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

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What is Indoor Localization?

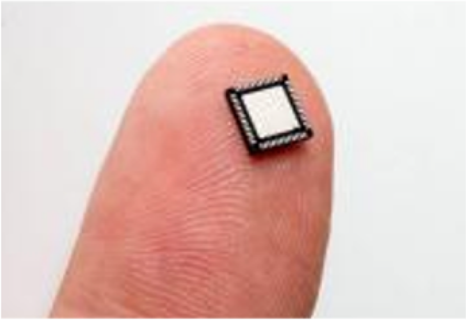
- Finding location of people, things, and places ***indoors***
- Market size: $18.74 billion by 2025*

Navigation

Tracking

* https://www.reportlinker.com/p05763837/Indoor-Location-based-Services-Market-Analysis-Report-By-Product-By-Technology-By-Application-By-End-Use-And-Segment-Forecasts.html

Ultra-wideband (UWB) Radios



Decawave DW1000 chip

- "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

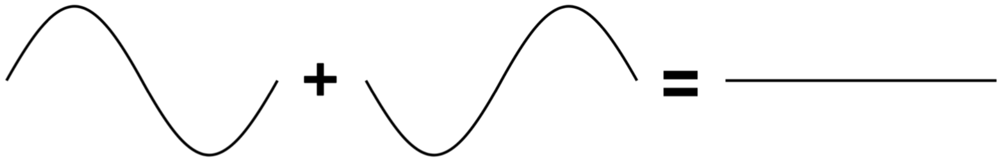
    NXP, Qorvo, Decawave, Bosch, Samsung, Hyundai

Wireless interference will be an issue

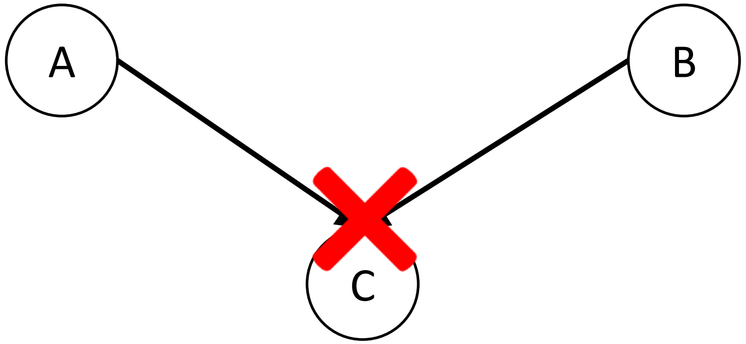
* https://www.absolutereports.com/global-ultra-wideband-market-15311454

** https://www.bloomberg.com/news/articles/2019-10-14/apple-s-lower-prices-users-aging-handsets-drive-iphone-demand

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

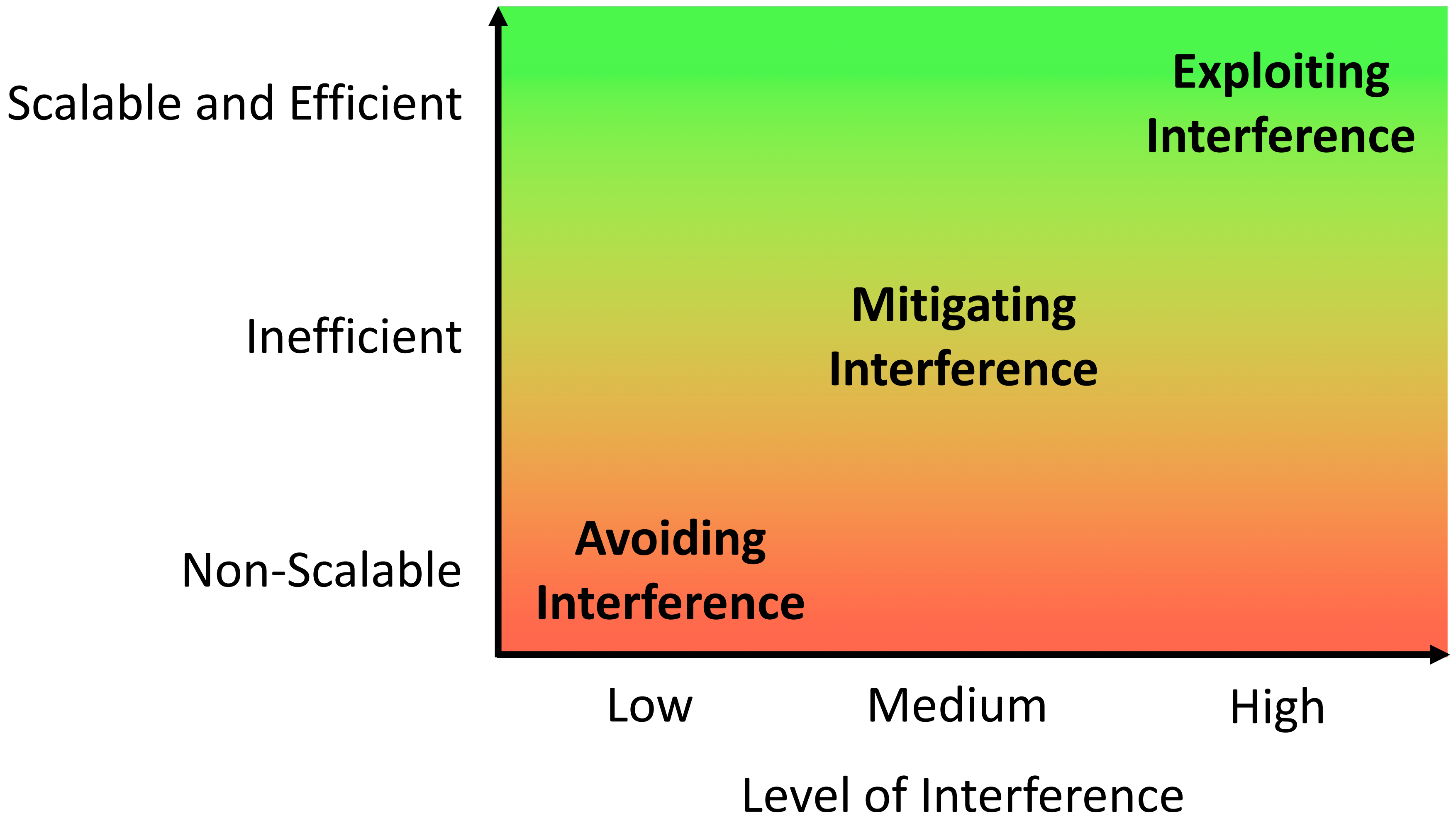


Destructive interference prevents packet reception

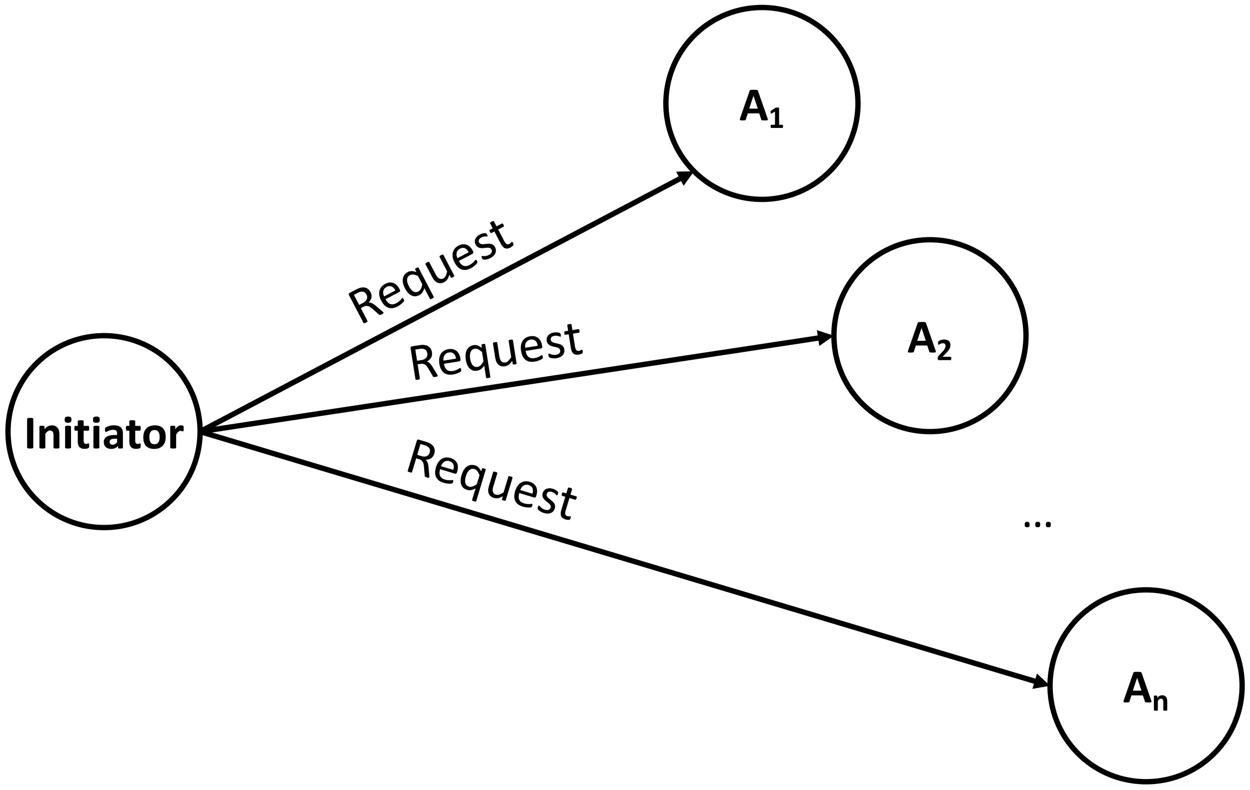
Not Scalable

Not Efficient

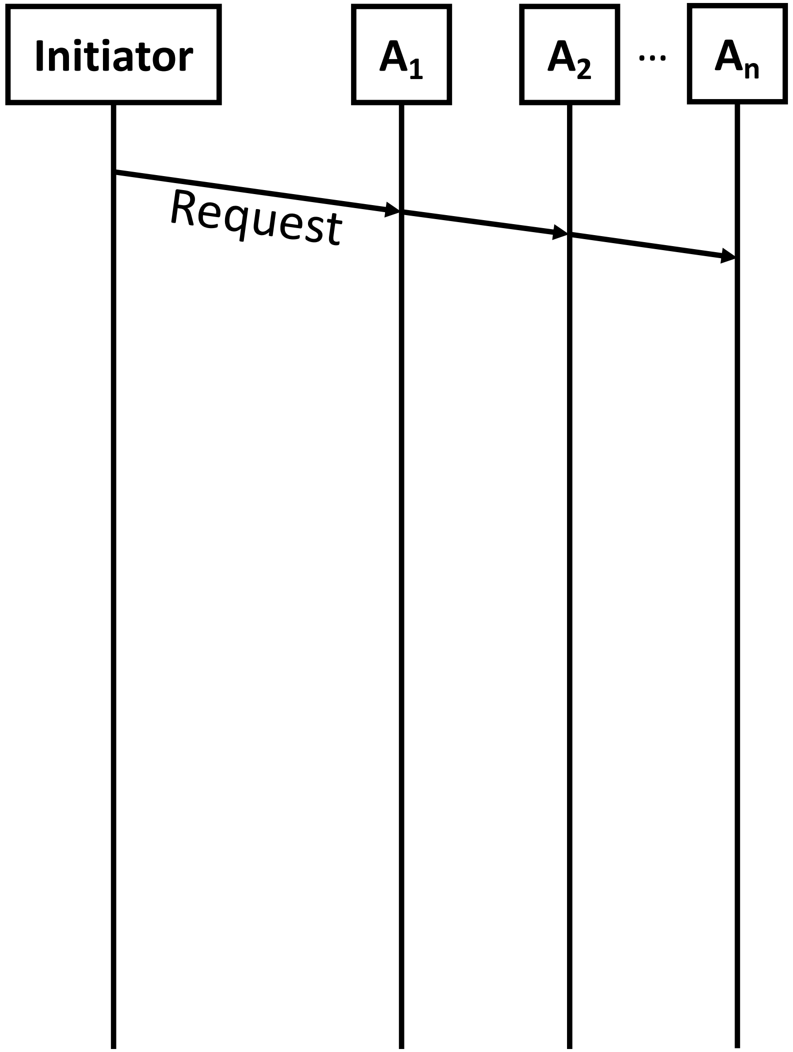
Wireless Interference vs. Scalability and Efficiency



