# Tagoram: Real-Time Tracking of Mobile RFID Tags to High-Precision Accuracy Using COTS Devices

**Xiang-Yang Li**

Lei Yang, Yekui Chen
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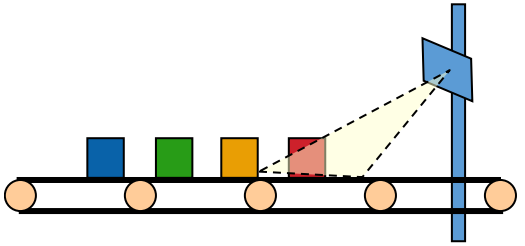
ILLINOIS INSTITUTE OF TECHNOLOGY

Tsinghua University



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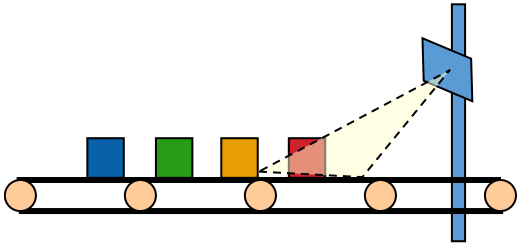
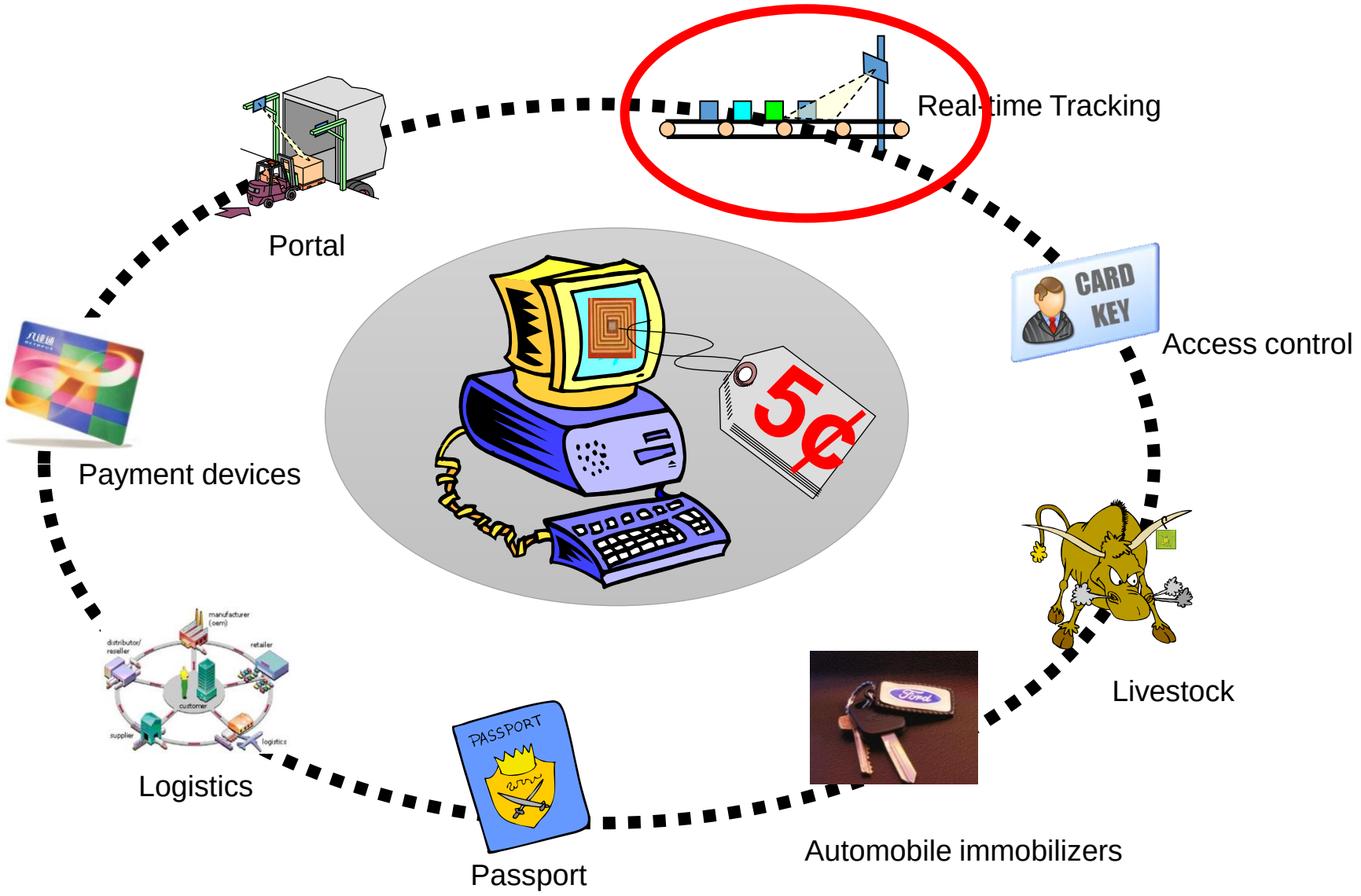


# Outline

# 1 Motivation

# RFID Technology



# RFIDs

Imagine you can localize RFIDs to within 10 to 15 cm!

