AnguLoc: Concurrent Angle of Arrival Estimation for Indoor Localization with UWB Radios

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What is Indoor Localization?

• Finding location of people, things, and places *indoors*
• Market size: $18.74 billion by 2025*

Ultra-wideband (UWB) Radios

• “GPS at the scale of your living room” [Apple Inc.]
• Accurate (10 cm)
• Global market size of $58 million in 2019*
• At least 75 million units of iPhone 11 by the end of 2019**
• The UWB market is expected to grow significantly
  • iPhone 12
  • Android
  • UWB Alliance and FiRa Consortium
    NXP, Qorvo, Decawave, Bosch, Samsung, Hyundai

Wireless interference will be an issue

* https://www.absolutereports.com/global-ultra-wideband-market-15311454
UWB Interference

- Avoiding Interference
  - Time-division multiple access (TDMA)
  - ALOHA
  - Carrier sensing not feasible

- Mitigating Interference
  - Forward Error Correction (FEC)
  - Retransmissions

- Exploiting Interference
  - Concurrent Transmissions

Destructive interference prevents packet reception

Not Scalable

Not Efficient
Wireless Interference vs. Scalability and Efficiency

- Scalable and Efficient
  - Level of Interference:
    - Low
    - Medium
    - High

- Inefficient
  - Avoiding Interference
  - Mitigating Interference
  - Exploiting Interference

- Non-Scalable

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Sequential Localization - 1

Initiator \rightarrow A_1 \rightarrow A_2 \rightarrow \ldots \rightarrow A_n

One Request

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Sequential Localization - 2

Sequential Responses

Initiator

A1

A2

An

Request

Response 1

5 ms

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Sequential Localization - 3

Sequential Responses

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Sequential Localization - 4

Sequential Responses
Concurrent Localization - 1

One Request

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Concurrent Localization - 2

Concurrent Responses

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Concurrent Packets in IEEE 802.15.4 UWB PHY

We can only demodulate Data from the first arriving packet.
TX Scheduling Uncertainty

- In concurrent localization protocols: $t_{TX} = t_{RX} + \delta_{TX}$
- Difference between precision of $t_{TX}$ and $t_{RX}$
  - Causes inaccuracy in ToA estimation
  - Causes up to 2.4 m of localization error in DW1000
- State-of-the-art concurrent TDoA solutions
  - Wired correction: deployment issues
  - Wireless correction: additional packets, antenna delay calibration, 1-cycle lag
- Our solution (AnguLoc): Concurrent AoA
Concurrency-based Localization Solutions

<table>
<thead>
<tr>
<th>Related Work</th>
<th>Feasibility Study</th>
<th>Solution for TX Scheduling Uncertainty</th>
<th>Accuracy</th>
<th>Localization Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>TREK1000 (Sequential)</td>
<td>-</td>
<td>-</td>
<td>0.30 m</td>
<td>TWR(^1)</td>
</tr>
<tr>
<td>Corbalán [EWSN’18]</td>
<td>Concurrent TWR</td>
<td>×</td>
<td>~ 2 m</td>
<td>TWR</td>
</tr>
<tr>
<td>Corbalán [IPSN’19] Chorus</td>
<td>Concurrent TDoA(^2)</td>
<td>×</td>
<td>~ 1.2 m</td>
<td>TDoA</td>
</tr>
<tr>
<td>Großwindhager [IPSN’19] SnapLoc</td>
<td>Concurrent TDoA</td>
<td>Wired/Wireless Correction</td>
<td>~ 1.2 m (without correction)(^5)</td>
<td>TDoA</td>
</tr>
<tr>
<td>Heydariaan [DCOSS’19]</td>
<td>×</td>
<td>×</td>
<td>~ 2 m</td>
<td>TWR</td>
</tr>
<tr>
<td>Heydariaan [DCOSS’20] AnguLoc</td>
<td>Concurrent AoA(^3)</td>
<td>Immune Against TX Scheduling Uncertainty</td>
<td>0.67 m</td>
<td>ADoA(^4)</td>
</tr>
</tbody>
</table>

