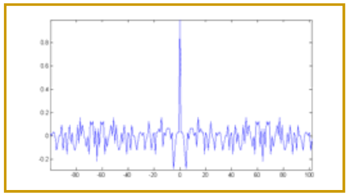
EE 5660 – Spread Spectrum Communications
Spring 2008



Instructor: R. Michael Buehrer

Lecture #24: Alternate Wideband Approaches – UWB

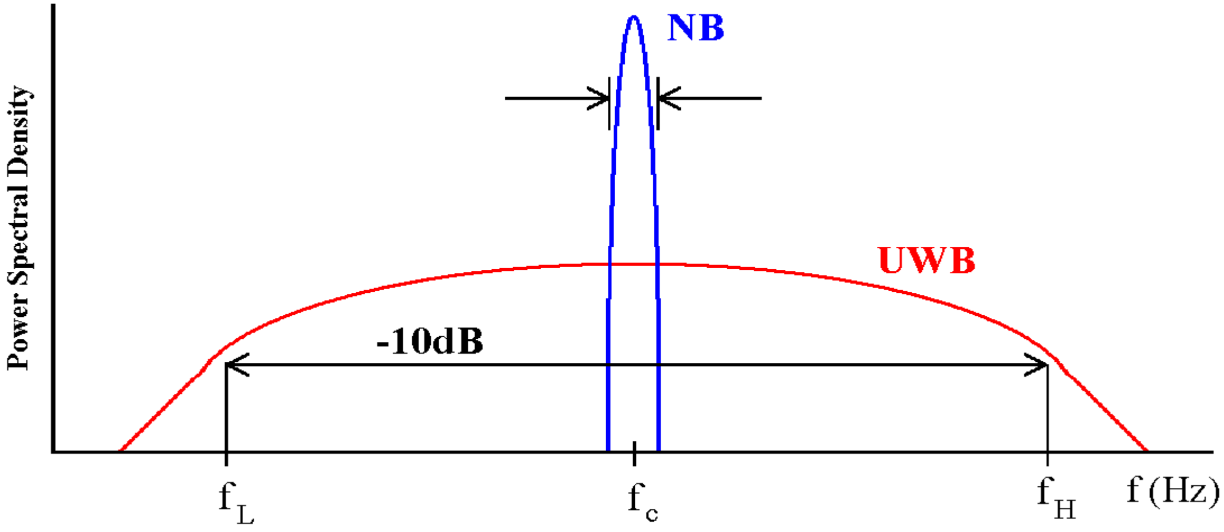
What is Ultra Wideband Useful For?

- Potential Applications
  - Wireless Communications Systems
    - Local and Personal Area Networks (LAN/PAN)
    - Roadside Info-station
    - Short range radios
    - Military Communications
  - Radar and Sensing
    - Vehicular Radar
    - Ground Penetrating Radar (GPR)
    - Through Wall Imaging (Police, Fire, Rescue)
    - Medical Imaging
    - Surveillance
  - Location Finding
    - Precision location (inventory, GPS aid)

So, what defines a system as UWB??

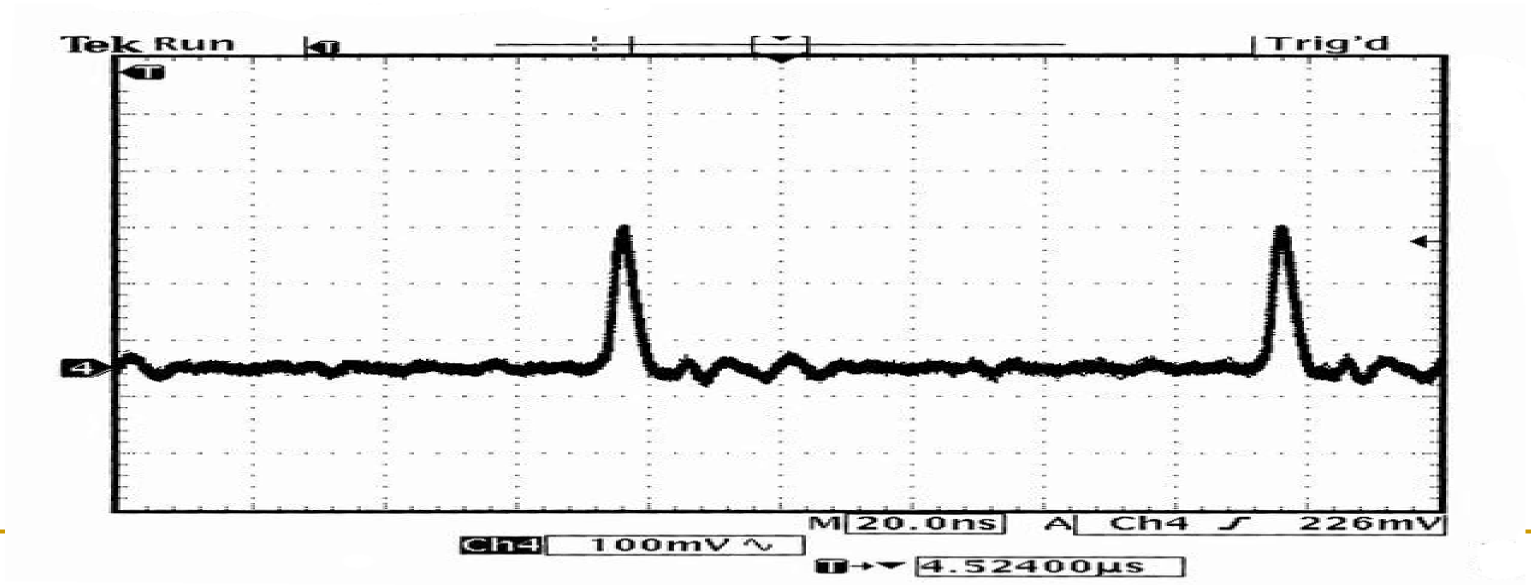
UWB Definition

- DARPA Definition of UWB
  - Fractional bandwidth = $(f_H - f_L)/f_c > 25\%$ or
  - Total BW > 1.5 GHz.
- FCC Definition of UWB
  - Fractional bandwidth (measured at the -10dB points), $(f_H - f_L)/f_c$, > 20% or
  - Total BW > 500 MHz.

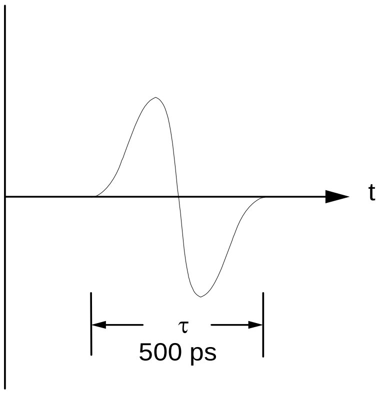


Impulse Radio

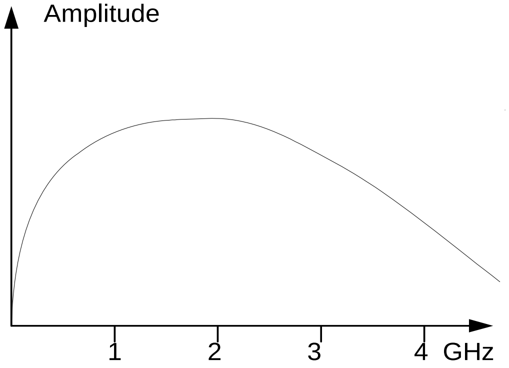
- UWB typically implies Impulse Radio (IR), but not necessarily.
- IR: Uses extremely short duration baseband pulses (sub-nanosecond) instead of continuous waves to transmit information.
- Typically very low duty cycle (on the order 1/100 or less)
- The pulse directly generates a very wide instantaneous bandwidth
- Occupied Bandwidth >> Information Bandwidth



Baseband UWB

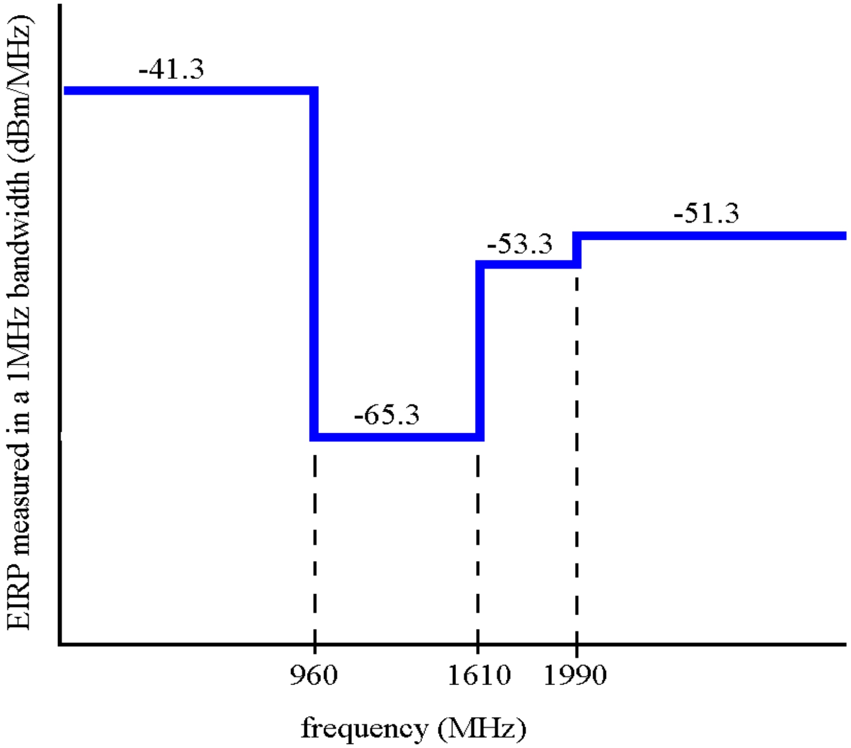


Gaussian Monocycle



Pulse Spectrum Envelop
Line at Pulse Repition Rate

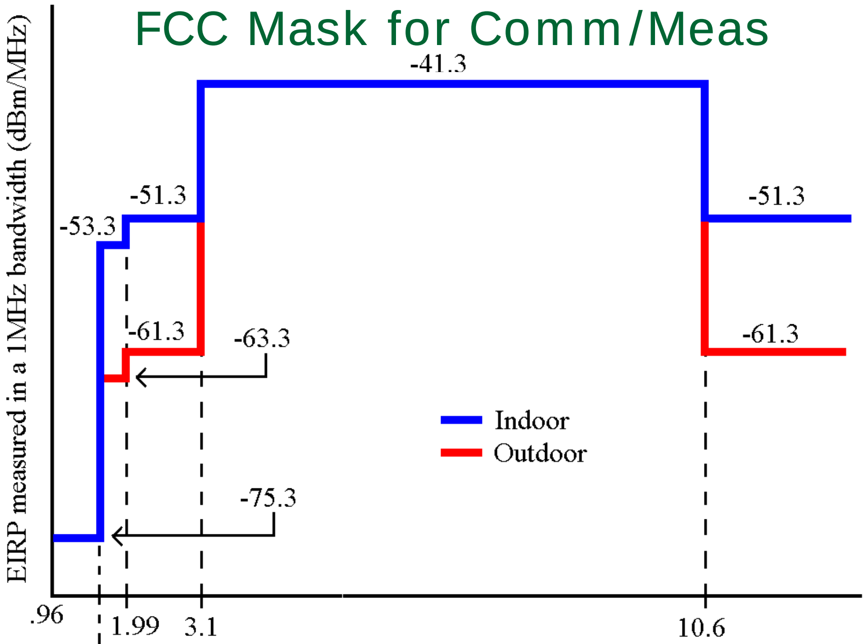
FCC Mask for Imaging (Low Freq)

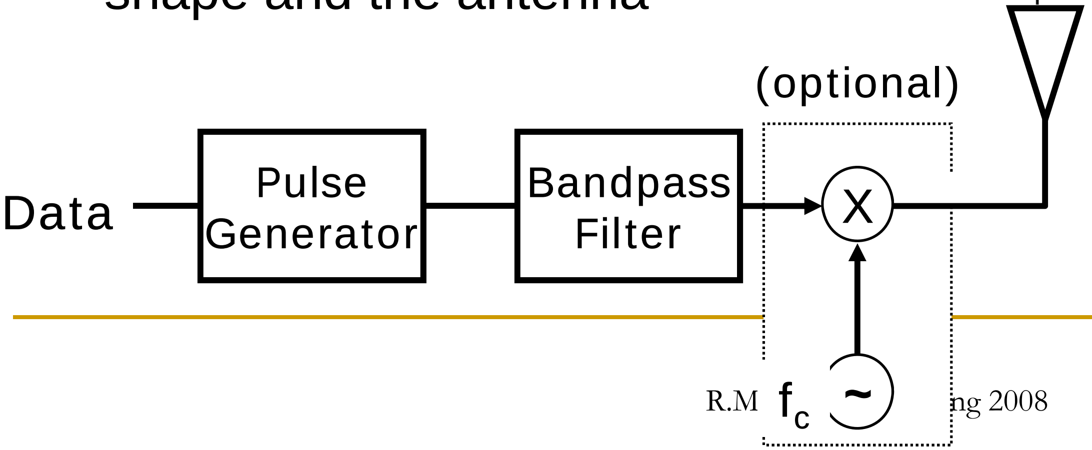


- UWB pulse transmitted directly
- Potential problem with GPS and licensed bands
- Typically used in ranging applications due to FCC mask

Bandpass UWB

- Pulses are run through a bandpass filter
- Center frequency controlled by filter center frequency.
  - Can also be modulated onto carrier for higher frequency bands
- Pulse shape and spectrum controlled by filter impulse response, input pulse shape and the antenna





Potential Advantages of UWB

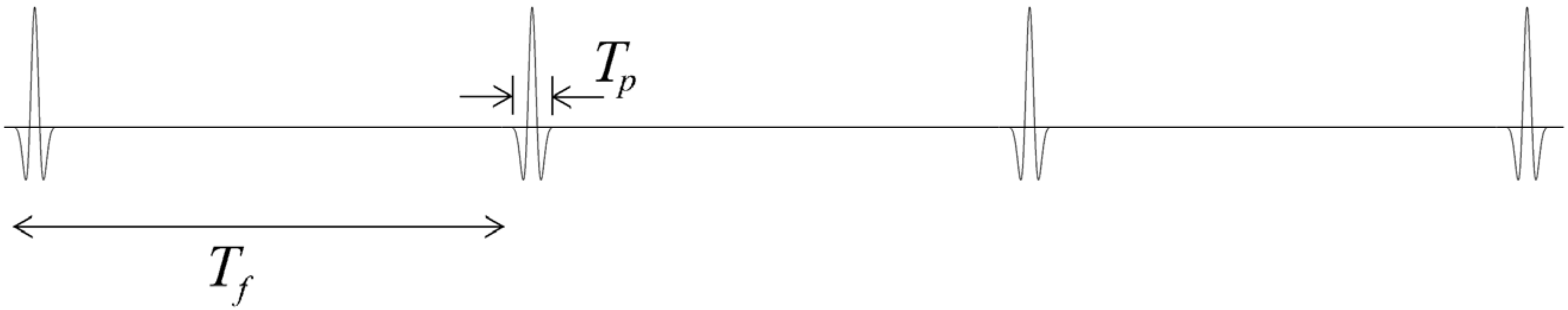
- Low Power Consumption
- Low cost: nearly ‘all-digital’, with minimal RF electronics.
- A low probability of detection (LPD) signature
- Integrated Services: Communications and Radar.
- Communications
    - Extremely high data rate over short distances in multi-user scenarios.
    - Relativity immune to multipath cancellation effects as observed in mobile and in-building environments.
    - Low interference to existing narrowband systems due to low power spectral density.

