UWB Double-Directional Channel Sounding

- Why and how? -

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• Antennas and propagation in UWB
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UWB Systems

• Low power
  – Short range
• Location awareness
  – High resolution in time domain
• Example applications
  – IEEE 802.15.3a : high speed PAN
  – IEEE 802.15.4a : low speed and location aware
  – Ground penetrating radar
Impulse radio

- Simple hardware
- Low power consumption

< 2ns
Indoor Multipath Environment
Transmission in Multipath Environment

Tx pulse (500MHz BW)

\[ \sim 2\text{ns} \]

\[ t \]

Rx pulse

\[ \sim 2\text{ns} \]

\[ t \]

Multipath components can be distinct

\[ \sim 14\text{ns} \]
Free Space Transfer Function

- Friis’ transmission formula

\[ H_{\text{Friis}}(f) = H_{\text{FreeSpace}}(f, d) \cdot H_{\text{Tx}}(f, \Omega_{\text{Tx}}) \cdot H_{\text{Rx}}(f, \Omega_{\text{Rx}}) \]

\[ \propto \frac{1}{f} \]

Normalized by isotropic antenna
Ideal Antenna Cases

- **Constant aperture size**
  
  Example: Pyramidal horn
  
  \[ H_{\text{Ant}} \propto f \]

- **Constant gain**
  
  Example: Biconical
  
  \[ H_{\text{Ant}} = \text{const.} \]

Both are too idealized.

\[ H_{\text{Friis}} \propto \frac{1}{f} \]
Frequency Characteristics of Antenna

4.8cm Dipole (resonant at 3.1GHz)

- Transfer function
  - Frequency dependent
  - Angular dependent
Directional Transfer Function of Antenna

Drastically changed by direction
Directional Impulse Response of Antenna
## Conventional System vs UWB

### Antenna and propagation issues

<table>
<thead>
<tr>
<th></th>
<th>Conventional systems</th>
<th>UWB-IR</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Antenna</strong></td>
<td>Gain (frequency flat)</td>
<td>Distortion</td>
</tr>
<tr>
<td><strong>Multipath</strong></td>
<td>Distortion</td>
<td>Distinction</td>
</tr>
</tbody>
</table>
Conventional Channel Model

IEEE 802.15.3a Model

Channel includes antennas and propagation

Valid only for test antennas (omni)!
Channel Modeling Approach of UWB

Antennas and Propagation shall be separated in the model.
Directive Polarimetric Frequency Transfer Function

\[
H_{\text{Ant}}(f, \theta, \varphi) = \hat{\theta}(\theta, \varphi) H_{\theta,\text{Ant}}(f, \theta, \varphi) + \hat{\phi}(\theta, \varphi) H_{\varphi,\text{Ant}}(f, \theta, \varphi)
\]

Solid angle \[\Omega = (\theta, \varphi)\]
How to Get Antenna Model Parameters

• Electromagnetic (EM) wave simulator
  – MoM (NEC, FEKO, …)
  – FEM (HFSS, …)
  – FDTD (XFDTD, …)
  – …

• Spherical polarimetric measurement
  – Three antenna method for testing antenna calibration
Propagation Modeling

Double-directional model
- Direction of departure (DoD)
- Direction of arrival (DoA)
- Delay time (DT)
- Magnitude (polarimetric, frequency dependent)
Double Directional Ray Model

\[ H_{\text{Multipath}}(f, \Omega_{\text{Tx}}, \Omega_{\text{Rx}}) = \]

\[ \sum_{l=1}^{L} a_l(f) \delta(\Omega_{\text{Tx}} - \Omega_{\text{Tx},l}) \delta(\Omega_{\text{Rx}} - \Omega_{\text{Rx},l}) \exp(-j2\pi f \tau_l) \]
Double Directional Channel Model