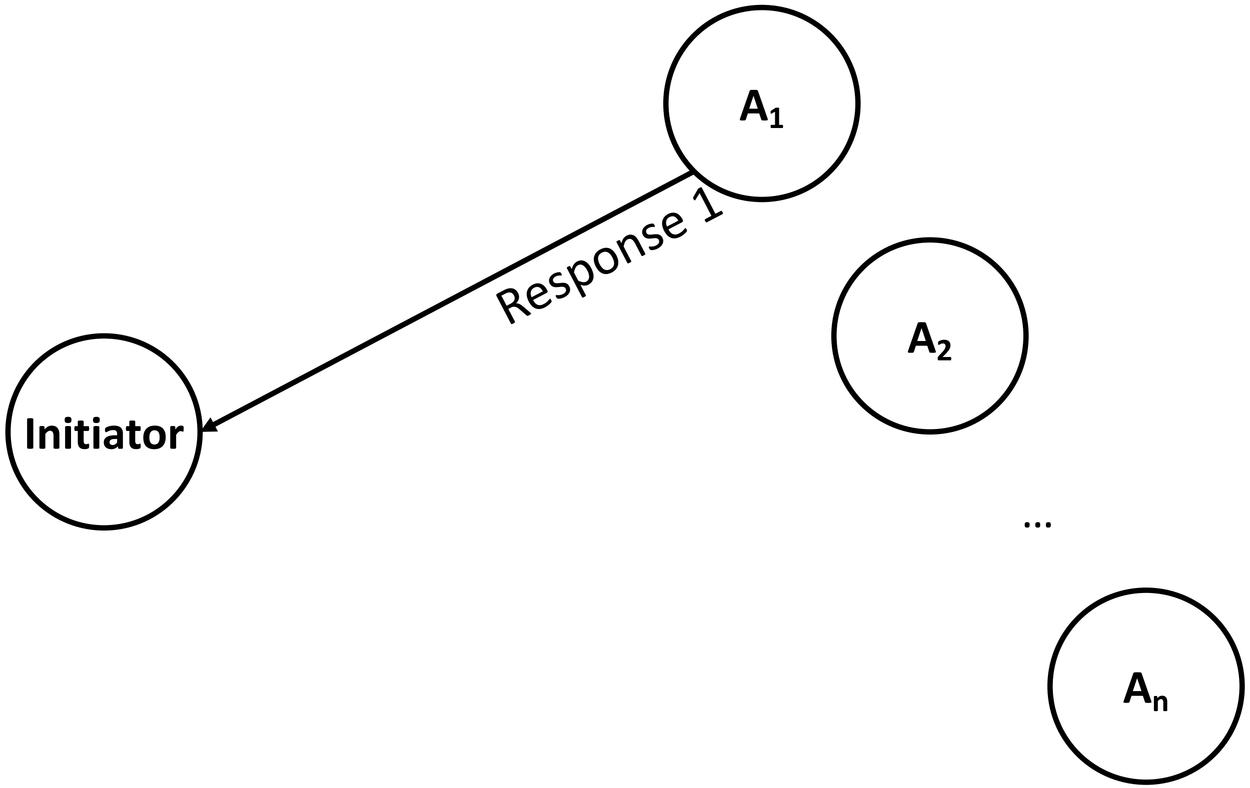
Sequential Localization - 1



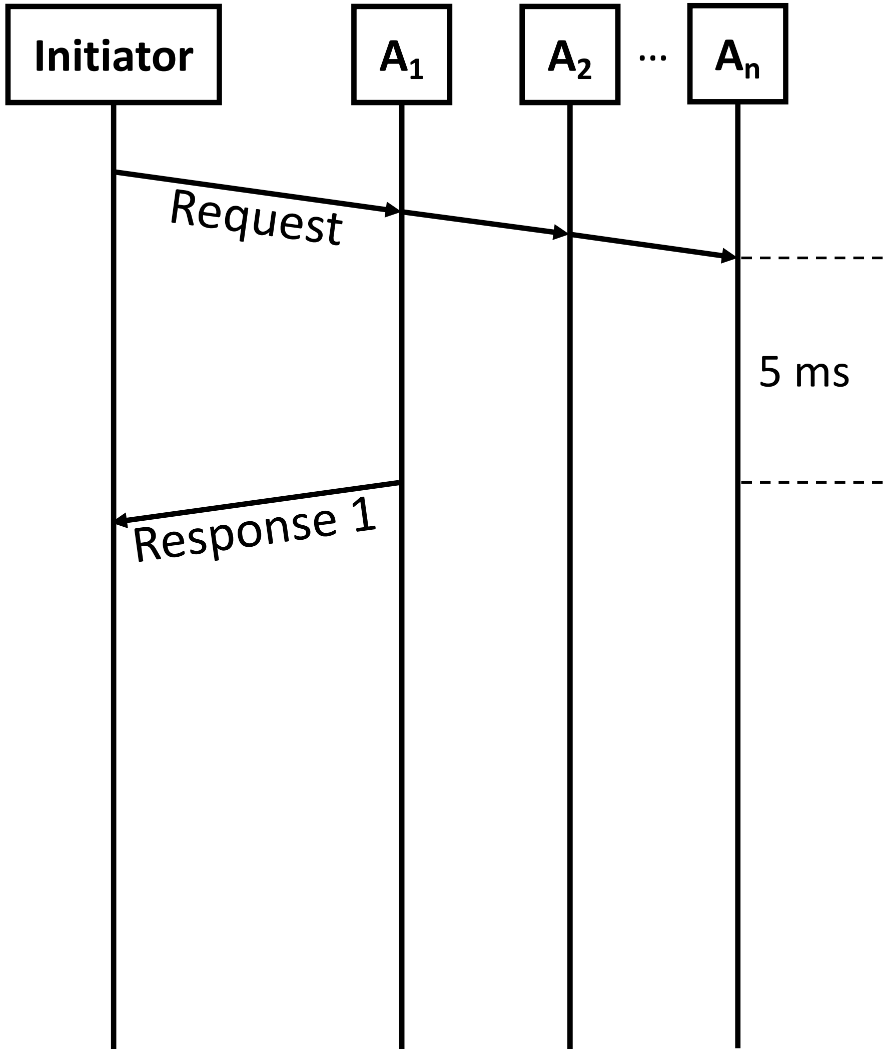
One Request



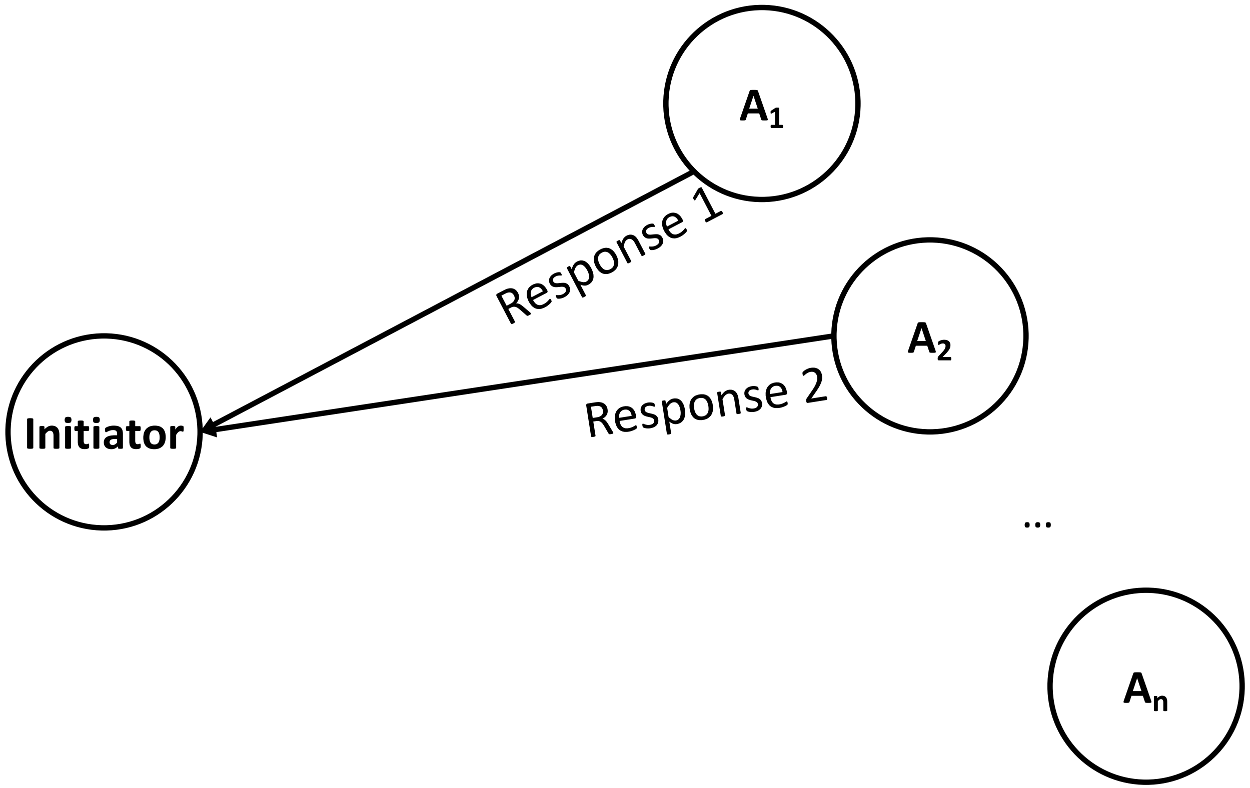
Sequential Localization - 2



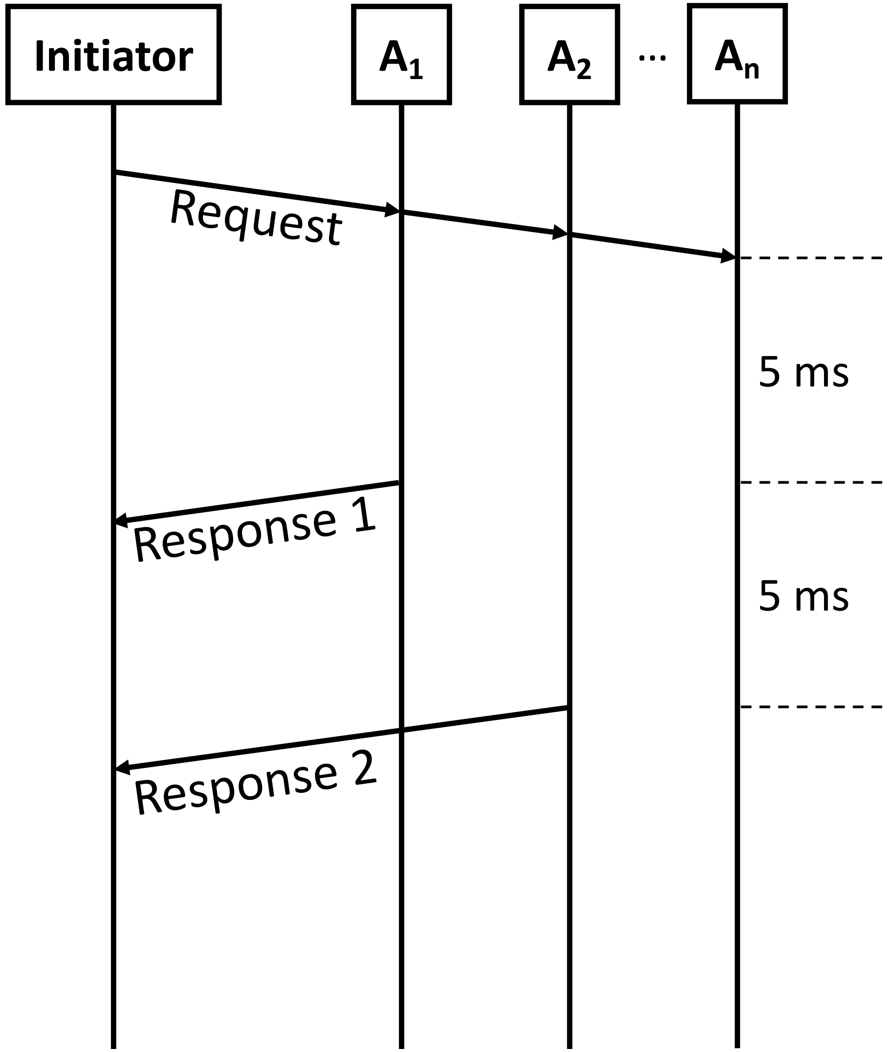
Sequential Responses



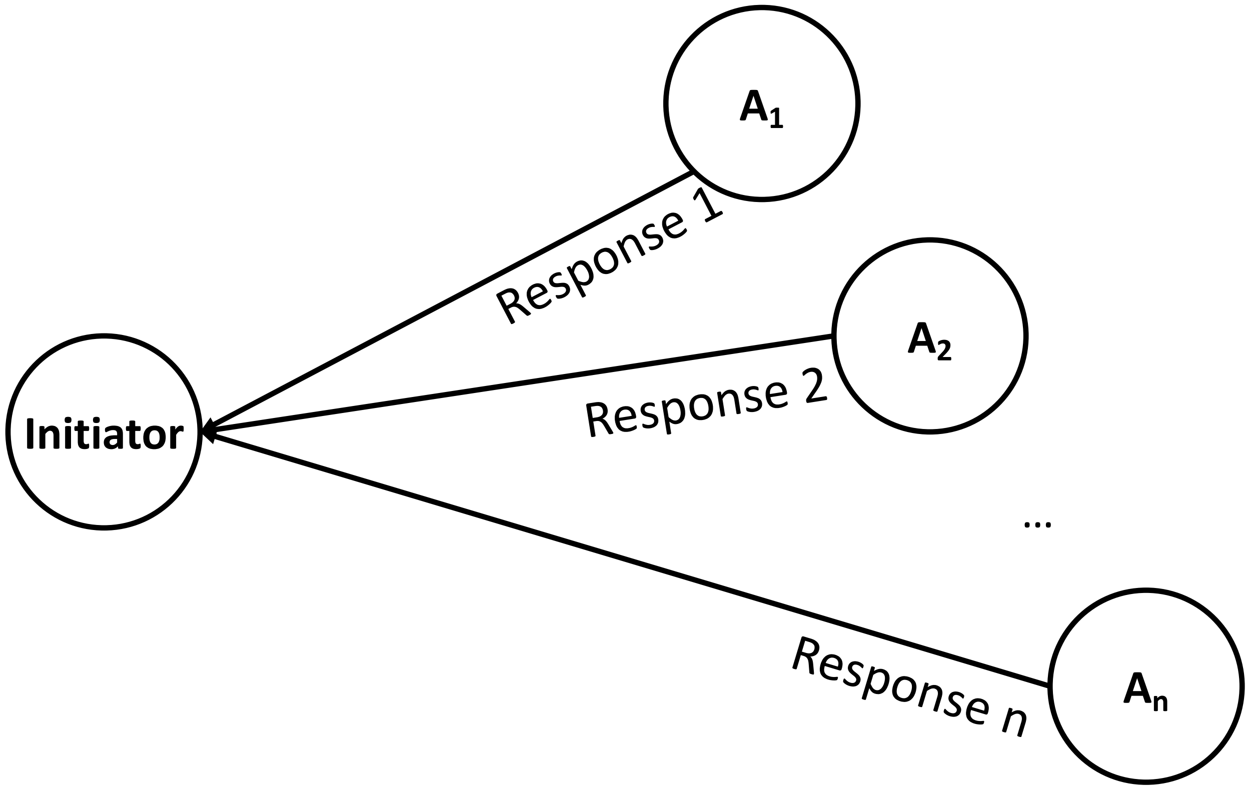
Sequential Localization - 3



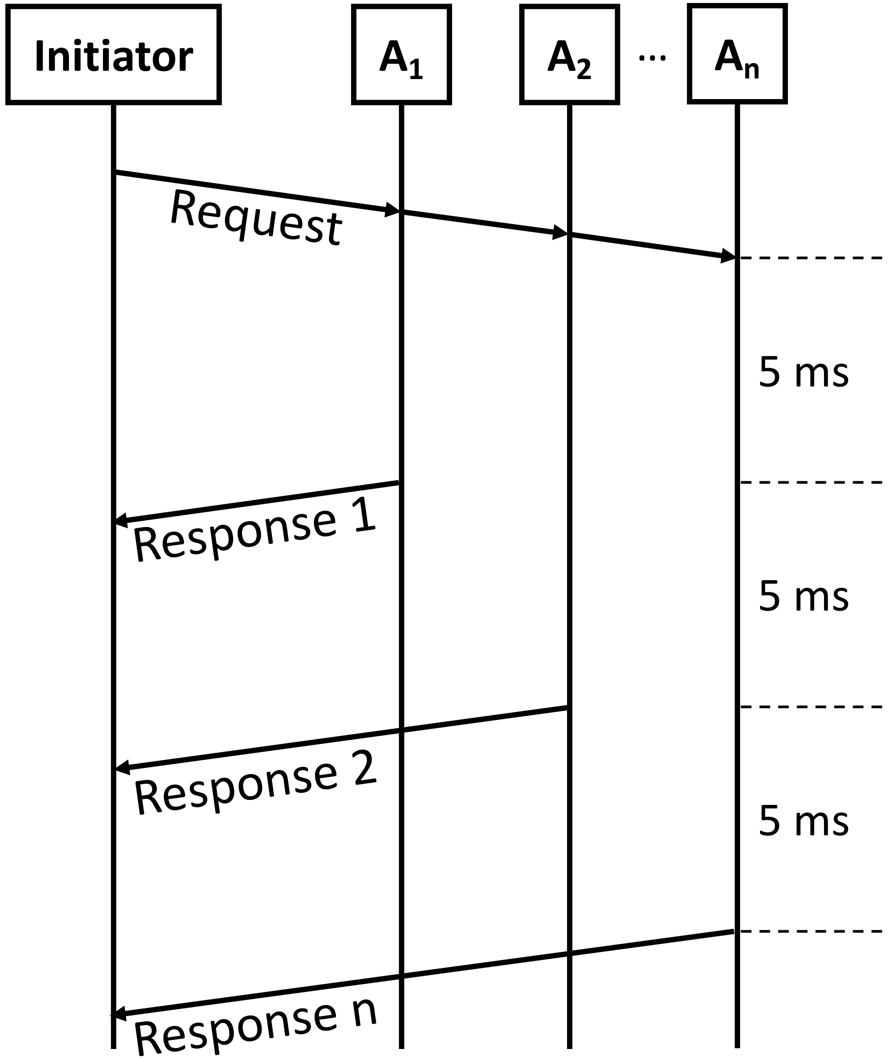
Sequential Responses



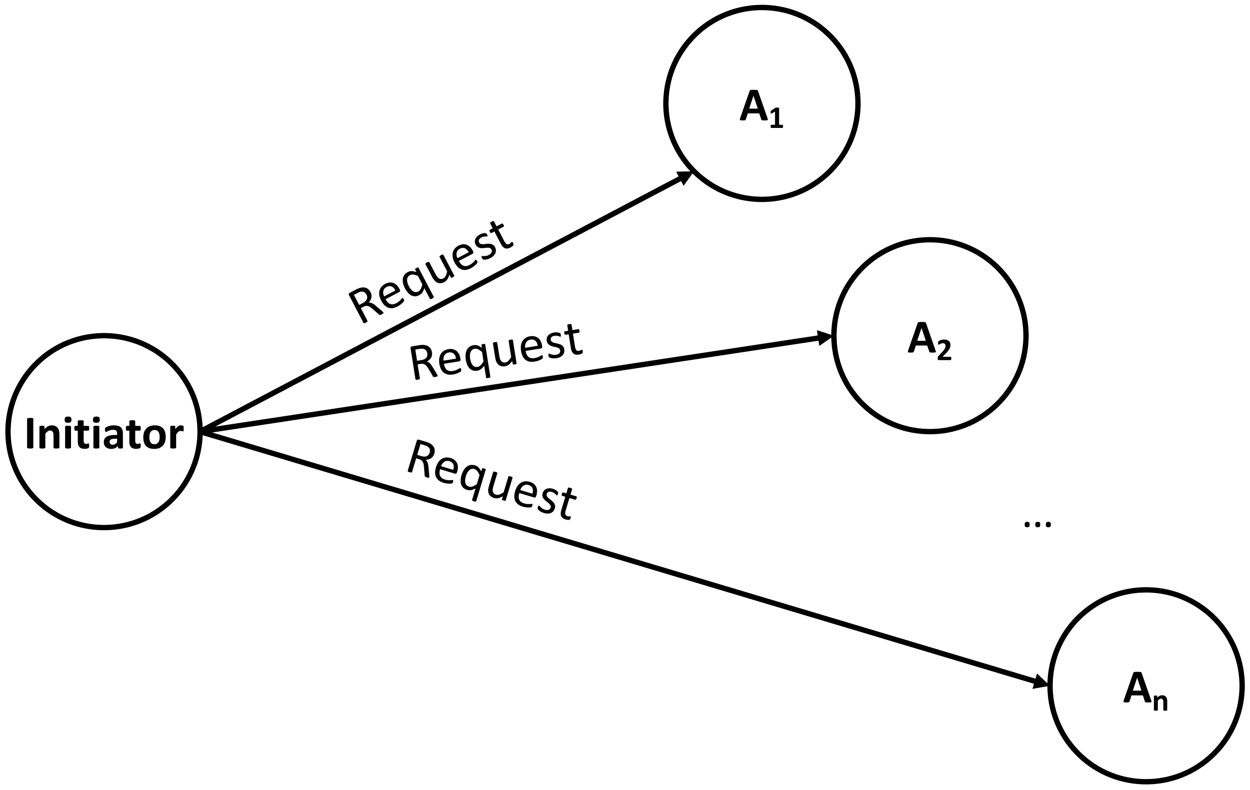
Sequential Localization - 4



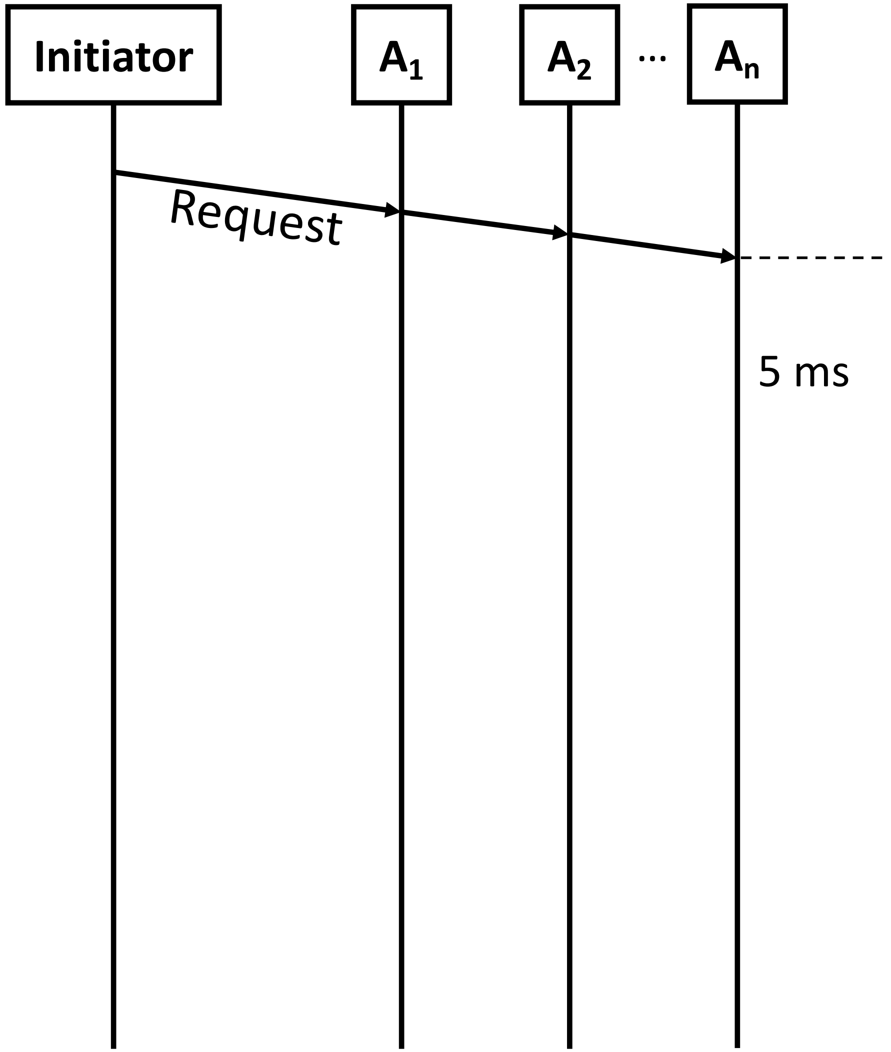