UWB System Example

Impulse Radio using Time Hopping

- Impulse Radio
  - Very low duty cycle ($T_f / T_p > 100$)
  - ‘Pulse train’
  - One pulse transmitted per frame (T_f)

uniform pulse train (no modulation, no dithering)



UWB System Model

- Received signal model for the kth user:

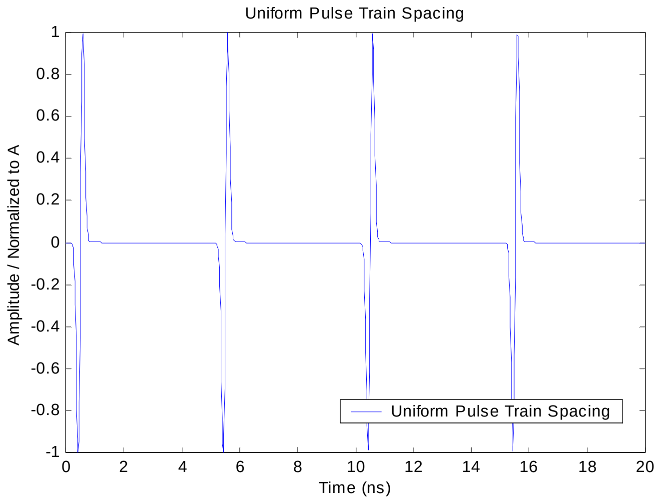
$$s^{(k)}(t) = \sum_{j} A^{(k)}_{[j/N_s]}\, p\left(t - jT_f - c_j^{(k)} T_c - \delta d^{(k)}_{[j/N_s]}\right)$$

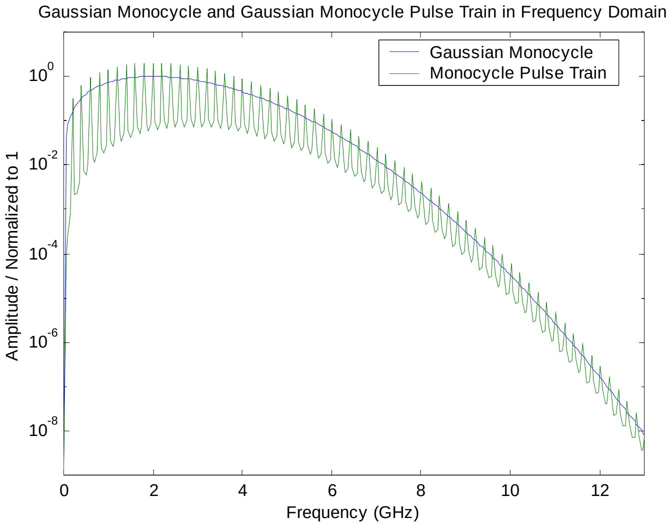
  - Time hopping, modulation, and pulse shape affect parameters.
    - A is the pulse amplitude
    - $p()$ is the normalized pulse shape
    - N_s is the pulse repetitions per information symbol
    - T_f is the frame time
    - c_j is the PN time hopping sequence
    - T_c is the time hop delay
    - δ is the PPM time delay parameter
    - $d[](k)$ is a function of the data sequence
    - The [ ] notation represents the integer portion of the argument

Reference: Scholtz, R.A. “Multiple Access with Time-Hopping Impulse Modulation”. *In Proc. of IEEE MILCOM '93, Communications on the Move*, vol, 2, 1993, pp. 447-450 vol.2

Pulse Train

- UWB systems typically use many pulse repetitions (100s) to represent each data symbol.
- A uniform pulse train has spectral lines present (not a smooth spectrum).
- For multiple access this could also lead to catastrophic collisions.
- Time-hopping is one possible solution….

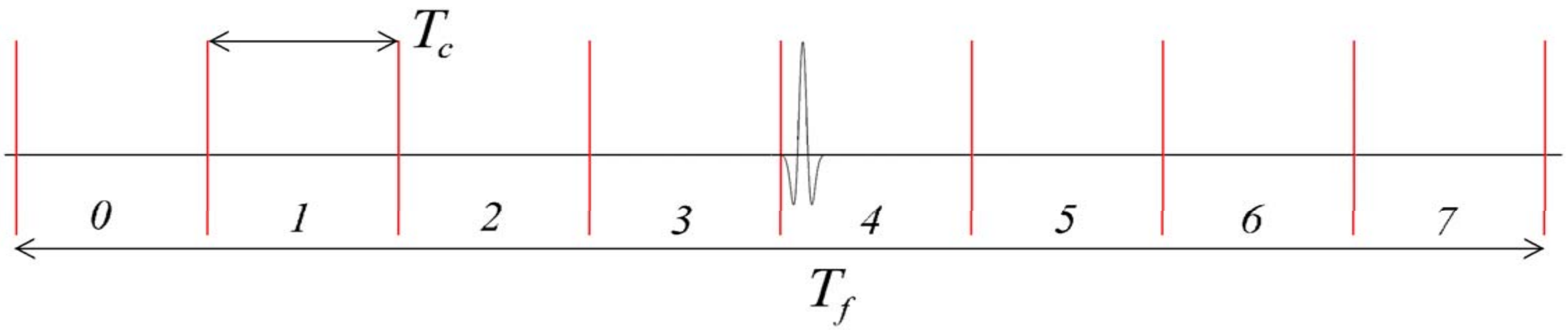




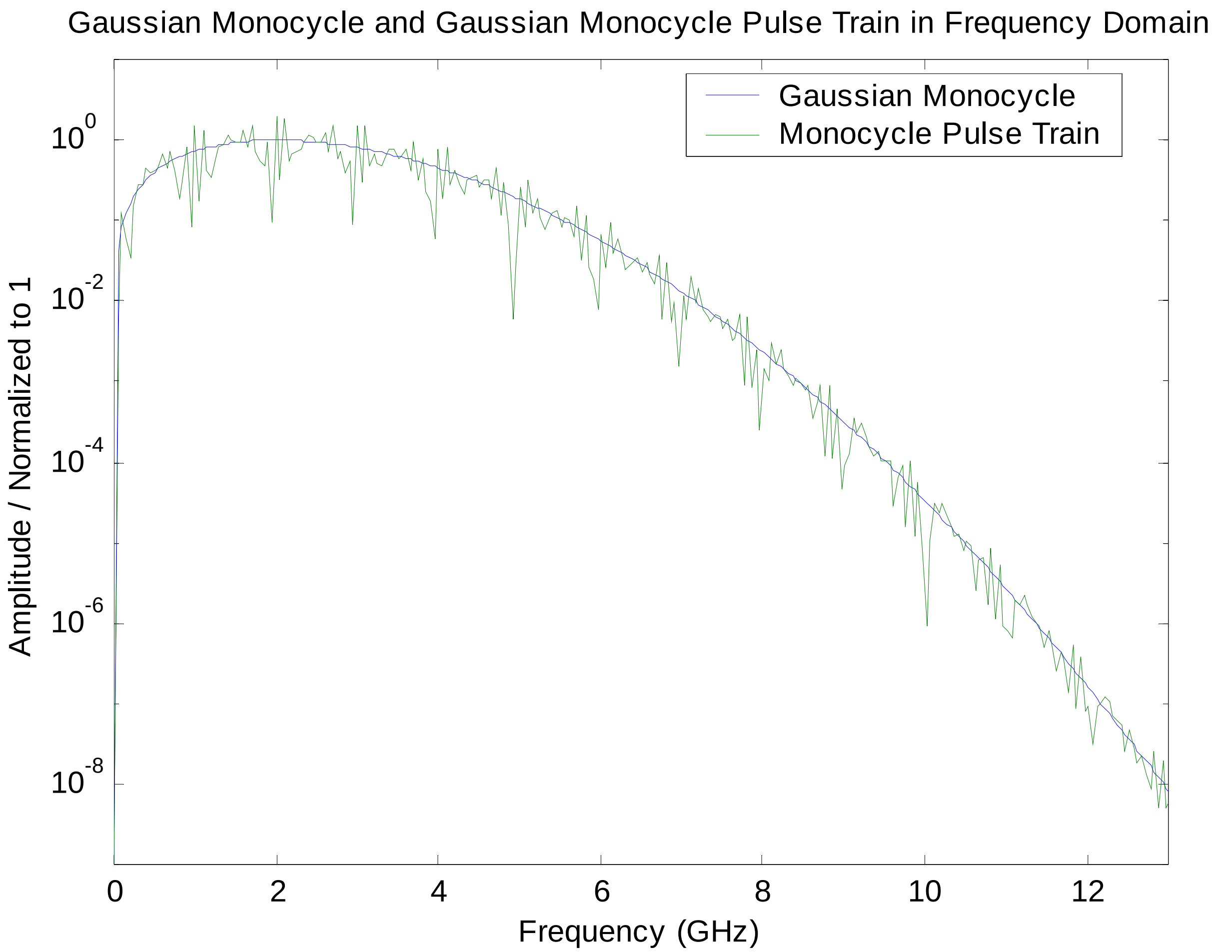
Time Hopping

- Within each frame time, the pulse is pseudo-randomly positioned in time.
  - Smoothes the spectrum
  - Allows for multiple access
- $c_i^{(k)}$ is a PN sequence, T_c is time diff. between hops

Example: pulse has been shifted to hop position 4 in a frame with 8 possible hop positions



Spectrum of Random/Pseudorandom Time-Hopping



Time hopping with a larger number of time slots would further smooth the spectrum.

Direct Sequence, DS-UWB

- Similar to conventional CDMA carrier based radios.
- PN sequence is multiplied by an impulse sequence at a duty cycles approaching a sinusoidal carrier.
- Channelization and modulation are provided as in CDMA.
- The chipping rate is some fraction, *1/N*, of the center frequency.

UWB Communications

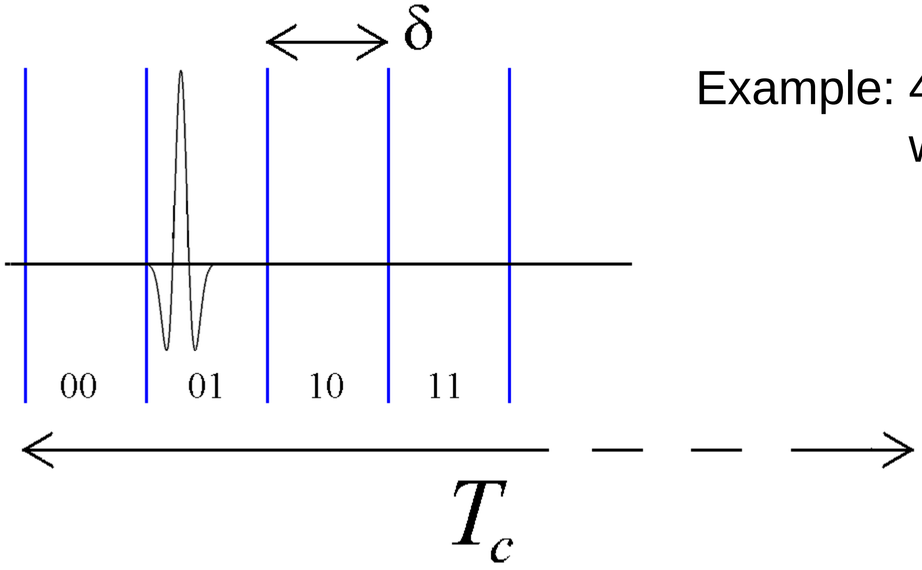
Modulation

- Pulse position modulation (PPM)
  - Binary/M-ary
- Bipolar Signaling (BPSK)
- Pulse Amplitude Modulation (PAM)
- On/Off Keying (OOK)
- Orthogonal pulse shapes

- Combinations of the above

Modulation Examples

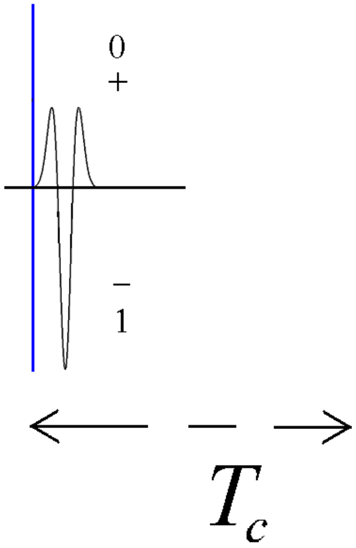
- Pulse Position Modulation (PPM)
  - The data is carried in the ‘fine’ time shift of the pulse.
  - *M*-ary PPM possible (higher *M* can mean fewer time hop positions for a given frame time)
  - Orthogonal (or better depending on pulse shape)



Example: 4-ary PPM,
with data 01

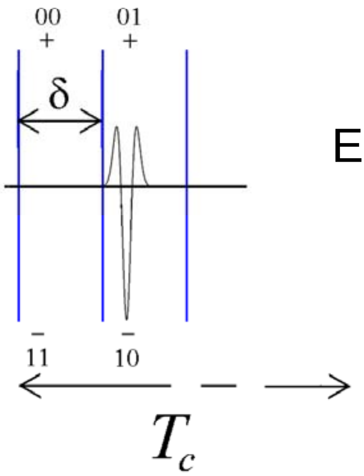
Modulation Examples

- Bipolar signaling
  - The data is carried in the polarity of the pulse.
  - Antipodal (very energy efficient)



Example: bipolar with data 1

- Biorthogonal signaling
  - Combination of PPM and bipolar signaling
  - M-ary biorthogonal has M/2 possible PPM shift

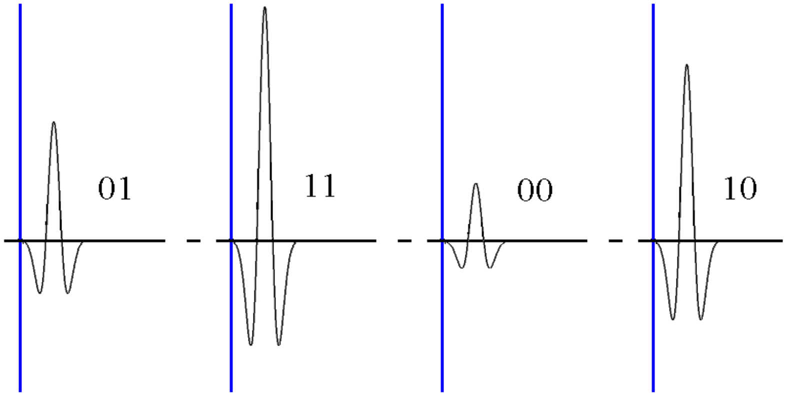


Example: 4-ary biorthogonal, with data 10

Modulation Examples

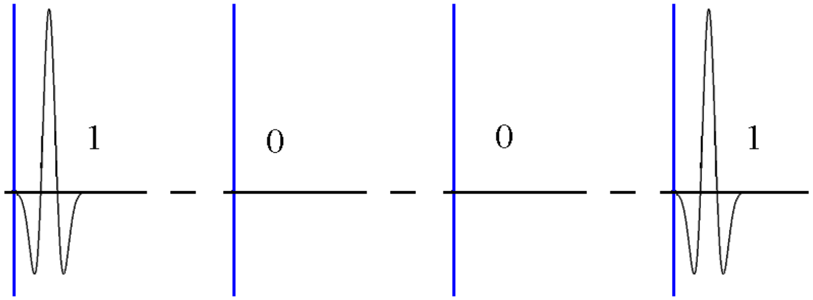
- PAM
  - Very poor energy efficiency.

Example: 4-ary PAM
with data seq: 01, 11, 00, 10



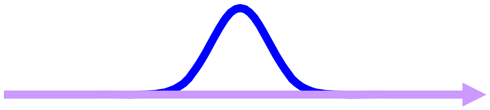
- OOK
  - Simple implementation.
  - Poor energy efficiency.

