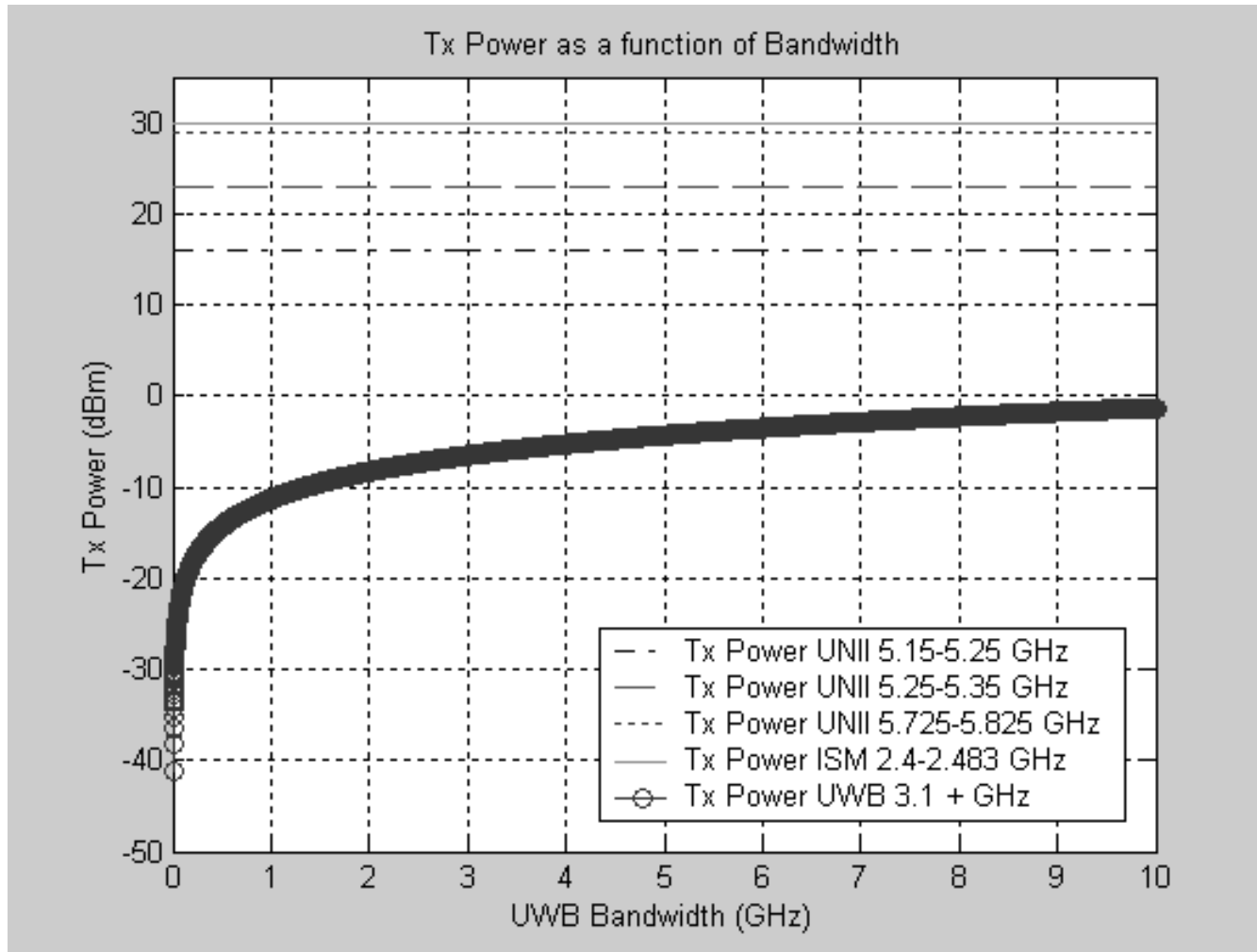
Capacity of a Gaussian Channel

# Introduction to UWB



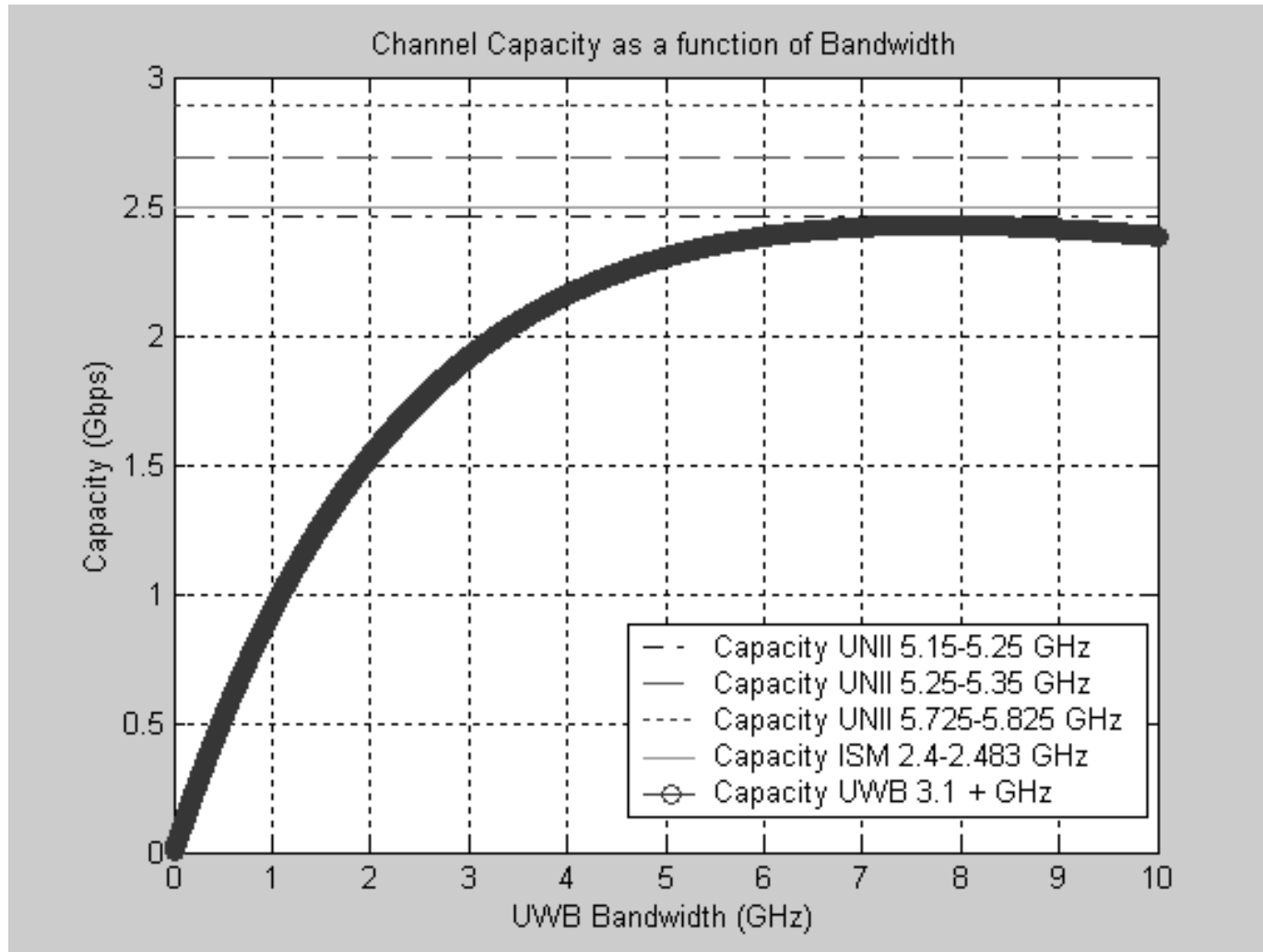
- Assumptions for graph: target distance = 10 m, distance loss factor = 2.0, min. occupied frequency = 3.1 GHz, UWB PSD limit = -41.3 dBm/MHz (same as current Part 15)