... has been studied for MIMO systems
Design of array antenna is a key issue of MIMO channel capacity.
\[
\overline{H}(f) = \iiint_{\text{Rx}} H_{\text{Rx}}(f, \Omega_{\text{Rx}}) H_{\text{Multipath}}(f, \Omega_{\text{Tx}}, \Omega_{\text{Rx}}) H^H_{\text{Tx}}(f, \Omega_{\text{Tx}}) \, d\Omega_{\text{Rx}} \, d\Omega_{\text{Tx}}
\]

Rx antenna array vector

Tx antenna array vector
<table>
<thead>
<tr>
<th></th>
<th>MIMO</th>
<th>UWB-IR</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Antenna</strong></td>
<td>Array configuration</td>
<td>Frequency distortion</td>
</tr>
<tr>
<td><strong>Multipath</strong></td>
<td>Double directional</td>
<td></td>
</tr>
<tr>
<td><strong>Magnitude</strong></td>
<td>Frequency flat</td>
<td>Frequency dispersive</td>
</tr>
</tbody>
</table>

Propagation modeling approaches are the same.
Two different aspects of propagation model

- Transmission system design
  - Stochastic, site generic
- Equipment design and installation
  - More deterministic, site specific
## UWB Channel Sounding

### Time domain vs Frequency domain

<table>
<thead>
<tr>
<th></th>
<th>Time domain (Pulse)</th>
<th>Frequency domain (VNA)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Tx Power</strong></td>
<td>Large</td>
<td>Small</td>
</tr>
<tr>
<td><strong>Calibration</strong></td>
<td>Difficult</td>
<td>Easy</td>
</tr>
<tr>
<td><strong>Data processing</strong></td>
<td>• Raw data</td>
<td>• Fourier transform</td>
</tr>
<tr>
<td></td>
<td>• Deconvolution</td>
<td>• Superresolution (subspace/ML)</td>
</tr>
<tr>
<td><strong>Resolution</strong></td>
<td>Fourier</td>
<td>High resolution</td>
</tr>
</tbody>
</table>
## UWB Channel Sounding

### Directive antenna vs Array antenna

<table>
<thead>
<tr>
<th></th>
<th>Directive antenna</th>
<th>Array antenna</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Tx Power</strong></td>
<td>Small</td>
<td>Large</td>
</tr>
<tr>
<td><strong>Sync.</strong></td>
<td>Timing</td>
<td>Timing and phase</td>
</tr>
<tr>
<td><strong>Data processing</strong></td>
<td>• Raw data</td>
<td>• Fourier transform</td>
</tr>
<tr>
<td></td>
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<td><strong>Resolution</strong></td>
<td>Fourier</td>
<td>High resolution</td>
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</tbody>
</table>
### UWB Channel Sounding

#### Real array vs Synthetic array

<table>
<thead>
<tr>
<th></th>
<th>Real array</th>
<th>Synthetic array</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Realization</strong></td>
<td>Multiple antennas, RF switch</td>
<td>Scanning</td>
</tr>
<tr>
<td><strong>Measurement time</strong></td>
<td>Short</td>
<td>Long</td>
</tr>
<tr>
<td><strong>Mutual coupling</strong></td>
<td>To be compensated</td>
<td>None</td>
</tr>
<tr>
<td><strong>Antenna spacing</strong></td>
<td>Limited by antenna size</td>
<td>No restriction</td>
</tr>
</tbody>
</table>
UWB Channel Sounding System

- Vector network analyzer + antenna positioner
  - Measurement of spatial transfer function automatically
UWB Channel Sounding System

• Architecture
  – Frequency domain
  – Synthetic array

• Pros and Cons
  – Short range ~ low power handling
    • Output power
    • Cable loss
  – Antenna scanning
    • Static environment
    • No array calibration

• Output power
• Cable loss

• VNA
• XY positioner
Double Directional Channel Model

- **Discrete path model**
  - Channel consists of discrete ray paths

\[
h_l(f) = h_0(f, \tau_l) \sum_{\beta_t=\psi, \phi} \sum_{\beta_r=\psi, \phi} \gamma_{\beta_t, \beta_r}(f) D_{\beta_t}(f, \Omega_{rl}) D_{\beta_r}(f, \Omega_{tl}),
\]  

