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Embracing "bad" Multipath for Device-Free Localization with COTS RFID Devices

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Motivation

Location is the key for many applications

Indoor navigation

Augmented reality

Flow monitoring

Smart home

Motivation

RF-based localization is popular

Applications

Indoor navigation

Augmented reality

Flow monitoring

Smart home

Geo-fencing

…

Technologies

Acoustic

Infrared

Camera

Visible light

Wi-Fi

…

RFID

Motivation

RF-based localization is popular

Applications

Indoor navigation

Augmented reality

Flow monitoring

Smart home

Geo-fencing

…

Technologies

Ubiquitousness and low cost

Wi-Fi … RFID

Motivation

RFID tag is cheap and ubiquitous deployed

- Each RFID tag costs 5 cents USD.
- RFID tags are widely used: bus card, room key card, clothing security tag.

Bus card

Key card

Clothing security tag

Motivation

RF-based location attracts a lot of efforts

Academia

[RADAR'00], [Cricket'04], [Horus'05],[Beepbeep'07], [SrndSense'09], [EZ'10], [BatPhone'11], [Zee'12], [Centaur'12],[ArrayTrack'13], [Guoguo'13] , [PinPoint'13], [Ubicarse'14],[Luxapose'14],[Tagoram'14],[SpotFi'15],[ToneTrack'15],[Chronos'16]...

Industry

Motivation

RF-based location attracts a lot of efforts

Academia

[RADAR'00], [Cricket'04],
[Horus'05] [Peanbean'07]
agoram'14],[SpotFi'15],[Tone
rack'15],[Chronos'16]...

Industry

Qualcomm IZat

walkbase

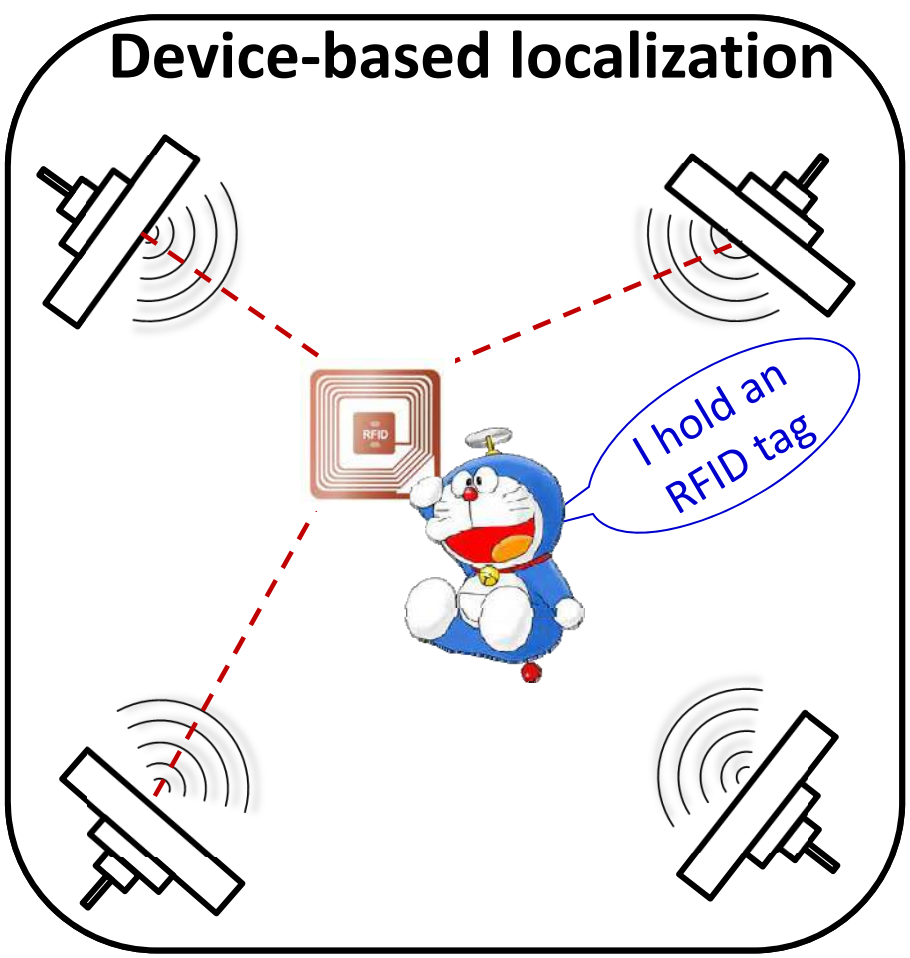
iBeacon

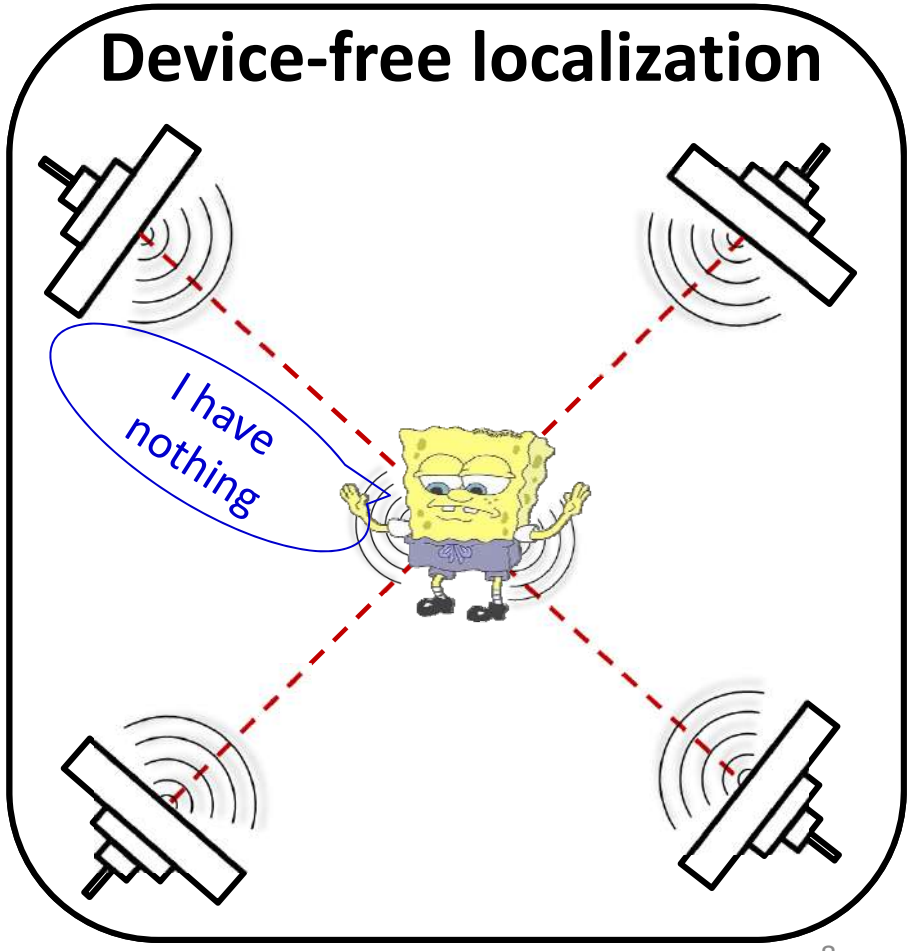
estimote

Why device-free localization?

Motivation

Device-based *v.s.* Device-free





Motivation

Elderly Care

Unwilling to wear a wearable device

Intruder Detection

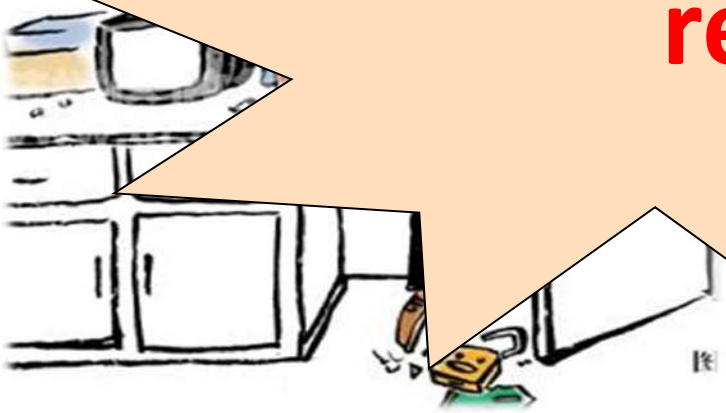
Not possible to attach a tracking device

Motivation

El

Unwi g to wear a
e d ice

Device-free localization is required

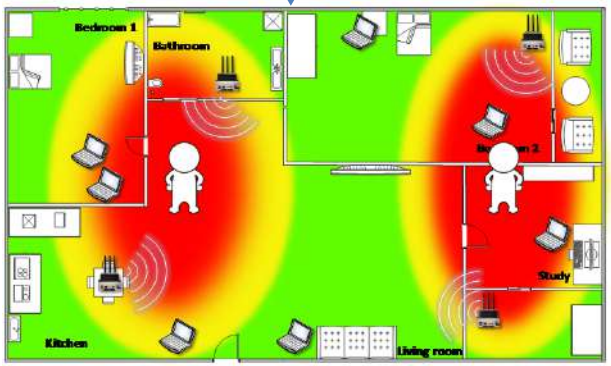


Intruder Detection

ble to
a ch a tracking device

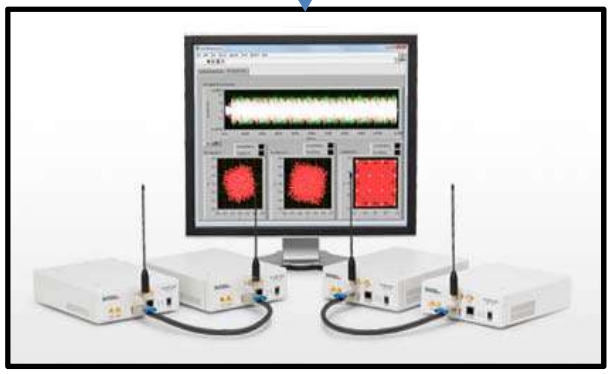
Limitations of Existing Work

High labor/hardware cost or low accuracy



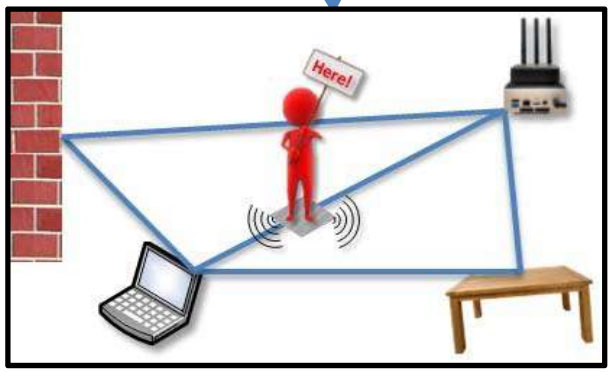
Build Fingerprint Database

Offline training causes high labor-cost



Demand Software-Defined-Radio

Not cost-effective for large deployment

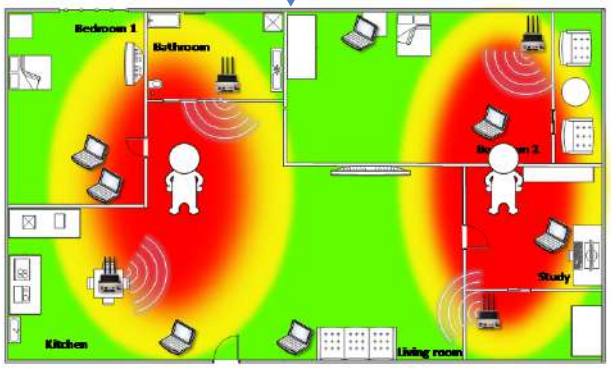


Low Accuracy in Multipath Scene

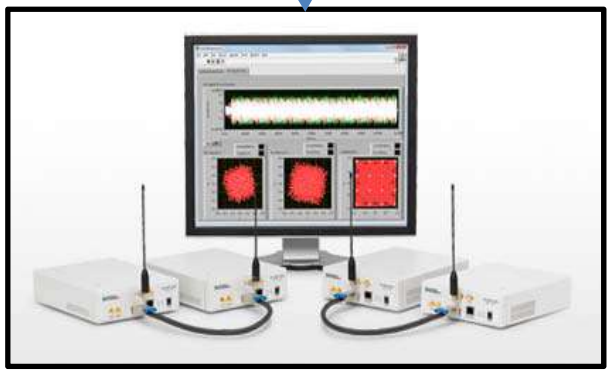
Multipath is inevitable in practice

Limitations of Existing Work

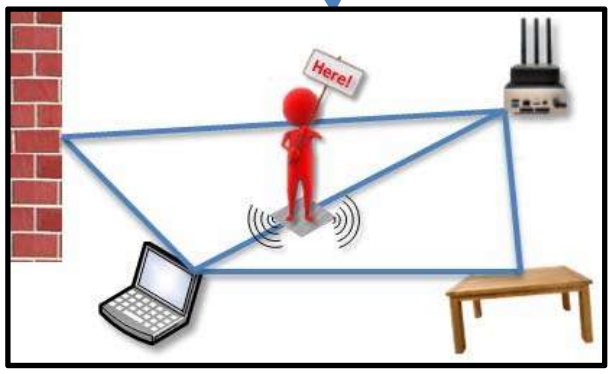
High labor/hardware cost or low accuracy



Build Fingerprint Database



Demand Software-Defined-Radio



Low Accuracy in Multipath Scene

Can we do better?

