UWBST & IWUWBS 2004

Looking for the UWB Communications Niche

R. A. Scholtz

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1978 Quote

From the Abstract of C. L. Bennett and G. F. Ross, "Time-Domain Electromagnetics and Applications," *Proc. IEEE*, March 1978:

"…More recently baseband pulse techniques have been applied to the problem of developing a short-range wireless communication link. Here, the low EM pollution and covertness of operation potentially provide the means for wireless transmission without licensing."

UWB Regulation

Approved FCC UWB Devices

Imaging Systems

1. Ground penetrating radars, wall imaging, medical imaging
2. Thru-wall imaging & surveillance systems

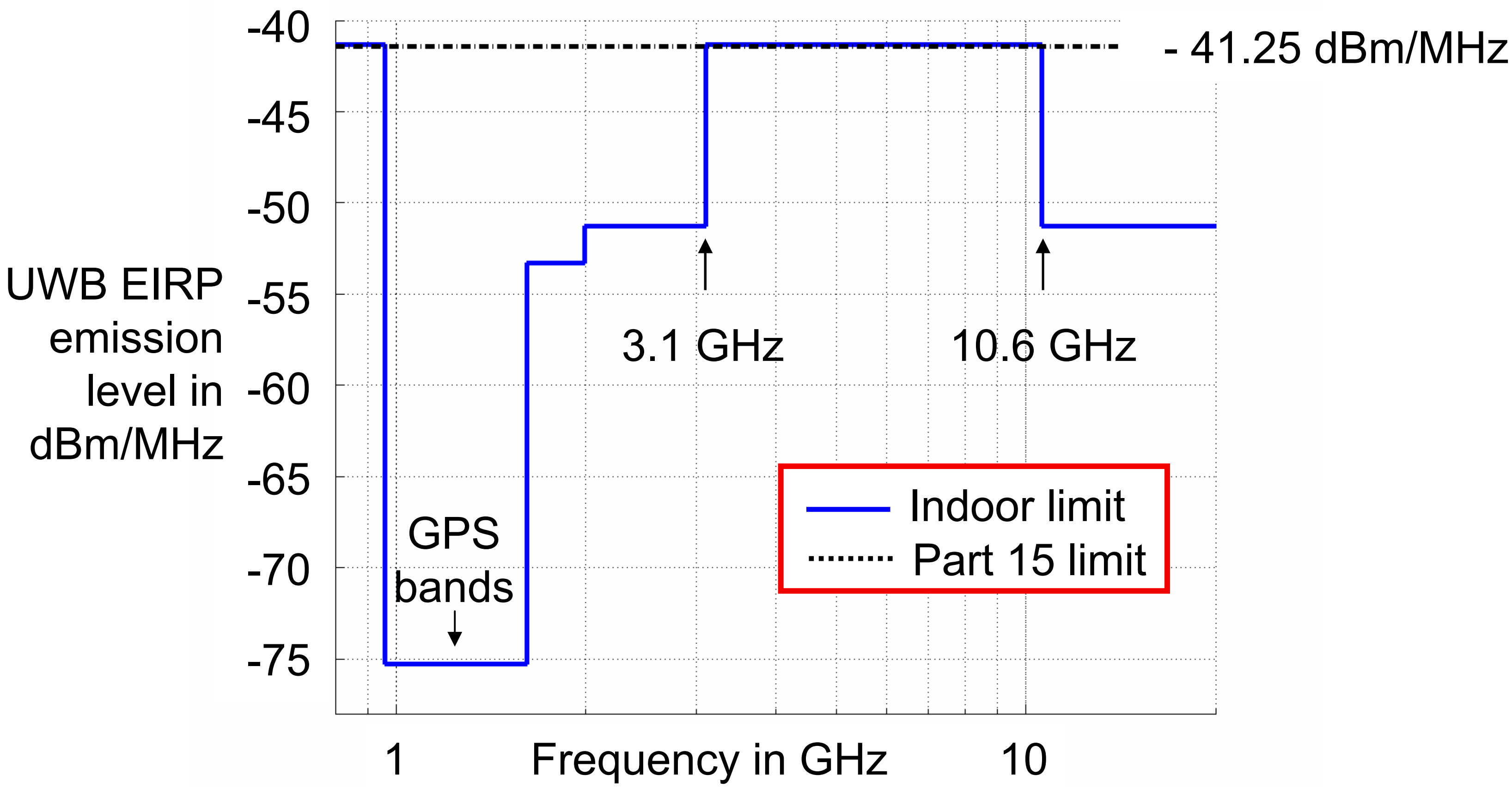
Communication and Measurement Systems

3. Indoor systems
4. Outdoor hand-held systems

Vehicular Radar Systems

5. Collision avoidance, improved airbag activation, suspension systems, etc.

UWB Emission Limit for Indoor Systems



Source: www.fcc.gov

Approximate Power Computations

FCC bound: 500 microvolts/meter/(MHz)$^{1/2}$ @ 3 meters
= -41.25 dBm/MHz EIRP

FCC band: 3.1 GHz to 10.6 GHz = 7500 MHz
→ -41.25 + 38.75 = -2.5 dBm EIRP (bound)

E_b/N_o at antenna terminals

< .56 mw

$$R_b(E_b/N_o) = (P_t G_t)(1/4\pi R^2)(G_r \lambda^2/4\pi/N_o$$

bit rate

energy per bit

equivalent receiver noise power spectral density

(Assuming free-space narrowband transmission, lossless antennas)

Comparison of Energy Link Loss

Input energy: $$W_{in} = \frac{1}{2\pi}\int_{BW} \frac{\left|V_G(\omega)\right|^2 R_T(\omega)}{\left|Z_T(\omega)+Z_G(\omega)\right|^2} d\omega$$

Receive energy: $$W_{rec} = \frac{1}{2\pi}\int_{BW} \frac{\left|V_L(\omega)\right|^2}{Z_L^*(\omega)} d\omega$$

Friis eq. w/ mismatch: $$\frac{W_{rec}(\omega)}{W_{in}(\omega)} = \frac{G_t(\omega)G_r(\omega)\lambda^2}{(4\pi r)^2}\left(1-\left|\Gamma(\omega)\right|^2\right)$$

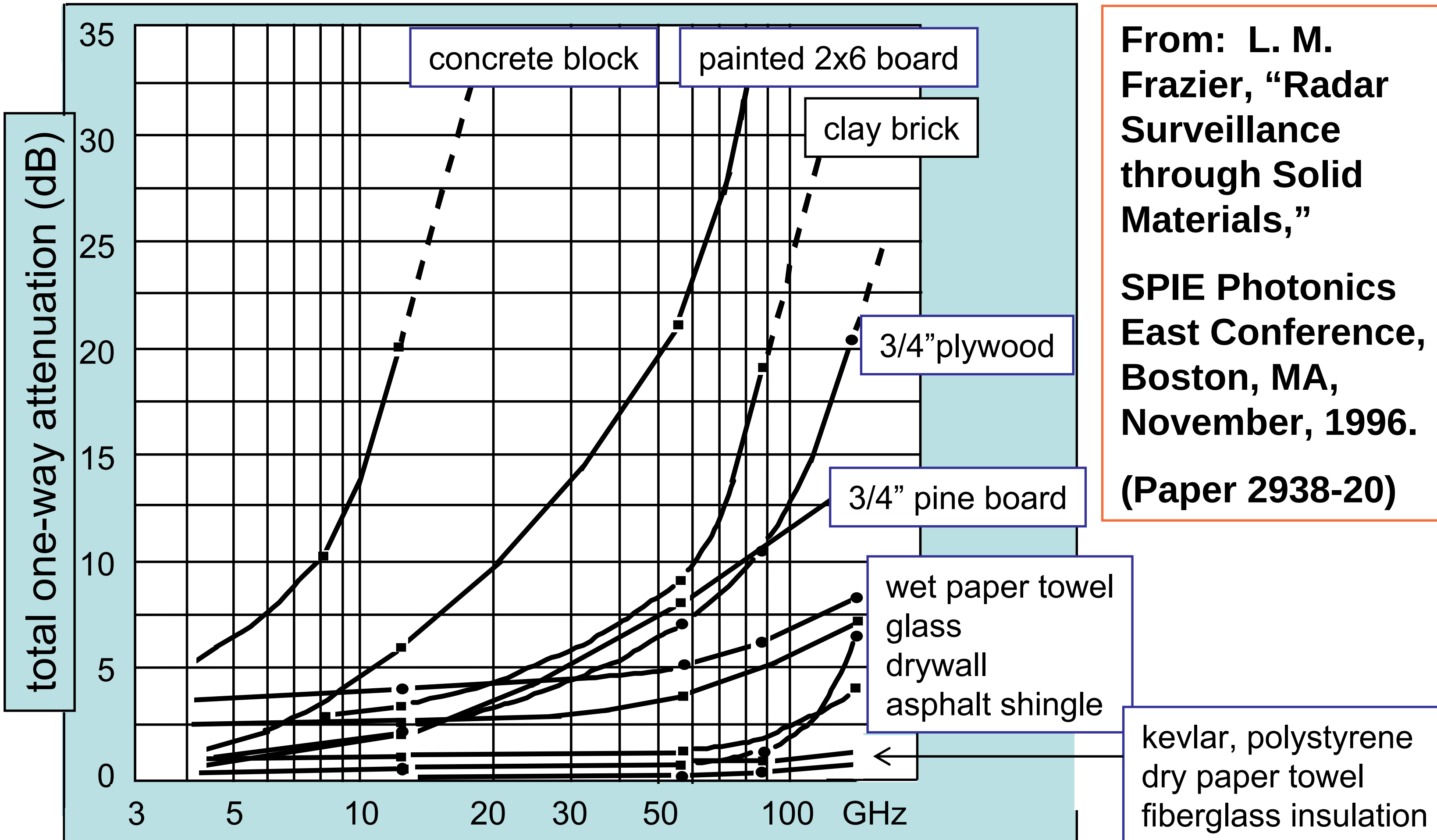
Link loss: $$L_{link} = \frac{W_{rec}}{W_{in}}$$

Normalized (*r* =1) Energy Link Loss for Various Antennas and Excitations

T/R Antennas (Dipoles)	Gaussian (rigorous)	Monocycle (rigorous)	Mid-band Frequency	Mid-band Friis eq.	Mid-band Friis w/ Z-Mismatch
Short	-85.5 dB	-84.0 dB	430 MHz	-20.8 dB	-87.0 dB
Resonant	-23.9 dB	-23.9 dB	500 MHz	-22.1 dB	-22.4 dB
Lossy	-43.1 dB	-41.8 dB	500 MHz	-22.1 dB	-22.3 dB

See D. Pozar, Closed-Form Approximations for Link Loss in an UWB Radio System Using Small Antennas, *IEEE Trans. on Antennas and Prop.*, Sept. ‘03.

Materials Penetration



From: L. M. Frazier, “Radar Surveillance through Solid Materials,”

SPIE Photonics East Conference, Boston, MA, November, 1996.

(Paper 2938-20)

Friis' Equation Adjustments

wavelength of mid-band frequency

$$R_b(E_b/N_o) = (P_tG_t)(1/L_{prop}4\pi\, R^2)\eta_{ant}(G_r\, \lambda^2/4\pi/N_o$$

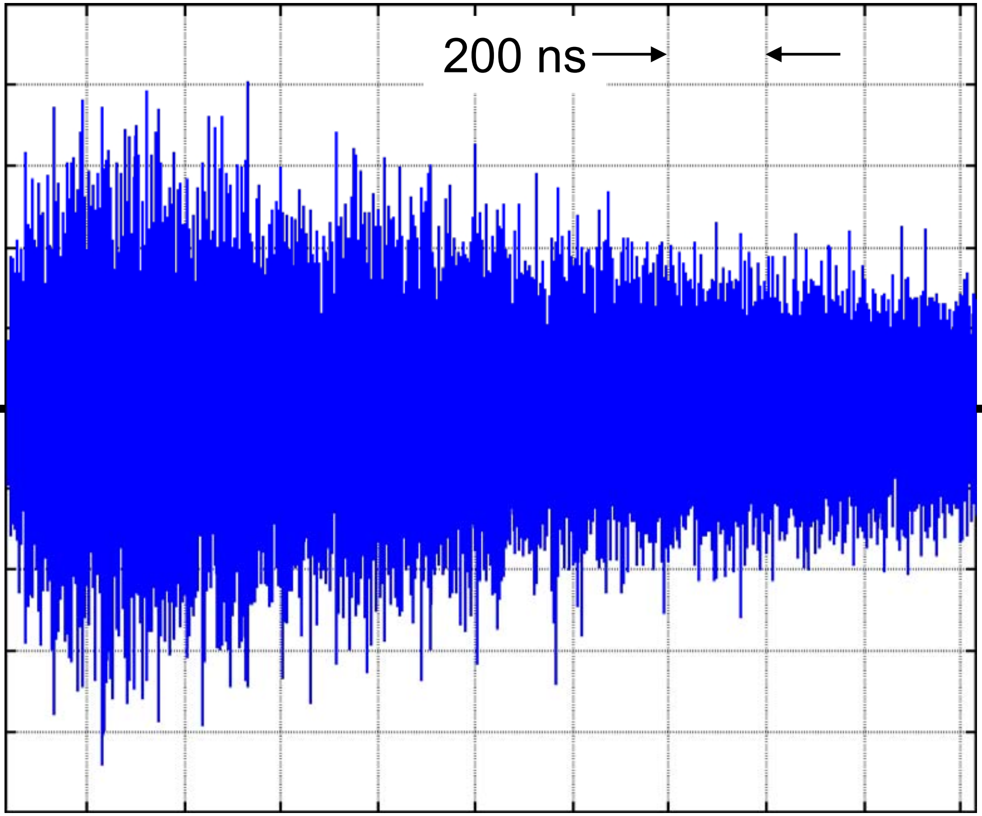
propagation losses

antenna mismatch, losses

UWB Propagation

A Pulse Response Gallery

shipboard:
cargo hold,
blocked
line-of-sight



USS Curtiss Measurements

Channel/Receiver Model Development

$m(t)$ = channel response waveform
$h(t)$ = correlator template function

Problem: Find $\{ a_n, t_n \}_{n=1}^{N}$ that provides a good estimate $\hat{m}(t)$ of the channel response function $m(t)$.

$$\hat{m}(t) = \sum_{n=1}^{N} a_n h(t - t_n)$$

Significance: N is a measure of Rake receiver complexity.

Simple CLEAN Analysis

QuickTime™ and a
Animation decompressor
are needed to see this picture.