Sequential Responses



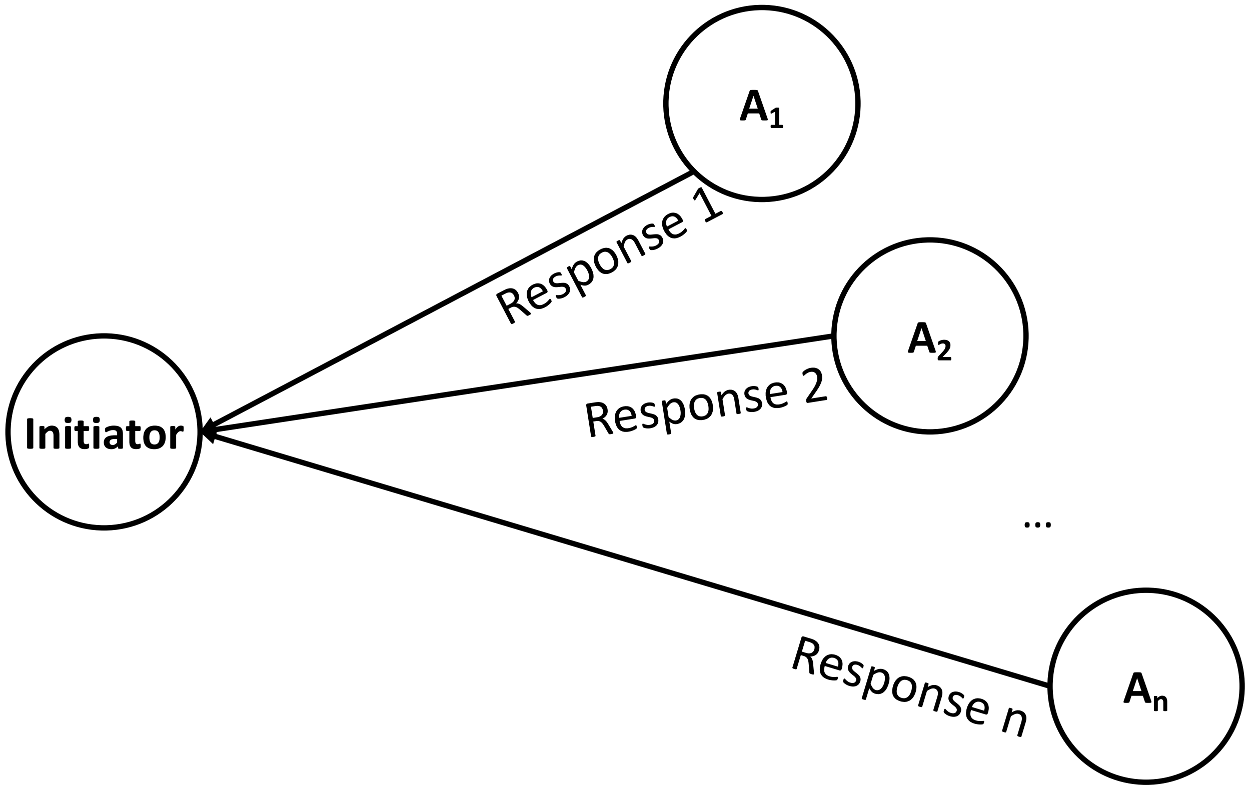
Concurrent Localization - 1



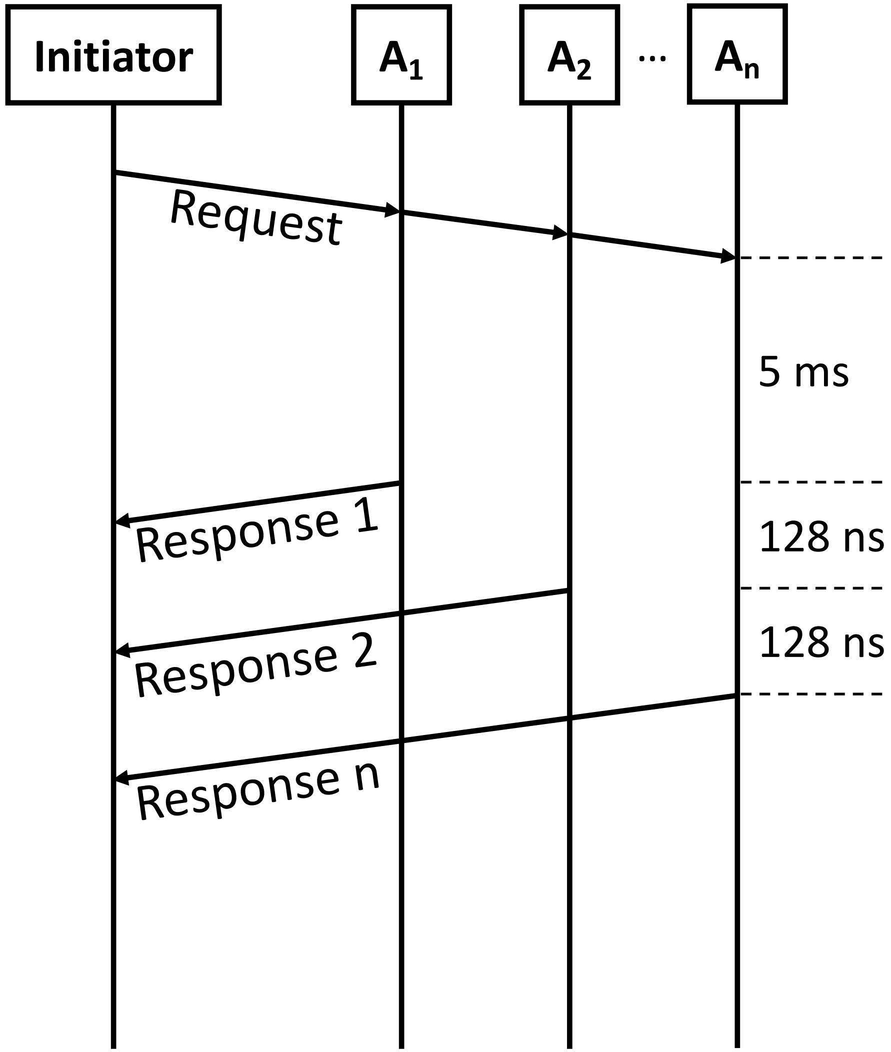
One Request



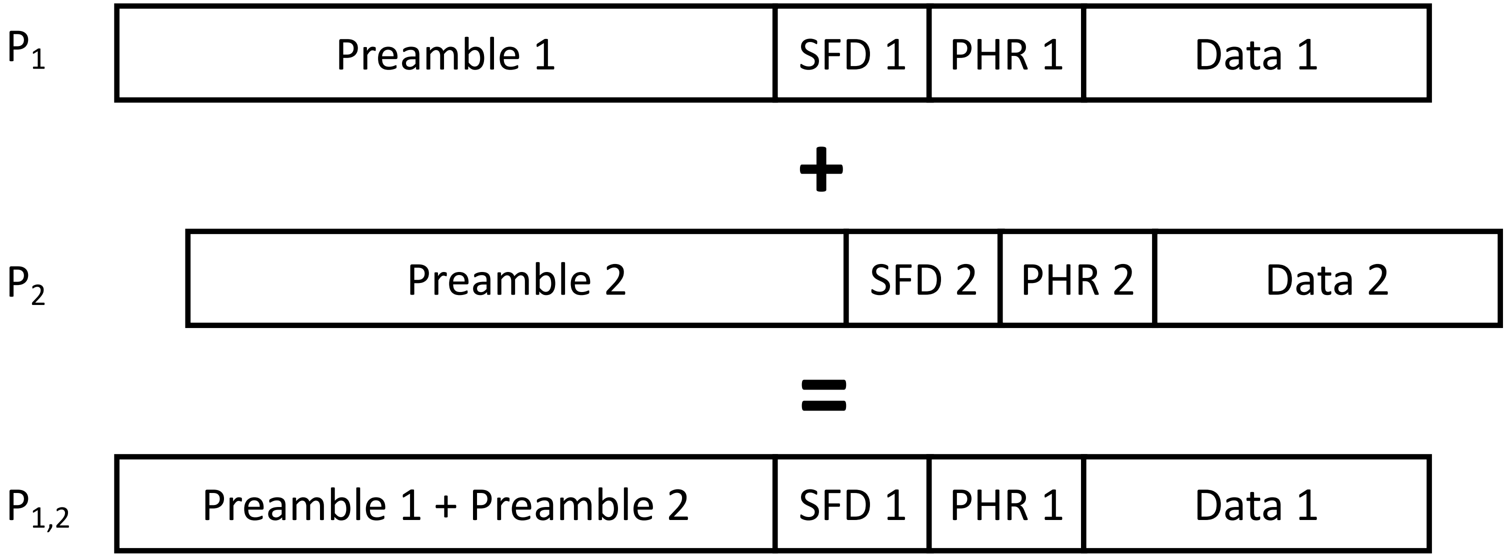
Concurrent Localization - 2



Concurrent Responses

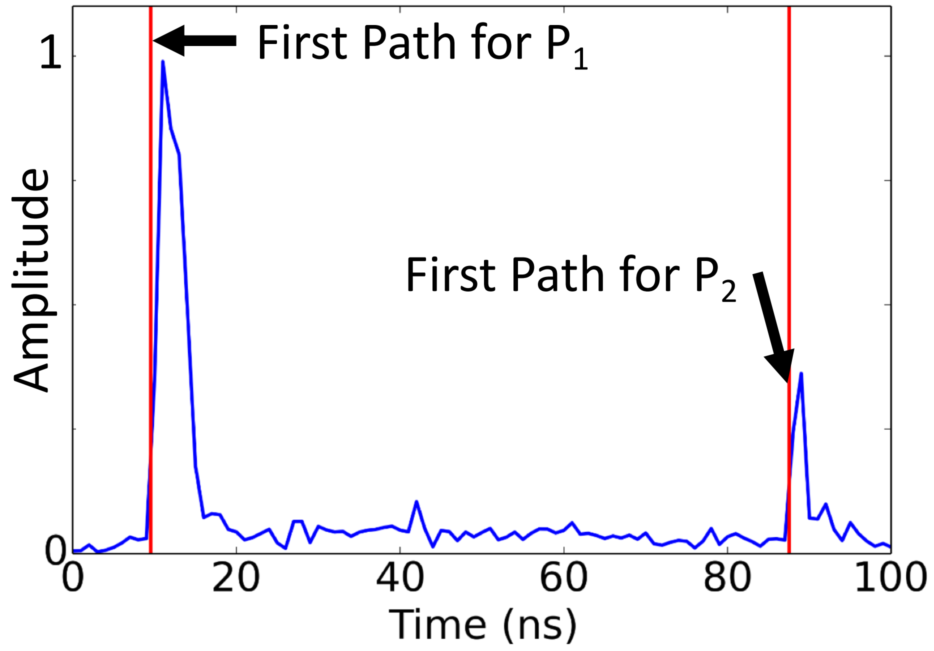


Concurrent Packets in IEEE 802.15.4 UWB PHY



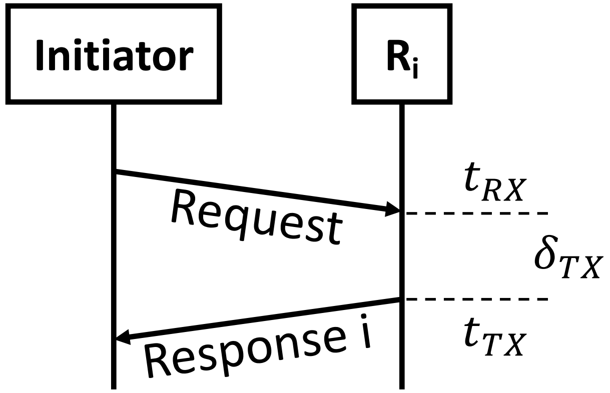
$P_{1,2} = P_1 + P_2$

We can only demodulate Data from the first arriving packet



We can observe combined preamble in channel impulse response (CIR)

