Helsinki University of Technology
S-72.4210 Postgraduate Course in Radio Communications

UWB
Theory, Channel, and Applications

Hafeth Hourani
hafeth.hourani@nokia.com

Contents

Next …

- **Introduction**
- UWB Channel Models
- Modulation Schemes
- References

A bit of History

- **Is it a new technology?**
  - The first *impulse system* patent was awarded in 1954
  - The basic concept was first described in 1960
  - The first landmark patent of UWB was awarded in 1973
  - It has been used since 1980 in military Radar applications
  - The term UWB was first used in 1989 by DoD
  - Up to 1994, all UWB studies were classified
  - A substantial change occurred in 2002 when UWB was made public (by FCC)
- **NO!**
  - The concept is 50 years old . . .

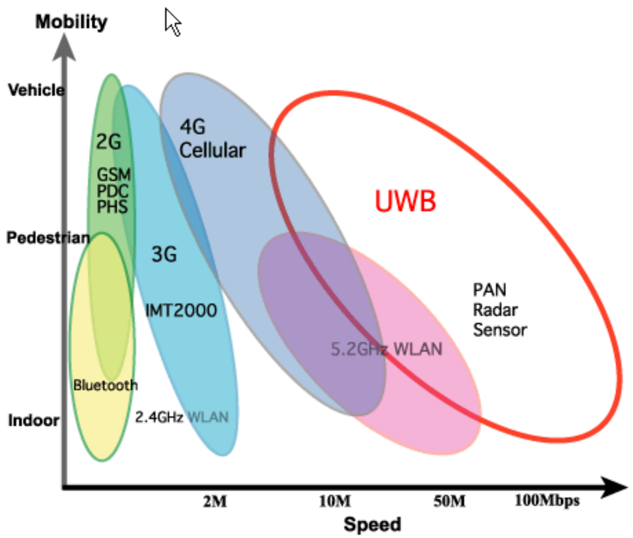
A Short Story

- The efforts to bring UWB to the mainstream were greeted with great hostility
  - The allocated band is 7.5 GHz – the largest allocation for BW to any commercial terrestrial system
    - The enormous BW means that UWB could offer Gbps data rates
    - The BW sat on top of many existing allocations. That causes many concerns
  - FCC allocated 1500-times the spectrum allocation of a single UMTS license
  - The band is FREE
- FCC received almost 1000 submissions opposing the proposed UWB
- In response
  - The maximum power was limited to ~ 0.5mW
- Therefore, UWB could be used to
  - Indoor, short-range communications for high data rates, OR
  - Outdoor, long-range, but for very low data rates

UWB Synonyms

- Other terms associated with “ultra-wideband” include
  - “impulse”,
  - “short-pulse”,
  - “non-sinusoidal”,
  - “carrier-less”,
  - “time domain”,
  - “super wideband”,
  - “fast frequency chirp”, and
  - “mono-pulse”

Where does it fit?

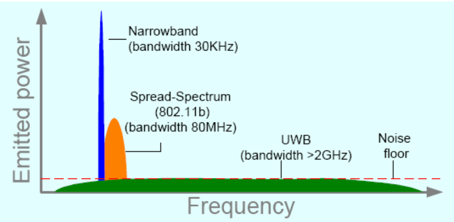


Fundamentals

- The basic idea is to develop, transmit and receive an extremely short duration burst of radio frequency energy
  - The resultant waveforms are extremely broadband
    - The very wideband nature of UWB means that it spans frequencies commonly used as carrier frequencies
- The UWB signal is carrierless. (NO carrier at all)
  - No upconversion nor downconversion
  - No local oscillator nor phase tracking loops
- UWB signal is noiselike
  - Low energy density
  - Pseudo-random characteristics

Narrowband, Wideband and Ultrawideband

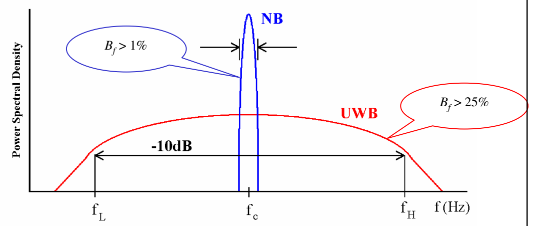
- Fractional Bandwidth (B_f) $B_f = \dfrac{f_H - f_L}{f_c}$



System	Transmission Power [W]	Bandwidth [Hz]	Power Spectral Density [W/MHz]	Classification
Radio	50 kW	75 kHz	666,600	narrowband
TV	100 kW	6 MHz	16,1700	narrowband
GSM-900	320 W	200 kHz	1,600	narrowband
GSM-1800	20 W	200 kHz	100	narrowband
WCDMA	20 W	5 MHz	4	wideband
WLAN	1 W	20 MHz	0.05	wideband
UWB	1 mW	7.5 GHz	0.013	ultrawideband

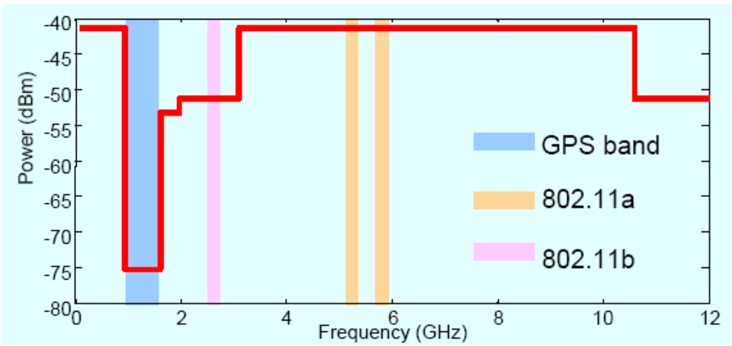
UWB Signal Definition

- FCC Definition
  - $B_f > 20\%$ (measured at -10 dB)
  - total BW > 500 MHz
- Common Definition
  - $B_f > 25\%$
  - total BW > 1.5 GHz