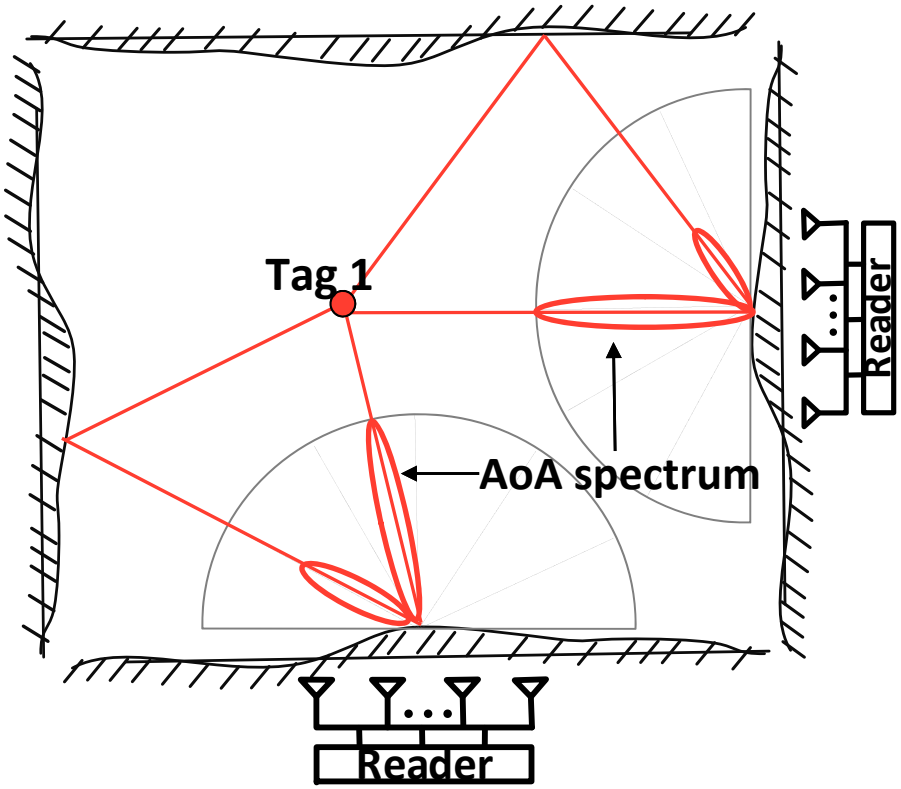
Our System: D-Watch

An accurate RFID-based device-free localization system leverages ``bad'' multipath

- *Low labor cost* : no labor-intensive offline training.
- *Low hardware cost*: cheap commodity RFID device.
- *High accuracy* : 16.5 cm and 5.8 cm median errors for ***device-free*** locating a human and his fist.

How does D-Watch Work?

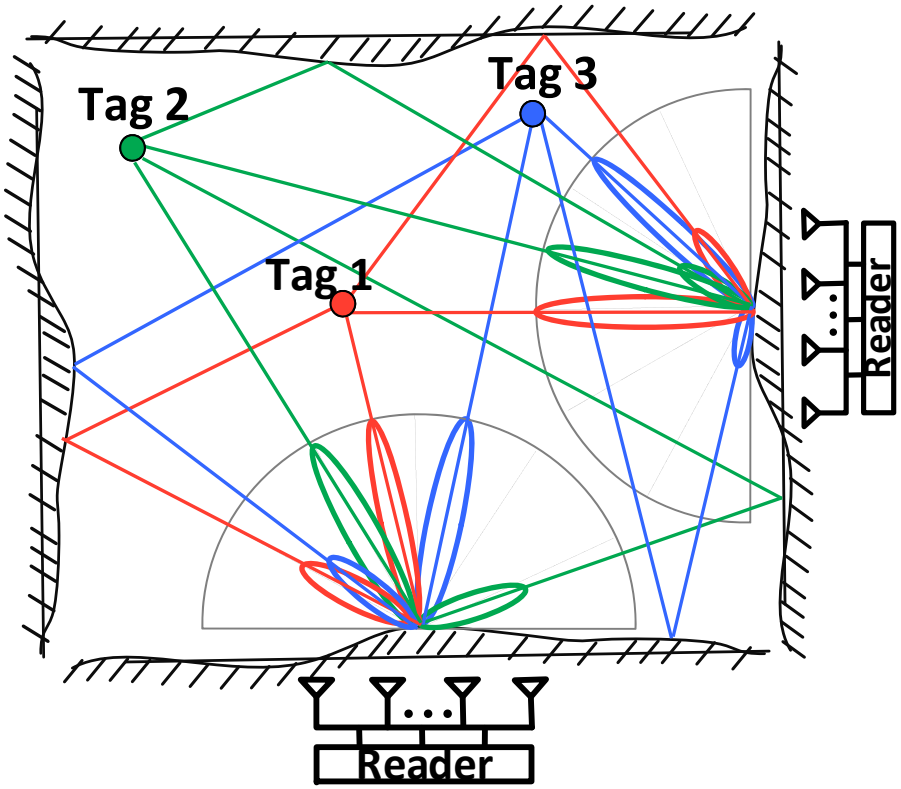
Working Example



- Reader overhears tag's reply signal.
- Reader generates AoA spectrum for a tag's signals.
  - AoA (angle-of-arrival) shows signal directions along direct and reflection paths

Working Example

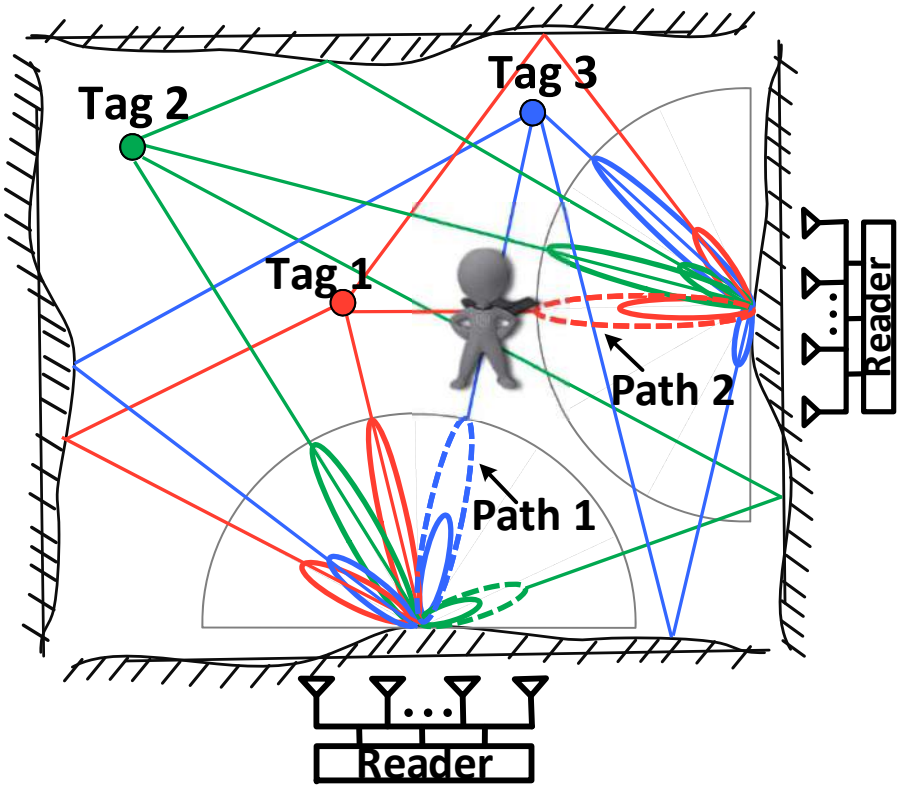
Add more tags …



- The number of signal paths increases rapidly with two more tags added.
- Enough signals can be utilized to localize a target.

Working Example

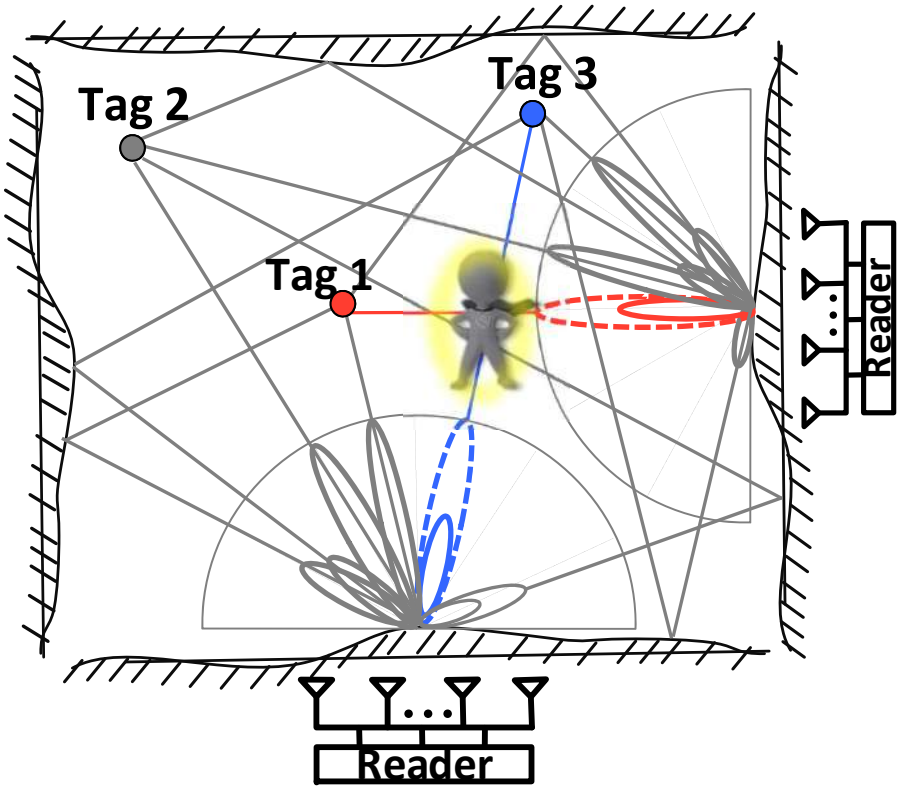
When target appears …



- The AoA spectrum peaks are decreased when a target appears and blocks signal paths.
  - Such as the path 1 and path 2 shown in the figure.

Working Example

Target be localized!



- By detecting AoA peak decrease, the target's direction can be identified.
- Target can be localized at the intersection point .

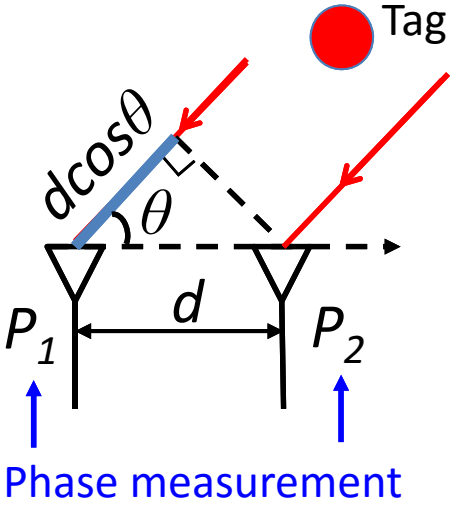
However, there are two major challenges!

Challenge 1:
Random phase offsets screw up AoA estimation

Background: AoA Estimation

Basic theory of AoA estimation

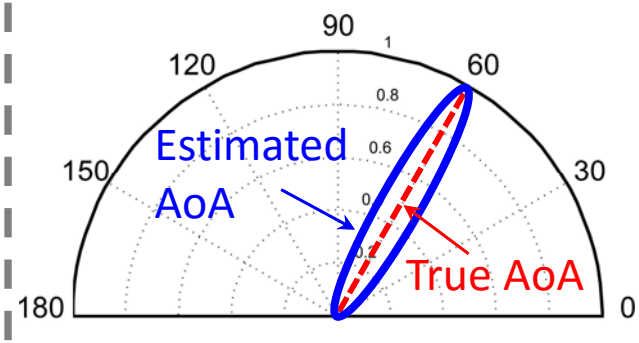
Deployment	Model	Estimation



AoA estimation:

$$\theta = \arccos\left(\frac{\lambda \cdot \Delta P}{2\pi d}\right)$$

$$\Delta P = |P_1 - P_2|$$

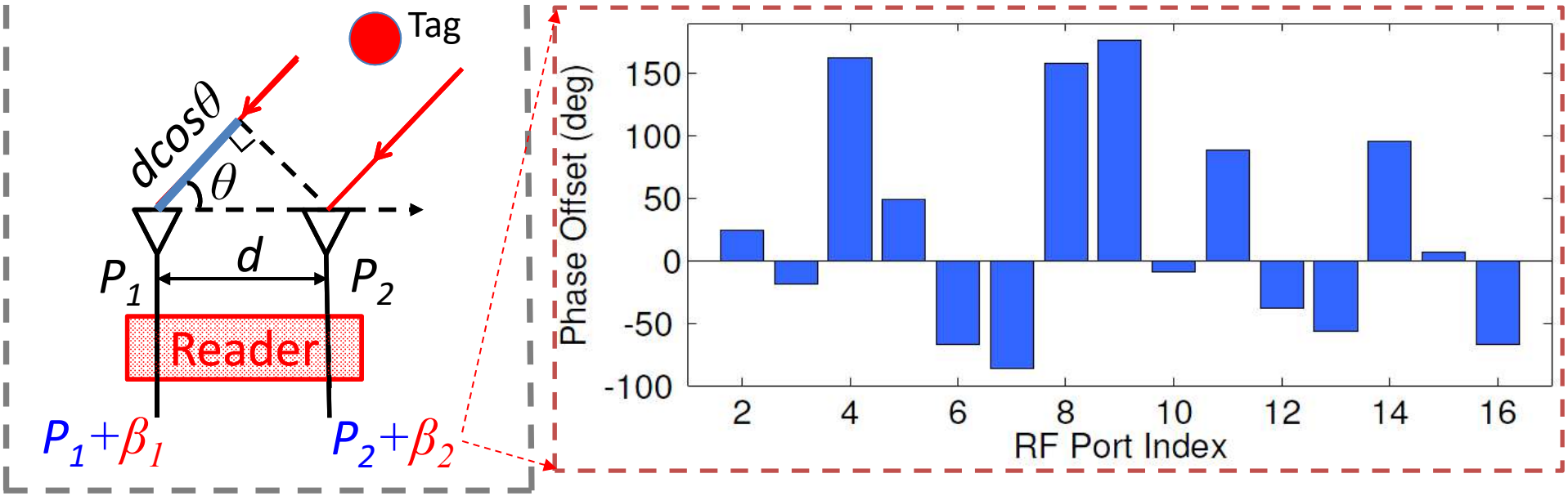


Phase measurements give tag's bearing to antenna

Background: AoA Estimation

AoA estimation in reality

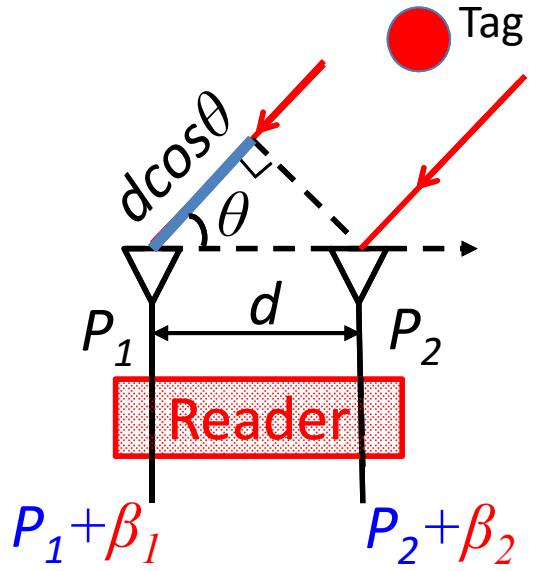
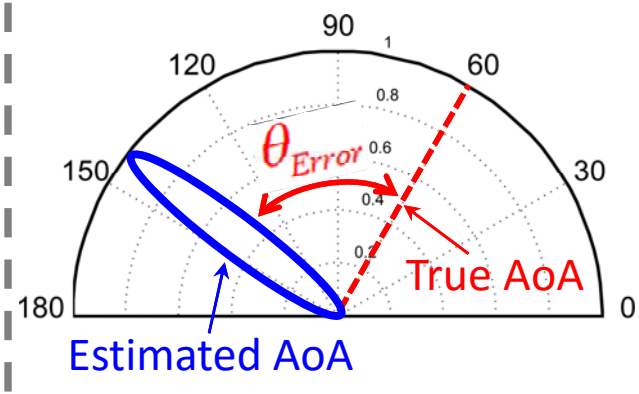
Deployment



Each radio front-end has a random phase offset

Background: AoA Estimation

AoA estimation in reality

Deployment	Model	Estimation
	AoA estimation: $\theta + \theta_{Error} = \arccos(\frac{\lambda(\Delta P + \Delta\beta)}{2\pi d})$ $\Delta P + \Delta\beta = \lvert P_1 - P_2 \rvert + \lvert \beta_1 - \beta_2 \rvert$	

Large errors occur if employing raw phase data for AoA estimation!

