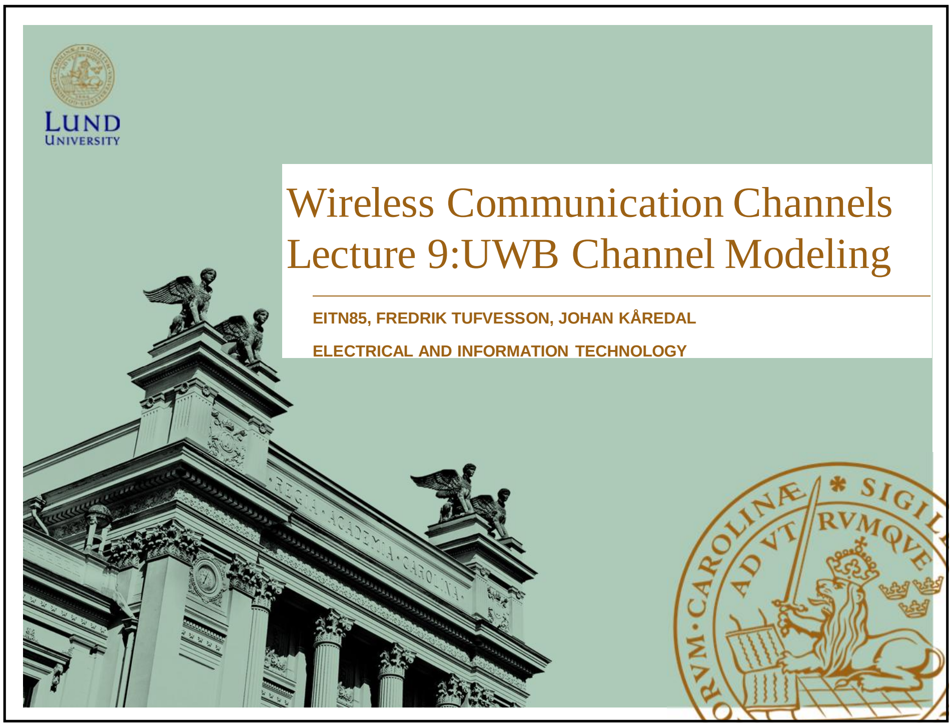

Wireless Communication Channels
Lecture 9:UWB Channel Modeling

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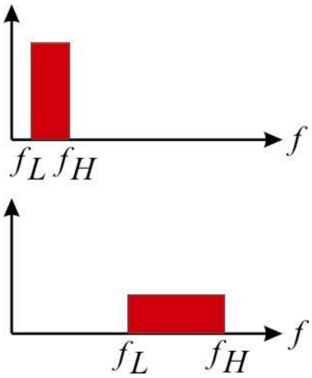
ELECTRICAL AND INFORMATION TECHNOLOGY

Overview

- What is Ultra-Wideband (UWB)?
- Why do we need UWB channel models?
- UWB channel modeling
- Standardized UWB channel models
- Summary

What is Ultra-Wideband (UWB)?

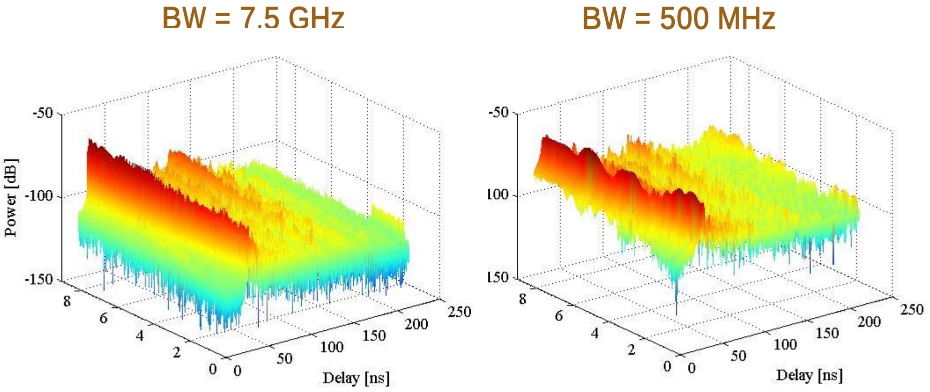
- Transmitted power is spread over high bandwidth
- Definition:
  - Signals having $f_H - f_L > 500\ \mathrm{MHz}$
  - and/or $\dfrac{2\,(f_H - f_L)}{f_H + f_L} > 0.2$



