3-Dimensional Localization via RFID Tag Array

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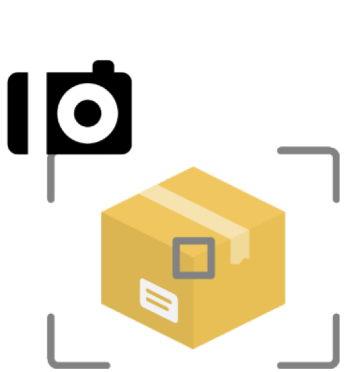
Outline

1. Motivation and Challenges
2. Modeling the 3D Localization
3. Our Solution: 3DLoc
4. Performance Evaluation
5. Conclusion

Motivation

- **Indoor Localization can be realized with the help of RFID.**



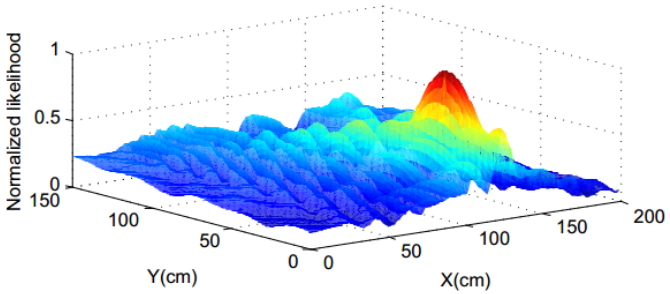
Accurate 3D Localization

Existing RFID Localization schemes

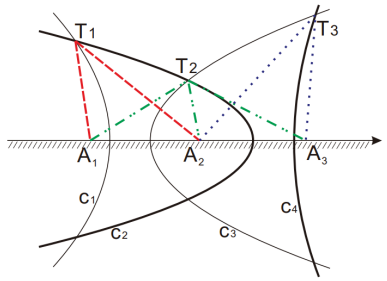
- **RFID localization**

2D localization

RF-IDraw
(SIGCOMM, 14)



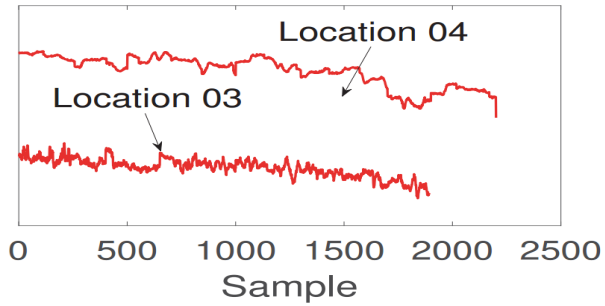
Tagoram
(MOBICOM , 14)



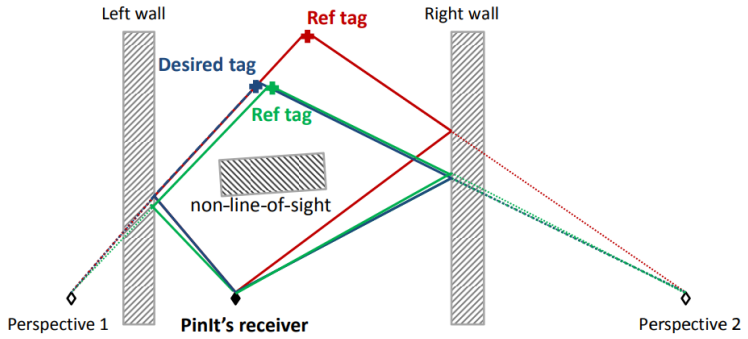
BackPos
(INFOCOM, 14)

- **Multipath suppression**

Multi-Frequency & Reference Tag



MobiTagbot
(MOBICOM, 2014)



PinIt
(SIGCOMM,13)

Challenges

- The 3D localization results can be impacted **multipath effect**
  - → AoA-based mobile scanning scheme

    Remove the unexpected according to linear relationship of the AoA parameters.

- The **orientation** of the tagged objects is essential to be firstly determined before performing accurate 3D localization
  - → Attach three tag arrays to three mutually orthogonal surfaces