5-cent stickers to tag any and every object

Reader's range is ~15m

# If we can locate RFID to within 10 to 15cm

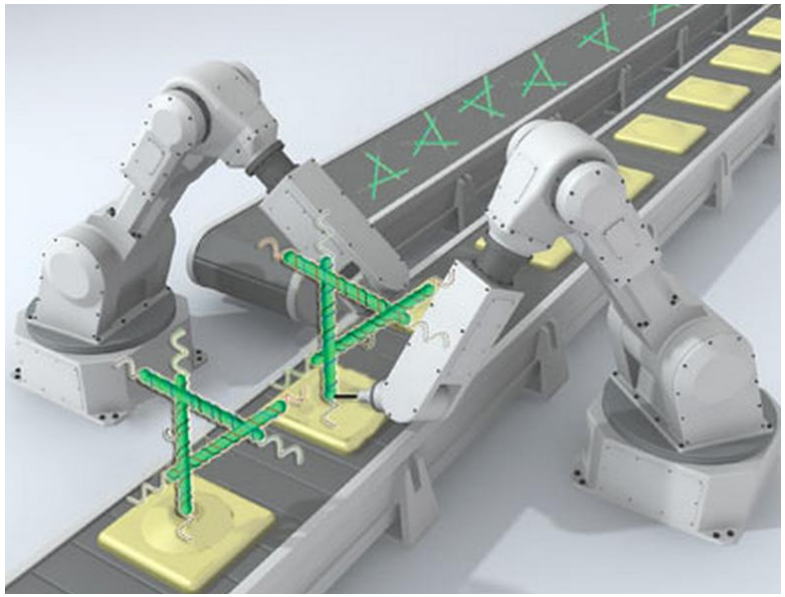
# No more customer checkout lines

SIGCOMM 2013 Hong Kong

# RFID Proximity as Indicator!

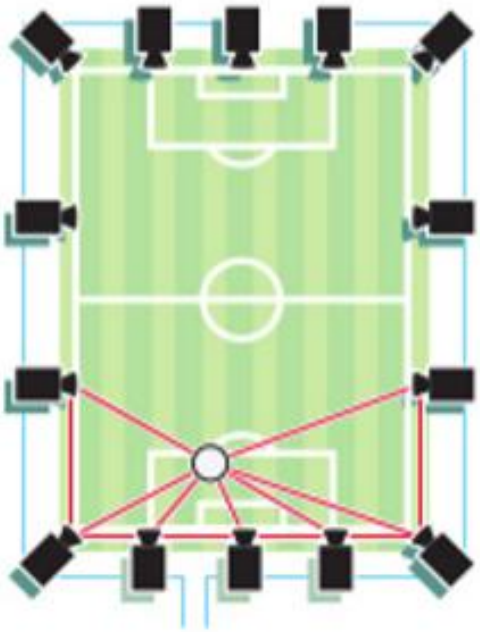
**RFIDs on Basket, goods**

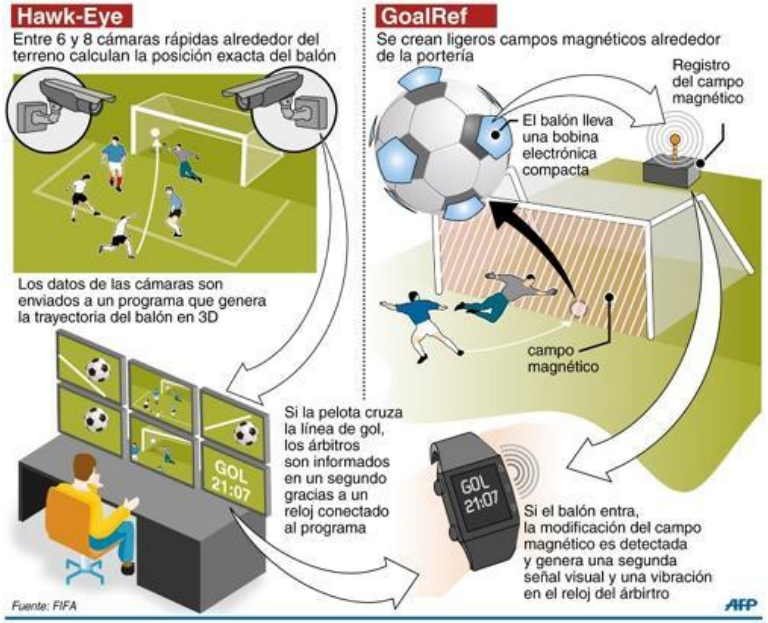
# Imagine you can localize RFIDs to within 0.1cm to 1 cm!



**Automatic production**

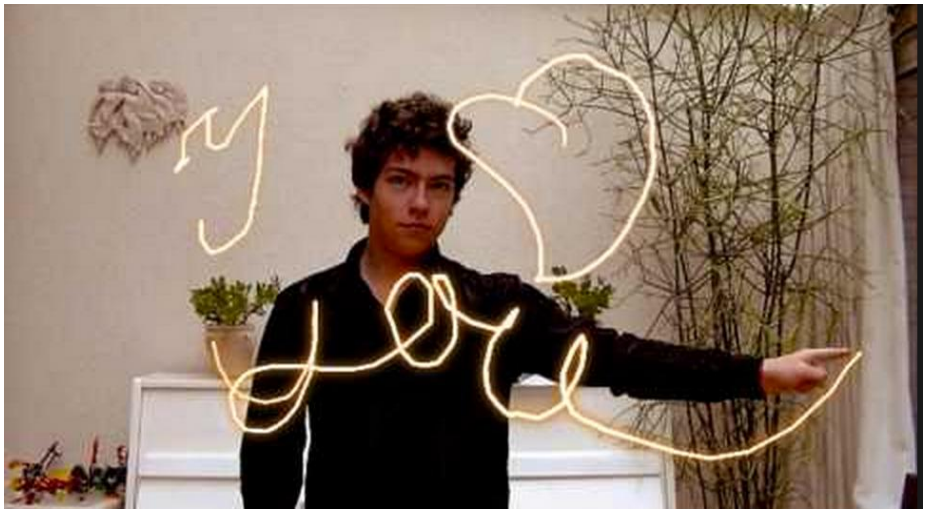
# Imagine you can localize RFIDs to within 0.1cm to 1 cm!