# Introduction to UWB



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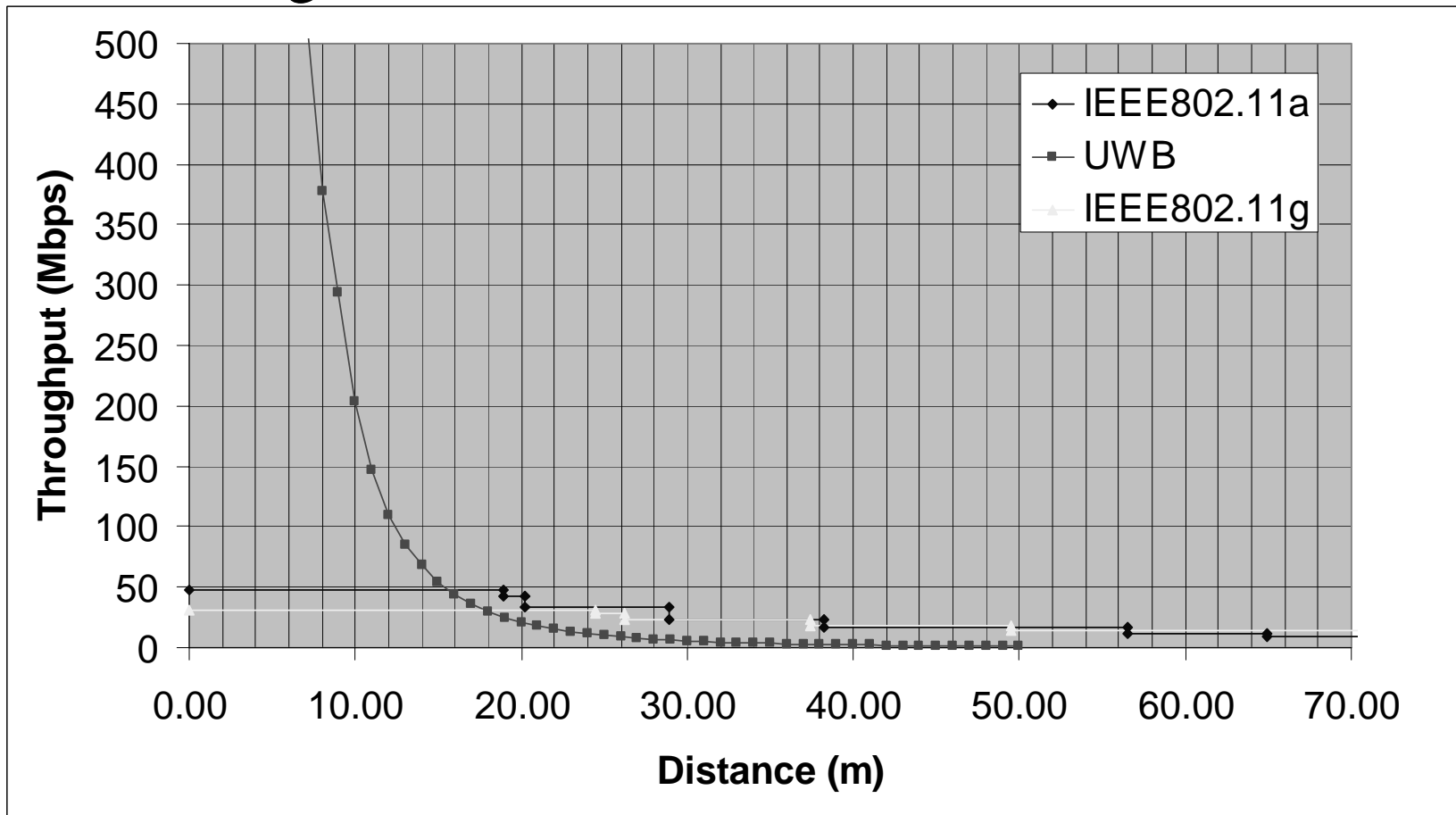
# Introduction to UWB



- Assumptions for graph: target distance = 30 m, distance loss factor = 2.0, min. occupied frequency = 3.1 GHz, UWB PSD limit = -41.3 dBm/MHz (same as current Part 15)

# Introduction to UWB

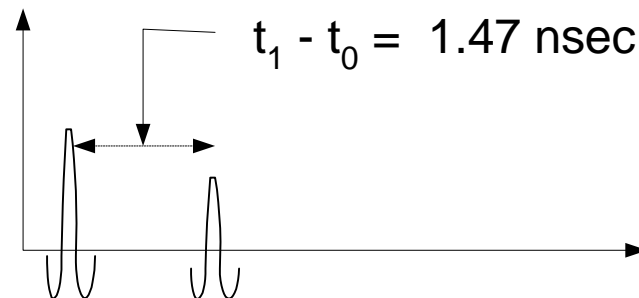
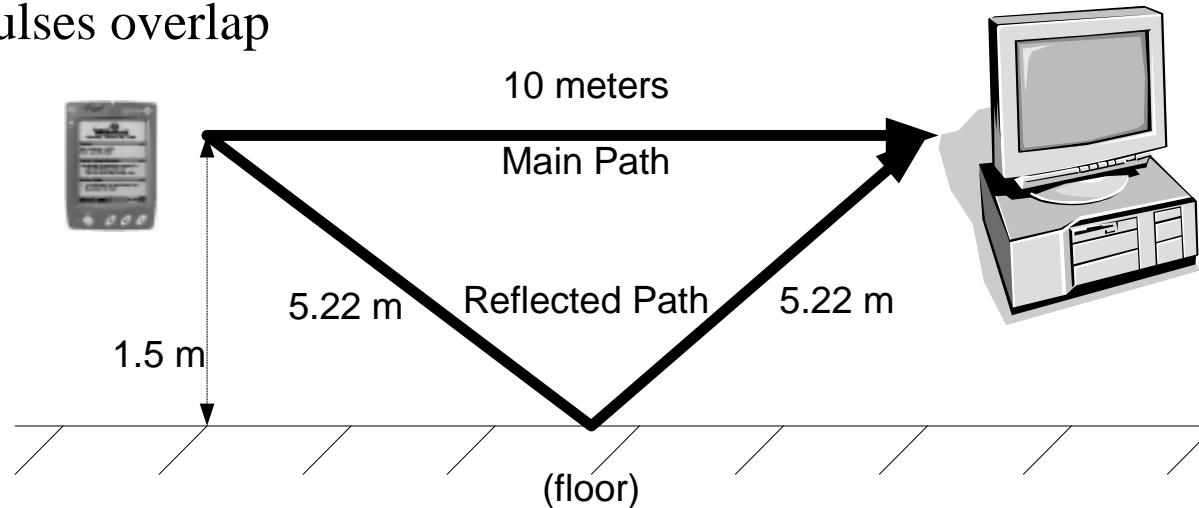
- Performance of UWB with realistic link budget assumptions...shows significant throughput potential at short ranges.





