3-Dimensional Localization via RFID Tag Array

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Motivation

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

Accurate 3D Localization
Existing RFID Localization schemes

- **RFID localization**
  - RF-IDraw (SIGCOMM, 14)
  - Tagoram (MOBICOM, 14)
  - BackPos (INFOCOM, 14)

- **Multipath suppression**
  - MobiTagbot (MOBICOM, 2014)
  - PinIt (SIGCOMM, 2013)

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Motivation and Challenges  Modeling the 3D Localization  Our Solution: 3DLoc  Performance Evaluation  Conclusion
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
AOA-based Localization

Phase difference $\rightarrow$ angle of arrival

\[
\Delta \phi_{1,2} = 2\pi \cdot \frac{2\Delta d_{1,2}}{\lambda} + 2k\pi
\]

\[
\cos \theta = \frac{\lambda(\Delta \phi_{1,2} - 2k\pi)}{4\pi \Delta x}
\]

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

\[
\theta = \cos^{-1}\left(\frac{\lambda \cdot \Delta \phi_{1,2}}{4\pi \Delta x}\right)
\]

\[
x = \frac{x_1 + x_2}{2}
\]
Modeling the 3D Localization

- AOA-based Localization

\[ \theta = \cos^{-1} \left( \frac{\lambda \Delta \phi}{4\pi \Delta x} \right) \]

Motivation and Challenges  
Modeling the 3D Localization  
Our Solution: 3DLoc  
Performance Evaluation  
Conclusion
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 $\theta$ be the angle of arrival of the tag at position $x$, then and $x$ and $\cot \theta$ 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 \((\tilde{x}_i, \cot \tilde{\theta}_i)\) in two cases
Modeling the 3D Localization

- Tag Array-based Localization

✓ Accuracy
✓ Accuracy
✓ Orientation
Modeling the 3D Localization

- Tag Array-based Localization

Rotation

Flip

Motivation and Challenges  Modeling the 3D Localization  Our Solution: 3DLoc  Performance Evaluation  Conclusion
Modeling the 3D Localization

- Flip State

Maximum Z coordinate

Minimum Z coordinate

Same Z coordinate

Different Z coordinate

Target Tag Array
Modeling the 3D Localization

- Rotation Angle

Rotation angle $\alpha$
Modeling the 3D Localization

1. **Rotation Angle** (four cases)

   - For \( i^{th} \) tag, its coordinates \((x_i, y_i)\) are related to the rotation angle \(\alpha\) and tag array center \((x_0, y_0)\):
   
   \[
   \begin{align*}
   x_i &= x_0 + p_i \cdot d \cos \beta \\
   y_i &= y_0 + q_i \cdot d \sin \beta \\
   \beta &= f(\alpha)
   \end{align*}
   \]

   - **Case (a)**: \(0 \leq \alpha < \frac{\pi}{2}\)
   - **Case (b)**: \(\frac{\pi}{2} \leq \alpha < \pi\)
   - **Case (c)**: \(\pi \leq \alpha < \frac{3\pi}{2}\)
   - **Case (d)**: \(\frac{3\pi}{2} \leq \alpha < 2\pi\)
3DLoc —— System Overview

**Localization for single tag**
- AoA Localization via Mobile Scanning
- Multi-path Suppression

**Calibration by tag arrays**
- Orientation Estimation
- Target Tag Array Localization
- Object Localization

3D location

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3DLoc —— Localization for a single tag

- **AoA Localization via Mobile Scanning**

\[ R = \{(\bar{x}_0, \bar{\theta}_0), ..., (\bar{x}_m, \bar{\theta}_m)\} \]

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

\[ P = \{(\bar{x}_0, \cot \bar{\theta}_0), ..., (\bar{x}_m, \cot \bar{\theta}_m)\} \]

Linear least squares optimal solution \( x_0 \) and \( d_0 \)

\[
\arg \min_{d_0, x_0} \sum_{i=0}^{m} \left| \left( -\frac{1}{d_0} \cdot (\bar{x}_i - x_0) \right) - \cot \bar{\theta}_i \right|^2
\]
3DLoc — Localization for a single tag

- **Multipath Suppression**

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

\[ P_i = \{ (\tilde{x}_{i,1}, \cot(\tilde{\theta}_{i,1})), \cdots, (\tilde{x}_{i,k_i}, \cot(\tilde{\theta}_{i,k_i})) \} \]

Tag array center \((x_c, y_c, z_c)\)

Rotation angle \(\alpha\)
3DLoc —— Calibration by tag arrays

- Object Localization

3D coordinate of the object

\[
\begin{align*}
    x_o &= x_c + \frac{l_2}{2} \cdot \sin \alpha \\
    y_o &= z_o = z_c \cdot \cos \alpha \\
    z_o &= z_c
\end{align*}
\]
Performance Evaluation

• Implementation
Performance Evaluation

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

Fig. 12. Window size for multipath suppression

set $\omega$ to 15cm as a trade-off
**Performance Evaluation**

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

![Graph showing error (cm) vs. X for different tags with and without suppression](image)

**Fig. 13.** The performance of multipath suppression
Performance Evaluation

- Macro-Benchmarks

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.

Fig. 16. Scheme vs. error
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 !