Phase offset needs to be removed before correct AoA estimation

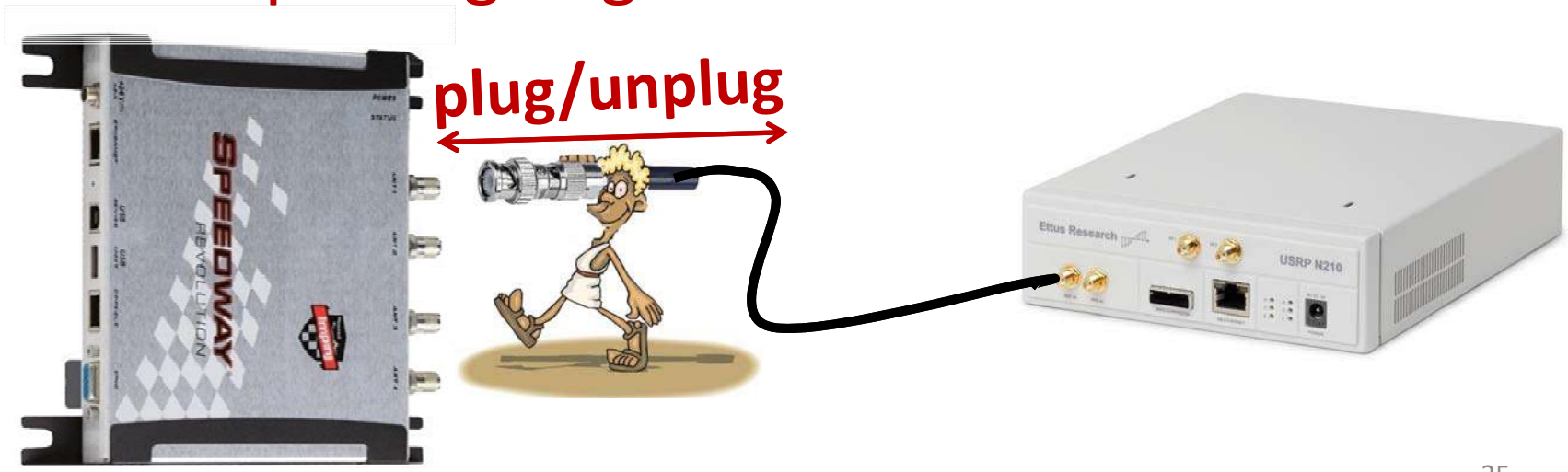
Limitation of Existing Solution for Removing Phase Offset

1. **State-of-the-art wired phase calibration method**

   (ArrayTrrack in NSDI'13**)**

Limitation: Need to plug/unplug antennas.

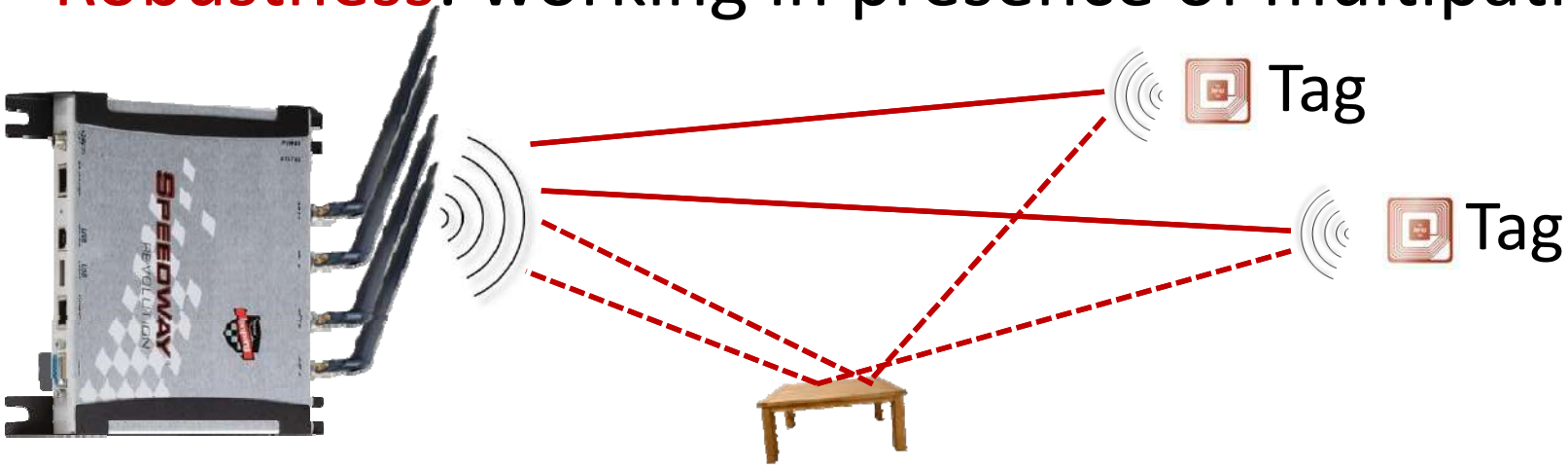
- Time consuming.
- Interrupts ongoing data transmission.



Solution: *Wireless Phase Calibration*

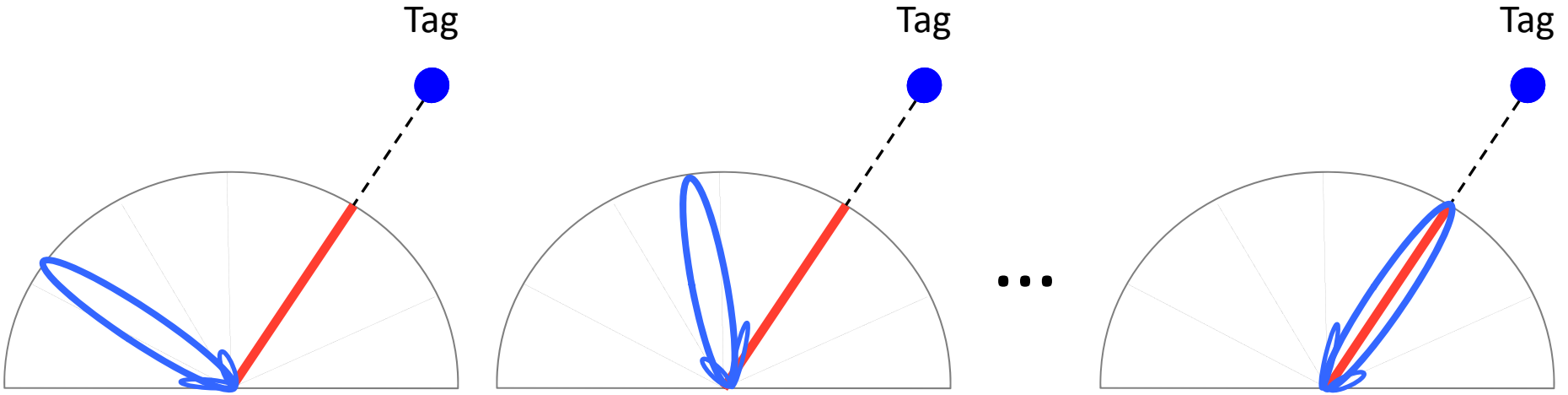
2. Our method for removing phase offset

- Wireless and runs automatically: without interrupting ongoing data transmission.
- Low hardware cost: working with commodity devices, such as RFID devices.
- Robustness: working in presence of multipath.



Solution: *Wireless Phase Calibration*

- **Intuition**: With a given true signal direction, the correct phase offset calibration makes estimated AoA and true direction match.



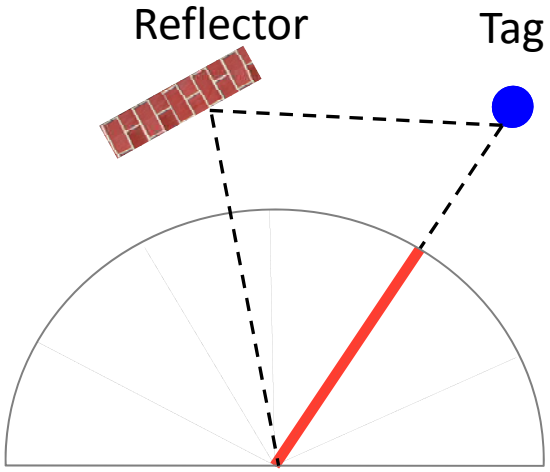
Try:
Phase offset=$\Delta\beta_1$

Try:
Phase offset=$\Delta\beta_2$

Try:
Phase offset=$\Delta\beta_{\text{true}}$

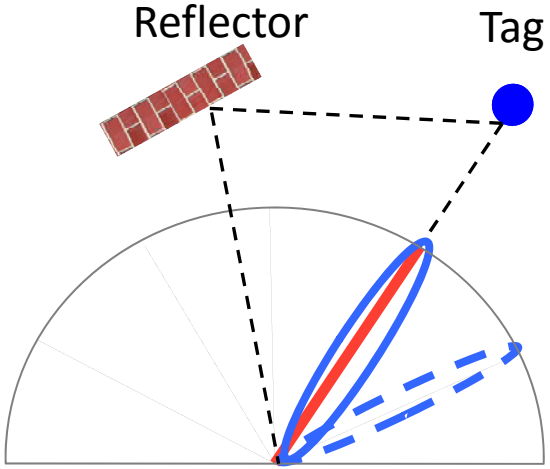
Solution: *Wireless Phase Calibration*

- **Not working in reality**: Ambiguity due to multipath.



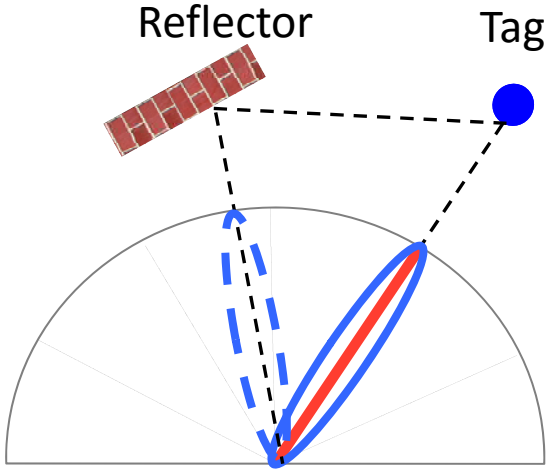
Solution: *Wireless Phase Calibration*

- **Not working in reality**: Ambiguity due to multipath.



Try:

Phase offset=$\Delta\beta_1$



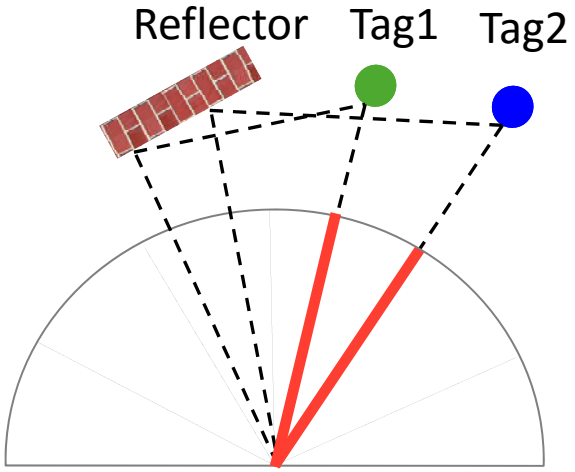
Try:

Phase offset=$\Delta\beta_{\text{true}}$

Which one is right?

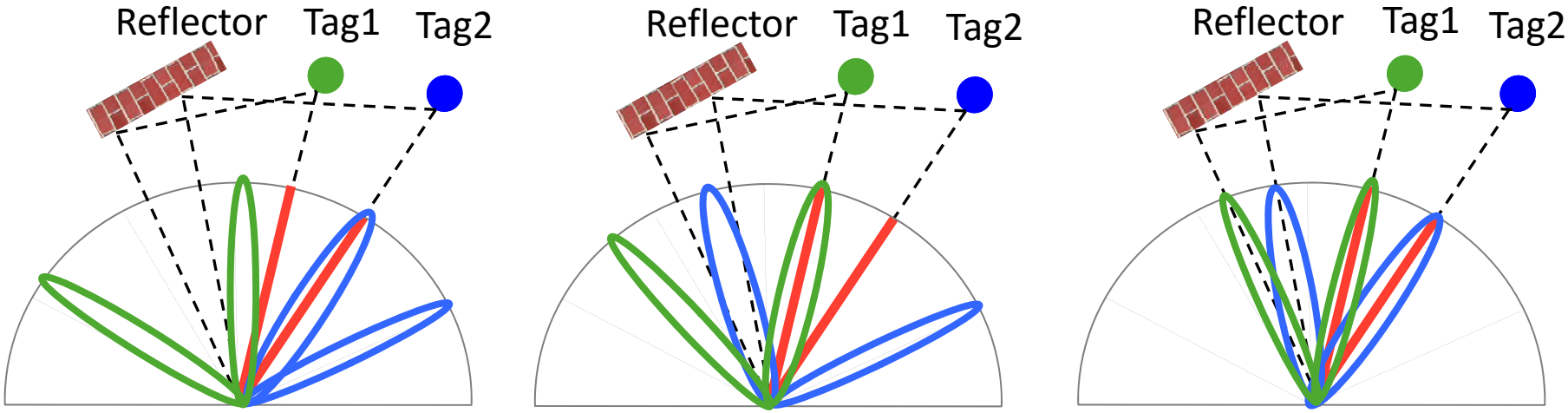
Solution: *Wireless Phase Calibration*

- **Removing ambiguity**: Spatial diversity of tags.



Solution: *Wireless Phase Calibration*

- **Removing ambiguity**: Spatial diversity of tags.