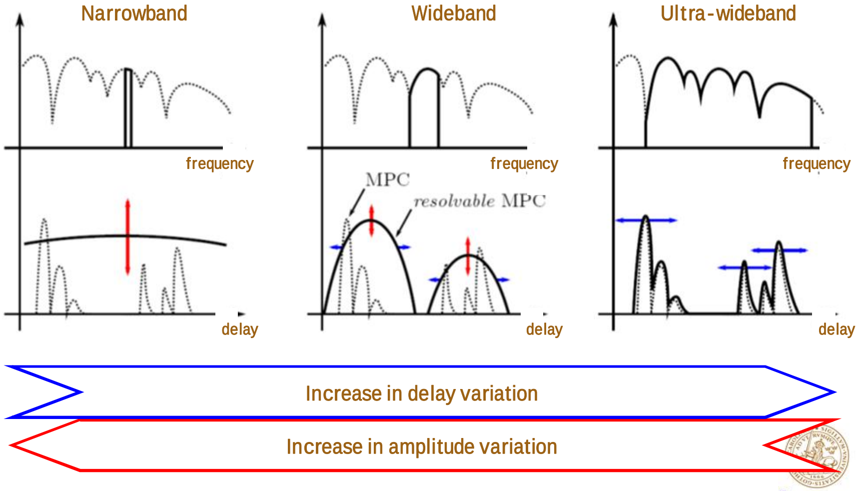
Large Bandwidth Implications

- High resistance to fading
  - Fine delay resolution; impulse response resolved into many delay-bins
  - Fading within each delay-bin is smaller
  - Sum of all bins have even less fading
- Good ranging capability
- Good wall and floor penetration (for some frequency ranges)
  - Low-frequency components can go through material

A Measured Impulse Response



Wireless Channel Bandwidth



Increase in delay variation

Increase in amplitude variation

Two Possible UWB Techniques

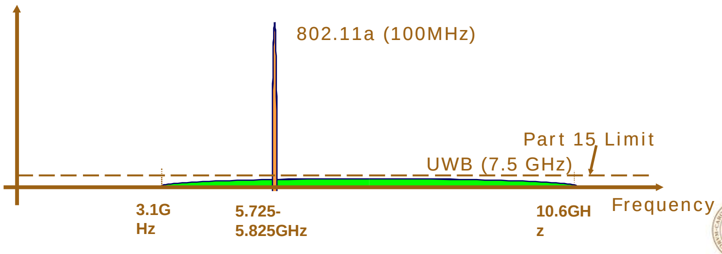
- Pulse based UWB (impulse radio)
  - Transmission through ultra short time domain pulses in the baseband
  - Evolution of the radar concept
  - Time hopping codes (Pulse Position Modulation)
- Multiband OFDM
  - OFDM-principle with frequency hopping in predefined subbands
  - Generation of UWB signals within carrier based systems
  - Especially for high data rate systems

Basic Principle

UWB makes use of same spectrum as existing services:

1. Information spread over wide spectrum; low power spectral density
2. Very low power

   ð Small interference – looks like noise to other systems

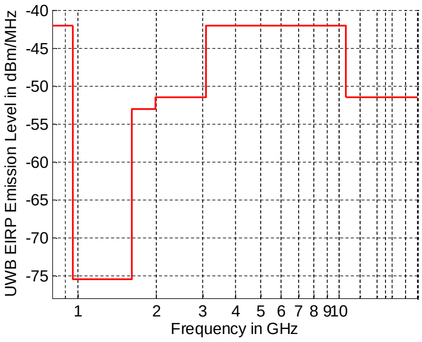


Applications

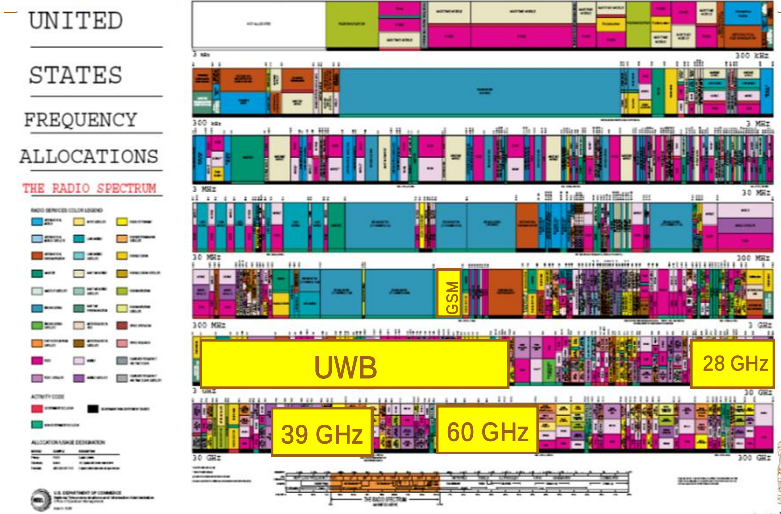
- Personal area networks
  - Small range
  - Home networks (residential and office environments)
  - Consumer electronics
- Positioning, sensor networks
- Other
  - Military applications (frequency range < 1GHz)
  - Through-wall radars

Frequency Regulation, FCC 3-10 GHz

- Regulations restrict frequency range that can be used
- Measurements and models only practically useful in that frequency range
- FCC spectral mask:
- Stricter mask in Europe



Frequency Regulations (cont’d)



A Fundamental Question

Q: Why do we need UWB Channel Models?

A: UWB channels are fundamentally different from narrowband channels.

Narrowband channel measurements and modeling cannot be directly reused!

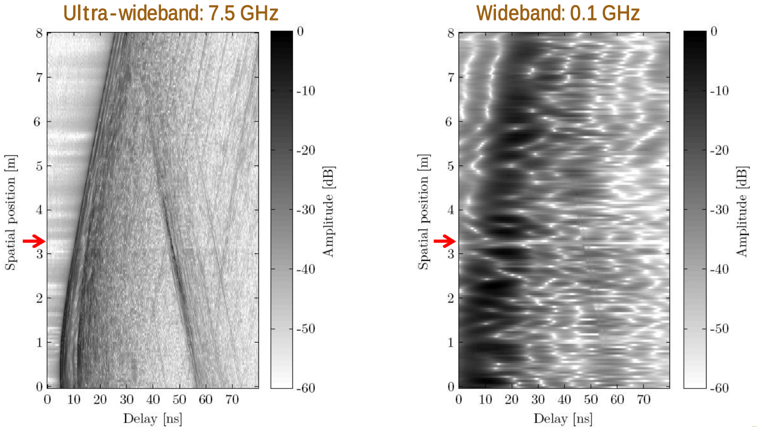
Narrowband vs. UWB Channel Models

- Assumptions about standard wireless channels:
  - “Narrowband” in the RF sense (bandwidth much smaller than carrier frequency
  - WSSUS assumption
  - Complex Gaussian fading (Rayleigh or Rice) in each delay tap
- Specialties of UWB channel:
  - Bandwidth comparable to carrier frequency
  - Different frequency components can “see” different reflection/ diffraction coefficients of obstacles
  - Few d orem (Gaussian fading) not valid anymore

New channel models are needed!!

Introduction

Bandwidth Effect on Delay Tap Amplitude


Ultra-wideband: 7.5 GHz

Wideband: 0.1 GHz

Ultra-wideband is immune to multipath.

Propagation Processes

Fundamental propagation processes:

- Free space propagation
- Reflection and transmission
- Diffraction
- Diffuse scattering

All are frequency dependent!