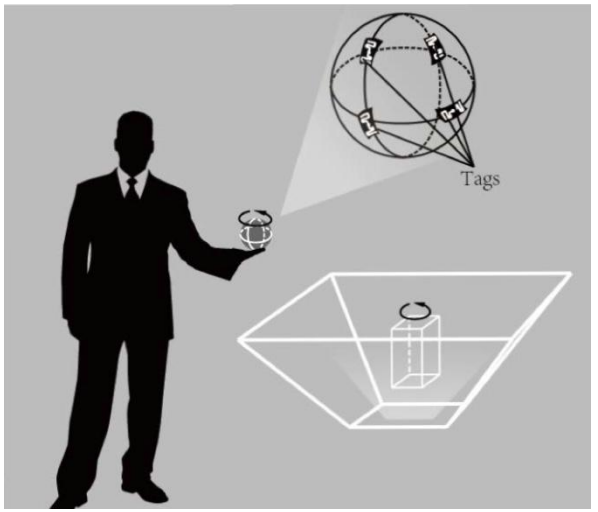





## Goal-line technology

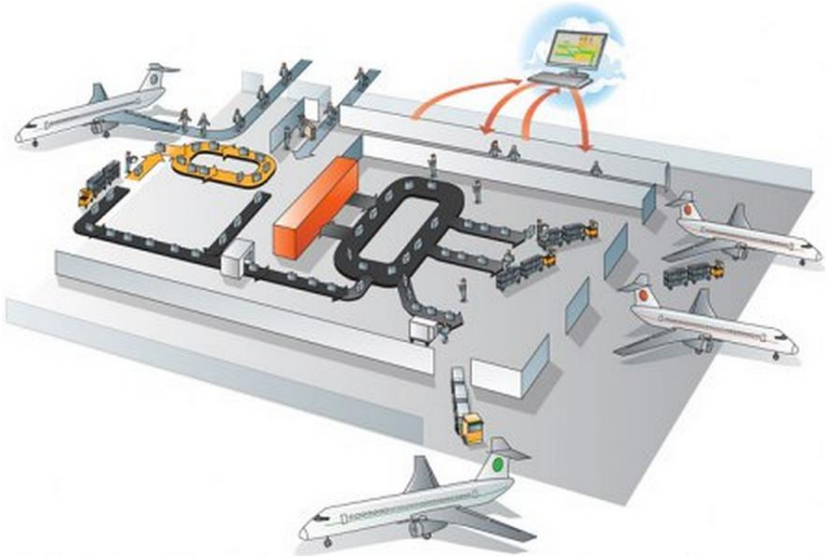
# Imagine you can localize RFIDs to within 0.1cm to 1 cm!






