Revisiting the image source model: Towards geometry-based modeling of agent-to-agent channels

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Geometry-based multipath propagation

Motivation

- indoor positioning requires infrastructure, e.g. anchor nodes
- multipath propagation contains position-related information

→ omit anchors and utilize multipath propagation

Challenge

- modeling of multipath propagation agent-to-agent channels
- widely used multipath models assume static anchors

Contribution

- revisit multipath propagation model
- rephrase propagation models to deal with cooperative agent nodes
- analyze covered information in multipath delays

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Contents

Multipath assisted indoor localization

Agent node m at $\mathbf{p}^{(m)} \in \mathbb{R}^2$ locates its position using multipath channel propagation to anchor m' at known position $\mathbf{p}^{(m')} \in \mathbb{R}^2$.

- Setup

Multipath assisted indoor localization

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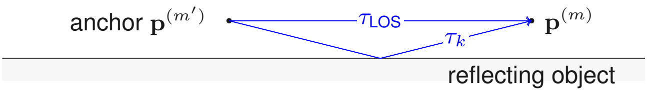
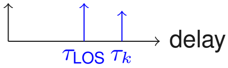


- Measurement: multipath components (MPC) contained in channel impulse response



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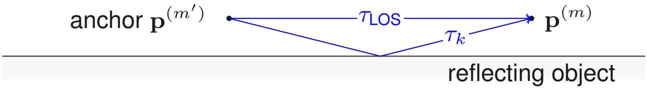

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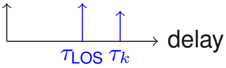


- Objective: estimate agent position $\mathbf{p}^{(m)}$ using MPCs $\tau_{\text{LOS}}, \tau_k$.

Multipath assisted indoor localization

Modeling of specular reflection τ_k

- (optical) ray model[1]
- neglect propagation effects like diffraction or penetration

Prominent solution for non-cooperative setup

- image source model[2]

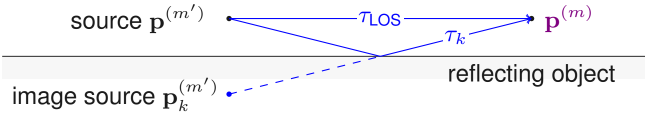
[1] Kuttruff: Room Acoustics. Elsevier. 1973

[2] J Kulmer, E Leitinger, P Meissner, S Hinteregger, K Witrisal: "Cooperative indoor localization using multipath channel information", ICL-GNSS 2016

Image source model

Modeling of specular reflection τ_k using image source model

- define anchor as *source*
- obtain *image sources* at reflective objects



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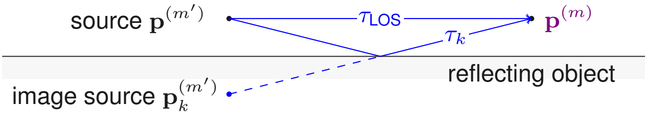

MPC delays result as geometric distances

- measurement model:

$$\tau_{\text{LOS}} = \|\mathbf{p}^{(m')} - \mathbf{p}^{(m)}\|/c$$

$$\tau_k = \|\mathbf{p}_k^{(m')} - \mathbf{p}^{(m)}\|/c$$

- estimate agent position $\mathbf{p}^{(m)}$ using τ_{LOS} and τ_k

Image source model

Limitations

- one node (source) needs to be static
  - appropriate for non-cooperative setup
  - in cooperative setup there is no static anchor
- dependencies among MPCs are not considered
  - single reflective object is bounced by several MPCs
  - impact of object parameters on MPC delays

[3] J Kulmer, E Leitinger, S Grebien, K Witrisal: "Anchorless cooperative tracking using multipath channel information", IEEE Transactions on Wireless Communications, 17 (4), 2018

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Proposal[3]: relate MPC delays to reflective objects rather than to static image sources

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Proposed geometry model

Incorporate parameters of reflective objects in measurement function

- image source model: MPCs are related to image sources

$$\tau_k = \|\mathbf{p}_k^{(m')} - \mathbf{p}^{(m)}\|/c$$

- proposal: relate MPCs to reflective objects

$$\tau_k = \|d\big(\mathbf{p}^{(m)}, \mathbf{p}^{(m')}, \{\text{reflective object parameters}\}\big)\|/c$$