Modeling the 3D Localization

- **AOA-based Localization**

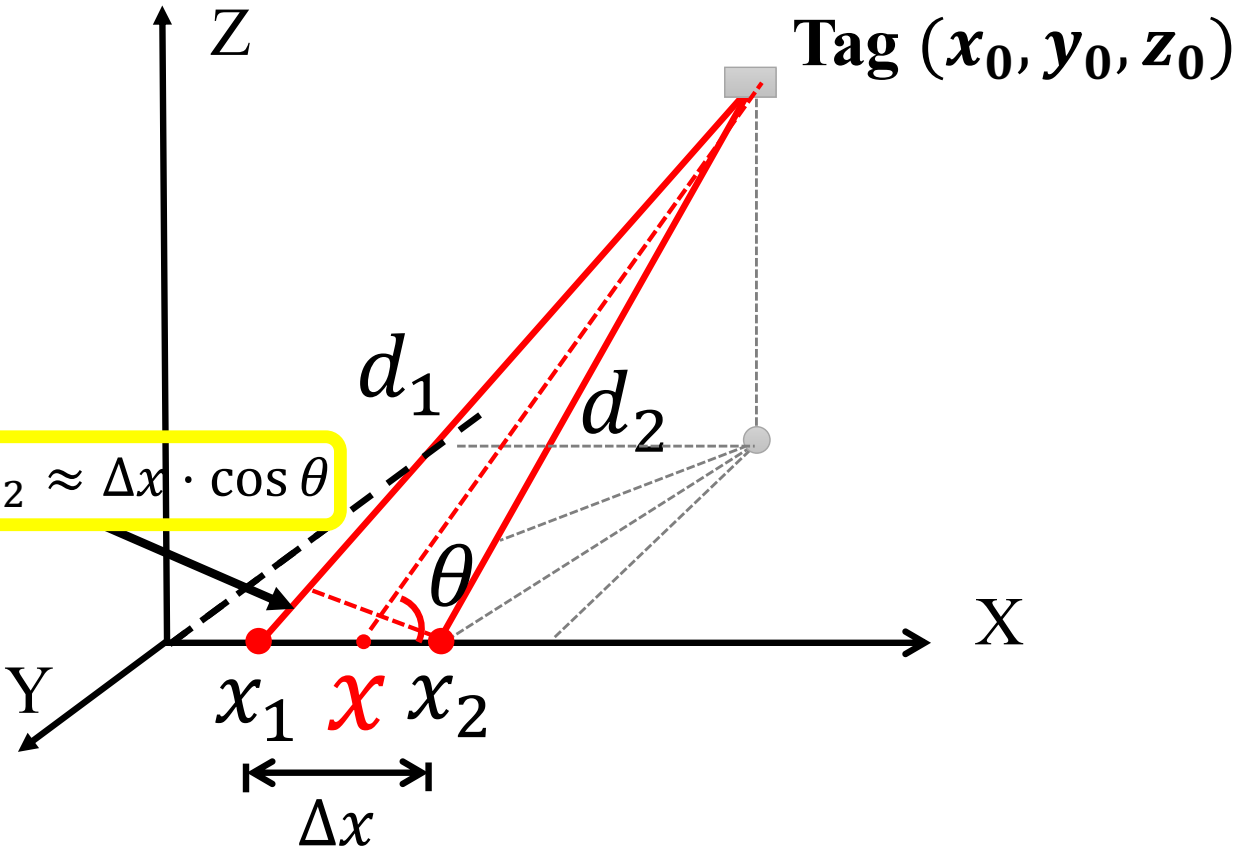
phase difference → angle of arrival

$$\Delta\emptyset_{1,2} = 2\pi \cdot \frac{2\Delta d_{1,2}}{\lambda} + 2k\pi$$

$$\cos\theta = \frac{\lambda(\Delta\emptyset_{1,2} - 2k\pi)}{4\pi\Delta x}$$

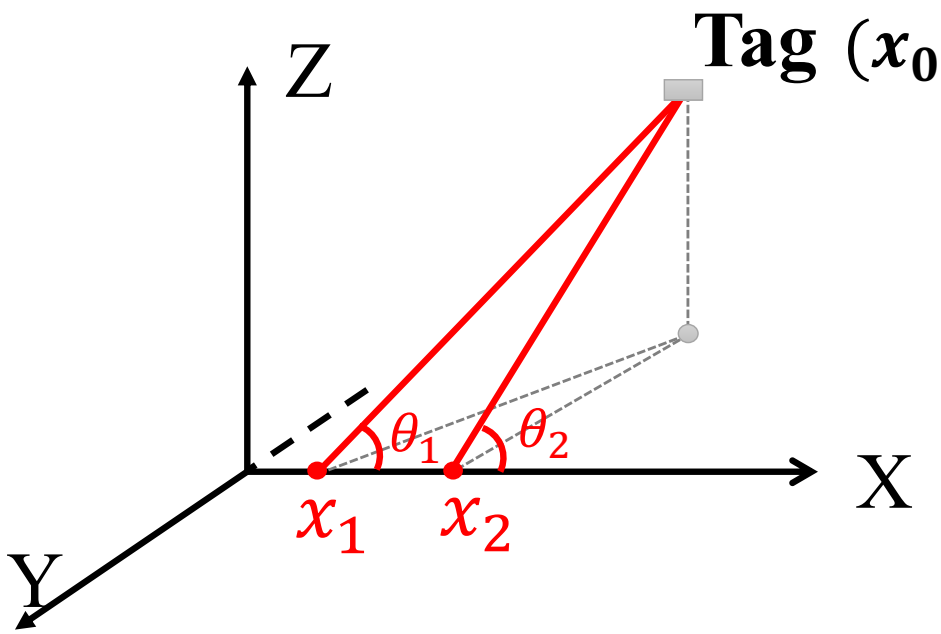
$$\begin{cases} \theta = \cos^{-1}\left(\frac{\lambda \cdot \Delta\emptyset_{1,2}}{4\pi\Delta x}\right) \\ x = \frac{x_1 + x_2}{2} \end{cases}$$

$$\Delta d_{1,2} \approx \Delta x \cdot \cos\theta$$



Modeling the 3D Localization

- **AOA-based Localization**

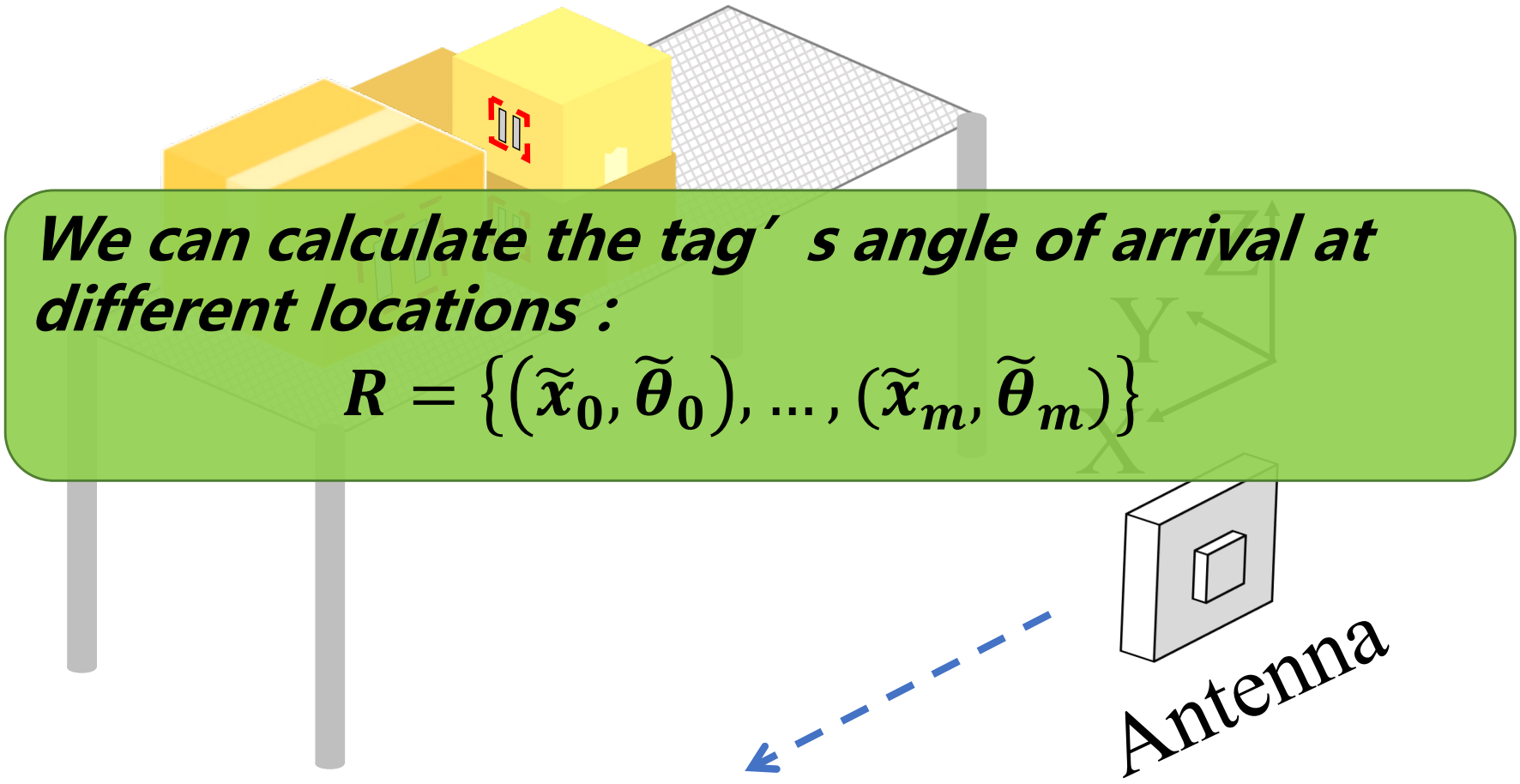


multipath effect

$$\emptyset \Rightarrow \theta = \cos^{-1}\left(\frac{\lambda \cdot \Delta\emptyset}{4\pi\Delta x}\right) \Rightarrow$$

Localization Error

Modeling the 3D Localization



We can calculate the tag's angle of arrival at different locations :

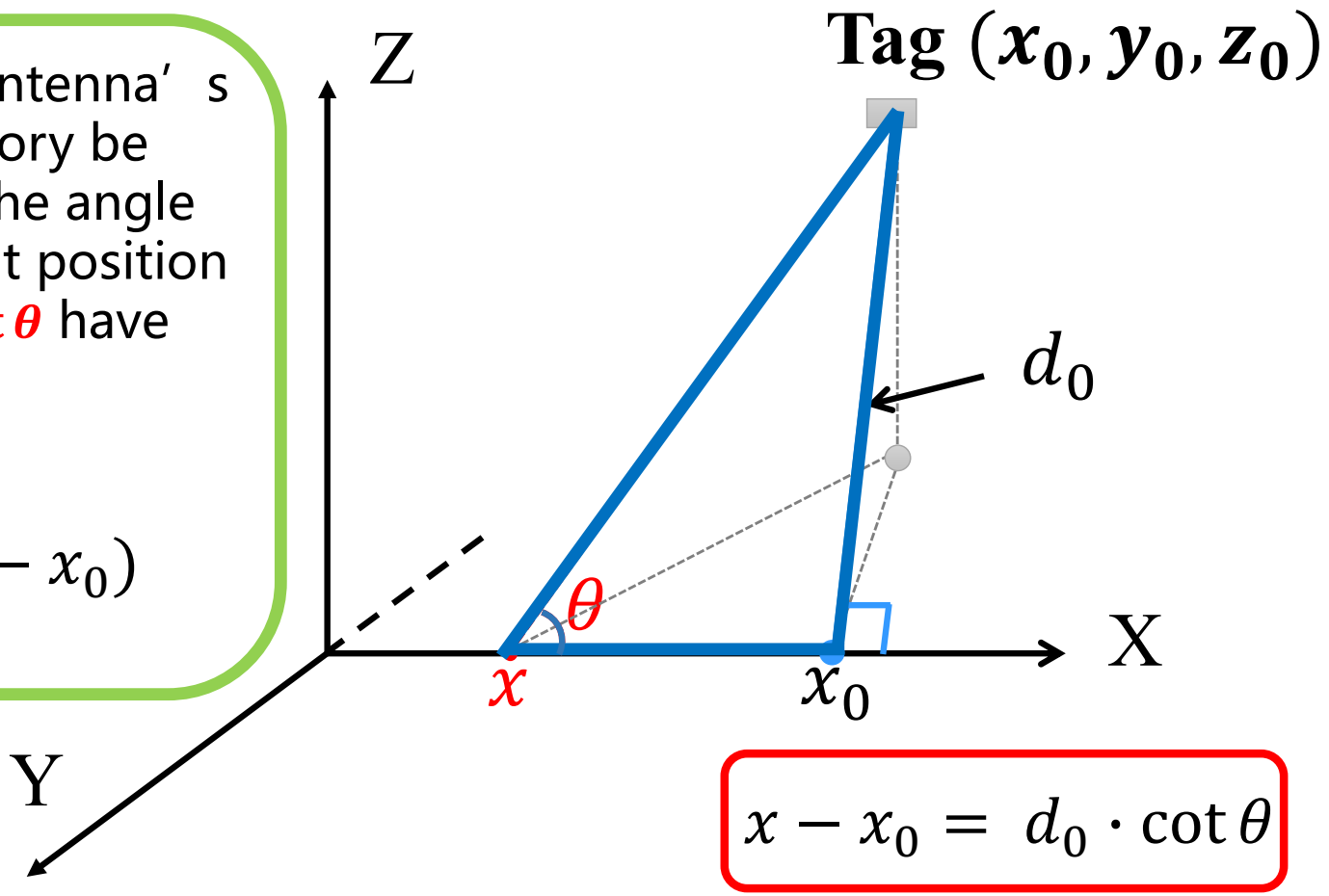
$$R = \{(\tilde{x}_0, \tilde{\theta}_0), \ldots, (\tilde{x}_m, \tilde{\theta}_m)\}$$