\(^1\) TWR: Two-Way Ranging
\(^2\) TDoA: Time Difference of Arrival
\(^3\) AoA: Angle of Arrival
\(^4\) ADoA: Angle Difference of Arrival
\(^5\) Authors said they achieved better results with wired/wireless corrections
Concurrent Angle of Arrival Localization – Challenges and Opportunities

• Opportunities
  • Concurrent AoA is more accurate than concurrent TDoA
    Concurrent AoA is not affected by TX scheduling uncertainty
  • Self-localization is highly scalable
    An unlimited number of tags

• Challenges
  • Front-back ambiguity of angle measurements
  • Unknown tag tilting

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Contributions

• Feasibility of concurrent AoA

• Angle difference of arrival algorithm overcomes
  • Front-back ambiguity of angle measurements
  • Unknown tag tilting

• Increasing accuracy of concurrency-based localization
Angle of Arrival Using Phase Difference of Arrival

\[ p = d \sin \theta \]

\[ \lambda = \frac{2\pi}{f} \]

\[ \alpha = \frac{2\pi}{\lambda} \quad p = \frac{f}{c} \quad p \]

\[ \theta = \sin^{-1} \frac{\alpha \lambda}{2\pi d} \]

We calculate \( \alpha \) by calculating phase for first path in CIR.

Angle of Arrival with two receivers running on the same crystal oscillator (Xtal).
Angle of Arrival Hardware

Decawave PDoA node (DWM1002)
Concurrent Angle of Arrival

- AoA is $\theta = \sin^{-1} \frac{\alpha \lambda}{2\pi d}$
- $\lambda$ is the wavelength
- $d$ is the distance between antennas
- $\alpha$ is the difference in phase between two antennas calculated at each responder’s first path

We can calculate phase information by detecting first path of each responder.
Concurrent Self-Localization Protocol

\[\text{Diagram of nodes and connections} \]

A\textsubscript{1} – A\textsubscript{2} – A\textsubscript{3} – A\textsubscript{4} – T\textsubscript{1} – T\textsubscript{2} – T\textsubscript{3} – T\textsubscript{4} – T\textsubscript{5} – T\textsubscript{6} – A\textsubscript{REF}
Concurrent Self-Localization Protocol

1. $A_{\text{REF}}$ broadcasts SYNC
Concurrent Self-Localization Protocol

1. $A_{\text{REF}}$ broadcasts SYNC
2. $A_i$’s reply concurrently
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1. $A_{REF}$ broadcasts SYNC
2. $A_i$’s reply concurrently
3. Tags ($T_1$ through $T_6$) receive all replies and measure AoA concurrently
Evaluation of Concurrent AoA

- Sequential AoA as baseline
- Ideally should have similar accuracy
Concurrent AoA Experimental Setup

We change angle of one responder when the other one is static. Dipole antenna performance expected to degrade near extreme angles.

We change distance of one responder when the other one is static. C-AoA performance expected to degrade at longer distances.
Performance of Concurrent AoA for 2 anchors

Concurrency does not significantly affect AoA estimation in different angles (100 measurements per data point).

Concurrency only affects AoA estimation in longer distances (100 measurements per data point).
Concurrency does not significantly affect AoA estimation when adding more anchors showing 100 measurements per box plot. Number of receiver tags are still unlimited.
2D Self-Localization with Angle Difference of Arrival
Angle difference between 1 pair of anchors. Possible locations are shown with 2 curves. Infinite possible locations.
2D Self-Localization with Angle Difference of Arrival

Angle difference between 2 pairs of anchors. Possible locations are shown with 4 curves. 2 possible locations.
2D Self-Localization with Angle Difference of Arrival

Angle difference between 3 pairs of anchors. Possible locations are shown with 6 curves. 1 possible location.
2D Self-Localization with Angle Difference of Arrival

\[ J(x, y) = \sum_{j>i} (\theta_{i,j} - \hat{\theta}_{i,j})^2 \]

\[ \hat{T} = \arg \min_{x,y} J(x, y) \]

Angle difference between 3 pairs of anchors. Possible locations are shown with 6 curves. 1 possible location.
ADoA Challenges – Front-back Ambiguity

\[ \theta_{1,2} = \theta_1 + \theta_2 \]

\[ \theta_{1,2} = |\theta_1 - \theta_2| \]
ADoA Challenges – Unknown Tilting

6 cases for tags inside the room in a 4-anchor setting. We run 6 optimizations and choose the answer with the least residual error.
Performance of ADoA-based Algorithm