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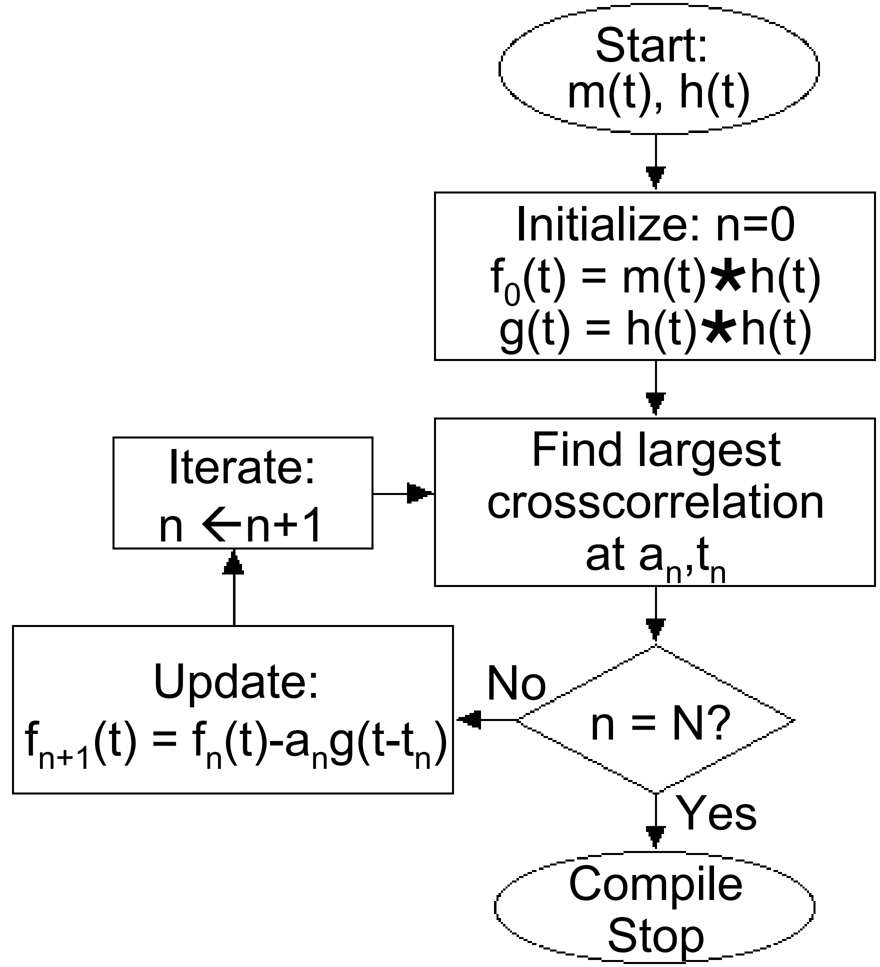


UWB Array Processing

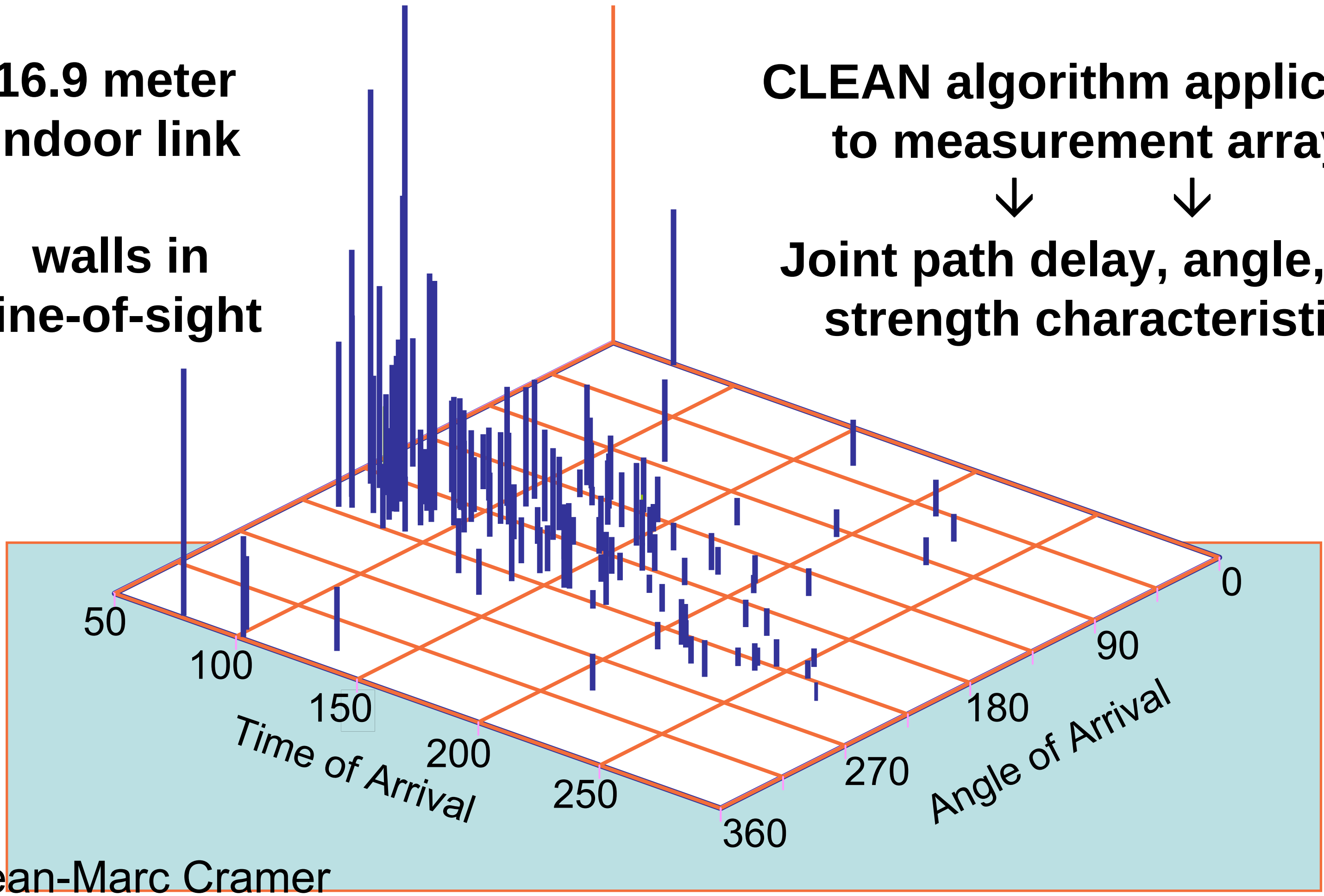
16.9 meter indoor link

walls in line-of-sight

CLEAN algorithm application to measurement arrays

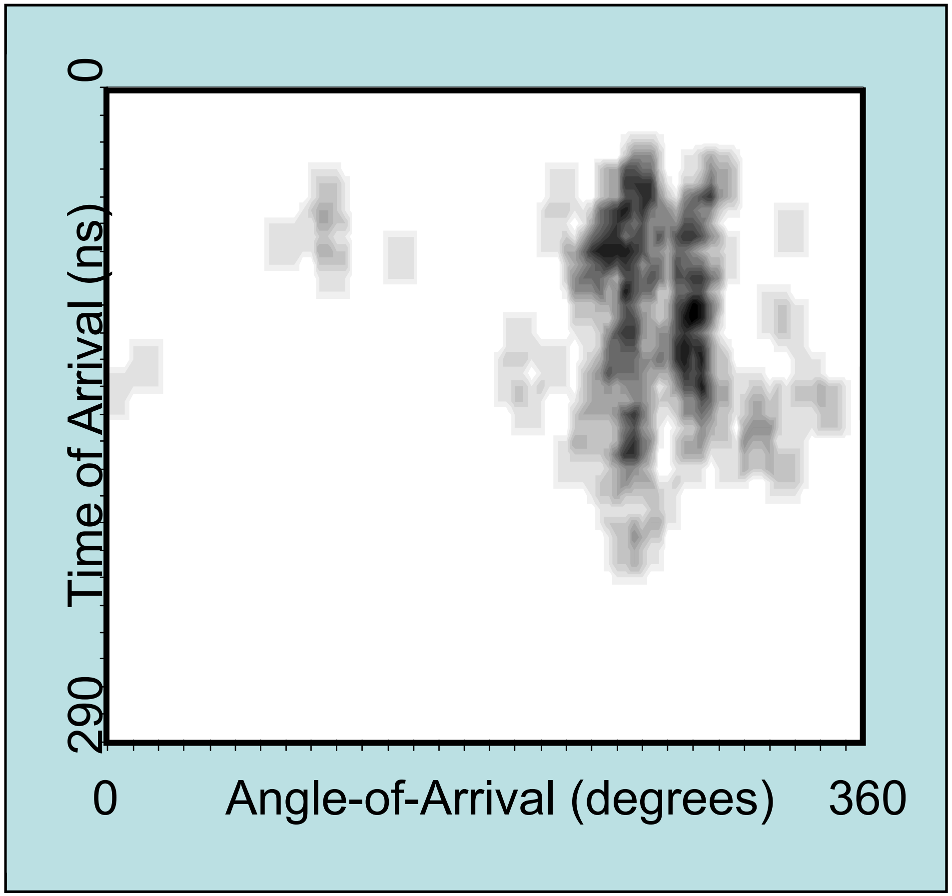
↓ ↓

Joint path delay, angle, and strength characteristics



Jean-Marc Cramer

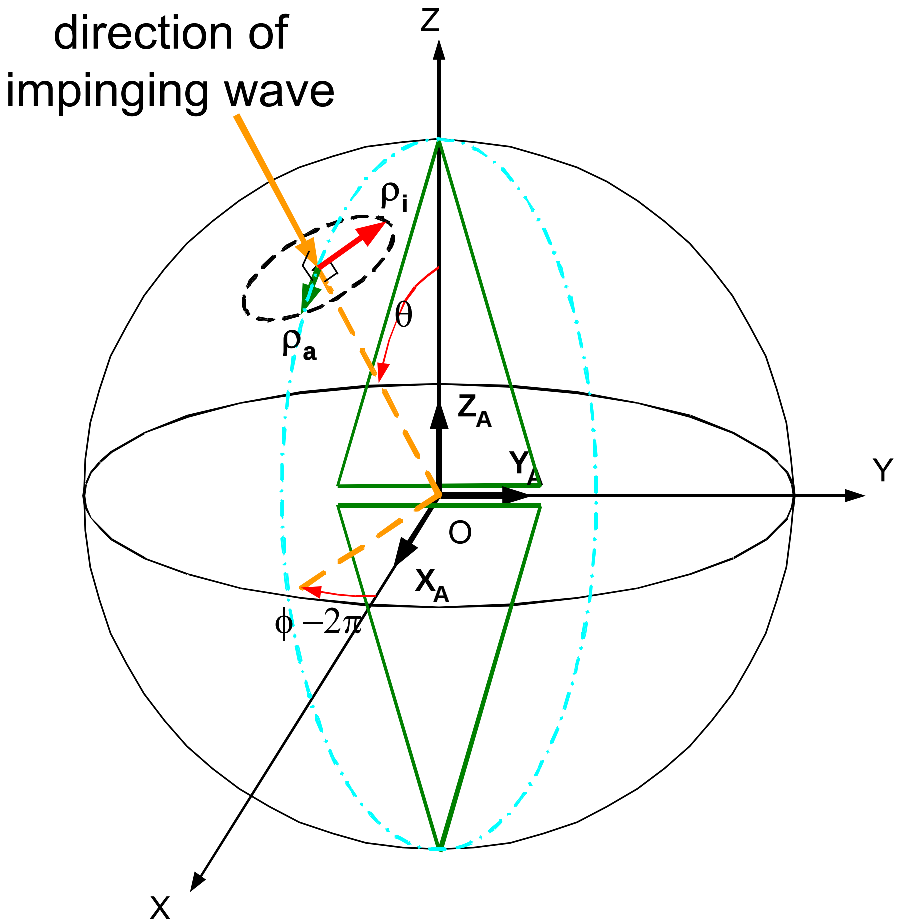
Cluster Models



See J. Cramer, R. Scholtz, and M. Win, "Evaluation of an Ultra-Wide-Band Propagation Channel," *IEEE Trans. On Antennas and Propagation*, May 2002.

Jean-Marc Cramer

Multipath Polarization Measurement



Sanghyun Chang

Make array measurements in 3 different polarizations

CLEAN *x*

CLEAN *y*

CLEAN *z*

Group path measurements
Path *i* : t_i, θ_i, ϕ_i, $v_{xi}(t)$, $v_{yi}(t)$, $v_{zi}(t)$

Estimate direction, polarization and e-field waveform for each path.