Example: OOK
with data seq: 1, 0, 0, 1

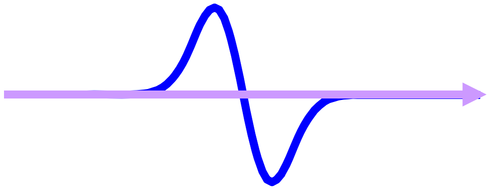


Pulse Shape

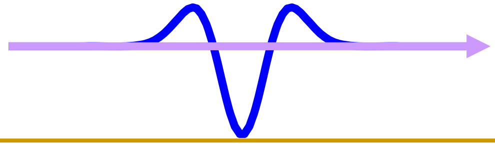
- The received pulse shape is dependant on the pulse generation, pulse shaping filter and the antenna responses.
- Example Pulse shapes
  - Gaussian pulse



  - Gaussian monopulse (monocycle)
    (1st derivative of Gaussian pulse)

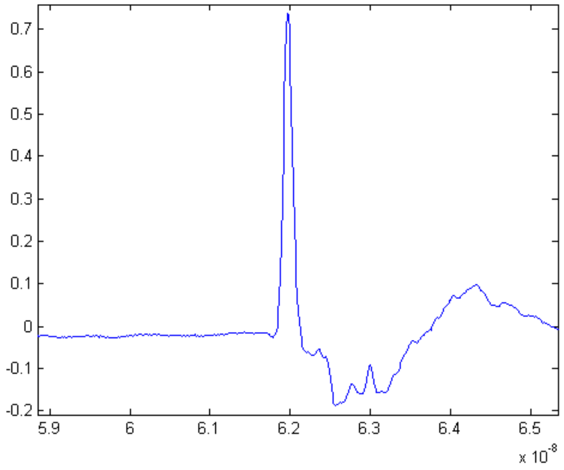


  - Gaussian doublet
    (2nd derivative of Gaussian pulse)

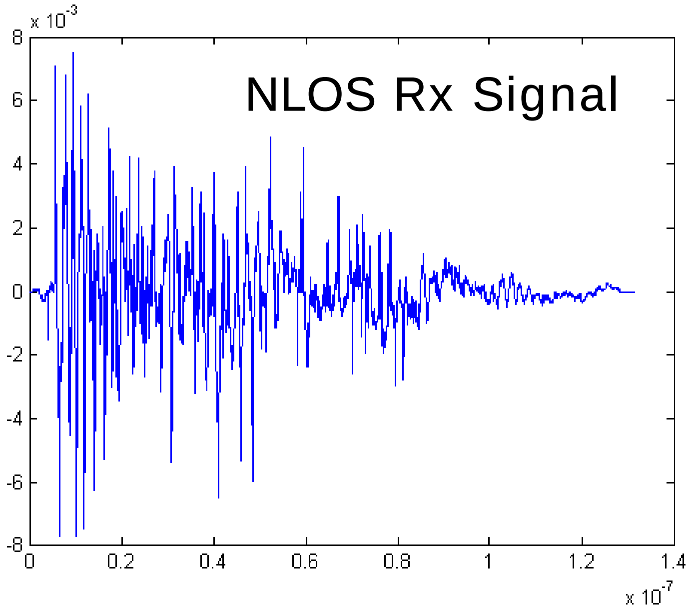


UWB Indoor Channels

- Indoor Example

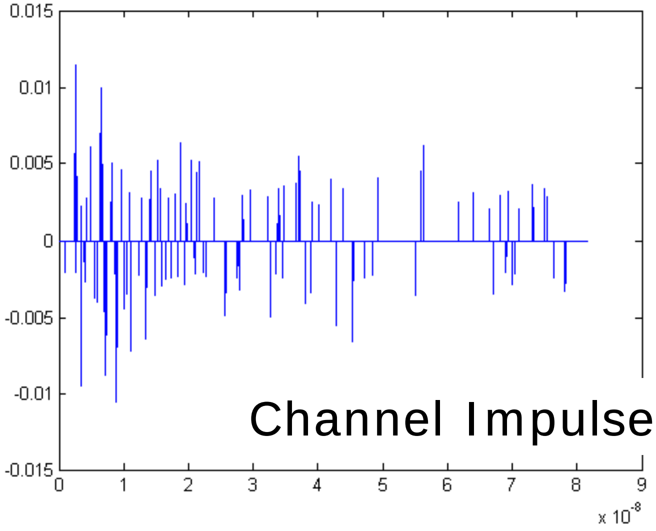


LOS ‘Clean’ Rx Pulse



NLOS Rx Signal

Large number of multipath
Pulse shape distorted



Channel Impulse Response

Channel Statistics

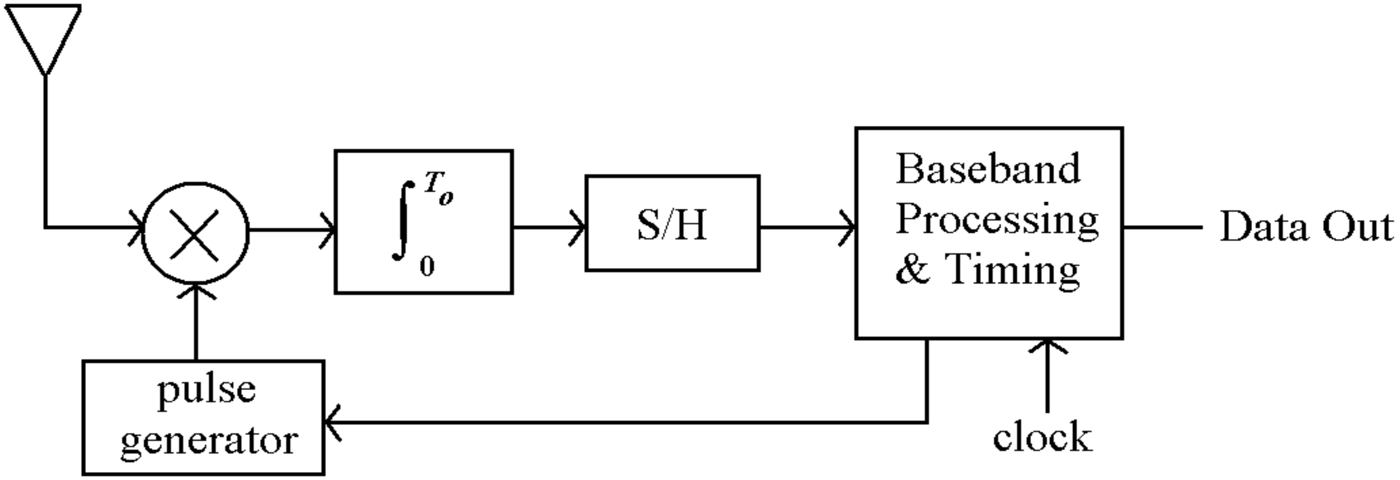
- Time Dispersion Statistics

	Bicone				**TEM**			
Threshold	**15 (dB)**		**20 (dB)**		**15 (dB)**		**20 (dB)**	
	NLOS	**LOS**	**NLOS**	**LOS**	**NLOS**	**LOS**	**NLOS**	**LOS**
Mean Excess Delay	16.0ns	5.19ns	20.1ns	10.5ns	2.4ns	0.55ns	5.6ns	1.2ns
Max Excess Delay	65.7ns	28.4ns	78.6ns	56.8ns	16.1ns	2.7ns	43.1ns	12.4ns
RMS Delay Spread	13.7ns	5.4ns	16.2ns	8.5ns	3.3ns	0.75ns	7.1ns	1.7ns
Number of Paths	72.8	24.3	153.9	64.6	28.7	6.4	99.1	15.8
Inverted Paths	49.0%	47.6%	49.3%	48.7%	50.7%	39.5%	49.8%	43.9%
Inverted Energy	44.2%	45.0%	45.4%	45.6%	34.3%	24.2%	37.7%	25.9%

UWB Correlation Receiver

- The received signal is correlated with the expected received pulse (may differ from the transmitted pulse due to distortion by the antennas and channel).
- Simple design, less RF hardware than narrowband receivers.

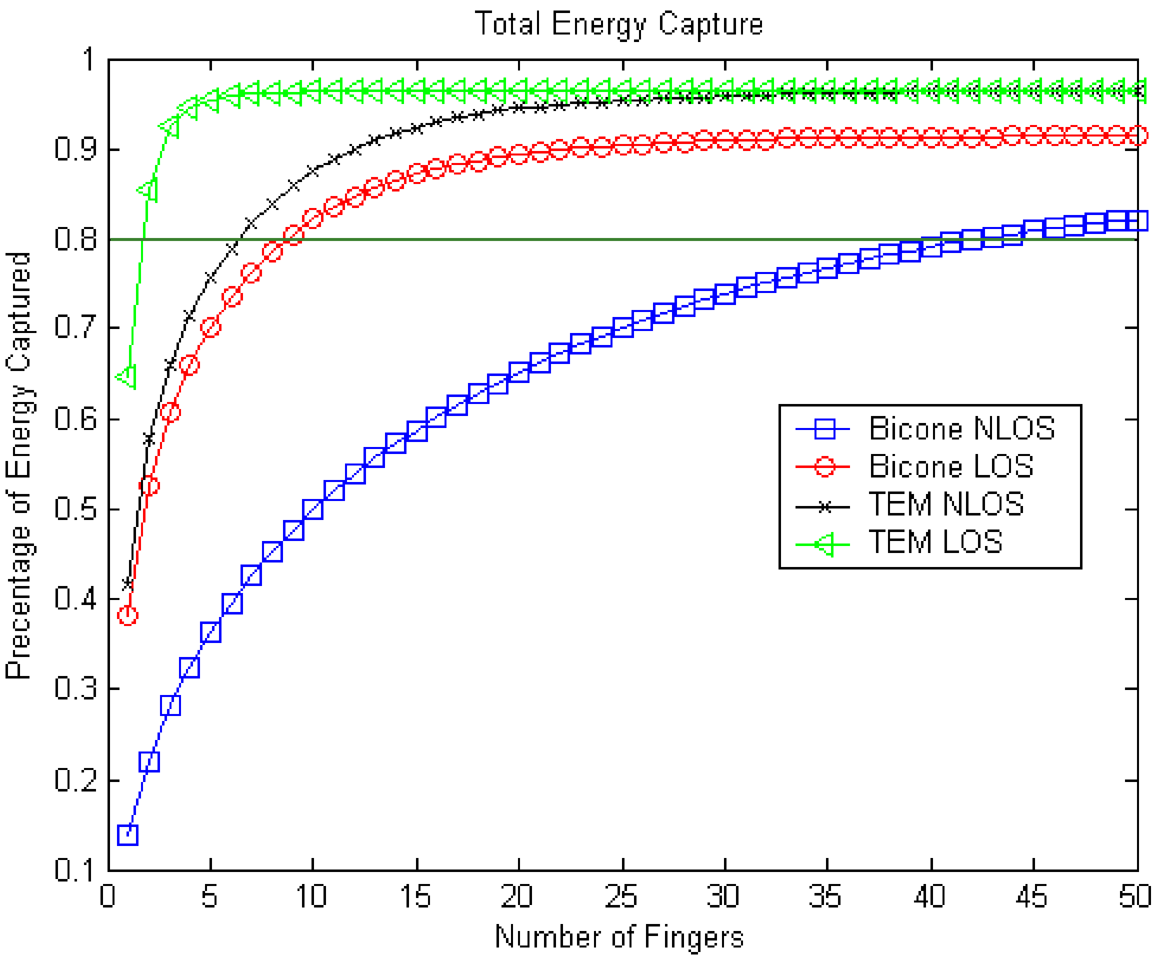
UWB correlation receiver



UWB Rake Receiver

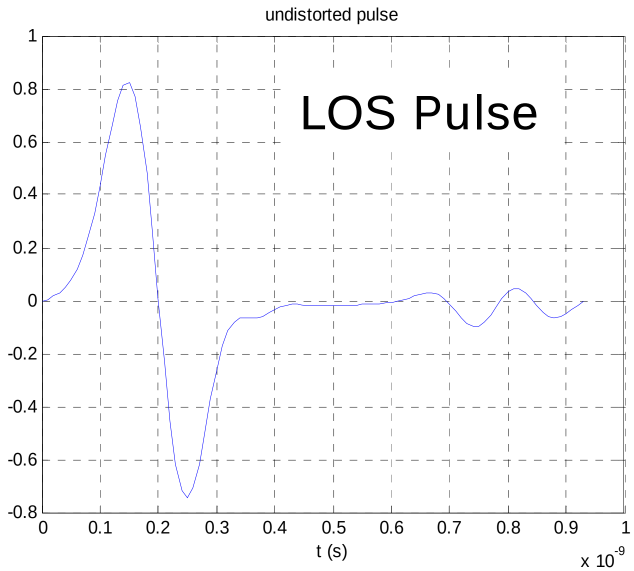
- UWB signals can have as many as 30 or more resolvable multipath components.
- Energy can be combined using a Rake receiver to improve performance.
- Each path has very small energy, difficult to perform accurate channel estimation for each path.
    - Each path could have experienced different distortion.
    - Complexity to estimate 30 different paths can be high.
- Can complexity be reduced and still exploit multipath?
    - Energy detector or voltage threshold detector receivers possible.

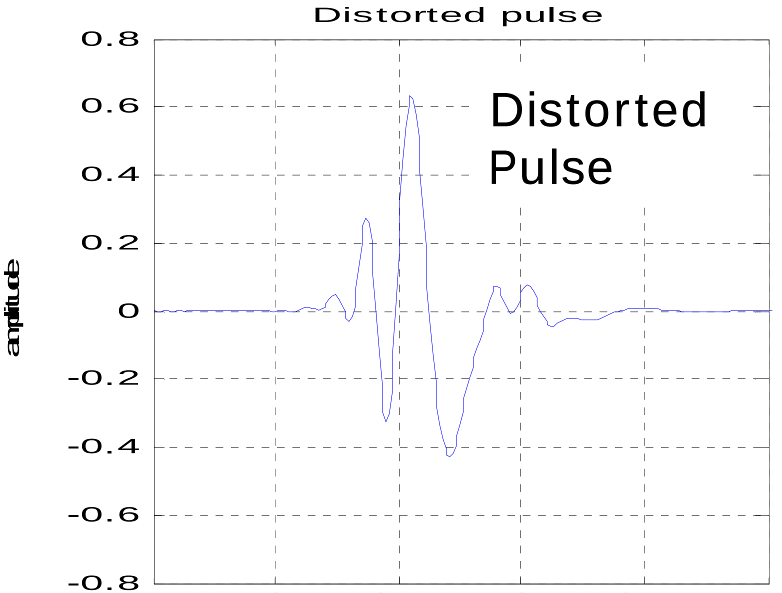
Energy Capture – Rake Fingers

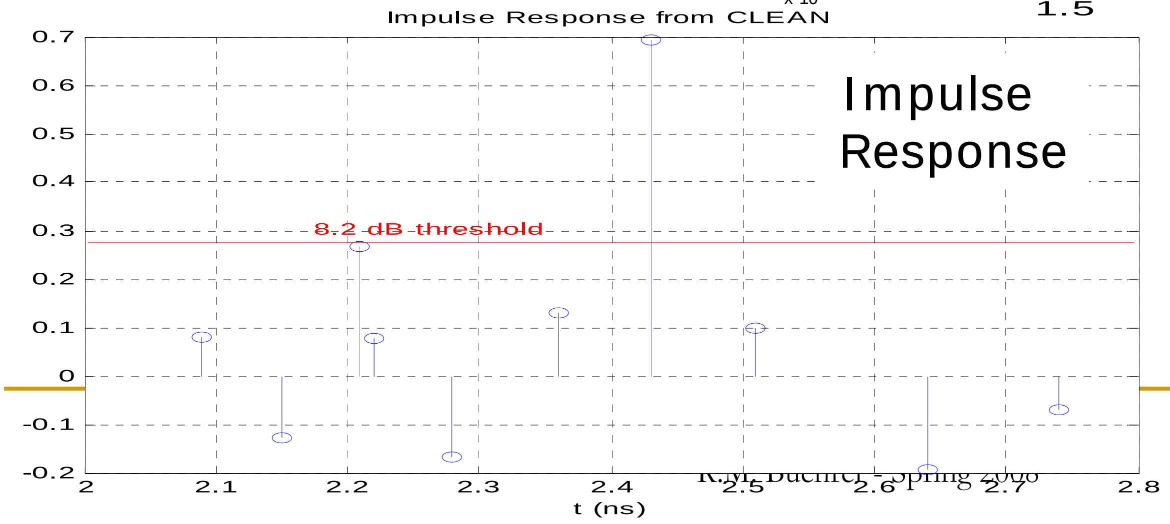


- Large number of Rake fingers needed for bicone NLOS channels
- Counters the advantage of lower path loss and smaller standard deviation