- **Multipath model**

\[
H(f) = \sum_{l=1}^{L} h_l(f)
\]
Model of Synthetic Array

- Complex gain changes due to position

\[ D_{t\beta m_r}(f, \Omega_r) = D_{r\beta}(f, \Omega_r) \exp \left( j \frac{2\pi f}{c} \cdot r_{rm_r} \cdot \hat{\omega}_r \right). \quad (21.6) \]

\[ r_{rm_r} = \hat{x}x_{rm_r} + \hat{y}y_{rm_r} + \hat{z}z_{rm_r}, \quad (21.5) \]

Position vector

\[ \hat{\omega}_r = \hat{x} \cos \psi_r \cos \phi_r + \hat{y} \cos \psi_r \sin \phi_r + \hat{z} \sin \psi_r. \quad (21.7) \]

Propagation vector

\[ DOA \text{ or } DOD \]
\[ h_l(f) = h_0(f, \tau_l) \sum_{\beta_r=\psi,\phi} \sum_{\beta_i=\psi,\phi} \gamma_{\beta_r\beta_i} (f) D_{r\beta_r}(f, \Omega_{rl}) D_{t\beta_i}(f, \Omega_{ul}), \quad (21.9) \]

- \( \gamma \) can not be considered as constant over UWB bandwidth.
  - Piecewise constant
• For short range paths, plane wave approximation is not appropriate.
  – Spherical wave model

Scattering center

Spherical wavefront

Coordinates origin

Direction of propagation can not be treated as constant.
Spherical Wave Model at Rx Array

\[ h_{lm,m_r}(f) = h_0(f, \tau_l) \gamma_l(f) D_r(f, \Omega_{rl}) D_t(f, \Omega_{tl}) \]

\[ \exp \left[ j \frac{2\pi f}{c} \left( \| R_{rl} - r_{lm_r} \| - R_{rl} \right) \right] \exp \left( -j \frac{2\pi f}{c} r_{tm_t} \cdot \hat{\omega}_{tl} \right). \quad (21.9) \]

Phase delay correction wrt origin

Scattering center

Spherical wavefront

Coordinates origin
Issue on Spherical Wave Model

- Not always compatible with double-directional model
Issue on Spherical Wave Model

- Not always compatible with double-directional model

Incompatible case
Issue on Spherical Wave Model

- SIMO and MISO (single-directional) processing
- Matching by using ray-tracing
  - Accurate time delay due to UWB
• Parametric channel model
  – Free from antenna geometry
  – Resolution still influenced by measurement configuration

\[
h_{lm,m_r}(f) = h_0(f, \tau_l)\gamma_l(f)D_r(f, \Omega_{rl})D_t(f, \Omega_{tl}) \\
\exp\left[j\frac{2\pi f}{c} \left(\|R_r - r_{rm}\| - R_{rl}\right)\right] \exp\left(-j\frac{2\pi f}{c} r_{tm} \cdot \hat{\omega}_{tl}\right). \tag{21.9}
\]

Parameters to be estimated

• Two major approaches
  – Subspace based
  – ML based
Parametric Channel Model

- Measured data contaminated by Gaussian noise

\[ y_{m,k} = H_{m,k} + n_{m,k}, \quad (21.11) \]

\[ \text{var}(n_{m,k}) = \sigma^2 \]

- Parameters to be estimated

\[ \mu_l = \left\{ \{ y_{li} \}_{i=1}^I, \psi_{rl}, \phi_{rl}, R_l, \tau_l \right\}, \quad (21.12) \]

\[ \mu = \bigcup_{l=1}^L \mu_l. \quad (21.13) \]
Likelihood Function

- Conditional probability of the observation data assuming parameter set
  - Likelihood function
    \[
    p(y | \mu) = \prod_{k=1}^{K} \prod_{m_r=1}^{M_r} \left[ \frac{1}{\pi \sigma} \exp \left( -\frac{1}{\sigma^2} \right) \right].
    \] (21.15)
  - Observed data
    \[
    y = \{ y_{m_r,k} | 1 \leq m_r \leq M_r, 1 \leq k \leq K \} \] (21.14)