Directional Effects - Large Antennas

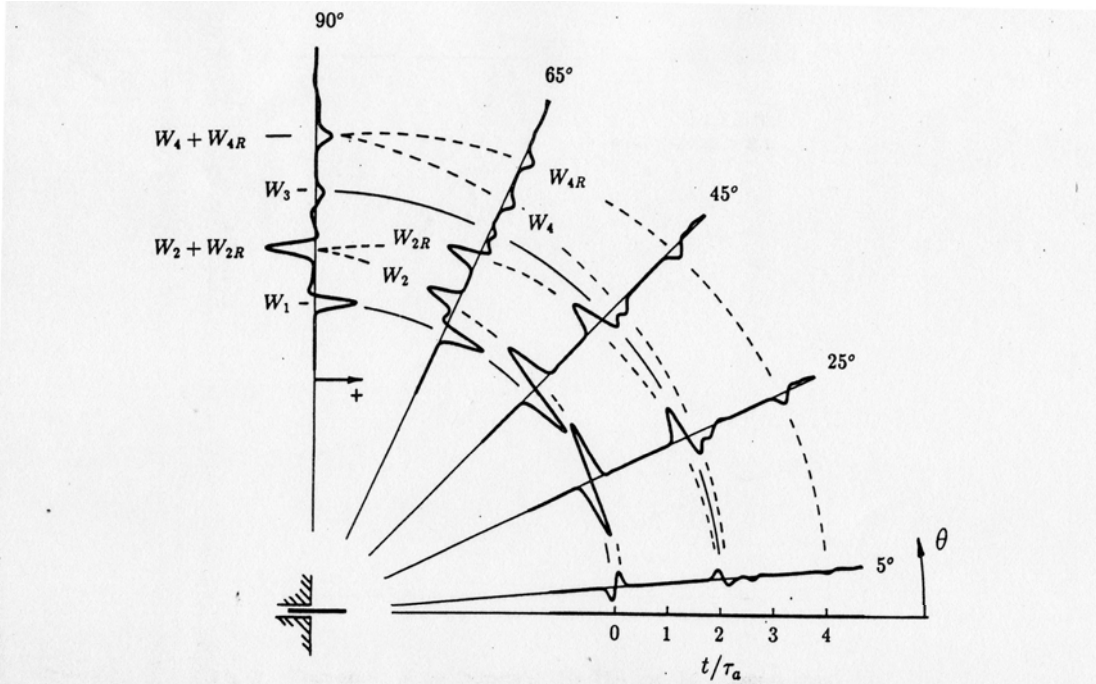


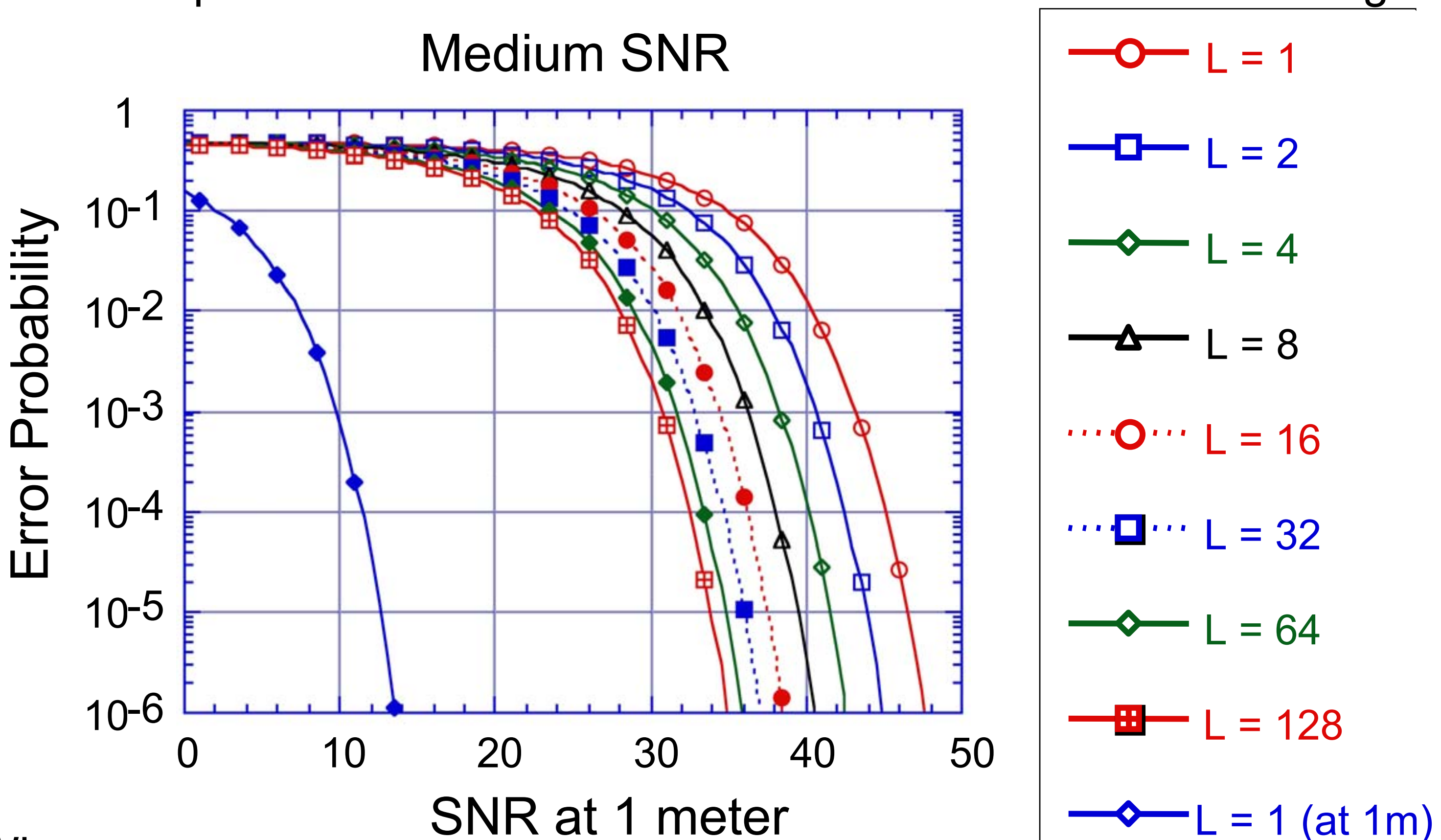
Fig. 7. Radiation of a Gaussian pulse from a cylindrical monopole antenna. Each trace shows the far-zone electric field $\mathcal{E}_\theta^r$ at a fixed polar angle θ as a function of the normalized time t/τ_a. $b/a = 2.30$, $h/a = 65.8$, and $\tau_p/\tau_a = 8.04 \times 10^{-2}$.

From: J. Maloney et al., “Accurate Computation of the Radiation from Simple Antennas Using the Finite-Difference Time-Domain Method,” *IEEE Trans. On Antennas and Propagation*, July 1990.

UWB Receiver Design

Selective Rake Performance

1 ns transmitted pulse



Moe Win

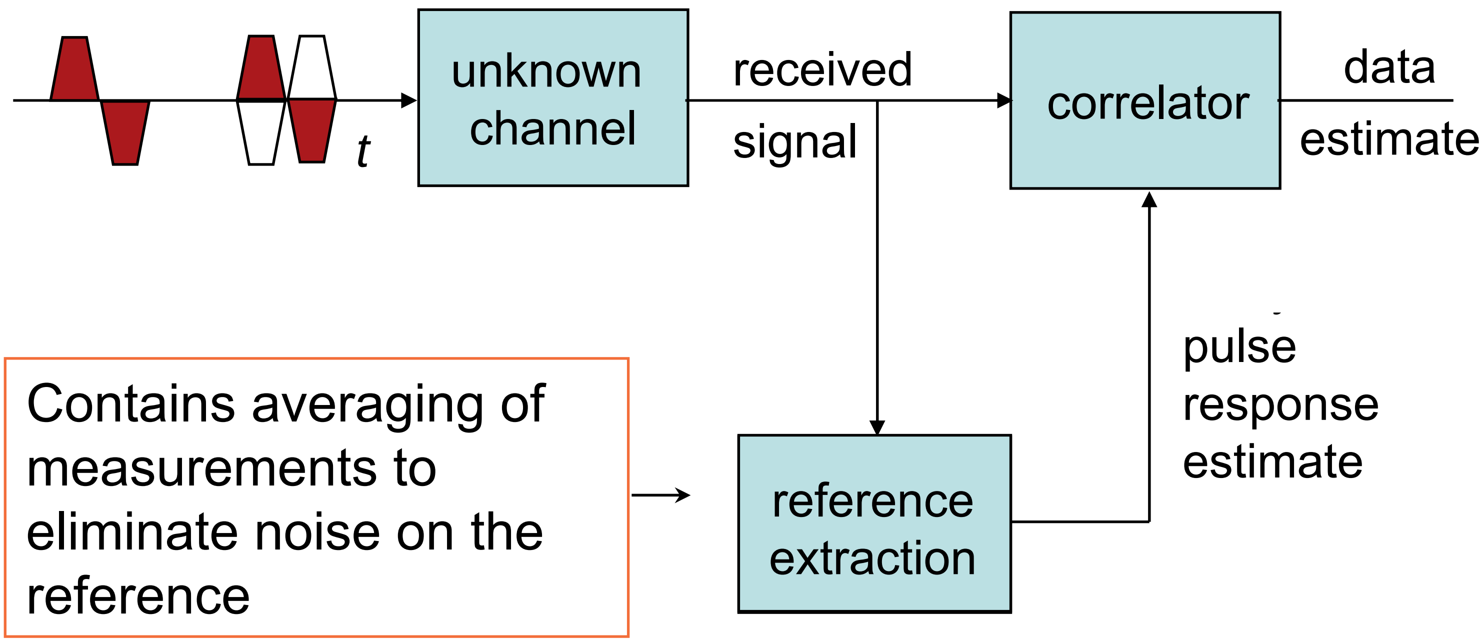
Selective Rake Performance

For a description of the development of these curves of selective Rake performance, see:

M. Win and R. Scholtz, “Characterization of Ultra-Wide Bandwidth Wireless Indoor Channels: A Communication Theoretic View,” *IEEE JSAC*, December 2002.

Propagation data and papers are available at:
http://click.usc.edu/New_Site/

Transmitted-Reference System



From R. Scholtz, *Coding for Adaptive Capability in Random Channel Communications*, PhD Thesis, Stanford University, 1963.

TR and SR UWB Comparisons

Stored reference (one Rake finger) receiver performance:

$$P_{\mathrm{eSR}} = Q\left(\sqrt{2E_{\mathrm{p}}N_{\mathrm{p}}\eta_{\mathrm{capSR}}/N_{\mathrm{o}}}\right)$$

Transmitted reference receiver (analog delay) performance:

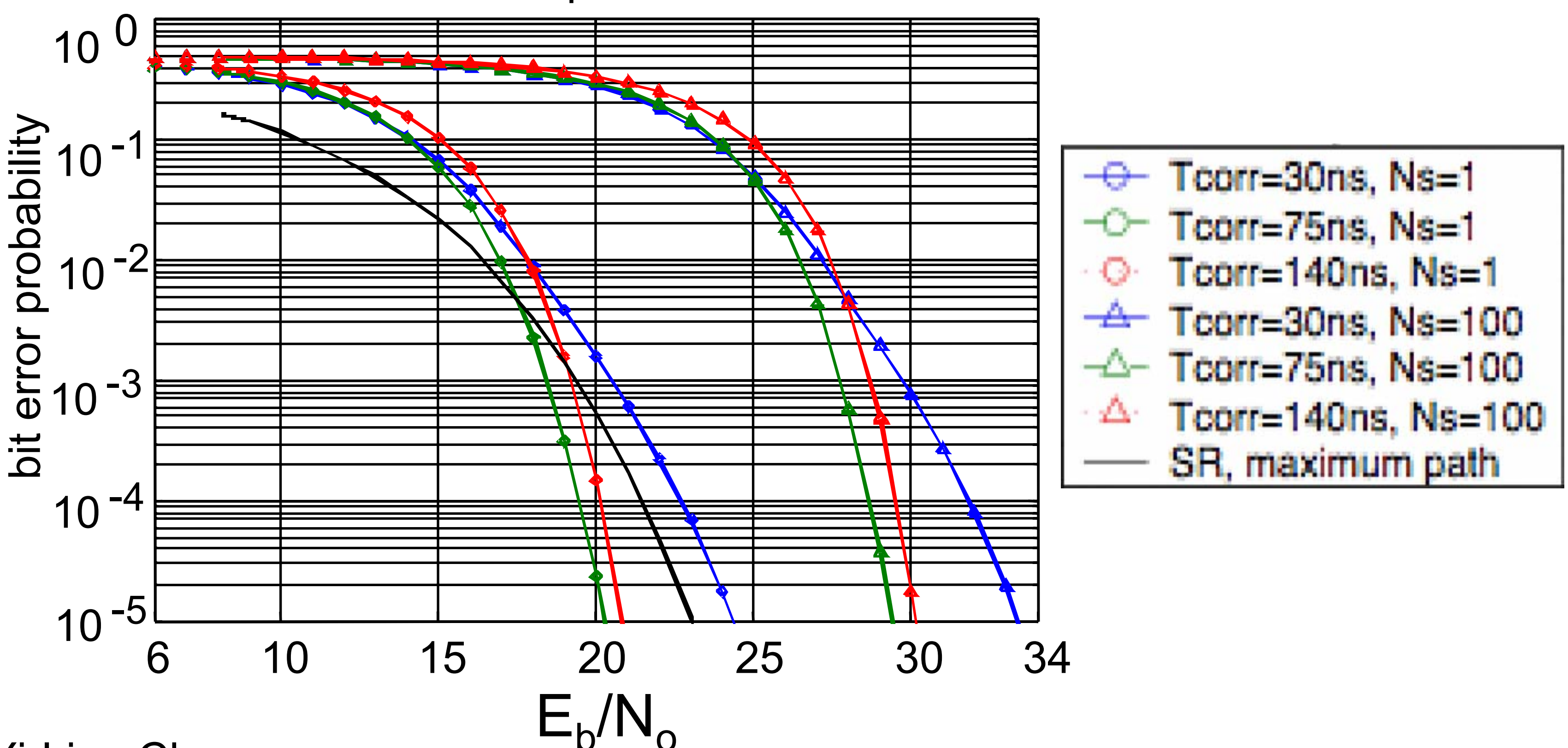
$$P_{\mathrm{eTR}} \approx Q\left(\left[\frac{2}{N_{\mathrm{p}}}\left(\frac{N_{\mathrm{o}}}{\eta_{\mathrm{capTR}}E_{\mathrm{p}}}\right) + \frac{WT_{\mathrm{corr}}}{N_{\mathrm{p}}}\left(\frac{N_{\mathrm{o}}}{\eta_{\mathrm{capTR}}E_{\mathrm{p}}}\right)^{2}\right]^{-\frac{1}{2}}\right)$$

(uncoded binary transmission with antipodal flip modulation)