Pulse Distortion due to Materials

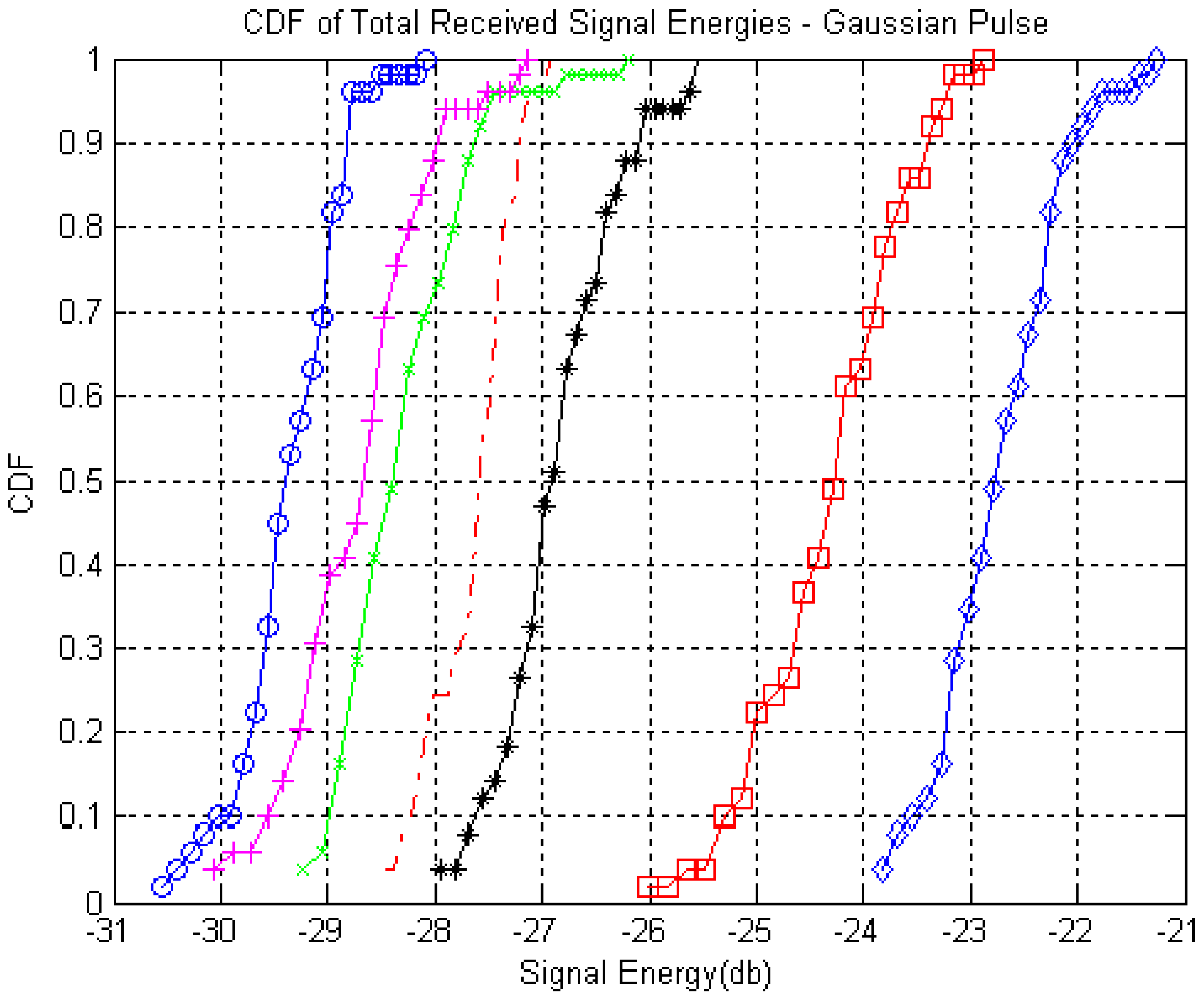






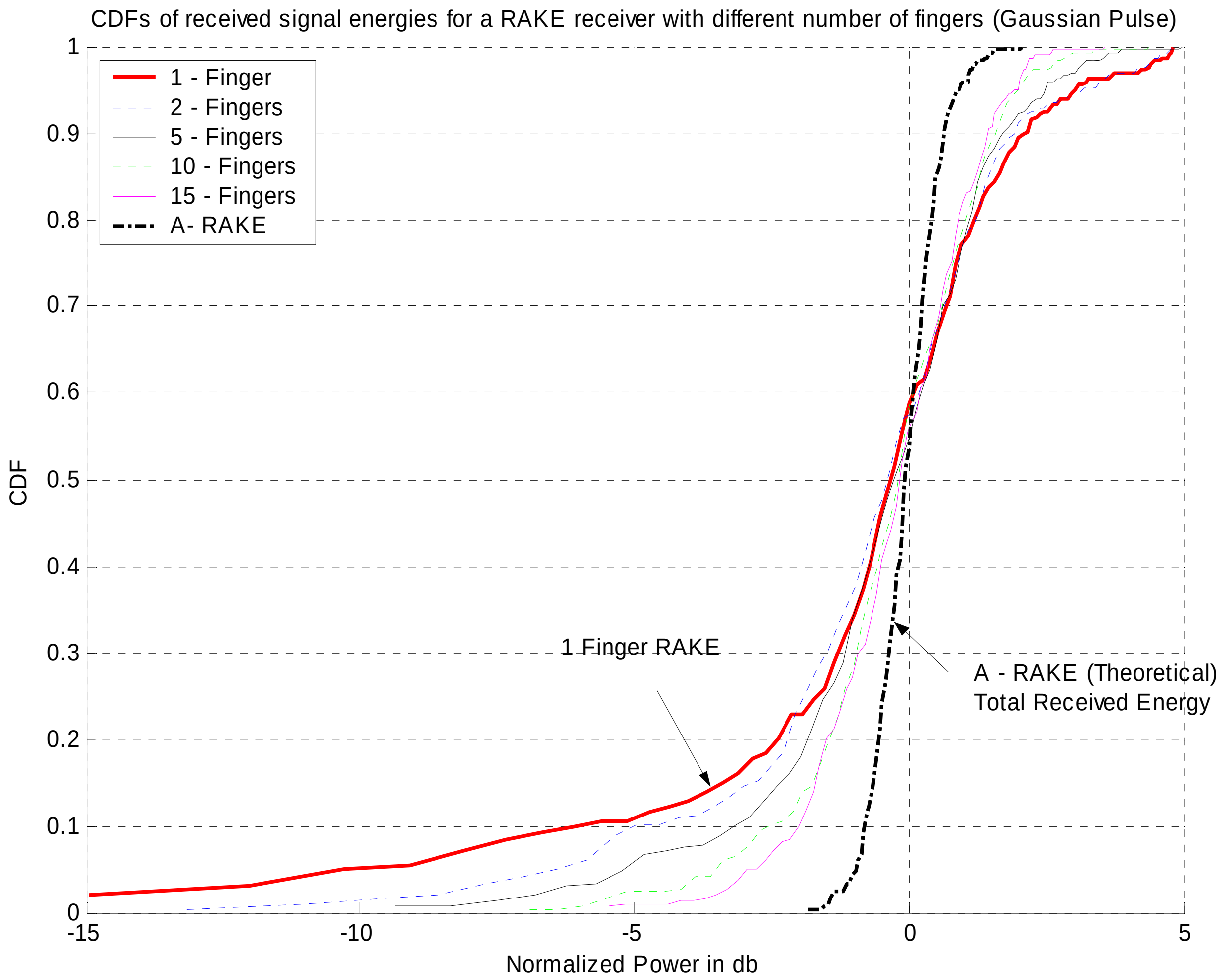
Impact of traveling through plywood

Spatial Fading – 200ps Pulse



- Very low local fading
- Significantly less margin required in link budget than narrowband system

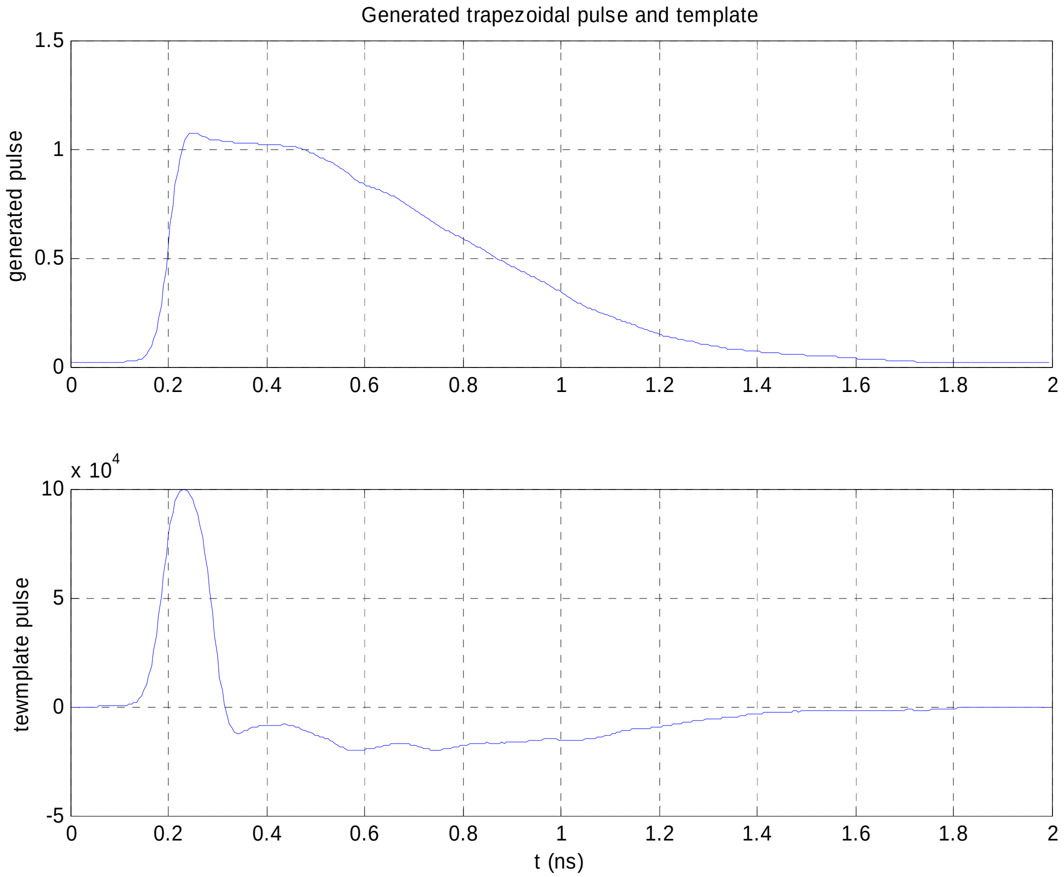
Rake Impact on Fading



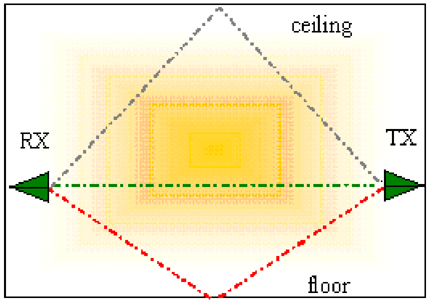
- 200ps pulse
- 1,2,5,10,15, and “all” fingers
- Fading reduced with moderate number of fingers
- Fading worse than 2ns pulse with same number of fingers (except “all” fingers)

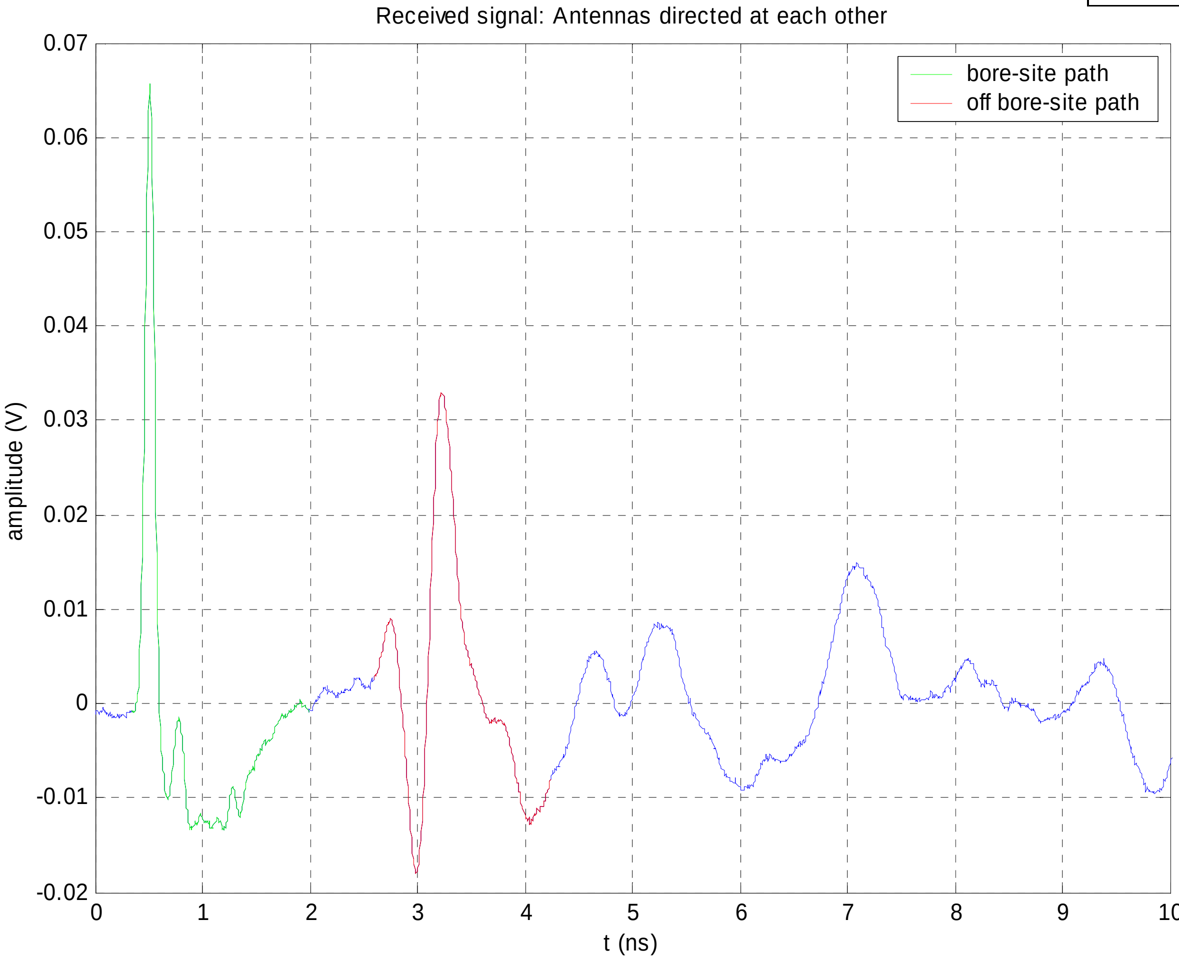
Antenna Effects (TEM horns)