# Introduction to UWB

- UWB robustness to fading
  - Short impulse (< 1 nsec typically) prevents destructive interference from multipath
  - Multipath components can be individually resolved (good and bad)
  - Carrier-less nature of waveform results in less fading, even when pulses overlap



# Introduction to UWB

- Capacity
  - Possibility of achieving high throughput, robustness to co-channel interference and narrowband jammers, and greater spectrum sharing
- Low Power and Low Cost
  - Can directly modulate a baseband pulse...no need for mixers or PA.
  - High capacity can be achieved with much lower Tx power levels
  - Promising for mobile applications (low cost/low battery usage).
- Fading robustness
  - Wideband nature of the signal reduces time varying amplitude fluctuations (fading). This reduces fade margin in link budgets.
- Position location capability
  - Short impulse (wideband signal) allows for accurate delay estimates, which can be used for accurate position location.
- Flexibility
  - Can easily and dynamically trade-off throughput for distance, making the technology compatible for a large number of applications.
- Challenges
  - Receiver complexity (RAKE combining, synchronization, narrowband jammers)
  - Multiple access and modulation schemes to take advantage of capacity

# UWB Performance Example

- Question: How high can we push the throughput of UWB systems?
  - Higher order modulation
  - Transmit pulses at a much higher rate (PRF)
  - Orthogonal codes? Space-time codes? Other?
  - Need to consider equalizer complexity vs. performance trade-offs
- Problem: Need to better understand the propagation channel.
  - Probably not white noise limited as the pulses get closer together
  - Not much UWB based modeling published to date (some measurements with general observations and some recent attempts at channel models)
  - Preliminary results based upon a discrete channel impulse response model for short-range, indoor channels (mainly from offices)...plan on extending results to include much wider bandwidth measurement data from internal measurement campaign

# UWB Channel Modeling

- Discrete multipath model

$$h(t) = \sum_{l=0}^{L-1} \alpha_l \delta(t - lT_m)$$

where

- $\alpha_l$  is the amplitude fading factor on path  $l$
- $T_m$  is the minimum resolvability of the pulse shape
- $L$  is the number of resolvable multipath components

# UWB Channel Modeling

Model	Description of Arrivals	Comments
<b>Modified <math>\Delta</math>-K Model</b> (extended by Hashemi to indoor channel)	Modified Poisson arrival process with a 2-state Markov process modeling arrival rates to allow clustering/spreading of arrivals.	Based on large data set at distance separations of 5-30 meters. 5 nsec resolvability.
Saleh-Valenzuela Model	Cluster model with cluster arrivals and rays within a cluster are modeled as Poisson process with different arrival rates and MIP decay factors.	Recently extended to model UWB channel by Cramer/Scholtz.
Ray Tracing Model	Deterministic model using 3-D model of indoor channel taking into account reflection and diffraction of electromagnetic waves from objects based upon material.	Too many reflectors to track. Difficult to extend to different channels
Cassioli, Win, Molisch model (VTC2001)	Based on office channel measurements with UWB waveforms and 2 nsec resolvability.	Large number of realizations needed for statistical accuracy.

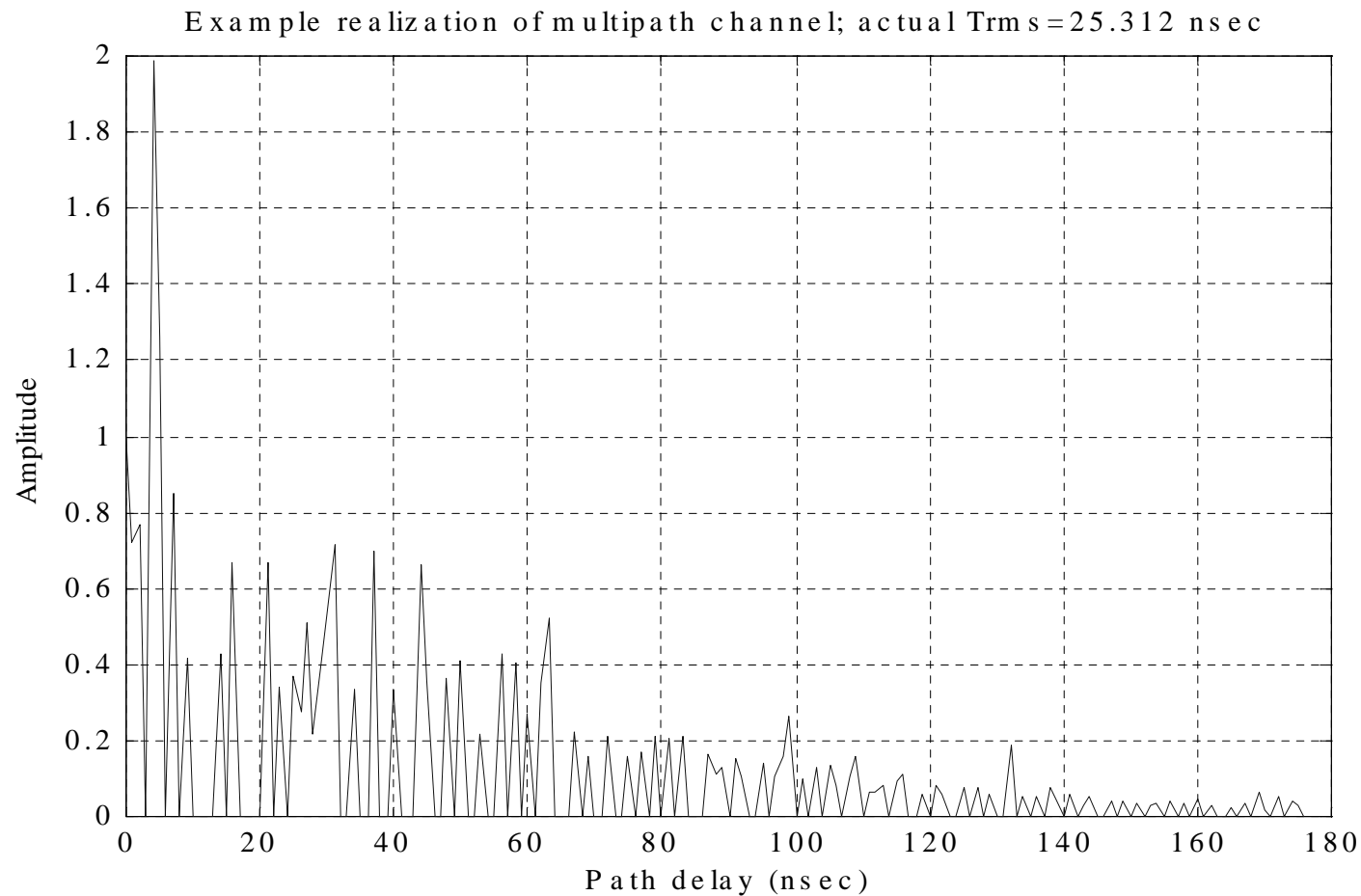
- Analysis easily extended to other channel models and/or measurements (semi-analytical technique of averaging over multiple channel realizations),<sub>21</sub>

# UWB Channel Modeling

- Specific properties of channel model
  - Multipath delay spread
    - Mean RMS delay spreads between 20-30 nsec (chose 25 nsec for results)
  - Multipath intensity profile
    - Exponentially decaying (linear in dB)
  - Multipath amplitude fading distribution
    - Log-normal distribution with STD 3-5 dB (3 dB)
  - Multipath arrival times
    - Based upon a modified Poisson process (known as  $\Delta$ -K model) which uses a 2 state Markov process for determining arrival probability
- Interested in relative trade-offs between systems. Currently completing measurements for propagation within a home environment.

