An Ultra-Wideband Local Positioning System for Highly Complex Indoor Environments

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Outline

- Motivation and Goals of this Work
- Local Positioning Radar Principles
- Multipath Issues
- Channel Measurement
- System Expansion to UWB
- Demonstrator System
- System Evaluation and Measurement Results
Motivation

- High demand for indoor wireless local positioning
  - Tool tracking
  - Indoor guidance
  - Security applications
  - Surgery assistance
- Key features: accuracy and multipath robustness
- Resolution and multipath robustness is proportional to applied bandwidth → UWB
Tool Tracking in Industrial Environment
Goals

• Development of an accurate and precise local positioning system with enhanced robustness towards multipath interference
• Identical hardware setup for base station and mobile client

• Simple RTOF concept:
  1. Synchronize mobile client to base station
  2. Send synchronized reply back to base station
  3. Base station calculates distance from Round-Trip Time-of-Flight (\(\tau\))
Synchronization

- Multiply both signals and evaluate spectrum
- Const. mixing products during upsweep & downsweep
- Correct $\Delta t$, $\Delta f$ offsets in time and frequency

\[ \Delta f = \frac{f_2 + f_1}{2} \]
\[ \Delta t = \frac{T}{B} \frac{f_2 - f_1}{2} \]
Distance Measurement

- Standard FMCW approach
- Distance measurement during downsweep
- Multiply LO and RX signal and evaluate spectrum
Multipath Issues
Multipath Issues
Multipath Issues
Multipath Issues
Multipath Issues
Multipath Resolution

The ability to resolve closely spaced paths depends on:

- Type of window function
- FFT bin size (frequency resolution)
- Sweep bandwidth $B$

$\rightarrow$ Multipath resolution $\sim \frac{1}{B}$
Multipath Resolution

\[ d_{NL\text{OS}_1-LOS} = 90\,\text{cm} \]
\[ d_{NL\text{OS}_2-LOS} = 210\,\text{cm} \]
\[ d_{NL\text{OS}_3-LOS} = 300\,\text{cm} \]

\[ \Delta f_1 = 450\,\text{Hz} \]
\[ \Delta f_2 = 1.05\,\text{kHz} \]
\[ \Delta f_3 = 1.5\,\text{kHz} \]
Multipath Resolution

$B = 300 \text{ MHz}$

$d_{\text{NLOS}_1-\text{LOS}} = 90\text{ cm}$
$d_{\text{NLOS}_2-\text{LOS}} = 210\text{ cm}$
$d_{\text{NLOS}_3-\text{LOS}} = 300\text{ cm}$

$\Delta f_1 = 900\text{ Hz}$
$\Delta f_2 = 2.1\text{ kHz}$
$\Delta f_3 = 3\text{ kHz}$
$d_{\text{NLOS}_1-\text{LOS}} = 90\,\text{cm}$

$\Delta f_1 = 1.5\,\text{kHz}$

$\Delta f_2 = 3.5\,\text{kHz}$

$\Delta f_3 = 5\,\text{kHz}$

$\Delta f_3 = 5\,\text{kHz}$

$B=500\,\text{MHz}$
\[ d_{NL01-LOS} = 90 \text{ cm} \]
\[ d_{NL02-LOS} = 210 \text{ cm} \]
\[ d_{NL03-LOS} = 300 \text{ cm} \]
\[ \Delta f_1 = 3 \text{ kHz} \]
\[ \Delta f_2 = 7 \text{ kHz} \]
\[ \Delta f_3 = 10 \text{ kHz} \]

Multipath Resolution

B=1 GHz
Measurement Setup
Measurement Constellation
Measured Impulse Responses
• Expansion of sweep bandwidth to 1GHz
• UWB Measurement settings:
  – RBW = 1 MHz
  – VBW = 3 MHz
  – RMS detector
  – Sweep time =
    =(no. of bins x 1 ms)
  – Average PSD each bin