**Human-computer interface**

# Imagine you can localize RFIDs to within 0.1cm to 1 cm!



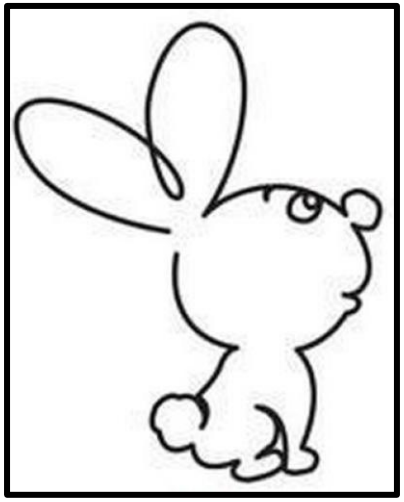
**Baggage sortation in airport**

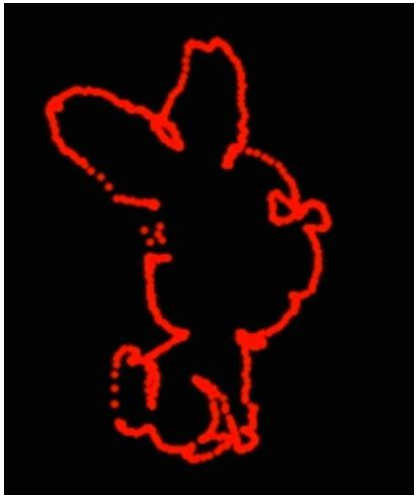
# Demonstration

http://young.tagsys.org/tracking/tagoram/youtube

# High-Precision RFID Tracking Using COTS Devices

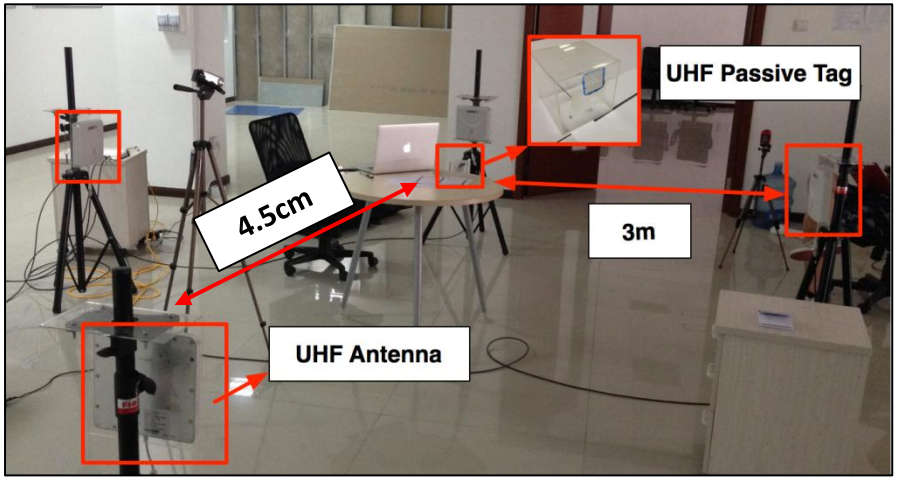
## Drawing in the Air

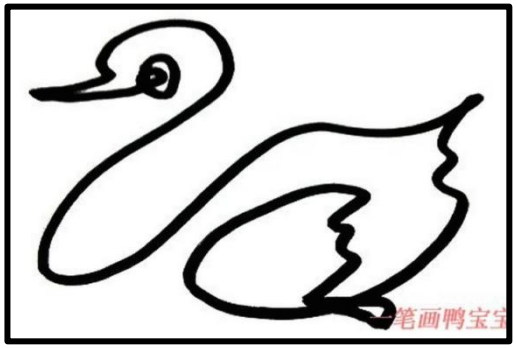


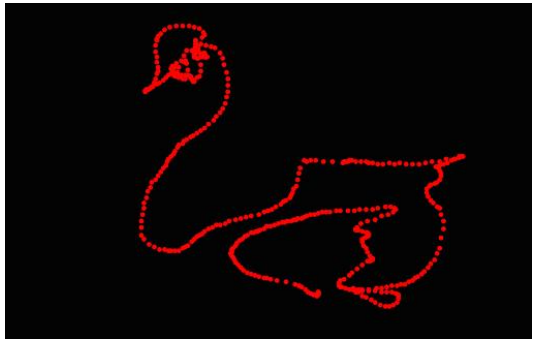


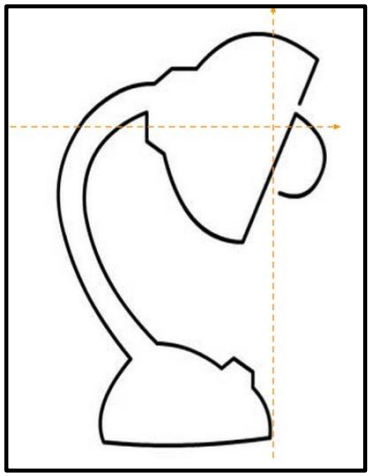