Benefits

- single equation for each MPC
- consider mutual dependencies of MPCs

Proposed geometry model

Measurement function

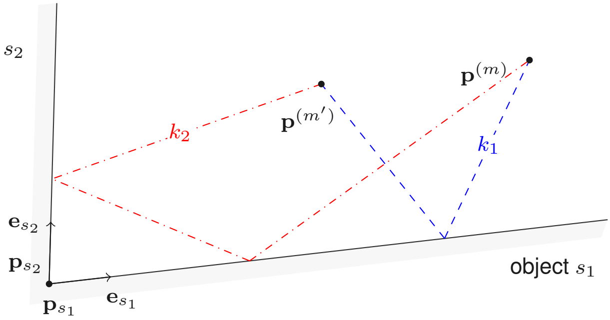
$$\tau_k = \|d\big(\mathbf{p}^{(m)}, \mathbf{p}^{(m')}, \{\text{reflective object parameters}\}\big)\|/c$$

Insights

- represent reflective objects by one point on its surface $\mathbf{p}_s$ and by its orientation $\mathbf{e}_s$
- $d\big(\mathbf{p}^{(m)}, \mathbf{p}^{(m')}, \{\mathbf{p}_s, \mathbf{e}_s\}\big)$
  - affine transformation of $\mathbf{p}^{(m)}$, $\mathbf{p}^{(m')}$ and $\{\mathbf{p}_s\}$
  - non-linear transformation of $\{\mathbf{e}_s\}$
- how are vectors $\mathbf{p}^{(m)}$, $\mathbf{p}^{(m')}$ and $\{\mathbf{p}_s\}$ affected by the measured scalars τ_{LOS} and τ_k?

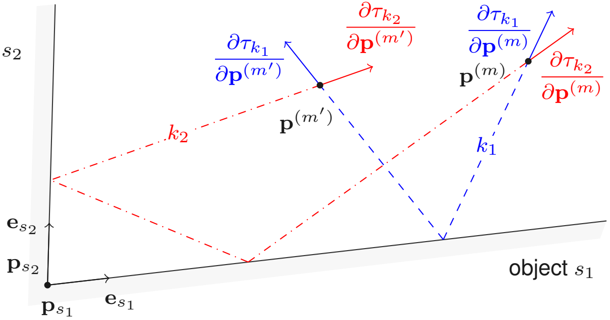
Covered information in MPCs

Illustration of single bounce k_1 and double bounce reflection k_2



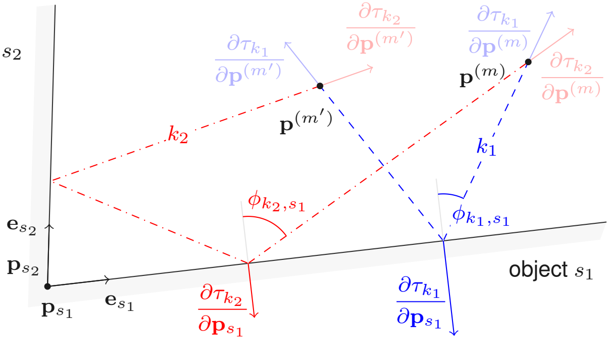
Covered information of agent positions

$$\|\partial\tau_k/\partial\mathbf{p}^{(m)}\| = \|\partial\tau_k/\mathbf{p}^{(m')}\| = 1/c$$



Covered information of reflective object locations

$$\|\partial\tau_k/\partial\mathbf{p}_s\| = -2\cos(\phi_{k,s})\mathring{\mathbf{e}}_s/c$$



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Insights

Contained information in MPCs regarding agent positions

- position information in direction of arriving / departing MPCs
- independent of arrangement of agents
- change of $|\Delta\tau| = 1$ translates to $\|\Delta\mathbf{p}^{(m)}\|/c = 1$

Information regarding locations of reflective objects

- obtained information perpendicular to object orientation
- arrangement of agents determines arriving angle
- change of $|\Delta\tau| = 1$ yields (up to) doubled sensitivity $\|\Delta\mathbf{p}_s\|/c = 2$

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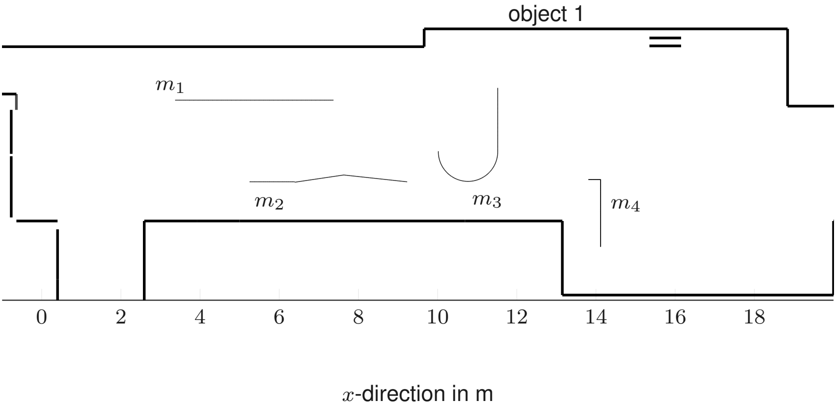
MPC delays are more sensitive to object locations than agent positions