• Violating EIRP limit
• Pure FMCW system ≠ UWB system
Chopping of TX signal

Pulsed Frequency Modulated UWB

→ PFM UWB

- Spectrum broadening
  \[ t \cdot P_{drop} = 20 \log_{10} \left( \frac{t_{pw}}{T_{pp}} \right) \]

Chopping of TX signal
• FCC conform system design:
  
  - Peak power = 0 dBm
  - $t_{pw} = 3\text{ns}$
  - $T_{pp} = 36\text{ns}$
    \[ \Rightarrow f_{pr} = 27.8\text{MHz} \]
  - $t_{pw}/T_{pp} = 1/12$
  - Instantaneously occupied spectrum
    $B_{UWB} > 500\text{ MHz}$
- Reconstruction of chopped RX signal
- Mixing with continuous LO signal
- Low-pass filtering with $f_{lp} \ll f_{pr}$
- IF signal easy to digitize
Hardware Implementation
Prototype System
RF Board
Prototype System
• Connection of 2 units via a 100m coax cable
• Measurement of electrical length of delay line
• No distortions caused by multipath components
Delay Line Measurements

- 2500 measurement samples
- Gaussian distribution
- $\sigma_d = 6.57 \text{ mm}$
- Sync. Results
  - $\sigma_{\Delta f} < 45 \text{ Hz}$
  - $\sigma_{\Delta t} < 45 \text{ ps}$
Outdoor Measurements

- 1D distance measurement in outdoor environment
- Base station at fixed position, mobile client on trolley
- Reference measurement by laser distance system
- Max. distance $d_{\text{max}} = 72\text{m}$
Outdoor Measurements

The graph depicts the measured distance over time. As time progresses, the distance decreases linearly, indicating a constant speed. The y-axis represents the measured distance in meters, while the x-axis represents time in seconds.
Indoor Measurements

- 1D distance measurement in office environment
- Base station at fixed position, mobile client on automatic sledge
- Highly accurate reference system
Indoor Measurements

- 1D distance measurement in narrow hallway
- Distinctive multipath characteristic
- Base station at fixed position, mobile client on trolley
- Use of omnidirectional antennas
- Reference measurement by laser distance system
- Max. distance $d_{\text{max}} = 33\text{m}$
Exemplary IF-Spectrum @ d=20m
Indoor Measurements
Final Demonstration at BMW Fabrication Hall

cordless screwdriver with PFM-UWB-LPR mobile client

base stations
Ongoing Research

PFM USR
Components and Concepts for Pulsed Frequency Modulated Ultra-Wideband Secondary Radar Systems

LokProd3D

Project in the DFG SPP 1202:

UKoLoS
Ultrabreitband-Funktechniken für Kommunikation, Lokalisierung und Sensorik

Bayern Forschung
Innovation Technologie

Europäische Union
„Investition in Ihre Zukunft“
Europäischer Fonds für regionale Entwicklung
LokProd3D: Chip Integration of Multi-Channel-System
LokProd3D: FMCW-Synthesizer

PFD + CP

MMD

VCO with $K_{VCO}$-Linearization
LokProd3D: RF-Frontend

- Distribution NW & RF-Switches
- Mixers
- Variable Gain Amplifier
PFM USR: Switched Injection-Locked Oscillator Approach
PFM USR: SILO-Based Harmonic Sampling
PFM USR: 7 GHz SILO Chip Photograph
Conclusions

- Channel measurement campaign to gain knowledge of industrial UWB channels
- Expansion of common FMCW to Ultra Wideband
- First time demonstrated positioning system using PFM-UWB signals for synchronization and distance measurement
- High accuracy and precision maintained in distinctive multipath environments
  - 1D accuracy ≤ 5 cm in office environment
  - ≤ 15 cm in narrow hallway
  - Standard deviation ≤ 1.2 cm in all measurement scenarios
Thank You!