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

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

[1] TWR: Two-Way Ranging
[2] TDoA: Time Difference of Arrival
[3] AoA: Angle of Arrival
[4] ADoA: Angle Difference of Arrival

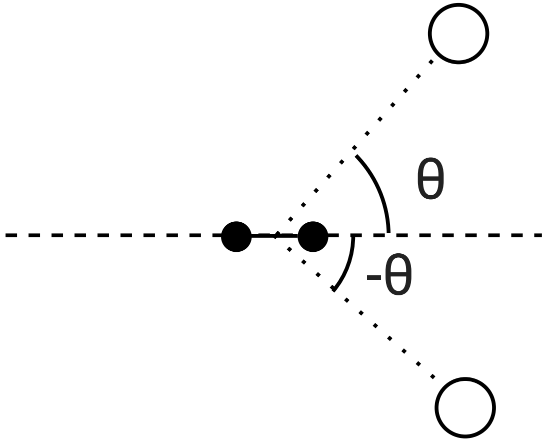
[5] Authors said they achieved better results with wired/wireless corrections

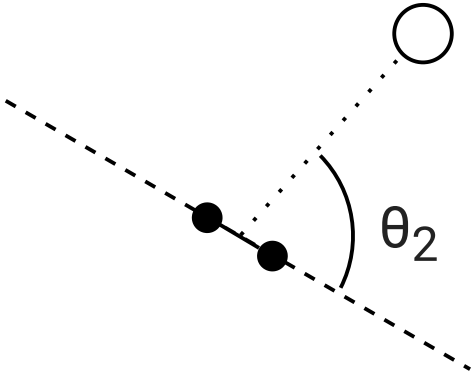
Concurrent Angle of Arrival Localization – Challenges and Opportunities

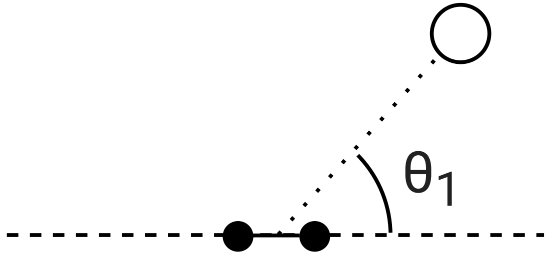
- Opportunities
  - Concurrent AoA is more accurate than concurrent TDoA

    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



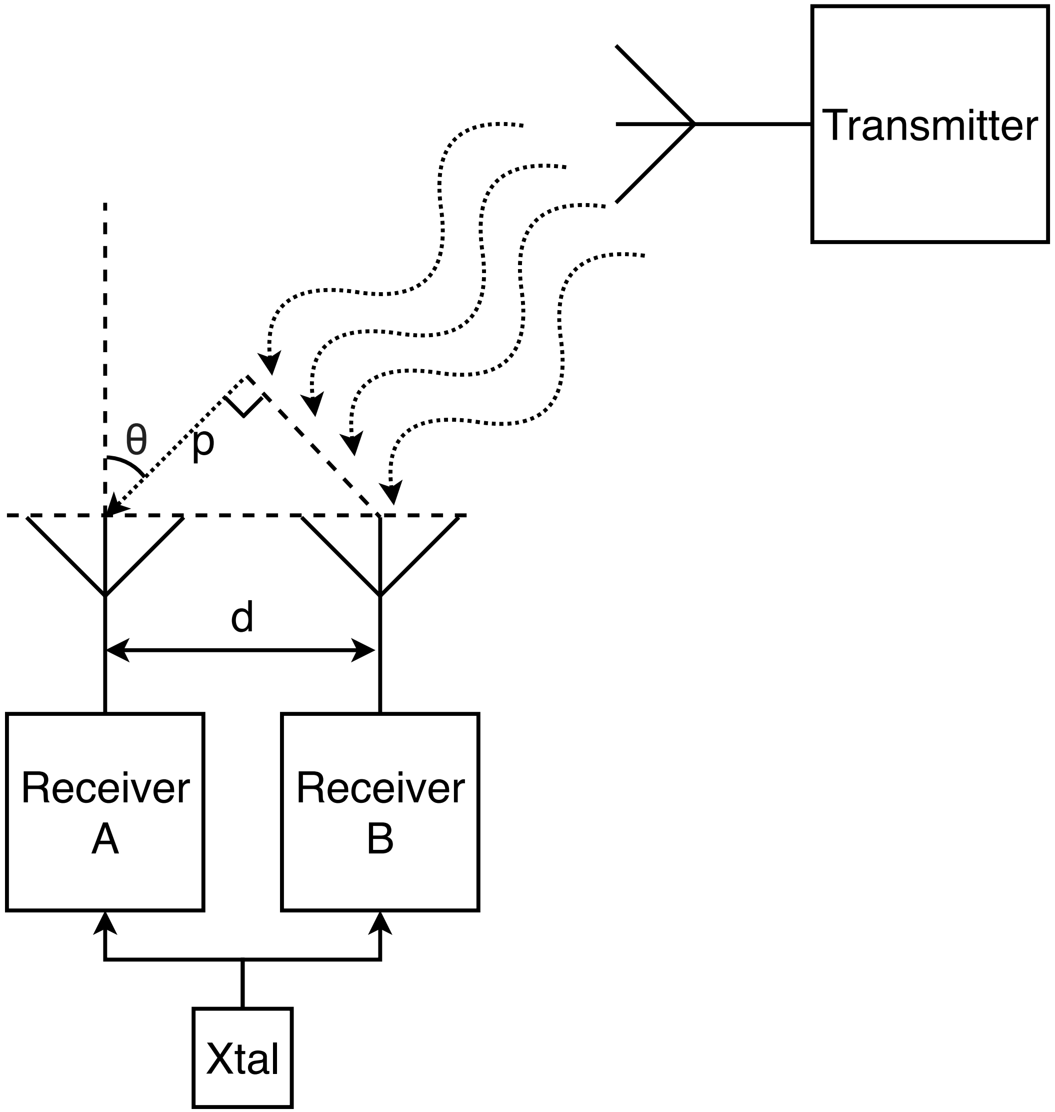




Contributions

- 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



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

$$p = d \sin\theta$$

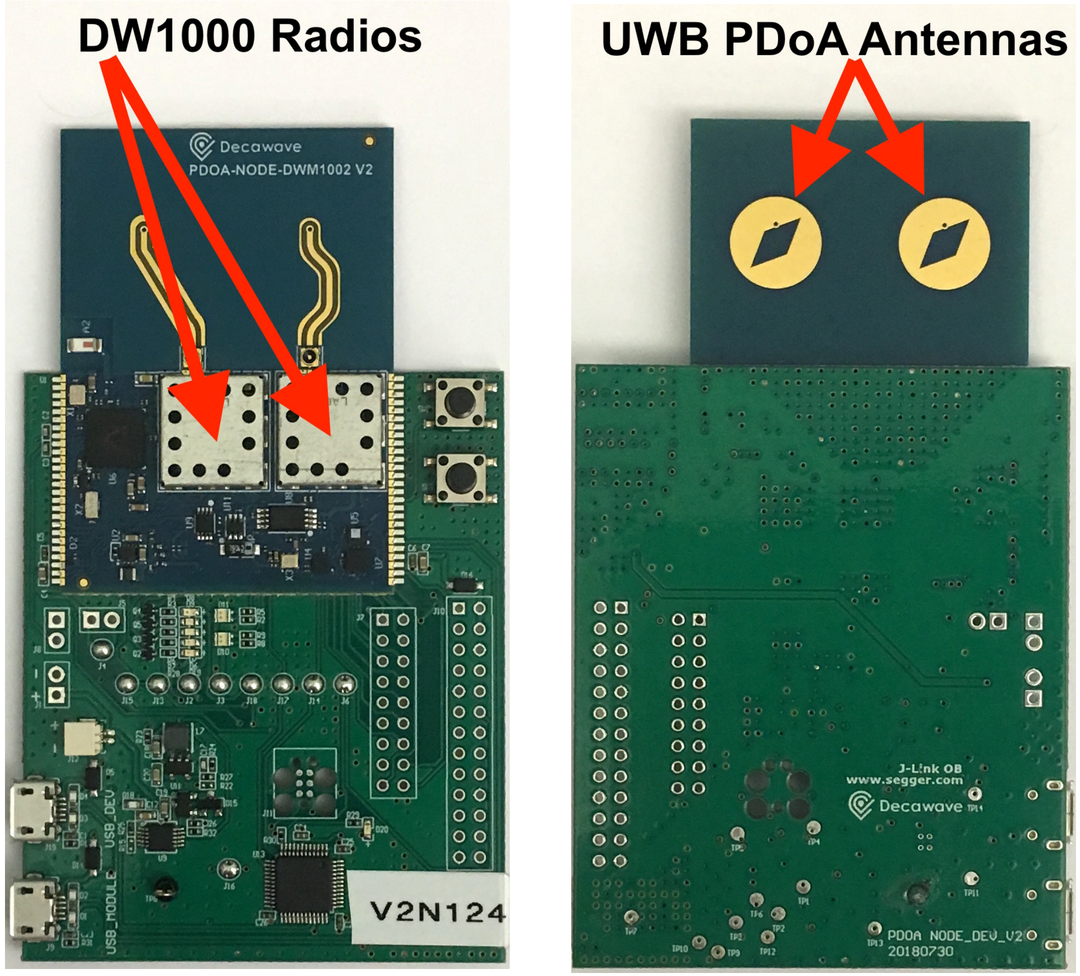
$$\lambda = \frac{2\pi}{f}$$

$$\alpha = \frac{2\pi}{\lambda} p = \frac{f}{c} p$$

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

We calculate α by calculating phase for first path in CIR

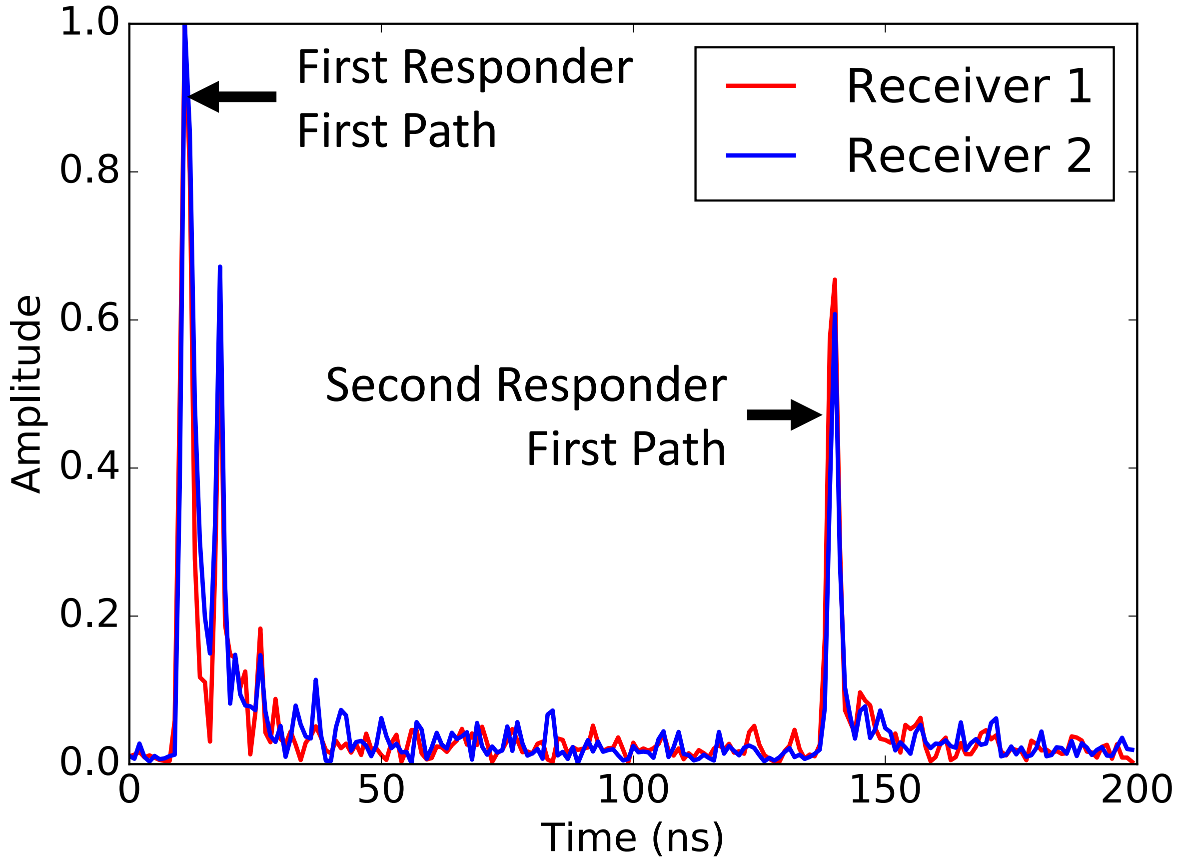
Angle of Arrival Hardware



Decawave PDoA node (DWM1002)