Spectral Mask

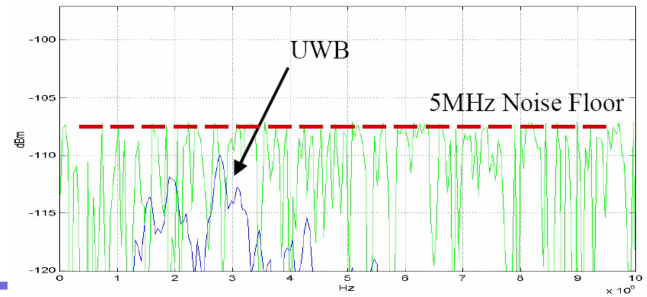
- UWB system cover a large spectrum and interfere with existing licensed spectrum



UWB Coexistences

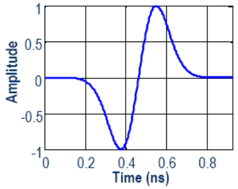
- "Polite" coexistence with Licensed spectrum
  - The *Aggregate Interference* from UWB is "undetectable" to narrowband Rx.
    - The Power Spectral Density is at *Narrow Band Thermal Noise* level or below

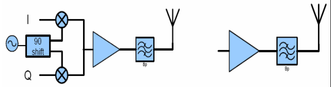
$$PSD = \frac{P_t}{BW}$$



Unique Features

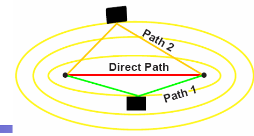
- Ultra-short pulses
  - High data rate
  - Precise ranging capability
- Baseband transmission
  - Low transceiver complexity
    - No upconversion nor downconversion
    - No local oscillator nor phase tracking loops
- Low duty cycle operation
  - High energy efficiency

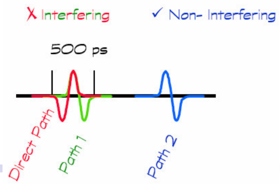




Prominent Features (1/2)

- Low probability of detect/intercept (LPD/I)
  - Extremely low power spectral density (below noise level)
    - Extremely narrow pulse-width
    - Low duty cycle
- Resiliency to multipath fading
    - Can resolve multipath signals having differential delays on order of 1 ns
    - Possible to distinguish reflecting surfaces separated by centimeters
    - For pulse duration 2ns – 0.13ns => resolvable pathlength 60cm – 4 cm



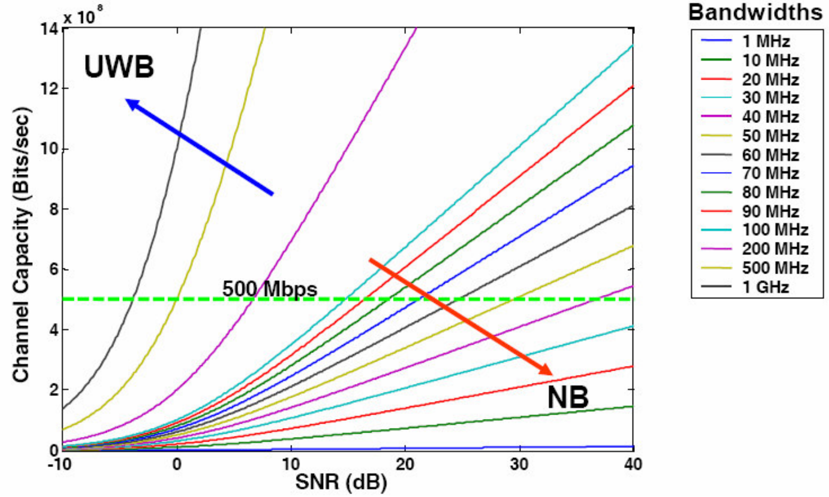


Prominent Features (2/2)

- Low complexity of UWB transceiver
  - Carrier-less transmission results in low cost manufacturing
  - Nearly all-digital, with minimum RF electronics
- Precise ranging capability
  - Have very good time domain resolution allowing for location and tracking applications
    - Precise timing required to receive sub-nanosecond pulses presents the opportunity to precisely determine range between Tx. And Rx. In order of several centimeters

