Inter-Node Distance Estimation from Multipath Delay Differences of Channels to Observer Nodes

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**Standard Approach:**
Compute distance estimate \( \hat{d} \) given CIR \( h(\tau) \)

- **Received Signal Strength**
  - Poor accuracy (fluctuations)

- **Round-Trip Time of Arrival**
  - Complex hardware at both ends
  - Large relative error at short distance
  - Requires line of sight

- **Time Difference of Arrival**
  - Requires precise anchor sync.
  - Requires line of sight

(indirectly)
Wireless Distance Estimation: Proposed Paradigm

**Idea:** Compute a distance estimate $\hat{d}$ by comparing the wideband CIRs $h_A(\tau)$ and $h_B(\tau)$ to an observer node.

- Can this idea be realized? How to estimate $d$?
- Does the concept offer advantages to wireless localization?
Outline

Distance Estimation from Multipath Delays: Basic Principle

Estimation-Theoretic Properties

Performance in Realistic Conditions

Technological Advantages & Opportunities

Summary & Outlook
Channel Impulse Response: Shifts due to Local Displacement

Explanation videos are hosted at:


https://www.nari.ee.ethz.ch/wireless/research/downloads/ICC2019ConceptVideoDelayDiff.mp4

Channel Impulse Response:  
Shifts due to Local Displacement (Video Backup)
Distance Estimation from Multipath Delays: 
Basic Principle

Multipath components $k = 1 \ldots K$ extracted from both $h_A(\tau)$ and $h_B(\tau)$. Directions of arrival/departure are unknown. We consider the delay differences

$$\Delta_k = \tau_{B,k} - \tau_{A,k}.$$ 

Propagation at speed of light $c$ inflicts the bound

$$d \geq c \cdot |\Delta_k| \quad \forall k = 1 \ldots K.$$ 

For rich multipath from diverse directions, the largest $c \cdot |\Delta_k|$ will be close to $d$. This yields an estimation rule (synchronous case)

$$d \approx c \cdot \max_k |\Delta_k|.$$
Distance Estimation from Multipath Delays: Asynchronous Case

Without precise synchronization, the delay differences

\[ \tilde{\Delta}_k = \Delta_k + \epsilon \]

are observed subject to an unknown clock offset \( \epsilon \).

The \( \tilde{\Delta}_k \) are bounded by

\[ -d + c\epsilon \leq c\tilde{\Delta}_k \leq d + c\epsilon \]

and thus, for rich multipath,

\[ d + c\epsilon \approx c \cdot \max_k \tilde{\Delta}_k \]
\[ -d + c\epsilon \approx c \cdot \min_k \tilde{\Delta}_k \]

Addition and subtraction yield estimation rules (async. case)

\[ d \approx \frac{c}{2} \left( \max_k \tilde{\Delta}_k - \min_k \tilde{\Delta}_k \right) \]
\[ \epsilon \approx \frac{1}{2} \left( \max_k \tilde{\Delta}_k + \min_k \tilde{\Delta}_k \right) \]
Estimation-Theoretic Properties

Employed **assumptions:**

1. MPC **directions** have i.i.d. **uniform** distribution in 3D
2. Delays $\tau_{A,k}$ and $\tau_{B,k}$ can be **associated**
3. Delays $\tau_{A,k}$ and $\tau_{B,k}$ were extracted **without error**

<table>
<thead>
<tr>
<th></th>
<th>Synchronous</th>
<th>Asynchronous</th>
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</thead>
<tbody>
<tr>
<td>Maximum-Likelihood Estimate</td>
<td>$\hat{d}_{\text{ML}} = c \cdot \max_k</td>
<td>\Delta_k</td>
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<tr>
<td>Bias-Corrected (UMVUE)</td>
<td>$\hat{d} = \frac{K+1}{K} \hat{d}_{\text{ML}}$</td>
<td>$\hat{d} = \frac{K+1}{K-1} \hat{d}_{\text{ML}}$</td>
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<tr>
<td>RMSE of $\hat{d}$</td>
<td>$\approx d/K$</td>
<td>$\approx \sqrt{2} \cdot d/K$</td>
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Consider delay differences $T_k = \Delta_k + n_k$ observed with error $n_k$. Estimates that account for the error statistics are given by

**Sync. case:**

$$\hat{d}_{ML} \in \arg \max_d \frac{1}{dK} \prod_{k=1}^K I_k(T_k, d)$$

**Async. case:**

$$\left(\hat{d}_{ML}, \hat{\epsilon}_{ML}\right) \in \arg \max_{d, \epsilon} \frac{1}{dK} \prod_{k=1}^K I_k(\tilde{T}_k - \epsilon, d)$$

where $I_k(T_k, d) = F_{n_k}(T_k + \frac{d}{c}) - F_{n_k}(T_k - \frac{d}{c})$ is a soft version of indicator function $\mathbb{1}_{\left[-\frac{d}{c}, \frac{d}{c}\right]}(T_k)$ and $F_{n_k}$ is the CDF of $n_k$. 
Performance in Realistic Conditions: Ray-Tracing Study in an Indoor Environment

- Reflections at walls, floor, ceiling
- MPC detection criterion considers diffuse multipath and AWGN for 1 GHz bandwidth
Technological Advantages of the Scheme

- **Adding observers** is trouble-free and improves accuracy
- **Does not require line of sight**
- **Does not require precise time synchronization** ...
  ... between node A and B (although it helps)
  ... between an observer and node A or B
  ... between observers
- **Does not require knowledge of propagation environment**
- **Does not require knowledge of observer location**
  ➞ mobiles can be observers!
Application & Opportunities 1

Distance estimate to **low-power transmit-only beacon** → ranging or **regioning** (fingerprinting with live re-calibration)

Distance estimates to **multiple beacons** → estimate mobile position (**trilateration**)
Application & Opportunities 2

Conventional wireless localization: trilateration with $d$-estimates to anchors

Our scheme offers a novel way for inter-mobile distance estimation in an anchor setup, e.g. for cooperative localization.
Wireless **network** with unknown arrangement

Each mobile can serve as observer!

Use inter-user $d$ estimates to compute network arrangement (cooperative **network localization**)

1.)

2.)

3.)

... (repeat for all pairs)
Summary & Outlook

- We proposed a novel paradigm for distance estimation between two wireless nodes by comparing their CIRs to an observer node.
- We derived distance estimates from multipath delay shifts . . .
  . . . with/without precise time synchronization
  . . . with/without errors on the extracted delays
- The scheme offers great advantages and opportunities to wireless indoor localization.
- [open] Performance in practice?
- [open] Impact of MPC association problem?
- [open] Other ways to realize the paradigm?