- ML estimate
  - \( \mu \) maximizing \( p \) for given \( y \)
Maximum Likelihood Estimation

- Exhaustive joint search of $\mu$

$$p(y | \mu) = \prod_{k=1}^{K} \prod_{m_r=1}^{M_r} \left[ \frac{1}{\pi \sigma} \exp \left( - \frac{|y_{m_r,k} - H_{m_r,k}(\mu)|^2}{\sigma^2} \right) \right]. \quad (21.15)$$
• Estimate of “complete data” \( x \) from “incomplete data” \( y \) (E-step)

\[
x_i = h_i + b_i(y - H).
\] (21.17)

• ML applied to “complete data” (M-step)

\[
\arg \max_{\mu} p(x_i | \mu) = \arg \min_{\mu_i} \| x_i - h_i(\mu_i) \|^2. 
\] (21.19)

Least square problem to be solved by matched filtering
• Matched filter detection

\[ \mu_l = \arg \max_{\mu_l} \frac{\left| a^H(\mu_l)x_l \right|}{\sqrt{a^H(\mu_l)a(\mu_l)}}. \]  \hspace{1cm} (21.22)

\[ \hat{\gamma}_{li} = \frac{a^H_i(\mu_l)x_{li}}{a^H_i(\mu_l)a_i(\mu_l)}, \]  \hspace{1cm} (21.23)
• Sequential search of parameters

\[
\hat{\psi}_{rl} = \arg \max_{\psi_{rl}} \frac{\left| a^H (\psi_{rl}, \phi_{rl}, R_l, \tau_l) x_l \right|}{\sqrt{a^H (\psi_{rl}, \phi_{rl}, R_l, \tau_l) a (\psi_{rl}, \phi_{rl}, R_l, \tau_l)}}, \quad (21.24)
\]

\[
\hat{\phi}_{rl} = \arg \max_{\phi_{rl}} \frac{\left| a^H (\hat{\psi}_{rl}, \phi_{rl}, R_l, \tau_l) x_l \right|}{\sqrt{a^H (\hat{\psi}_{rl}, \phi_{rl}, R_l, \tau_l) a (\hat{\psi}_{rl}, \phi_{rl}, R_l, \tau_l)}}, \quad (21.25)
\]

\[
\hat{R}_l = \arg \max_{R_l} \frac{\left| a^H (\hat{\psi}_{rl}, \hat{\phi}_{rl}, R_l, \tau_l) x_l \right|}{\sqrt{a^H (\hat{\psi}_{rl}, \hat{\phi}_{rl}, R_l, \tau_l) a (\hat{\psi}_{rl}, \hat{\phi}_{rl}, R_l, \tau_l)}}, \quad (21.26)
\]

\[
\hat{\tau}_l = \arg \max_{\tau_l} \frac{\left| a^H (\hat{\psi}_{rl}, \hat{\phi}_{rl}, \hat{R}_l, \tau_l) x_l \right|}{\sqrt{a^H (\hat{\psi}_{rl}, \hat{\phi}_{rl}, \hat{R}_l, \tau_l) a (\hat{\psi}_{rl}, \hat{\phi}_{rl}, \hat{R}_l, \tau_l)}}, \quad (21.27)
\]

– Good initial estimate is necessary.
Successive Cancellation Approach

$l = 1$

- Rough global search of $l$-th path
- Fine local search of $l$-th path by SAGE
- Subtraction of $l$-th path from observation

Convergence?

