Positioning for 5G Wireless Systems and the Internet-of-Things:
Location-Awareness for 5G Networks and Beyond

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*Topic addressed (c.f. book chapter; white paper)*

- Introduction
  - New applications and challenges
  - Features and limitations of 5G and IoT technologies
- Measurement acquisition
  - Including channel modeling
- Position estimation and data fusion
- Multipath assisted positioning
  - Environment modeling and location-awareness
- System studies and system-level performance
- Testbeds and prototyping activities

- Highlights: Workshop in Graz; White Paper > 3500 reads on RG
High-accuracy Positioning: Applications

**Objectives:** Positioning; navigation; activity det.; mapping; control

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

**Challenges:**
- Heterogeneity: scenarios and technologies; multipath

**Manufacturing**

**Retail**

**Autonomous Driving**

**Logistics**

**Smart Labeling**

**Assisted Living**

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Fotos: Ubisense, Imagotag GmbH, brighamyen.com, Witrisal, Jungheinrich, slashgear.com
Location-aware Communications: Many system parameters depend on the position

- Path Loss: $\|x - x_o\|^{-\eta}$
- Distance: $\|x - x_o\|^{-\eta}$
- Doppler: $f_D = \|x(t)\|/\lambda$
- Velocity: $f_D = \|x(t)\|/\lambda$
- Shadowing: $\exp\left(-\frac{\|x - x_j\|}{d_c}\right)$
- Spatial Correlation: $\exp\left(-\frac{\|x - x_j\|}{d_c}\right)$
- Interference: $\|x_i - x_s\| < R$
- Spatial Reuse: $\|x_i - x_j\| > R_{nt}$
- MIMO: $h(\phi(x, x_s))$
- Angle of Arrival: $h(\phi(x, x_s))$
- Routing: $\min_j \|x_j - x_d\|$
- Next Hop: $\min_j \|x_j - x_d\|$
- Propagation Delay: $\tau = \|x - x_o\|/c$
- Distance: $\tau = \|x - x_o\|/c$
- Proactive Allocation: $p(x(t))$
- Predictable Behavior: $p(x(t))$

Positioning principles

Measurement techniques:
- **Distance**
  - Time-of-flight
  - Received signal strength (RSS)
- **Angle**
  - Angle-of-arrival / -departure
  - Array antennas

- **Time-of-flight** is most accurate
  - Reciprocal to SNR & BW
  - Impact of multipath!

Positioning networks:
- Multiple anchors
  - Multilateration / -angulation
  - Drawback: infrastructure need
- Single anchor
  - Distance and angle
  - Specular multipath
- Cooperative
  - Measure in-between agents

- Reliance on line-of-sight!
- Robustness
Time-of-flight Ranging: The Challenge of Multipath
**Time-of-flight Ranging:** *The Challenge of Multipath*

Ranging performance:

- Ultra-wide bandwidth is beneficial – to resolve multipath
- Impact of (current) environment conditions – large-scale variations

**Conclusion:**

- Ultra-wide bandwidth is beneficial – to resolve multipath
- Impact of (current) environment conditions – large-scale variations

Modeling the dense multipath

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

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

- useful signal
- interference
- noise

$$\tau^{(j)} = \frac{1}{c} \| p - p^{(j)} \|$$

PDP; uncorrelated scattering model

SINR for ranging

SINR (for AoA)

Lower Bounds for AOA and TOA

Uniform Linear Antenna Array with 2 elements

- MLE
- MFE
- REB
- REB AWGN

DM influence


Performance limits in dense multipath

Lower Bounds for AOA and TOA

Uniform Linear Antenna Array with 2 elements

Gain $\propto \sqrt{M}$

DM influence

Effect of unknown DM statistics

Uniform Linear Antenna Array with 16 elements

Gain $\propto D^2_\lambda(\phi)M$

[10]

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[T. Wilding et al., "Accuracy bounds for array-based positioning in ...," Sensors 2018, 18.]

5G Networks: Features and Limitations
Higher capacity, lower latency, ultra-dense deployment

Diversity of services, use cases and (extreme) requirements

- **5G technologies:** mm-wave; massive MIMO; small cells; D2D

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**IoT: Features and Limitations**

- **Typical properties**
  - Low power
  - Low throughput
  - Low cost
  - **Undesireable** for positioning!

- **Short-range technologies**
  - Bluetooth low energy (BLE)
  - Radio frequency identification (RFID)
  - Ultra-wideband (UWB)
  - **Allow for medium to high accuracies**
RFID Positioning –
Experimental validation

Wideband/UWB RFID Readers:
- UWB for ranging
- DSSS signal (@ 50 MHz) for **ranging**
  *(TU Vienna, Arthaber)*
- **MIMO** 3 x 3: AoA and AoD
- **Multiband** reader and tag:
  - 2.4 GHz for positioning
  - UHF for power and comms.
RFID Positioning

*Exploiting wideband MIMO measurements at 2.4 GHz*

- 9% of measured positions are outliers with error larger 1m
- 80% of measured positions show a error **smaller 15 cm**
- LOS condition

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Reliance on Line-of-Sight

Measurement of body influence (off-body channel)

Measurement Setup

Characterization of LOS

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Robustness

Reliance on Line-of-Sight

*Impact of body shadowing*

Walking along trajectory
- two fixed anchors

Ranging
- outliers

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Multipath-assisted Indoor Positioning:

- Exploit (specular) multipath components
  - Less infrastructure; **more robustness**; better accuracy
  - Environment model: **predictability** of multipath (location awareness)

Concept:

Signals (UWB):

Environment model:

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GP regression for specular MPC amplitudes

Scenario:
Multipath-assisted positioning

SMC amplitude pred.:

Validation measurement:

Gaussian process regression for specular MPC (SMC) amplitudes

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Tracking algorithms exploiting multipath

- (0) multipath parameters (ToA/AoA) estimated from **received signals**
- (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**

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Multipath-based SLAM

Particle convergence

For real data:

Channel Parameter Estimation

Utilizing Sparse Bayesian Learning

Measured data:

- 3x3 antenna array (2cm spacing)
- Pulse RRC
  - pulse duration 1 ns; roll-off-factor 0.6; center frequency 6 GHz
- AWGN: 30 dB SNR
- DMC: Double exponential PDP

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Channel Parameter Estimation

Utilizing Sparse Bayesian Learning

Probability of Artifact and Probability of Detection - ROC
- Single component in DMC plus AWGN

Channel Parameter Estimation

Utilizing Sparse Bayesian Learning

Low-cost dependable UWB positioning: Using an adaptable directive antenna

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

Solution:
- Switched directive antennas; separation of multipath components in angular domain
- Direct positioning: maximum likelihood

Multipath-assisted indoor positioning for IoT devices

DEPENDABLE THINGS
Dependable Internet of Things in Adverse Environments

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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 cm \( \rightarrow \) 25 cm @ 90 %)
- **Robustness** (55 % \( \rightarrow \) 90 % @ 25 cm)
- **Outliers** (10 % > 0.6 m \( \rightarrow \) 0 %)
Conclusion:
Features and Limitations

- **Time-of-flight** most accurate
  - (Dense) **multipath limits performance** (*modeling*)
  - Advantage of **wide bandwidth** and **multiple antennas**

- **Robustness:** reliance on line-of-sight
  - Site-specific influence of **environment**
  - Exploit specular multipath – redundancy; **environment awareness**

- **5G:** more BW; more antennas; densification; D2D

- **IoT:** potential for short-range technologies

- **Limitations:** large environments; large number of nodes; fast mobility; low latency; low energy & **high robustness**