Free-Space Propagation

Path gain of free-space propagation:

$$G_{\text{path}}(d,f) = \frac{P_{RX}}{P_{TX}} = \underset{\uparrow}{G_{TX}}(f)\,\underset{\uparrow}{\eta_{TX}}(f)\,\underset{\uparrow}{G_{RX}}(f)\,\underset{\uparrow}{\eta_{RX}}(f)\left(\frac{c_0}{4\pi \underset{\uparrow}{f} d}\right)^2$$

where the antenna gain is given by

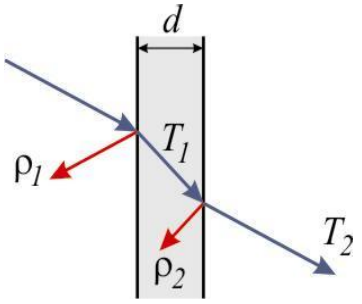
$$G_{RX}(f) = \frac{4\pi \overset{\swarrow}{f^2}}{c_0^2}\underset{\uparrow}{A_{RX}}(f)$$

Frequency dependent!

Reflection and Transmission

- Dielectric properties of materials vary with frequency
- Transmission (through two layered structure):

$$T = \frac{T_1 T_2 e^{-j\alpha(f)}}{1 + \rho_1 \rho_2 e^{-j2\alpha(f)}}$$



where the electrical length is given by

$$\alpha(f) = \frac{2\pi}{c_0} f \sqrt{\varepsilon_r} d_{\text{layer}} \cos\theta$$

Frequency dependent!

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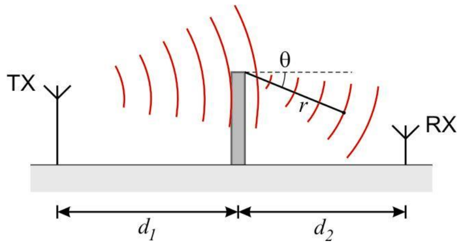
Diffraction

Diffraction from single screen:



Total electric field:

$$E_{\text{total}} = \left(\frac{1}{2} - \frac{e^{j\pi/4}}{\sqrt{2}} F(\nu_F)\right) e^{-jk_0 r}$$

where $F(\nu_F) = \int_0^{\nu_F} e^{-j\pi t^2/2} dt$ and $\nu_F = \theta \sqrt{\frac{2 f d_1 d_2}{c_0 (d_1 + d_2)}}$

Frequency dependent!

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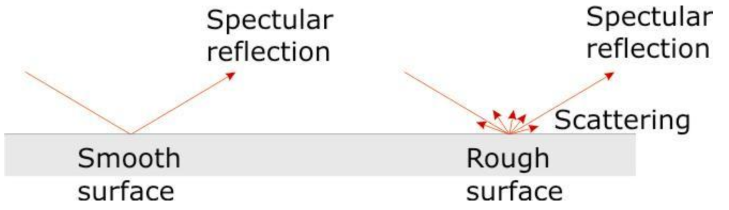
Scattering



Rough scattering according to Kirchoff theory:

$$\rho_{\text{rough}} = \rho_{\text{smooth}} \exp\left[-2\left(k_0 \sigma_{\text{h}} \sin\psi\right)^2\right]$$

Frequency dependent!

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Frequency Dependency of UWB

Narrowband:	1 MHz
Wideband:	100 MHz
Ultra-wideband:	7500 MHz

Propagation phenomina:

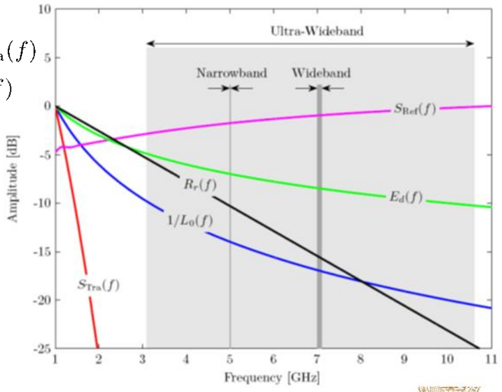
Free-space path-loss $L_0(f)$

Dielectric layer transmission $S_{\text{Tra}}(f)$

Dielectric layer reflection $S_{\text{Ref}}(f)$

Edge diffraction $E_d(f)$

Rough surface scatte$R_r(f)$



all propagation phenominas have a frequency dependency.