Yi-Ling Chao

TR and SR UWB Comparisons

second derivative Gaussian pulse with duration = 0.7ns



Yi-Ling Chao

E_b/N_o Adjustment I

Effective E_b/N_o at the data detector

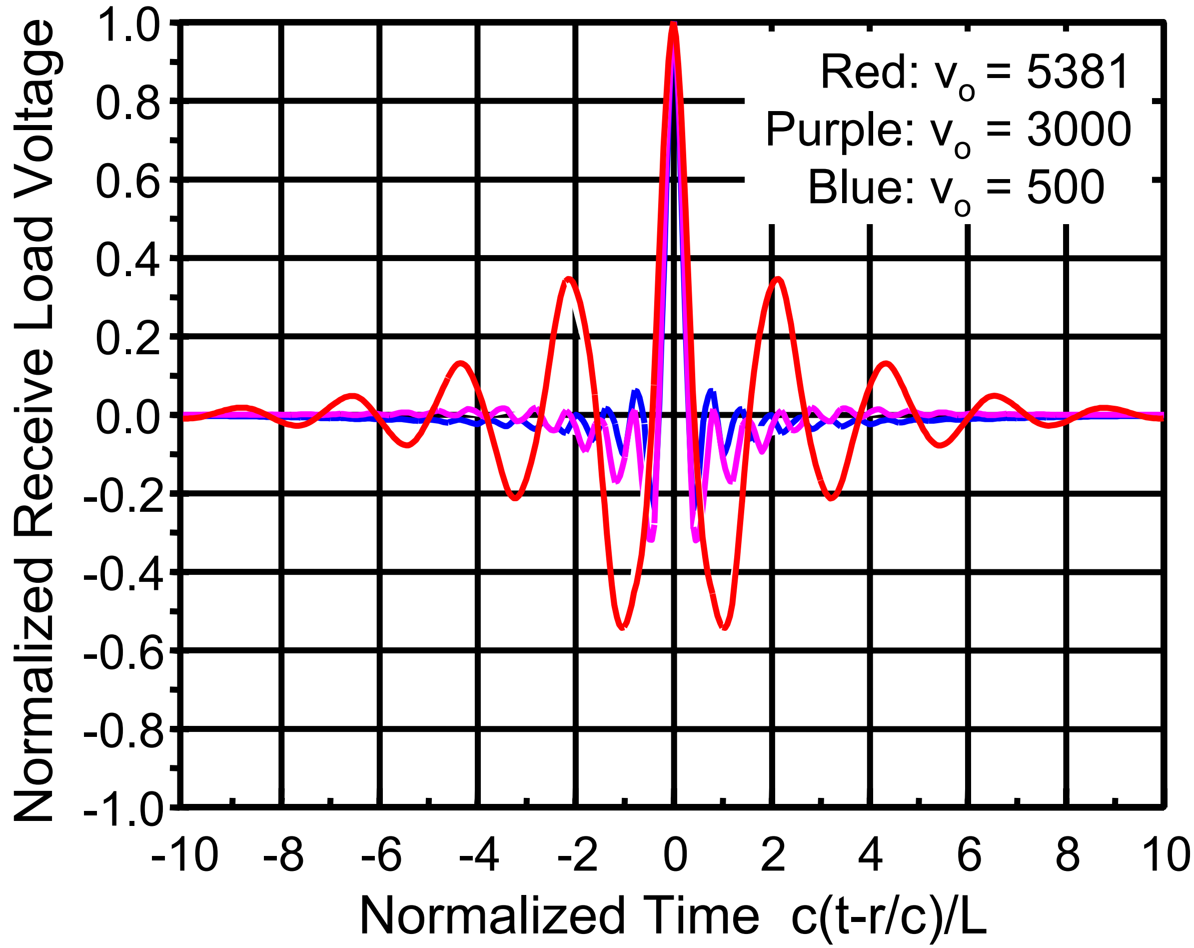
$$R_b(E_b/N_o)_{eff} = (P_t G_t)(1/L_{prop} 4\pi R^2) \cdot (G_r \lambda^2/4\pi)\, \eta_{ant}\, \eta_{cap} / N_o$$

energy capture efficiency

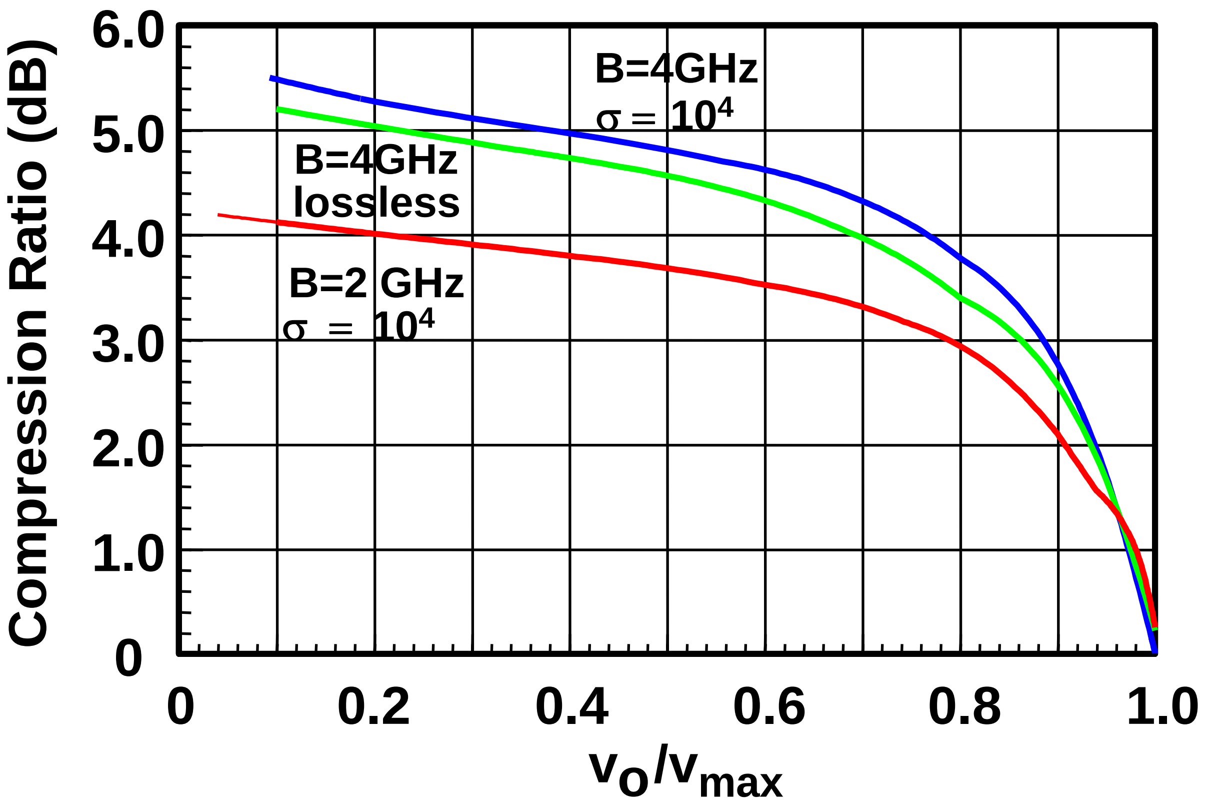
Pulse Design

Received Pulse Width Minimization

See: D. Pozar, "Waveform Optimizations for Ultra-Wideband Radio Systems," *IEEE Trans. Antennas and Prop.*, September 2003.

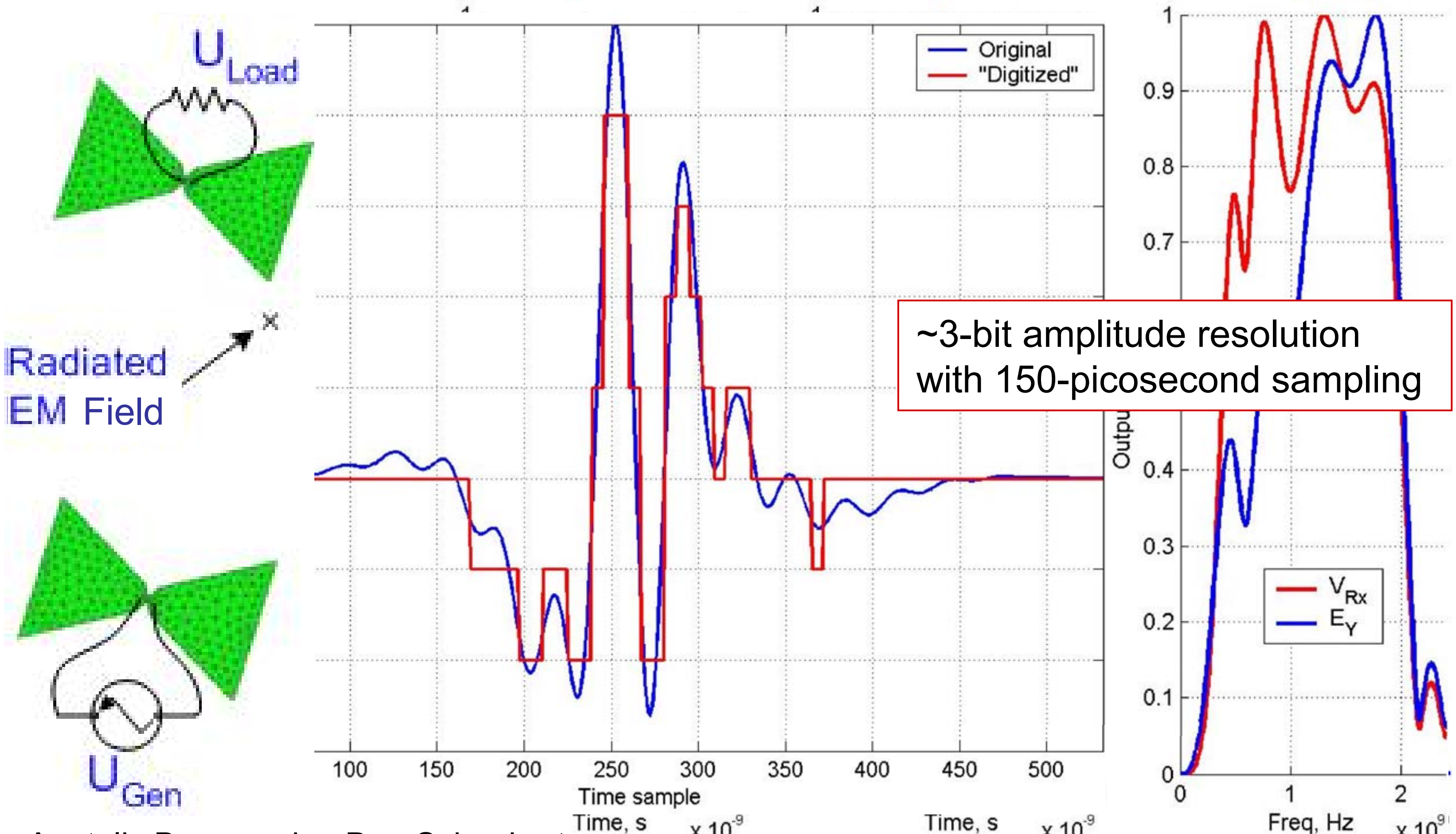


Pulse Compression



David Pozar

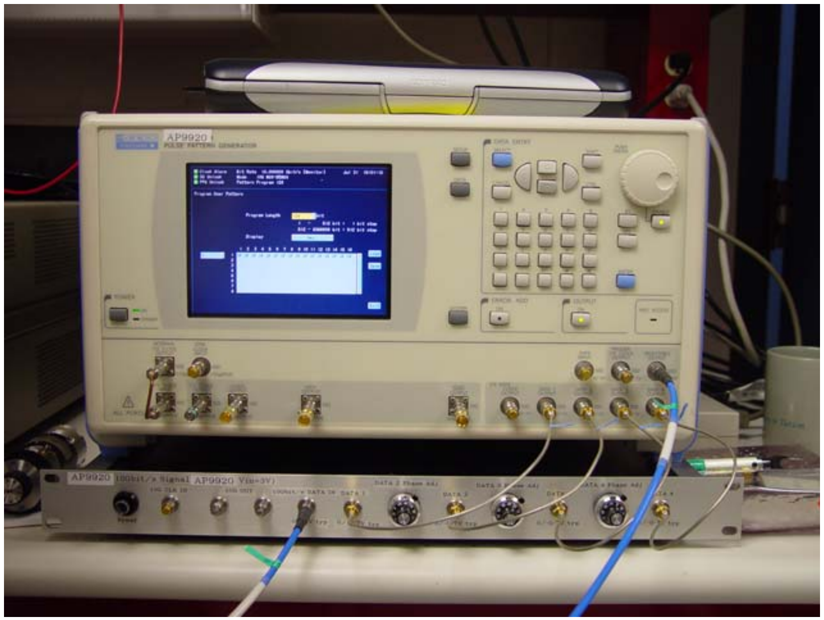
Antenna-Circuit Interactions



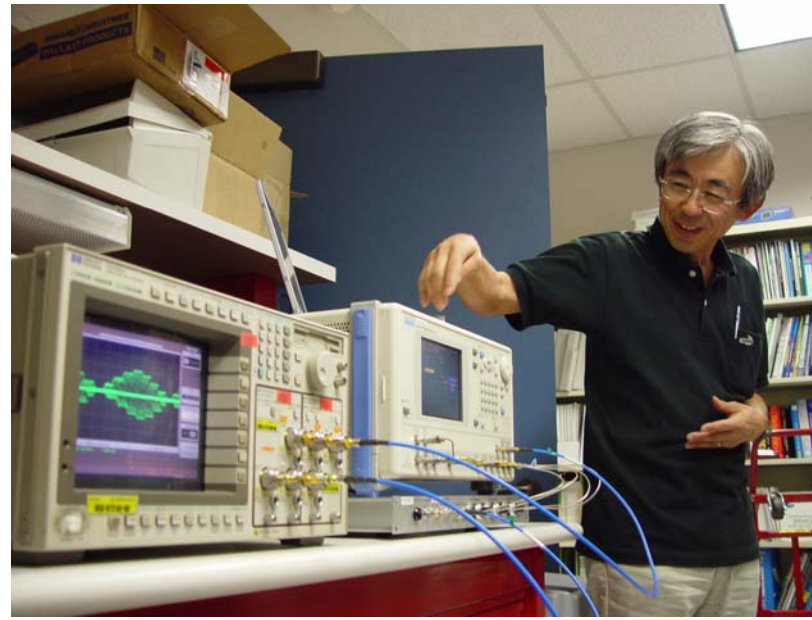
~3-bit amplitude resolution with 150-picosecond sampling

Anatoliy Boryssenko, Dan Schaubert

UWB Signal Synthesizer



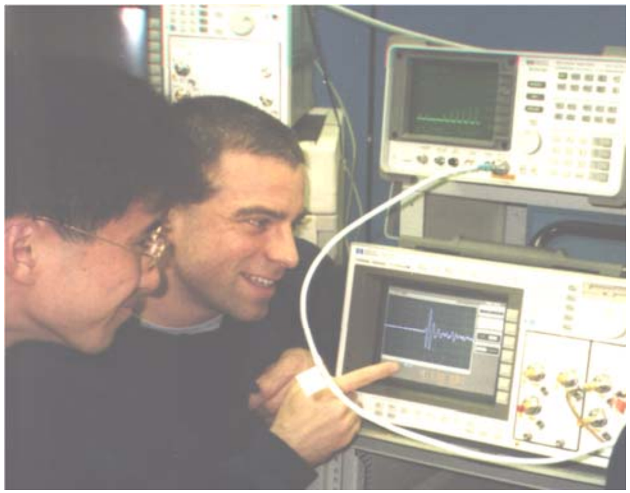
AP9950 and BX4120 UWB Ultra Wideband Signal Generator, Ando Electric Co., Ltd, Yokohama, Japan.

