High-accuracy Positioning in Multipath Channels:
Location-Awareness for 5G Networks and Beyond

Klaus Witrisal

Joint work with my PhD students / Post Docs:
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High-accuracy Positioning: Applications

Manufacturing

Retail

Autonomous Driving

Logistics

Smart Labeling

Assisted Living

Objectives: Positioning and navigation; activity recognition; control

Requirements: Accuracy (5 – 20 cm); Reliability (90 – 100%)

Challenges: Heterogeneity: scenarios and technologies; multipath

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Location-aware Communications:

many system parameters depend on the position

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many system parameters depend on the position
Outline

- Introduction
- Ranging and positioning in dense multipath
  - Bandwidth scaling (1) and MIMO gain (2)
  - Multipath-assisted indoor positioning (3)
  - Theory and modeling
  - Algorithms
- Cognitive positioning and location awareness (4)
- Conclusions

Four ingredients for high-accuracy positioning and location awareness
An experiment: *transmission of a (UWB) pulse in an indoor environment*
Time-of-flight Ranging

Propagation at B=2.0 GHz (6.00 GHz-8.)

channel impulse response 1

channel impulse response 2

channel impulse response 3

channel impulse response 4

channel impulse response 5

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Time-of-flight Ranging:
Problem: Multipath Radio Propagation
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Time-of-flight Ranging:
Problem: Multipath Radio Propagation

transmit pulse; channel impulse responses

received pulse signal; bandwidth = 20 MHz
Ranging and positioning in dense multipath

Signal Processing for Robust Ranging (& Pos.)

- Experiment
- Modelling
- Performance limits
- Algorithms
- Improvements

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Modeling the dense multipath

to derive the theoretical limit (CRLB)

Received signal from anchor \( j \) located at \( \mathbf{p}^{(j)} \): \( s(t) \): TX signal

\[
r^{(j)}(t) = \alpha^{(j)} s(t - \tau^{(j)}) + (s \ast \nu^{(j)})(t) + w(t)
\]

useful signal

interference

noise

\[
\tau^{(j)} = \frac{1}{c} \| \mathbf{p} - \mathbf{p}^{(j)} \|
\]

\[
E\{\nu(\tau)\nu^*(u)\} = S_{\nu}(\tau)\delta(\tau - u)
\]

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CRLB for ranging (in dense multipath (DM))

**AWGN only**
\[
r_\ell(t) = \alpha_\ell s(t - \tau_\ell) + w(t)
\]

**CRLB**
\[
\text{var}\{\hat{\tau}\} \geq \left(8\pi^2 \beta^2 \text{SNR}\right)^{-1}
\]
- mean-squared bandwidth
  \[
  \beta^2 = \int f^2 |S(f)|^2 df
  \]
- signal-to-noise ratio
  \[
  \text{SNR} = \frac{E_{\text{LOS}}}{N_0}
  \]

**AWGN + dense multipath**
\[
r_\ell(t) = \alpha_\ell s(t - \tau_\ell) + (s * v_\ell)(t) + w(t)
\]

**CRLB → whitening**
\[
\text{var}\{\hat{\tau}\} \geq \left(8\pi^2 \beta_w^2 \text{SINR} \sin^2(\varphi)\right)^{-1}
\]
- **BW gain**
  \[
  \beta_w^2 = \beta^2 \gamma; \quad \gamma \geq 1
  \]
- **reduced** SNR due to DM
  \[
  \text{SINR} = \frac{E_{\text{LOS}}}{N_0 + \text{DM}} \leq \text{SNR}
  \]
- **cost** for nuisance estim.
  \[
  \sin^2(\varphi) \in [0, 1]
  \]

➢ CRLB scales with **squared bandwidth** and SNR

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Ranging error bound and SINR shows the *bandwidth scaling*

\[
\text{var}\{\hat{r}\} \geq \left(8\pi^2 \beta^2 \text{SINR}\right)^{-1}
\]

\[
\text{SINR} = \gamma \text{SINR} \sin^2(\varphi)
\]

Parameters

- \(\text{SNR} = 30 \, \text{dB}\)
- \(K_{\text{LOS}} = 1 \ldots \text{LOS-to-DM-power}\)