# UWB Channel Modeling

- Example channel realization
  - Channel 1: severe multipath channel



# Performance Analysis

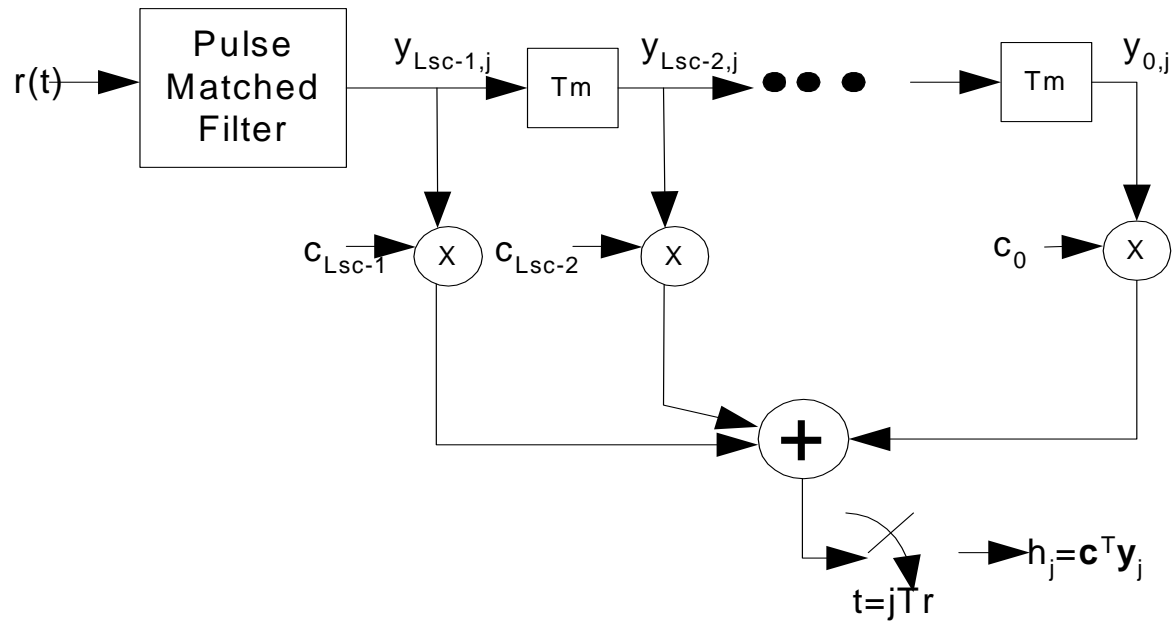
- As a representative example, considered performance of M-PAM (M=2, 4, 8, and 16)
- Same throughput for all M-PAM systems
  - As M increases, the PRF decreases by  $\log_2(M)$
  - Is it better to increase the PRF with low order modulation or reduce the PRF with higher order modulation
- Transmitted signal:

$$s(t) = \sqrt{P} \sum_{i=-\infty}^{\infty} b_i a(t - iT_r)$$



# Performance Analysis

- RAKE receiver structure



# Performance Analysis

- Selection of tap weights (assuming  $L_{sc}$  taps)
  - Maximal Ratio Combining (MRC)
    - Select first non-zero  $L_{sc}$  paths to combine using MRC.
    - Requires path amplitude knowledge.
  - Equal Gain Combining (EGC)
    - Select first non-zero  $L_{sc}$  paths to combine using EGC.
    - Does not require path amplitude knowledge.
  - Maximal Ratio - Selection Combining (MR-SC)
    - Select maximum  $L_{sc}$  paths to combine using MRC.
    - Requires path amplitude knowledge.
  - Equal Gain – Threshold Combining (EG-TC)
    - Select first  $L_{sc}$  paths greater than a threshold to combine using EGC.
    - Does not require path amplitude knowledge.
- Can study various combination of  $L_{sc}$  and combining methods to trade-off complexity and performance.

# Performance Analysis for M-PAM

- Average bit error probability is given by:

$$P_b(e/\alpha) = \frac{1}{kM^Q} \sum_{j=1}^{M^Q} P_s(e/\alpha, \mathbf{b}_j)$$

$$P_s(e/\alpha, \mathbf{b}_j) = 1 - \frac{1}{2} \operatorname{erfc}(\gamma_{-1}) + \frac{M-2}{2M} \operatorname{erfc}(\gamma_1)$$

$$\gamma_k = \sqrt{\frac{3\gamma_{ave}}{(M^2-1)\mathbf{c}^T\mathbf{c}}} \mathbf{c}^T \mathbf{A}_j^k \mathbf{a}$$

- Average SNR is given by:

$$\gamma_{ave} = E_s / \eta_0 = P_{ave} T_p / \eta_0 = [P_{sd} / \eta_0] \times [B_s / B_p]$$

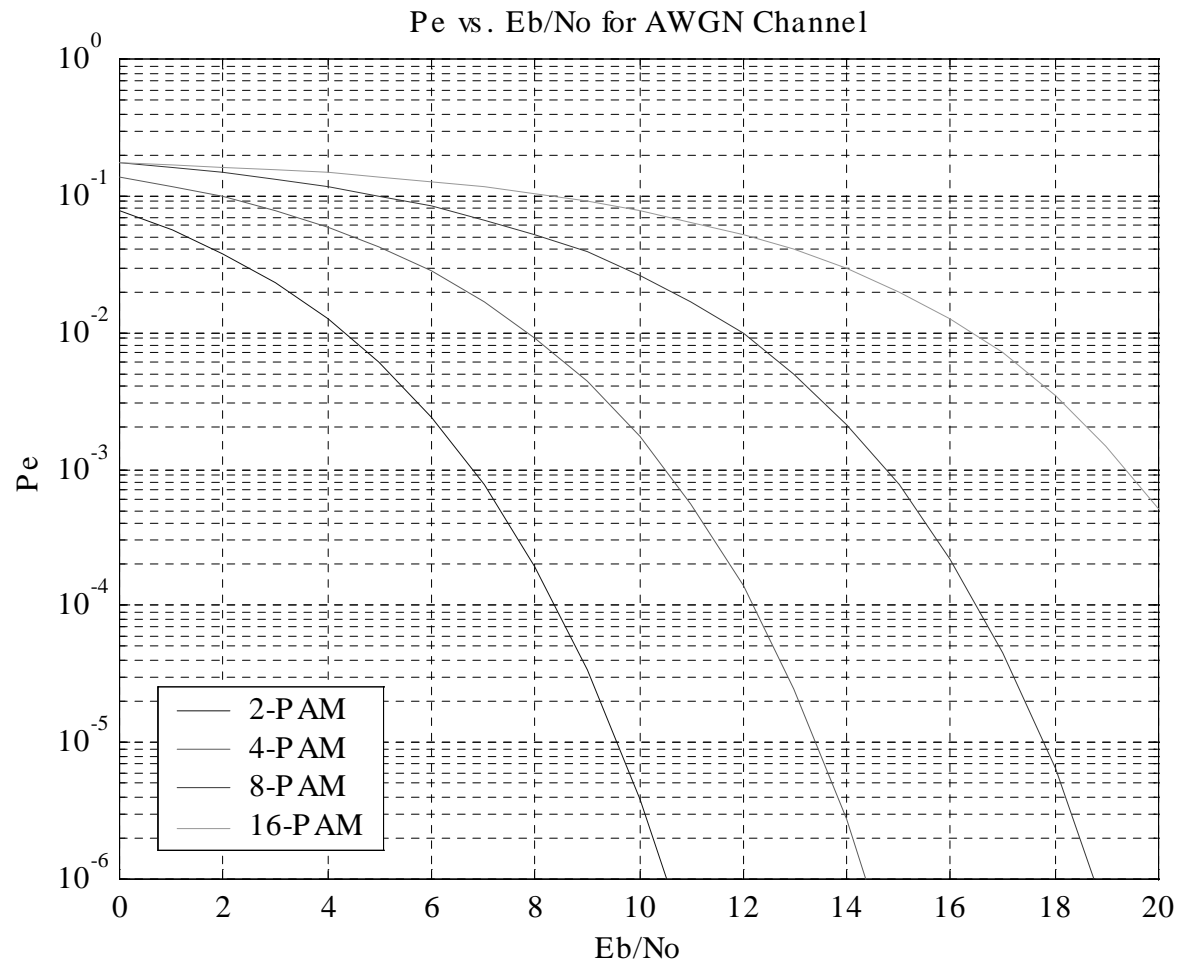
The term  $[B_s/B_p]$  is analogous to a processing gain. This factor is the reason UWB can operate with low PSD.