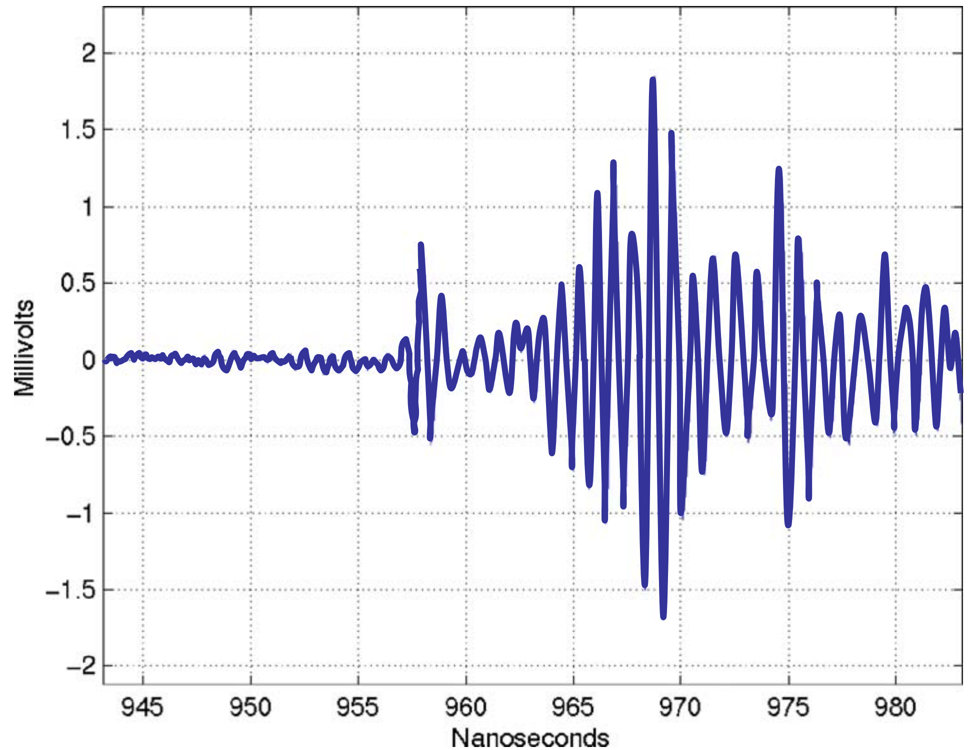


Shusaku Shimada demonstrating equipment at the UltRa Lab, July 30 - August 3, 2003.

Time Resolution and Ranging

Ranging Algorithms





Where is the beginning of the first return?

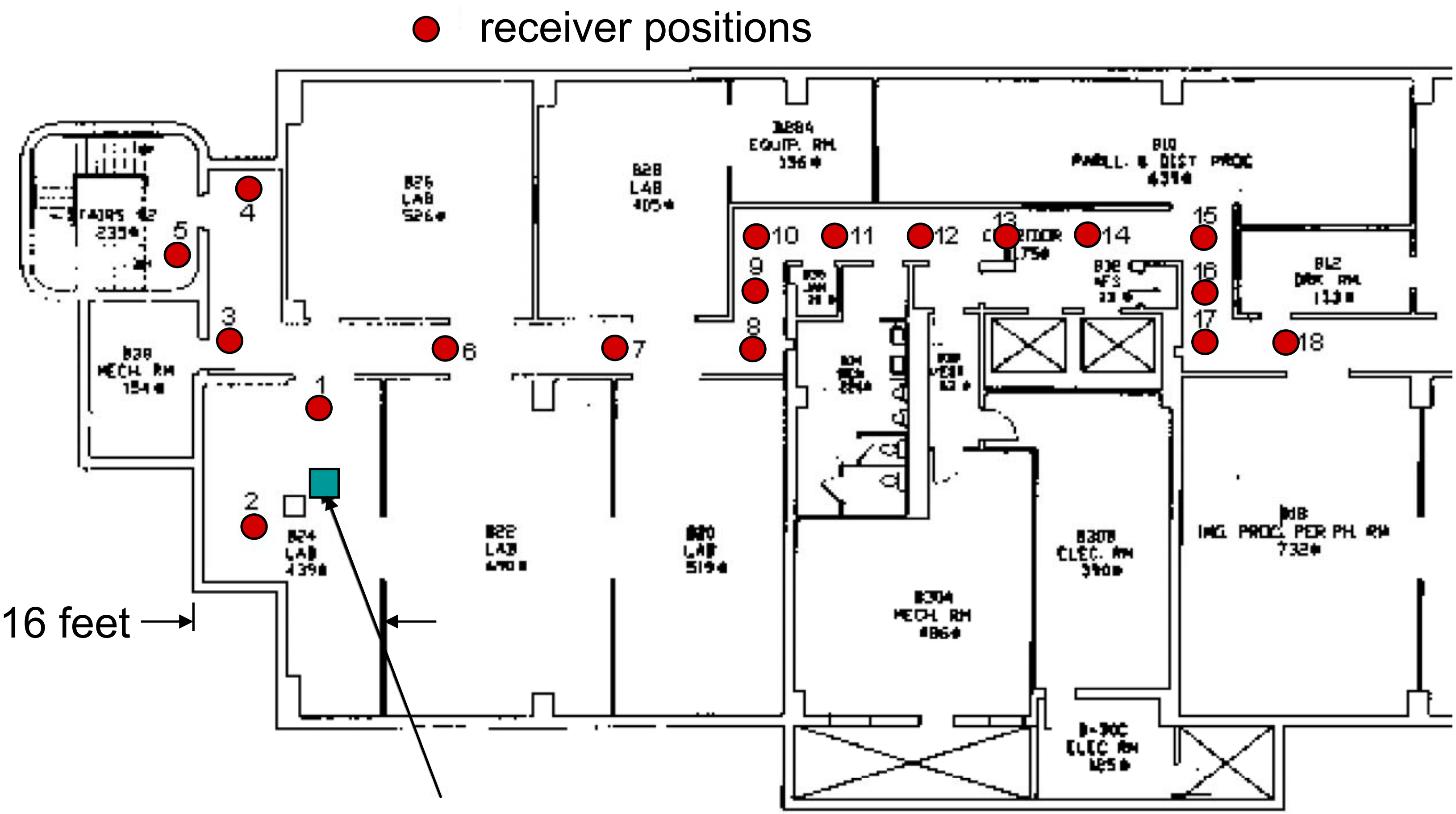
Is the line-of-sight blocked?

1 ns (time) → | | ← **1 foot (space)**

Joon-Yong Lee

Ultra-Wideband Radio

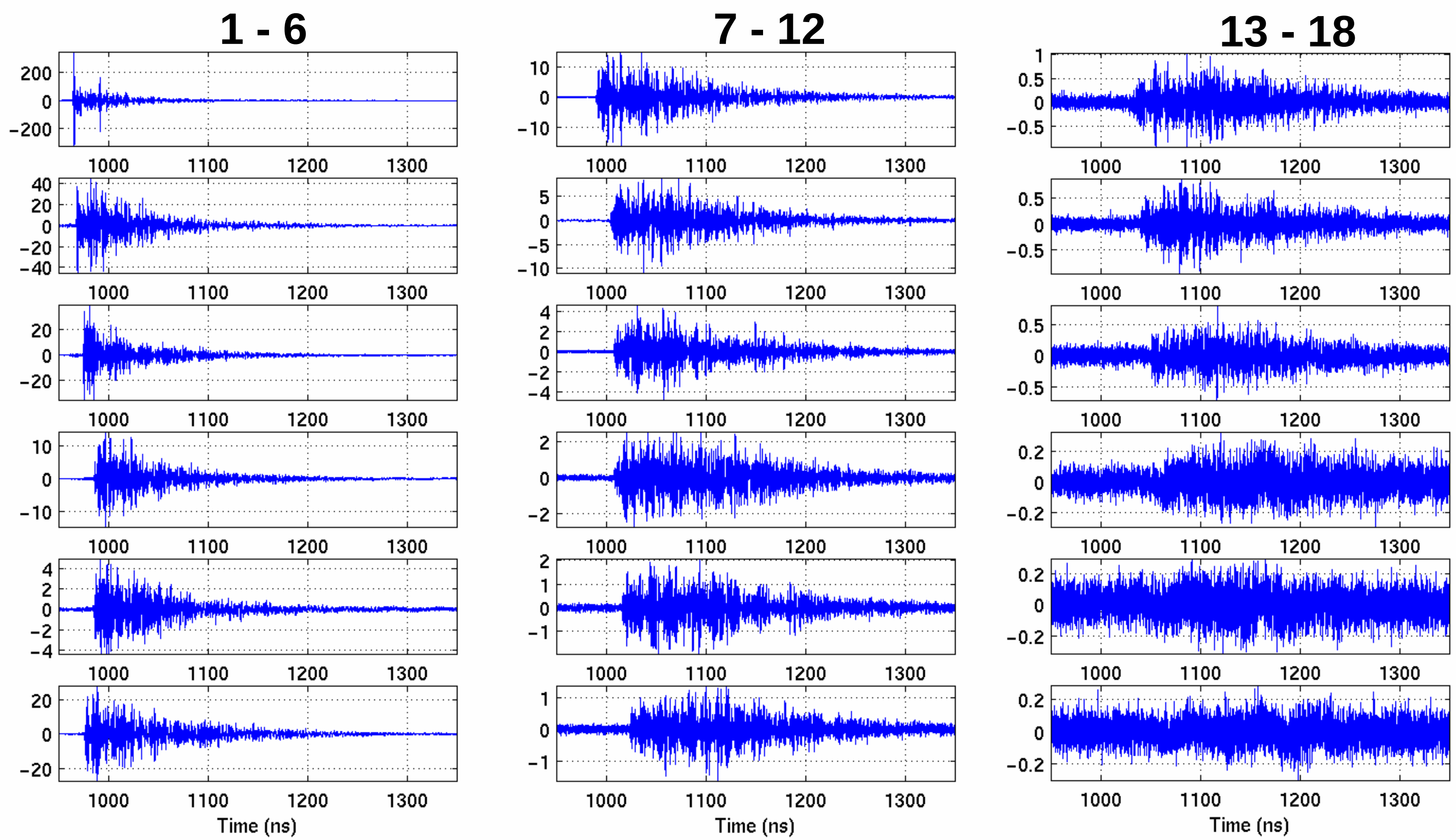
Test Site (Basement, EEB, USC)