Theoretical Motivation: Channel Capacity

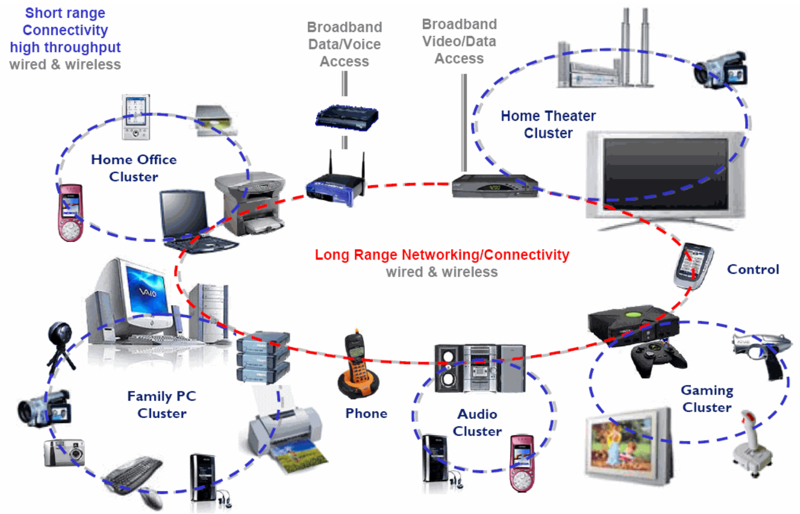
$$C = B * \log_2(1 + SNR)$$



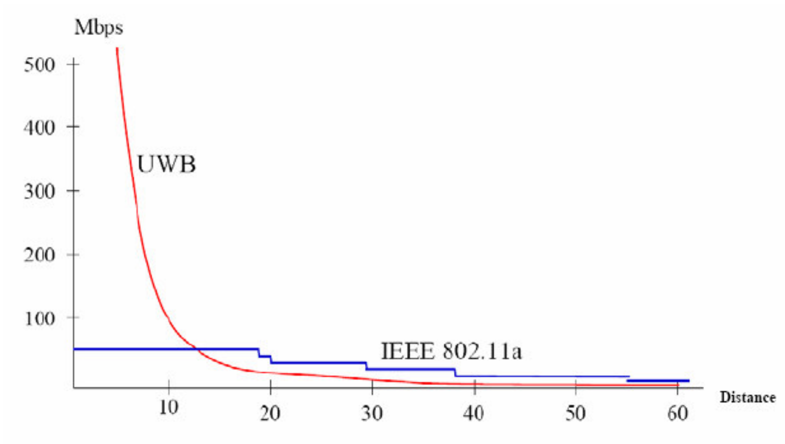
Applications

- Wireless Communication Systems
  - LAN & PAN
  - Roadside info-station
  - Short-range radios
  - Military communications
- Radar & Sensing
  - Vehicular radar
  - Medical imaging
  - Surveillance

Home Connectivity



UWB Data Rates



Regulatory Bodies

- Regulation in the USA
  - In Feb 2002, the FCC issued the UWB rulings that provided the first radiation limitations for UWB
- Regulation in Europe
  - Currently, there are no dedicated frequency bands for UWB applications in ETSI or ITU
  - It is expected that ETSI/CEPT will follow the FCC

Related Standards

- IEEE 802.15 : Wireless Personal Area Network (WPAN)
- IEEE 802.15.1 : Bluetooth, 1Mbps
- IEEE 802.15.3 : WPAN/high rate, 50Mbps
- IEEE 802.15.3a: WPAN/Higher rate, 200Mbps, UWB
- IEEE 802.15.4 : WPAN/low-rate, low-power, mW level, 200kbps

Next . . .

- Introduction
- **UWB Channel Models**
- Modulation Schemes
- References

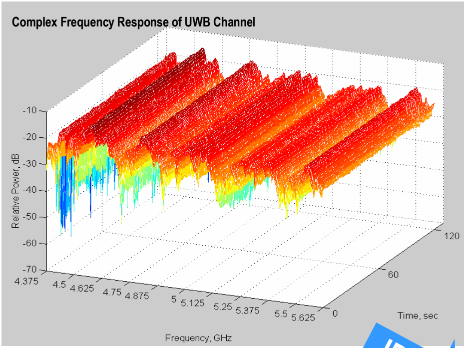
UWB Channels

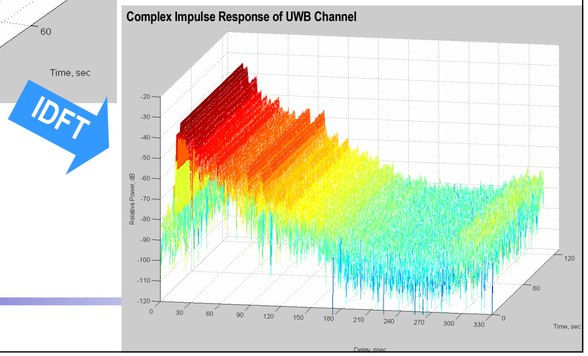
- Indoor
  - Within a room (LOS & NLOS)
  - Investigates the impact of
    - Distance
    - Rx/Tx antenna heights
    - Antenna polarization
- Outdoor
  - Campus environment
  - Low altitude
  - Mobility

UWB Channel Sounding

- Frequency Domain (FD) channel sounding
  - Measures the Frequency Response of the channel
    - The channel is excited using a frequency sweeping sinusoidal signal
    - The received signal is an approximation of the channel transfer function
- Time Domain (TD) channel sounding
  - Measures the Impulse Response of the channel
    - The channel is excited using an very short pulse

UWB Channel Sounding





UWB Channel Model Characteristics

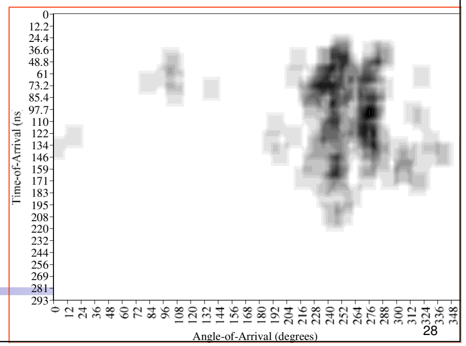
- Compared to the "conventional" channel models, the UWB channel has the following characteristics
  - Only few multipath components overlap within each resolvable delay bin
    - The amplitude fading characteristics are NO longer the usual Rayleigh
  - Due to the large bandwidth, the propagation phenomena are different in the lower band and the upper band of the spectrum
    - The size of the Fresnel zone will be remarkably different at the lower and higher frequency bands. (Fresnel zone is a function of frequency)
    - The higher frequency components are attenuated more than the lower frequencies

Channel Models

- Modified Saleh-Valenzuela (SV) Model
  - Adopted by the IEEE 802.15.3 WG as the reference model
  - The model assumes
    - *Cluster Arrival Time*, and
    - *Ray Arrival Time*
    - Both arrival times are modeled independently by Poisson processes
- Modified Δ-K model
- Ray Tracing model