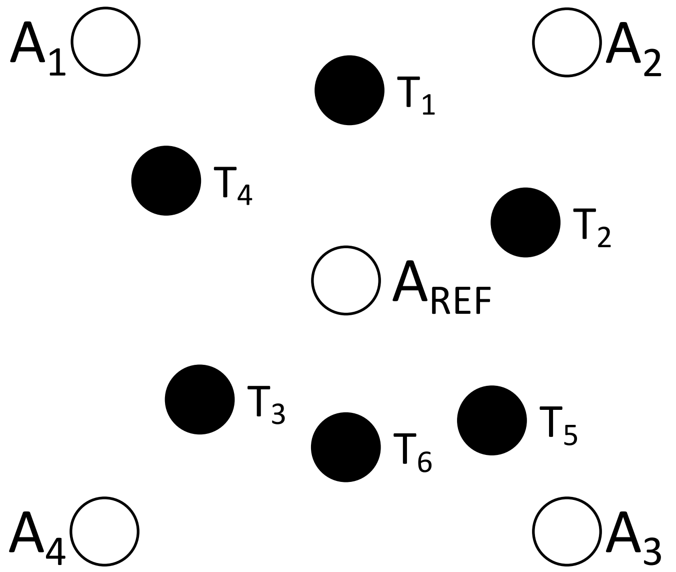
Concurrent Angle of Arrival

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



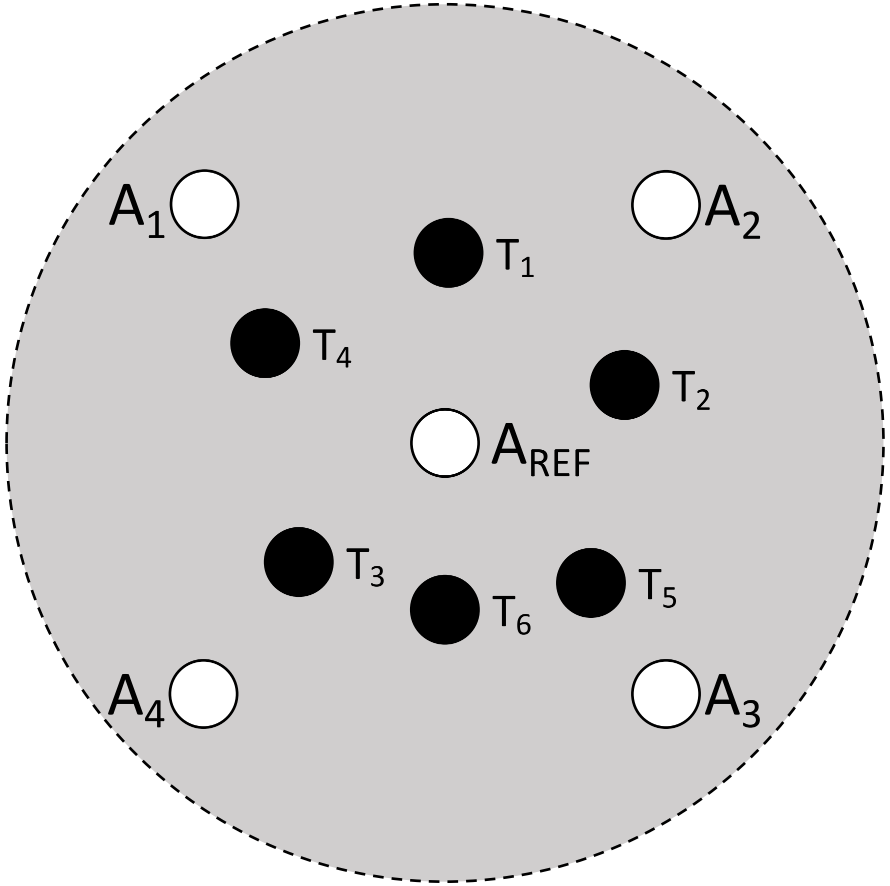
We can calculate phase information by detecting first path of each responder

Concurrent Self-Localization Protocol



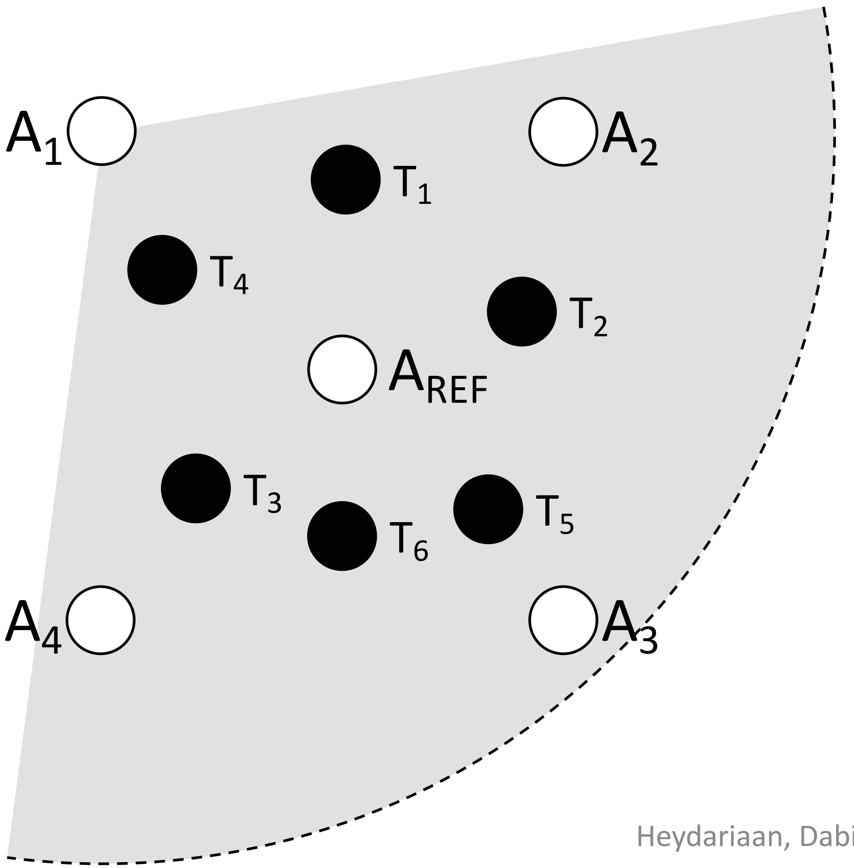
Concurrent Self-Localization Protocol

1. A_{REF} broadcasts SYNC



Concurrent Self-Localization Protocol

1. A_{REF} broadcasts SYNC
2. A_i's reply concurrently



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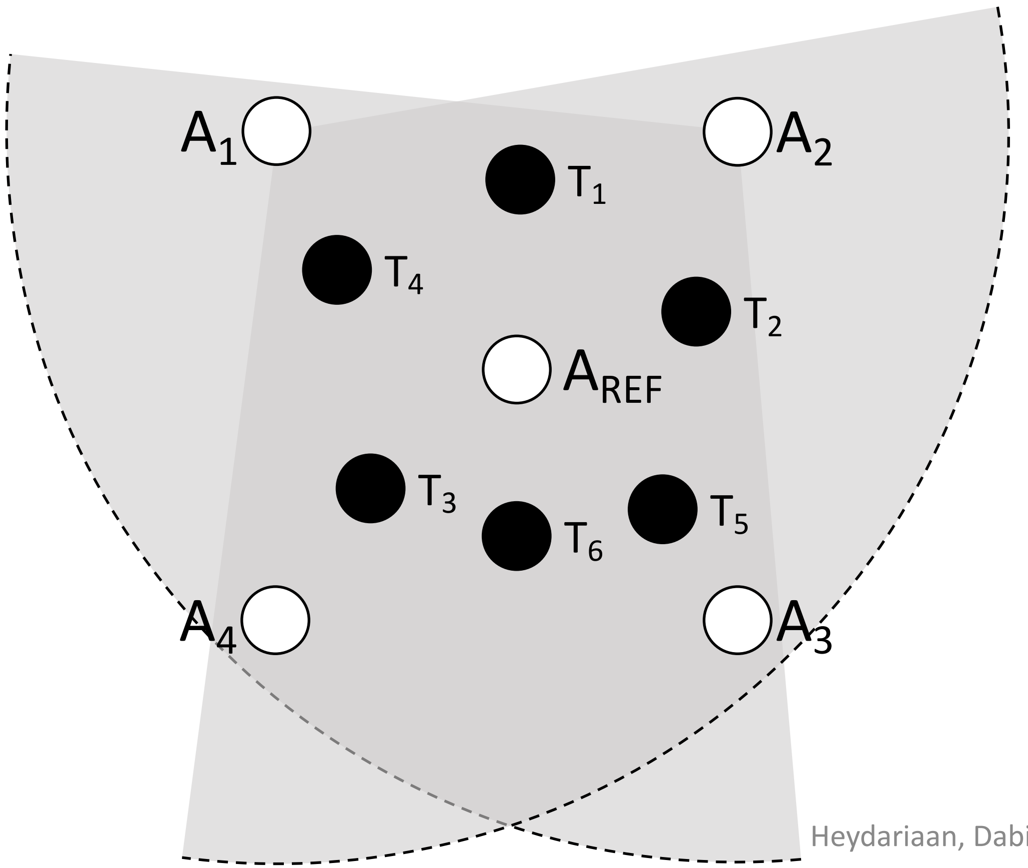

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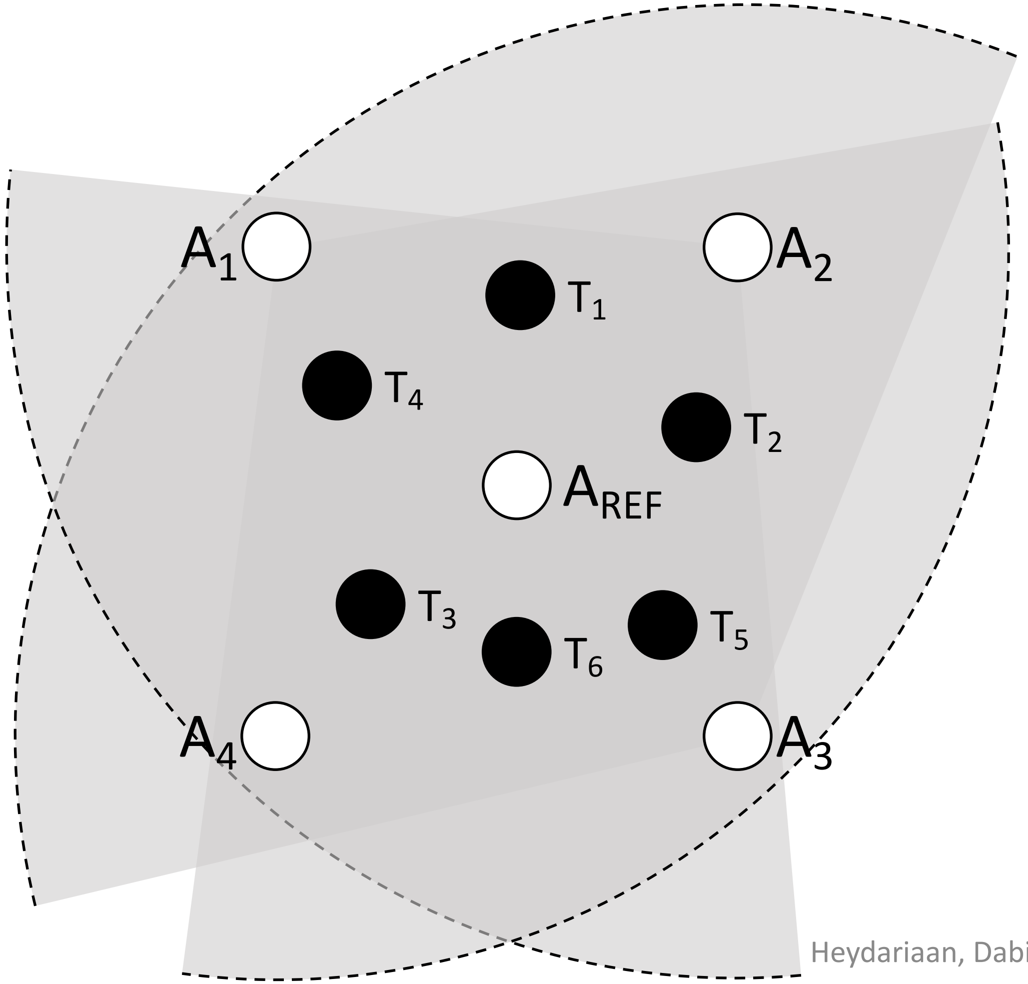
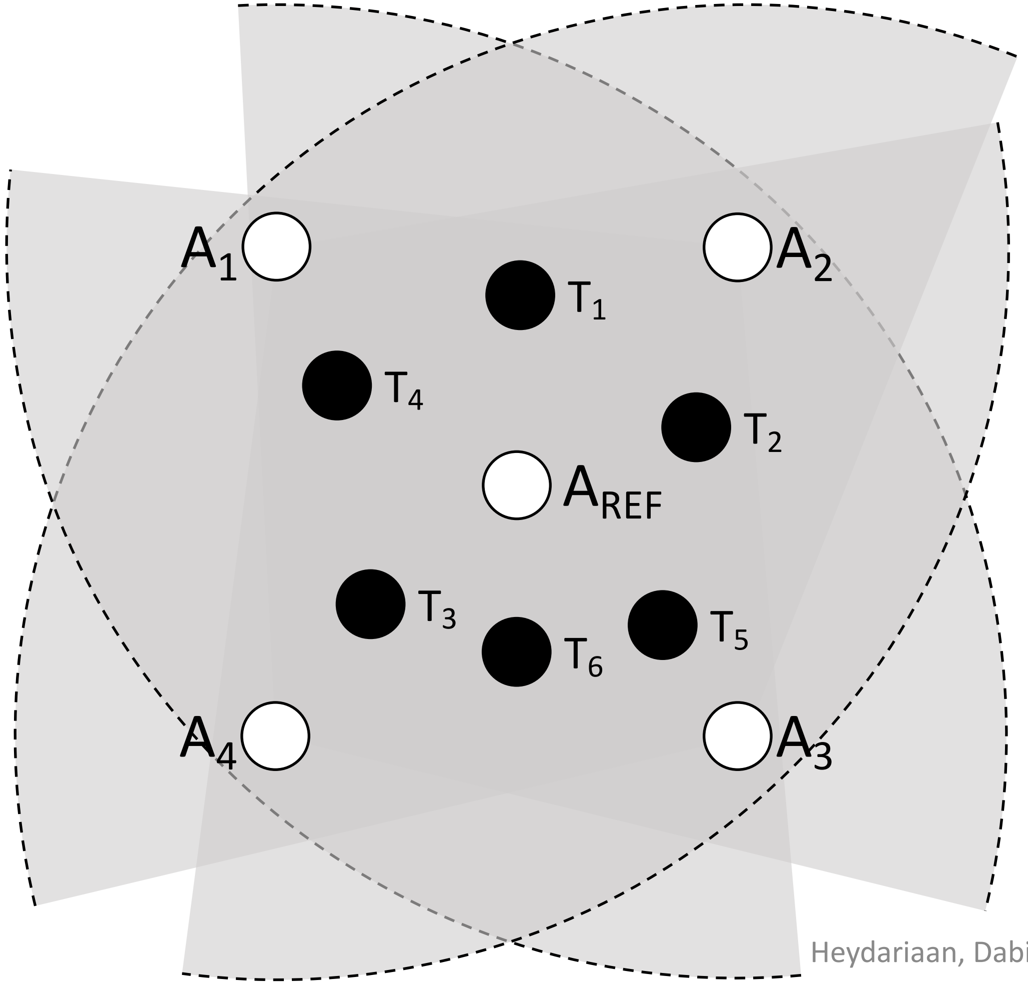