Joon-Yong Lee

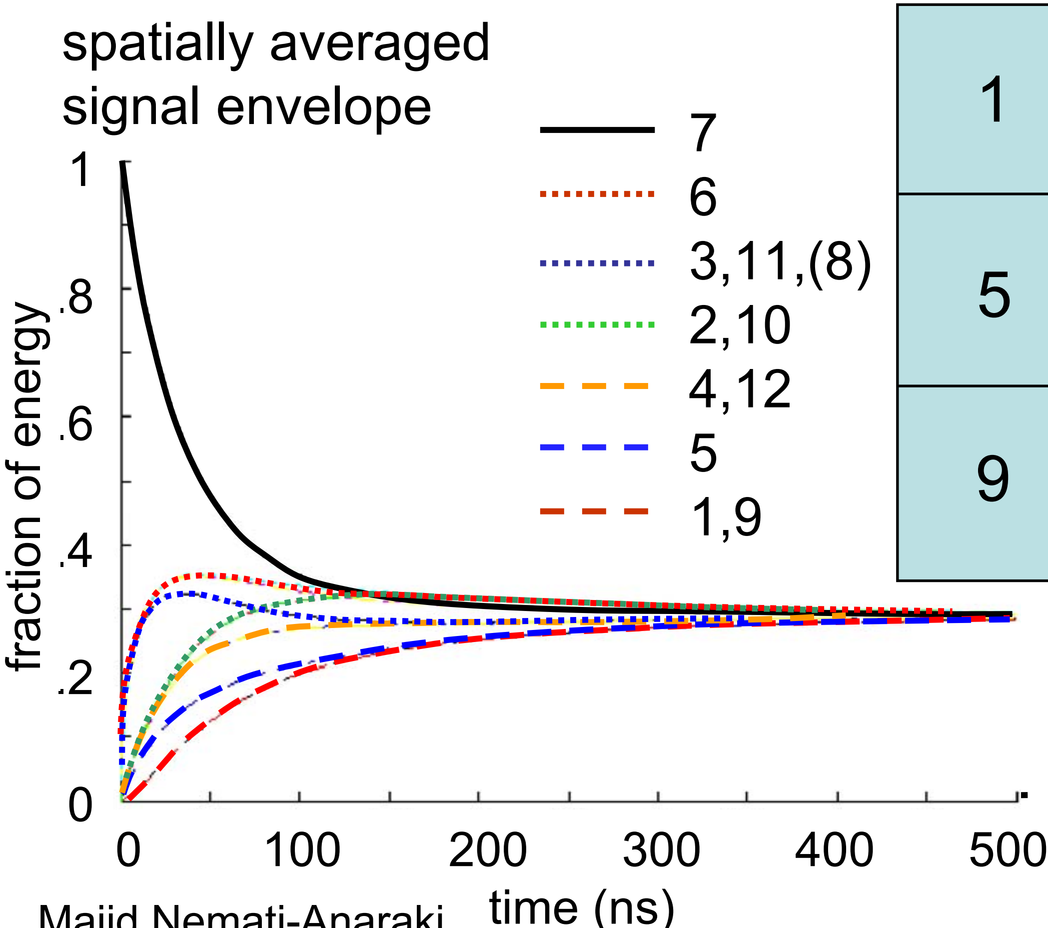
Transmitter

Measured Signals

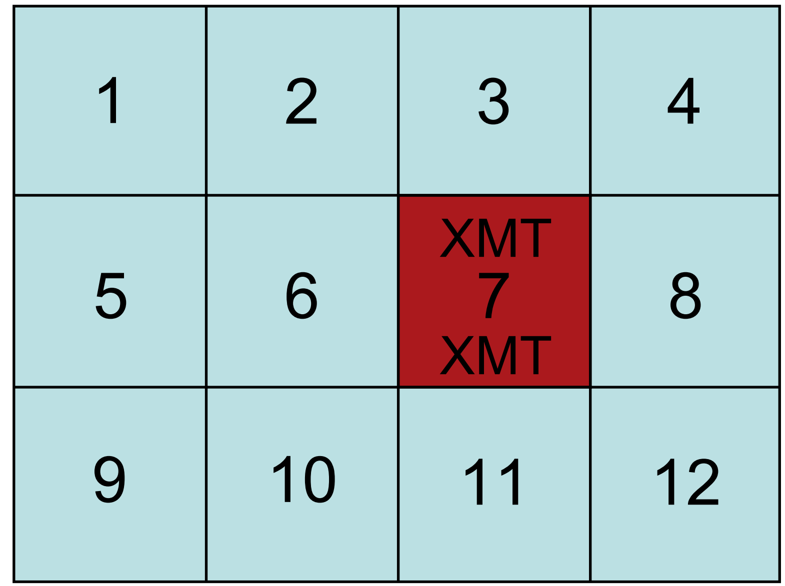


Joon-Yong Lee

Diffusion Models



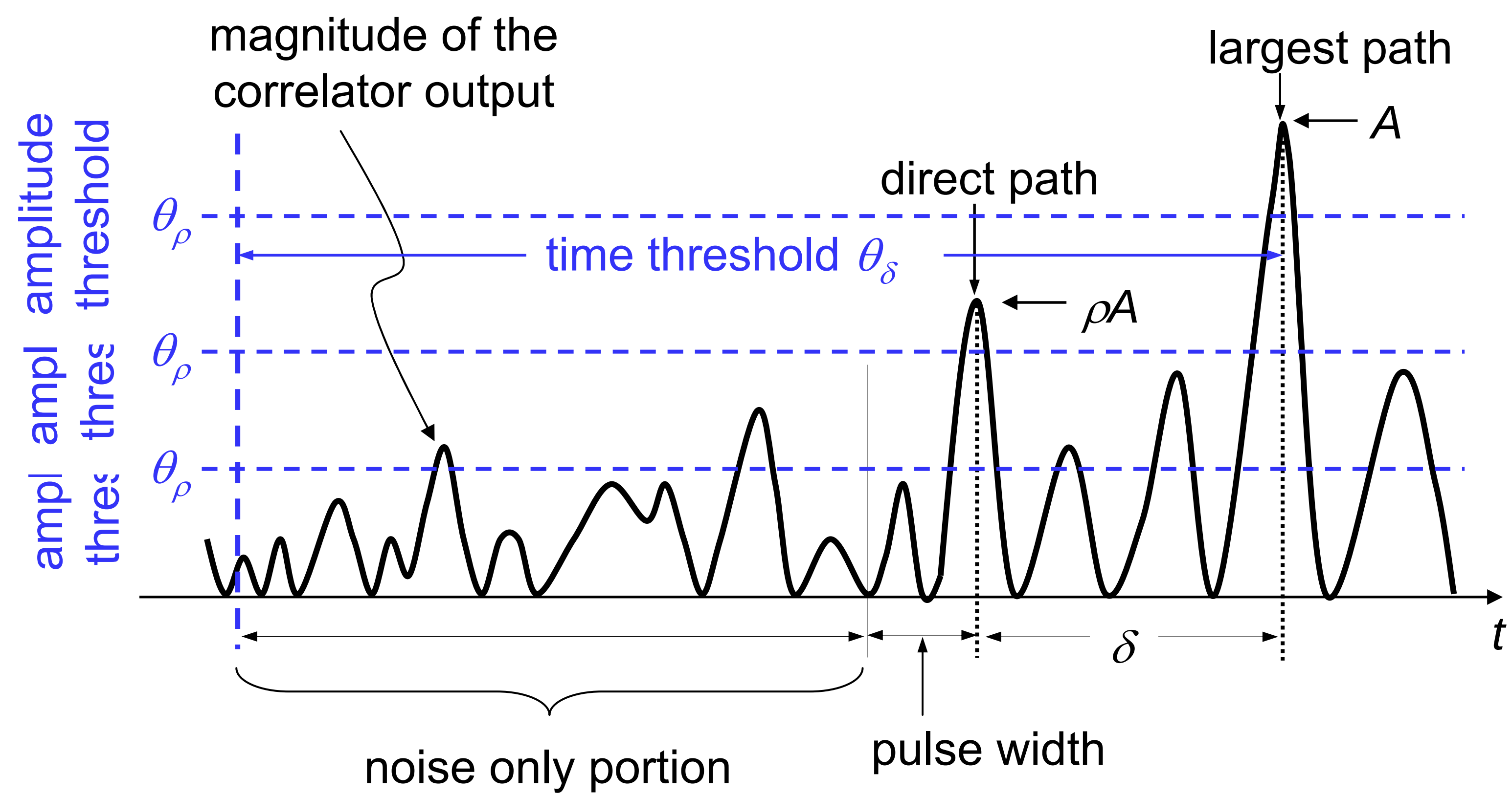
Majid Nemati-Anaraki



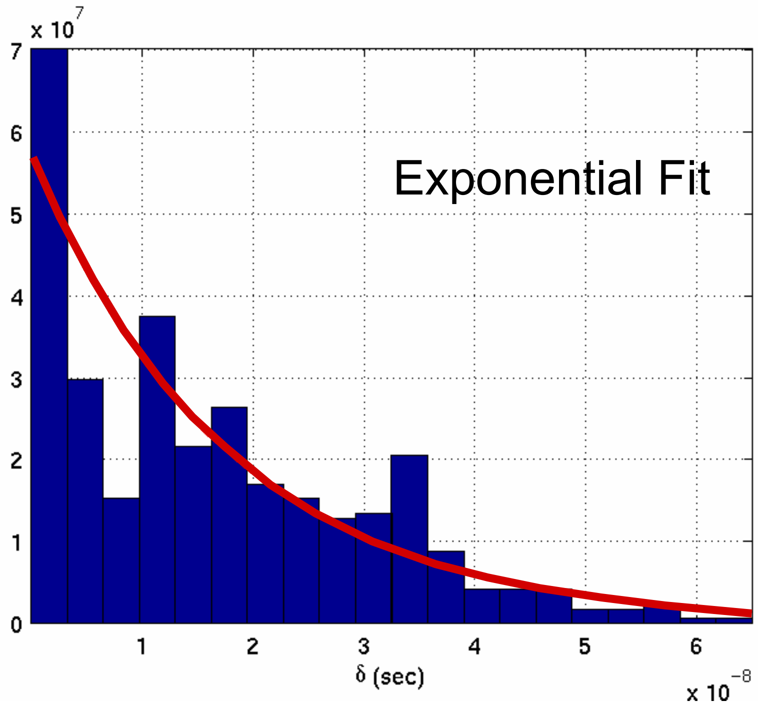
<u>Model assumptions</u>:

- many reflectors in indoor environment
- homogeneous energy distribution in each room

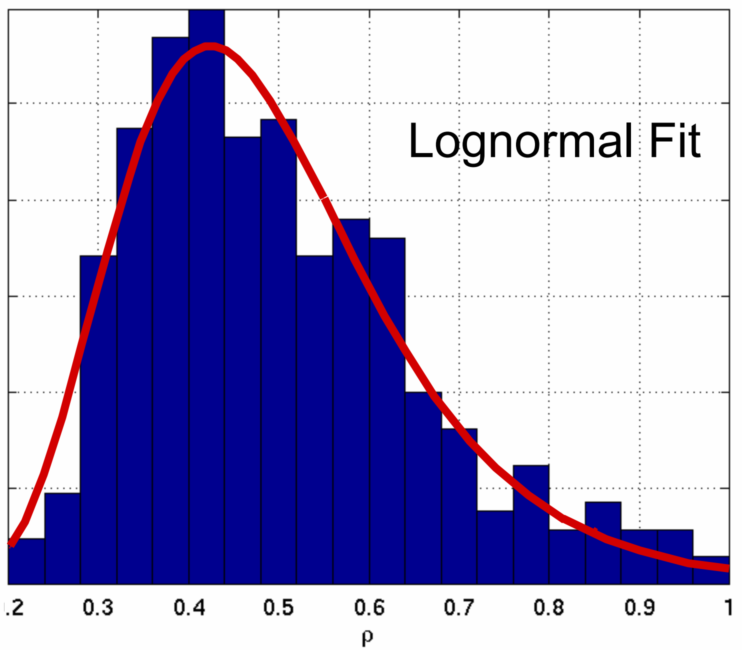
Thresholding Effects



Statistics of δ and ρ

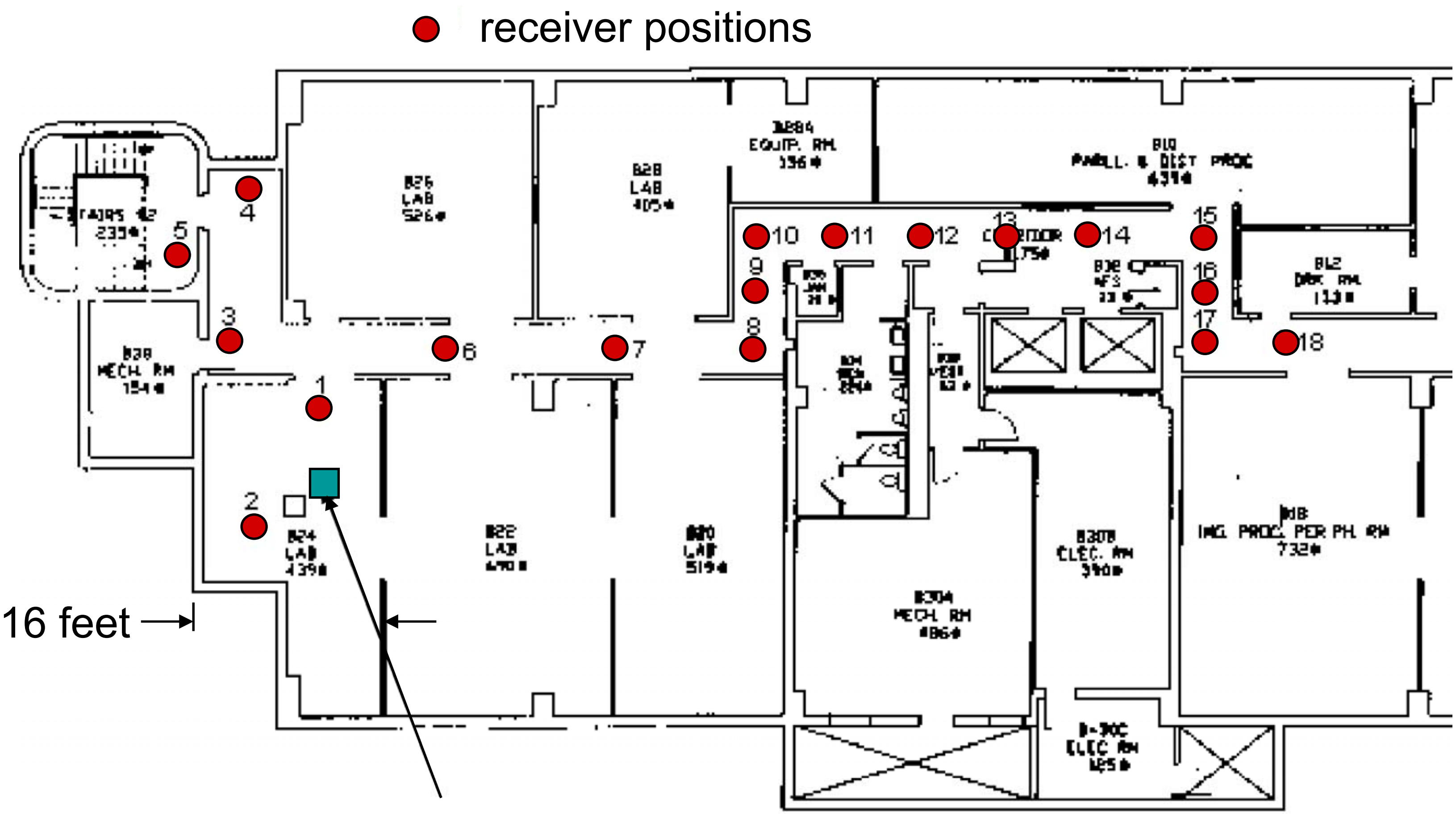


Differential delay between direct and strongest path signals when these signals are distinct.



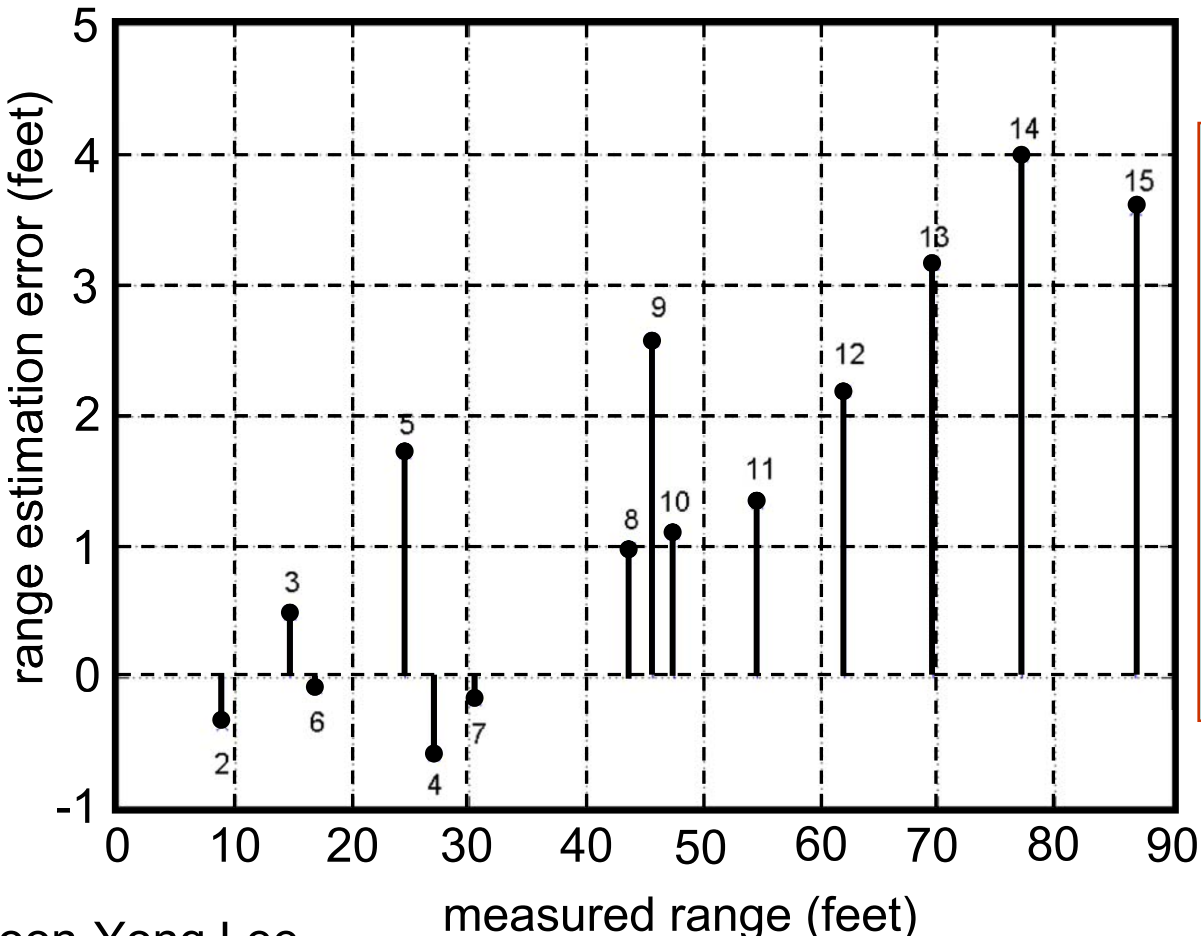
Amplitude ratio of direct-path signal to strongest path signal when these signals are distinct.