Clustering Models

- Previous models for indoor propagation reported the existence of clusters of multipath components
- Example
  - 4cm pathlength difference, gives rise to two multipath components separated by 133ps
  - Thus, different parts of the same reflector (e.g., furniture piece) can give rise to several multipath components
  - These components would be part of the same ***cluster***



SV Impulse Response Model

$$h_i(t) = X_i \sum_{l=0}^{L} \sum_{k=0}^{K} \alpha_{k,l}^{i} \delta\left(t - T_l^i - \tau_{k,l}^i\right)$$

- i^{th} realization
- Log-normal shadowing
- Multipath gain coefficients
- Delay of l^{th} cluster
- Delay of k^{th} multipath component relative to the l^{th} cluster arrival time

SV Impulse Response Model

- The channel coefficients $\alpha_{k,l}$ are defined by

$$\alpha_{k,l} = p_{k,l}\beta_{k,l}\xi_l, \text{ and } 20\log_{10}\left(\beta_{k,l}\xi_l\right) \propto N\left(\mu_{k,l}, \sigma_1^2 + \sigma_2^2\right)$$

$$\Rightarrow \left|\beta_{k,l}\xi_l\right| = 10^{\left(\mu_{k,l}+n_1+n_2\right)/20}$$

  - Where $n_1 \propto N\left(0,\sigma_1^2\right)$ and $n_2 \propto N\left(0,\sigma_2^2\right)$

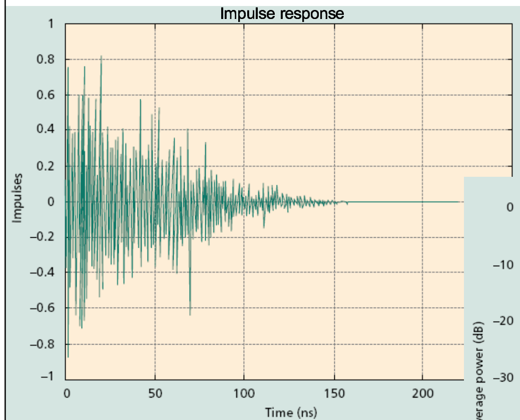
- Model inputs
  - *Cluster Arrival Rate* **Λ** (1/nsec)
  - *Ray Arrival Rate* **λ** (1/nsec)
  - *Cluster Decay Factor* **Γ**
  - *Ray Decay Factor* **γ**
  - Standard deviation for *Cluster lognormal fading* $\boldsymbol{\sigma_1}$ (in dB)
  - Standard deviation for *Ray lognormal fading* $\boldsymbol{\sigma_2}$ (in dB)
  - Standard deviation for total multipath lognormal fading $\boldsymbol{\sigma_x}$ (in dB)

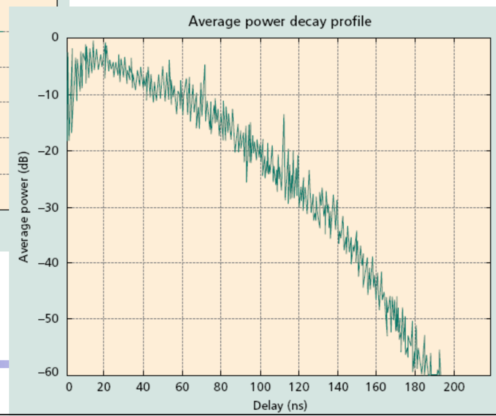
Main Parameters of SV-Model

	SV-1	SV-2	SV-3	SV-4
	LOS 0-4 m	NLOS 0-4 m	NLOS 4-10 m	NLOS 4-10 m extreme multipath
Model Parameters				
Cluster Arrival Rate Λ (1/nsec)	0.0233	0.4	0.0667	0.0667
Ray Arrival Rate λ (1/nsec)	2.5	0.5	2.1	2.1
Cluster Decay Factor Γ	7.1	5.5	14	24
Ray Decay Factor γ	4.3	6.7	7.9	12
Cluster lognormal fading σ1 (dB)	3.3941	3.3941	3.3941	3.3941
Ray lognormal fading σ2 (dB)	3.3941	3.3941	3.3941	3.3941
multipath lognormal fading σx (dB)	3	3	3	3
Model Characteristics				
Mean excess delay (nsec)	5.0	9.9	15.9	30.1
RMS delay (nsec)	5	8	15	25
Channel energy mean (dB)	-0.4	-0.5	0	0.3
Channel energy standard dev. (dB)	2.9	3.1	3.1	2.7
# of paths within 10dB of the peak	12.5	15.3	24.9	41.2
# of paths capturing 85% of the energy	20.8	33.9	64.7	123.3