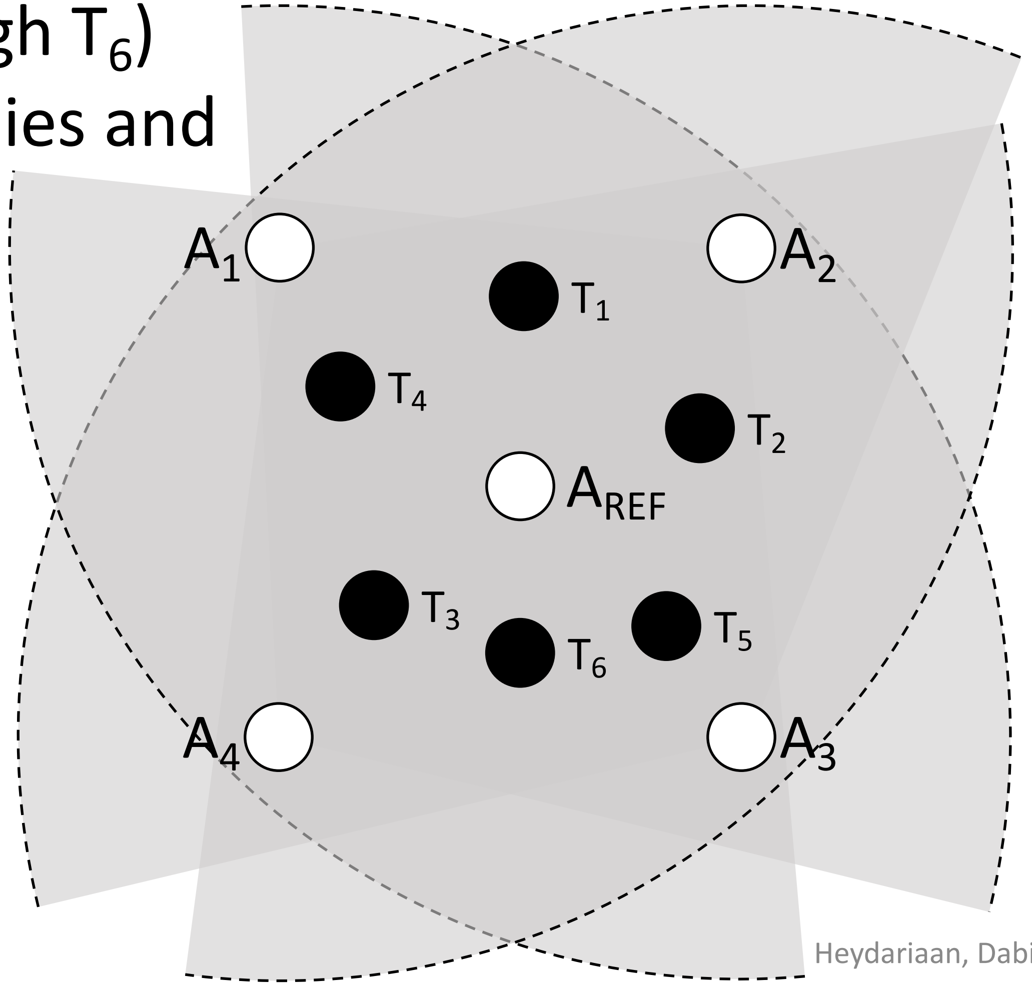
Concurrent Self-Localization Protocol

1. A_{REF} broadcasts SYNC
2. A_i's reply concurrently

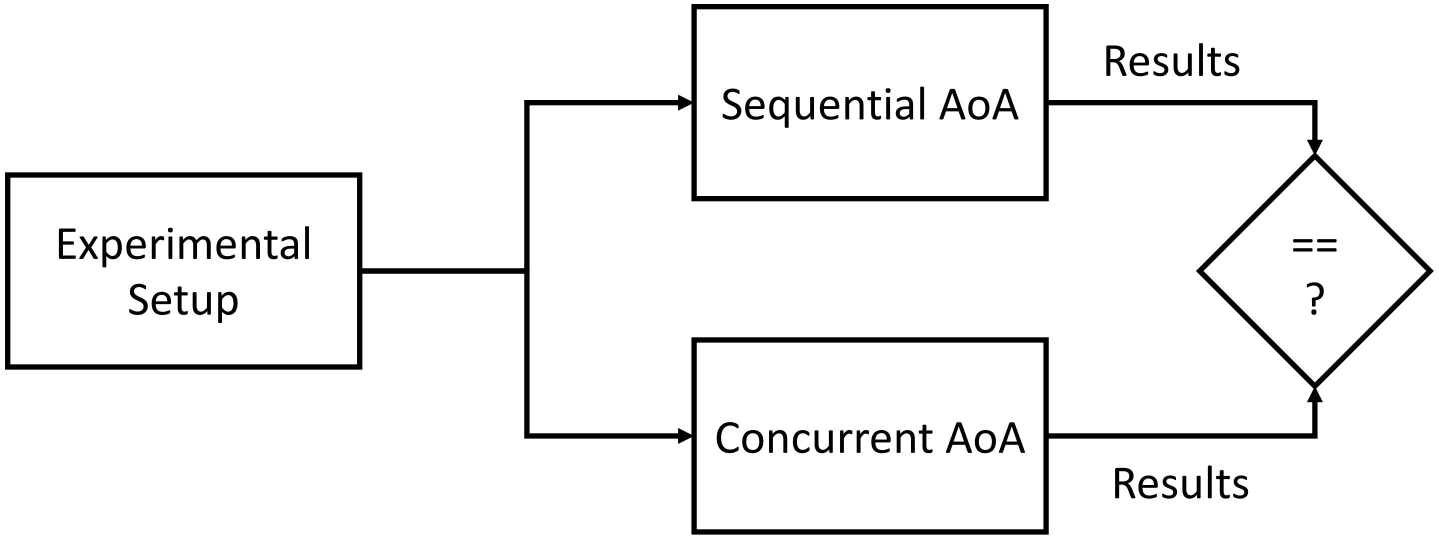


Concurrent Self-Localization Protocol

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

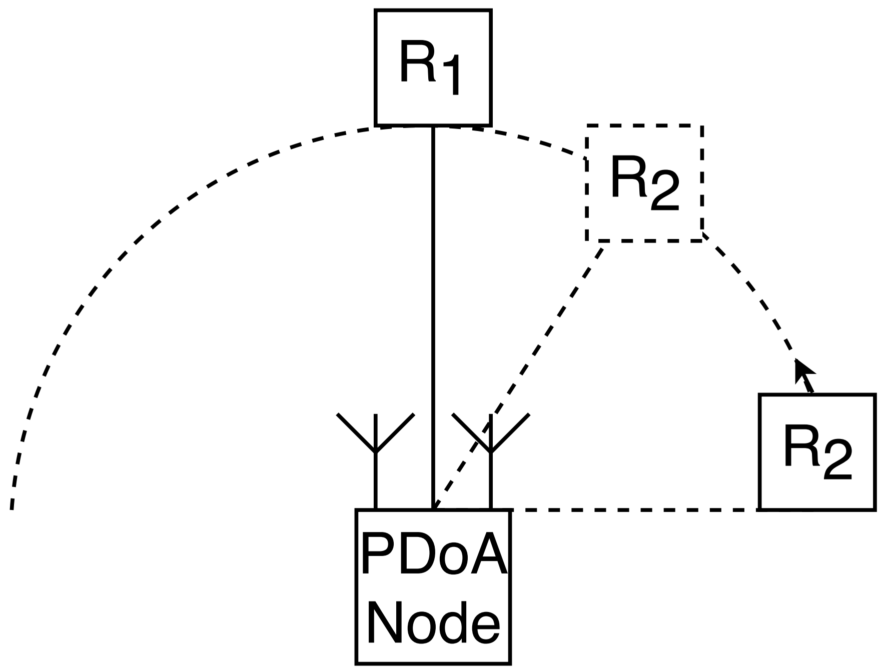


Evaluation of Concurrent AoA

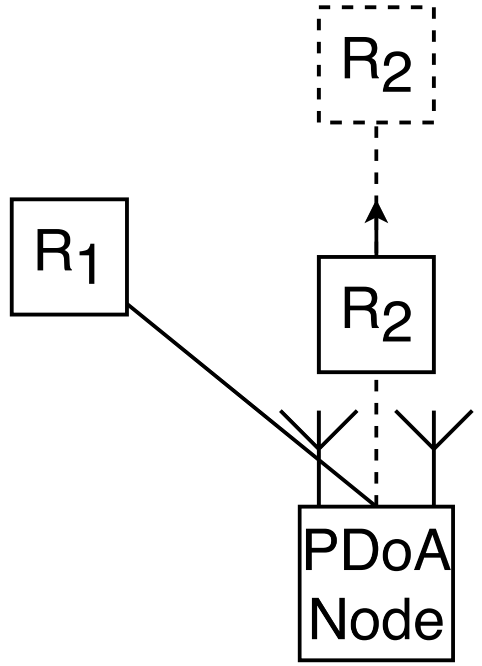


- Sequential AoA as baseline
- Ideally should have similar accuracy

Concurrent AoA Experimental Setup

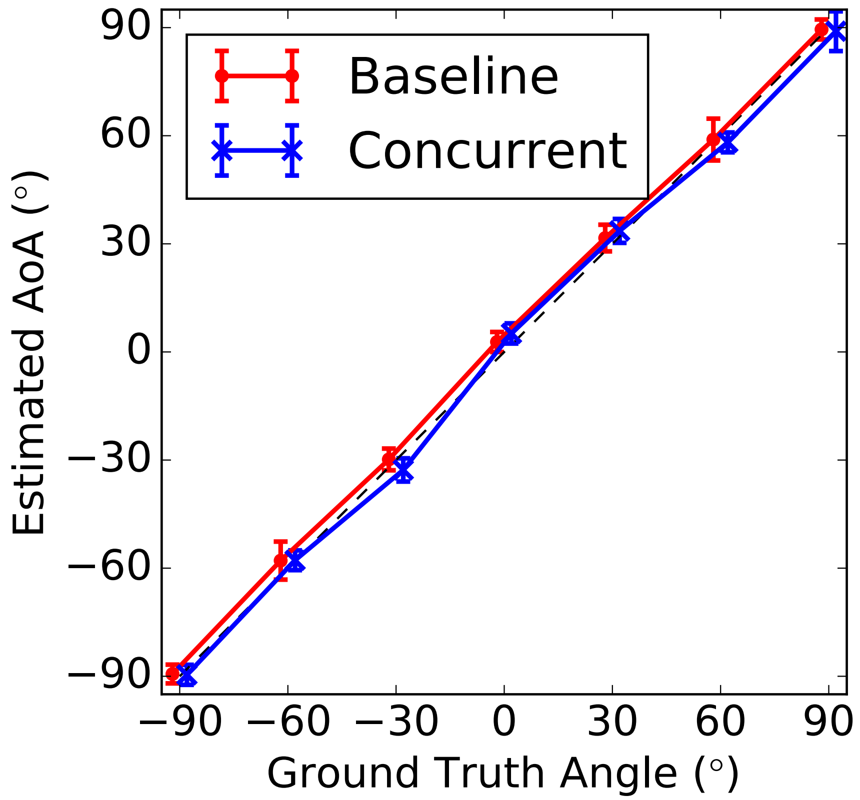


We change angle of one responder when the other one is static. Dipole antenna performance expected to degrade near extreme angles.

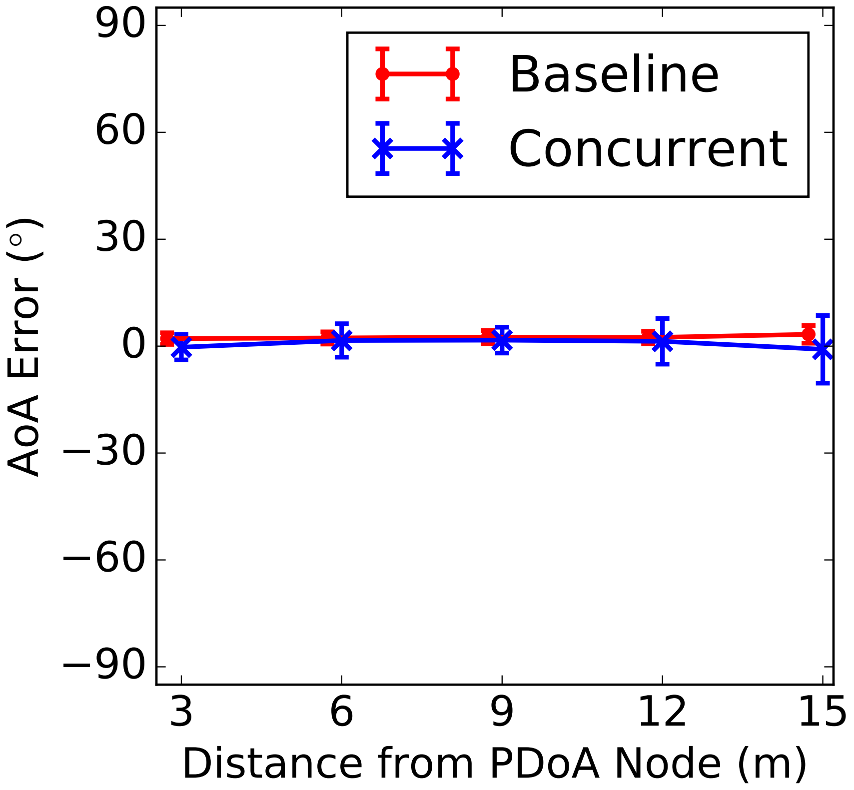


We change distance of one responder when the other one is static. C-AoA performance expected to degrade at longer distances.

Performance of Concurrent AoA for 2 anchors

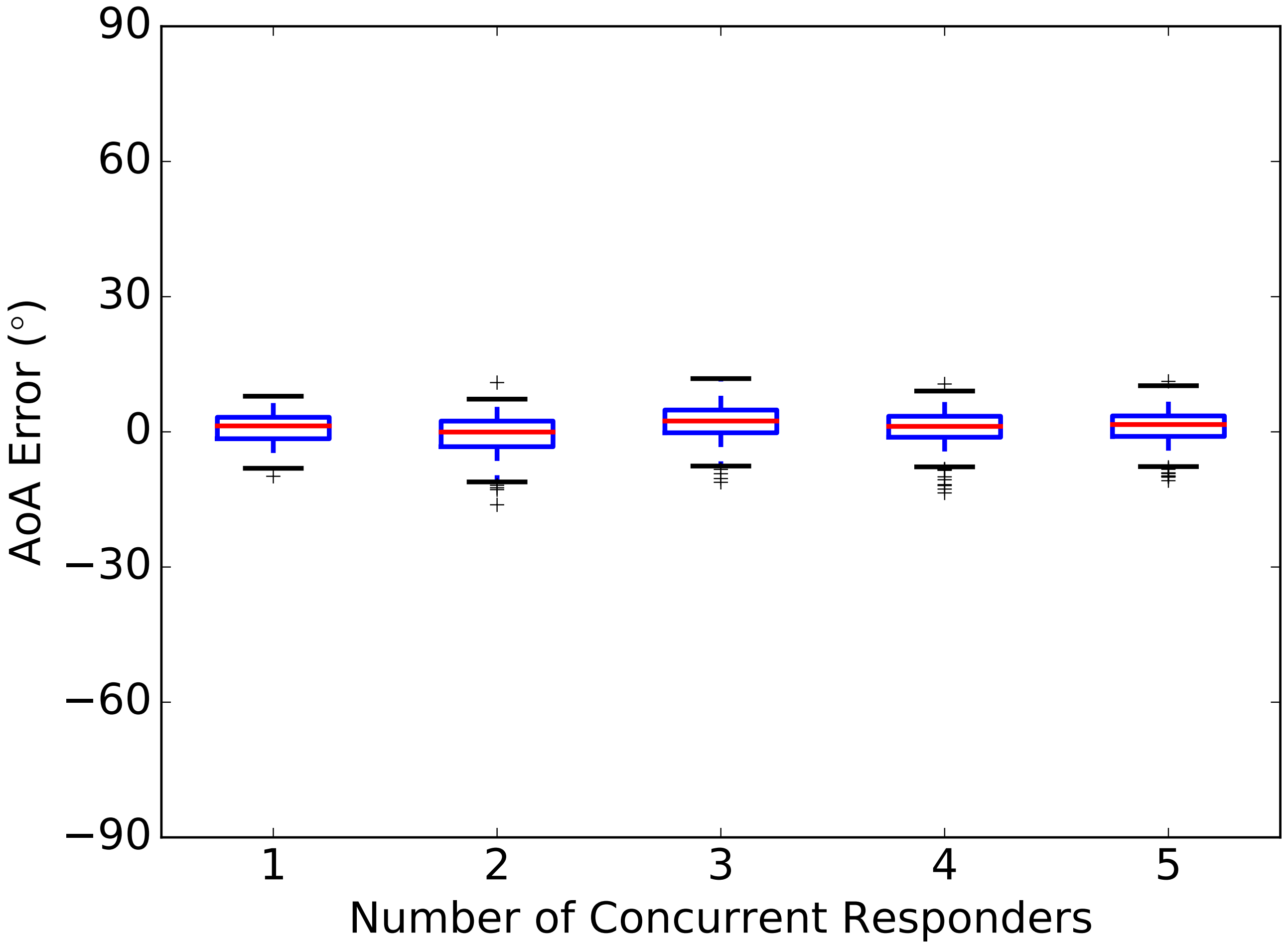


Concurrency does not significantly affect AoA estimation in different angles (100 measurements per data point)



