University of Stuttgart
Institute of Telecommunications

Non-line-of-sight Positioning for mmWave Communications

F. Fellhauer*, J. Lassen*, A. Jaber*, N. Loghin†, and S. ten Brink*

*University of Stuttgart, Institute of Telecommunications, Pfaffenwaldring 47, 70569 Stuttgart, Germany
†Sony European Technology Center (EuTEC), Stuttgart, Germany

{fellhauer, tenbrink}@inue.uni-stuttgart.de, nabil.loghin@sony.com

Summary

- we present a method to estimate a **users position based on mmWave channel state information (CSI)**, using: angle of arrival (AOA), angle of departure (AOD) and time of flight (TOF)
- an approach to **overcome dependence** on an **angular reference**, using differential AOA & AOD
- **performance is analyzed** with respect to accuracy of AOA-/AOD- and TOF estimation and **compared to theoretical limit** (Cramér-Rao lower bound (CRLB))
  - in indoor scenario
  - in absence of LOS (NLOS)
  - using absolute AOA/AOD
  - using differential AOA/AOD

⇒ **Results show:**

- **user localization is possible even without angular reference**
- **partial CSI of NLOS-channels holds valuable information for positioning**
- **for viable accuracy of input data, user localization can reach a positioning error of $\leq$ 30 cm in 90 % of observations**

Introduction

- **indoor localization** is still not widely deployed, as classical approaches like **GPS** are **not applicable**
- multiple approaches have been discussed as solutions
  - dedicated infrastructure
  - geomagnetic fingerprinting
  - installed infrastructure for communications like WiFi or 5th-Generation Wireless Cellular Systems (5G)
- IEEE already **develops scalable standard** using WiFi
  - IEEE 802.11az (11az) will specify Fine Time Measurement (FTM) in 5- and 60 GHz-spectrum [1]
- **physical properties in mmWave spectrum** allow to estimate **geometrical channels properties** like AOA, AOD and TOF
- this geometrical CSI can **hold information on a users location**
- usage for outdoor positioning already known [2, 3, 4]
- common **drawback of known methods is assumption on presence of an angular reference** e.g. "Geographical North"
- we focus on:
  - **typical indoor scenario** for mmWave-WiFi
  - problem of **angular reference**

Geometrical Problem Formulation

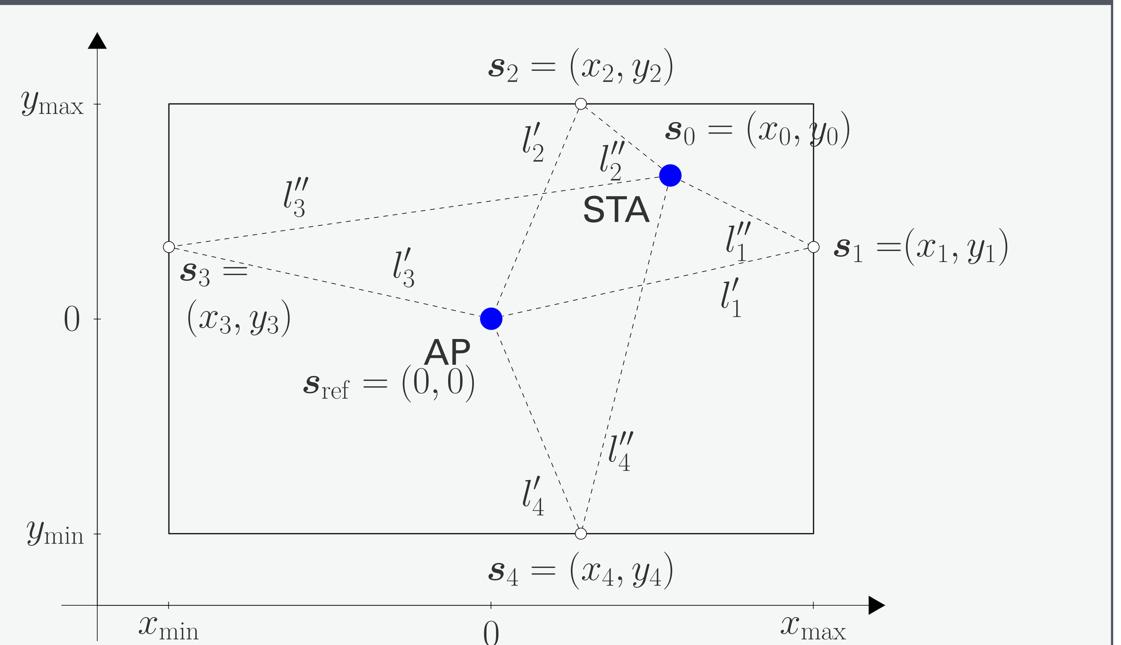


Fig. 1: Scenario with Access Point (AP), Station (STA) and scatterers $s_{1...4}$