Position error bound

Fisher information $J_p$

Position error variance (CRLB):

$$\text{var}\{\hat{p}\} \geq \text{tr}\{J_p^{-1}\}$$

- $J$ independent measurements:

$$J_p = \frac{8\pi^2 \beta^2}{c^2} \sum_{j=1}^{J} \text{SINR}(j) J_r(\phi(j))$$
(2) Diversity (MIMO) gain

Fisher information $J_p$

- $J$ independent measurements:

$$J_p = \frac{8\pi^2 \beta^2}{c^2} \sum_{j=1}^J \frac{\bar{\text{SINR}}(j)}{\text{SINR}} J_r(\phi(j))$$

Diversity combining (SIMO, MISO, MIMO):

- approx. equal geometries
- effective SINRs are added up:

$$J_p = \frac{8\pi^2 \beta^2}{c^2} \sum_{\ell=1}^L \left[ \sum_{j \in \mathcal{N}_\ell} \frac{\bar{\text{SINR}}(j)}{\text{SINR}} \right] J_r(\phi_{\ell})$$

[SINR gain]

Multi-antenna configurations – diversity (MIMO) gain for ranging

- 4 x 4 MIMO vs. SISO (1 x 1)
  - 16 independent measm.
  - 16-fold SINR (LOS-to-multipath-power-ratio):
    - theoretical limit reduced by factor 4
    - detection probability strongly improved

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[Ranging and positioning in dense multipath](#)

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CRLB for **angle** estimation (phased array)

**AWGN only**

\[ r_m(t) \approx a e^{-j2\pi f_c t_m} s(t) + w(t) \]

**CRLB for AoA**

\[
\text{var}\{\hat{\phi}\} \gtrapprox \left(8\pi^2 f_c^2 D^2(\phi)\text{SNR}\right)^{-1}
\]

- squared effective aperture

\[
D^2(\phi) = \sum_{m=1}^{M} \left[\frac{d_m}{c} \sin(\phi - \psi_m)\right]^2
\]

- signal-to-noise ratio

\[
\text{SNR} = \frac{E_{\text{LOS}}}{N_0}
\]

**AWGN + dense multipath**

\[ r_m(t) \approx a e^{-j2\pi f_c t_m} s(t) + (s * \nu_m)(t) + w(t) \]

towards anchor

- multipath interference limits the performance

- CRLB scales with $f_c$ (carrier), **squared aperture** and SNR

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Multi-antenna configurations – diversity gain for angle estimation in dense multipath

- CRLB for AoA
  - uniform linear array (ULA)
  - **bandwidth** scales SINR
  - matched filter diverges from CRLB
  - minimum SINR needed for maximum likelihood

- 16-element array
  - > 20-fold aperture
  - 16-fold SINR
  - → detectability strongly improved

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Application to RFID – experimental validation

Wideband/UWB RFID Readers:
- UWB for ranging
- DSSS signal (@ 50 MHz) for ranging (TU Vienna, Arthaber)
Position error bound and MIMO gain: applied to multistatic RFID positioning

Three configurations are compared:
1. Each reader has:
   - 1 antenna for TX and RX (1 TRX)
   - yielding 2 range measurements

2. Each reader has:
   - separated TX/RX antennas
   - yielding 2 range + 2 bistatic meas.

3. Each reader has
   - 2 pairs of separated TX/RX ant.
   - yielding 8 independent range plus 8 independent bistatic measurem.

[Hinteregger, Witrisal, et al., "MIMO Gain and Bandwidth Scaling for RFID Positioning in Dense Multipath Channels," in 2016 IEEE Intern. Conf. on RFID, 2016.]
Ranging and positioning in dense multipath

**Position error bound and MIMO gain:**
applied to multistatic RFID positioning

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Integration Measurement Campaign

3 Campaigns
• TU Graz Demoroom
• Detego – Semi-industrial hall
• TU Wien Laboratory

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Integration Measurement Campaign - Results

TU Graz – Maximum Likelihood
Integration Measurement Campaign - Results

TU Graz – Positioning Accuracy

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Conclusion (1)

- **High-accuracy positioning** in dense multipath requires *large bandwidth* and/or *multi-antenna systems*
  - 5G systems to employ mm-wave and massive MIMO!
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Multipath-assisted Indoor Navigation and Tracking (MINT) – *concept and geometric model*

- **Idea:**
  - exploit range/position information from *reflected* multipath

- **Benefits:**
  - less anchor nodes;
  - more redundancy, i.e. robustness in NLOS;
  - higher accuracy