Modeling the 3D Localization

- **AoA Localization via Mobile Scanning**

Theorem 1: Let the antenna's linear moving trajectory be the X axis and θ be the angle of arrival of the tag at position x, then and $\boldsymbol{x}$ and $\boldsymbol{\cot\theta}$ have the following **linear relationship**:

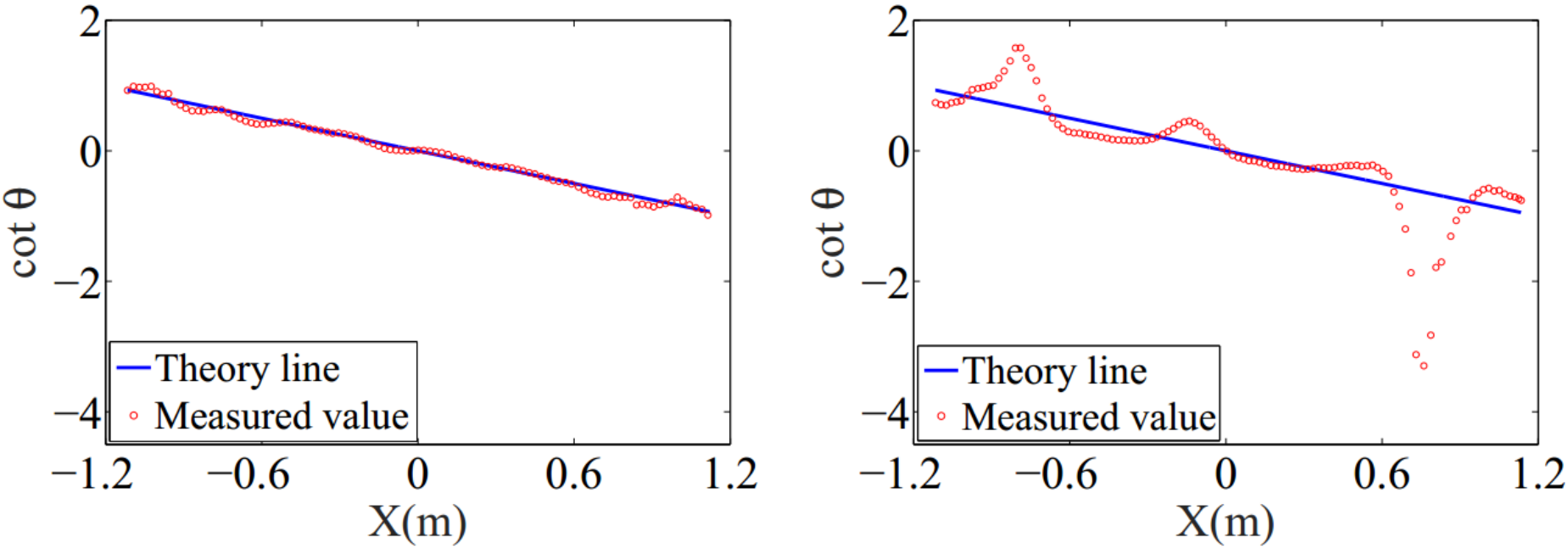
$$\cot\theta = -\frac{1}{d_0}(x - x_0)$$



$$x - x_0 = d_0 \cdot \cot\theta$$

Modeling the 3D Localization

- **AoA Localization via Mobile Scanning**

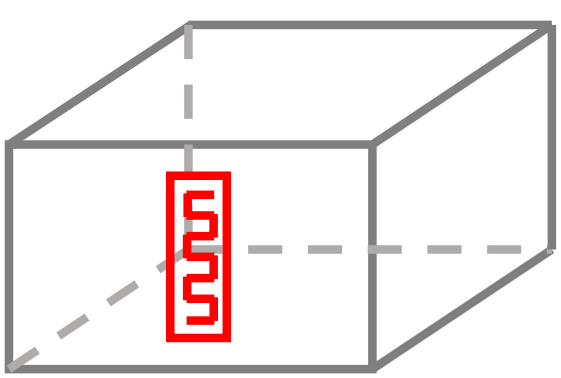


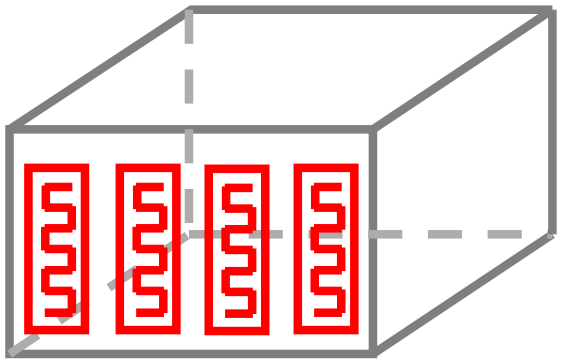
(a) Free space (b) Severe multipath

Fig. 3. Comparisons of $\left(\tilde{x}_i, \cot\tilde{\theta}_i\right)$ in two cases