$$l_k(s_k, s_0) = \underbrace{\sqrt{x_k^2 + y_k^2}}_{l_k'} + \underbrace{\sqrt{(x_0 - x_k)^2 + (y_0 - y_k)^2}}_{l_k''}, \quad (1)$$

$$\alpha_k(s_k) = \arctan\frac{y_k}{x_k}, \ \delta_k(s_k, s_0) = \arctan\frac{y_k - y_0}{x_k - x_0} \quad (2)$$

$$y = (l_1, \ldots, l_K, \alpha_1, \ldots, \alpha_K, \delta_1, \ldots, \delta_K)^{\mathrm{T}}. \quad (3)$$

Observation vector:

$$y = F(s) = \Big(l(s_1), \ldots, l_K(s_K), \alpha_1(s_1), \ldots, \alpha_K(s_K), \delta_1(s_1, s_0), \ldots, \delta_K(s_K, s_0)\Big)^{\mathrm{T}}, \quad (4)$$

with **scenario vector** $s = (s_0, s_1, \ldots, s_K)^{\mathrm{T}}$.

To **simulate inaccuracy** of **measurements**, observed values are superimposed by IID **Gaussian noise** with $n_{k,\measuredangle} \sim \mathcal{N}(0, \sigma_\measuredangle^2)$ for angular- and $n_{k,t} \sim \mathcal{N}(0, \sigma_t^2)$ for temporal noise, respectively:

$$\tilde{\alpha}_k = \alpha_k + n_{k,\measuredangle}, \ \tilde{\delta}_k = \delta_k + n_{k,\measuredangle} \text{ and } \tilde{l}_k = l_k + n_{k,l} \quad (5)$$

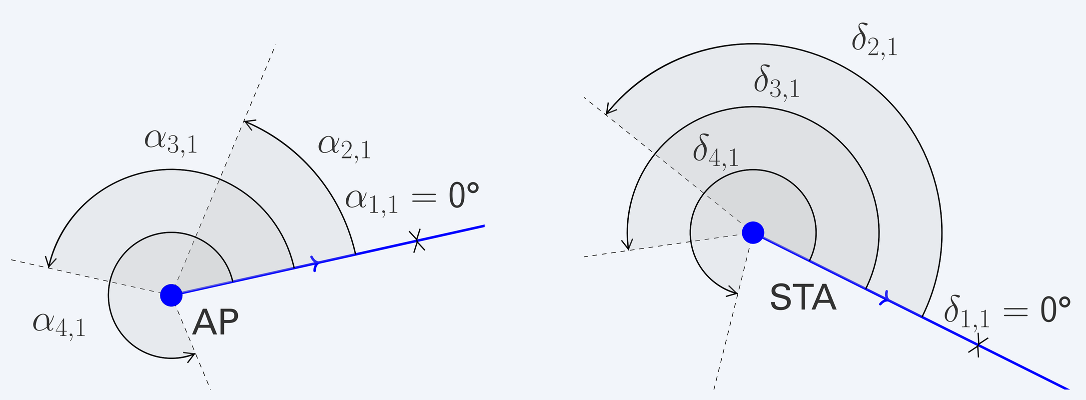
We get the resulting **noisy observation vector**:

$$\tilde{y} = (\tilde{l}_1, \ldots, \tilde{l}_K, \tilde{\alpha}_1, \ldots, \tilde{\alpha}_K, \tilde{\delta}_1, \ldots, \tilde{\delta}_K)^{\mathrm{T}} \quad (6)$$

Differential Angular Measurement

Eq. (2) resulting in (4) **requires** all **angles** to be **measured against a common reference** direction e.g. x-axis in Fig. 1 or **Geographical North** in an implementation.

