On the Unimportance of Phase-Coherent Measurements for Beampattern-Assisted Positioning

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Indoor localization using a single anchor

Motivation

- reduce number of required anchor nodes to a single anchor
- multipath propagation contains position-related information

→ exploit spatial and delay domain of multipath propagation

Challenge

- combining information from multiple antennas requires phase-coherent processing
- maintaining stable clocks for consecutive measurements is challenging

Contribution

- derive single-anchor indoor positioning algorithm
- approximate solution for non phase-coherent measurements
- evaluation with synthetic and measured data

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Multipath assisted indoor localization

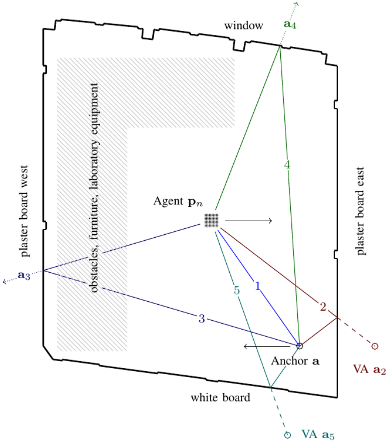
Setup

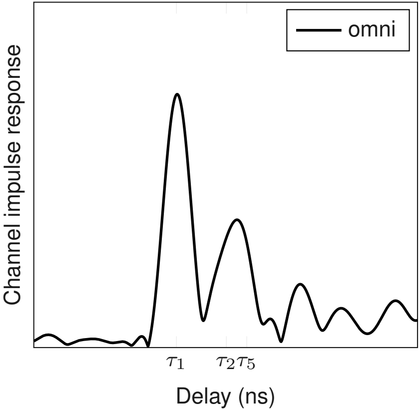
- Indoor scenario with provided floorplan
- Agent node at $\mathbf{p}$
  - single antenna (omnidirectional)
- Anchor node at $\mathbf{a}$
  - M directional antennas with antenna index m

Measurements

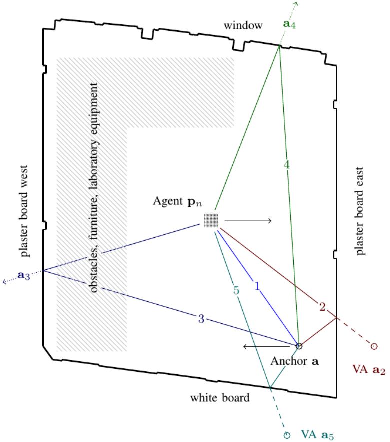
- channel impulse response between $\mathbf{p}$ and mth antenna at $\mathbf{a}$
- consecutive measurements are non phase-coherent

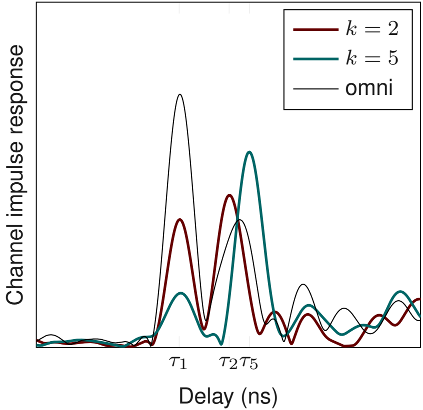
Temporal and spatial dimension





Temporal and *spatial* dimension





Multipath assisted indoor localization

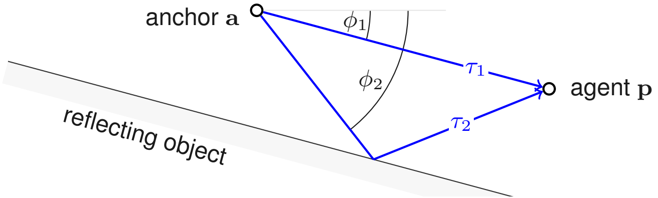
- Channel impulse response $r_m(t)$ at mth antenna with beampattern $b_m(\phi)$ for transmitted signal $s(t)$

$$r_m(t) = e^{j\varphi_m} \sum_{k=1}^{K} b_m(\phi_k)\alpha_k s(t - \tau_k) + w_m(t),$$