Generated pulse and transmitted pulse

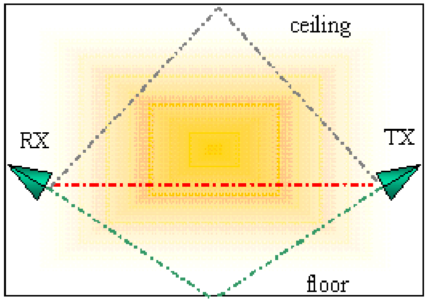


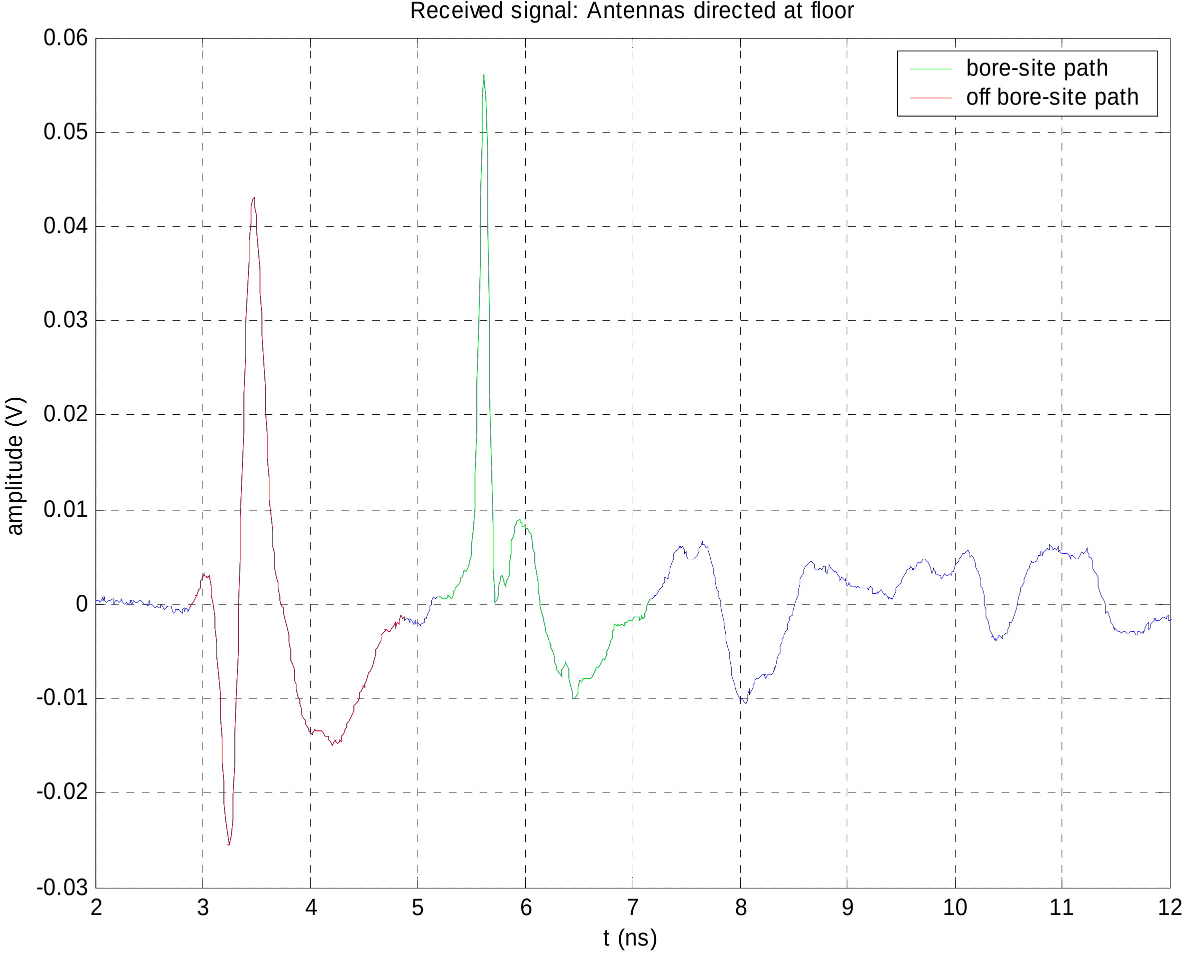
Antennas facing





Antennas to floor

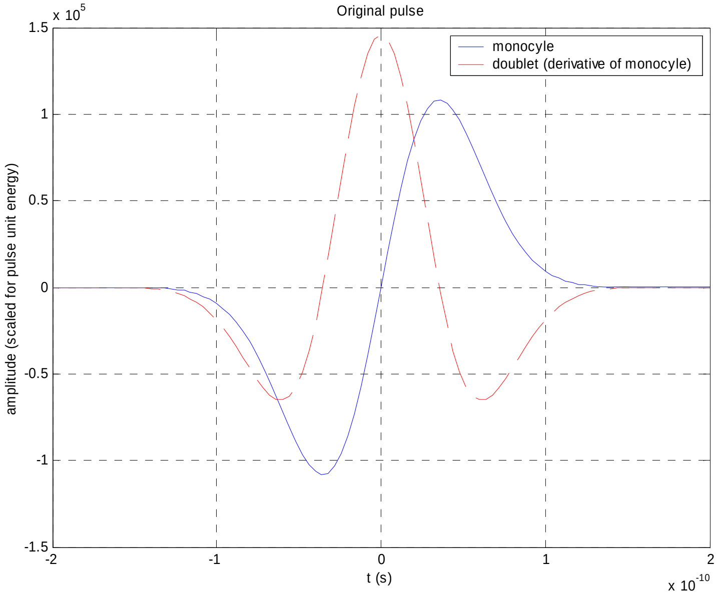




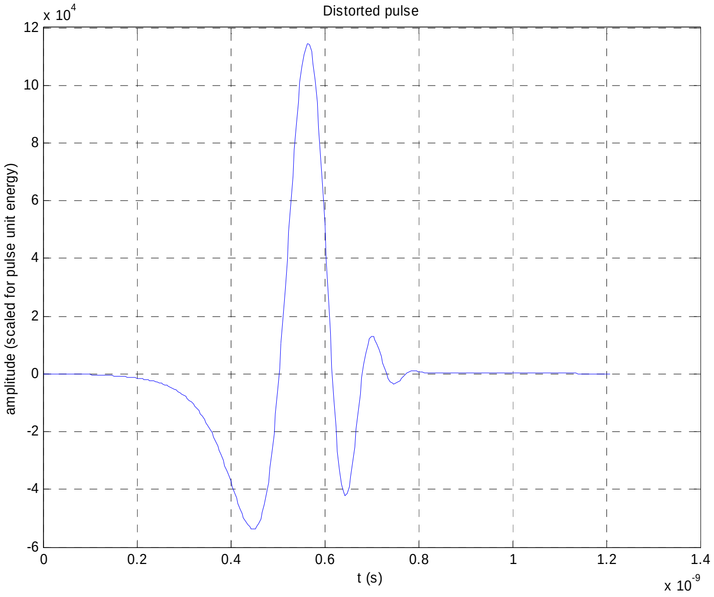
UWB Pulse Distortion

Simulated the effect of various pulses passing through a material (bricks)

Transmitted pulse (blue)



Distorted pulse



Ex: Correlation with transmitted pulse captured 80.4% of the energy.

Distortion worse on signals with low frequency content.

Loss from Transmission Through Specific Materials

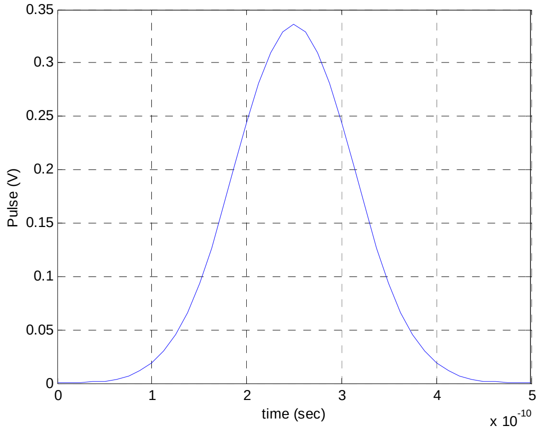
Assuming the use of a single correlator matched to the undistorted pulse we observe the following energy loss (in dB)

Material	Loss (dB)
Drywall (‘Wallboard’)	0.46
Office partition	2.38
Particle board (‘structure wood’)	1.35
Wooden Door	1.78
Plywood	1.69
Glass	1.05
Styrofoam	-0.03
Bricks	3.87
Concrete Blocks	6.81

System Model: Biphase Modulation

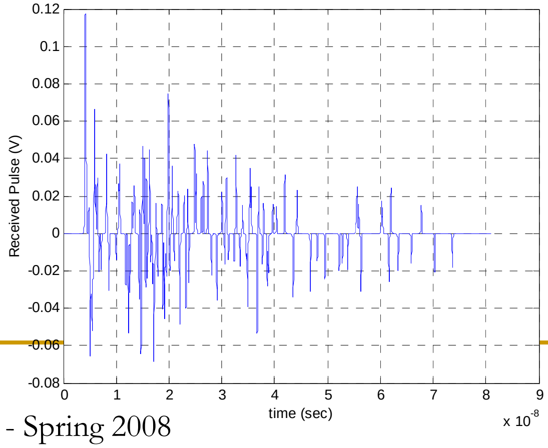
- Transmitted Pulse:

$$s(t) = b_j w(t), b_j = \pm 1$$



- Received Pulse:

$$r(t) = \sum_{l=0}^{L-1} \alpha_l b_j w(t - \tau_l) + n(t)$$



Receiver Performance: Optimal Receiver

- Assume we have perfect knowledge of the received signal template:

$$h(t) = \sum_{l=0}^{L-1} \alpha_l w\left(t - \tau_l\right)$$

- Decision Statistic:

$$g = \int_0^{T_{bit}} \left[b_j h\left(t\right) + n\left(t\right) \right] h\left(t\right) dt$$

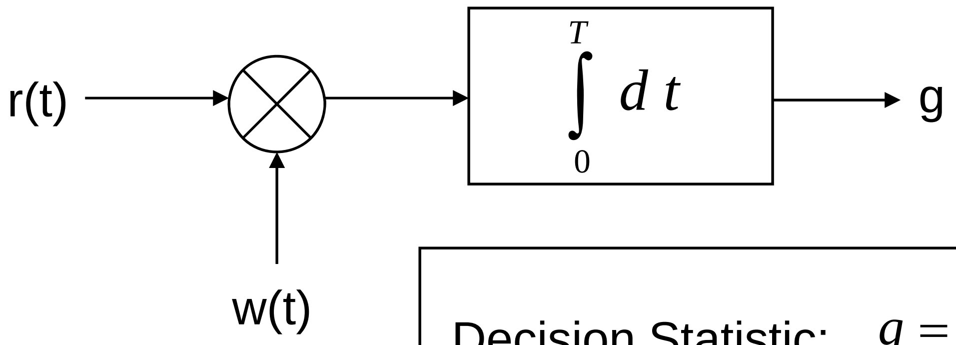
Receiver Performance: Optimal Receiver

$$P_e = Q\left(\sqrt{\frac{2E_p\cdot\left[1+\sum_{i=0}^{L-1}\sum_{\substack{j=0\\ j\neq i}}^{L-1}\alpha_i\alpha_j R\left(\tau_i-\tau_j\right)\right]}{N_0}}\right)$$

Maximum energy capture

On average, $\sum_{i=0}^{L-1}\sum_{\substack{j=0\\ j\neq i}}^{L-1}\alpha_i\alpha_j R\left(\tau_i-\tau_j\right)=0 \quad \Longrightarrow \quad P_e = Q\left(\sqrt{\frac{2E_p}{N_0}}\right)$

Pulse Matched Filter



Decision Statistic: $g = \int_0^{T_{bit}} r(t).w(t)\,dt$

Decision Rule:

$$g \geq 0 \rightarrow b_j = 1$$

$$g < 0 \rightarrow b_j = -1$$

Performance depends on channel and wave autocorrelation function

Pulse Matched Filter

- Autocorrelation function: $$R(\tau)=\frac{\int_{-\infty}^{\infty} w(t).w(t-\tau)\,dt}{E_p}$$

- Pulse Energy: $$E_p=\int_{-\infty}^{\infty} w^2(t)\,dt$$

- BER: $$P_e=Q\left(\frac{u_g}{\sigma_g}\right)=Q\left(\sqrt{\frac{2E_p\left(\sum_{l=0}^{L-1}\alpha_l R(\tau_l)\right)^2}{N_0}}\right)$$

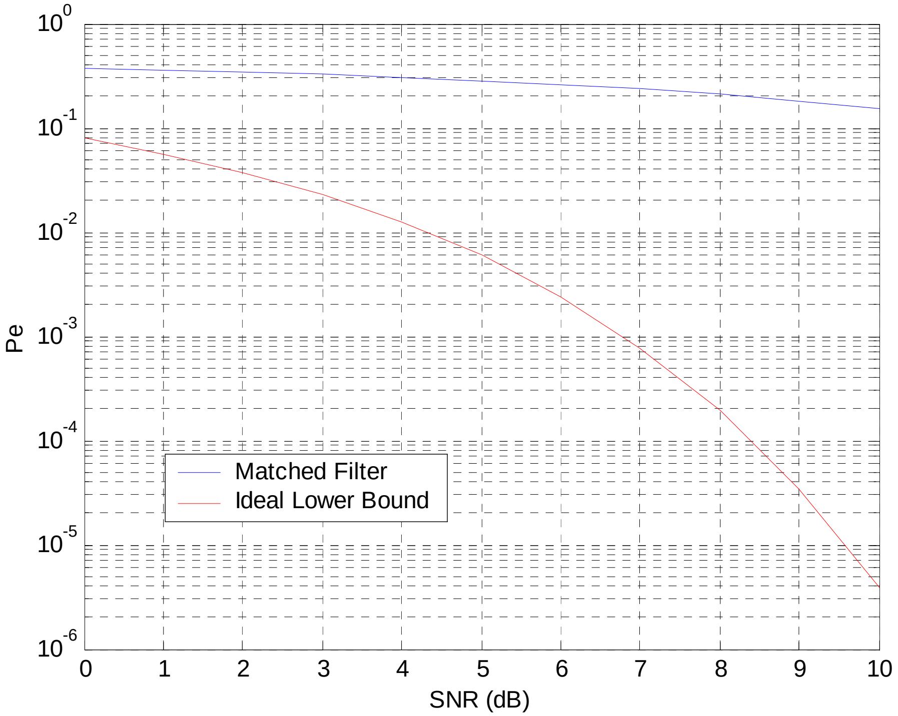
Pulse Matched Filter

$$P_e = Q\left(\sqrt{\frac{2E_p\left(\sum_{l=0}^{L-1}\alpha_l R(\tau_l)\right)^2}{N_0}}\right)$$

$R(\tau) = 0 \;\; for \; \tau > T_{pulse}$

→ Most paths are lost

→ Limits Received Energy



Rake Receiver

- *F* correlators each matched to one of the *F* strongest paths
- Equivalent template created by *F*-Finger RAKE:

$$h(t) = \sum_{i=1}^{F} \alpha_{f_i} w\left(t - \tau_{f_i}\right)$$

- Decision statistic:

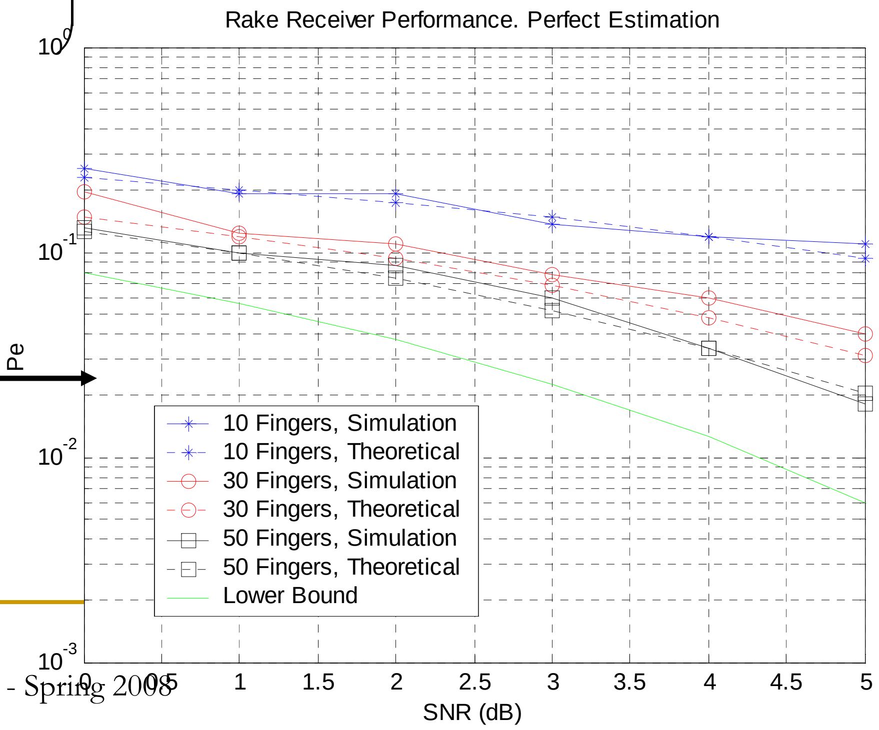
$$g = \int_0^T r(t) h(t)\, dt = \int_0^T \left[\sum_{l=0}^{L-1} \alpha_l w(t - \tau_l) + n(t) \right] . \sum_{i=1}^{F} \alpha_{f_i} w\left(t - \tau_{f_i}\right) dt$$

Rake Receiver

$$P_e = Q\left(\sqrt{\frac{2E_p}{N_0}\frac{\left(\sum_{k=0}^{F-1}\alpha_{f_k}^2+\sum_{k=0}^{F-1}\sum_{\substack{l=0\\l\neq k}}^{L-1}\alpha_l\alpha_{f_k}R\left(\tau_l-\tau_{f_k}\right)\right)^2}{\sum_{i=0}^{F-1}\sum_{j=0}^{F-1}\alpha_{f_i}\alpha_{f_j}R\left(\tau_{f_i}-\tau_{f_j}\right)}}\right)$$

Represents the energy capture. Need large number of fingers to get good energy capture.

Theoretical Expression is accurate for perfect channel estimation



A More Realistic Rake Receiver

- Assume *N*-Pilot Channel Estimation
- Assuming *N* pilots, estimated weights are:

$$\hat{\alpha}_f = \alpha_f + \sum_{\substack{l=0 \\ l \neq f}}^{L-1} \alpha_l R\left(\tau_l - \tau_f\right) + n_f = \alpha'_f + n_f$$

- n_f is zero mean Gaussian with variance $\frac{N_0}{2NE_p}$
- Errors caused by noise and path correlations
- Receiver picks the *F* strongest paths $\hat{\alpha}_f$

A More Realistic Rake Receiver

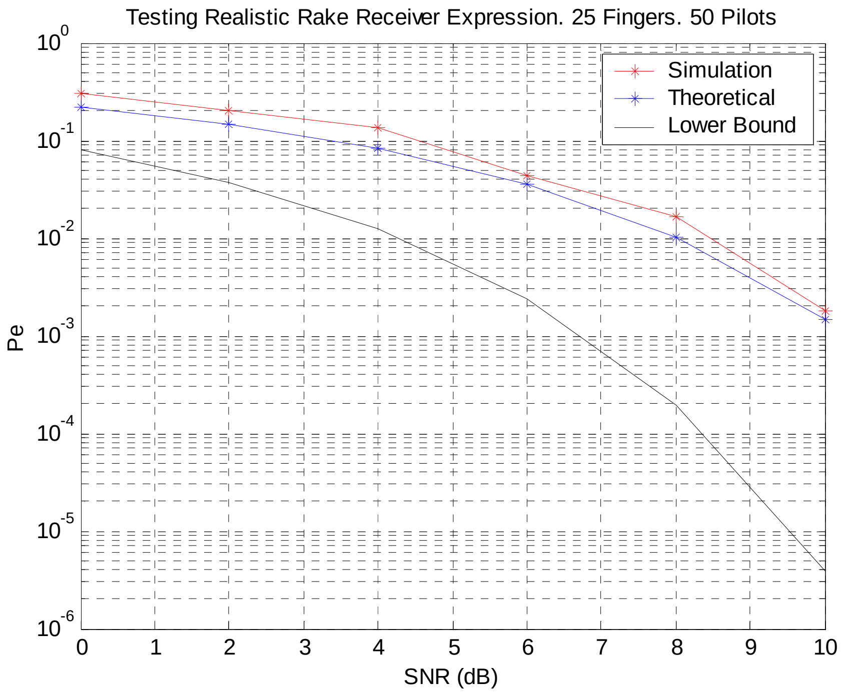
$$P_e = Q\left(\sqrt{\frac{2E_p}{N_0}\cdot\frac{\left[\sum_{k=0}^{F-1}\alpha_{f_k}^{'2}+\sum_{i=0}^{F-1}\sum_{\substack{j=0\\ j\neq i}}^{L-1}\alpha_j\alpha_{f_i}^{'}R\left(\tau_j-\tau_{f_i}\right)\right]^2}{Y_1+\frac{Y_2}{N}+\left(\frac{2N}{F}\frac{E_p}{N_0}\right)^{-1}}}\right)$$

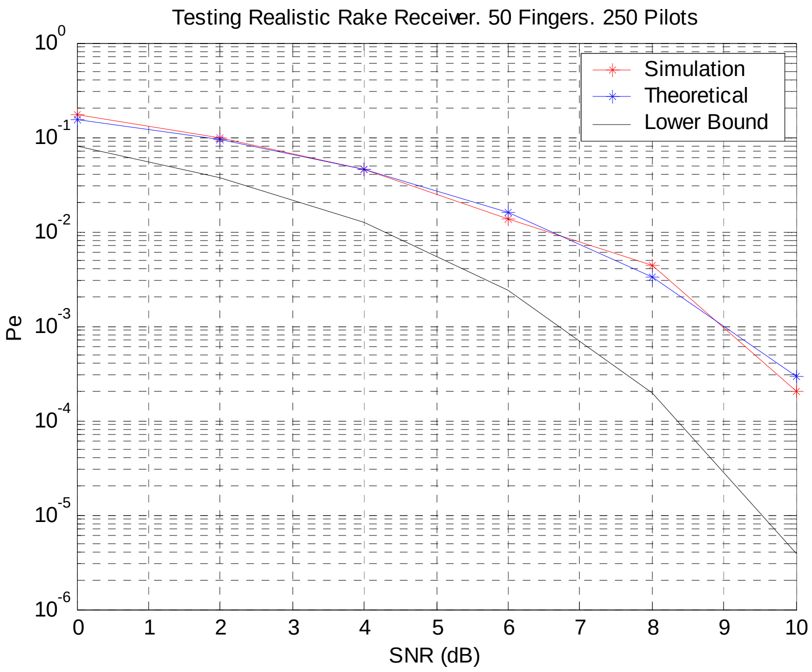
"Pilot" dependent term

$$Y_1 = \sum_{i=0}^{F-1}\alpha_{f_i}^{'2} + \sum_{i=0}^{F-1}\sum_{\substack{j=0\\ j\neq i}}^{F-1}\alpha_{f_i}^{'}.\alpha_{f_j}^{'}.R\left(\tau_{f_i}-\tau_{f_j}\right)$$

$$Y_2 = \sum_{l_1=0}^{L-1}\sum_{l_2=0}^{L-1}\sum_{i=0}^{F-1}\alpha_{l_1}\alpha_{l_2}R\left(\tau_{l_1}-\tau_{f_i}\right)R\left(\tau_{l_2}-\tau_{f_i}\right)$$

A More Realistic Rake Receiver





- Theoretical Expression picks strongest α'_f
- Simulation picks strongest $\hat{\alpha}_f$
- Match Improves for higher *N* and large SNR

Receiver Performance: Pilot-assisted Receiver

- Pilots are used to get an estimate of the received pulse shape to perform matched filtering

$$\hat{h}(t)=\frac{1}{N}\sum_{i=0}^{N-1}\left[\sum_{l=0}^{L-1}\alpha_l w(t-\tau_l)+n_i(t)\right]=\sum_{l=0}^{L-1}\alpha_l w(t-\tau_l)+\frac{1}{N}\sum_{i=0}^{N-1}n_i(t)$$

- Decision Statistic:

$$g=\int_0^{T_{bit}}\left[b_j\sum_{l=0}^{L-1}\alpha_l w(t-\tau_l)+n(t)\right]\hat{h}(t)\,dt$$

Receiver Performance: Pilot-assisted Receiver

Received Filtered Signal Energy

Pilot Noise

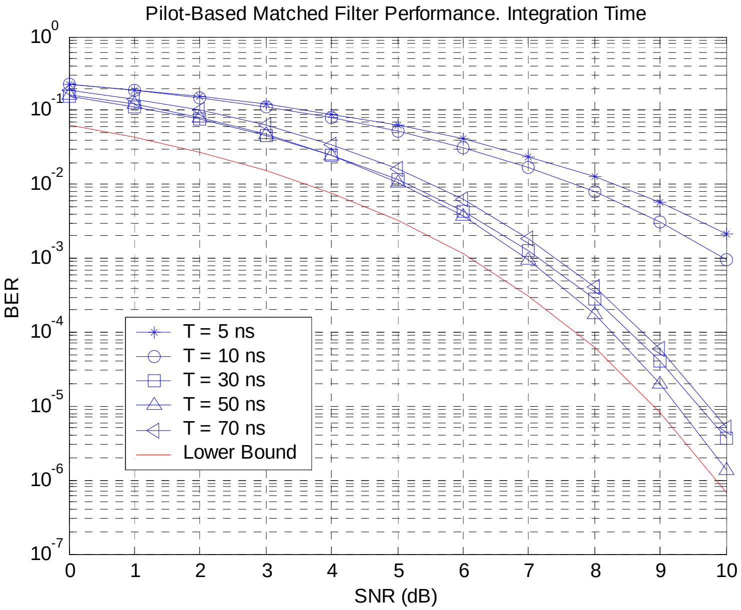
$$P_e = Q\left(\sqrt{\frac{E_p}{N_0}\cdot\frac{\left[\int_0^{T_{bit}} s_0'^2(t)\,dt\right]^2}{X_2+\frac{1}{N}X_2+\left(\frac{NE_p}{N_0X_1}\right)^{-1}}}\right)$$

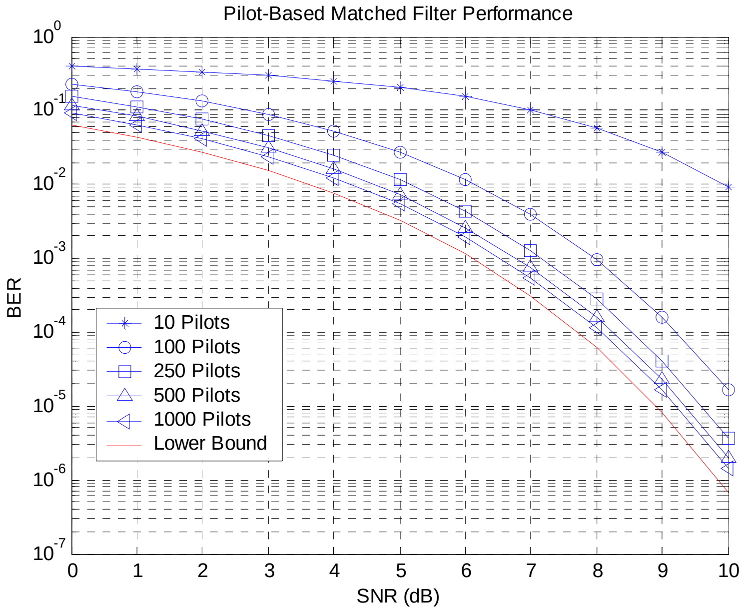
“Noise on Noise” Term

$$X_1 = W^2\int_0^{T_{bit}}\int_0^{T_{bit}}\sin c^2\left(W\left(t-\lambda\right)\right)\cos^2\left(2\pi f_c\left(t-\lambda\right)\right)dtd\lambda$$

$$X_2 = W\int_0^{T_{bit}}\int_0^{T_{bit}} s_0'(t)\,s_0'(\lambda)\sin\left(W\left(t-\lambda\right)\right).\cos\left(2\pi f_c\left(t-\lambda\right)\right)dtd\lambda$$

Receiver Performance: Pilot-assisted Receiver





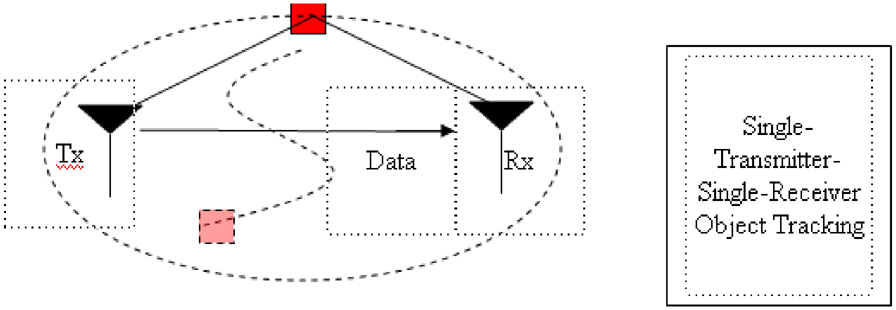
- Performance depends on Integration time *T* and number of pilots N
- Performance improves with *T* up to a certain point
- Bandpass Filter should be wide enough not to cause pulse Distortion
- Larger bandwidth = more noise → Compromise.

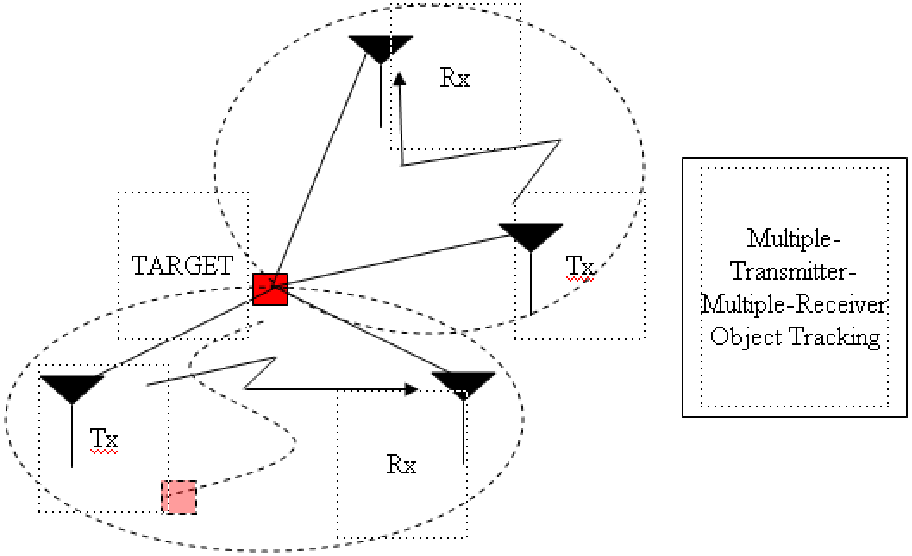
UWB Position Location and Tracking

- Accurate ranging is possible between UWB devices due to short pulses
- Is accurate position location and tracking possible?
- Change of position of objects causes changes in the multipath profile.
- Can we exploit these changes in the multipath profile *while simultaneously transmitting data?*
- This feature be very useful in the envisioned "smart" environments.