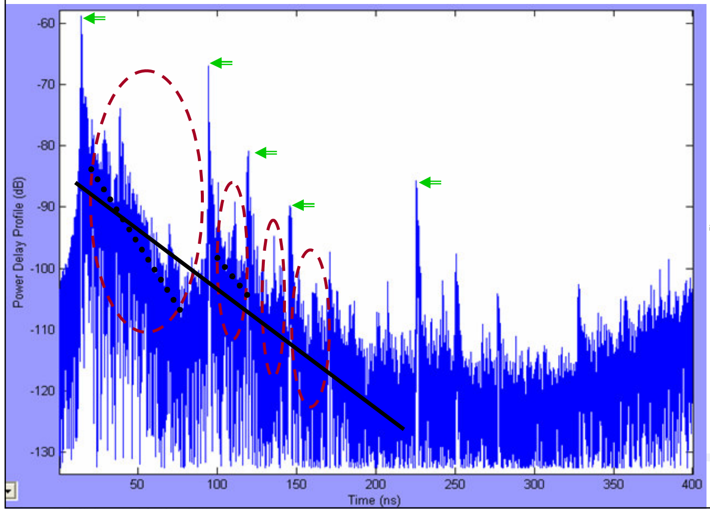
SV Impulse Response Model

SV-3 Model





Closer look at the Power Delay Profile



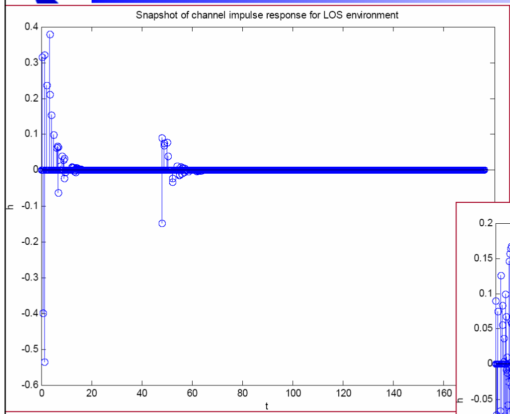
Strong rays

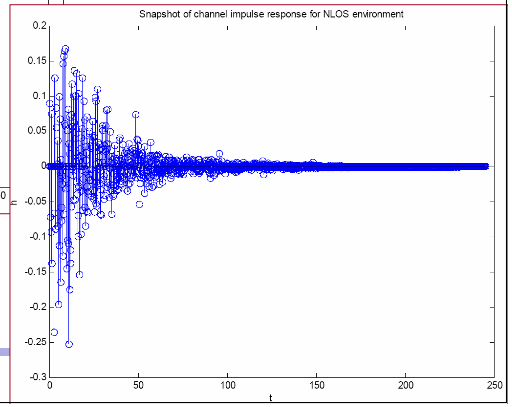
Cluster of rays (multipath cluster)

Exponential time decay of ray energy

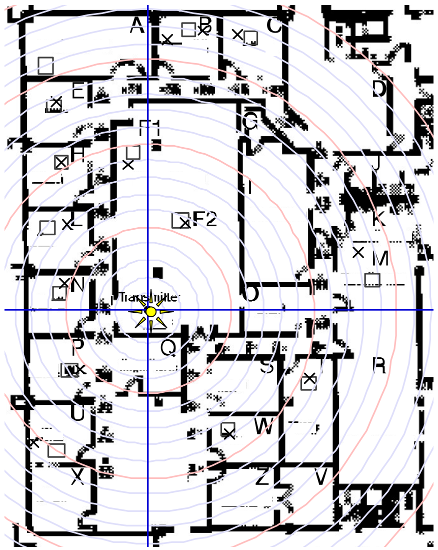
Exponential time decay of power

LOS vs. NLOS Impulse Response



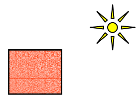


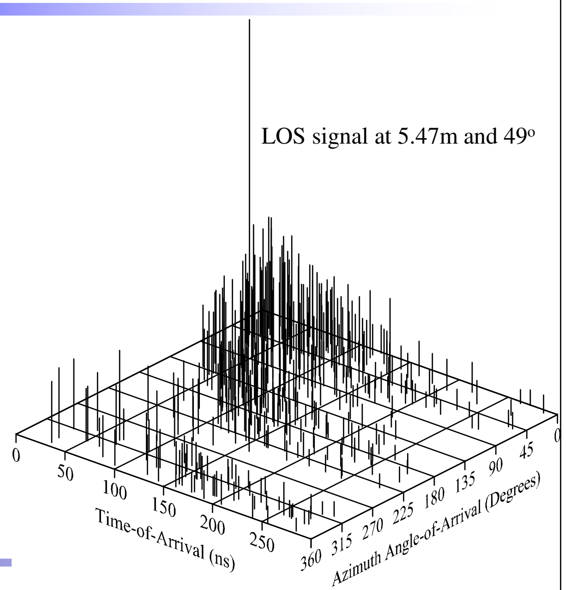
Example: UWB Channel Measurements



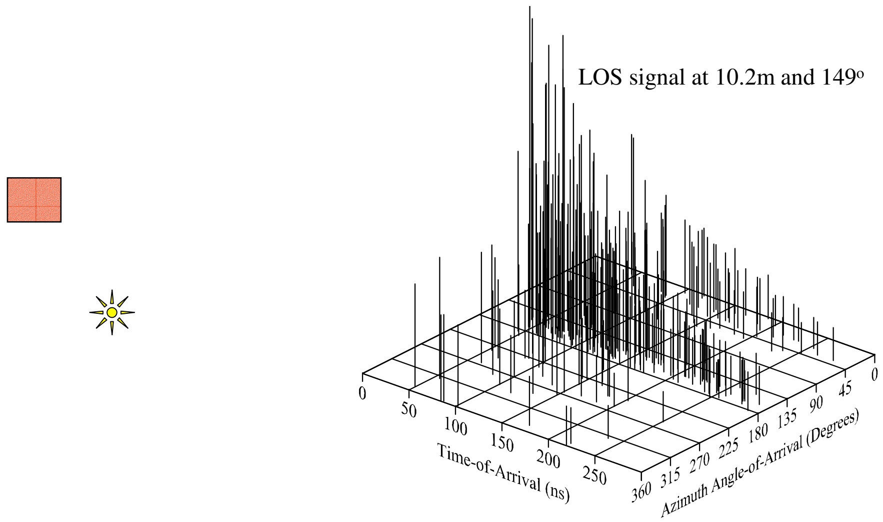
Location	d_{LOS} (m.)	AOA (°)
P	5.47	49
B	16.92	191
F2	5.61	203
H	10.20	149
C	17.23	198
F1	8.68	172
L	7.04	136
N	5.29	107
A	16.13	184
E	13.54	156
M	13.07	255
T	10.48	293
U	10.57	41
W	8.87	327