Application

Employ proposed geometry model for multipath assisted indoor tracking using real data

Setup

- four cooperative agents $m_1 \dots m_4$ move on trajectories of $n \in \{1 \dots 200\}$ steps in a hallway
- at each step n, agents perform UWB measurements with an Ilmsense Channel Sounder
- bandwidth 1 GHz at center frequency of 7 GHz
- no information from an anchor node, position information entirely captured from MPCs



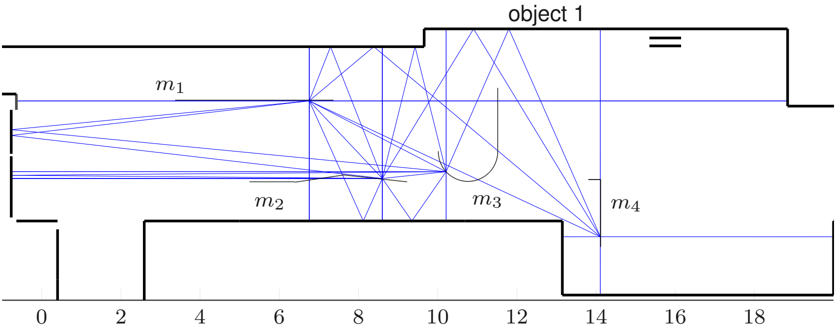
- consider objects with size $> 25\,\text{cm}$ (walls, windows, doors)

Application

Algorithm

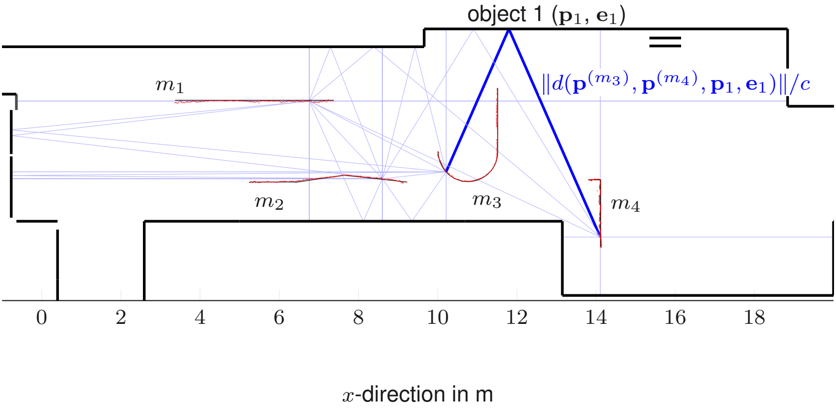
- estimation of MPC parameters $\{\tau_k^{(m',m)}\}$
- Kalman Filter to recursively update position estimates $\mathbf{p}_n^{(m_1)} \dots \mathbf{p}_n^{(m_4)}$ contained in state vector $\mathbf{x}_n$ using MPC delays $\{\tau_k\}$
  - linear motion model $\mathbf{x}_n = f(\mathbf{x}_{n-1}) +$ noise
  - measurement model

$$\begin{bmatrix} \tau_1^{(m_1,m_2)} \\ \tau_1^{(m_1,m_3)} \\ \dots \end{bmatrix} = \begin{bmatrix} \|d(\mathbf{p}_n^{(m_1)}, \mathbf{p}_n^{(m_2)}, \cdot, \cdot)\|/c \\ \|d(\mathbf{p}_n^{(m_1)}, \mathbf{p}_n^{(m_3)}, \cdot, \cdot)\|/c \\ \dots \end{bmatrix} + \text{noise}$$



x-direction in m

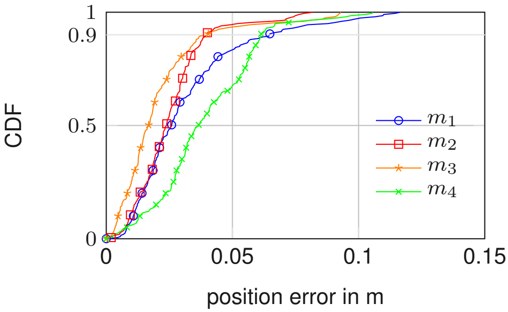
- multipath propagation at step $n = 30$ in blue



- illustration of gained information from specular reflection between m_3 and m_4

Application

Results



- position error in sub-meter range
- increased performance of m_2 and m_3

Summary

Summary

- revisit geometric multipath models for agent-to-agent channels
- analyzed impact of agent position and reflective object locations on multipath propagation
- utilized multipath model for tracking of cooperative agents without using information from anchors

Future work

- expansion of geometry model to point scatters and complex shapes
- investigations on impact of reflector orientation