40cm

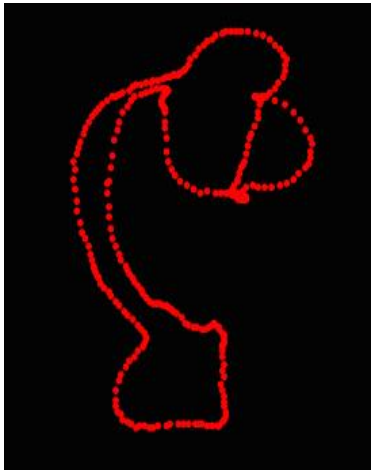
30cm



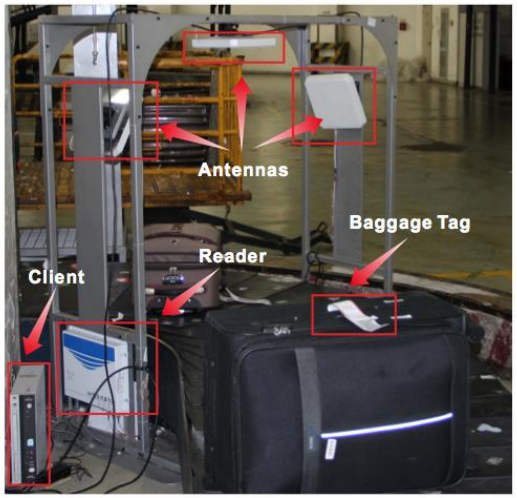







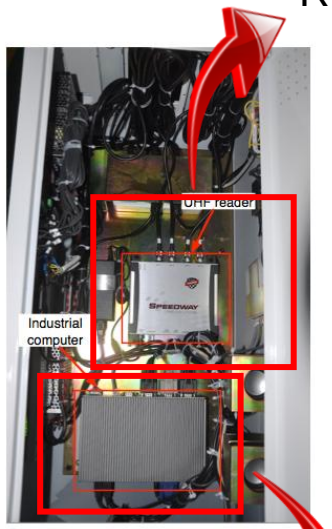


# TrackPoint Deployed at Airports




(a) Version 1.0


(b) Version 2.0




(c) Internal structure

Industrial computer

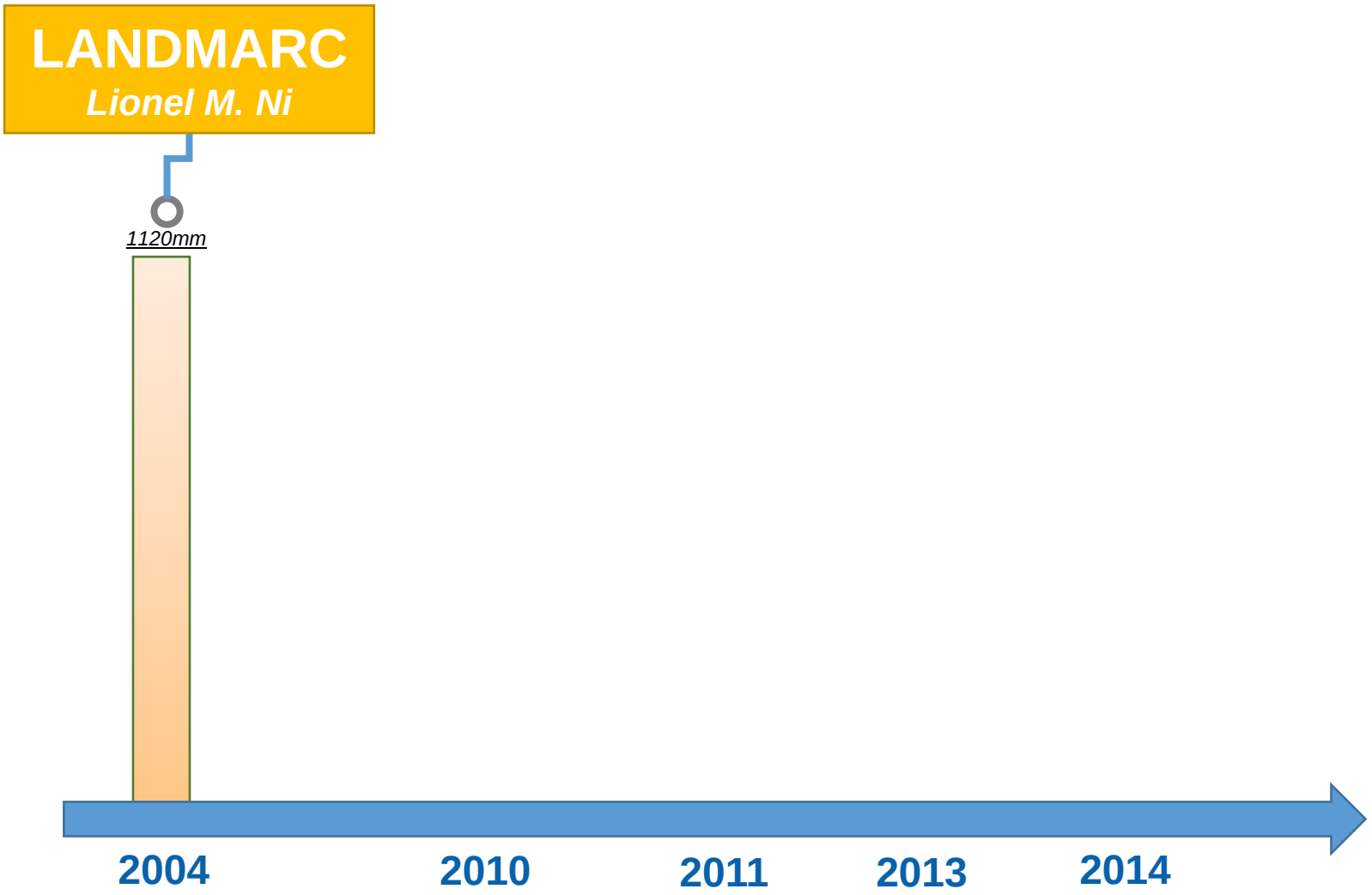
(a) Two TrackPoints


(b) Version 2.0

# 2 State-of-the-art

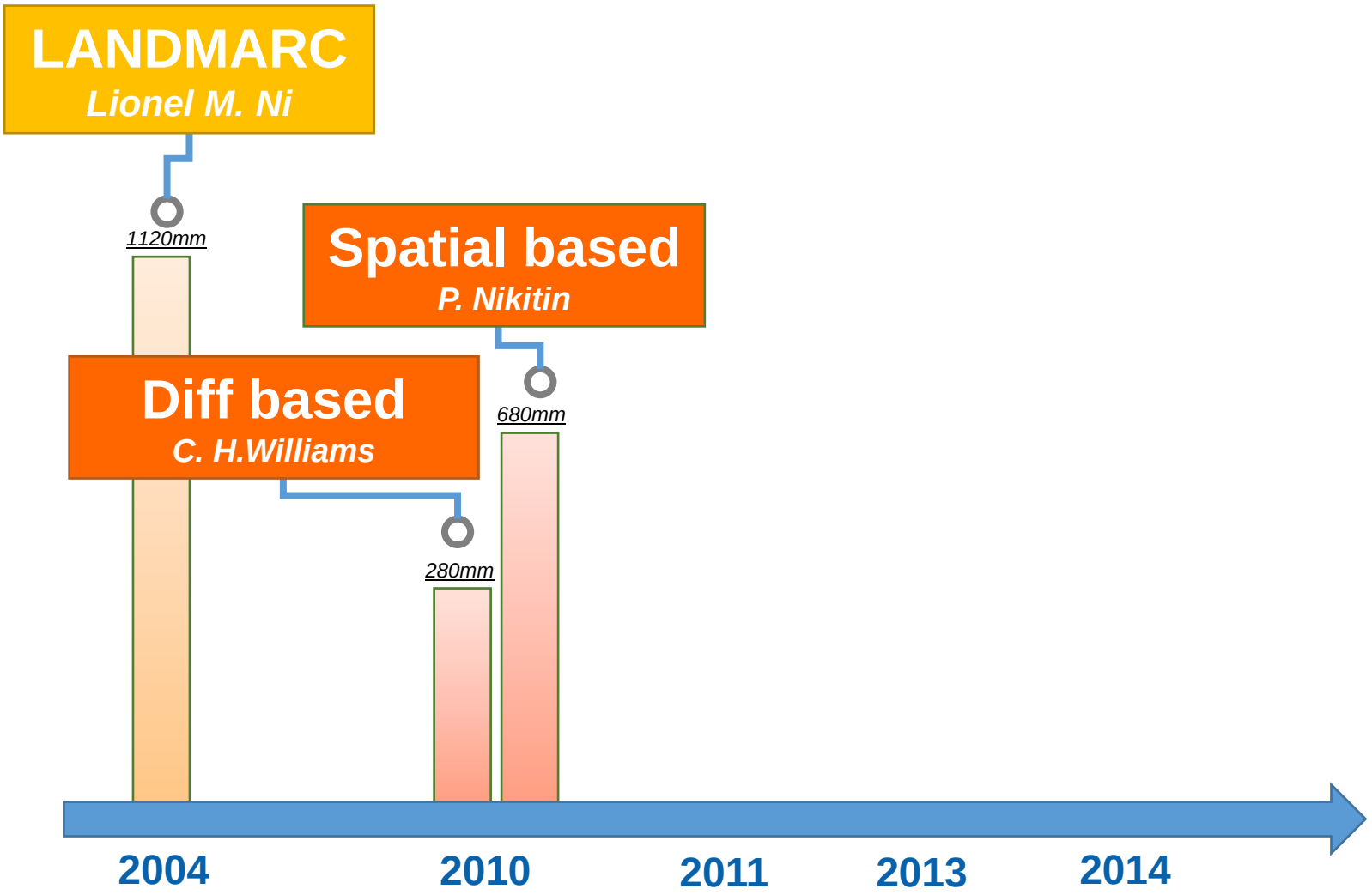
# RFID Tracking & Localization

## State-of-the-art



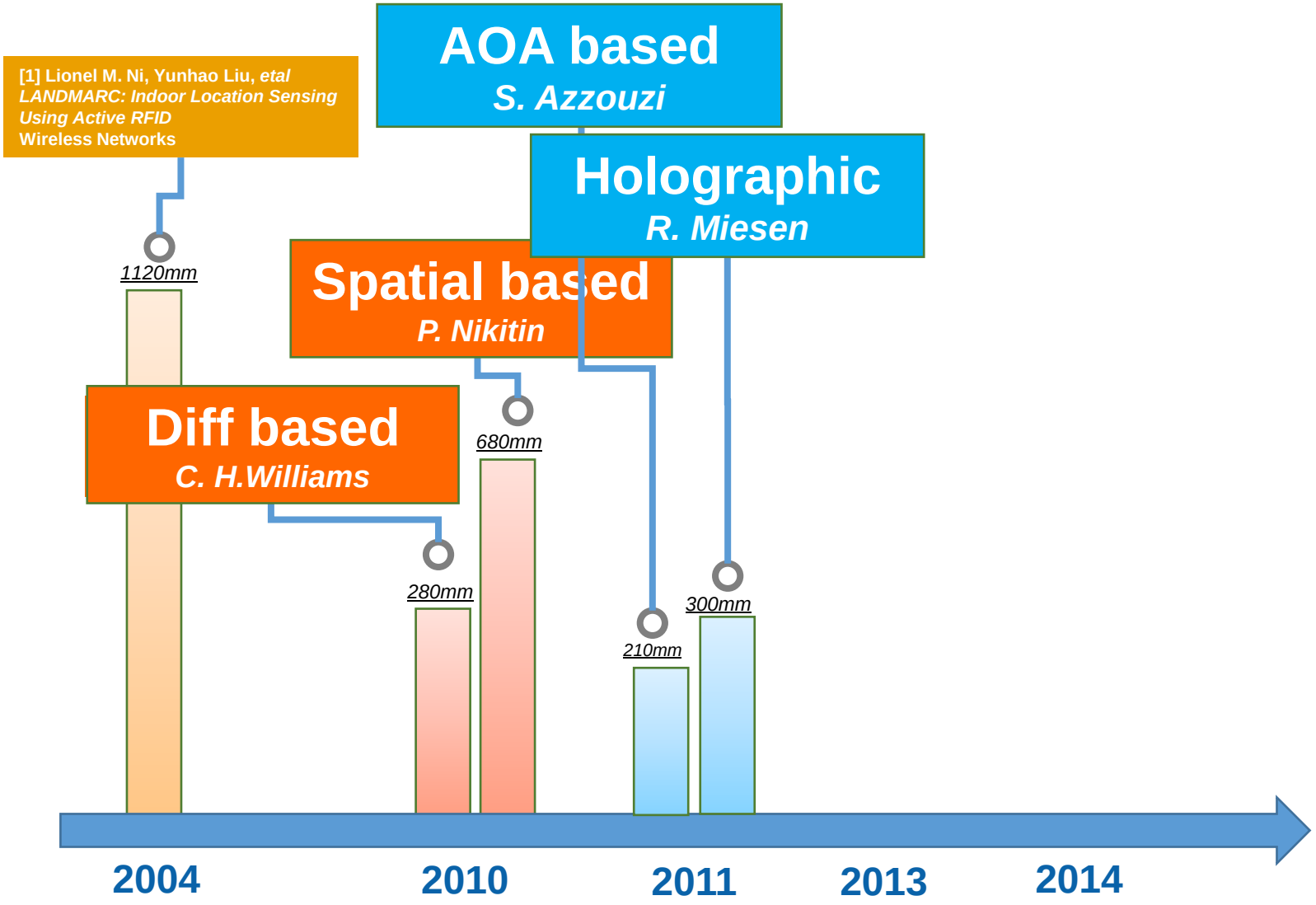