Try:

Phase offset=$\Delta\beta_1$ ✗

Try:

Phase offset=$\Delta\beta_2$ ✗

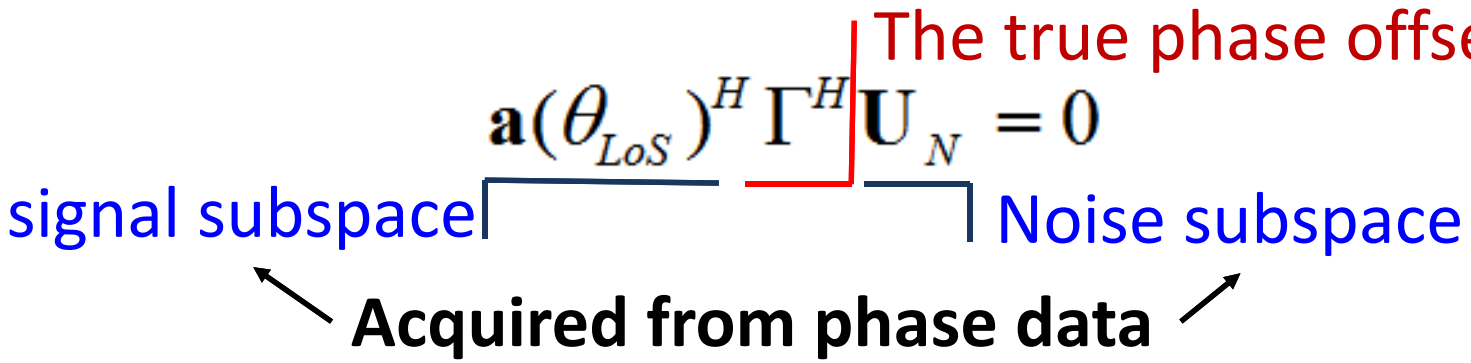
Try:

Phase offset=$\Delta\beta_{\text{true}}$ ✓

This try&test-method is not efficient!

Solution: *Wireless Phase Calibration*

- **Key Observation**: Orthogonality between the signal subspace and noise subspace as:

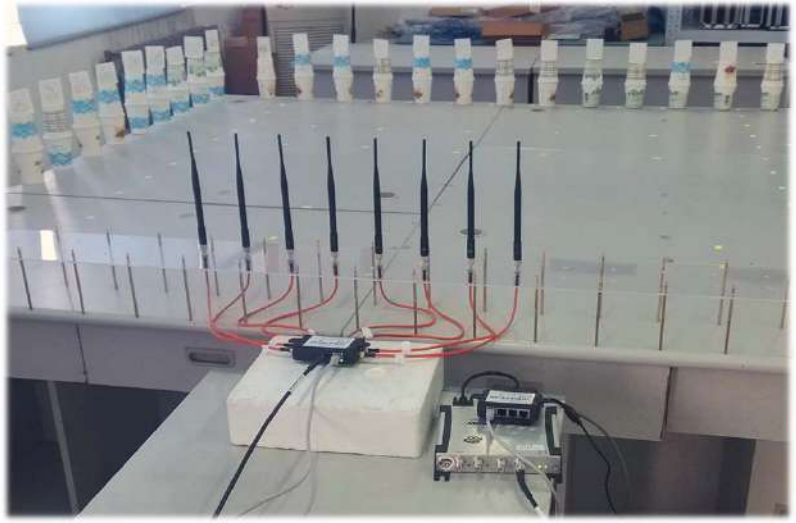


- **Optimization** : Find phase offset that minimize:

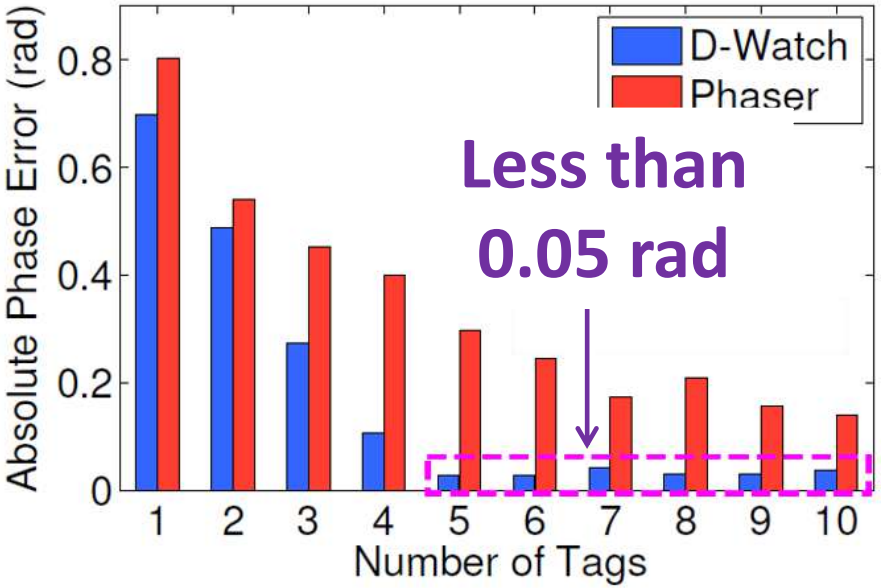
$$\hat{\Gamma} = \arg\min_{\Gamma} \sum_{k=1}^{K} \left\| \mathbf{a}(\theta_{LoS}^{(k)})^H \Gamma^H \mathbf{U}_N^{(k)} \right\|_{l_2}^2$$

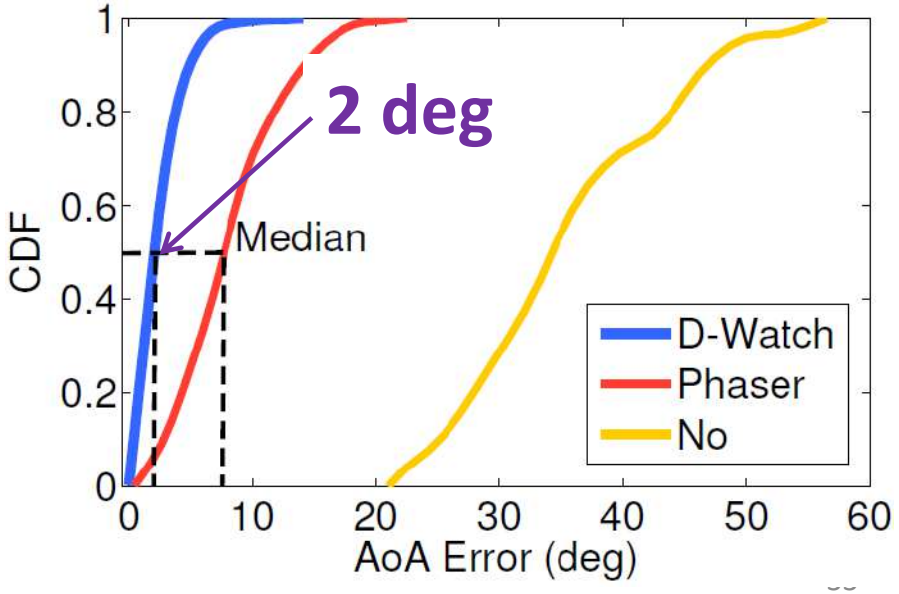
where *K* is the total number of tags.

Benchmark: Phase Calibration Verification



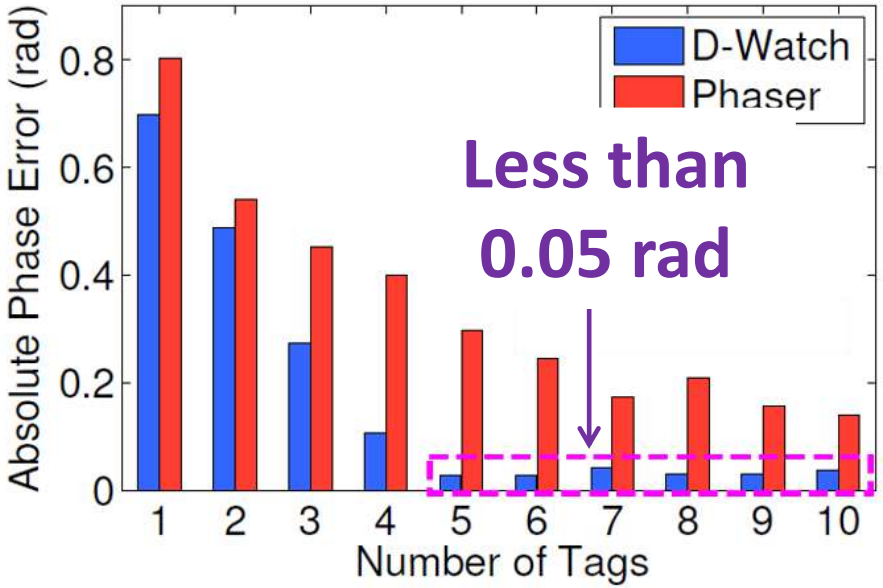
- **Environment:** Indoor
- **Array**: 8 omni-antennas
- **Ground truth**： wired calibration in ArrayTrack[1]

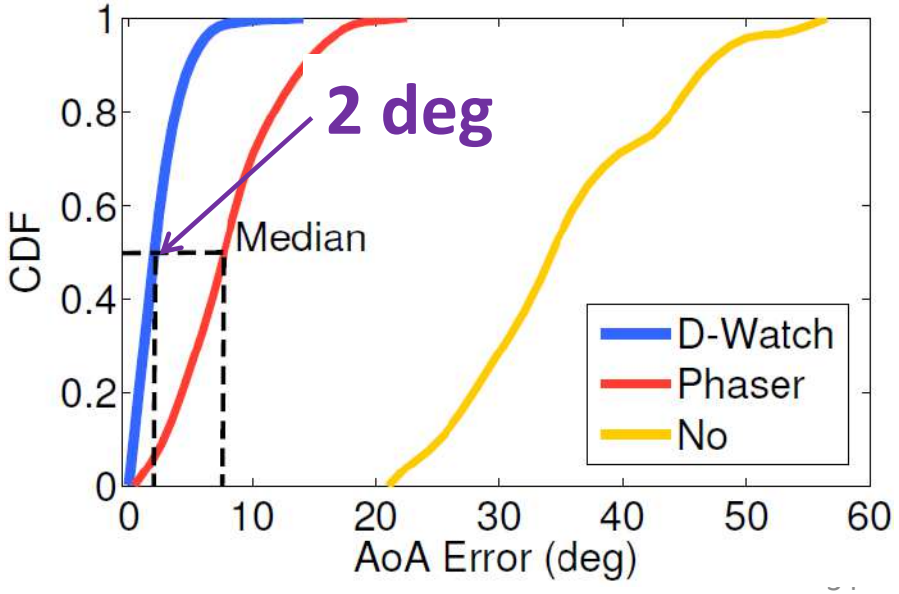




Benchmark: Phase Calibration Verification

Our phase calibration method removes all phase offsets and enables a high precision AoA estimation





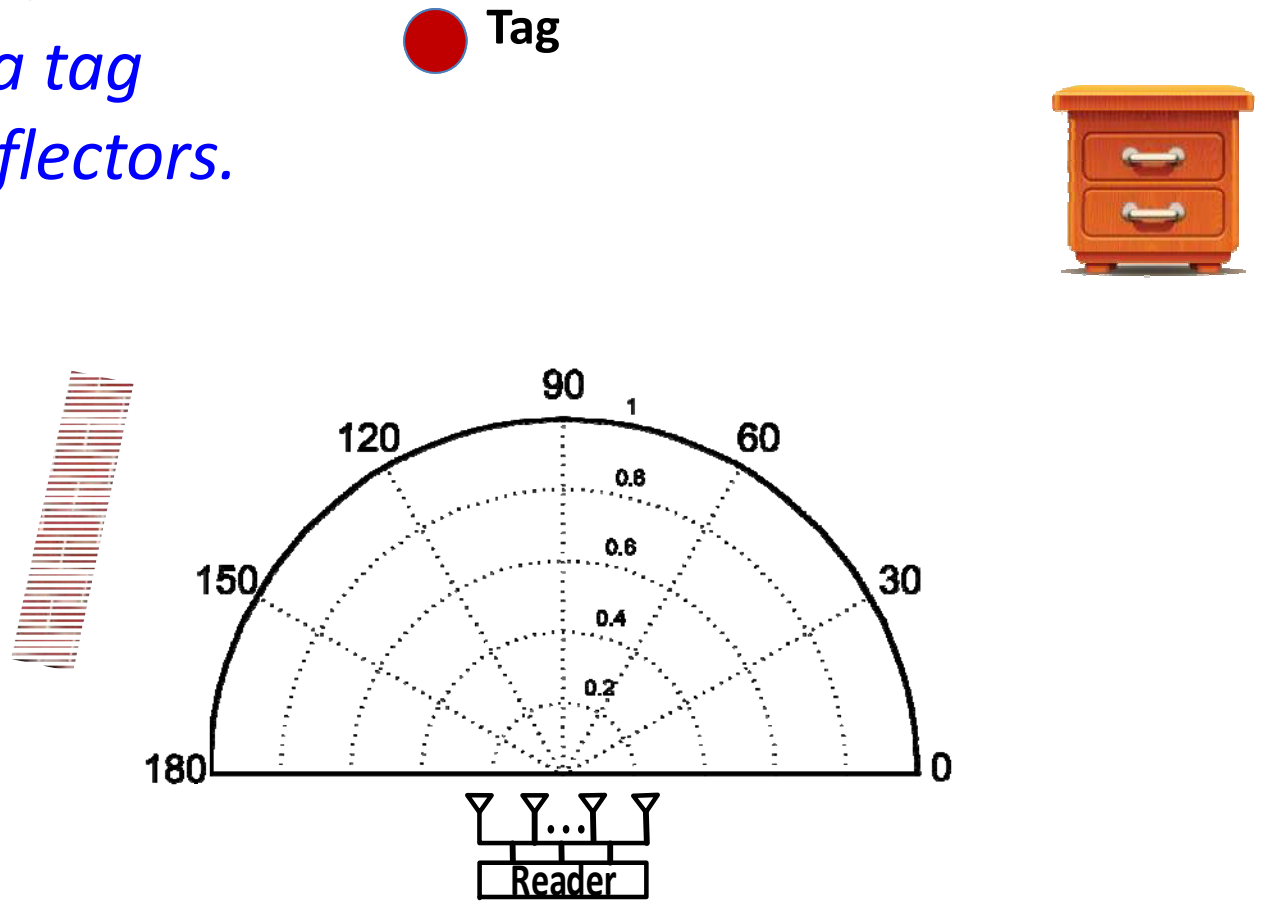
Challenge 2:
MUSIC spectrum is *not* showing the *power* information, results in missing target detection

Limitation of Power Estimation

- Spectrum peak obtained by MUSIC is not a power indication, **results in missing target detection.**

Benchmark:

Deploying a tag and two reflectors.