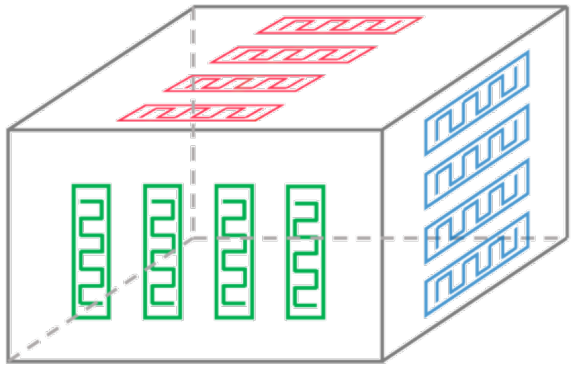
Modeling the 3D Localization

- **Tag Array-based Localization**





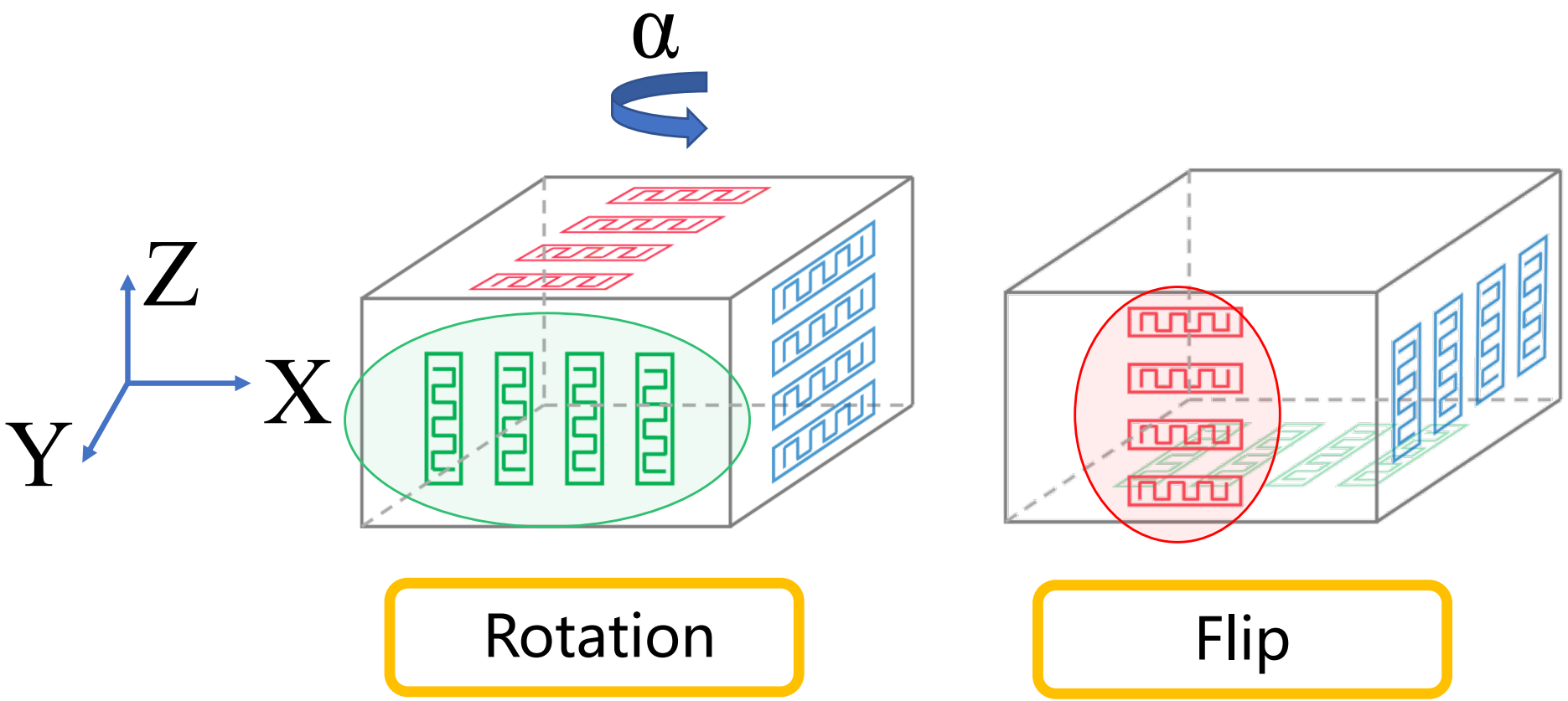
✓ **Accuracy**



✓ **Accuracy**
✓ **Orientation**

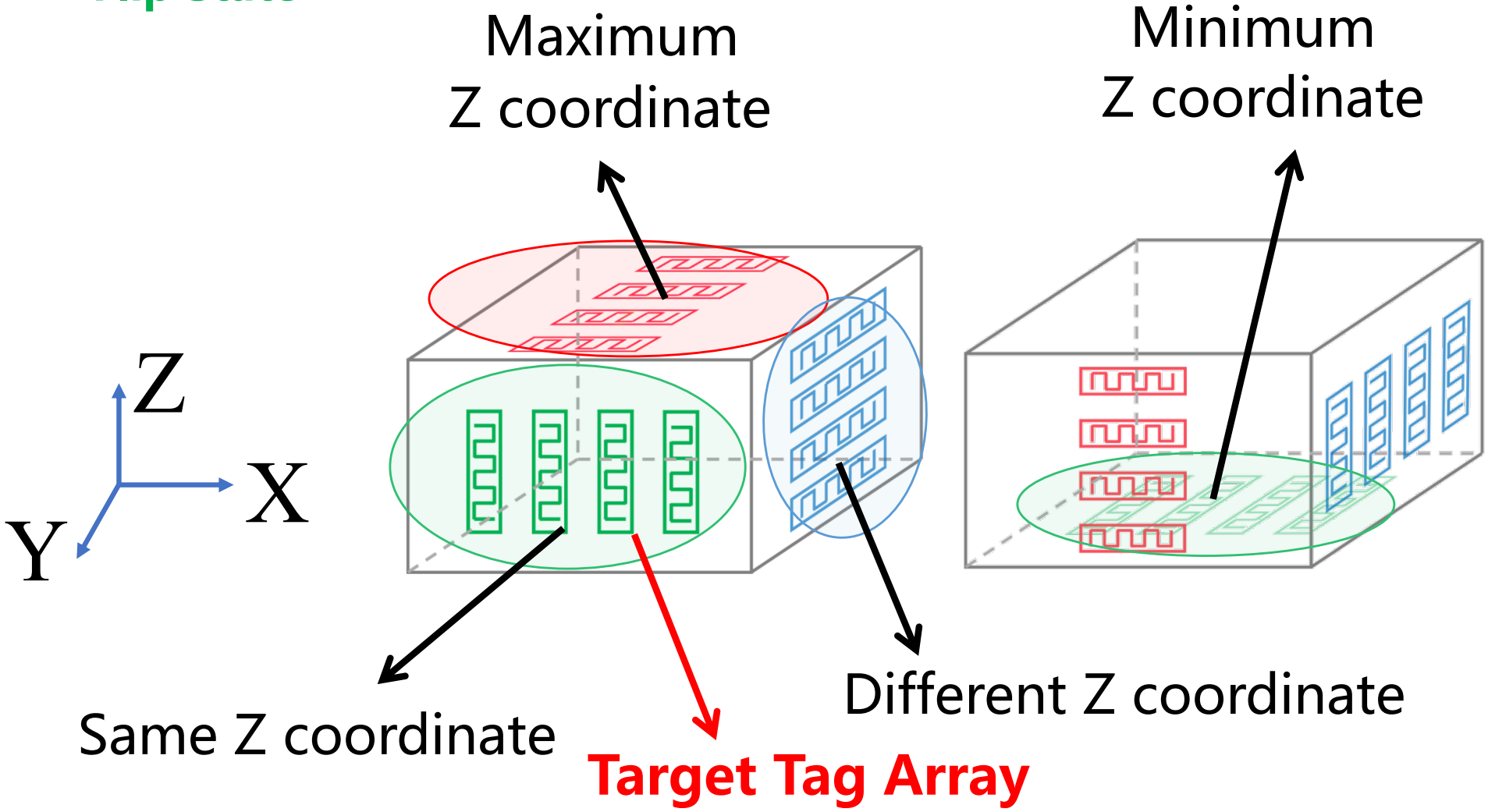
Modeling the 3D Localization

- **Tag Array-based Localization**



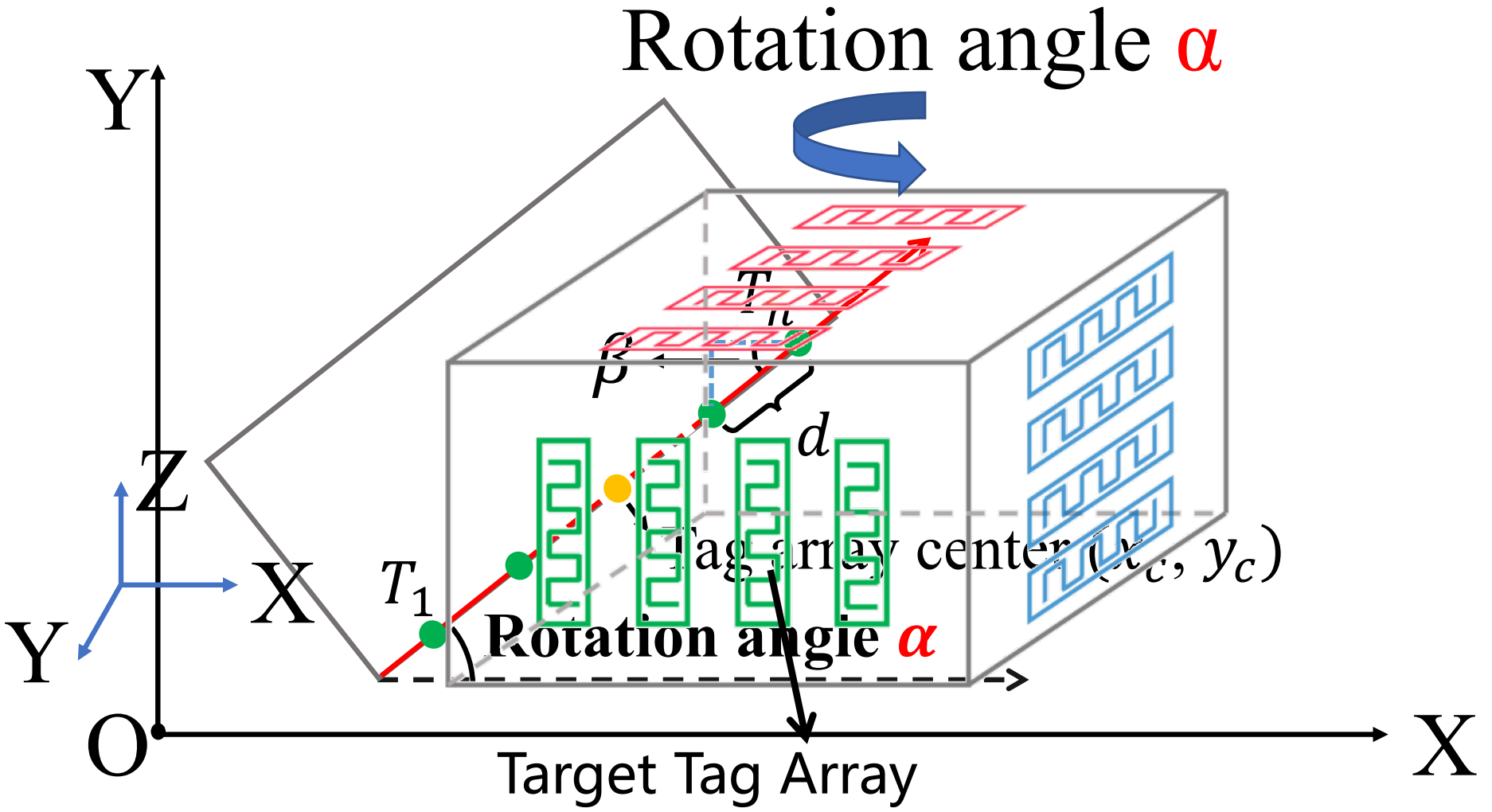
Modeling the 3D Localization

- **Flip State**



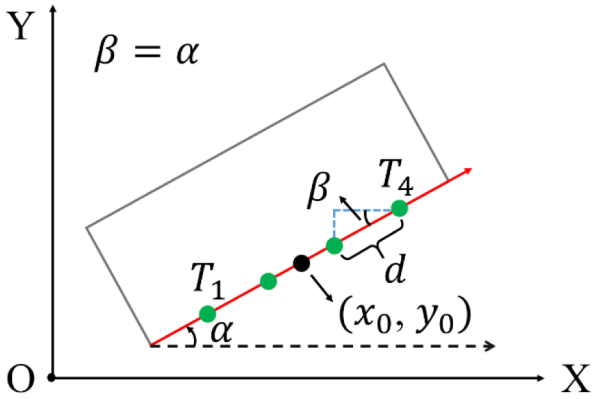
Modeling the 3D Localization

- **Rotation Angle**

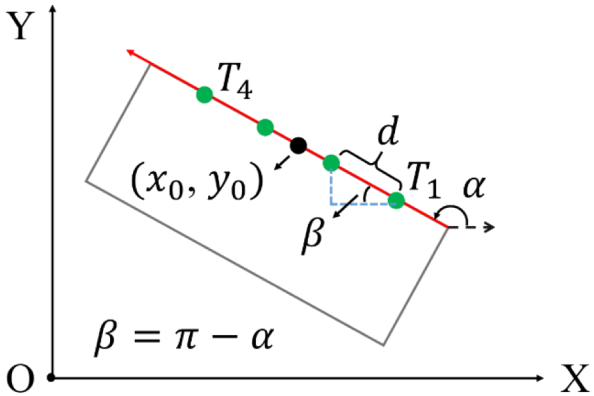


Modeling the 3D Localization

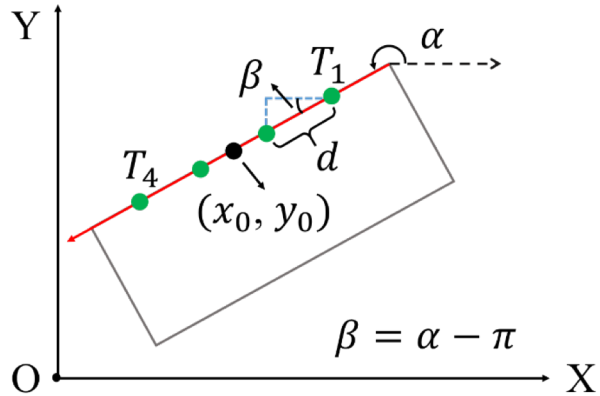