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UWB Channel Modeling

Generic Channel Representation

- Tapped delay line model:

$$h(t,\tau) = \sum_{i=1}^{N} a_i(t)\,\delta(\tau - \tau_i)$$

- For UWB, each MPC show distortion:

$$h(t,\tau) = \sum_{i=1}^{N} a_i(t)\,\chi_i(t,\tau) \otimes \delta(\tau - \tau_i)$$

where $\chi_i(t,\tau)$ is the distortion function.

- Adjacent taps are influenced by a single physical MPC ð WSSUS assumption violated.

Deterministic Modeling

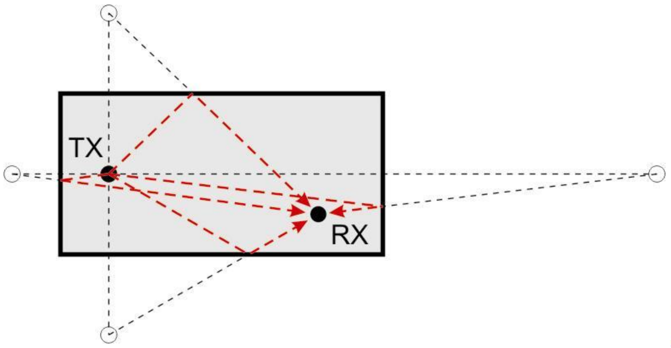
- Solve Maxwell’s equations with boundary conditions
- “Exact” solutions
  - Method of moments
  - Finite element method
  - Finite-difference time domain (FDTD)
- High frequency approximation
  - All waves modeled as rays that behave as in geometrical optics

    ð ray tracing
  - Refinements include approximation to diffraction, diffuse scattering, etc.

Principle of Ray Tracing

Determine rays that can go from one TX position to one RX position

- Determine complex attenuation for all possible paths
- Sum up contributions



Deterministic Modeling for UWB

- Interaction processes now all depend on frequency and/or direction
- Suggested solutions:
  - perform ray tracing at different frequencies, combine results
  - compute delay dispersion for each interaction process (possibly different for different directions), concatenate
- Combine deterministic rays with diffuse clutter (statistically described)

Statistical Channel Models

- Modeling of:
  - Pathloss (total power)
  - Large-scale effects
    - Shadowing
    - Delay dispersion (decay time constant)
    - Rice factor
    - Mean angle of arrival
    - “Parameters describing small-scale fading”
  - Small-scale effects
    - Small-scale fading

Modeling Path Gain

- Narrowband path gain:

$$G_{\text{path}}(d) = \frac{E\{P_{RX}(d, f_c)\}}{P_{TX}} = E\left\{|H(d, f_c)|^2\right\}$$

- For UWB channel, define frequency-dependent path gain:

$$G_{\text{path}}(d, f) = E\left\{\int_{f-\Delta f/2}^{f+\Delta f/2} \left|H\left(\tilde{f}, d\right)\right|^2 d\tilde{f}\right\}$$

- Simplified modeling:

$$G_{\text{path}}(d, f) = G_{\text{path}}(f)\, G_{\text{path}}(d)$$

Modeling Path Gain (cont’d)

- Distance dependent path gain:

$$G_{\text{path}}(d)\big|_{\text{dB}} = G_{\text{path}}(d_0)\big|_{\text{dB}} - 10n\log_{10}\left(\frac{d}{d_0}\right)$$

  - Path loss exponent varies from building to building ® can be modeled as a random variable

- Frequency dependent path gain:

$$\sqrt{G_{\text{path}}(f)} \propto f^{-\kappa}$$

  - *k* varies between 0.8 and 1.4 (including antennas) and -1.4 and 1.5 (excluding antennas)

Modeling Large-Scale Fading

Defined as the variations of the local mean around the path gain

- Commonly described as exhibiting a log-normal distribution
- Since large-scale fading is associated with diffraction and reflection effects, a frequency dependence would seem likely
- So far, measurements indicate no frequency dependence of shadowing variance

Multi-Cluster Models

- How is a cluster determined?
- Definition: components of cluster undergo same physical processes
- Extraction from continuous measurements
- Visual extraction from looks of (small-scale-averaged) power delay profile
- Fitting to measurement data
  - Very sensitive to small changes
- Better resolution when spatial information is taken into account