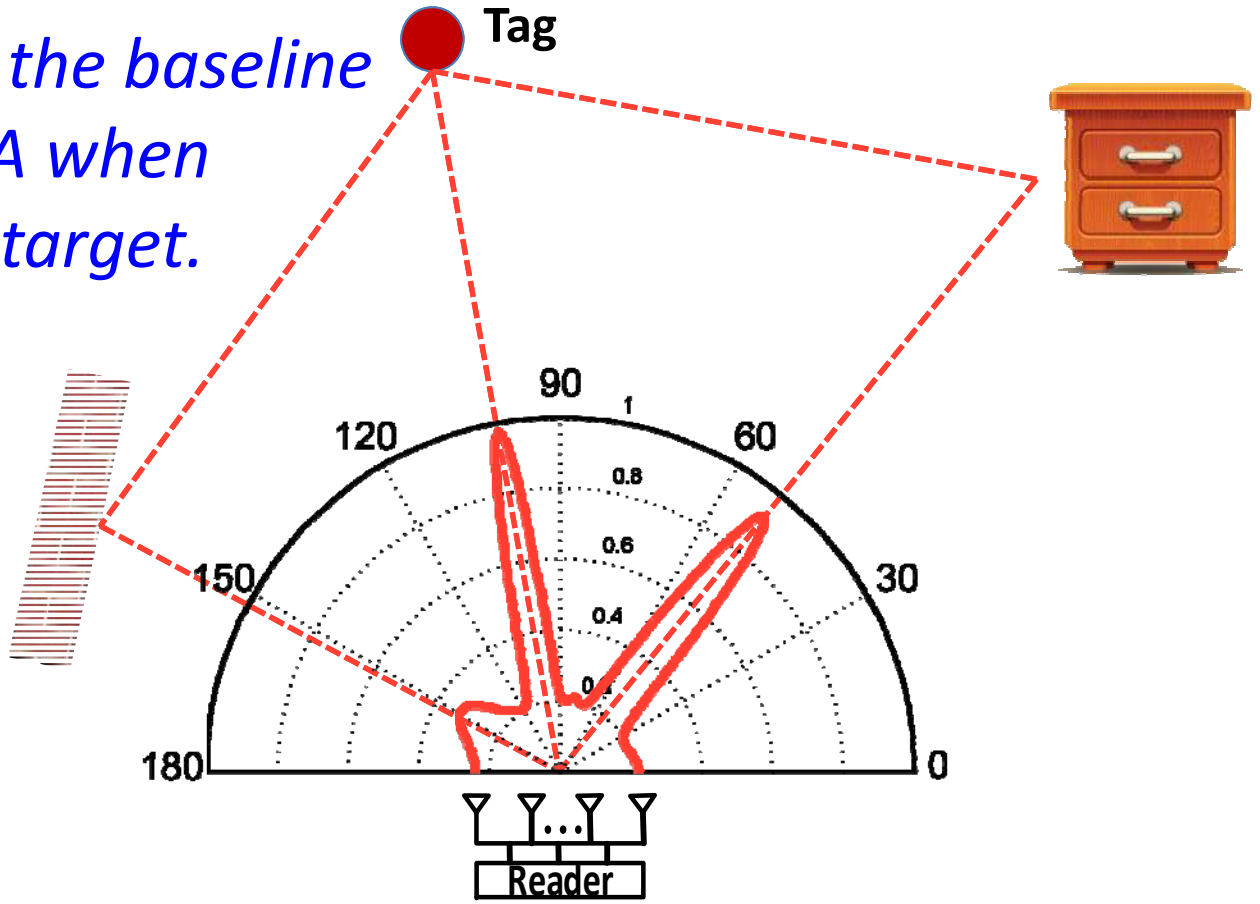


Limitation of Power Estimation

- Spectrum peak obtained by MUSIC is not a power indication, **results in missing target detection.**

Benchmark:

Measuring the baseline MUSIC AoA when there is no target.

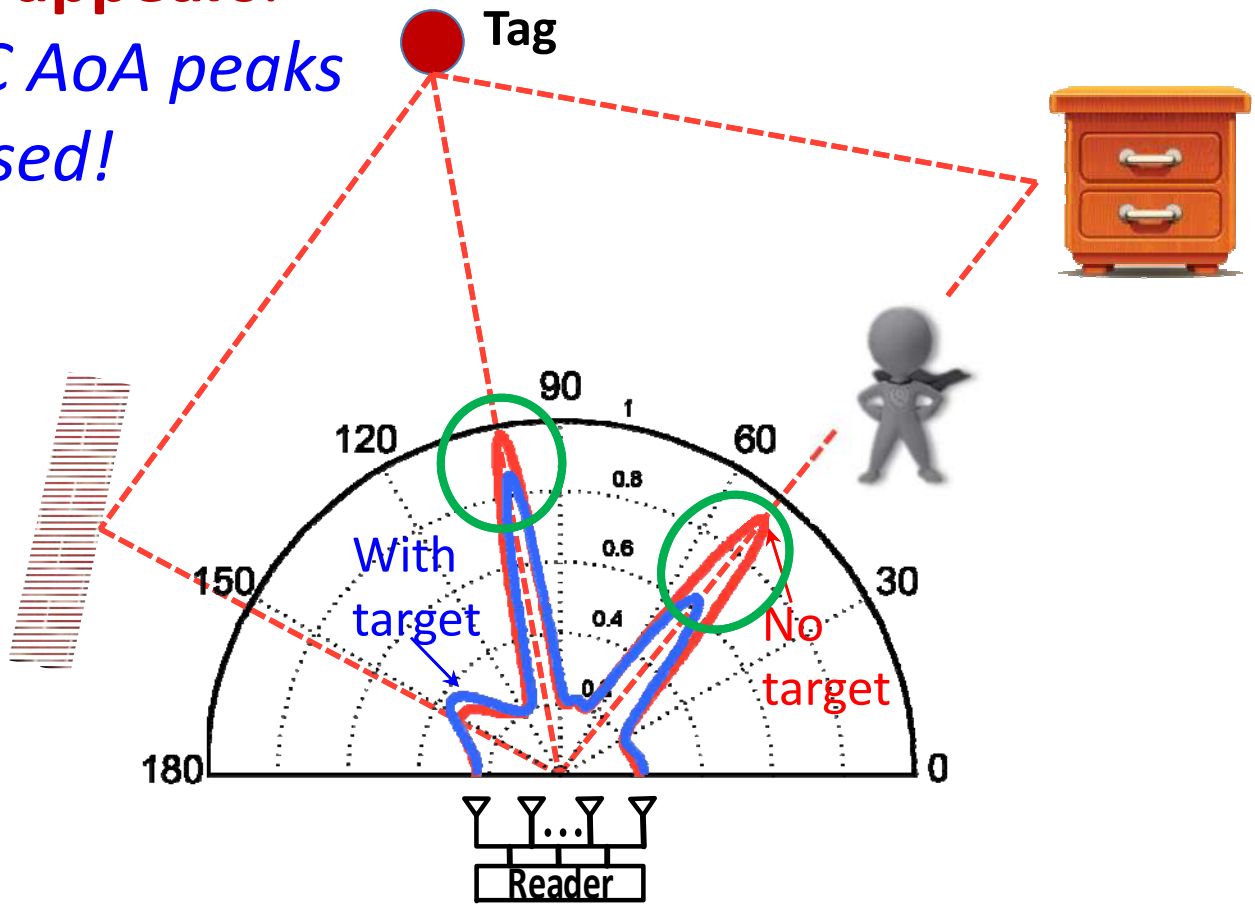


Limitation of Power Estimation

- Spectrum peak obtained by MUSIC is not a power indication, **results in missing target detection.**

One target appears:

Two MUSIC AoA peaks are decreased!

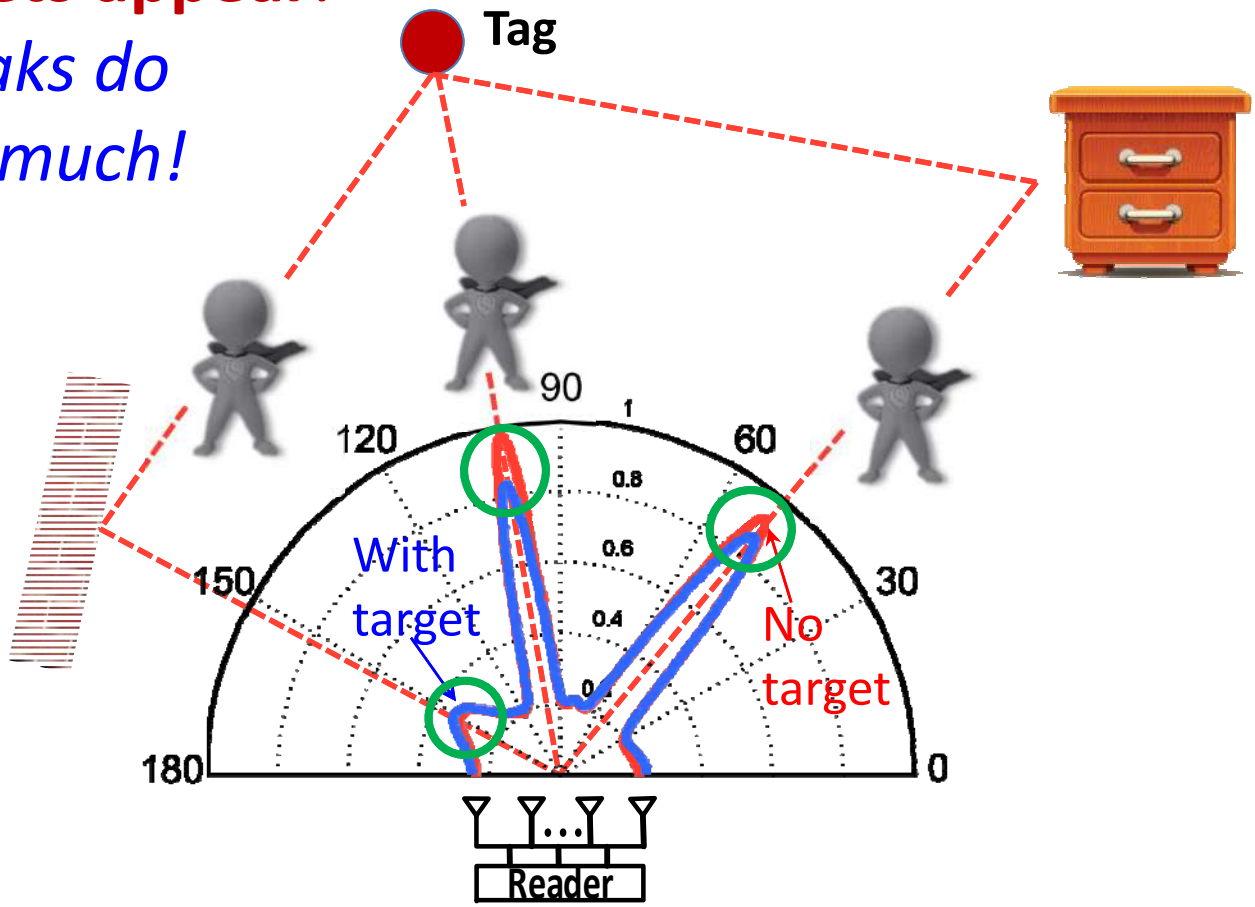


Limitation of Power Estimation

- Spectrum peak obtained by MUSIC is not a power indication, **results in missing target detection.**

Three targets appear:

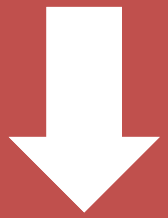
All AoA peaks do no change much!



Limitation of Power Estimation

- Spectrum peak obtained by MUSIC is not a power indication, **results in missing target detection.**

MUSIC will miss some blocked paths

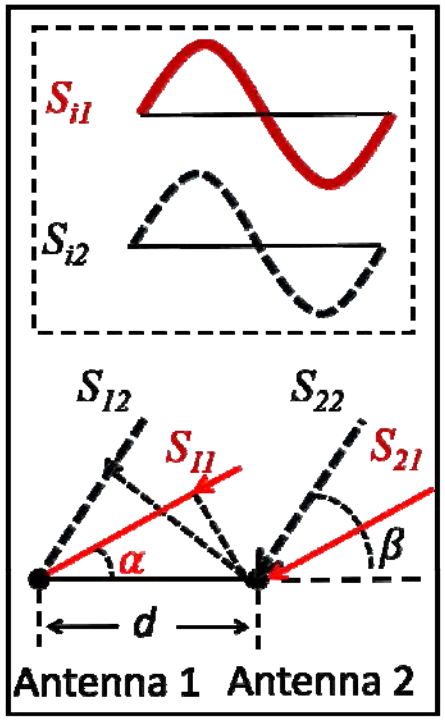


Targets may not be detected!

Key objective:
obtain the accurate signal power along each path

Signal Path Power Estimation

- **Key idea**: leveraging spatial diversity of signal phase to boost power at desired directions.



(a)

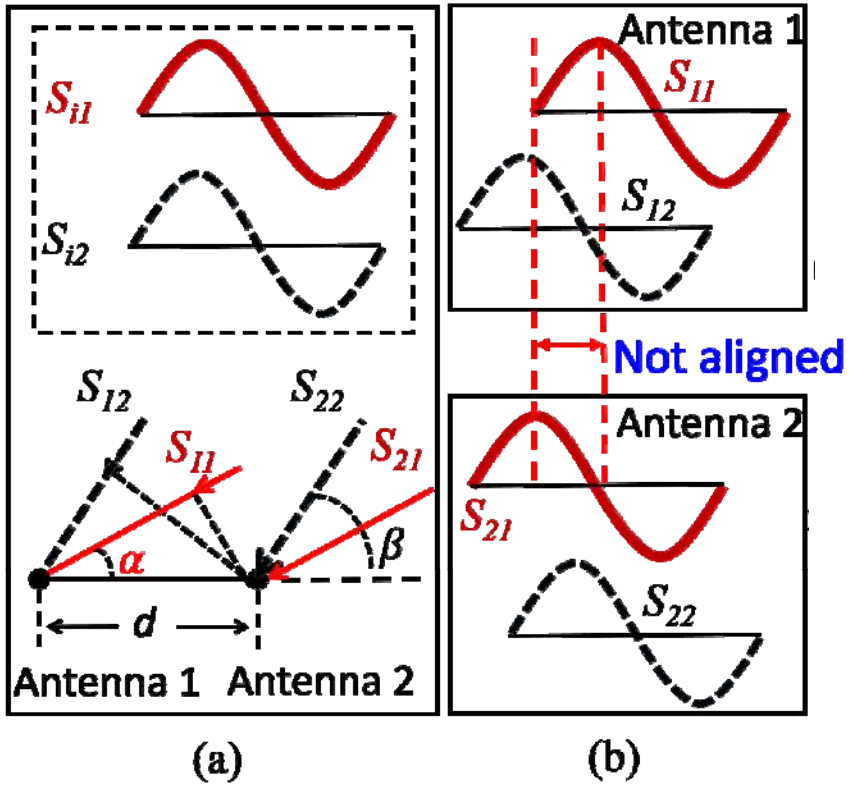
Objective

- Boost ***S1*** in red
- Average out ***S2*** in black

Fig(a)-(d). Illustration of obtaining the desired signal at one particular direction

Signal Path Power Estimation

- **Key idea**: leveraging spatial diversity of signal phase to boost power at desired directions.