# Parameters for Results

- Parameters used to calculate results
  - 1,000 channel realizations (semi-analytical results, same set of realizations for all systems)
  - Average RMS delay spread = 25 nsec
    - Results in multipath out to 177 nsec @ -30 dBc
  - 2-PAM PRF = 20 MHz (50 nsec pulse period) for ISI results
  - 2-PAM PRF = 5 MHz (200 nsec pulse period) for no-ISI results
  - Total average received power normalized to 1 (except when otherwise noted)
  - Minimum path spacing = 1 nsec (assuming no overlap of pulses to avoid partial inter-pulse interference)
  - Assumed perfect synchronization and tracking of amplitude fades (when appropriate).

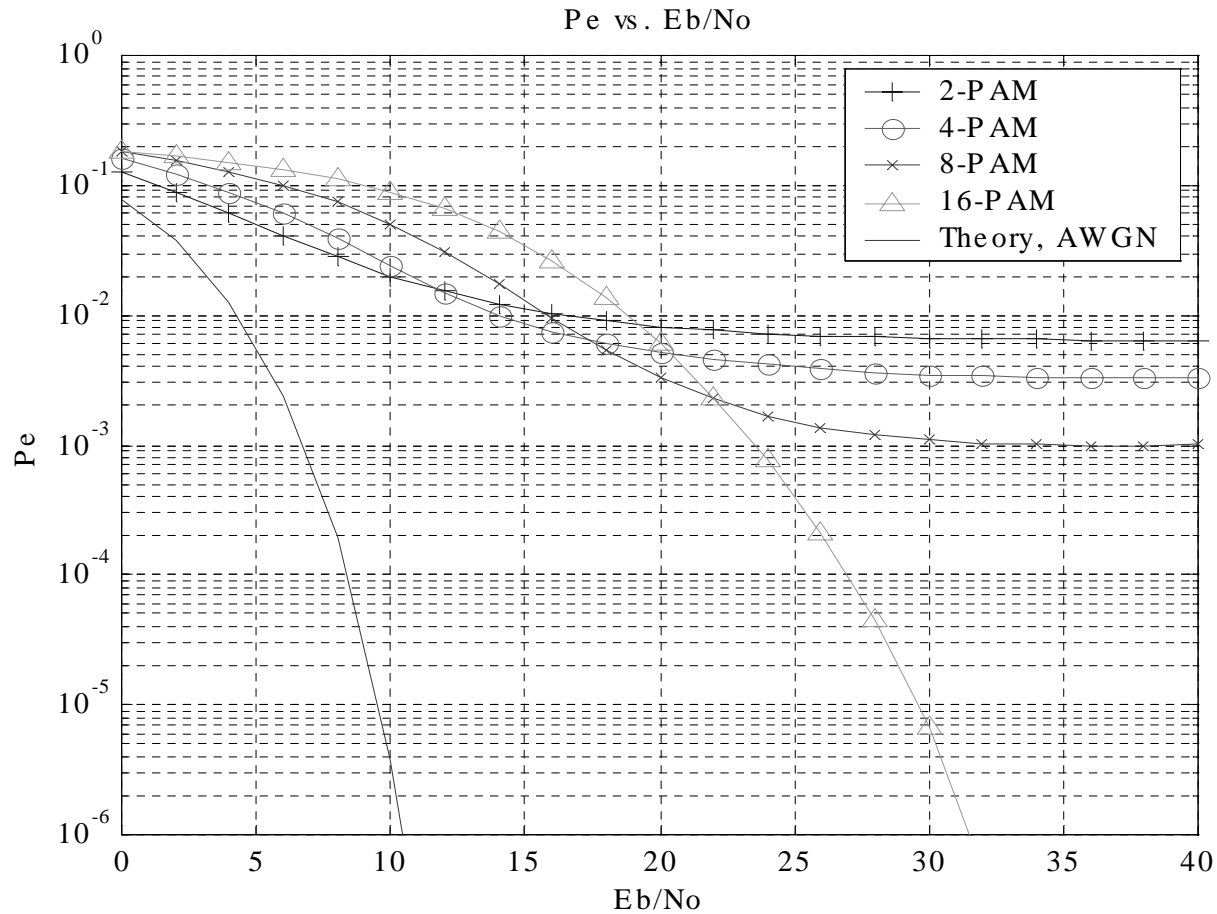
# Results for M-PAM

- Recall, PAM is very spectrally efficient, but not power efficient.



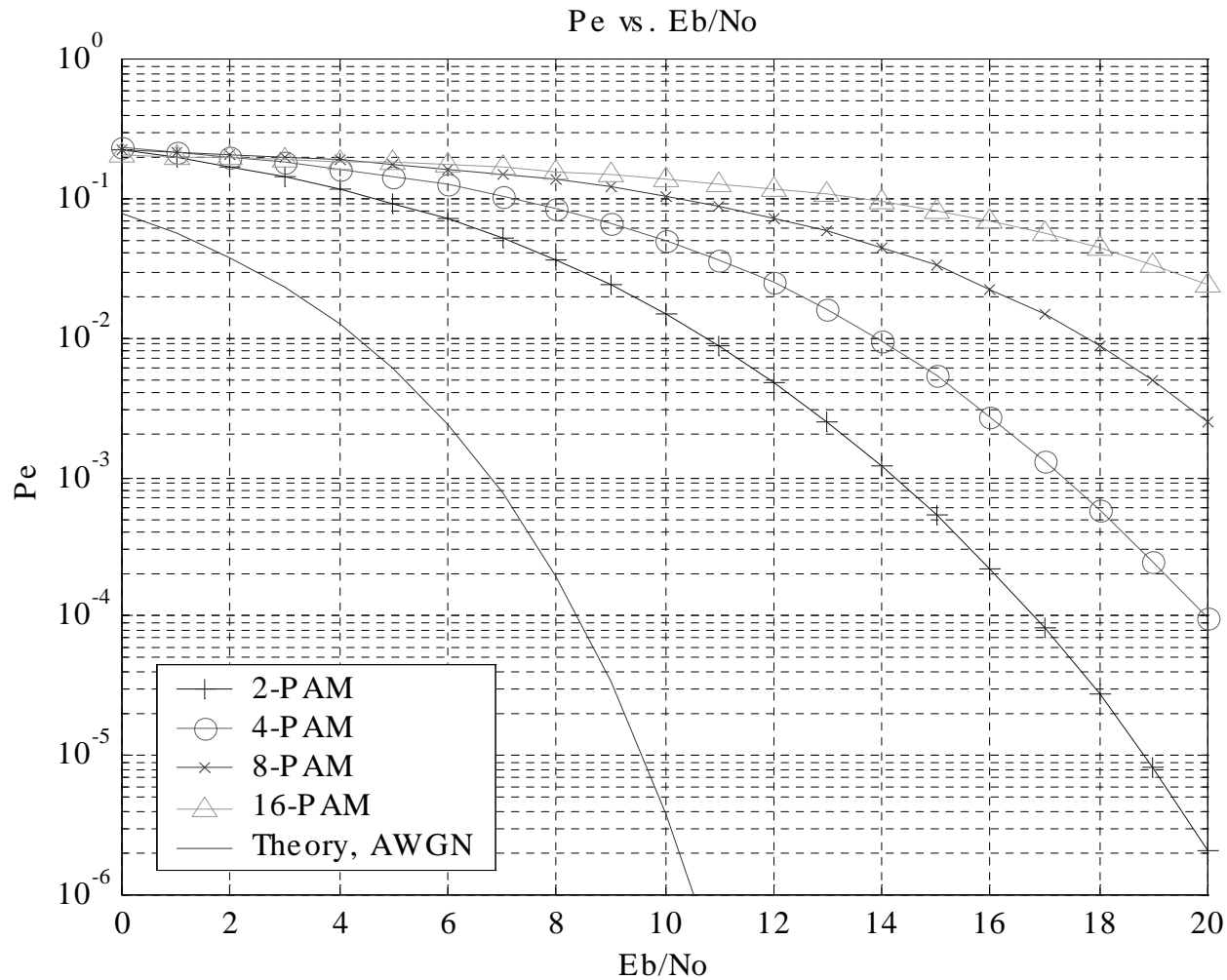
# Results for M-PAM

- PAM with  $L_{sc}=1$  and first path normalized power equal to 1.