Example: UWB Channel Measurements

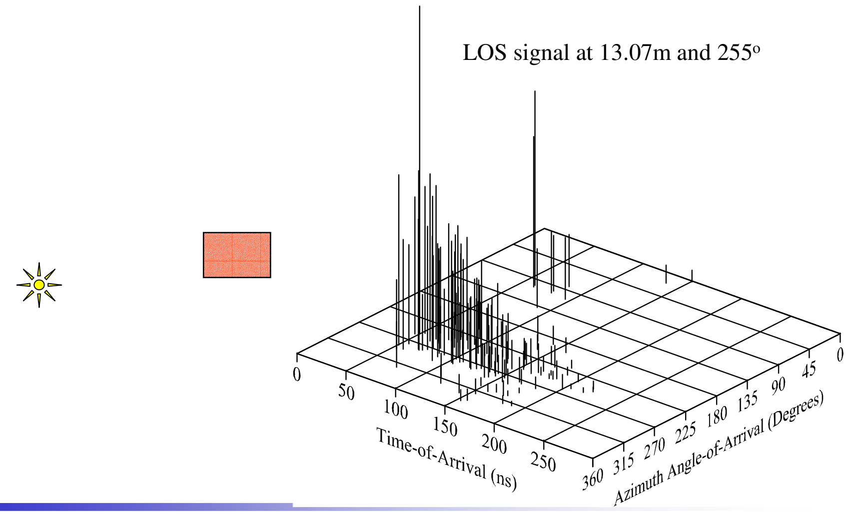




Example: UWB Channel Measurements



Example: UWB Channel Measurements



Path Loss Model

- The general path loss is given by

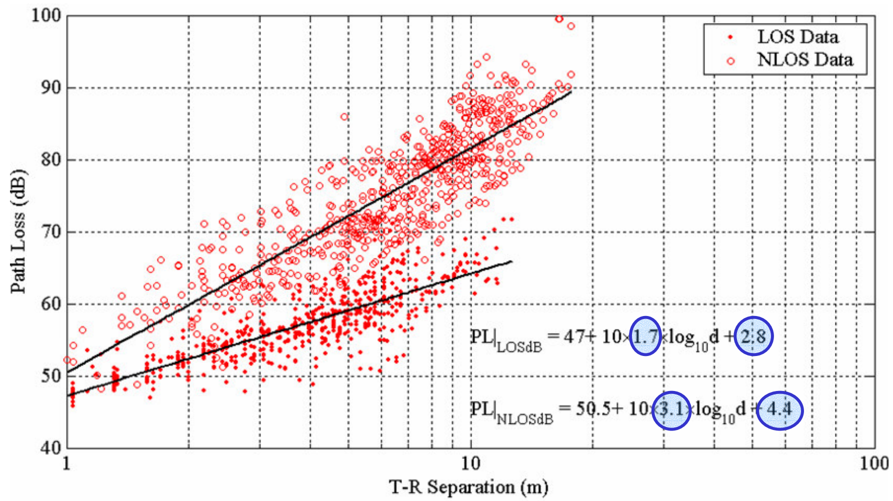
$$PL(d)_{dB} = PL_0 + n10\log_{10}(d_m) + X_\sigma$$

Path loss component

Received power at reference distance (1m)

Lognormal shadowing term

Path Loss Model



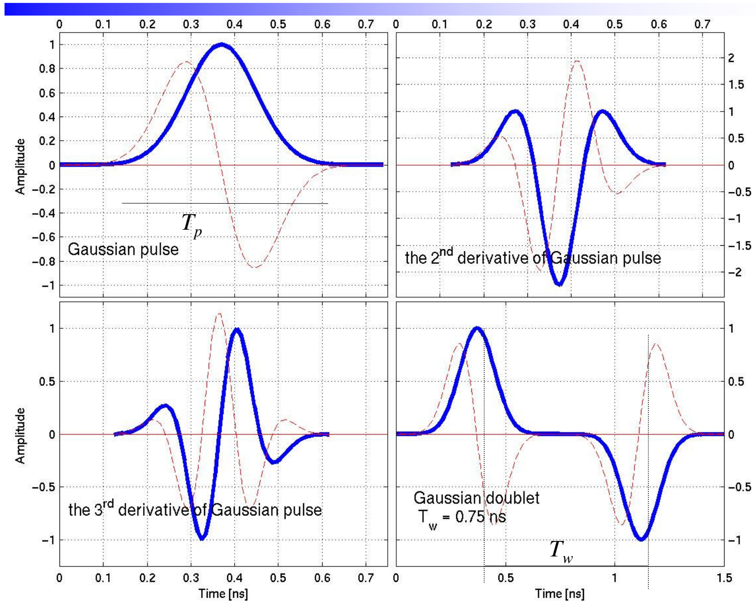
Next . . .

- Introduction
- UWB Channel Models
- **Modulation Schemes**
- References

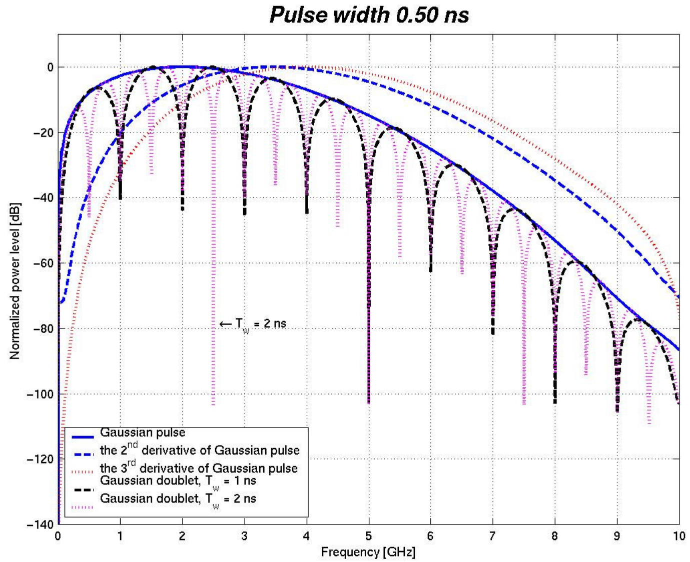
Impulse Radio

- UWB modulation is based on the *Impulse Radio* concept
  - Generation of a series of very short duration pulses
  - Any given pulse will have very low energy
    - The permitted power levels for UWB are very low (~ 0.5mW)
  - Because of the low energy, many pulses are combined to carry the information of one bit
- Impulse Radio is a mere baseband technique