- Phase-offset φ_m
  - non stable clock at consecutive measurements
  - not predictable
- Position-related information in specular reflections
  - delay τ_k
  - angle ϕ_k

Multipath component parameters

- Specular reflections



- Characterization of multipath components
  - delay $\tau_k = f_k(\mathbf{p}, \mathbf{a})$
  - angle $\phi_k = g_k(\mathbf{p}, \mathbf{a})$

Derivation of likelihood function

- Channel impulse response $\mathbf{r} = [\ldots, \mathbf{r}_m \ldots]$ factorizes to

$$\mathbf{r} = \boldsymbol{\Phi}\,\mathbf{X}(\mathbf{p})\,\boldsymbol{\alpha} + \mathbf{w}$$

with phase-offsets $\boldsymbol{\Phi}$, position-related parameters $\mathbf{X}(\mathbf{p})$ and multipath amplitudes $\boldsymbol{\alpha}$

- Assuming AWGN, likelihood function results in

$$\log p(\mathbf{r};\mathbf{p}) \propto \text{const} - \|\mathbf{r} - \boldsymbol{\Phi}\mathbf{X}(\mathbf{p})\boldsymbol{\alpha}\|^2$$

- Maximization with respect to agent position

$$\hat{\mathbf{p}}^{\text{coh}} = \arg\max_{\tilde{\mathbf{p}}} \log p(\mathbf{r};\mathbf{p})$$

$$= \arg\max_{\tilde{\mathbf{p}}} -\sum_{m=1}^{M} \|\mathbf{r}_m - \mathbf{X}_m(\mathbf{p})e^{j\varphi_m}\boldsymbol{\alpha}\|^2$$

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Likelihood function - Insights

- Maximum likelihood estimate of multipath amplitudes $\hat{\boldsymbol{\alpha}}$

$$\hat{\boldsymbol{\alpha}} = \mathbf{X}^{+}(\mathbf{p})\boldsymbol{\Phi}^{H}\mathbf{r}$$

- Amplitude α_k of kth (non-overlapping) multipath component

$$\hat{\alpha}_k = \text{const} \sum_{m=1}^{M} e^{-j\varphi_m} |b_m(\phi_k)|^2 \hat{\alpha}_{k,m}$$

Weighted average of estimated amplitudes $\hat{\alpha}_{k,m}$ at each antenna m

- Undo phase-offset $\hat{\alpha}_{k,m} = e^{j\varphi_m}\alpha_k$
- Weigh by the beampattern $b_m(\phi_k)$

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Non phase-coherent processing

Limitations

- Missing phase-offset prevents joint position estimation
- Reliable amplitude estimate is required
- Phase-offset affects phase only

Proposal

- estimate magnitude as weighted average of antenna's magnitude estimates
- keep noisy phase (including the phase-offset)

Non phase-coherent processing

Proposal: estimate magnitude $|\hat{\alpha}_{k,m}|$ and phase $\angle\hat{\alpha}_{k,m}$ of kth multipath at $\bar{m}$th antenna separately

$$\hat{\alpha}_{k,m} = |\hat{\alpha}_k| e^{j\angle\hat{\alpha}_{k,m}}$$

constant magnitude $|\hat{\alpha}_k|$ for all m but independent phase $\angle\hat{\alpha}_{k,m}$

- Approximation of magnitude

$$|\hat{\alpha}_k| = \left| \mathrm{const} \sum_{m=1}^{M} e^{-j\varphi_m} |b_m(\phi_k)|^2 \hat{\alpha}_{k,m} \right|$$
$$\approx \mathrm{const} \sum_{m=1}^{M} |b_m(\phi_k)|^2 |\hat{\alpha}_{k,m}|$$