$l = l + 1$

No model order estimation in advance.
Experiment in an Indoor Environment (1)

- Measurement site: an empty room
• Floor plan of the room

Floor to ceiling: 2.6m

Rx
(h: 0.70m)

Scanning Plane

4.33m

Tx
(h: 1.58m)

7.67m

6.67m
• Estimated parameters: DoA (Az, El), DT

• Measured data:
  – Spatially 10 by 10 points at Rx
  – 801 points frequency sweeping from 3.1 to 10.6 [GHz] (sweeping interval: 10 [MHz])

• Antennas: Biconical antennas for Tx and Rx

• Calibration: Function of VNA, back-to-back

• IF Bandwidth of VNA: 100 [Hz]

• Wave polarization: Vertical - Vertical

• Bandwidth of each subband: 800 [MHz]
• The result of ray path identification

There 6 waves detected and are almost specular waves.
Measurement Result (2)

6 specular waves were observed.

Frequency range: 3.1 ~ 10.6 [GHz]
Tx, Rx: Biconical antennas
Spatial scanning: horizontal plane, 10 × 10 points whose element spacing is 48 [mm]
#4 is a reflection from the back of Rx
- Transfer functions of antennas are already deconvolved.
- The phase component is the deviation from free space phase rotation (ideally flat).
• Comparison of the measurement result in 9 different Rx position

The path type detected in each measurement was almost same.
Measurement Result (5)

- Estimated source position for direct wave

Maximum deviation is 17cm from source point.

Estimated by measurement
Measurement Result (6)

- Estimated reflection points in back wall reflection

All the reflection points are above those predicted by GO.

- Predicted by GO
- Estimated by measurement
• Some problems have been appeared.
  – 2 ~ 4 spurious waves detected during the estimation of 6 waves
  – Residual components after removing dominant paths
  – Signal model error (plane or spherical)
  – Estimation error based on inherent resolution of the algorithm implementation
  – Many distributed source points (diffuse scattering)

→ Further investigation in simple environment
Performance Evaluation in Anechoic Chamber

Anechoic chamber

- Tx1
- Tx2
- 3-dB power splitter
- VNA
- GPIB
- PC
- Synthesized URA
- X-Y Scanner
- GPIB
Specifications of Experiment

- Frequency: 3.1 ~ 10.6 GHz
  - 0.13 ns Fourier resolution
- Antenna scanning plane: 432 mm square in horizontal plane
  - 10 deg Fourier resolution
  - 48 mm element spacing (less than half wavelength @ 3.1 GHz)
- Wideband monopole antennas were used
  - Variation of group delay < 0.1 ns within the considered bandwidth
- SNR at receiver: About 25 dB
Aim of Anechoic Chamber Test

- Evaluation of spatio-temporal resolution
  - Separation and detection of two waves that
    - Spatially 10 deg different and same DT
    - Temporally 0.67 ns ( = 20 cm ) different and same DoA
Setup of Experiment

Rx

X-Y scanner

Tx
Spatial Resolution Test (1)

Tx1 10 deg Tx2

10 deg
Spatial Resolution Test (2)

• 10 deg separated waves are accurately separated.
  – Parameters and spectra are accurately estimated.
  – The estimated phase denotes a deviation from free space phase rotation (~ 3 mm).
  – Antenna characteristics are already deconvolved.
Temporal Resolution Test (1)

Tx1, Tx2

20 cm
Temporal Resolution Test (2)

- 0.67 ns separated waves are accurately resolved.
  - Subband width: 1.5 GHz
  - Spectrum estimation is impossible in the higher and lower frequency region of
    \[
    \left(\frac{1}{\Delta\tau = 0.67\,[\text{ns}]}/2\right) = 0.75[\text{GHz}]
    \]
Subband Processing (1)

- … relieves a bias of parameter estimation due to amplitude and phase fluctuation within the band
- Tradeoff between the resolution and accuracy of parameter estimation: some optimization is needed!!
How to choose the optimum bandwidth of subband?
  - Suppose two waves are $\Delta \theta$ and $\Delta \tau$ separated