Saleh-Valenzuela Model

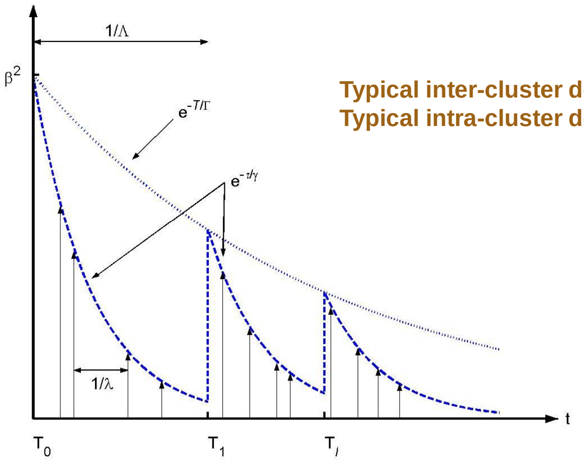
- Originally not for UWB [A.M. Saleh, R.A. Valenzuela, 1987]
- MPCs arrive in clusters
- Impulse responses given by

$$h(t) = \sum_{l=0}^{\infty} \sum_{k=0}^{\infty} \beta_{kl} e^{j\theta_{kl}} \delta(t - T_l - \tau_{kl})$$

$$\overline{\beta_{kl}^2} \equiv \overline{\beta^2(T_l, \tau_{kl})} = \overline{\beta^2(0,0)} e^{-T_l/\Gamma} e^{-\tau_{kl}/\gamma}$$

- Path interarrival times given by Poisson-distributed arrival process
- Different occurance rates for clusters (L) and rays (l)

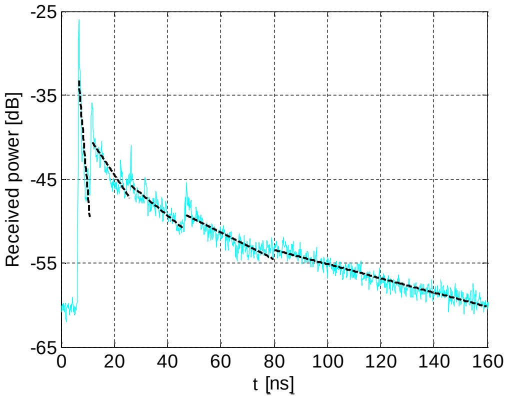
Saleh-Valenzuela Model (cont’d)



Typical inter-cluster decay: 10-30 ns
Typical intra-cluster decay: 1-60 ns

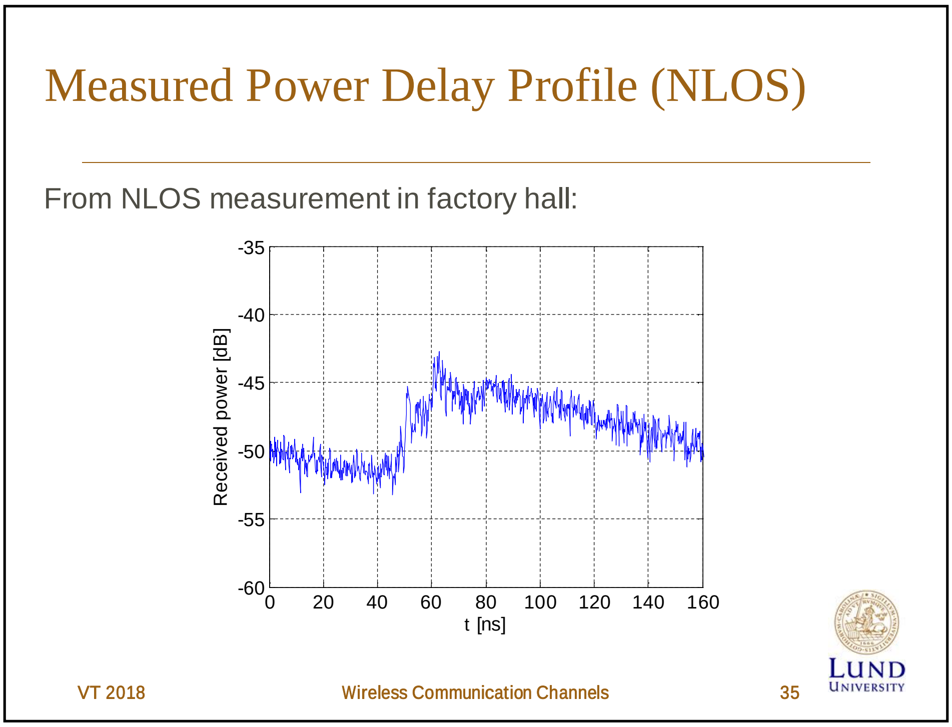
Measured Power Delay Profile (LOS)