CDF of localization error, simulated for different noise levels. Sub-meter accuracy for noise level below 5°

CDF of localization error, comparing AnguLoc with CTDoA in 2 experiments
- Static with 3000 points: 44.33% improvement
- Mobile with 200 points: 21.46% improvement
Conclusions and Discussion

• Scalability
  • Anchors: Up to 5 nodes. We can make multiple groups of concurrent nodes
  • Tags: Unlimited

• Efficiency: At least 4 times faster than than sequential AoA

• Accuracy (compared to CTDDoA)
  • 44.33% improvement for static nodes
  • 21.46% improvement for mobile nodes

• Limitations
  • Larger errors on the sides of dipole antennas
  • Larger errors in longer distances (lower SNR)

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Backup Slides
Benefits of UWB Radios

- Accurate (10 cm)
- Long range (290 m)
- Low power consumption
- Potential for use in indoor and outdoor applications
  - 3D localization
  - Construction zone safety
  - Mars exploration
# UWB Use Cases

<table>
<thead>
<tr>
<th>Hands-Free Access Control</th>
<th>Location-Based Services</th>
<th>Device-to-Device (Peer-to-Peer) Applications</th>
</tr>
</thead>
</table>
| • Residential access control  
  • Restricted enterprise access | • Employee mustering in emergencies  
  • Bike sharing | • Conference systems  
  • Drone-controlled delivery  
  • V2X*, autonomous driving |
| Smart Home and Enterprises | Smart Cities and Mobility | Smart Transportation |
| | • Parking garage  
  • Vehicle digital key (standardized by CCC) | • Rider identification (private transport services) |
| Consumer | Smart Retail | Industry 4.0 and Healthcare |
| | • Logical access control | • Unmanned store access  
  • Barrier-free and restricted access control |
| | | • Indoor navigation  
  • Foot traffic and shopping behavior analytics  
  • Asset tracking  
  • Patient tracking |

*Connected Vehicle-to-Everything Communication

[https://www.firaconsortium.org/discover/use-cases](https://www.firaconsortium.org/discover/use-cases)
## Localization Technologies

<table>
<thead>
<tr>
<th>TECHNOLOGY</th>
<th>WHERE USED</th>
<th>ACCURACY</th>
<th>RELIABILITY</th>
<th>RANGE / COVERAGE</th>
<th>DATA COMMUNICATIONS</th>
<th>SECURITY (PHY LAYER)</th>
<th>LATENCY</th>
<th>SCALABILITY DENSITY</th>
<th>POWER &amp; BATTERY</th>
<th>TOTAL COST</th>
</tr>
</thead>
<tbody>
<tr>
<td>Decawave LWB</td>
<td>Indoor, Outdoor</td>
<td>1-5 meters</td>
<td>Strong immunity to multipath, obstructions and interference</td>
<td>Typical 50m, Max 200m per anchor</td>
<td>Up to 27Mbps</td>
<td>Can be spoofed using relay attack</td>
<td>Typ. 4ms to get #1</td>
<td>Unlimited</td>
<td>2xAA-3V, 3kB RX, Coin Cell</td>
<td>$3</td>
</tr>
<tr>
<td>Bluetooth</td>
<td>Indoor, Outdoor</td>
<td>1-5 meters</td>
<td>Very sensitive to multipath, obstructions and interference</td>
<td>Typical 25m, per beacon (for 2m accuracy)</td>
<td>Up to 2Mbps</td>
<td>Can be spoofed using relay attack</td>
<td>Typ. 4ms to get #1</td>
<td>Unlimited</td>
<td>2xAA-3V, 3kB RX, Coin Cell</td>
<td>$3</td>
</tr>
<tr>
<td>Wi-Fi</td>
<td>Indoor, Outdoor</td>
<td>5-15 meters</td>
<td>Very sensitive to multipath, obstructions and interference</td>
<td>Typical 100m, per access point (for 1m accuracy)</td>
<td>Up to 1Gbps</td>
<td>Can be spoofed using relay attack</td>
<td>Typ. 10ms to get #1</td>
<td>Unlimited</td>
<td>2xAA-3V, 3kB RX, Lithium Battery</td>
<td>$5-$6</td>
</tr>
<tr>
<td>RFID</td>
<td>Indoor, Outdoor</td>
<td>2-20 meters</td>
<td>Very sensitive to obstructions</td>
<td>Typical 1m, Max 5m per reader</td>
<td>N/A</td>
<td></td>
<td></td>
<td>Unlimited</td>
<td>Non-rechargeable</td>
<td>$5-$6</td>
</tr>
<tr>
<td>GPS</td>
<td>Indoor, Outdoor</td>
<td>3-20 meters</td>
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</tbody>
</table>