To **overcome this restriction** we measure all **angles relative to a reference-path** $k_{\mathrm{ref}} \in \{1 \ldots 4\}$



Leading to **relative observation vector**:

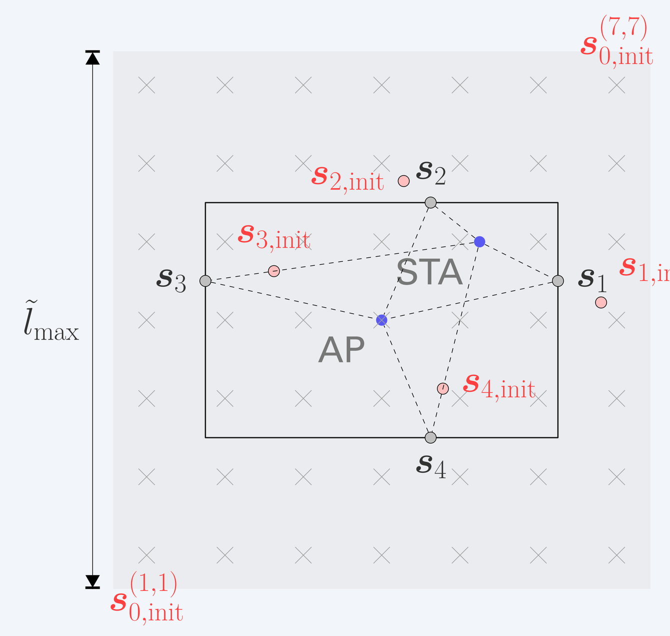
$$y_{\mathrm{rel}} = F_{\mathrm{rel}}(s, k_{\mathrm{ref}}) = \Big(l_1(s_1), \ldots, l_K(s_K), \alpha_{1,k_{\mathrm{ref}}}(s_1), \ldots, \alpha_{K,k_{\mathrm{ref}}}(s_K), \delta_{1,k_{\mathrm{ref}}}(s_1, s_0), \ldots, \delta_{K,k_{\mathrm{ref}}}(s_K, s_0)\Big)^{\mathrm{T}} \quad (7)$$

Position Estimation

- the problem of finding an estimated scenario vector $\hat{s}$ and therefore $\hat{s}_0$ can the be formulated as

$$\hat{s} = \arg\min_{s} \|\tilde{y} - F(s)\|_2^2. \quad (8)$$

- to **solve** (8) based on (4) or (7), we use the **Levenberg-Marquardt (LM)-method** using initial values that are systematically derived from $\tilde{y}$:
  - to find **initial values** for $s_{0,\mathrm{init}} = (x_{0,\mathrm{init}}, y_{0,\mathrm{init}})$, we span a grid with edge length of $\tilde{l}_{\max} = \max(\tilde{l}_1, \ldots, \tilde{l}_K)$
  - for initial values of scatterers $s_{k,\mathrm{init}} = (x_{k,\mathrm{init}}, y_{k,\mathrm{init}})$, we use $x_k = r \cdot \tilde{l}_k \cdot \cos\tilde{\alpha}_k$ and $y_k = r \cdot \tilde{l}_k \cdot \sin\tilde{\alpha}_k$.
  - Leaving $r = [0, 1]$ as an implementation specific parameter.
- using the LM-method, we **iterate over the set of initial seeds**:



- most promising **solution is selected** by evaluation of respective **residual vector**

$$\rho^{(N_{\mathrm{seed}})} = \tilde{y} - F\left(\hat{s}^{(N_{\mathrm{seed}})}\right) \quad (9)$$

- finding the best solution for estimated Station position

$$\hat{s}_0 = \left(x_0^{(\hat{N}_s)}, y_0^{(\hat{N}_s)}\right) \ \text{ with } \hat{N}_s = \arg\min_i \left\|\rho^{(i)}\right\|_2^2. \quad (10)$$

Cramér-Rao lower bound

- as lower **performance bound**, we evaluate the **CRLB**:

$$\Phi = \left(\frac{\partial F^{\mathrm{T}}(s)}{\partial s} Q^{-1} \frac{\partial F(s)}{\partial s}\right)^{-1} \quad (11)$$

- for systematic characterization, the (2×2) sub-matrix Σ and its elements $\sigma_{ij} = \Phi_{ij}$ with $i, j \in \{1, 2\}$ is interpreted as covariance-matrix of estimated x- and y-coordinates of the station (STA)
- by diagonalization of the covariance matrix, we get variances $\sigma_{\hat{X}}^2, \sigma_{\hat{Y}}^2$ for two independent Gaussian distributed random variables $\hat{X}$ and $\hat{Y}$
- the resulting positioning error (eq. (12)) which corresponds to the Euclidean norm of these independent random variables is Hoyt distributed [5]
- Q/Q_{rel}: covariance matrix of TOA and AOA/AOD measurements (diagonal for absolute angles) and modified respectively for differential angular measurements