- **Geometric model (GPEM):** *virtual anchors (VAs) (mirror sources)*

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[Meissner, Steiner, Witrisal, "UWB Positioning with Virtual Anchors and Floor Plan Information," in WPNC, Dresden, March 2010.]
Signal Model

*(Geometry-based stochastic channel model - GSCM)*

- Received signal: \((s(t): \text{TX signal})\)

\[
    r(t) = \sum_{k=1}^{K} \alpha_k s(t - \tau_k) + \int_{-\infty}^{\infty} s(\lambda)\nu(t - \lambda) d\lambda + w(t)
\]

- \(K\) deterministic multipath components
  - Anchor (LOS), virtual anchors (NLOS), deterministic scatterers
  
- **Diffuse** multipath \(\nu(t)\)
  - PDP \(S_{\nu}(\tau)\)

- **MPCs** characterized by

\[
    \text{SINR}_k := \frac{|\alpha_k|^2}{N_0 + T_s S_{\nu}(\tau_k)}
\]
Position error bound for MINT
(Cramér-Rao lower bound derived from LHF)

- **Position error variance** is bounded by
  \[ \text{var}\{\hat{p}\} \geq \text{tr}\{J_p^{-1}\} \]
  - If no “path-overlap” occurs (orthogonal signals from VAs)
  \[
  J_p = \frac{8\pi^2 \beta^2}{c^2} \sum_{k=1}^{K} \text{SINR}_k J_r(\phi_k)
  \]

- **Effective SINR** \( \text{SINR}_k \) determines **ranging information intensity**
  - for MPC from \( k \)-th virtual anchor
  \[
  \text{SINR}_k := \frac{|\alpha_k|^2}{N_0 + T_s S_\nu(\tau_k)}
  \]

- **Ranging direction** matrix accounts for geometry

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Validation of the signal model –
and prediction of the position error bound

SINR estimation, BW 2 GHz, $f_c = 7$ GHz,
Anchor 2, traj. 2
Tracking algorithms exploiting multipath

- (1) **data association** of multipath ranges and **state-space tracking**
- (2) **ranging uncertainty** is estimated from multipath amplitudes
- (3) a SLAM-style algorithm is used to **discover new VAs**

Experimentation

**employing a lab-grade UWB channel sounder**

- Validation steps:
  - GSCM/GPEM-based *simulation model* → measurement-based *analysis* → channel-sounder-based *real-time implementation*

- (2 anchors) (1 anchor)

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Online model updates

**GPEM** – environment model
- position and cov. of VAs

**GSCM** – channel model
- SINR-values of MPCs

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Tracking performance

- Analysis of *accuracy and robustness* (non-diverging runs)
- Channel/environment *model awareness yields robustness*

Experimentation

- Lab-grade UWB channel sounder (IlmSense; > 40 kEUR)
- Can it be replaced by low-cost hardware?
  - DecaWave DW1000 based radio nodes

Sequitur: DW1000 + Raspberry Pi
Pozyx: DW1000 + Arduino

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DecaWave DW1000 – RX Pulse shape

*obtained from DW1000 chip*

Channel 2 (500 MHz) (top); Channel 4 (900 MHz) (bottom)
- sampled at 1.016 GHz (oversampled for time-domain fig.)
- unknown time alignment

Raised-cosine pulse; duration ~2.4ns

Raised-cosine pulse; duration ~1.5ns

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Analysis of Multipath-Components

**$SINR$-values in $dB$; two alignment methods**

<table>
<thead>
<tr>
<th>MPC</th>
<th>Channel 2</th>
<th></th>
<th>Channel 4</th>
<th></th>
<th></th>
<th>Avg. distance</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>a)</td>
<td>b)</td>
<td>a)</td>
<td>b)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LOS</td>
<td>19.6</td>
<td>19.9</td>
<td>21.5</td>
<td>22.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>plaster board east</td>
<td>3.2</td>
<td>3.7</td>
<td>21.5</td>
<td>22.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>plaster board west</td>
<td>−4.1</td>
<td>2.3</td>
<td>nan</td>
<td>nan</td>
<td></td>
<td></td>
</tr>
<tr>
<td>white board</td>
<td>8.6</td>
<td>8.6</td>
<td>11.5</td>
<td>11.8</td>
<td></td>
<td>3.3 m</td>
</tr>
<tr>
<td>window</td>
<td>7.0</td>
<td>8.3</td>
<td>5.8</td>
<td>6.7</td>
<td></td>
<td>4.4 m</td>
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<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>9.5 m</td>
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<td></td>
<td></td>
<td>4.9 m</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>10.5 m</td>
</tr>
</tbody>
</table>