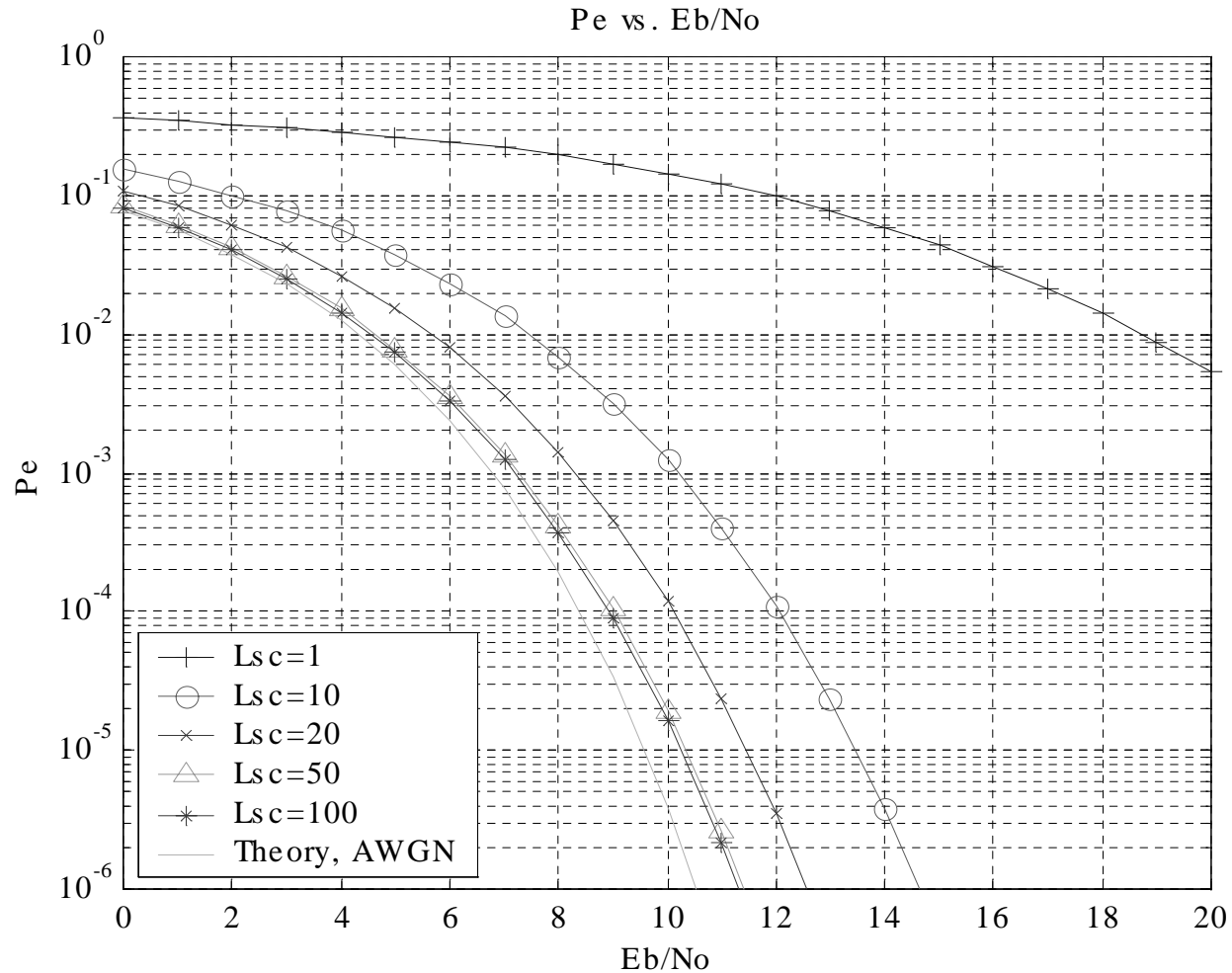
# Results for M-PAM

- PAM with MRC-RAKE,  $L_{sc}=3$  is the number of resolvable paths.



# Results for M-PAM

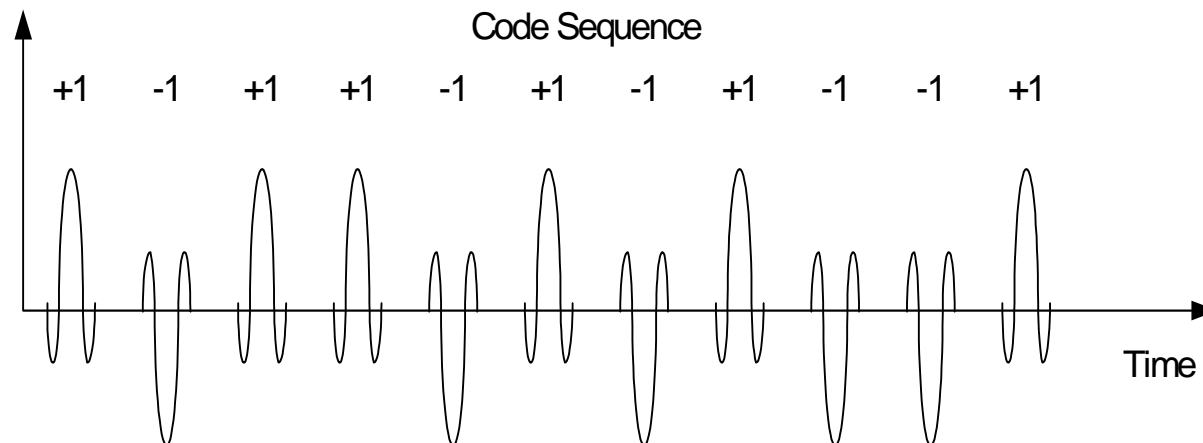
- 2-PAM with MRC-RAKE with  $L_{sc}$  taps (pulse repetition period = 200 nsec, so no ISI).





