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

![Frequency Diagram](image-url)

- **802.11a (100MHz)**
- **UWB (7.5 GHz)**
- **Part 15 Limit**

- **Frequency**
  - 3.1GHz
  - 5.725-5.825GHz
  - 10.6GHz
Applications

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

• Sensor networks
  – Lower data rate ⇒ larger range (up to 300 m)
  – 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:

![Graph showing frequency in GHz against UWB EIRP Emission Level in dBm/MHz]
Frequency Regulations (cont’d)

United States Frequency Allocations

The Radio Spectrum

Radio Services Color Legend

Activity Code

Allocation Usage Designation

U.S. Department of Commerce

Fredrik Tufvesson - ETIN10

2011-02-21
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!!
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:

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

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 the electrical length is given by

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

Frequency dependent!
Diffraction

Diffraction from single screen:

Total electric field:

\[ E_{\text{total}} = \left( \frac{1}{2} - \frac{e^{j\pi/4}}{\sqrt{2}} F(\nu_F) \right) e^{-jk_0r} \]

where

\[ F(\nu_F) = \int_{0}^{\nu_F} e^{-j\pi t^2/2} dt \]

and

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

Frequency dependent!
Rough scattering according to Kirchoff theory:

\[
\text{rough } f \quad \text{smooth } \exp \left[ 2 \left( \frac{2}{c_0} f \sin \theta \right)^2 \right]
\]

**Frequency dependent!**
Frequency Dependency of UWB

Propagation phenomena:

- 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 scatter $R_r(f)$

All propagation phenomena have a frequency dependency.

<table>
<thead>
<tr>
<th>Bandwidth</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Narrowband:</td>
<td>1 MHz</td>
</tr>
<tr>
<td>Wideband:</td>
<td>100 MHz</td>
</tr>
<tr>
<td>Ultra-wideband:</td>
<td>7500 MHz</td>
</tr>
</tbody>
</table>
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 \( \implies \) 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
    • “Parameters describing small-scale fading”
  – Small-scale effects
    • Small-scale fading
Modeling Path Gain

- Narrowband path gain:

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

- 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:

\[ G_{\text{path}}(d, f) = G_{\text{path}}(f) G_{\text{path}}(d) \]
• **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 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

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

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

- Path interarrival times given by Poisson-distributed arrival process
- Different occurrence rates for clusters (♀) and rays (♂)
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
  \[ l \quad k \quad T_l \quad 0 \]
- 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 measured power delay profile. The x-axis represents the time delay in nanoseconds (τ [ns]), ranging from 0 to 160, and the y-axis represents the received power in dB, ranging from -60 to -35. The graph displays a smooth curve with some fluctuations indicating the power delay profile.](image-url)
Modified Shape of Power Delay Profile

Can be modeled through a soft onset:

\[ \beta_{kl}^2 \propto \left(1 - \xi e^{-\tau_{kl}/\gamma_{\text{rise}}} \right) e^{-\tau_{kl}/\gamma_1} \]
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

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

- 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):

\[ m = \frac{(K_r + 1)^2}{(2K_r + 1)} \iff K_r = \frac{\sqrt{m^2 - m}}{m - \sqrt{m^2 - m}} \]
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

<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>
</tr>
<tr>
<td>NP$_{10dB}$ (number of paths within 10 dB of the strongest path)</td>
<td></td>
<td></td>
<td>35</td>
<td></td>
</tr>
<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>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<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>
</tr>
<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>
</tr>
<tr>
<td>$\Gamma$ (cluster decay factor)</td>
<td>7.1</td>
<td>5.5</td>
<td>14.00</td>
<td>24.00</td>
</tr>
<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>
<td>3.4</td>
<td>3.4</td>
<td>3.4</td>
<td>3.4</td>
</tr>
<tr>
<td>$\sigma_2$ [dB] (stand. dev. of ray lognormal fading term in dB)</td>
<td>3.4</td>
<td>3.4</td>
<td>3.4</td>
<td>3.4</td>
</tr>
<tr>
<td>$\sigma_x$ [dB] (stand. dev. of lognormal fading term for total multipath realizations in dB)</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Model Characteristics$^5$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\tau_m$</td>
<td>5.0</td>
<td>9.9</td>
<td>15.9</td>
<td>30.1</td>
</tr>
<tr>
<td>$\tau_{rms}$</td>
<td>5</td>
<td>8</td>
<td>15</td>
<td>25</td>
</tr>
<tr>
<td>NP$_{10dB}$</td>
<td>12.5</td>
<td>15.3</td>
<td>24.9</td>
<td>41.2</td>
</tr>
<tr>
<td>NP (85%)</td>
<td>20.8</td>
<td>33.9</td>
<td>64.7</td>
<td>123.3</td>
</tr>
<tr>
<td>Channel energy mean [dB]</td>
<td>-0.4</td>
<td>-0.5</td>
<td>0.0</td>
<td>0.3</td>
</tr>
<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