[https://www.decawave.com/technology1/](https://www.decawave.com/technology1/)
ALOHA and TDMA in UWB-based Localization

• ALOHA
  4 tags up to 4 packets per second each (total of 16 per second)

• TDMA
  8 tags with 10 packets per second each (total of 80 per second)
  7 anchors with total of 12 packets per second
Concurrent Window and Clock Drift

Concurrent window. The time window for multiple responses to arrive concurrently. For DW1000, theoretically 1016 ns.

Longer response delay moves the responder peak due to larger clock skew.
23 ms additional delay causes clock skew of 40 ns.

Large clock skew can break concurrency
Time-based AoA Estimation Using DW1000

• Path difference: \( p = d \times \sin \theta \)
• Goal: Precision of 5°
• With one radio using CIR
  • Resolution of 1001.6 \( ps \) or 0.30048 \( m \)
  • Antenna separation: \( d = \frac{0.30048}{\sin 5^\circ} = 3.497 \ m \)
• With two radios using ToA
  • Resolution of 15.6 \( ps \) or 0.00469 \( m \) \( \rightarrow \) \( d = \frac{0.00469}{\sin 5^\circ} = 0.053 \ m \)
  • Precision of 333.3 \( ps \) or 0.1 \( m \) \( \rightarrow \) \( d = \frac{0.1}{\sin 5^\circ} = 1.147 \ m \)
Response Position Modulation

- $t_{TX} = t_{RX} + \delta_{TX} + \delta_i$
- $\delta_i = 128 \times (i - 1)$
- $i = \text{node id}$

Concurrent responses separated by 128 ns
Search and Subtract (SS) Algorithm

1. Divide CIR into multiple chunks of 128 ns
2. Upsample each chunk using FFT with upsampling factor of L=30
3. Normalize upsampled CIR chunk
4. Cross-correlate each chunk with a signal template and output the index with maximum correlation
5. Consider the index as a peak if value exceeds a noise threshold of $\eta = 12 \times \sigma_{noise}$
Concurrent AoA Algorithm

Algorithm 1 Concurrent AoA Estimation

Input: \( \text{MaxNumResponses}, CIR_1[], CIR_2[] \)

Output: \( \text{AoA}[] \)

\[ N \leftarrow \text{MaxNumResponses} \]

\[ \text{Peaks}[1 \ldots N][1] \leftarrow \text{FindPeaks}(N, CIR_1[]) \]

\[ \text{Peaks}[1 \ldots N][2] \leftarrow \text{FindPeaks}(N, CIR_2[]) \]

for \( i \leftarrow 1 \) to \( N \) do

\[ \text{AoA}[i] \leftarrow \text{CalcAoA}(\text{Peaks}[i][1, 2], CIR_1[], CIR_2[]) \]

end for
Localization with Angle Difference of Arrival

\[ \theta_{i,j} = \cos^{-1} \frac{TA_i \cdot TA_j}{|TA_i \cdot TA_j|} \]

\[ = \cos^{-1} \frac{(x - x_i)(x - x_j) + (y - y_i)(y - y_j)}{\sqrt{((x - x_i)^2 + (y - y_i)^2)( (x - x_j)^2 + (y - y_j)^2 )}} \]

\[ J(x, y) = \sum_{j > i} (\theta_{i,j} - \hat{\theta}_{i,j})^2 \]

\[ \hat{T} = \arg\min_{x,y} J(x, y) \]