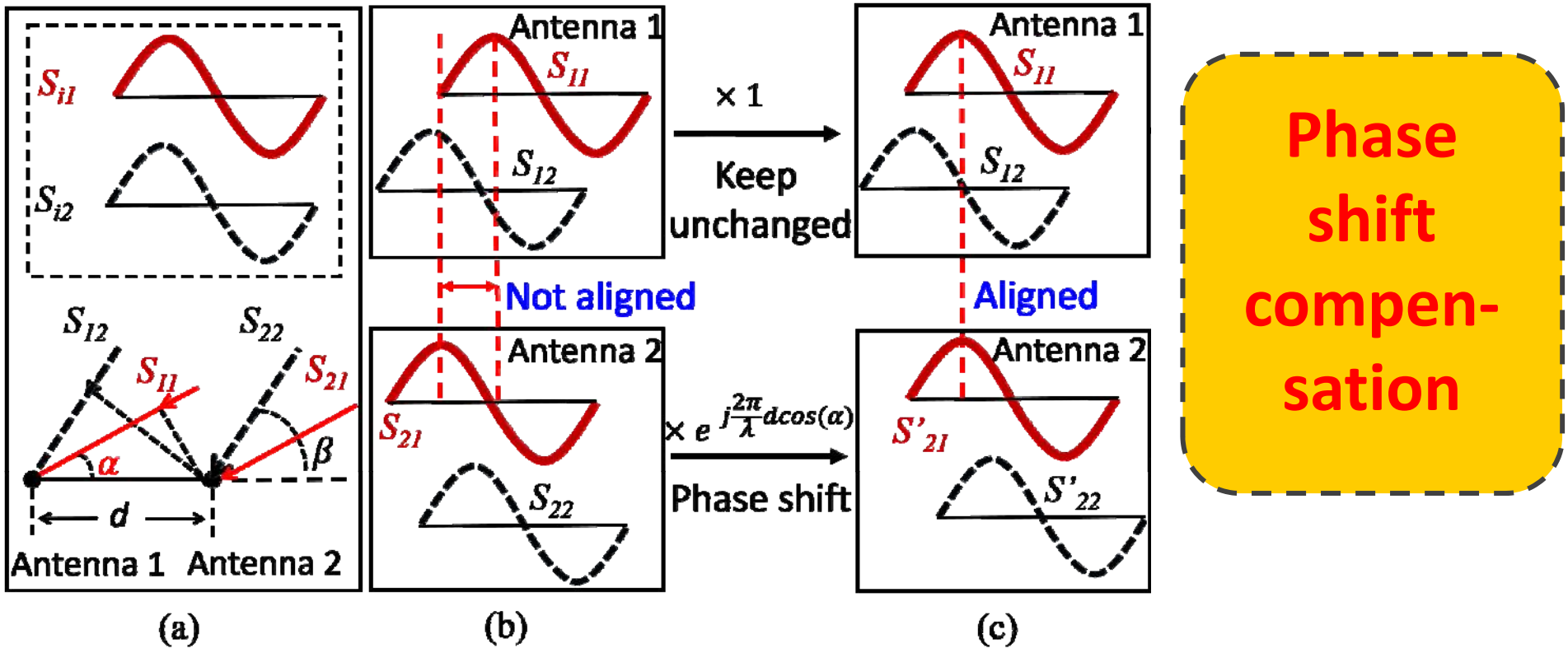
Spatial diversity

- Received signals are not aligned.
- Phase shift can be determined.

Fig(a)-(d). Illustration of obtaining the desired signal at one particular direction

Signal Path Power Estimation

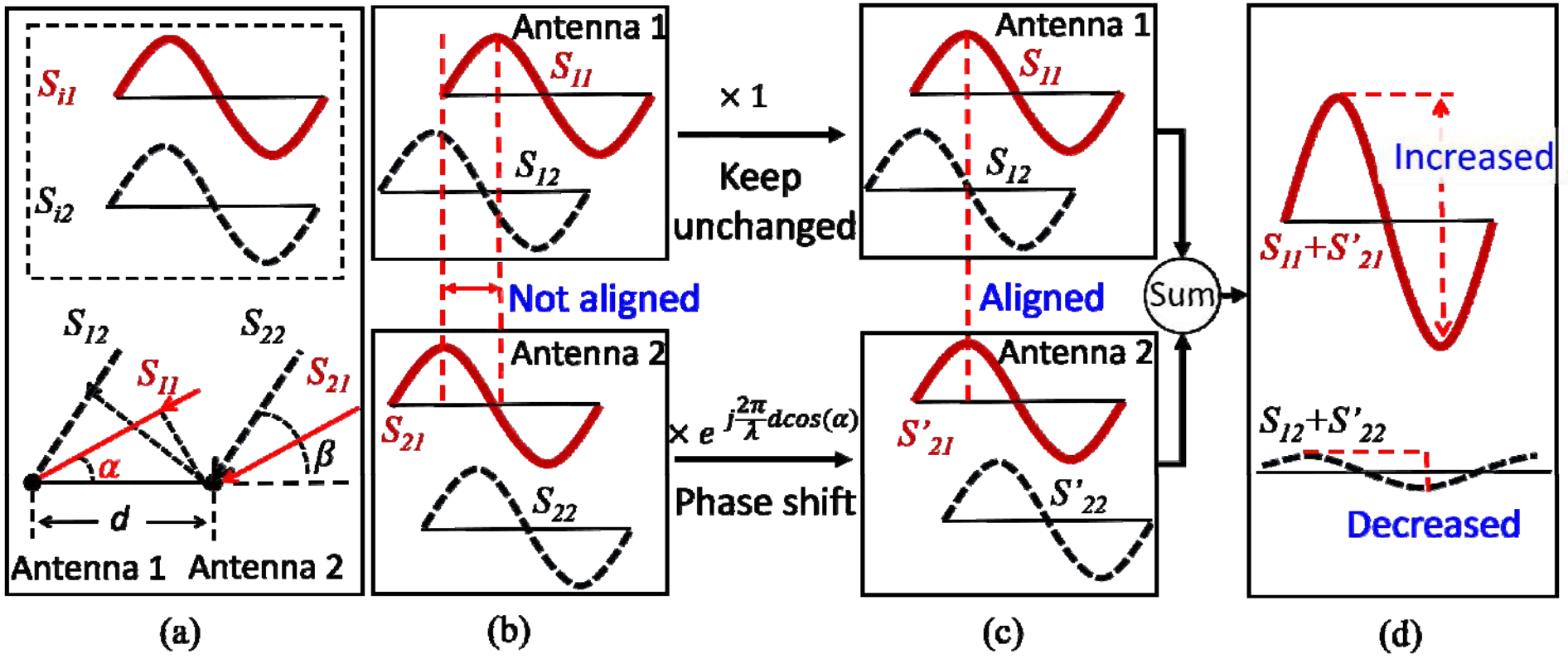
- **Key idea**: leveraging spatial diversity of signal phase to boost power at desired directions.



Fig(a)-(d). Illustration of obtaining the desired signal at one particular direction

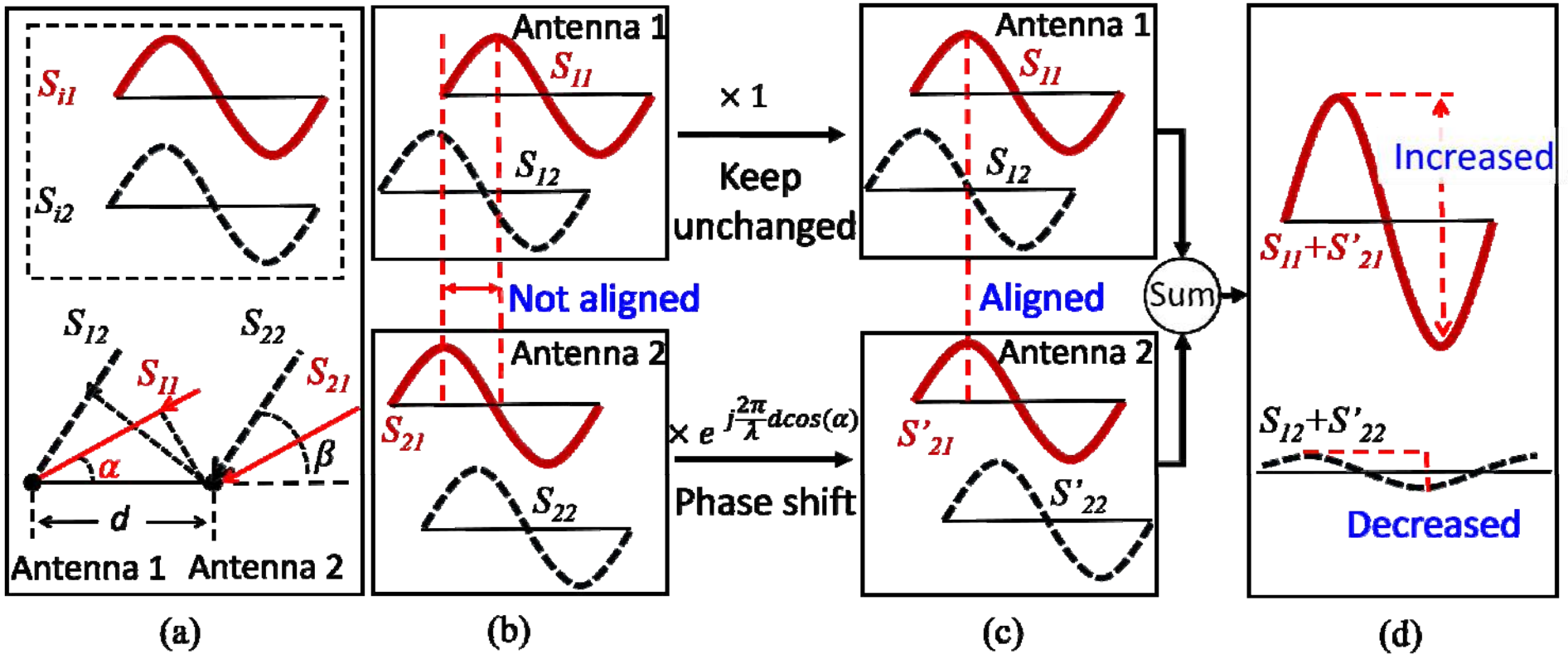
Signal Path Power Estimation

- **Key idea**: leveraging spatial diversity of signal phase to boost power at desired directions.



Fig(a)-(d). Illustration of obtaining the desired signal at one particular direction

With more antennas, signal power along designed direction will be much higher than power along other directions!



Fig(a)-(d). Illustration of obtaining the desired signal at one particular direction

Putting Things Together: Power MUSIC

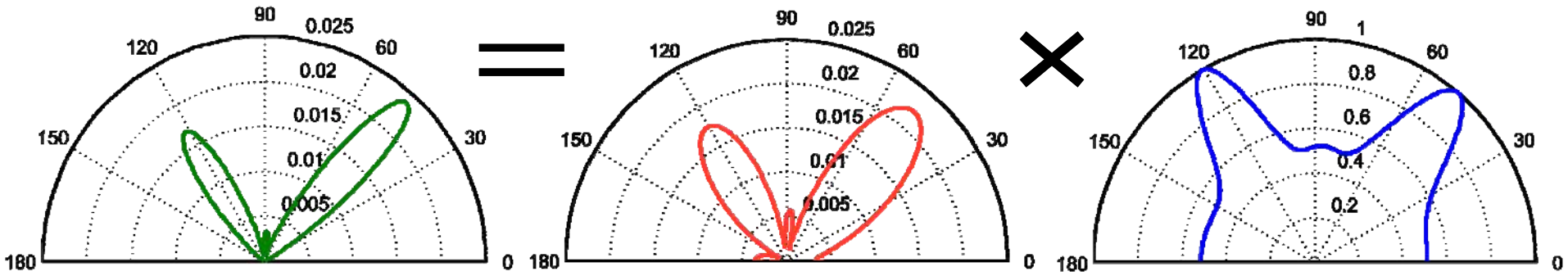
- Power MUSIC is a joint **AoA** and path **power** estimation method.
- The spectrum estimated by Power MUSIC is:

$$\Omega(\theta_p) = P(\theta_p) \times Nor(B(\theta_p))$$

Power MUSIC spectrum

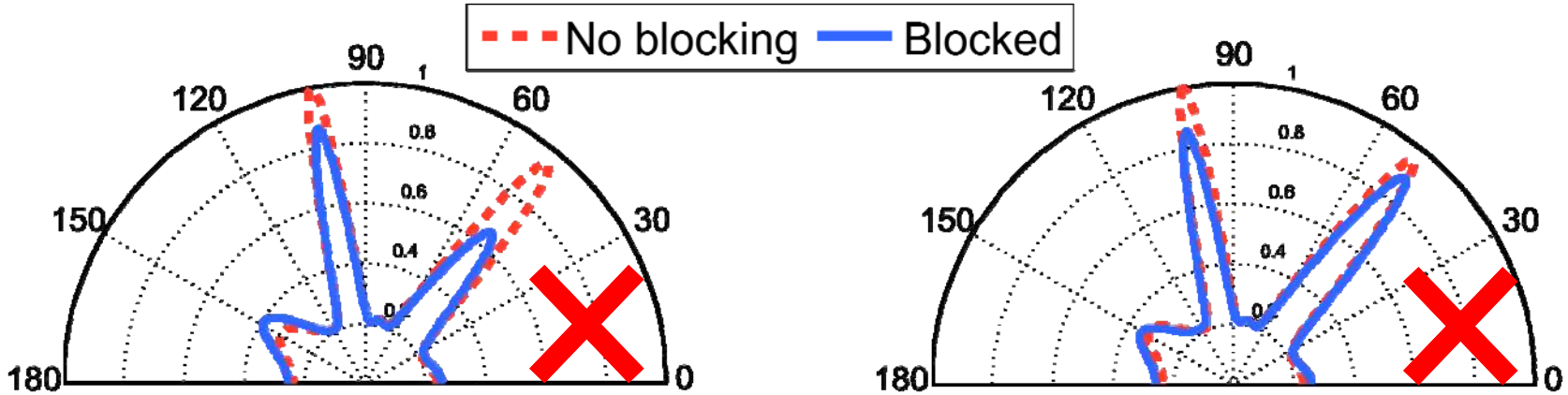
Power provided by this work

Angle provided by MUSIC



Benchmark: Power-MUSIC Verification

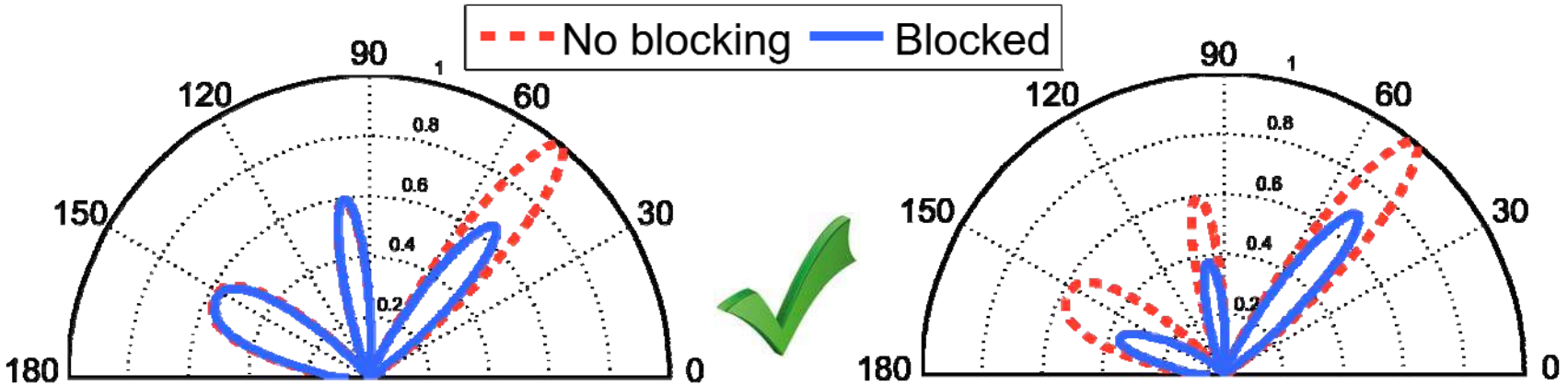
- **MUSIC**: Can not identify the power decrease



One path at 50° is blocked

All **three** paths are blocked

- **Power-MUSIC**: highly sensitive to power decrease



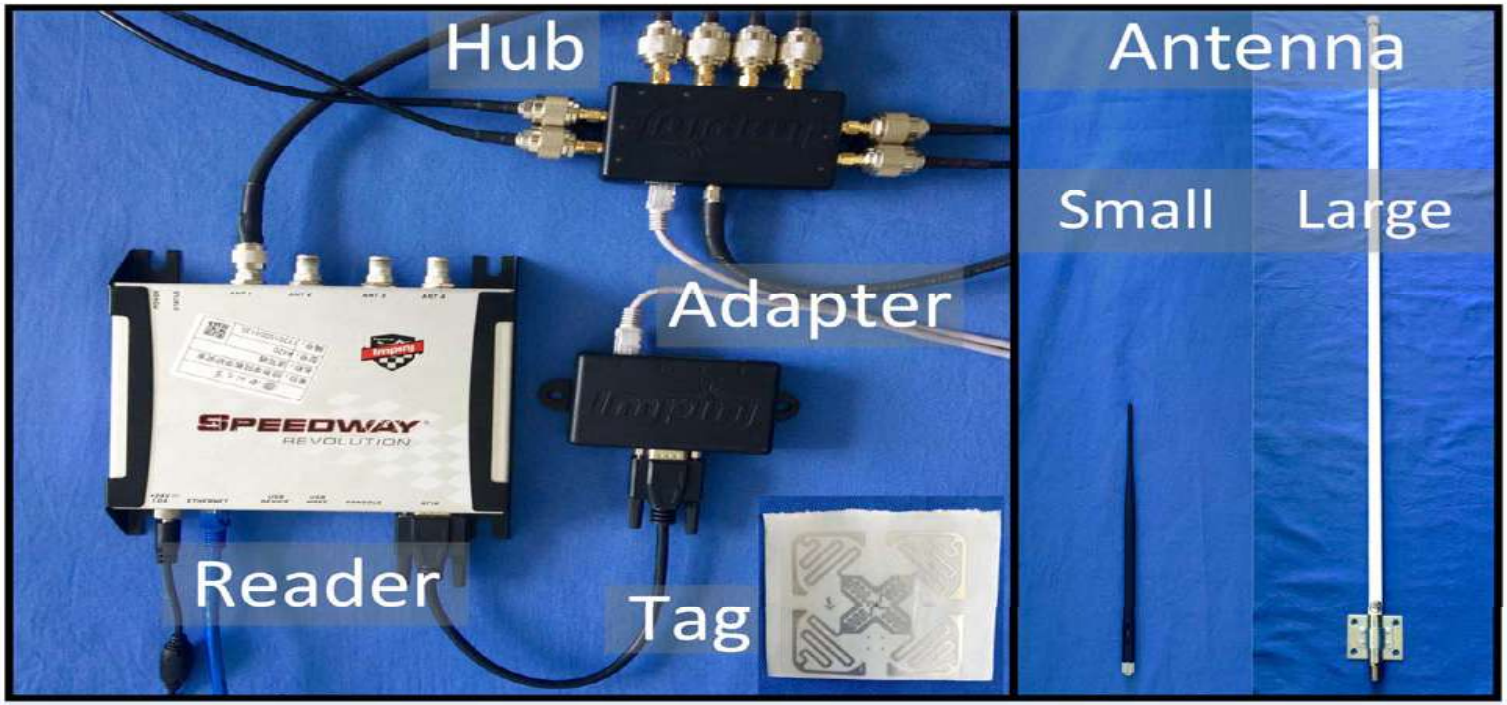
One path at 50° is blocked

All **three** paths are blocked

Implementation & Evaluation

Implementation

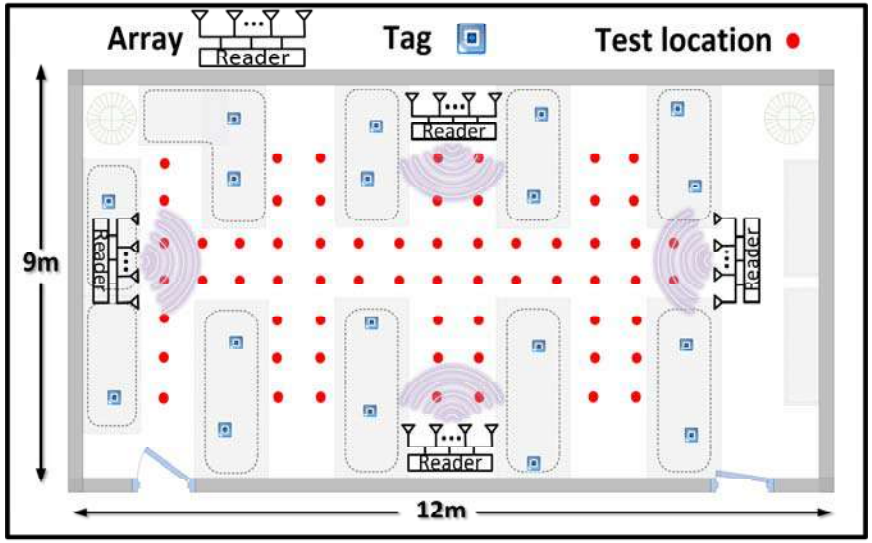
- **Reader and Tag**: **4** Impinj Speedway R420 readers; **21** cheap Alien ALN-9634 tags.
- **Objective**: ***Device-free*** localize a target (human).



Evaluation in Medium Multipath

- Laboratory environment: ***medium*** multipath.

Laboratory environment



Testbed floorplan

Evaluation in LoS & NLoS

- Hall and Library environments, corresponding to ***low*** and ***high*** multipath.

Strong LoS

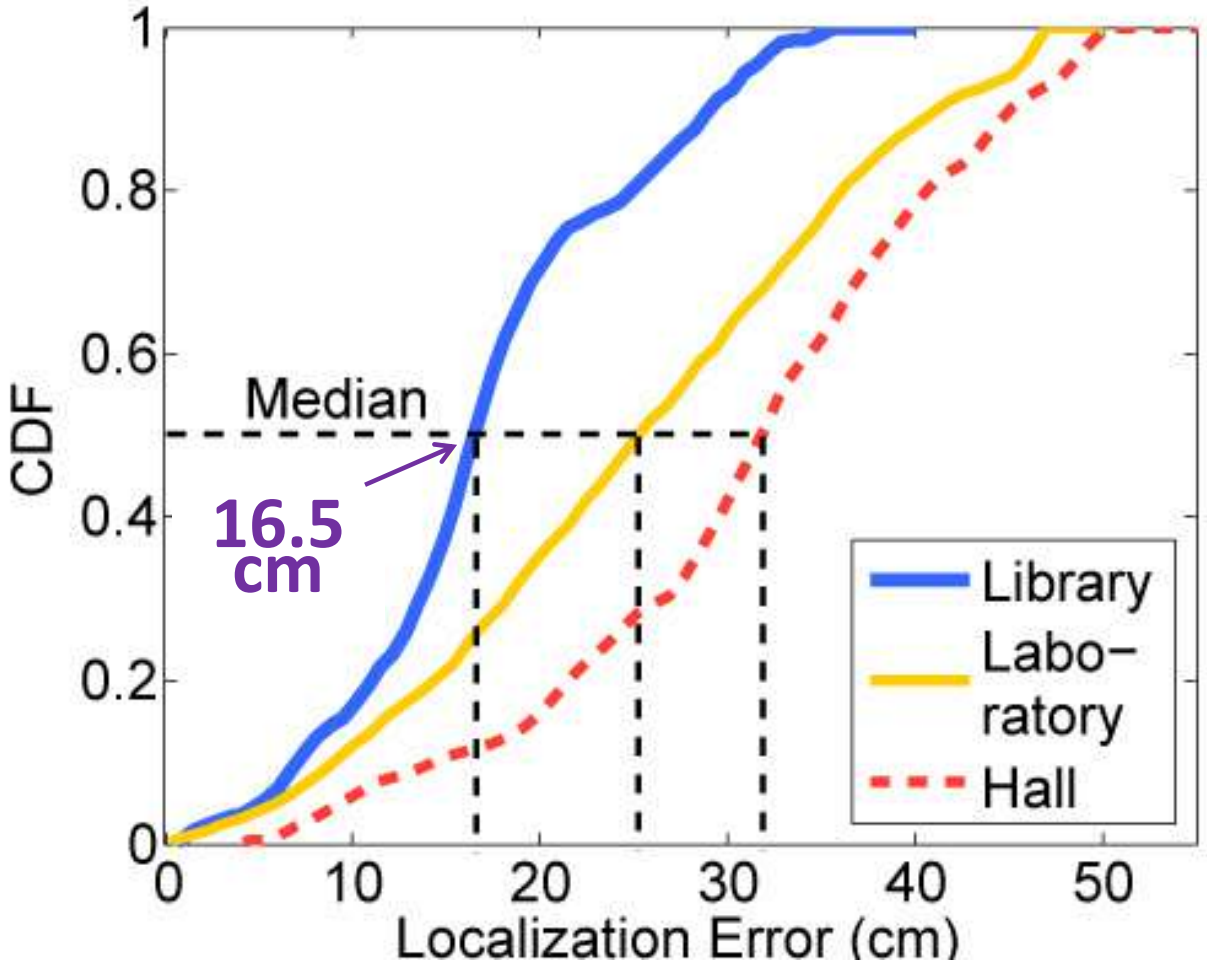
(7.2 m x 10.4 m)

Strong NLoS

(7 m x 10 m)

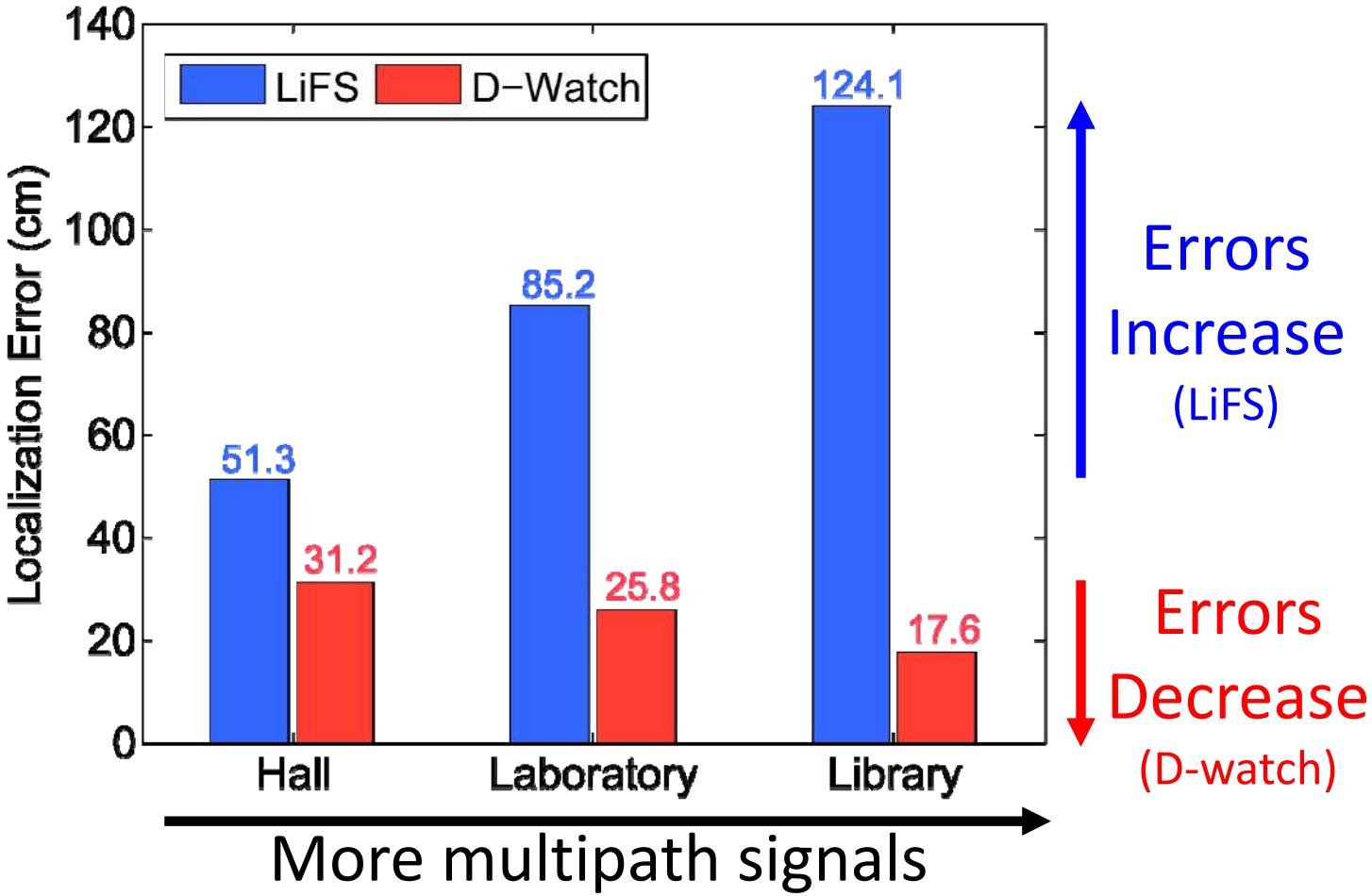
Experimental Results

- Localization errors under different environments.