- **Rotation Angle (four cases)**



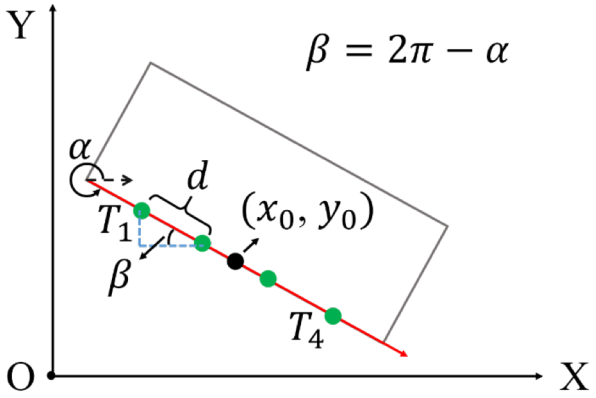
(a) $0 \le \alpha < \frac{\pi}{2}$



(b) $\frac{\pi}{2} \le \alpha < \pi$



(c) $\pi \le \alpha < \frac{3\pi}{2}$

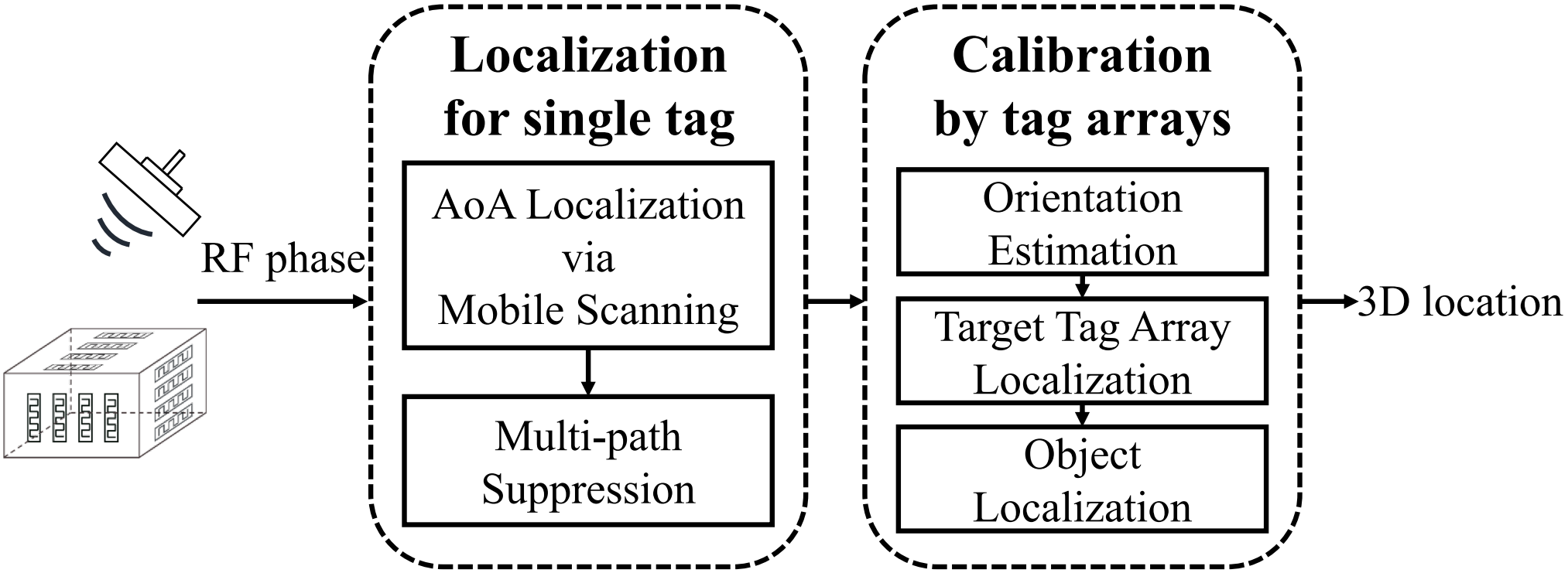


(d) $\frac{3\pi}{2} \le \alpha < 2\pi$

For i^{th} tag, its coordinates $(\boldsymbol{x_i}, \boldsymbol{y_i})$ are related to the rotation angle $\boldsymbol{\alpha}$ and tag array center $(\boldsymbol{x_0}, \boldsymbol{y_0})$

$$\begin{cases} \boldsymbol{x_i = x_0 + p_i \cdot d \cos \beta} \\ \boldsymbol{y_i = y_0 + q_i \cdot d \sin \beta} \\ \boldsymbol{\beta = f(\alpha)} \end{cases}$$