Results

Simulation parameters:

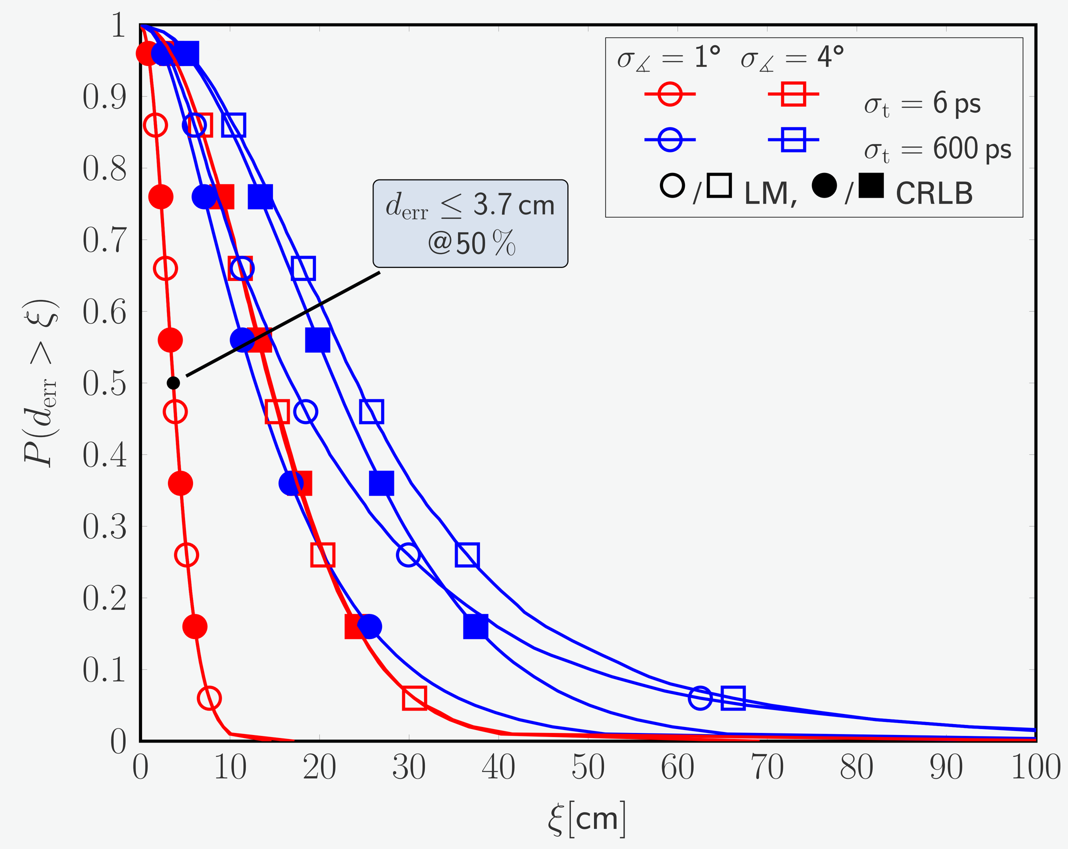
Scenario	Conference Room STA-AP $x = -1.5 \ldots 1.5\,\mathrm{m}$ $y = -2.25 \ldots 2.25\,\mathrm{m}$
STA-Position	s_0: 10×10-grid, margin at walls: $d_{\mathrm{sep}} = 0.1\,\mathrm{m}$
AP-Position	$(0, 0)$
Noise Realizations	absolute: $N_{\mathrm{n}} = 100$ differential: $N_{\mathrm{n,rel}} = 20$
Temporal Noise	$\sigma_{\mathrm{t}} = 6$ or $600\,\mathrm{ps}$
Angular Noise	$\sigma_\measuredangle = 1$ or $4°$
Seed-Grid	(10×10), $N_{\mathrm{s}} = 100$, $r = 1/2$
Initial damping factor for LM-method	$\lambda_0 = 0.01$

As **performance metric** we are interested in the distribution of the **positioning error**:

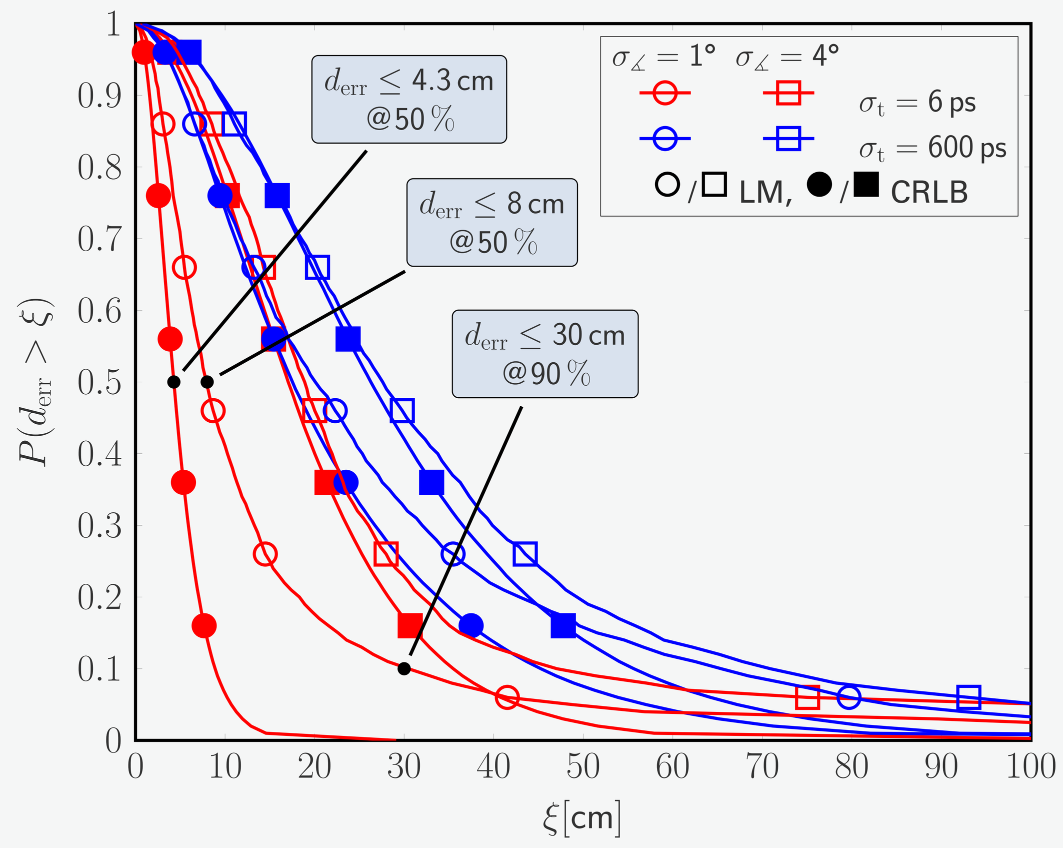
$$d_{\mathrm{err}} = \|s_0 - \hat{s}_0\|_2 \quad (12)$$

Complementary Cumulative Histogram and CCDF:

In presence of an absolute angular reference



Using differential angular measurements



⇒ User **localization** is **possible** even **without angular reference**

⇒ Gap to CRLB is relatively large for low temporal and angular noise when no angular reference is present

⇒ **Accuracy** of **<8 cm in 50 %** of situations is possible **without angular reference**

⇒ Even **<4 cm in 50 %** possible with angular reference

⇒ **Non-LOS** parts of **CSI** holds information for **user localization**

⇒ Additionally **scenario information** can be **extracted** from $\hat{s}$

- potential use-cases: beamforming, virtual reality, SLAM

References

[1] A. Zhu and J. Segev, "Proposed 802.11az Functional Requirements," IEEE Document 802.11-16/424, May 2016.

[2] J. Li, J. Conan, and S. Pierre, "Mobile Terminal Location for MIMO Communication Systems," IEEE Trans. Antennas and Propag., vol. 55, no. 8, pp. 2417–2420, Aug. 2007.

[3] B. Shikur and T. Weber, "TDOA/AOD/AOA Localization in NLOS Environments," in IEEE ICASSP, May 2014, pp. 6518–6522.

[4] J. Chen, D. Steinmetzer, J. Classen et al., "Pseudo Lateration: Millimeter-Wave Localization Using a Single RF Chain," Mar. 2017.

[5] R. S. Hoyt, "Probability Functions for the Modulus and Angle of the Normal Complex Variate," The Bell System Technical Journal, vol. 26, no. 2, pp. 318–359, Apr. 1947.