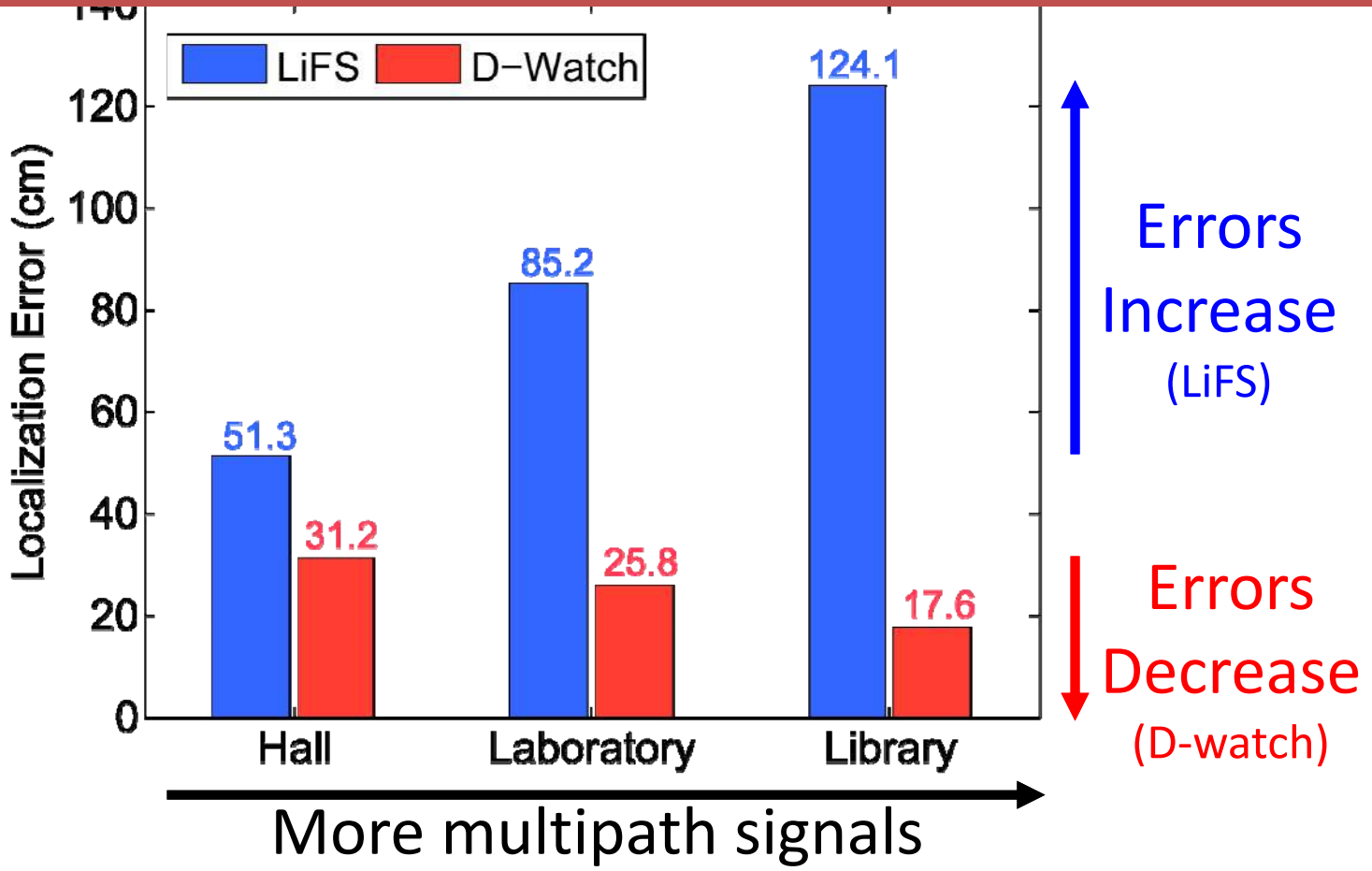
Experimental Results

- Accuracy comparison with LiFS (Mobicom'16)



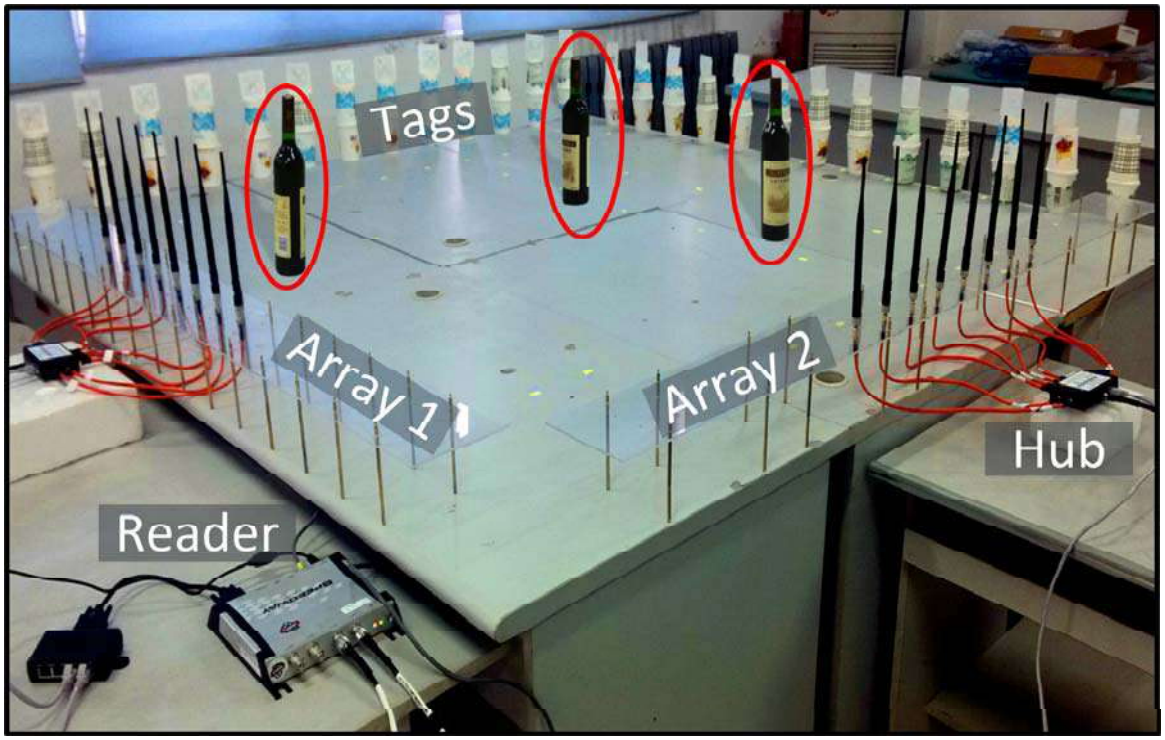
Experimental Results

D-Watch efficiently leverages multipath to improve the localization accuracy!



Three-Target Localization

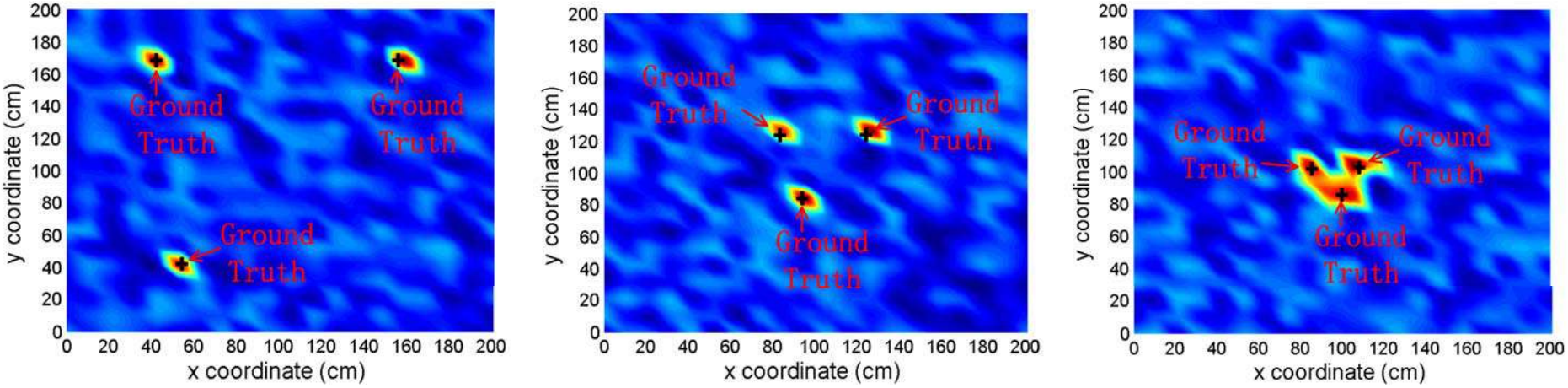
- **Intuition**: a target is not able to block all the paths simultaneously.



2m×**2m** table with three glass bottle targets

Three-Target Localization

- **Intuition**: a target is not able to affect all the wireless links simultaneously.

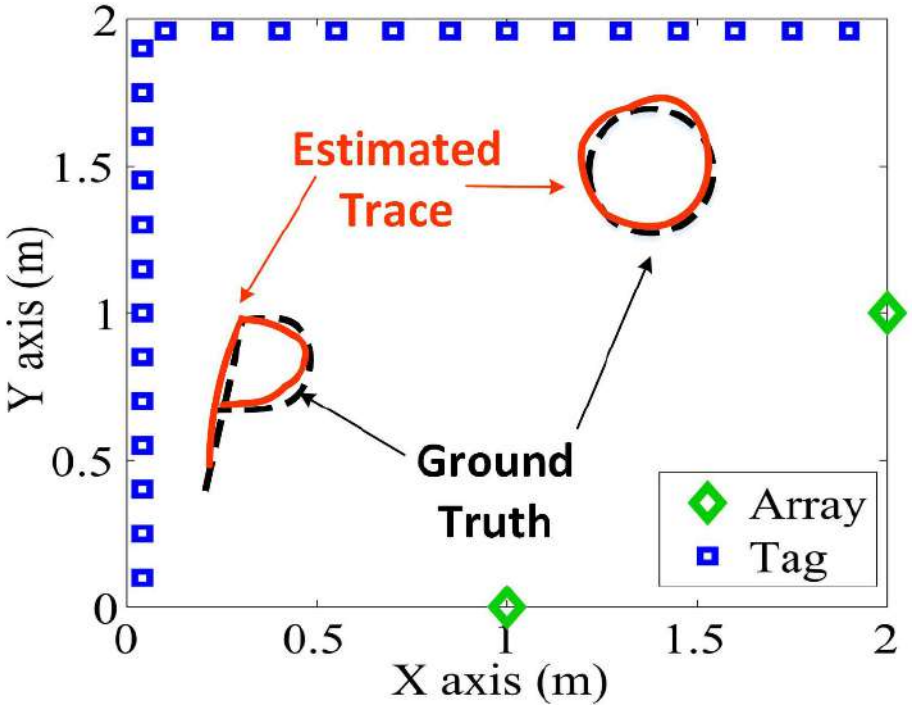


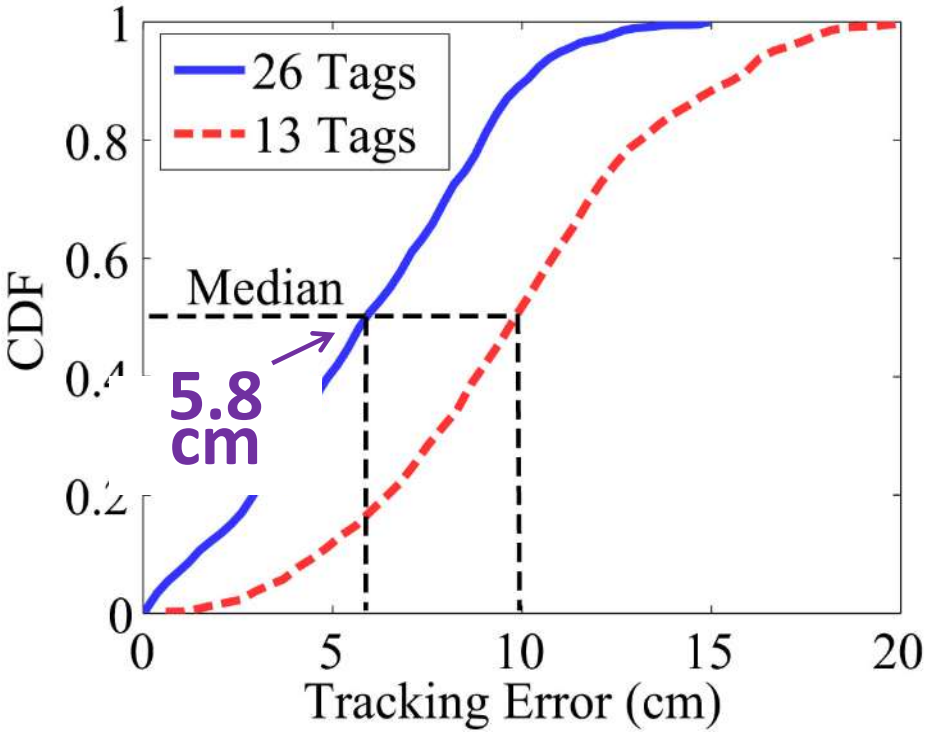
Three snapshot localization results when three targets are **130 cm**, **50 cm** and **20 cm** apart.

D-Watch localizes each individual target accurately when they are not too close!

Application : Tracking Fist in the Air

- Writing “P” and “O” with fist in the air.
- Passively tracking the fist’s writing.





Conclusion

- **Device-free localization** is important for many applications.
- D-Watch efficiently utilizes the **``bad'' multipath** to passively localize a target.