3DLoc ——System Overview



3DLoc ——Localization for a single tag

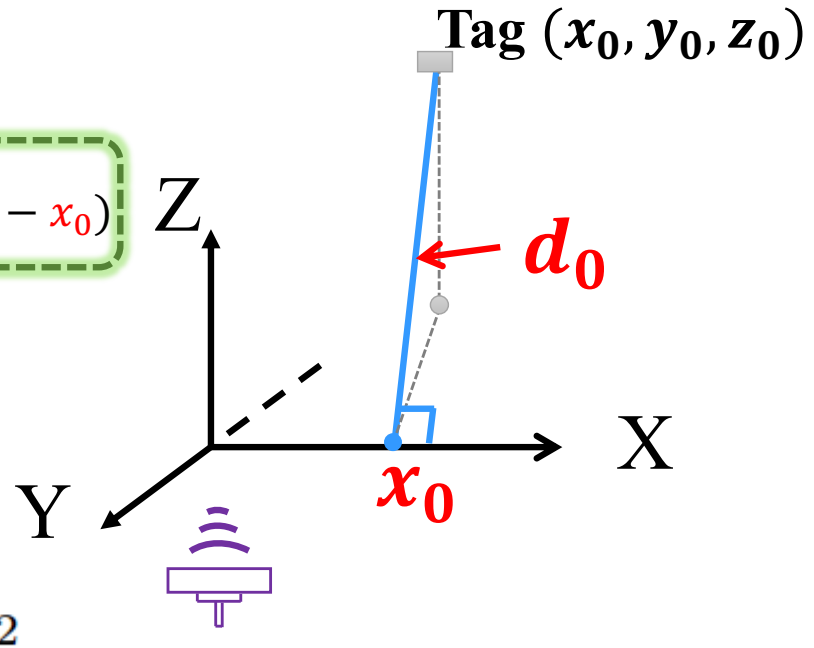
- **AoA Localization via Mobile Scanning**

$$\boldsymbol{R} = \{(\tilde{\boldsymbol{x}}_{\boldsymbol{0}}, \tilde{\boldsymbol{\theta}}_{\boldsymbol{0}}), \ldots, (\tilde{\boldsymbol{x}}_{\boldsymbol{m}}, \tilde{\boldsymbol{\theta}}_{\boldsymbol{m}})\}$$

Linear relationship: $\cot\theta = -\frac{1}{d_0}(x - x_0)$

$$\boldsymbol{P} = \{(\tilde{\boldsymbol{x}}_{\boldsymbol{0}}, \cot\tilde{\boldsymbol{\theta}}_{\boldsymbol{0}}), \ldots, (\tilde{\boldsymbol{x}}_{\boldsymbol{m}}, \cot\tilde{\boldsymbol{\theta}}_{\boldsymbol{m}})\}$$

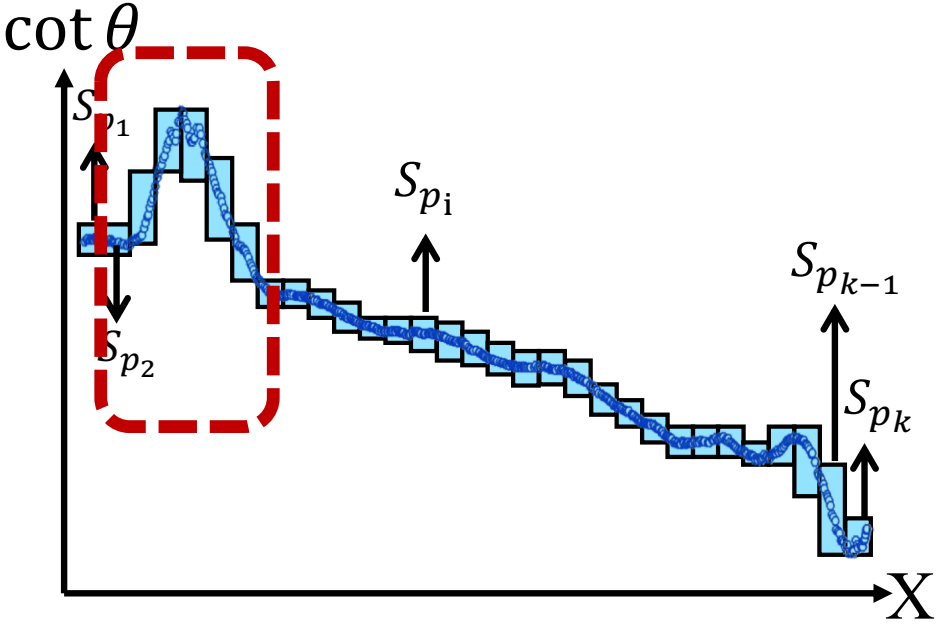
Linear least squares
optimal solution x_0 and d_0



$$\arg\min_{d_0, x_0} \sum_{i=0}^{m} \left| \left(-\frac{1}{d_0} \cdot (\tilde{x}_i - x_0) \right) - \cot\tilde{\theta}_i \right|^2$$

3DLoc ——Localization for a single tag

- **Multipath Suppression**



1. Input: Point set $\boldsymbol{P} = \{(\tilde{\boldsymbol{x}}_0, \cot\tilde{\boldsymbol{\theta}}_0), \ldots, (\tilde{\boldsymbol{x}}_m, \cot\tilde{\boldsymbol{\theta}}_m)\}$

2. Split P into k subset using a slide window

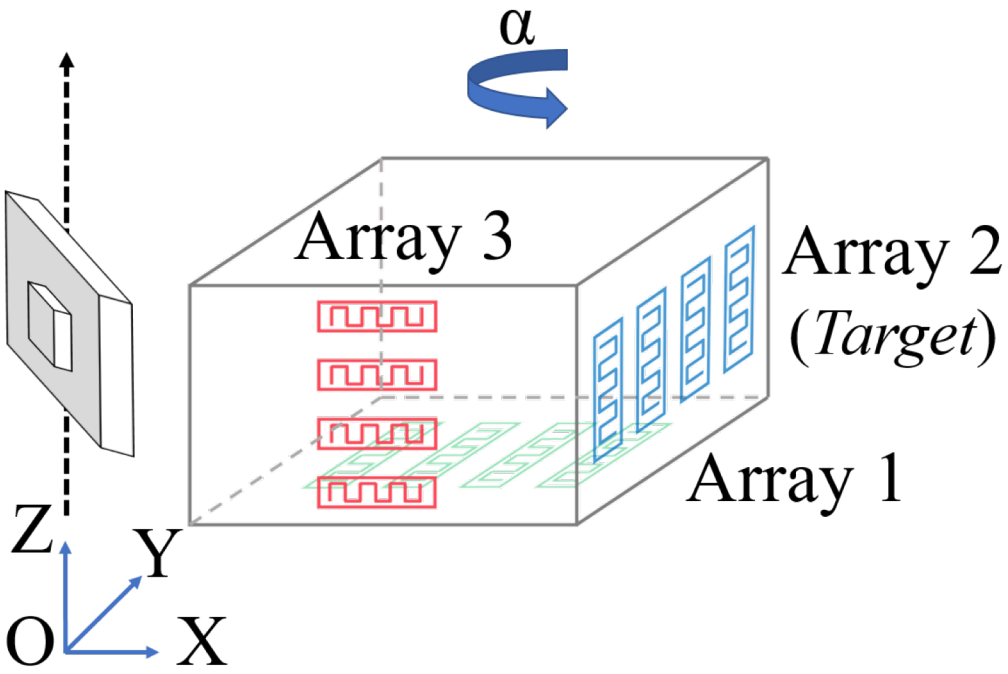
3. Calculation for average changing rate