# RFID Tracking & Localization

## State-of-the-art



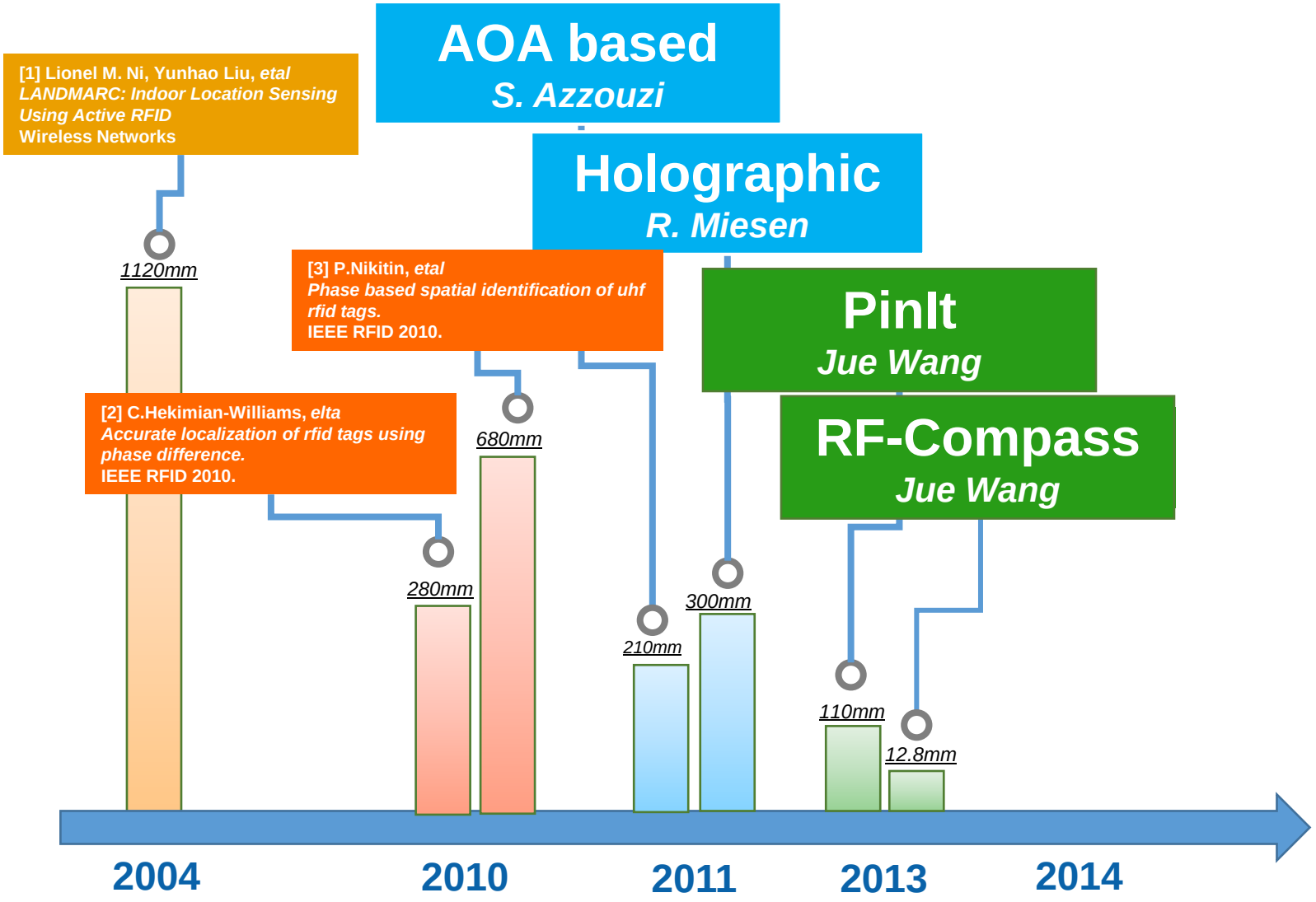
# RFID Tracking & Localization

## State-of-the-art



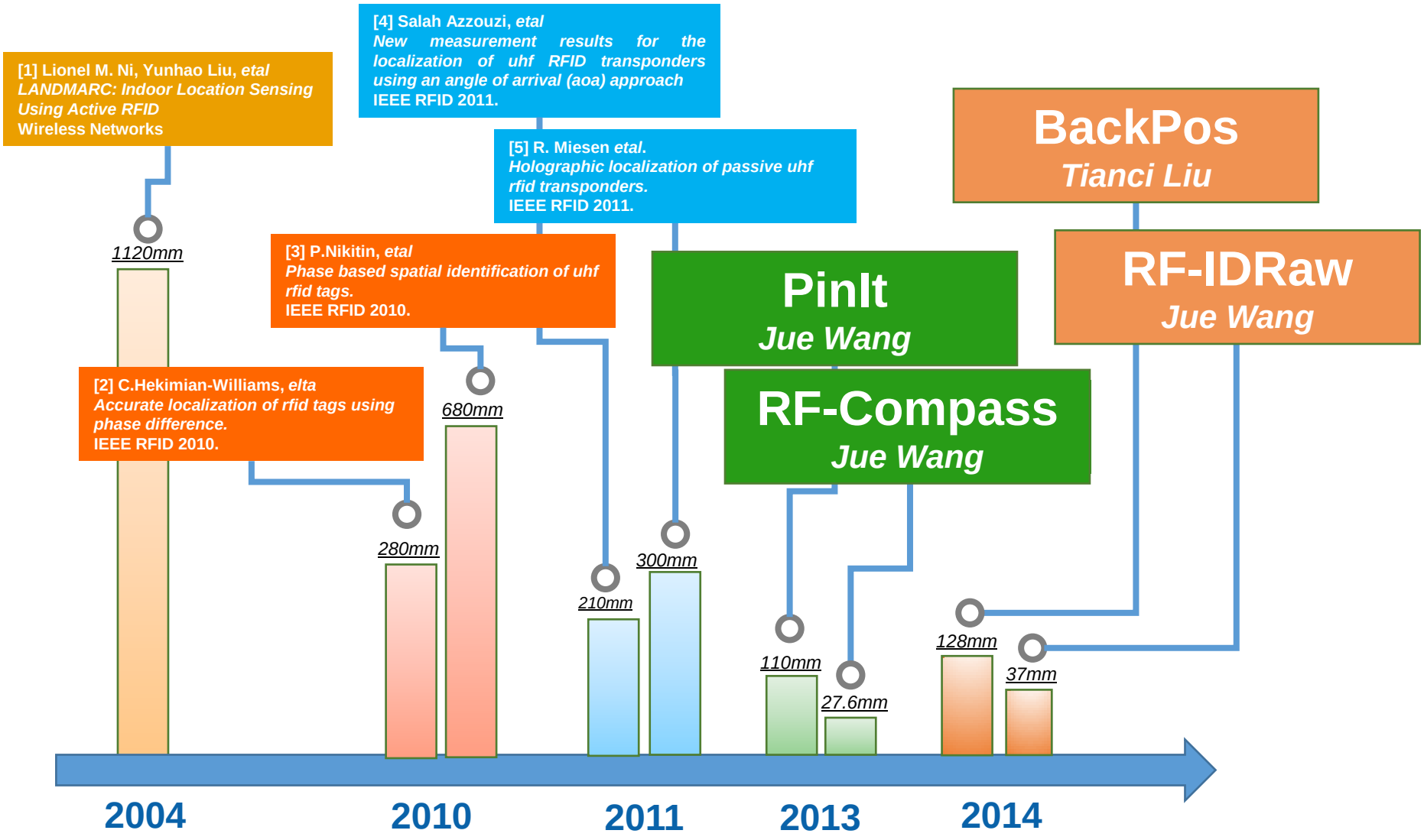
# RFID Tracking & Localization

## State-of-the-art



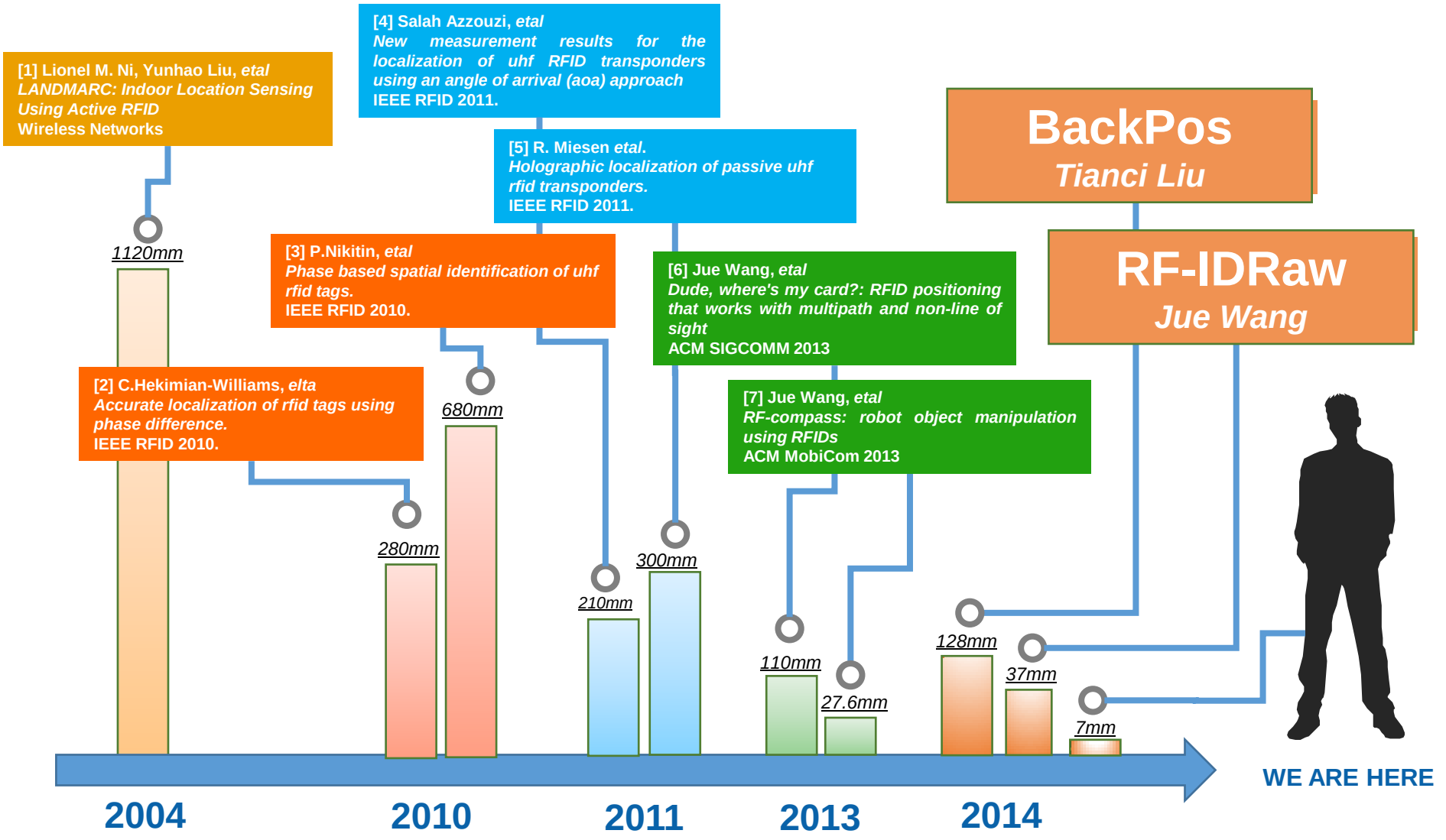
# RFID Tracking & Localization

## State-of-the-art



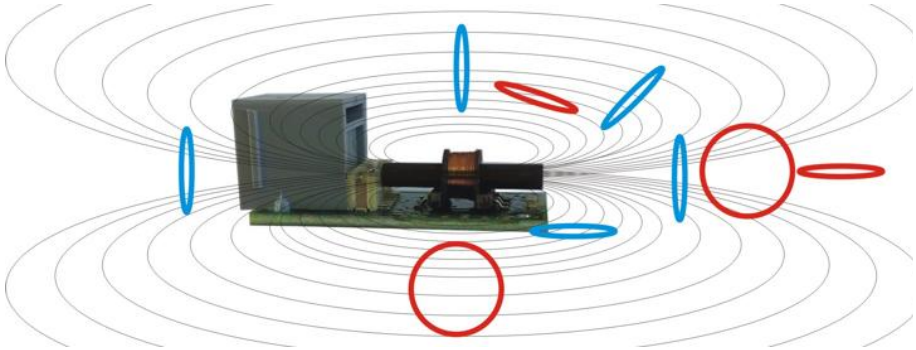
# RFID Tracking & Localization

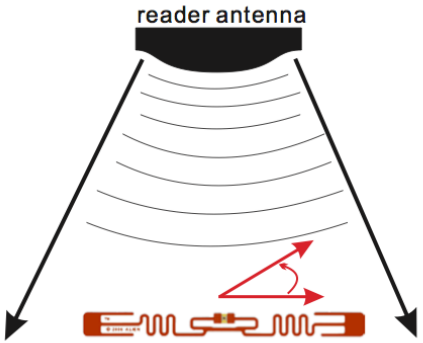