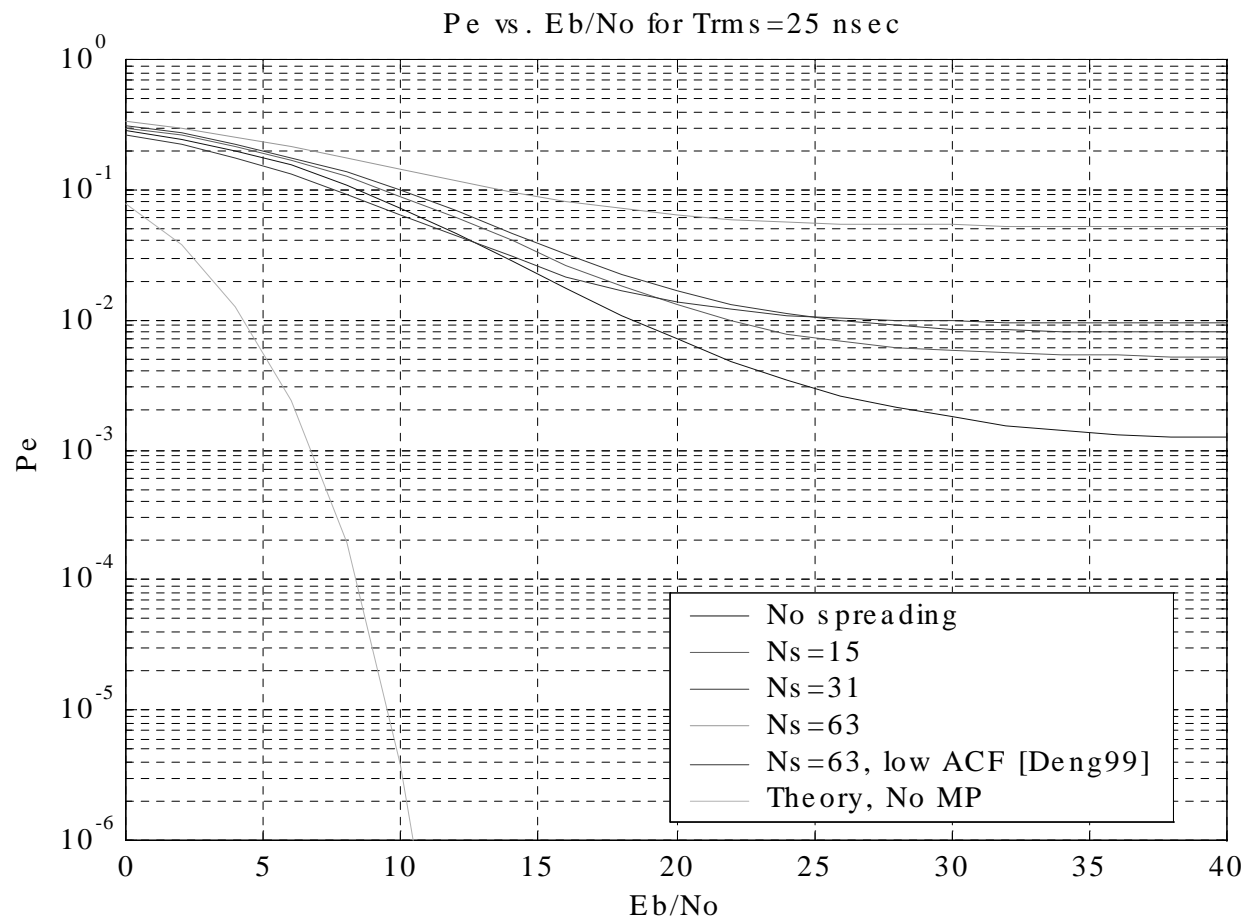
# Results for DS-SS

- Implications on CDMA code design
  - Traditional CDMA systems focus on good cross-correlation properties to maximize capacity while inter-chip interference is usually small compared to multiple access interference
  - For high-rate UWB systems, ISI may span several bit periods making auto-correlation (to combat the multipath) as well as cross-correlation an important design parameter
    - Could lead to new code sequence design considerations



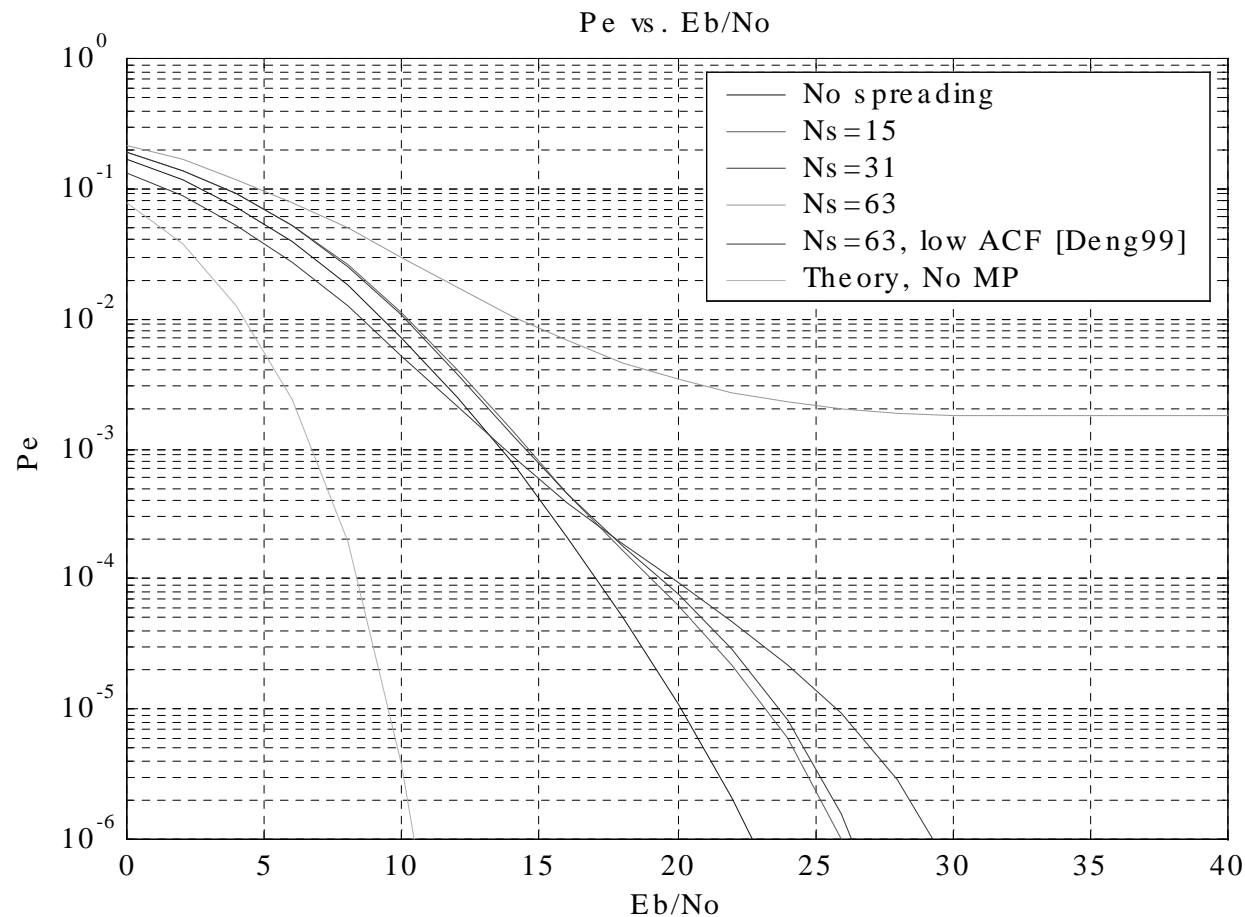
# Results for DS-SS

- 2-PAM with DS-SS, bit period  $\sim 63$  nsec, no RAKE, sequences: Kasami (15), Gold (31,63), Deng (ACF-optimized, 63).



# Results for DS-SS

- 2-PAM with DS-SS, bit period  $\sim 63$  nsec, 3-tap RAKE, sequences: Kasami (15), Gold (31,63), Deng (ACF-optimized, 63).