- Phase $\angle\hat{\alpha}_{k,m}$ estimated from mth measurement only

$$\angle\hat{\alpha}_{k,m} = \angle \frac{\mathbf{s}_{\tau_k}^H \mathbf{r}_m}{\|\mathbf{s}_{\tau_k}\|^2}$$

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Discussion

Phase-aware estimate $\mathbf{p}^{\text{coh}}$

- complex-valued average of M antenna amplitude estimates
- requires phase coherency

Approximation $\mathbf{p}^{\text{proposed}}$

- deals with non phase-coherent measurements
- magnitude calculated as weighted average
- employs noisy phase

Evaluation

Setup

- 2D indoor scenario, line-of-sight + 4 reflections
- Bandwidth of 400 MHz
- $M = 4$ antennas at anchor, half-power beamwidth of $\approx 90°$

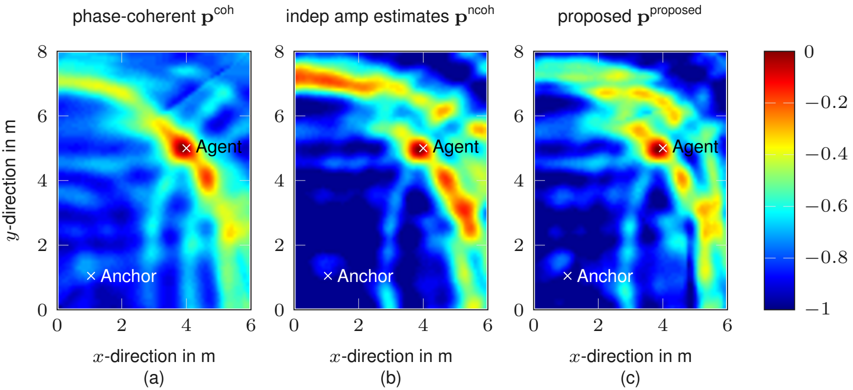
Algorithms

- phase-coherent $\mathbf{p}^{\text{coh}}$
- proposed $\mathbf{p}^{\text{proposed}}$
- independent amplitude estimates $\mathbf{p}^{\text{ncoh}}$

Evaluation

- illustration of likelihood functions (computer generated data)
- evaluation of position error (computer generated and real measured data)

Illustration of likelihood functions



Desired: single peak at true position

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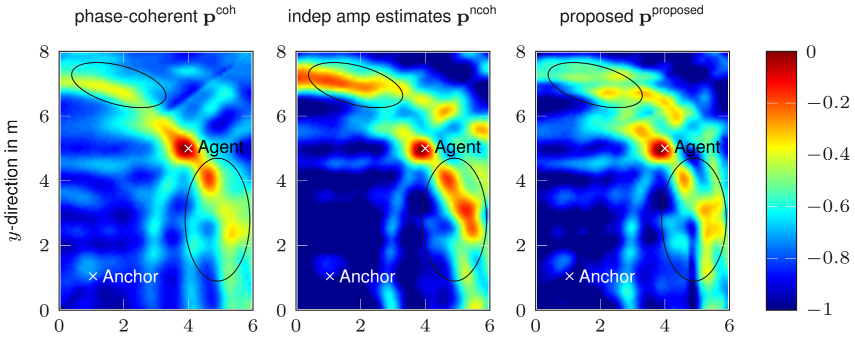


(a) (b) (c)

Local maxima are reduced

Position estimation using computer generated data

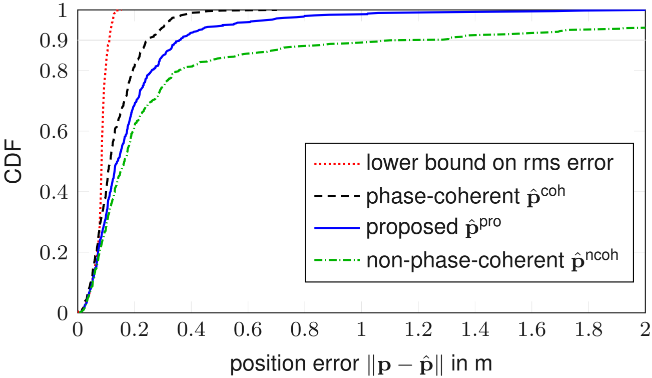
Setup

- place agent randomly
- calculate synthetic signals $r_m(t)$
- add AWGN with SNR (at 1 m distance) of 30 dB