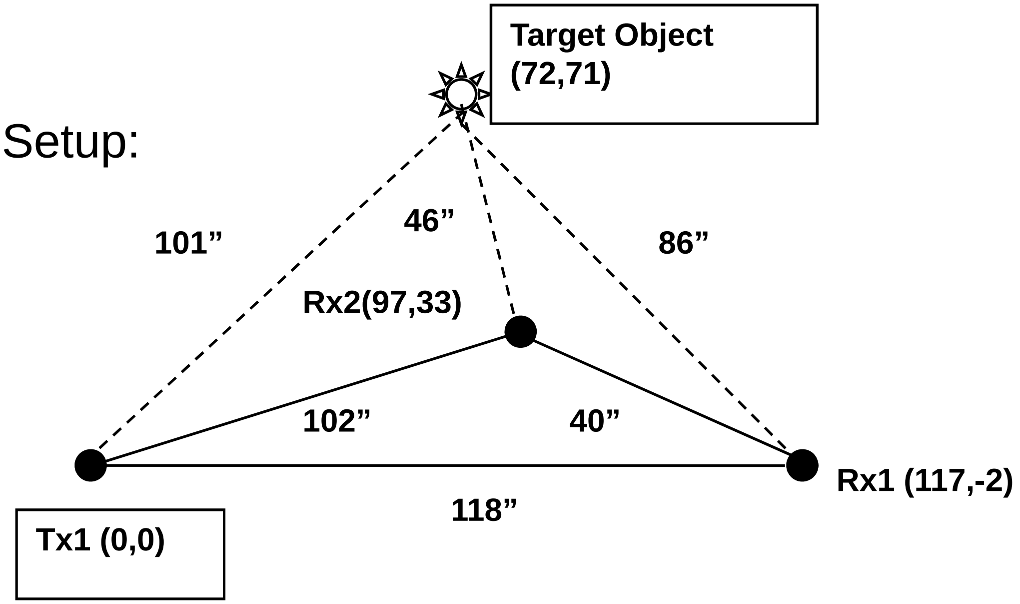
Basic Idea

- By observing the multipath profile, we determine *the sum of the distances of the object from the transmitter-receiver pair.*
- This localizes the position of the target object to within an ellipse with the Tx-Rx pair as foci
- In the presence of multiple tx/rx pairs we can pinpoint the exact location of the object.



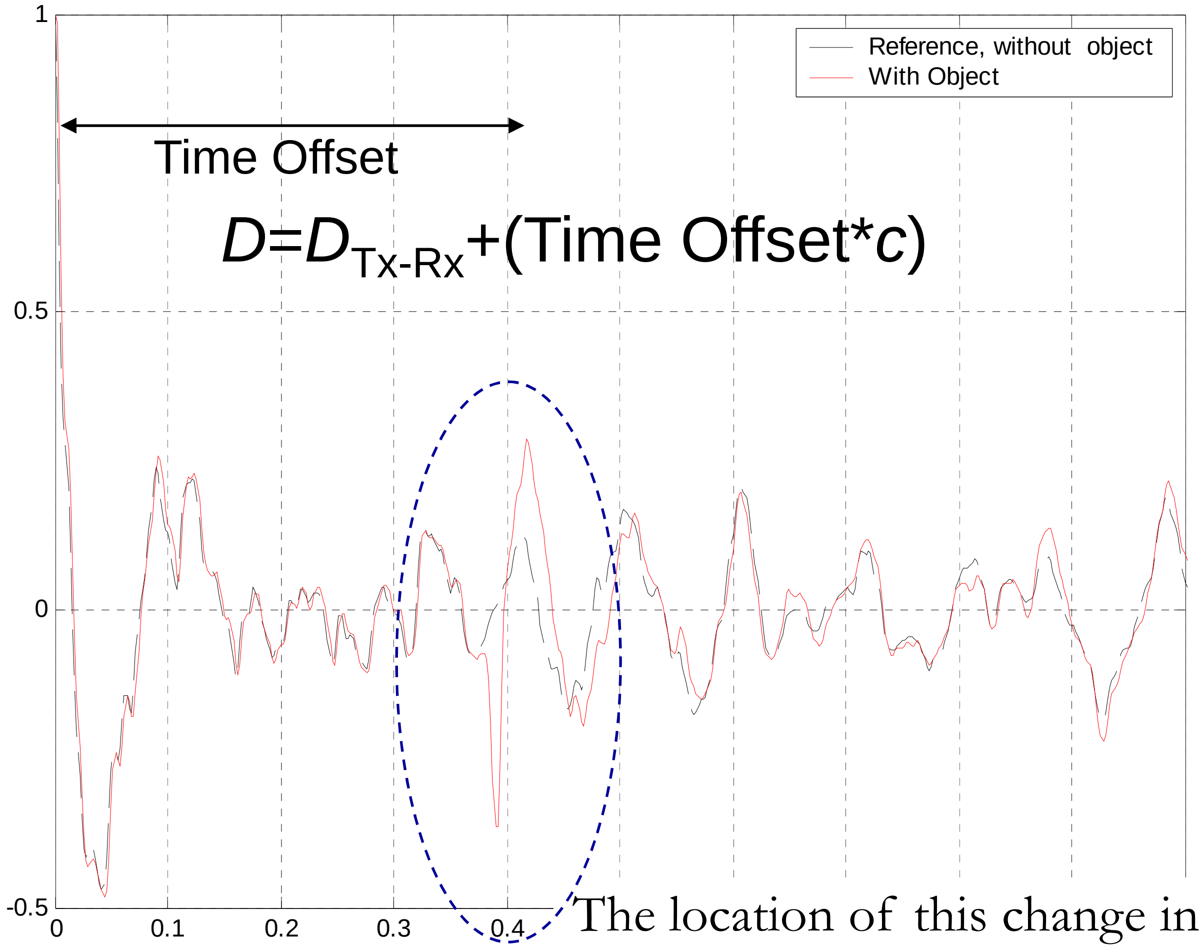


Sample Result: 467 Durham Hall



The antennas used were omnidirectional.
The objective is locate a target which was a large metallic object placed at (72”,71”). The transmitter is placed at (0,0) and the two Receiver positions used are (117”,-2”) and (97”,33”). Measurement of distance to the object is taken *at the probable point of reflection*.

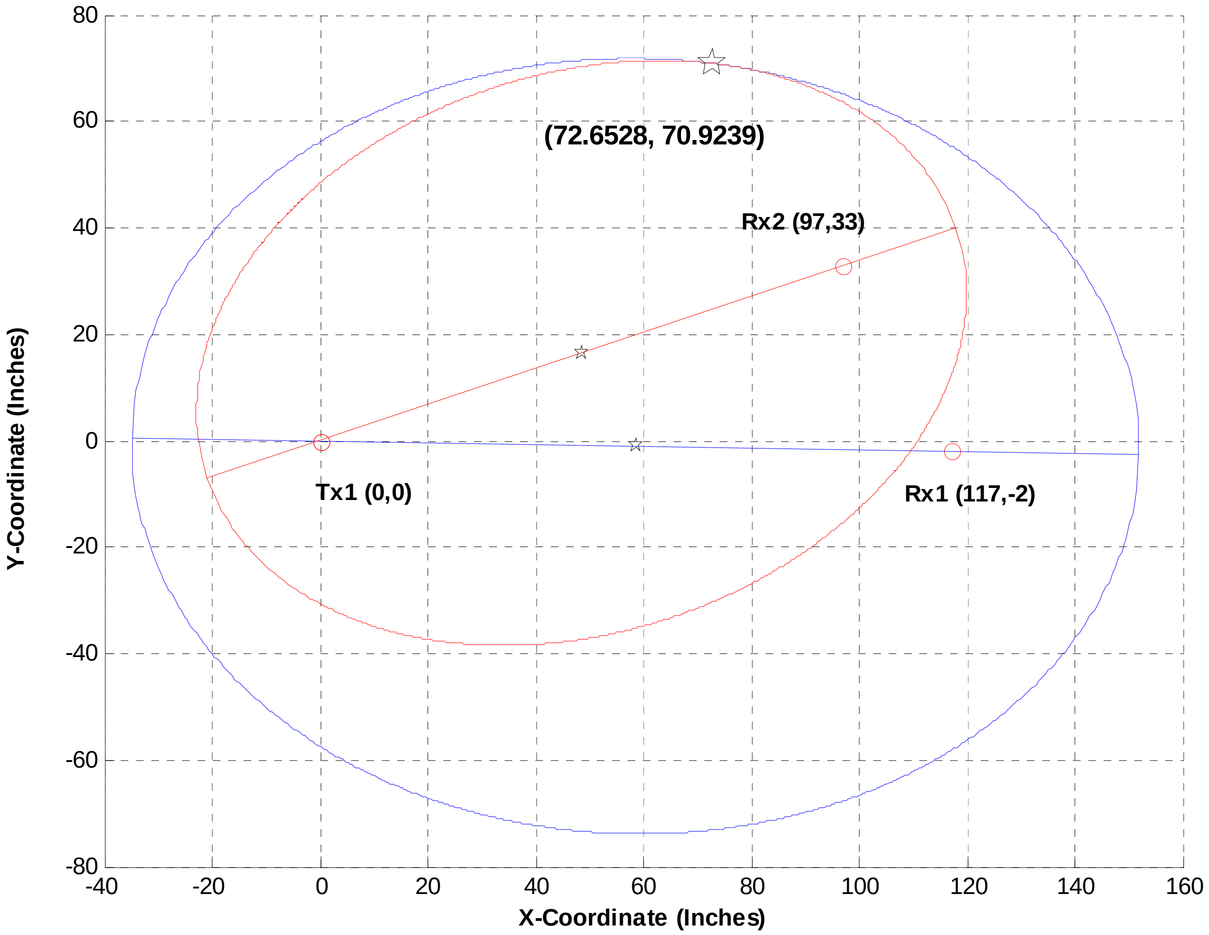
Multipath Profile



$$D=D_{\text{Tx-Rx}}+(\text{Time Offset}*c)$$

The location of this change in the multipath profile relative to the LOS path determines the extra distance traversed by the signal bouncing off the target.

Example – Cont.



True Location:

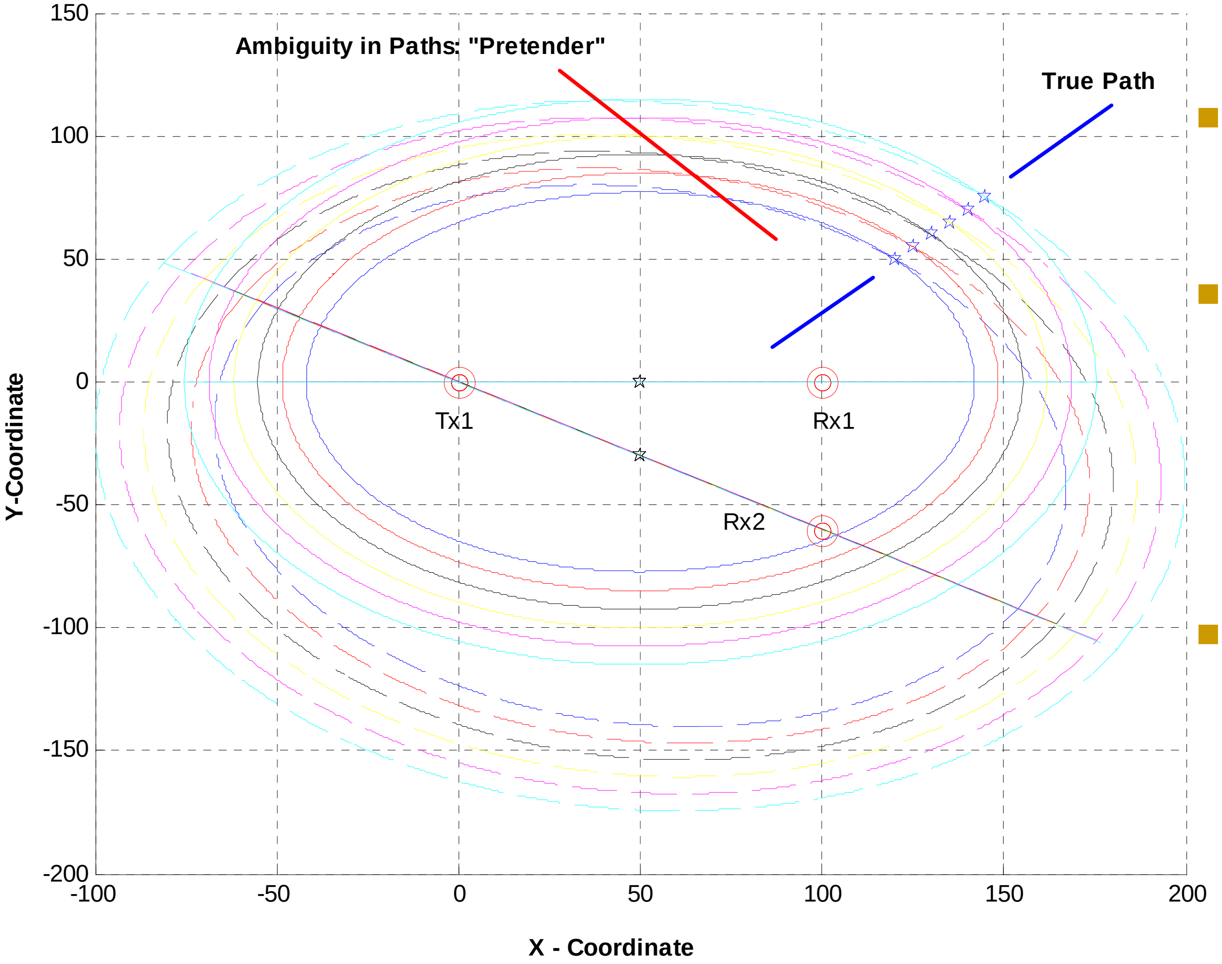
(72”,71”)

Estimated Location:

(72.6528”, 70.9239”)

The result is extremely accurate given that the object used is not a point object!

Motion Tracking



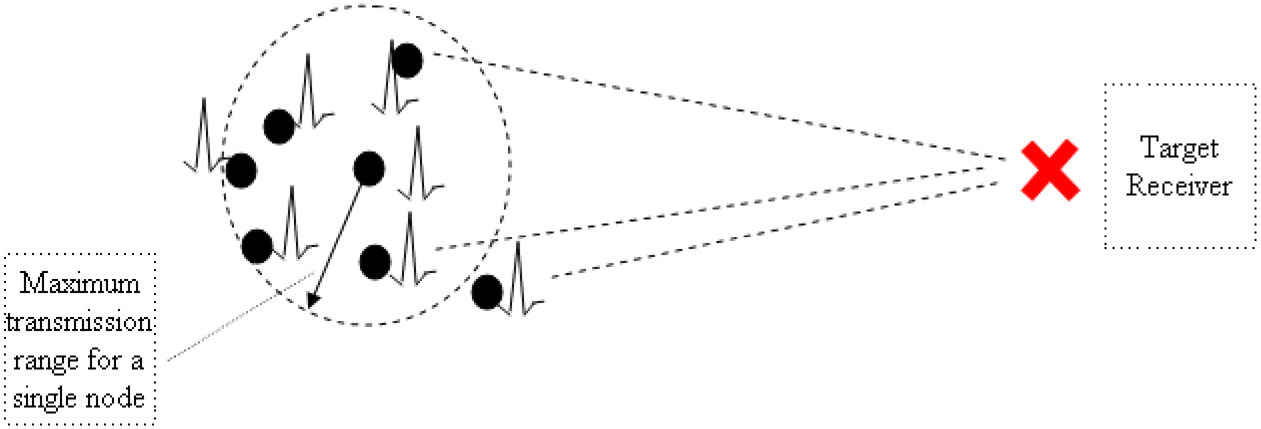
- The motion of an object can be tracked by several transmit receive pairs.
- For 2 pairs of Tx-Rx, an ambiguity in possible paths of the target object can arise due to multiple intersection points of ellipses.
- This can be resolved by using several transmit receive pairs.