# Summary of Results

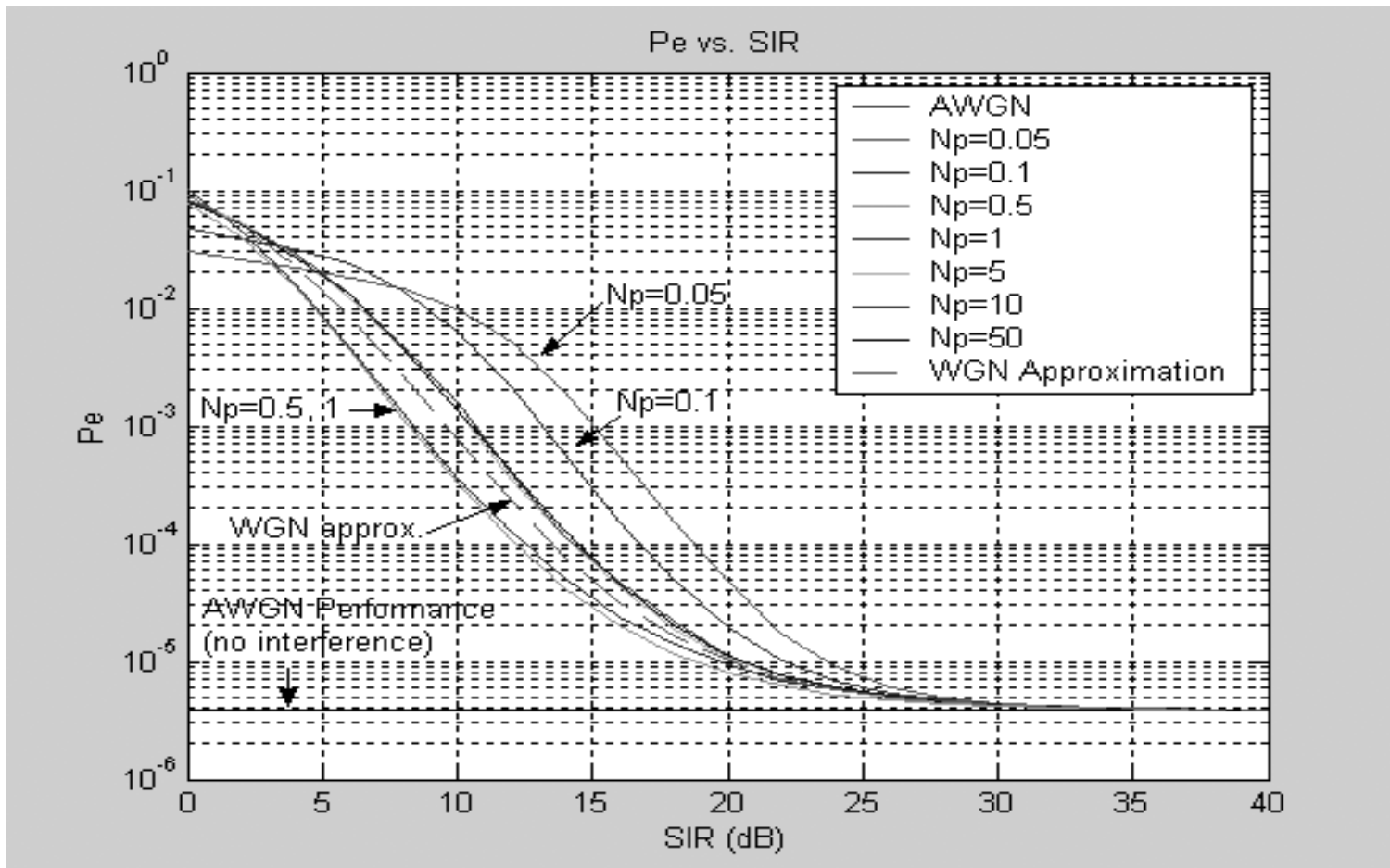
- Indoor channel model was applied to UWB propagation to get some insight into performance for high-rate systems and better understanding of receiver designs.
- RAKE reception seemed to significantly reduce the effects of ISI by providing an effective order of diversity (some paths had severe ISI while others did not).
- Raking in the energy from multiple paths yields significant gains due to the large amount of energy that exists in the multipath components. Number of required Rake taps depends on the channel.
- Spreading sequence design for DSSS systems has significant impact on performance...need to take into account both autocorrelation and cross-correlation properties in sequence design.
- Future work for investigation
  - Improve channel model by correlating with UWB specific measurements
  - Extend analysis to include methods for mitigating ISI (equalization), modulation schemes (orthogonal, PPM), and multiple access schemes (TH-CDMA, DS-CDMA, CSMA)

# UWB Coexistence

- How is UWB interference modeled?
  - Depends on modulation, PRF, and duty cycle of UWB Tx
  - Can be viewed as noise-like, CW-like, or pulse-like
  - Proper modulation (sufficient randomization) results in noise-like interference in most cases – can be mandated by regulations with proper emissions testing (*e.g.*, low resolution bandwidth to reduce ‘spikes’)
- How to determine impact of UWB interference on “narrowband” systems?
  - Define interference criteria: dB rise in noise floor, loss of signal lock, increased signal acquisition time, etc.
  - Consider typical operational scenarios (indoor, outdoor, antenna directivity, geographical location, expected separation, antenna heights, etc.)
  - Realistic propagation environment (typically not free space beyond 10 meters separation: Hata model for outdoor scenarios, for example)
  - Other sources of noise, both from unintentional radiators (computers, electronic devices) as well as from other intentional radiators (OOB interference from other devices, co-channel interference)

# UWB Coexistence

- Validity of “UWB as white, Gaussian noise” approximation
  - Factors to consider: UWB modulation (random bipolar +/- 1), PRF ( $B_p$ ), narrowband BW ( $B_f$ ), narrowband center frequency, narrowband waveform (root-raised cosine, for example), SNR, SIR,  $N_p=B_p/B_f$



# UWB Coexistence

- FCC Regulations process
  - Notice of Inquiry (NOI) issued in Sept. 1998.
  - Notice of Proposed Rule Making (NPRM) issued May 2000.
  - > 700 comments filed since NOI...shows lots of interest
  - Main concern...how much will UWB emissions interfere with other incumbent “narrowband” users?
  - Lots of studies submitted to the FCC docket analyzing interference of UWB on GPS, PCS, DARS, federal satellite systems, radar systems, etc.
- Proposed NPRM rules changes:
  - Allow devices to be unlicensed with a power spectral density limit
  - For frequencies > 2 GHz, emissions < -41.3 dBm/MHz
    - Same as current Part 15 limits for regulating emissions of digital devices (computers and other electronic devices)
  - For frequencies < 2 GHz, emissions 12 dB lower (-53.3 dBm/MHz)
  - Peak-to-average power < 20 dB in 50 MHz BW

# UWB Coexistence

## • Reasonable coexistence requirements

- Need to balance fair restrictions on UWB emissions with possible benefits of allowing new technology to be deployed
- For example, GPS studies considered 2-3 meter separation distance between a UWB emitter and a GPS receiver in terrestrial applications

## • Suggested changes to NPRM

- GPS interference studies suggested high sensitivity to spectral lines
  - Could reduce power allowed in spectral lines by adding requirement for lower resolution bandwidth when measuring compliance to regulations
- Concern about interference into GPS band if used for E911 services (safety-of-life concern)
  - Could reduce emissions in this region to sufficiently protect service – the GPS band will not be in main passband of UWB signals
- Some have proposed moving main starting point for UWB emissions greater than 2.0 GHz: 2.7, 3.1, and 6.0 GHz
- In general, capabilities of UWB slowly deteriorate as operational frequency increases, but still significant usefulness if move to 2.7 or even 3.1 GHz. A boundary of 6.0 GHz may be too restrictive.
- Indoor operation proposed to protect outdoor systems (U-NII precedent)<sup>40</sup>



# Conclusions

- UWB has some interesting properties that could be useful for short range applications (high throughput, interference robustness, low power, position location capability, flexibility).
  - Overlay approach may allow for greater use of the spectrum with high spatial reuse.
- Regulations are in process for allowing intentional UWB emissions, where interference to other narrowband systems is primary concern.
  - We believe reasonable regulations can be achieved that both protect the “narrowband” systems and allows UWB technology to be developed.
- Still exists interesting challenges in order to realize many of the promises of UWB technology.
- Intel is currently researching this technology.
  - Some areas of focus include: channel compensation, interference mitigation, fast acquisition/synchronization, capacity studies (multiple access), and implementation designs (esp. related to CMOS).
  - Also funding research with universities (UCSD and USC) in this area.<sup>41</sup>

# Invitation

## Intel's UWB Forum

October 11<sup>th</sup> (10:00AM) to 12<sup>th</sup> (1:00PM)

Featured speakers from USC, UCB, Rutgers U, UW, U of Colorado, Intel, Time Domain, XtremeSpectrum, LLNL, GE R&D, AT&T Labs

**FREE**

JFCC Auditorium  
Intel Jones Farm Campus  
Hillsboro, OR

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