Test Site (Basement, EEB, USC)



Joon-Yong Lee

Ranging Algorithm Performance



J.-Y. Lee and R. Scholtz, "Ranging in a Dense Multipath Environment Using an UWB Radio Link," *IEEE JSAC*, Dec. 2002.

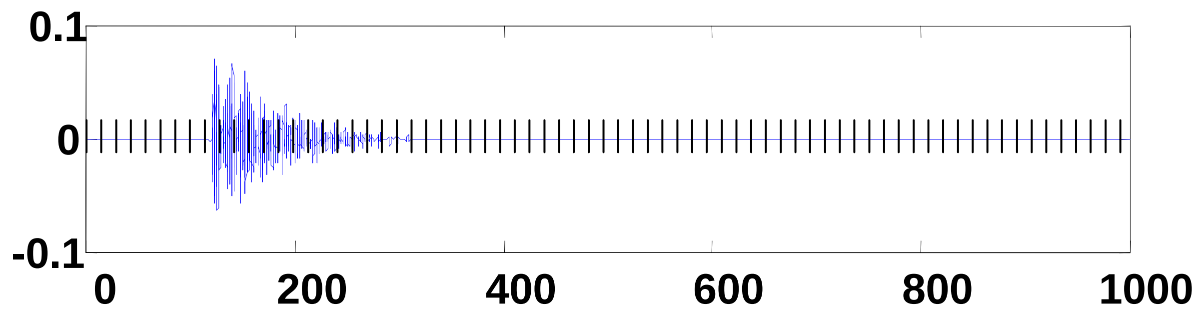
Joon-Yong Lee

Acquisition

Eric Homier

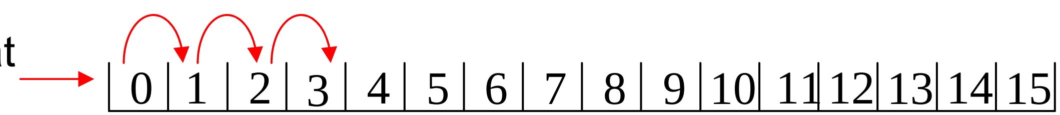
Two Types of Serial Searches

Coarse Acquisition:
Find some part of the received waveform



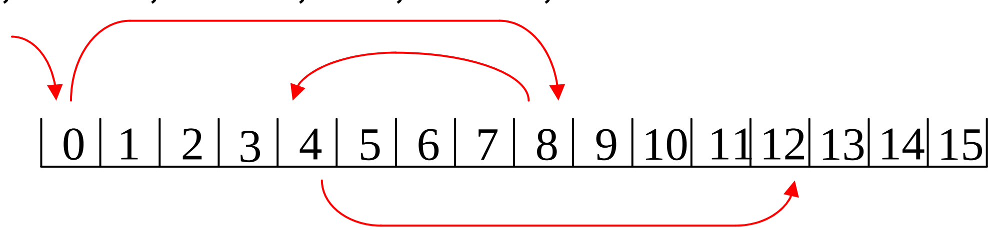
Linear Search:

Start at bin 0



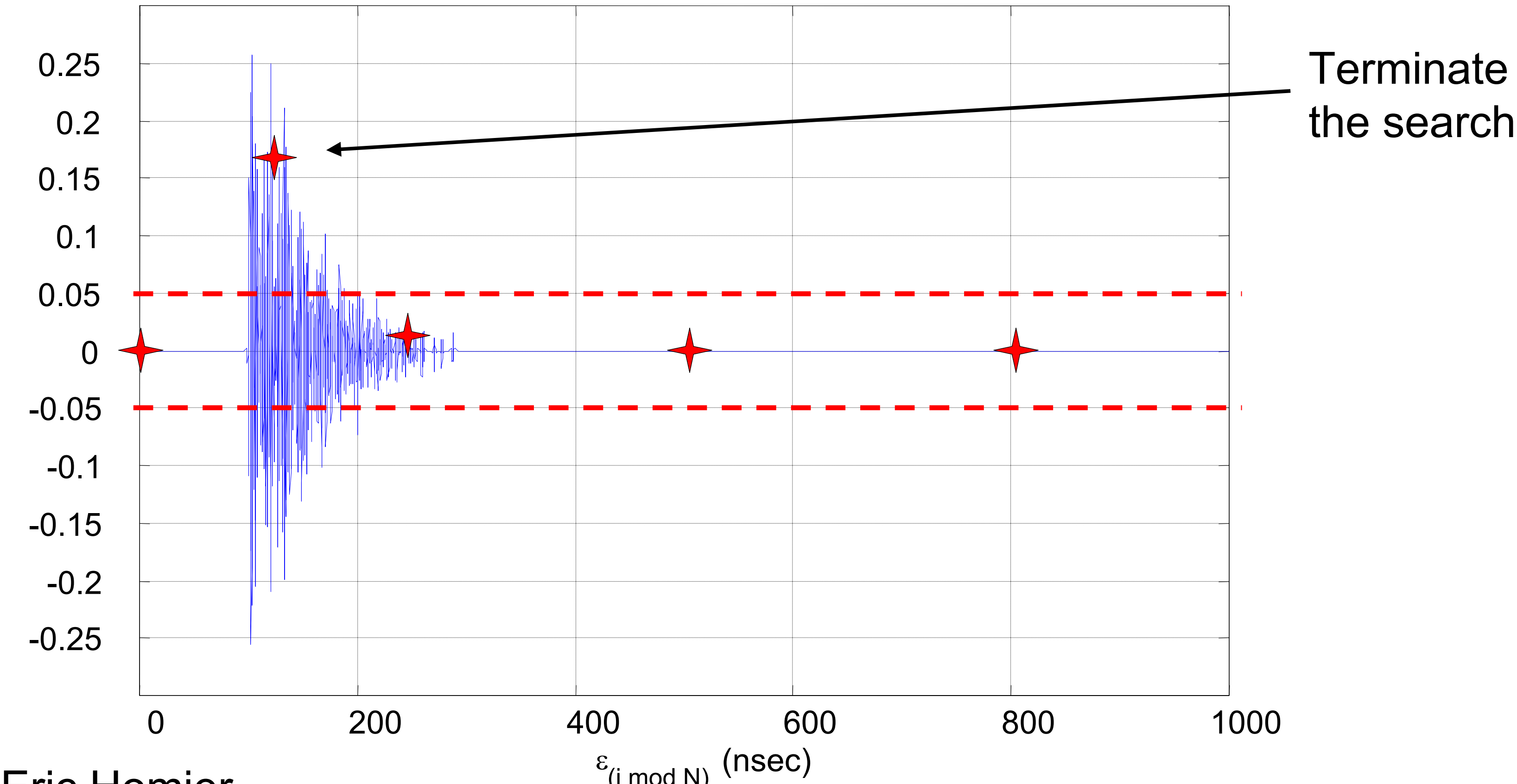
Bit Reversal Search: The linear search indices are ‘bit reversed’. For $N = 2^4$ the indices 0000, 0001, 0010, …, 1110, 1111 are bit reversed to yield the search order: 0000, 1000, 0100, …., 0111, 1111

Start at bin 0



Eric Homier

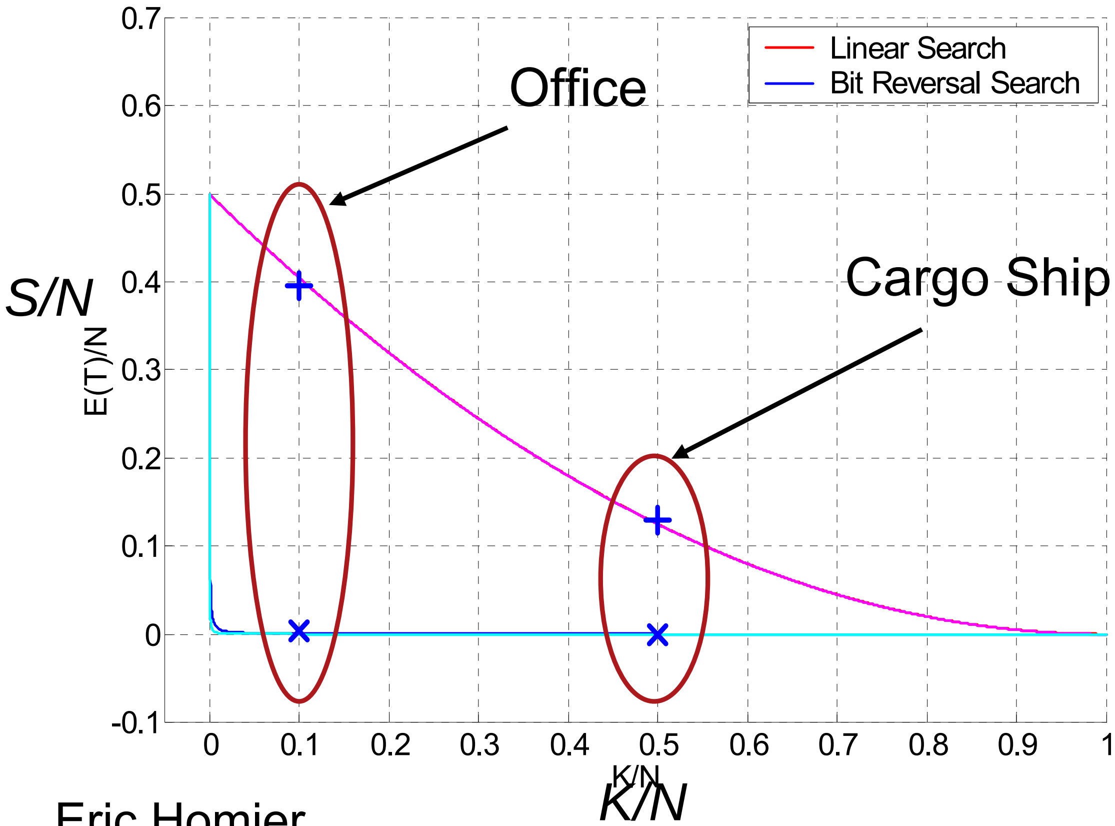
Bit-Reversal Serial Search



Eric Homier

Single-User Frame Acquisition

K = signal bins, N = bins per frame



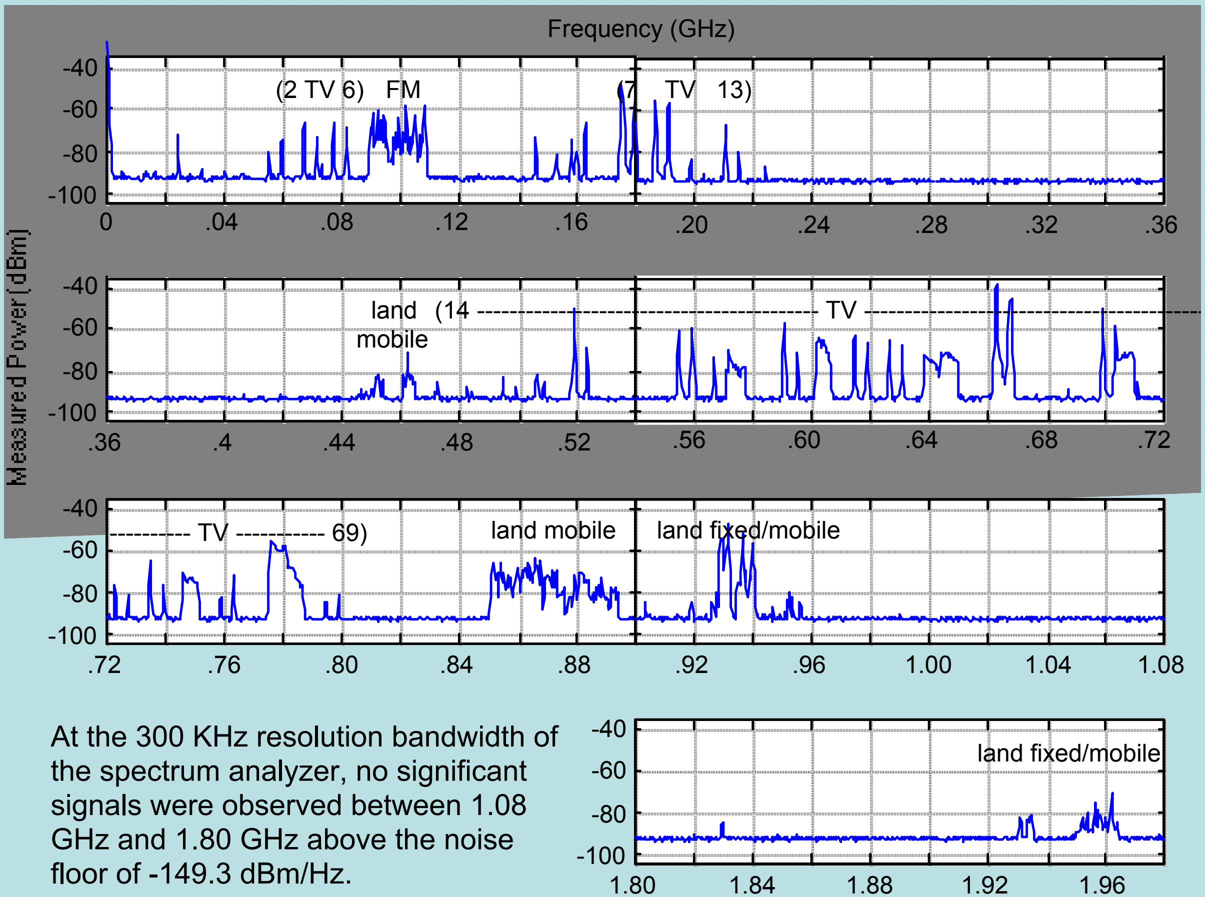
The terminating bins for the office environment (cargo ship) are approximately consecutive over 100 nsec (2000 nsec) so that K/N = 100/1000 = 0.1 (2000/4000 = 0.5)