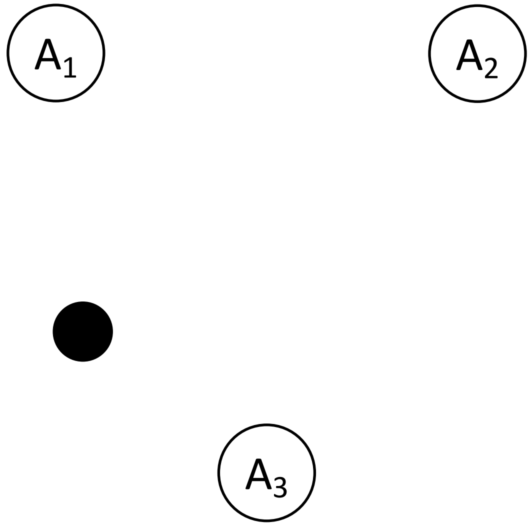
Concurrency only affects AoA estimation in longer distances (100 measurements per data point)

Performance of Concurrent AoA for 3+ anchors

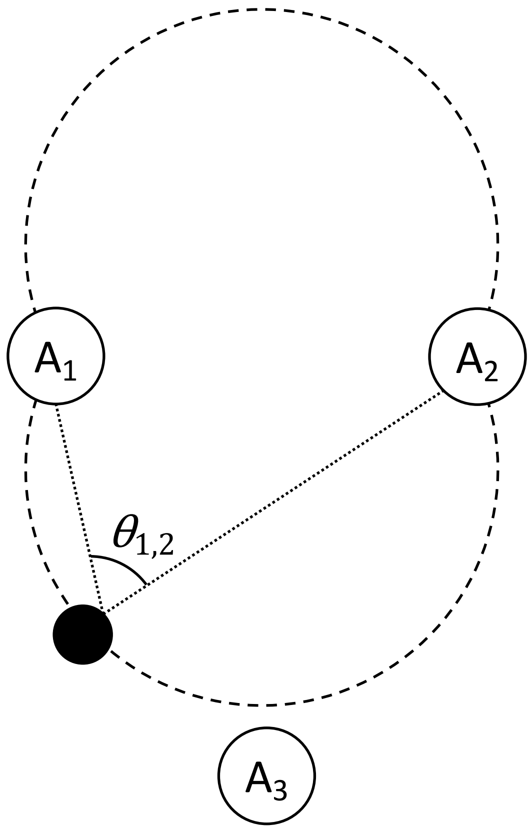


Concurrency does not significantly affect AoA estimation when adding more anchors showing 100 measurements per box plot. Number of receiver tags are still unlimited.

2D Self-Localization with Angle Difference of Arrival

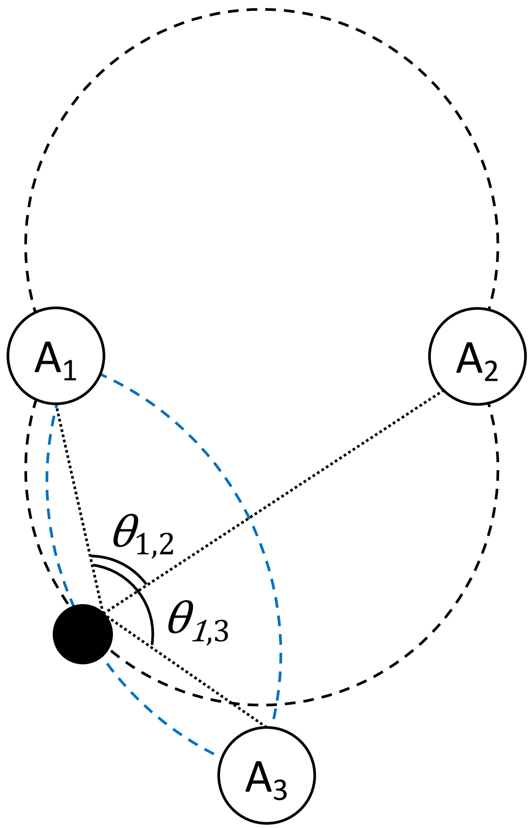


2D Self-Localization with Angle Difference of Arrival



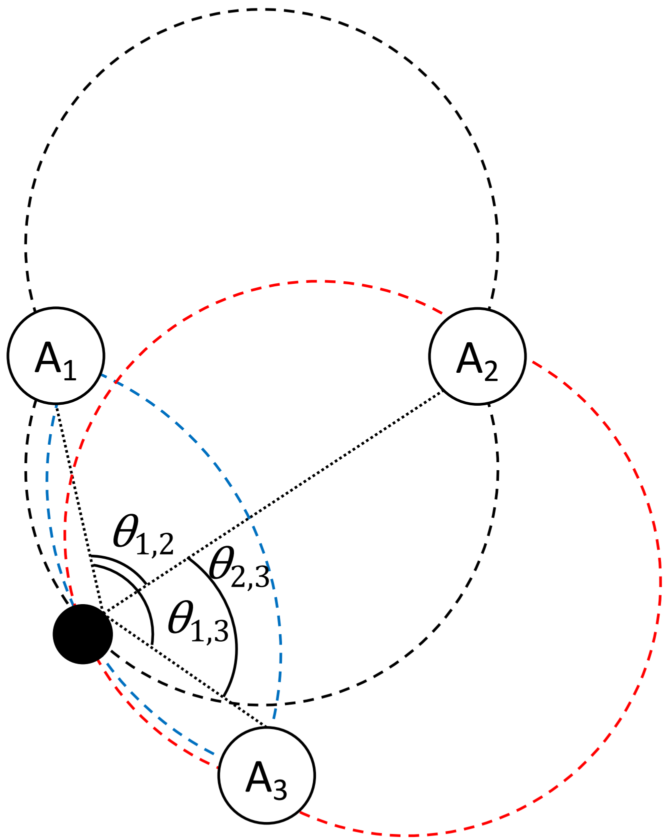
Angle difference between 1 pair of anchors.
Possible locations are shown with 2 curves.
Infinite possible locations.

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

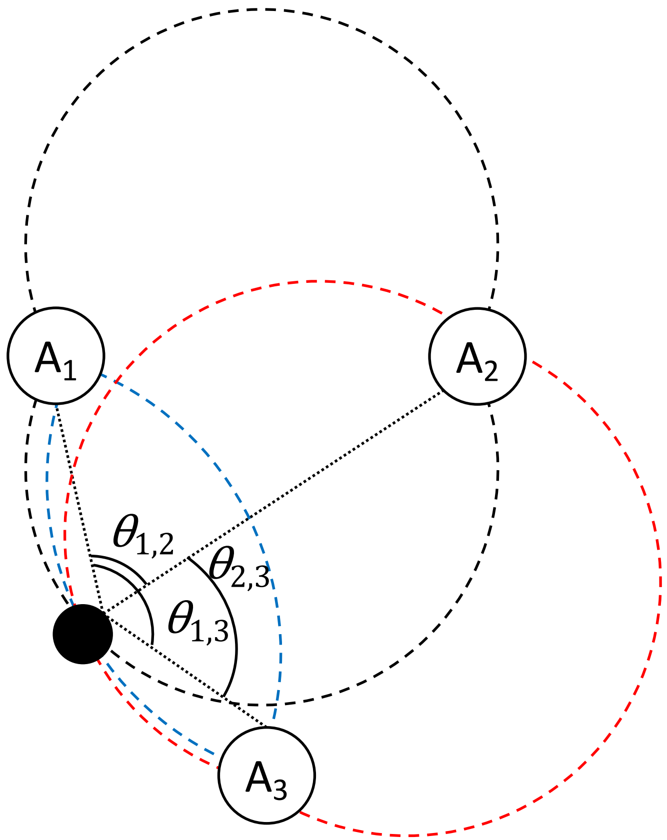


Angle difference between 3 pairs of anchors.
Possible locations are shown with 6 curves.
1 possible location.

2D Self-Localization with Angle Difference of Arrival

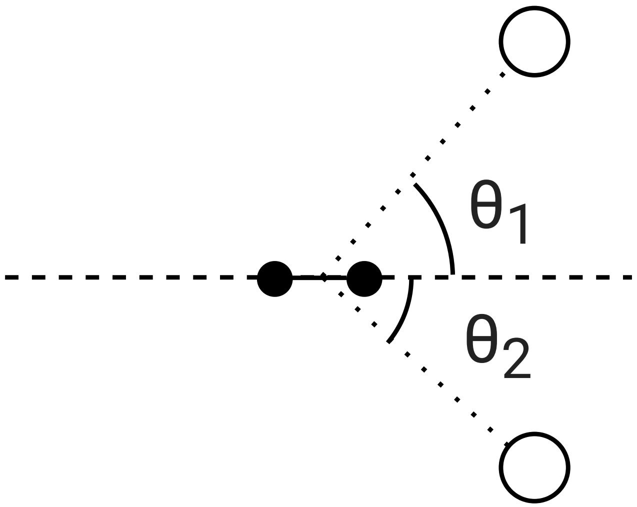
$$J(x,y) = \sum_{j>i} (\theta_{i,j} - \hat{\theta}_{i,j})^2$$

$$\hat{T} = \underset{x,y}{\operatorname{argmin}}\, J(x,y)$$

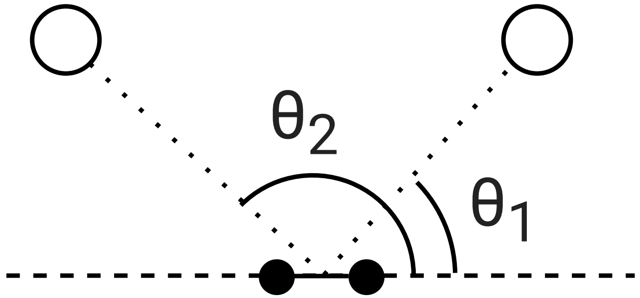


Angle difference between 3 pairs of anchors.
Possible locations are shown with 6 curves.
1 possible location.