- DW1000 and channel sounder reach similar levels
  - (difference ~ 1 – 2 $dB$, consistently)
- $SINR$s: “LOS” is best; “white board” and “window” still promising for positioning

Approximate ML Positioning

- **AWGN model (neglect DM)**
  \[ r = \sum_{k \in \mathcal{K}} \alpha_k s(\tau_k) + w = S(\tau)\alpha + w \]

- **approximate log likelihood**
  \[ p(r | \tau, \alpha) \propto -\| r - S(\tau)\alpha \|^2 \]
  \[ \tau_k = \frac{1}{c} \| p_n - a_k \| \quad \text{for all } k \in \mathcal{K} \]

- **Monte Carlo sampling**
  \[ d^{(i)} \sim \mathcal{N}(d_{DW}, \sigma^2) \]
  \[ \phi^{(i)} \sim \mathcal{U}(0, 2\pi) \]
  \[ p_n^{(i)} = [d^{(i)} \cos(\phi^{(i)}), d^{(i)} \sin(\phi^{(i)})]^\top + a \]
Positioning performance

at 100 measurement positions; DW 1000

- Ch. 4 (900 MHz) beats Ch. 2 (500 MHz)
- Select (virtual) anchors based on SINR values
  - improves robustness

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Low-cost dependable UWB positioning: Using adaptable directive antenna

Single-anchor positioning:
- Multipath components are exploited

Challenge:
- Very large bandwidth needed (~ 2 GHz) to separate multipath components

Solution:
- directive antenna; separation of multipath components in angular domain
Sectorized Antenna: Performance Results

Experiments based on measured signals
- One fixed anchor at $a_1$
- Agent position $p$ to be estimated
- Bandwidth is 500 MHz

Likelihood function:
- Probability of $p$ given the measurement
- $\rightarrow$ Sectorized antenna yields clear solution

CDF of position error:
- **Accuracy** ($60 \text{ cm} \rightarrow 25 \text{ cm @ 90\%}$)
- **Robustness** ($55 \% \rightarrow 90 \% @ 25 \text{ cm}$)
- **Outliers** ($10 \% > 0.6 \text{ m} \rightarrow 0 \%$)

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Maximum-Likelihood Positioning – using a single mm-wave access point

- accurate estimation of multipath delays → high position accuracy
- 7 x 7 array at the anchor (massive MIMO) →
  - AoA resolution: multimodality is reduced

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Conclusions (2)

- A multipath-assisted indoor positioning system relies on models of geometry and channel characteristics (environment model)
  - benefits from location awareness, raising robustness
  - yields location awareness to the underlying communications system (predictability of PHY-layer performance indicators)

- A single access point can support high-accuracy positioning in UWB, 5G networks, etc.
  - large bandwidth and smart antenna yield delay and angle resolution of MPCs
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Cognitive dynamic system – an engineering view inspired by cognitive neuroscience

- **Perception-action cycle** (PAC)
  - sensed environment in a closed loop → control of sensing
- **Cognitive perceptor**
  - extracts and separates relevant information (**memory, attention**)
- **Cognitive controller**
  - **act** on the environment to maximize information gain
- **Probabilistic reasoning**
  - mediates reciprocal coupling
- **Hierarchical structure**
  - different abstraction layers

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[Haykin and Fuster, Proceedings of the IEEE, 2014.]

Conclusions

- Large bandwidth / multiple antennas
  - yields high accuracy

- Exploiting multipath
  - yields high robustness

- Cognitive positioning
  - to yield high efficiency, low latency, etc.

- **foreseen** evolution of wireless networks
  - 5G: mm-wave, massive MIMO

- is becoming available (e.g.) with 5G mm-wave systems
  - environment model

- **mission critical** positioning
  - **massive** RFID tag populations
  - full location awareness

- **Time has come** for high-accuracy positioning, given current technology trends

- Location awareness is **a way of the future** for communications and positioning in 5G and beyond