From 2m LOS measurement in factory hall:



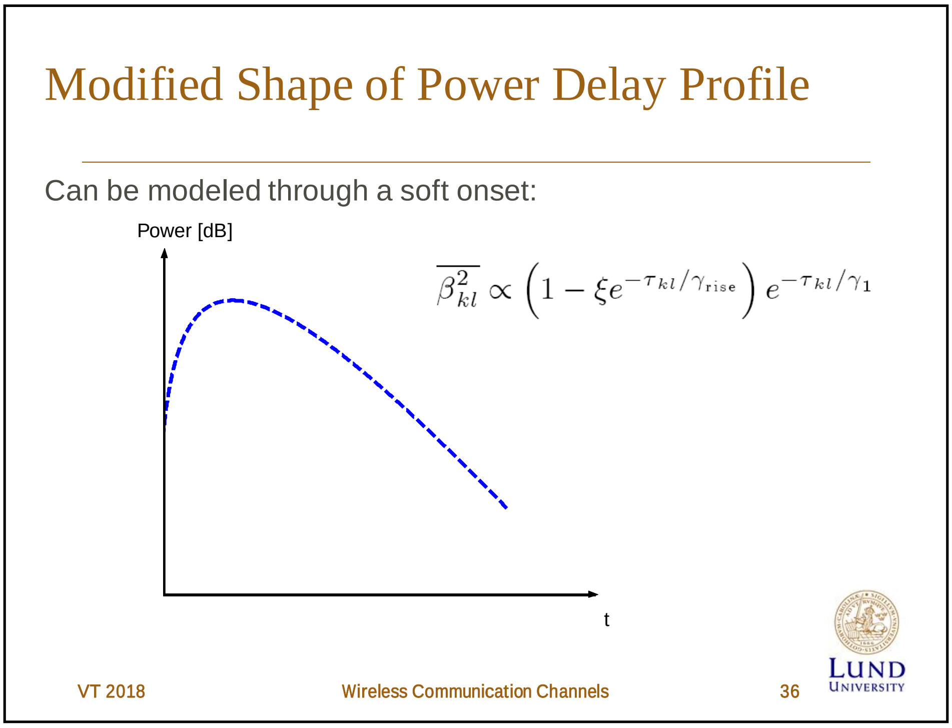
Generalizations

- Number of clusters as a random variable
- Cluster decay constants and arrival rates change with delay
- Ray arrival rates change with delay
- Cluster power varies due to shadowing
- Path interarrival times
  - Dense channel model - regularly spaced arrival times
  - Sparse channel model - Poisson arrival times



Measured Power Delay Profile (NLOS)

From NLOS measurement in factory hall:



Modified Shape of Power Delay Profile

Can be modeled through a soft onset:

$$\overline{\beta_{kl}^2} \propto \left(1 - \xi e^{-\tau_{kl}/\gamma_{\mathrm{rise}}}\right) e^{-\tau_{kl}/\gamma_1}$$

Small-Scale Fading Statistics

- Measurements report power within each bin being Gamma-distributed, amplitude is m-Nakagami distributed:

$$p(x) = \frac{2}{\Gamma(m)} \left(\frac{m}{\Omega}\right)^m x^{2m-1} \exp\left(-\frac{m}{\Omega}x^2\right)$$

  where m-factors are modeled as random variables

- Fading of delay bins is modeled as uncorrelated

- Phases modeled as uniformly distributed

Other Small-Scale Distributions

- Lognormal: looks similar to Nakagami with large m

$$p(x) = \frac{20/\ln 10}{x\sqrt{2\pi\sigma^2}} \exp\left(-\frac{\left(10\log_{10}(x^2) - \mu_{\mathrm{dB}}\right)^2}{2\sigma^2}\right)$$