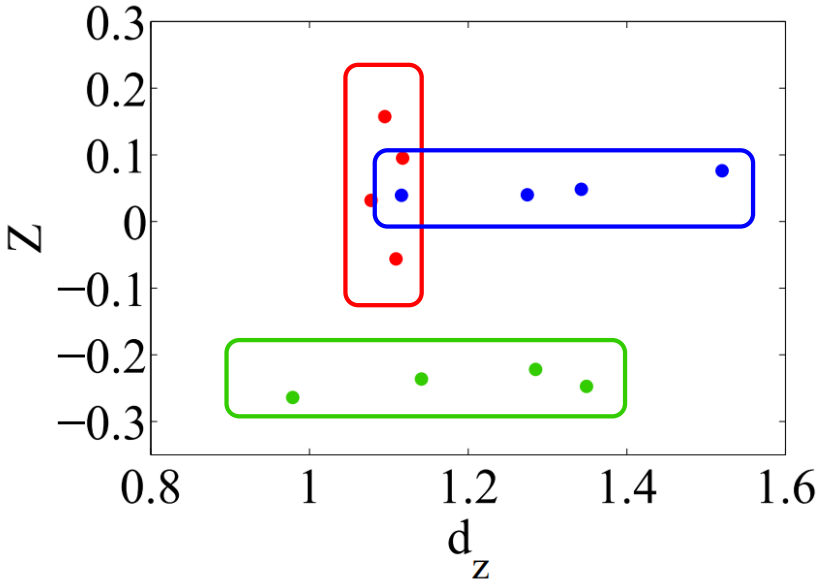
4. Outliers finding and removing

5. Output: new Point set P'

3DLoc ——Calibration by tag arrays

- **Orientation Estimation**





- **Distinguish** the three tag arrays
- **Judge** the **flip** state
- **Calibrate** the *Z*-coordinate of the target tag array

$$z_c = \frac{\sum_{i=1}^{n} \hat{z}_i}{n}$$

3DLoc ——Calibration by tag arrays

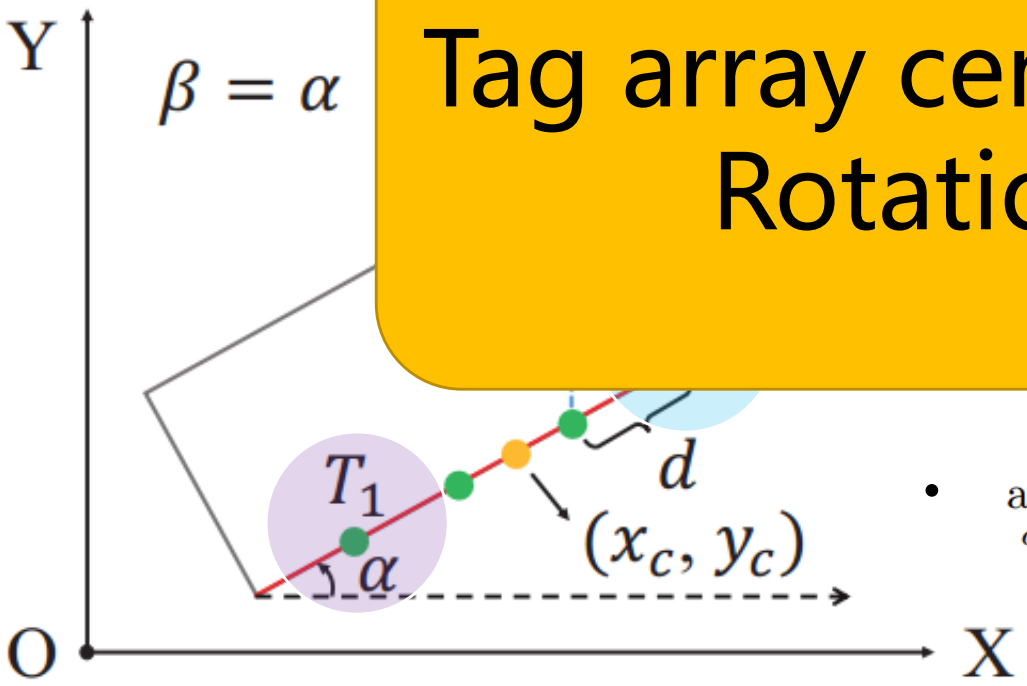
- **Target Tag Array Localization**

$$\{(\hat{x}_1, \hat{y}_1), \cdots, (\hat{x}_n, \hat{y}_n)\}$$

$$P_i = \left\{\left(\tilde{x}_{i,1}, \cot\left(\tilde{\theta}_{i,1}\right)\right), \cdots, \left(\tilde{x}_{i,k_i}, \cot\left(\tilde{\theta}_{i,k_i}\right)\right)\right\}$$

nd T_n

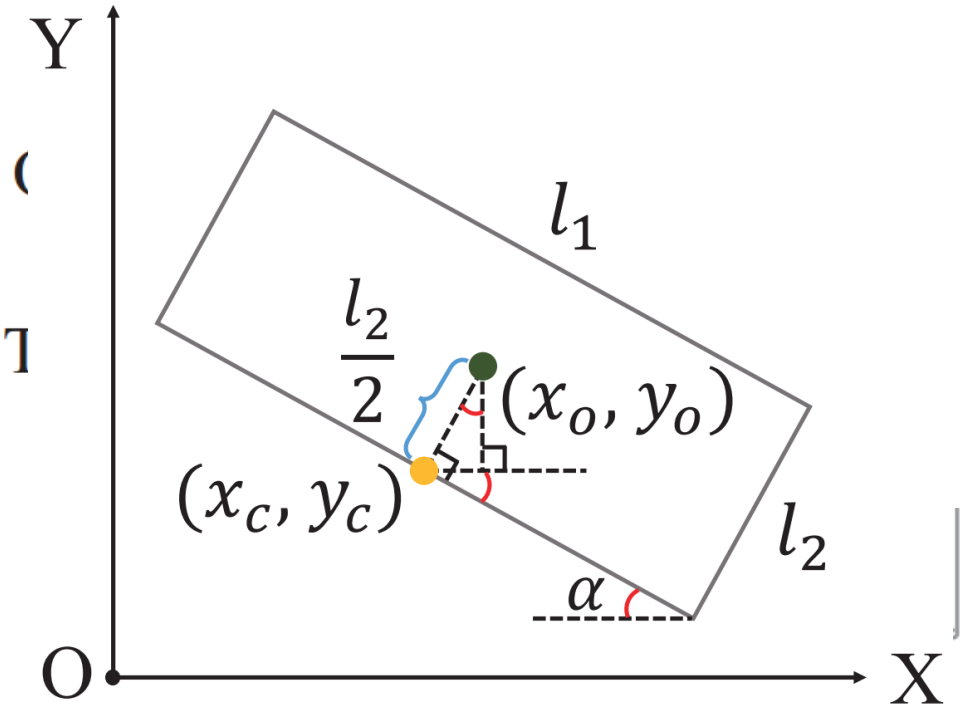
Tag array center (x_c, y_c, z_c)
Rotation angle α



- $$\arg\min_{\alpha, x_c, y_c} \sum_{i=1}^{n} \sum_{j=1}^{k_i} \left| -\frac{1}{y_i}\left(\tilde{x}_{i,j} - x_i\right) - \cot\left(\tilde{\theta}_{i,j}\right) \right|^2$$

3DLoc ——Calibration by tag arrays

- **Object Localization**



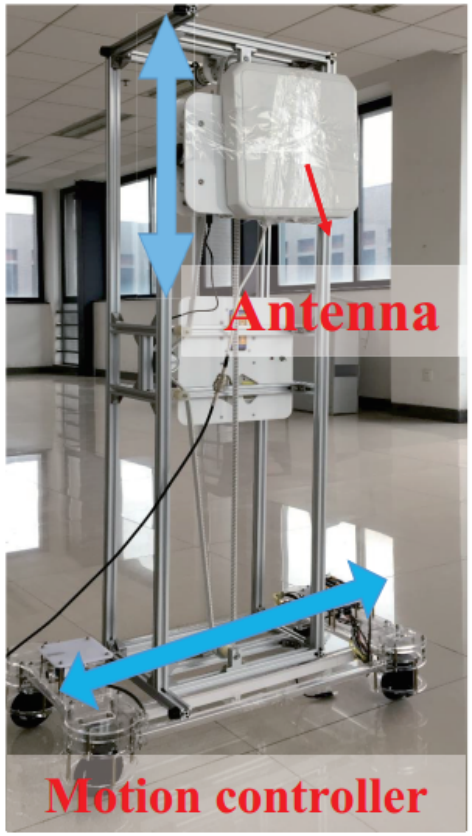
3D coordinate of the object

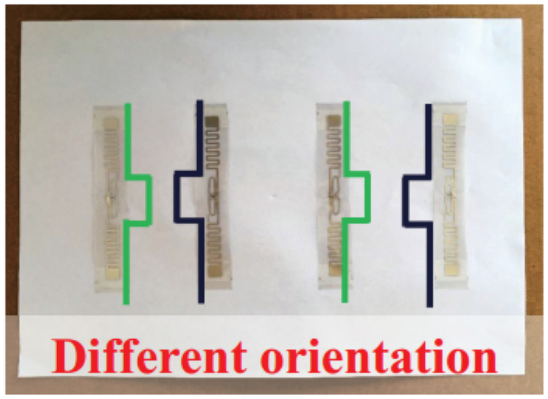
$$\begin{cases} x_o = x_c + l_2/2 \cdot \sin\alpha \\ y_o = z_o = z_c \quad \cdot \cos\alpha \\ z_o = z_c \end{cases}$$