Further Work

- Tracking was done with a metal object in order to produce sharp reflections. Tracking with other kinds of objects appears to be more difficult.
- This algorithm is based on the availability of a reference waveform.
- Tracking of objects when there is no LOS path.
- Tracking of objects in the presence of data modulation and/or time-hopping codes.

Distributed MIMO for UWB

- The system consists of a large number of nodes capable of UWB communication, whose range is restricted by the power limitations.
- If one of the nodes has to transmit data to a receiver outside this range, this transfer of data is achieved by an entire "team" of nodes.
- All members of this team of nodes transmits the *same data at approximately the same time* (exact synchronization is not required). This forms a *time-domain beamforming* system — effectively, the transmitted power and therefore the range of the node is increased.
- Rake or other flexible receiver structure used



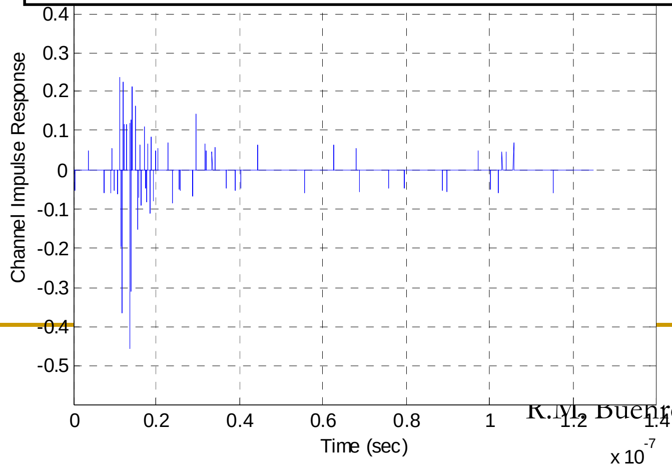
Analysis

- Suppose the system has N = 6 distributed nodes. The received signal is given by:

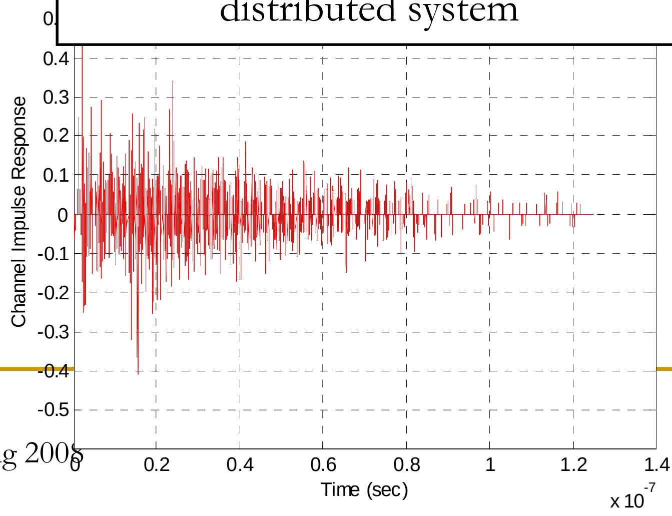
$$r(t)=\sum_{i=1}^{N} r_i(t)=\sum_{i=1}^{N}(s(t)*h_i(t))=s(t)*\sum_{i=1}^{N}h_i(t)=\sum_{i=1}^{N}\sum_{k}a_{k,i}\delta(t-\tau_{i,k})$$

- Therefore the effective channel impulse response is a superposition of the N impulse responses from the each of the nodes to the receiver.

Channel Impulse response for a single node



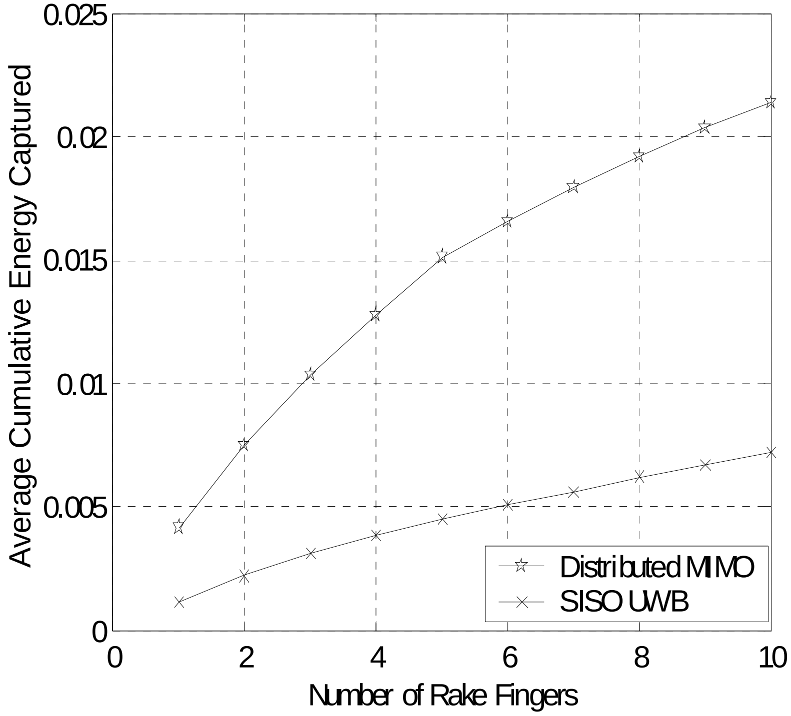
Channel impulse response for the distributed system



Results

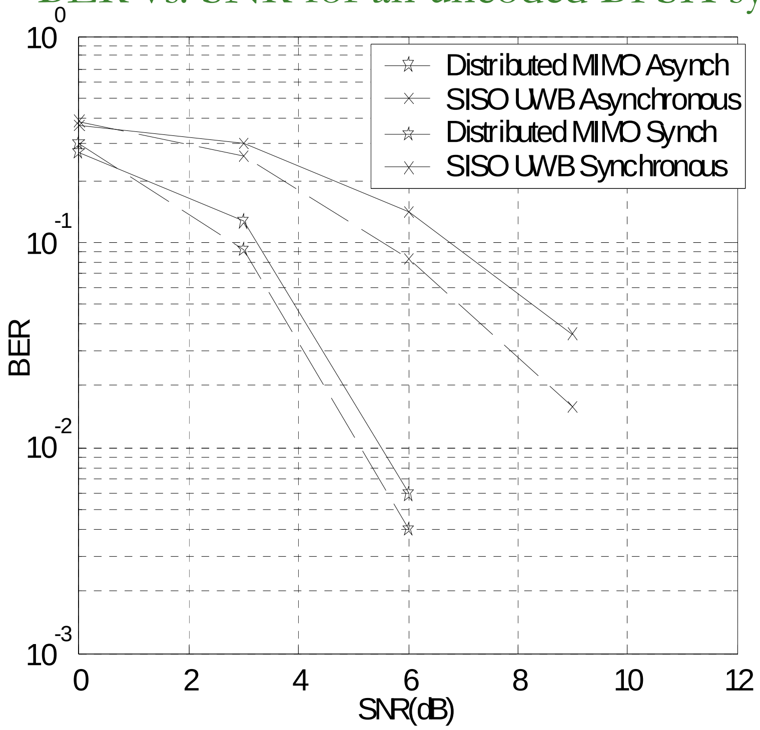
$N = 6$ distributed nodes

Cumulative Rake energy capture



Effective energy captured by the Rake Receiver increases.

BER vs. SNR for an uncoded BPSK system



Lack of synchronization does not drastically affect performance — reduced complexity.

Virginia Tech Research Activity

- Mobile and Portable Radio Research Group (MPRG)

  http://www.mprg.org/
  - Channel Modeling
  - Modulation, Waveform Design
  - Receiver Design
  - MAC layer design
  - Signal Processing
- Time Domain Laboratory (TDL)

  http://www.ee.vt.edu/~tdl/
  - Channel Measurement and Analysis
  - Material Propagation Characterization

VT Research Activity (con't)

- Center for Wireless Telecommunications (CWT)
  http://www.cwt.vt.edu/
  - Novel Channel Sounding Techniques
  - Hardware Design Issues
  - Channel Measurement and Modeling
- Virginia Tech Antenna Group (VTAG)
  http://antenna.ece.vt.edu/
  - Antenna Characterization
  - Antenna Design
- Virginia Tech VLSI for Telecommunications (VTVT)
  http://www.ee.vt.edu/~ha/research/research.html
  - CMOS and Digital Designs for UWB
  - Hardware Architectures

Commercial Development

- **Xtreme Spectrum Inc.** has released Trinity chip set.
- Data rates of 25, 50, 75 and 100 Mbps.
- MAC, baseband processor, RF transceiver, LNA, and antenna
- Streaming video applications.
- Wireless Fast Ethernet, USB2, and 1394.

Commercial Development

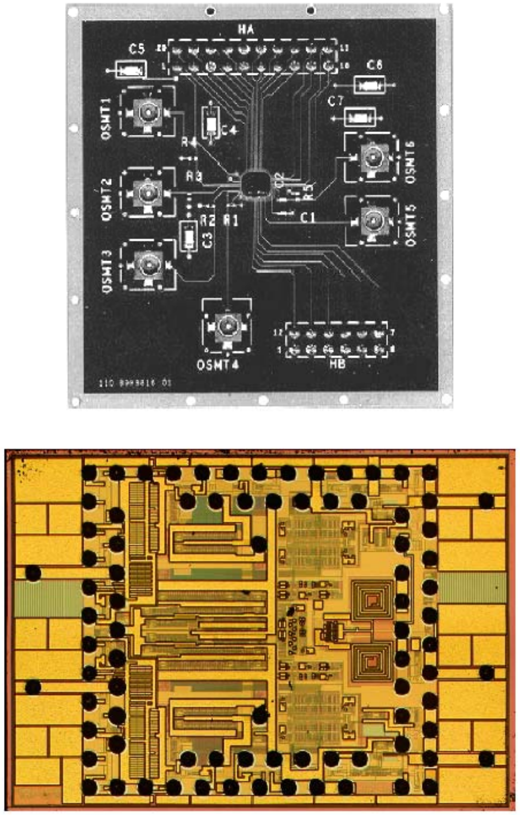


Image from Kelley, D., Reinhardt, S., Stanley, R., Einhorn, M. "PulsON Second Generation Timing Chip; Enabling UWB Through Precise Timing", Proc. of the *IEEE Conference on Ultra Wideband Systems and Technology 2002.*

- **Time Domain Corporation** is marketing PulsON family of UWB silicon products.
- Indoor wireless networking, 100's Mbps
- Indoor personnel and asset tracking systems.
- Precision measurement systems for surveying and measurement.
- Radar, 20 cm accuracy
- Through wall sensing.
- Industrial sensing for robotic controls.
- Automotive sensing for collision avoidance.
- Security bubbles for home and industrial security systems.

UWB Products, Communications

MultiSpectral Solutions Inc.

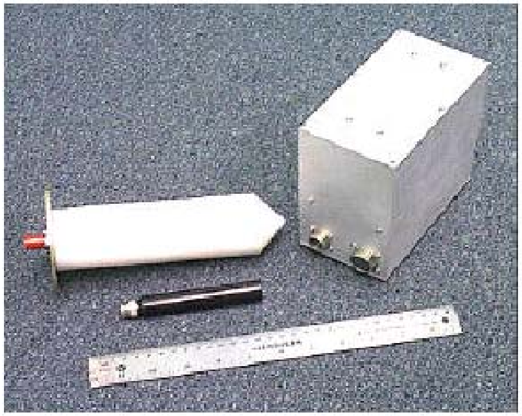
- Communications, Mobile ad hoc Network (MANET)
- 128 kbps voice, 115.2 kbps data or 1.544 Mbps (T1)
- Range: 1-2 km (node-to-node) with omni antennas

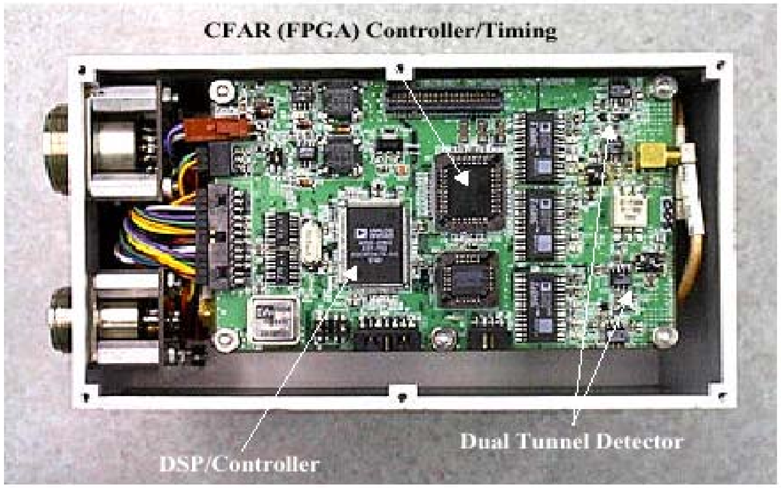
Reference: Fontana, R. “Ultra Wideband Technology - The Wave of the Future?” *ITC/USA 2000*, Oct. 2000.

UWB Products, Location

MultiSpectral Solutions Inc.

- High resolution, geolocation system, 3-D positioning
  - Sub-foot resolution
  - Range
    - Up to 2 km outdoors
    - Up to 300 feet indoors
  - UWB Geopositioning Example





Reference: Fontana, R. "Ultra Wideband Technology - The Wave of the Future?" *ITC/USA 2000*, Oct. 2000.

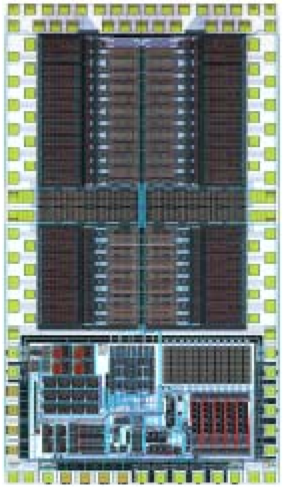
UWB Products, Location

Aether Wire & Locations (AWL)

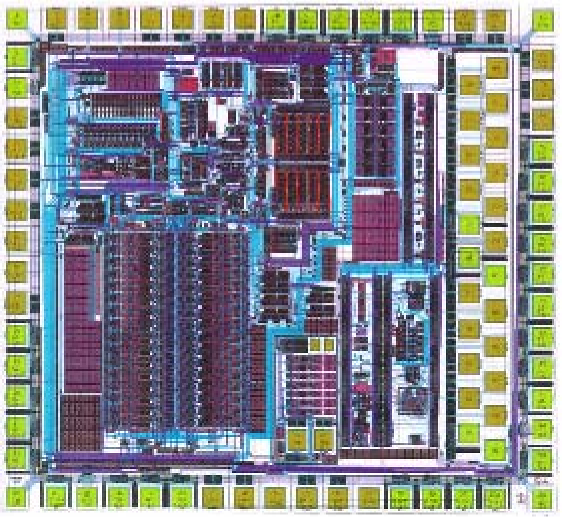
  - Development of pager-sized units that are capable of localization to *sub-meter* accuracy over 100-meter distances in networks of up to a few hundred localizers.

- A prototype localizer consists of two chips

Actual size with Dime



TX (Driver2)



RX (Aether5)

Reference: http://www.aetherwire.com/

Conclusion

- UWB holds great potential for a large number of unique communications and sensing applications.
  - Low cost.
  - Higher data rate communications.
  - Greater resolution radar.
  - Can offer combined communications and sensing.
- Much research still needs to be done to fully exploit the benefits of this powerful new technology.