## State-of-the-art

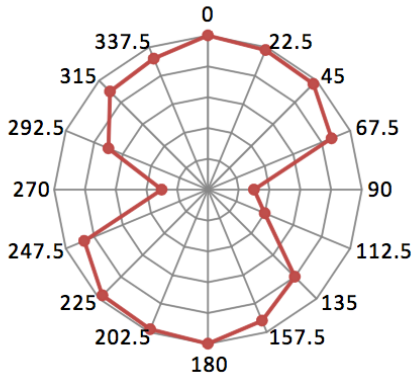


# State-of-the-art Techniques

## 1 RSS based Methods





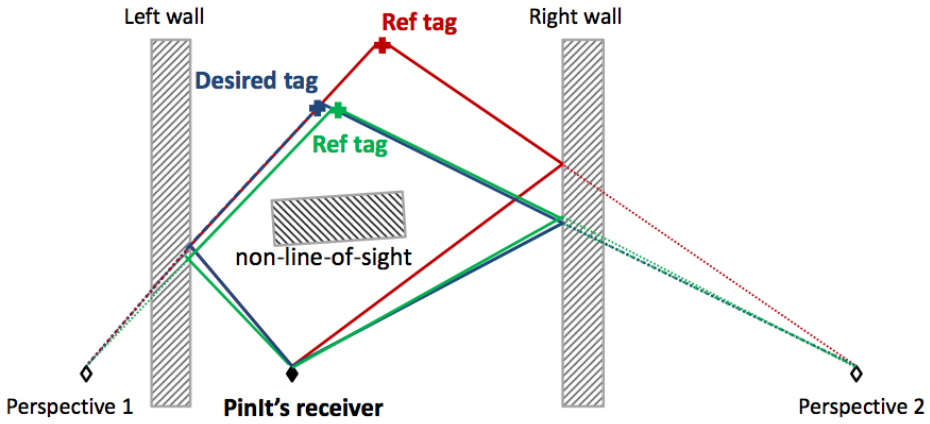




Orientation VS RSS

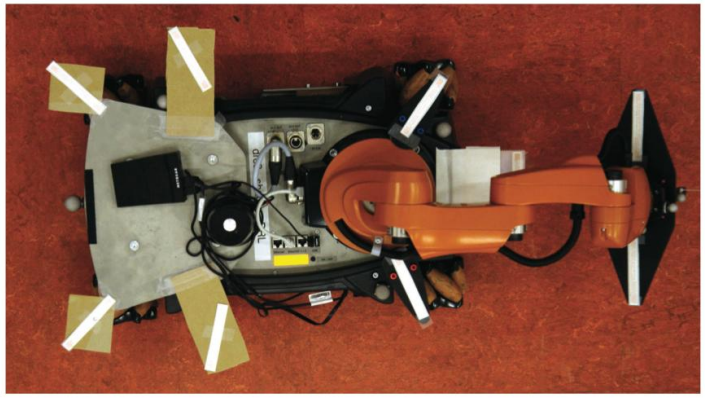
**RSS is not a reliable location indicator especially for UHF tags**

# State-of-the-art Techniques

## 2 Phase based Methods




PinIt (SIGCOMM 2013)



RF-Compass (MobiCom 2013)

**Needs to deploy dense reference tags**

# Summary of Challenges

- **Need mm-level localization accuracy achieved**