- Rayleigh: does usually not work

$$p(x) = \frac{x^2}{\sigma^2} \exp\left(-\frac{x^2}{2\sigma^2}\right)$$

- Rice: $$p(x) = \frac{x}{\sigma} \exp\left(-\frac{1}{2}x^2 + K_r\right) I_0\left(x\sqrt{2K_r}\right)$$

  can be converted to Nakagami (though slightly different tails):

$$m = \frac{(K_r+1)^2}{(2K_r+1)} \Leftrightarrow K_r = \frac{\sqrt{m^2-m}}{m-\sqrt{m^2-m}}$$

Standardized UWB Channel Models

IEEE 802.15.3a

- For evaluation of model proposals, standard channel model established
- Theoretical model: is only basis, from which impulse response realizations are generated
- 4 radio environments, all indoor (residential and office):
  - LOS: 0-4m
  - NLOS: 0-4m
  - LOS: 4-10m
  - NLOS: heavy multipath

Model Structure

- Saleh-Valenzuela model
- Multiple clusters, multiple paths within each cluster
- Small-scale fading is lognormal
- Superimposed lognormal cluster fading
- Pathloss model: free-space pathloss

Channel Parameters

Target Channel Characteristics[5]	**CM 1**[1]	**CM 2**[2]	**CM 3**[3]	**CM 4**[4]
t_m [ns] (Mean excess delay)	5.05	10.38	14.18	
t_{rms} [ns] (rms delay spread)	5.28	8.03	14.28	25
NP_{10dB} (number of paths within 10 dB of the strongest path)			35	
NP (85%) (number of paths that capture 85% of channel energy)	24	36.1	61.54	
Model Parameters				
L [1/nsec] (cluster arrival rate)	0.0233	0.4	0.0667	0.0667
l [1/nsec] (ray arrival rate)	2.5	0.5	2.1	2.1
G (cluster decay factor)	7.1	5.5	14.00	24.00
g (ray decay factor)	4.3	6.7	7.9	12
s_1 [dB] (stand. dev. of cluster lognormal fading term in dB)	3.4	3.4	3.4	3.4
s_2 [dB] (stand. dev. of ray lognormal fading term in dB)	3.4	3.4	3.4	3.4
s_x [dB] (stand. dev. of lognormal fading term for total multipath realizations in dB)	3	3	3	3
Model Characteristics[5]				
t_m	5.0	9.9	15.9	30.1
t_{rms}	5	8	15	25
NP_{10dB}	12.5	15.3	24.9	41.2
NP (85%)	20.8	33.9	64.7	123.3
Channel energy mean [dB]	-0.4	-0.5	0.0	0.3
Channel energy std dev. [dB]	2.9	3.1	3.1	2.7

IEEE 802.15.4a (high-frequency model)

- More general:
  - Larger ranges
  - More environments
  - More general structure

- Radio environments
  - 1. Indoor office
  - 2. Indoor residential
  - 3. Indoor industrial
  - 4. Outdoor
  - 5. Agricultural areas/farms
  - 6. Body-worn devices

Generic Model Structure

- Pathloss
  - Simple distance power law
  - No random variations of pathloss exponent
  - Lognormal shadowing for each cluster
- Delay dispersion
  - Saleh-Valenzuela model
  - Ray arrival times are mixed Poisson process
  - Cluster decay constants can increase with delay
  - Some environments have different shape of PDP (soft onset)
- Small-scale fading
  - Nakagami fading, m-factor independent of delay
  - First component of cluster can have larger m-factor

Summary

UWB is a promising area for

- home networks (consumer electronics)
- Positioning, sensor networks
- military applications

Fundamental differences of UWB channels to narrowband channels

- Propagation mechanisms processes are frequency dependent
- Different small-scale statistics of fading
- Sparse impulse responses occur

Standard channel models will not work for the UWB channel

Standardized channel models:

- IEEE 802.15.4a model:
  - » Covers most interesting environments
  - » Includes most relevant propagation effects
  - » For high and low frequency range

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