<table>
<thead>
<tr>
<th>Delay resolution $\tau_{res}$</th>
<th>Angle resolution: $\theta_{res}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau_{res} &lt; \Delta \tau$</td>
<td>$\theta_{res} &lt; \Delta \theta$</td>
</tr>
<tr>
<td></td>
<td>Bandwidth within which deviation of antennas and propagation characteristics is sufficiently small</td>
</tr>
<tr>
<td>$\tau_{res} &gt; \Delta \tau$</td>
<td>$\theta_{res} &gt; \Delta \theta$</td>
</tr>
<tr>
<td></td>
<td>$\approx \frac{1}{\Delta \tau}$</td>
</tr>
<tr>
<td></td>
<td>Impossible to resolve</td>
</tr>
</tbody>
</table>

Impossible to resolve
• Behavior for the detection of two waves closer than the inherent resolution of the algorithm
  – Regard two waves as one wave (ex. same incident angle)
  – Two separated waves, but biased estimation of power (ex. 5 deg different incident angles)
Deconvolution of Antenna Patterns

• Deconvolution of antennas
  – Construction of channel models independent of antenna type and antenna configuration
  – Deconvolution is post-processing (from the estimated spectrum by SAGE)
  • Simple implementation rather than the deconvolution during the search
Spherical vs Plane Wave Models (1)

- How these models affect for the accurate estimation?
  - Spurious (ghost path) and detection of weak paths
  - Empirical evaluation of model accuracy
Spherical vs Plane Wave Models (2)

- Detection of 20 dB different two waves
  - Is a weaker source correctly detected?

#2 = 15 deg
#1 = 0 deg

20 dB weaker
- Log-likelihood spectrum in the detection of weaker path

![Graph showing log-likelihood spectrum with different models and angles.](image)
Summary of Evaluation Works (1)

• Evaluation of the proposed UWB channel sounding system in an anechoic chamber
  – Resolved spatially 10 deg, temporally 0.67 ns separated waves
  – Spectrum estimation is partly impossible in the highest and lowest frequency regions of \( \frac{1}{2\Delta \tau} \).
  – The algorithm treats two waves closer than inherent resolution as one wave, or results in biased power estimation even if they are separated.
Summary of Evaluation Works (2)

- For reliable UWB channel estimation with SAGE algorithm
  - An optimum way to choose the bandwidth of subband
  - The number of waves estimation is done by SIC-type procedure

- Deconvolution of antennas effects from the results of SAGE
  - For channel models independent of antennas
• Spherical incident wave model is more robust than plane wave incident model
  – Spurious reduction is expected
  – Effective in the detection of weaker path
Indoor Double Directional Measurement (1)

(a) Top view

(b) Side view
Indoor Double Directional Measurement (2)

Azimuth-Delay spectrum

Tx side

Rx side

Above -80 [dB] ○
-80 to -90 [dB] □
-100 to -110 [dB] ×
Below -110 [dB] *

Cluster A
Cluster B
Cluster C
Cluster D
Cluster E
Cluster F
Cluster G
Cluster H
Cluster I
Cluster J
Cluster K
Cluster L
Cluster M
Cluster N&P

Direct wave

Azimuth angle [deg]

Delay time [nsec]
Indoor Double Directional Measurement (3)
Indoor Double Directional Measurement (4)

(e) Cluster E
(f) Cluster F
(g) Cluster G
(h) Cluster H
Indoor Double Directional Measurement (5)

(i) Cluster I

(j) Cluster J

(k) Cluster K

(l) Cluster L
Indoor Double Directional Measurement (6)

(m) Cluster M

(n) Cluster N

(p) Cluster P
Summary

• Background and motivation of double directional sounding
• Antennas and propagation in UWB
• UWB double directional channel sounding system
• Parametric multipath modeling for UWB
• ML-based parameter estimation
• Examples
• Jun-ichi Takada, Katsuyuki Haneda, and Hiroaki Tsuchiya, "Joint DOA/DOD/DTOA estimation system for UWB double directional channel modeling," to be published in S. Chandran (eds), "Advances in Direction of Arrival Estimation," to be published from Artech House, Norwood, MA, USA.