S = mean number of bins searched to achieve acquisition

Eric Homier

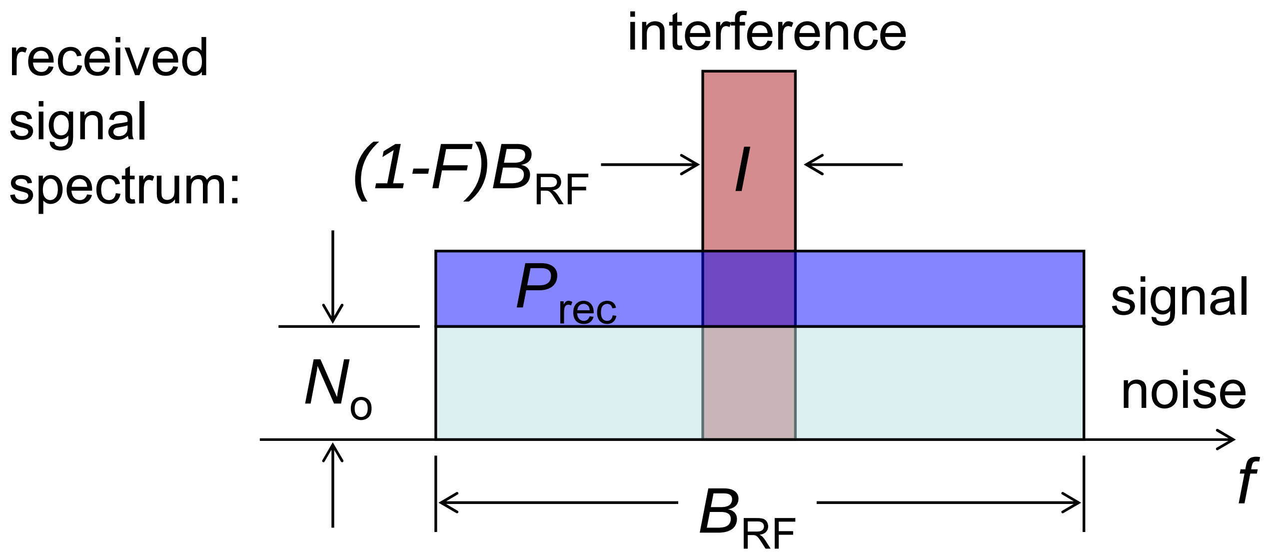
Interference Handling

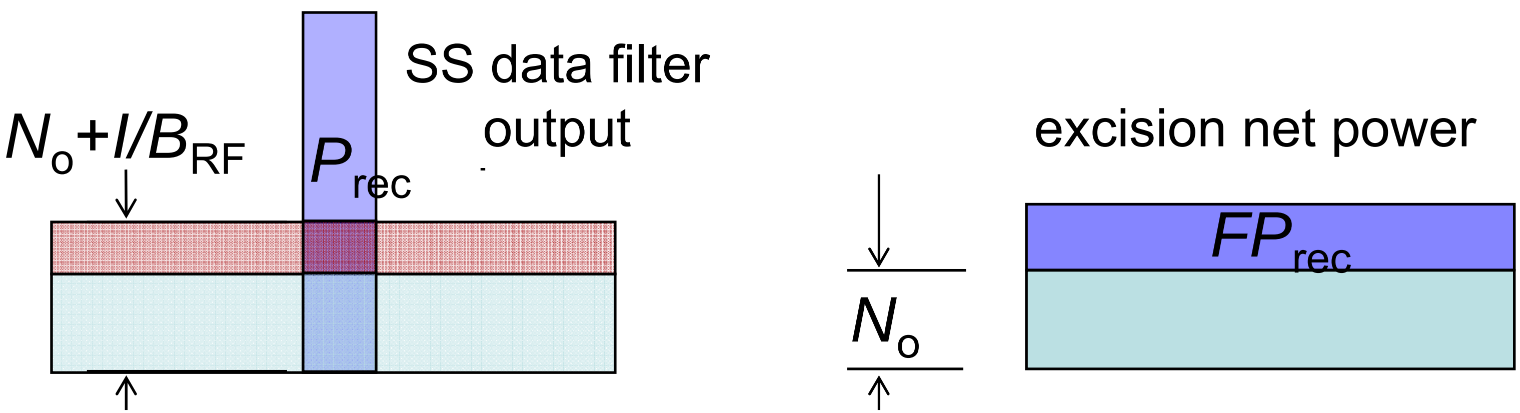
Interference in UWB Receiver



At the 300 KHz resolution bandwidth of the spectrum analyzer, no significant signals were observed between 1.08 GHz and 1.80 GHz above the noise floor of -149.3 dBm/Hz.

A Hypothetical Situation





A Performance Comparison

Spread Spectrum Processing:

$$\left(\frac{E_\mathrm{b}}{N_\mathrm{tot}}\right)_\mathrm{ss} = \frac{P_\mathrm{rec}/R_\mathrm{data}}{N_\mathrm{o} + I/B_\mathrm{RF}}$$

Interference Excision:

$$\left(\frac{E_\mathrm{b}}{N_\mathrm{tot}}\right)_\mathrm{int\ ex} = \frac{F P_\mathrm{rec}/R_\mathrm{data}}{N_\mathrm{o}}$$

A comparison:

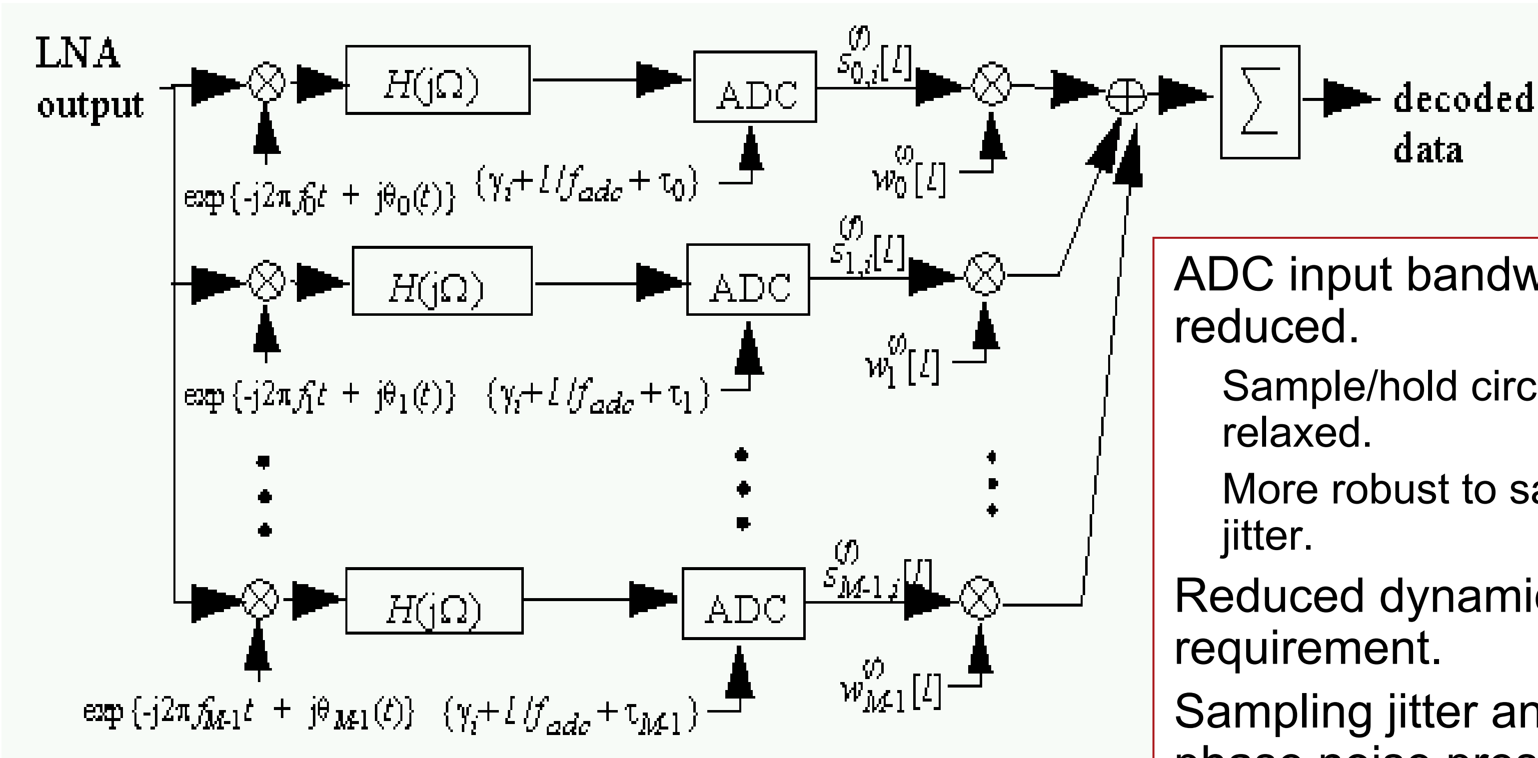
Fractional excision power loss

Fractional SS noise floor increase

$$\left(\frac{E_\mathrm{b}}{N_\mathrm{tot}}\right)_\mathrm{ss} > \left(\frac{E_\mathrm{b}}{N_\mathrm{tot}}\right)_\mathrm{int\ ex} \iff \frac{1}{F} > \frac{N_\mathrm{o} + I/B_\mathrm{RF}}{N_\mathrm{o}}$$

Problem: *F* and *I* not known *a priori*.

Frequency Channelized ADC



- ADC input bandwidth reduced.
  - Sample/hold circuitry relaxed.
  - More robust to sampling jitter.
- Reduced dynamic range requirement.
- Sampling jitter and mixer phase noise present.
- Interference excision simplified

Won Namgoong

E_b/N_o Adjustment II

Effective E_b/N_o at the data detector

$$R_b(E_b/N_{tot})_{eff} = (P_tG_t)(1/L_{prop}4\pi R^2)\ (G_r\ \lambda^2/4\pi) \cdot \eta_{ant}\eta_{cap}F/(N_o+I/B_{RF})$$

excision power reduction factor

noise floor increase caused by interference

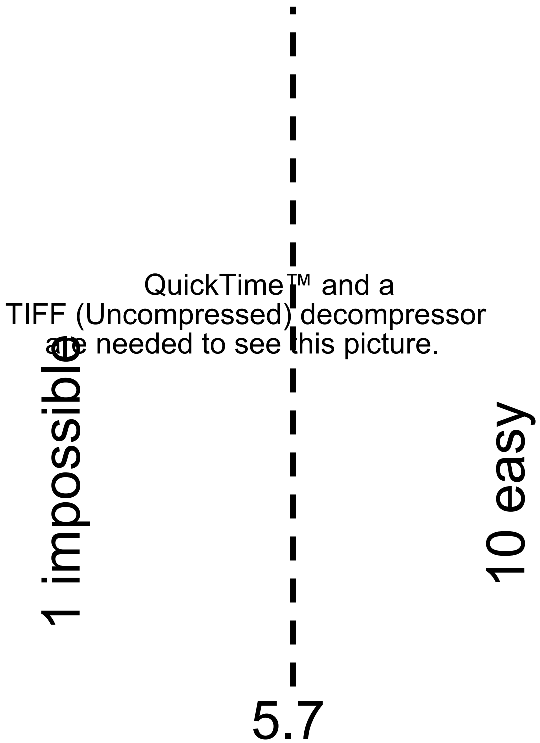
UWB Poll Respondents

Respondents	Pac.	Europe	N. Am.	other	Total
Faculty	9	5	14		28
Government	8		3		11
Industry	4	2	8	1	15
Student	2		16	2	20
(anonymous)				1	1
Total	23	7	41	4	75

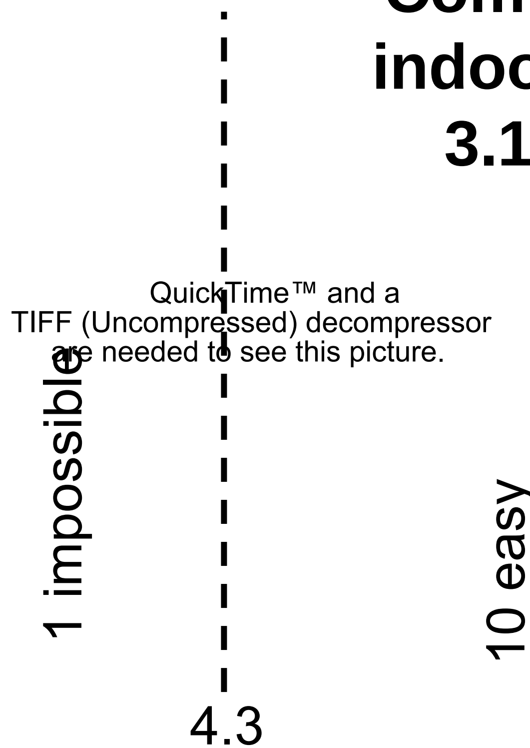
April 28, 2004

UWB Performance Challenges

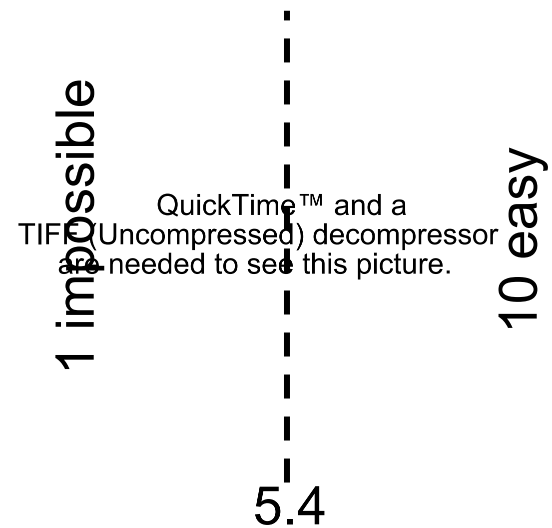
Commercial/consumer indoor operation in the 3.1-10.6 GHz band



1Gbps data rate
(single-link in-room)



1 Gbps multiple access
(aggregate capability)



Sub-centimeter
ranging accuracy

Hardware Challenge Checklist

For CMOS/SiGe full-band implementation in the 3.1-10.6 GHz band:

5.6	High-quality antenna (full-band)
5.3	LNA design (full-band)
5.6	Transmitter (full-band)
3.9	All-digital receiver (full-band)
5.6	Hybrid receiver (analog correlation)
6.1	500 MHz all-digital receiver

Scoring: 10 = easy 6 = possible now with effort
3 = may be available in 5 years 1 = impossible

UWB Indoor Application Checklist

(viable business applications in the next 3 years)

6.9	position location
6.3	imaging through materials
5.6	intrusion alarms
6.7	personal area networks
6.0	radio frequency tags

Score it: 10 = a sure money maker
6 = competitive in the marketplace
1 = a good way to lose money

DS-Impulse or OFDM?

Which is the better modulation for UWB communiucations in the 3.1-10.6 GHz band?

DS Impulse	OFDM
44%	56%

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

For More Information ...

See the UltRa Lab web site at

http://ultra.usc.edu/New_Site/

or

http://click.usc.edu/New_Site/