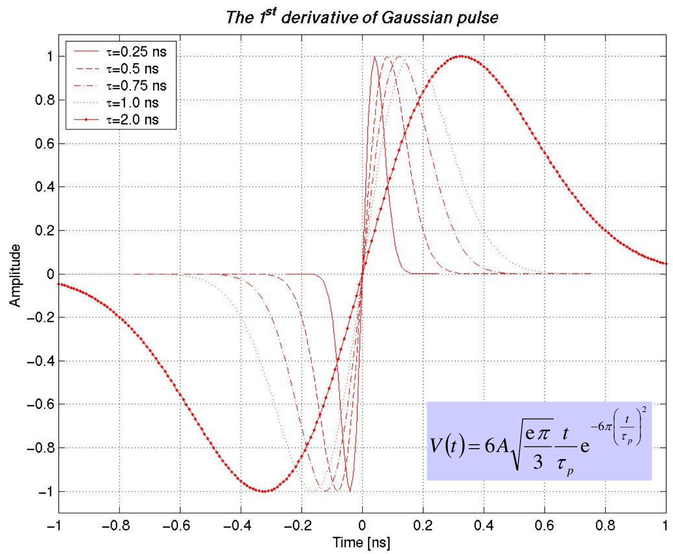
The Gaussian Pulse: Time



The Gaussian Pulse: Frequency

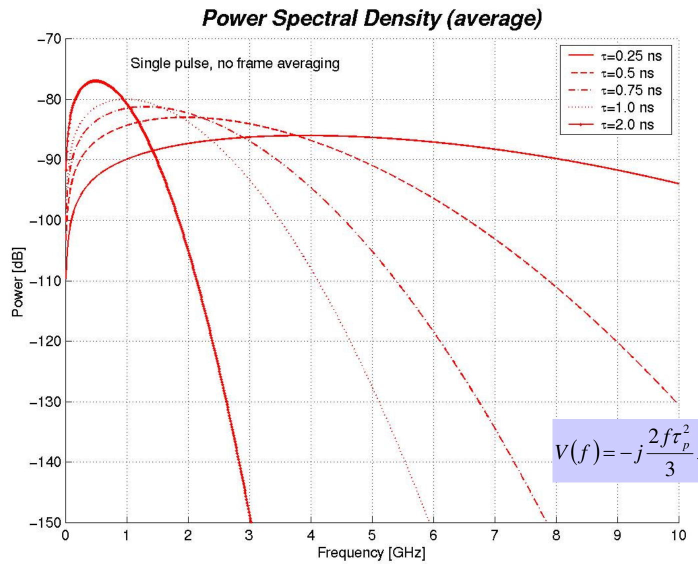


Closer Look at Gaussian Monocycle



$$V(t)=6A\sqrt{\frac{e\pi}{3}}\frac{t}{\tau_p}e^{-6\pi\left(\frac{t}{\tau_p}\right)^2}$$

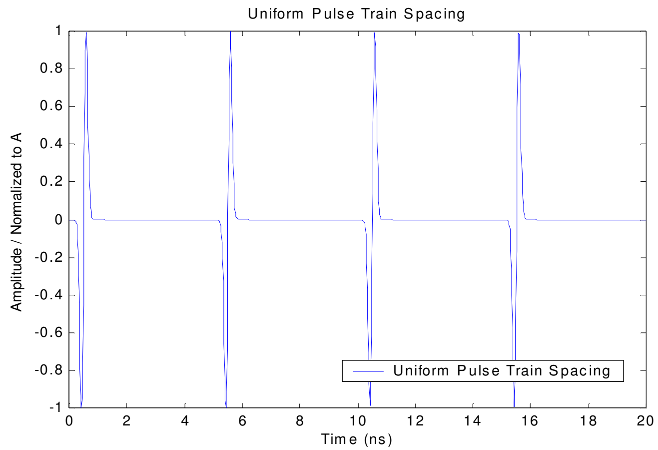
Closer Look at Gaussian Monocycle



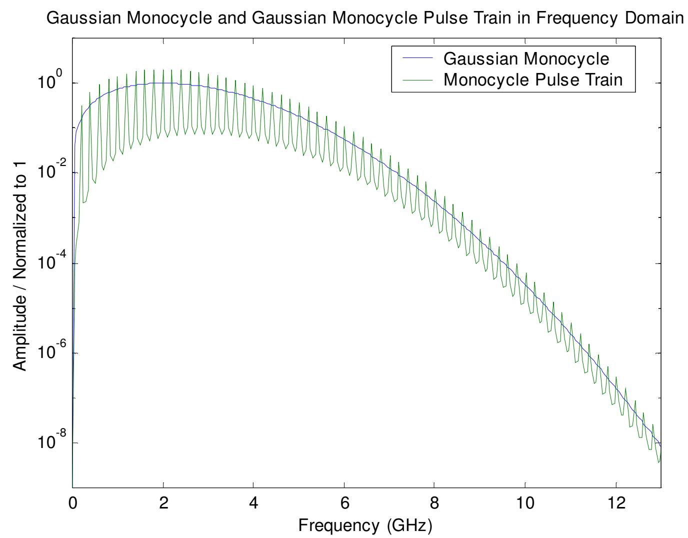
$$V(f)=-j\frac{2f\tau_p^2}{3}\sqrt{\frac{e\pi}{2}}e^{-\frac{\pi}{6}f^2\tau_p^2}$$