Evaluation

- evaluate likelihood functions for $\tilde{\mathbf{p}}$ on grid with spacing 25 cm (9 evaluation points per square) meter
- select $\tilde{\mathbf{p}}$ which maximizes likelihood function
- root mean-squared-error criterion

Position estimation using computer generated data



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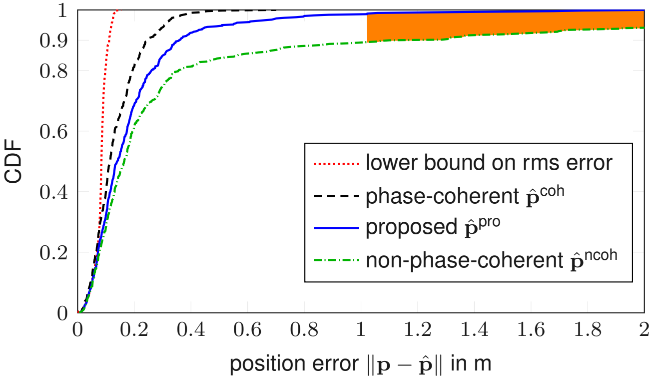


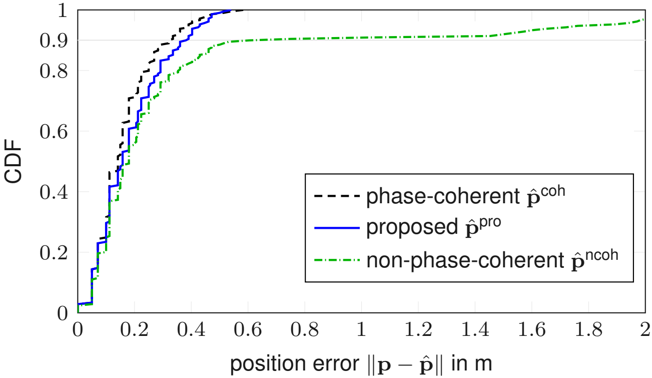
reduction of outliers

Position estimation using real measured data

Setup for measurement data

- measurement device: correlative channel sounder with $f_c = 5.4$ GHz, bandwidth 400 MHz
- four antennas at anchor, half-power beamwidth of 90°

Position estimation using real measured data



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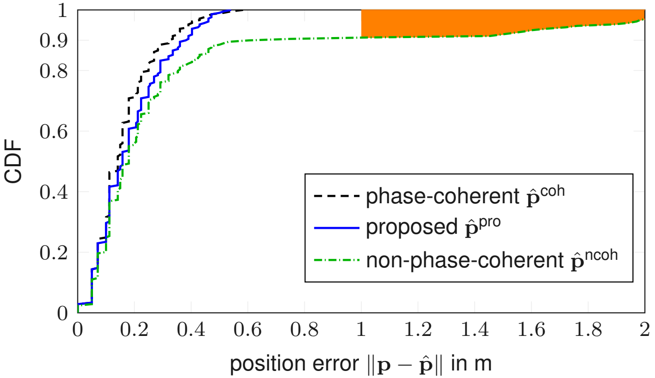

reduction of outliers

Summary

Dealing with non phase-coherent measurements for positioning

- exploit position-related information in multipath components
- strong reduction of local maxima in likelihood function due to improved amplitude estimates
- more robust to outliers, 90 % of rms error below 40 cm

Future work

- joint estimation of amplitudes and phase-offset
- incorporate prior amplitude information