UWB Channel Modeling
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
    \[ f_H - f_L > 500 \text{ MHz} \]
  – and/or
    \[ \frac{2 (f_H - f_L)}{f_H + f_L} > 0.2 \]
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

BW = 7.5 GHz

BW = 500 MHz
Wireless Channel Bandwidth

Narrowband

Wideband

Ultra-wideband

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
   ⇒ Small interference – looks like noise to other systems
Applications

• Personal area networks
  – Small range
  – Home networks (residential and office environments)
  – Consumer electronics

• Sensor networks
  – Lower data rate
  – Typically for industrial environments

• Other
  – Military applications (frequency range < 1GHz)
  – Geolocation
  – Through-wall radars

Viable candidate for several future applications!
Frequency Regulations

- Regulations restrict frequency range that can be used
- Measurements and models only practically useful in that frequency range
- FCC spectral mask:
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 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 components per delay bin → central limit theorem (Gaussian fading) not valid anymore

New channel models are needed!!
Bandwidth Effect on Delay Tap Amplitude

Ultra-wideband: 7.5 GHz
Wideband: 0.1 GHz

Ultra-wideband is immune to multipath.
Propagating 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:

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

where the antenna gain is given by

\[
G_{RX} (f) = \frac{4\pi f^2}{c_0^2} A_{RX} (f)
\]

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,

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

Frequency dependent!
Diffraction

Diffraction from single screen:

Total electric field:

\[
E_{\text{total}} = \left( \frac{1}{2} - \frac{e^{j\pi/4}}{\sqrt{2}} F(\nu_F) \right) e^{-j k_0 r}
\]

where \[ F(\nu_F) = \int_0^{\nu_F} e^{-j \pi t^2 / 2} dt \]

and \[ \nu_F = \theta \sqrt{\frac{2 f d_1 d_2}{c_0 (d_1 + d_2)}} \]

Fresnel integral

Frequency dependent!
Scattering

Rough scattering according to Kirchhoff theory:

\[ \rho_{\text{rough}} = \rho_{\text{smooth}} \cdot \exp\left(-2\left(\frac{2\pi f}{c} \sigma_{\text{height}} \sin \theta\right)^2\right) \]

Frequency dependent!
Frequency Dependency of UWB

Propagation phenomena:

- Free-space path-loss $L_0(f)$
- Dielectric layer transmission $S_{Tra}(f)$
- Dielectric layer reflection $S_{Ref}(f)$
- Edge diffraction $E_d(f)$
- Rough surface scattering $R_r(f)$

All propagation phenomena have a frequency dependency.
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 \( \Rightarrow \) 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
    ⇒ 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
  – 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 pathgain:

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

• Simplified modeling:

\[ G_{\text{path}}(d, f) = G_{\text{path}}(f) G_{\text{path}}(d) \]
Modeling Path Gain (cont’d)

• Distance dependent path gain:

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

– Path loss exponent varies from building to building \(\rightarrow\) can be modeled as a random variable

• Frequency dependent path gain:

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

– \(\kappa\) 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

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

- Path interarrival times given by Poisson-distributed arrival process (\( \frac{\beta_{kl}^2}{\beta^2} \equiv \beta^2(T_l, \tau_{kl}) \))
- Different occurrence rates for clusters (\( \Lambda \)) and rays (\( \lambda \))
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:

![Graph showing Received power vs. Delay Time](image)
Modified Shape of Power Delay Profile

Can be modeled through a soft onset:

\[
\beta_{kl}^2 \propto \left(1 - \xi e^{-\frac{\tau_{kl}}{\gamma_{\text{rise}}}}\right) e^{-\frac{\tau_{kl}}{\gamma_1}}
\]
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 $m$
  \[
p(x) = \frac{20/\ln 10}{x\sqrt{2\pi\sigma^2}} \exp\left(-\frac{(10\log_{10}(x^2) - \mu_{dB})^2}{2\sigma^2}\right)
  \]

- 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
- Superimposed lognormal cluster fading
- Pathloss model: free-space pathloss
## Channel Parameters

<table>
<thead>
<tr>
<th>Target Channel Characteristics(^5)</th>
<th>CM 1(^1)</th>
<th>CM 2(^2)</th>
<th>CM 3(^3)</th>
<th>CM 4(^4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\tau_m) [ns] (Mean excess delay)</td>
<td>5.05</td>
<td>10.38</td>
<td>14.18</td>
<td></td>
</tr>
<tr>
<td>(\tau_{rms}) [ns] (rms delay spread)</td>
<td>5.28</td>
<td>8.03</td>
<td>14.28</td>
<td>25</td>
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<tr>
<td>NP(_{10\text{dB}}) (number of paths within 10 dB of the strongest path)</td>
<td></td>
<td></td>
<td></td>
<td>35</td>
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<tr>
<td>NP (85%) (number of paths that capture 85% of channel energy)</td>
<td>24</td>
<td>36.1</td>
<td>61.54</td>
<td></td>
</tr>
<tr>
<td>Model Parameters</td>
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<tr>
<td>(\Lambda) [1/nsec] (cluster arrival rate)</td>
<td>0.0233</td>
<td>0.4</td>
<td>0.0667</td>
<td>0.0667</td>
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<tr>
<td>(\lambda) [1/nsec] (ray arrival rate)</td>
<td>2.5</td>
<td>0.5</td>
<td>2.1</td>
<td>2.1</td>
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<tr>
<td>(\Gamma) (cluster decay factor)</td>
<td>7.1</td>
<td>5.5</td>
<td>14.00</td>
<td>24.00</td>
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<tr>
<td>(\gamma) (ray decay factor)</td>
<td>4.3</td>
<td>6.7</td>
<td>7.9</td>
<td>12</td>
</tr>
<tr>
<td>(\sigma_1) [dB] (stand. dev. of cluster lognormal fading term in dB)</td>
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<td>3.4</td>
<td>3.4</td>
<td>3.4</td>
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<tr>
<td>(\sigma_2) [dB] (stand. dev. of ray lognormal fading term in dB)</td>
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<td>3.4</td>
<td>3.4</td>
<td>3.4</td>
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<tr>
<td>(\sigma_x) [dB] (stand. dev. of lognormal fading term for total multipath realizations in dB)</td>
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<td>3</td>
<td>3</td>
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<tr>
<td>Model Characteristics(^5)</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(\tau_m)</td>
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<td>15.9</td>
<td>30.1</td>
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<tr>
<td>(\tau_{rms})</td>
<td>5</td>
<td>8</td>
<td>15</td>
<td>25</td>
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<tr>
<td>NP(_{10\text{dB}})</td>
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<td>15.3</td>
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<tr>
<td>NP (85%)</td>
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<td>64.7</td>
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<tr>
<td>Channel energy mean [dB]</td>
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<td>-0.5</td>
<td>0.0</td>
<td>0.3</td>
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<tr>
<td>Channel energy std dev. [dB]</td>
<td>2.9</td>
<td>3.1</td>
<td>3.1</td>
<td>2.7</td>
</tr>
</tbody>
</table>
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 very promising area for
  - home networks (consumer electronics)
  - 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 802.15.3a model: were useful in the past
  - IEEE 802.15.4a model:
    - Covers most interesting environments
    - Includes most relevant propagation effects
    - For high and low frequency range