ADoA Challenges – Front-back Ambiguity

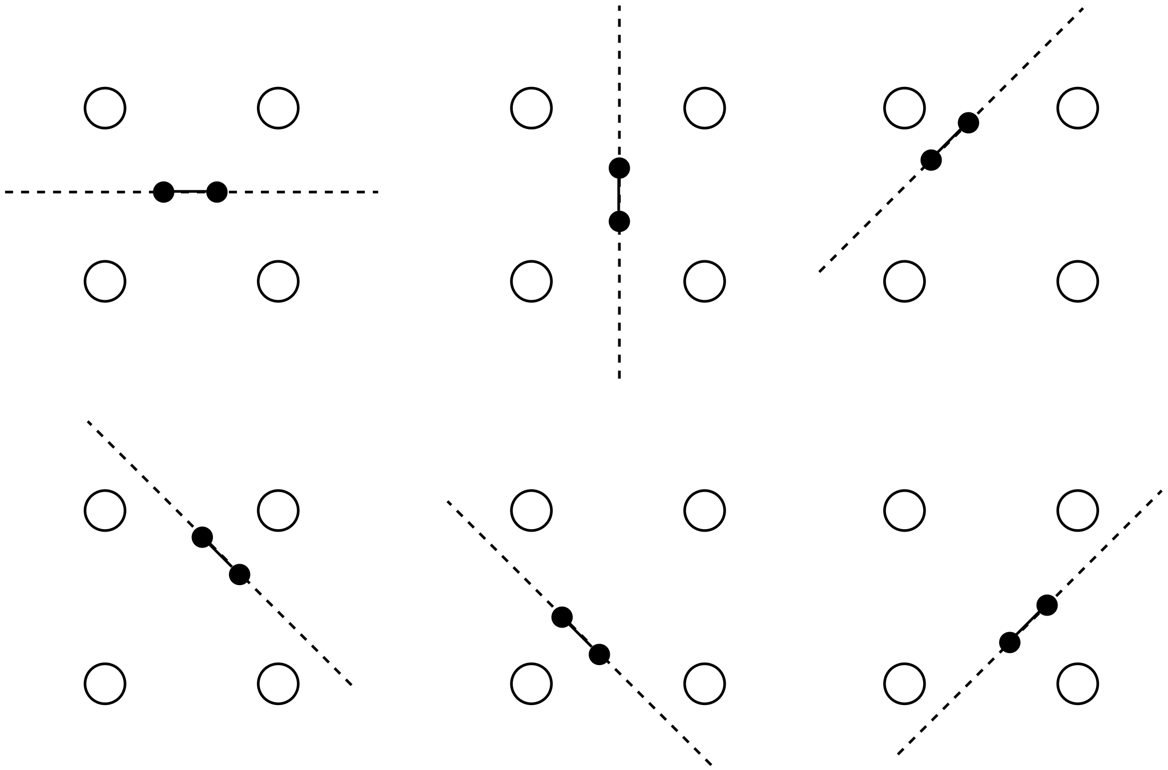


$\theta_{1,2} = \theta_1 + \theta_2$



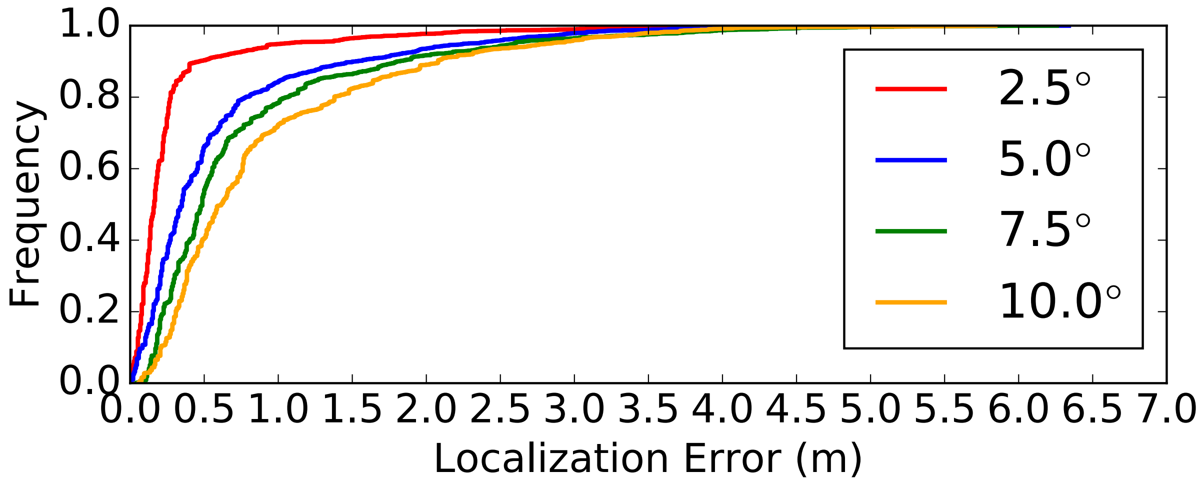
$\theta_{1,2} = |\theta_1 - \theta_2|$

ADoA Challenges – Unknown Tilting

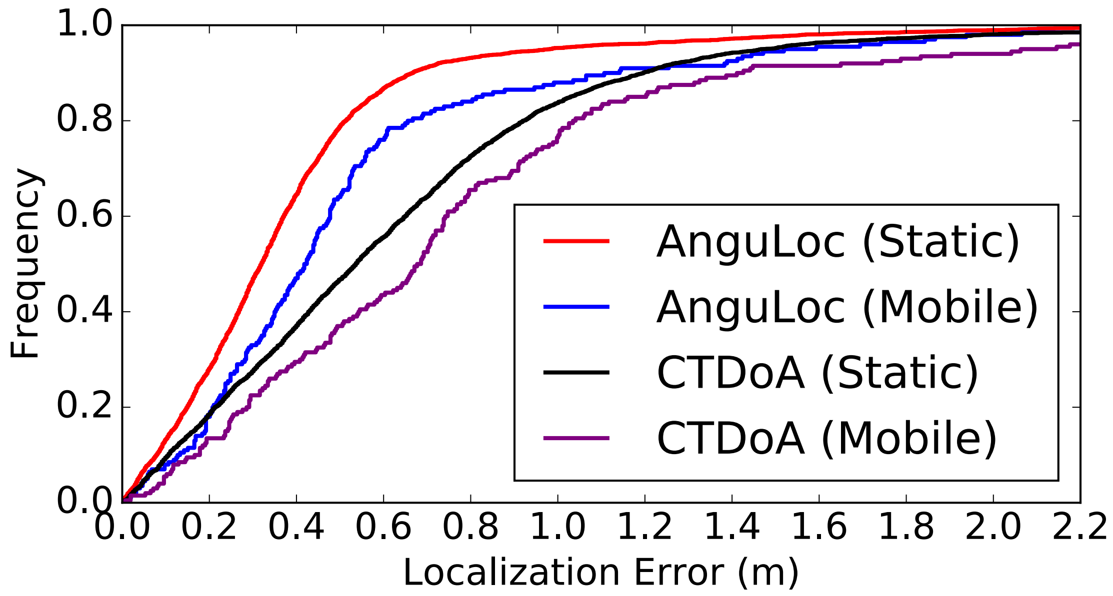


6 cases for tags inside the room in a 4-anchor setting.
We run 6 optimizations and choose the answer with the least residual error.

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 CTDoA)
  - 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

	Smart Home and Enterprises	Smart Cities and Mobility	Smart Transportation	Consumer	Smart Retail	Industry 4.0 and Healthcare
Hands-Free Access Control	• Residential access control • Restricted enterprise access	• Parking garage • Vehicle digital key (standardized by CCC)	• Rider identification (private transport services)	• Logical access control	• Unmanned store access	• Barrier-free and restricted access control
Location-Based Services	• Employee mustering in emergencies	• Bike sharing	• Ride sharing • Reserved seat validation	• AR gaming	• Indoor navigation • Foot traffic and shopping behavior analytics	• Asset tracking • Patient tracking
Device-to-Device (Peer-to-Peer) Applications	• Conference systems	• Drone-controlled delivery • V2X*, autonomous driving	• Ticket validation (public transport services)	• VR gaming and group play • Find someone nearby	• Targeted marketing • Tap-free remote payment	• Proximity-based patient data sharing • Find equipment

*Connected Vehicle-to-Everything Communication

https://www.firaconsortium.org/discover/use-cases

Localization Technologies

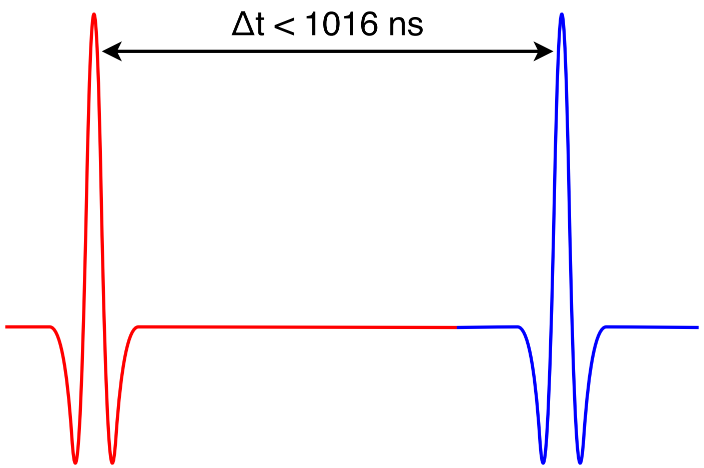
TECHNOLOGY	Decawave UWB ALLIANCE	Bluetooth	WiFi	RFID	GPS
WHERE USED					
ACCURACY	Centimeter	1-5 meters	5-15 meters	Centimeter to 1 meter	5-20 meters
RELIABILITY	★★★★★ Strong immunity to multi-path and interference	★☆☆☆☆ Very sensitive to multi-path, obstructions and interference	★☆☆☆☆ Very sensitive to multi-path, obstructions and interference	★★★★★	★★★☆☆ Very sensitive to obstructions
RANGE / COVERAGE	Typ. **70m** Max **250m** Typ. 250m² per anchor	Typ. **15m** Max **100m** Typ. 25m² per beacon (for 2m accuracy)	Typ. **50m** Max **150m** Typ. 100m² per access point (for 5m accuracy)	Typ. **1m** Max **5m** Typ. 25m² per reader	N/A
DATA COMMUNICATIONS	☑ up to 27Mbps	☑ up to 2Mbps	☑ up to 1Gbps	☒	☒
SECURITY (PHY LAYER)	★★★★★ Distance-Time bounded protocol	★☆☆☆☆ Can be spoofed using relay attack	★☆☆☆☆ Can be spoofed using relay attack	★☆☆☆☆ Can be spoofed using relay attack	N/A
LATENCY	★★★★★ Typ. <1ms to get XYZ	★☆☆☆☆ Typ. >3s to get XYZ	★☆☆☆☆ Typ. >3s to get XYZ	★★☆☆☆ Typ. 1s to get XYZ	★★★☆☆ Typ. 100ms to get XYZ
SCALABILITY DENSITY	★★★★☆ >10's of thousands of tags	★★☆☆☆ Hundreds to a thousand tags	★★☆☆☆ Hundreds to a thousand tags	★★★★★ Unlimited	★★★★★ Unlimited
POWER & BATTERY	5nJ/b TX · 9nJ/b RX **Coin Cell**	15nJ/b RX/TX **Coin Cell**	50nJ/b RX/TX **Lithium Battery**	**Passive**	**Lithium Battery**
TOTAL COST (infrastructure, tag, maintenance)	$	$	$$$	$$$	$$$

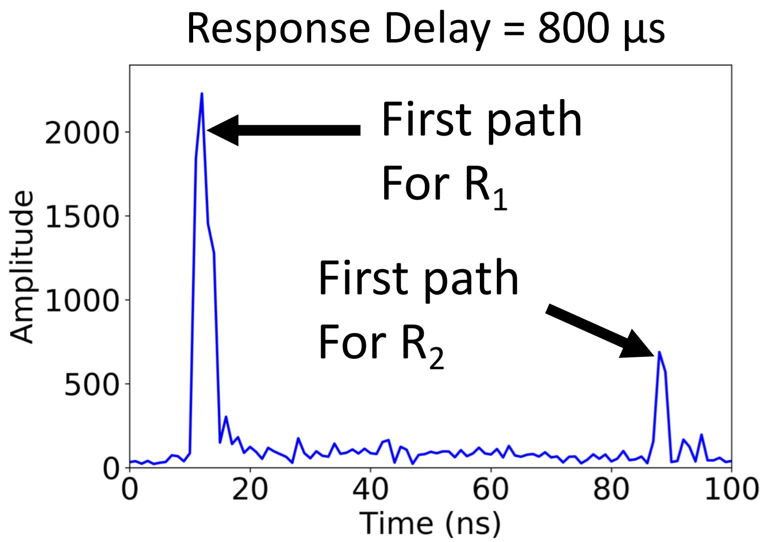
https://www.decawave.com/technology1/

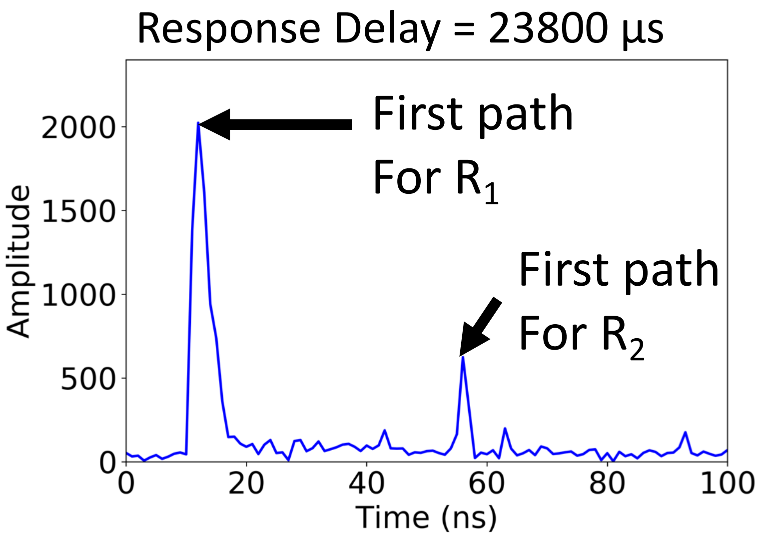
ALOHA and TDMA in UWB-based Localization

- 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

Concurrency Window and Clock Drift







Concurrency 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.

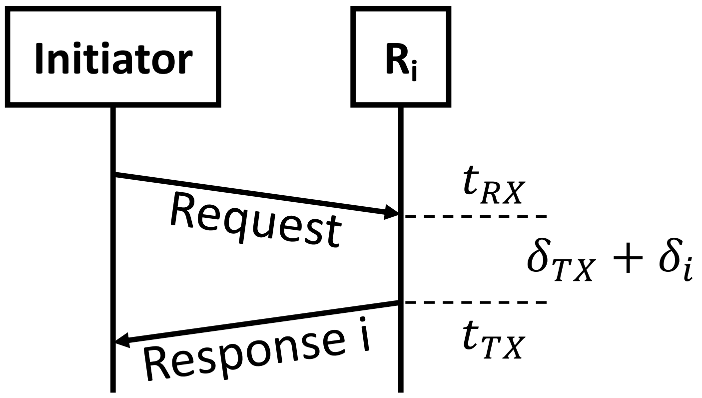
Large clock skew can break concurrency

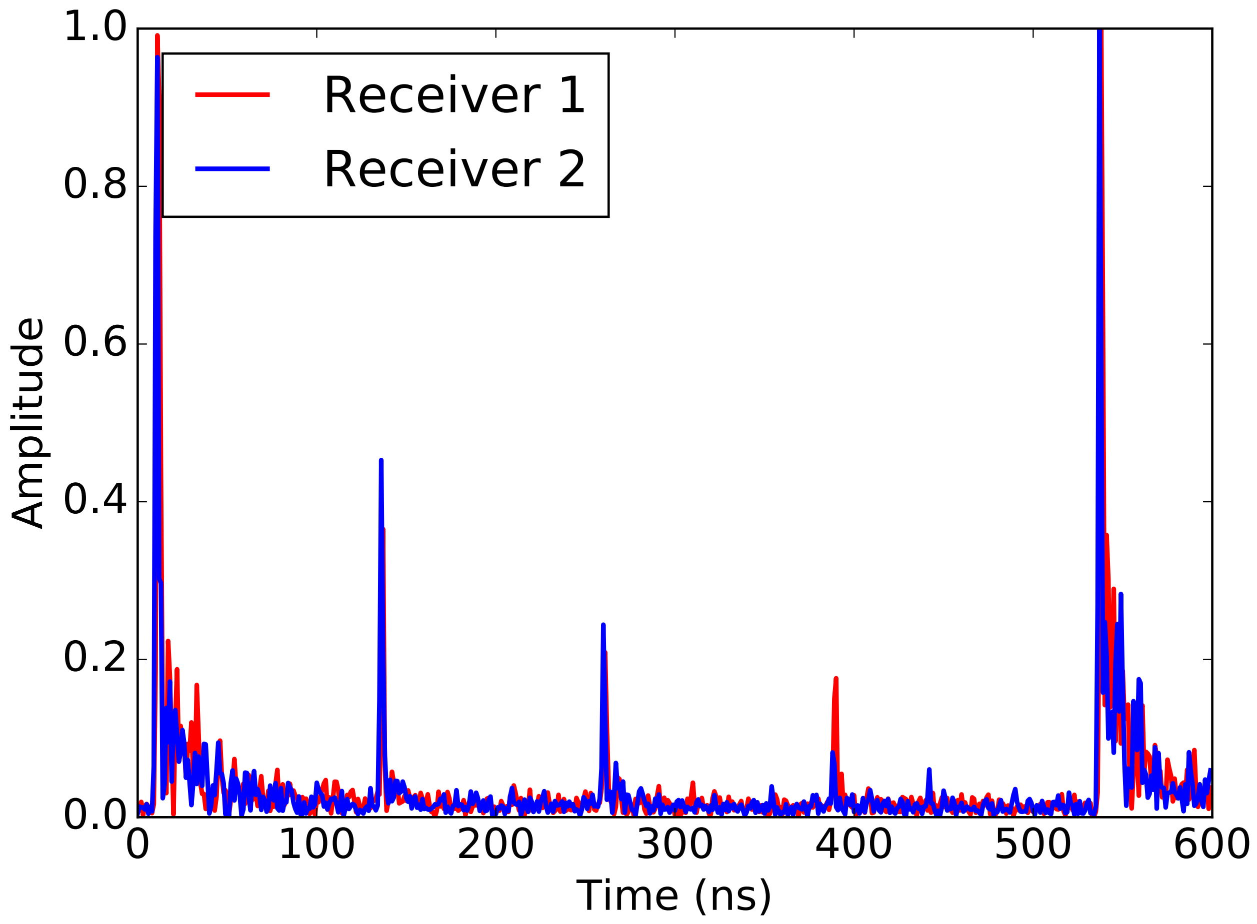
Time-based AoA Estimation Using DW1000

- 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 sparation: $d = \frac{0.30048}{sin\ 5°} = 3.497\ m$
- With two radios using ToA
  - Resolution of $15.6\ ps$ or $0.00469\ m$ -> $d = \frac{0.00469}{sin\ 5°} = 0.053\ m$
  - Precision of $333.3\ ps$ or $0.1\ m$ -> $d = \frac{0.1}{sin\ 5°} = 1.147\ m$

Response Position Modulation

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





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: $MaxNumResponses, CIR_1[], CIR_2[]$
Output: $AoA[]$

$N \leftarrow MaxNumResponses$
$Peaks[1 \ldots N][1] \leftarrow FindPeaks(N, CIR_1[])$
$Peaks[1 \ldots N][2] \leftarrow FindPeaks(N, CIR_2[])$
for $i \leftarrow 1$ to N **do**
  $AoA[i] \leftarrow CalcAoA(Peaks[i][1,2], CIR_1[], CIR_2[])$
end for

Localization with Angle Difference of Arrival

$$\theta_{i,j} = \cos^{-1} \frac{TA_i \cdot TA_j}{\left|TA_i \cdot TA_j\right|}$$

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

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

$$\hat{T} = \underset{x,y}{\operatorname{argmin}}\, J(x, y)$$