Z coordinate of the object

Performance Evaluation

- **Implementation**





Performance Evaluation

- **Micro-Benchmarks**
  - **Determine a proper window size for multipath suppression**

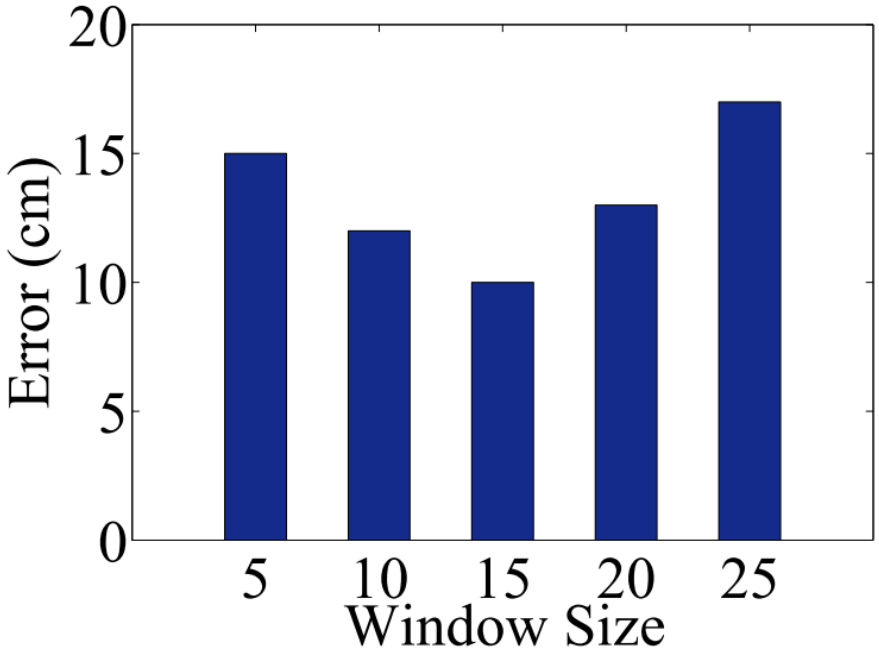


Fig. 12. Window size for multipath suppression

set ω to 15cm as a trade-off

Performance Evaluation

- **Micro-Benchmarks**
  - **With or without multipath suppression**

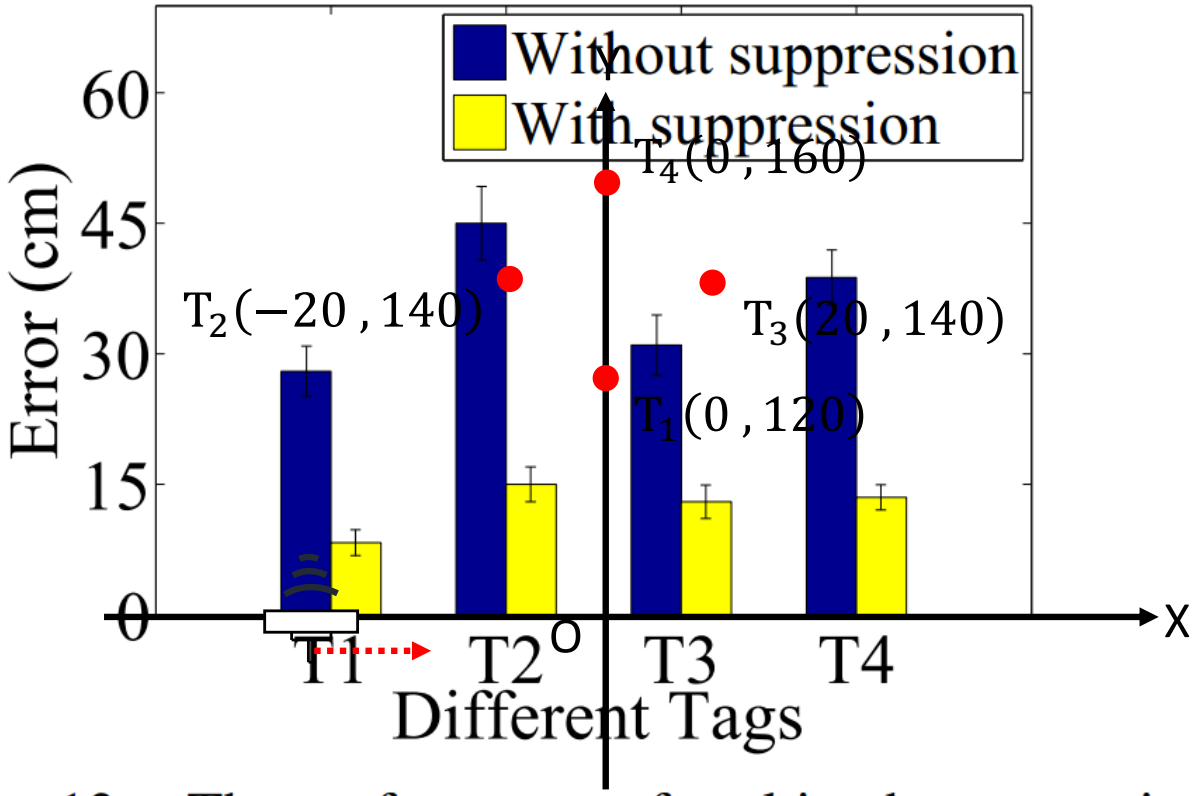


Fig. 13. The performance of multipath suppression

Performance Evaluation

- **Macro-Benchmarks**

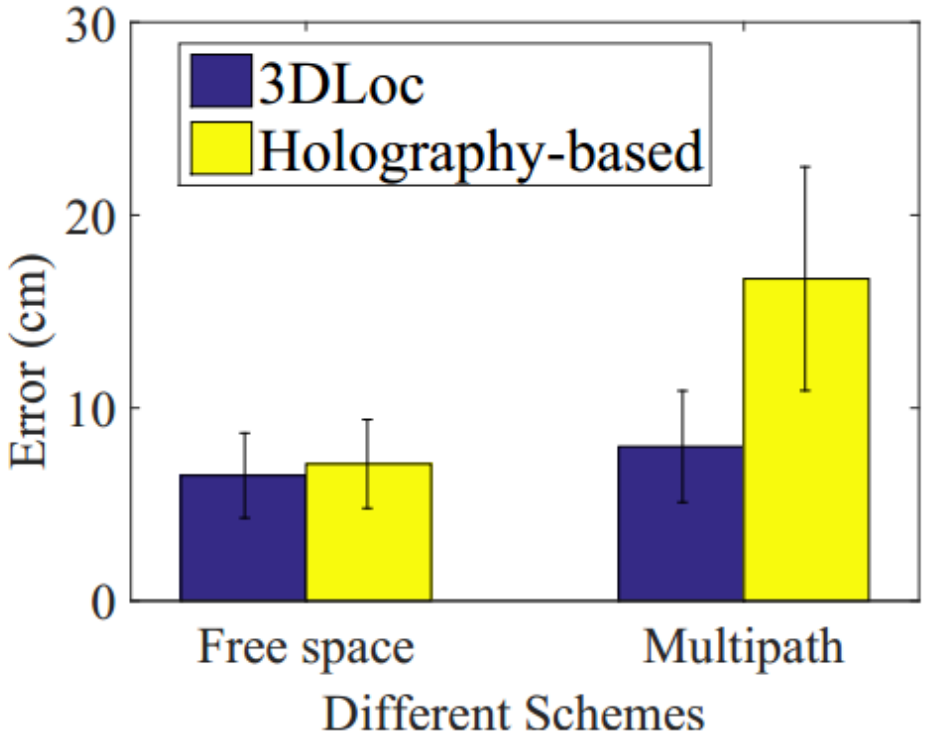


Fig. 16. Scheme vs. error

- Two methods both perform well in the **free space**.
- In the **multipath environment**, the errors for *3DLoc* and the Hologram-based method are 8cm and 16.7cm respectively.
- *3DLoc* **outperforms** the Hologram-based method significantly in the multipath environment.

Conclusion

- *3DLoc* uses the AoA-based **mobile scanning** scheme to accurately estimate the tagged objects' orientations and 3D coordinates in the 3D space referring to the **fixed layout** of the tag array.

- We propose a novel algorithm to **suppress** the localization errors caused by the **multipath effect**.

Questions ?

Thank you !