Pulse Train: Time

- UWB system typically use many pulse repetitions (hundreds) to represent each data symbol

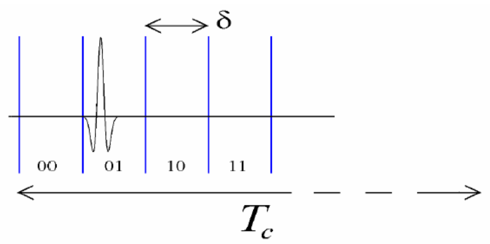


Pulse Train: Frequency



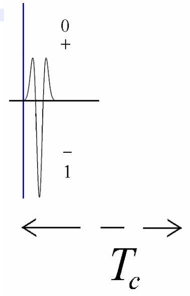
Data Modulation (1/3)

- Pulse Position Modulation (PPM)
  - The data is carried in the “fine” time shift of the pulse
    - While bit ‘0’ is represented by a pulse originating at the time instant 0, bit ‘1’ is shifted in time by the amount δ from 0.
  - Example
    - 4-ary PPM with data 01

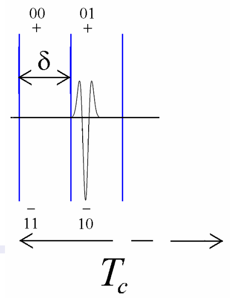


Data Modulation (2/3)

- Bipolar Modulation (BPM)
  - The data is carried in the polarity of the pulse
  - Very energy efficient

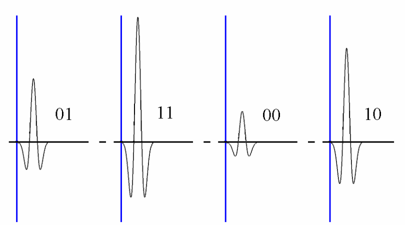


- Bi-orthogonal Modulation
  - Combination of PAM and BPM
  - M-ary bi-orthogonal has M/2 possible PPM shifts

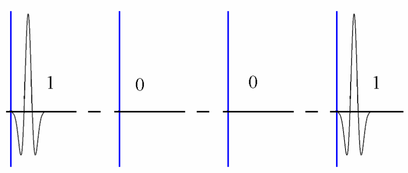


Data Modulation (3/3)

- Pulse Amplitude (PAM)
  - Very poor energy efficiency



- On-Off Keying (OOK)
  - Simple implementation
  - Poor energy efficiency



Next . . .

- Introduction
- UWB Channel Models
- Modulation Schemes
- **References**

References

- [1] Leonard E. Miller, "*Why UWB, A Review of Ultrawideband Technology*", National Institute of Standards and Technology, April 2003
- [2] Jeffrey Reed, et al., "*Introduction to UWB: Impulse Radio for Radar and Wireless Communications*", Virginia Polytechnique Institute & State University, URL: www.mprg.org
- [3] Cristian Muller, Martin Mittelbach, "*Study of coexistence between UWB and narrowband cellular systems*", Dresden University of Technology, Dec 2003
- [4] M. Saquid, "*UWB Communications for Military Applications*", The University of Texas
- [5] Saeed S. Ghassemzadeh, Vahid Tarokh, "*The Ultra-wideband Indoor Path Loss Model*", IEEE P802.15 Working Group for Wireless Personal Area Networks (WPANs), doc: IEEE 802.15-02/278r1-SG3a
- [6] Ben Allen, Mohammad Chavami, "*UWB Signals and Systems*", Kings College London
- [7] Moe Win, "*Recent Results on Ultra-Wide Bandwidth Channels with Unknown Distributions*", weWIN group, Massachusetts Institute of Technology
- [8] Georgios B. Giannanksi, "*Ultra Wideband Communications: An Idea whose Time has Come*", University of Minnesota
- [9] Liuqing Yang, *"Ultra-Wideband Communications*", University of Florida, April 2005
- [10] Ian Oppernamm, "*UWB, A Brief and Biased Overview*", Center of Wireless Communications, University of Oulu
- [11] Jean-Marc Cramer, "*An Evaluation of Indoor Ultra-Wideband Communication Channels*", IEEE P802.15 Working Group for Wireless Personal Area Networks (WPANs), doc: IEEE 802.15-SG3a-02/325
- [12] Martin Weisenhorn, "*Review of Ultra-Wideband Radio Channel Modeling*", Zurich Research Laboratory
- [13] Ian Oppermann, "UWB: Theory and Applications", John Wiley & Sons, Oct 2004

Abbreviations

- FCC: Federal Communications Commission
- ETSI: European Telecommunications Standards Institute
- ITU: International Telecommunications Union
- CEPT: European Conference of Postal and Telecommunications
- ALT PHY: Alternative Physical (layer)

Exercise

Q1. Given the multipath rich UWB channel. What kind of receiver do you suggest. Justify your selection. (1 point)

Q2. The Gaussian pulse (and its derivatives) are not the only possible pulse shape for UWB systems. List three other waveforms (pulses). (3 pints)

Q3. The ISI could seriously hinder the UWB system if not considered carefully. How would you counteract the ISI phenomena. (think about pulse generation) (2 points)

Q4. In this presentation, we addressed the advantages of the UWB systems. The life is not so rosy! There are many potential challenges in UWB implementations. Mention four of them with one line explanation per each. (4 points)