  - especially for mobile tags.

- **Small overhead, COTS devices**
  - infeasible for using many references for a tracking system spanning a long pipeline.

- **Fast-changing environment**
  - multipath reflection of RF signals
  - varied orientation of tags
  - Doppler effect

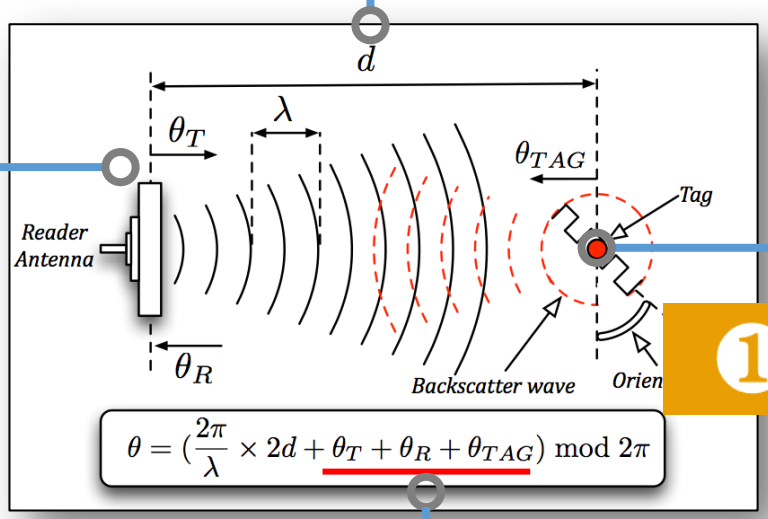
# 3 How Tagoram works?

## Overview the basic idea

# Backscatter Communication

❸ Continuous wave

❷ Double distance




❶ Battery free

❹ Device diversity

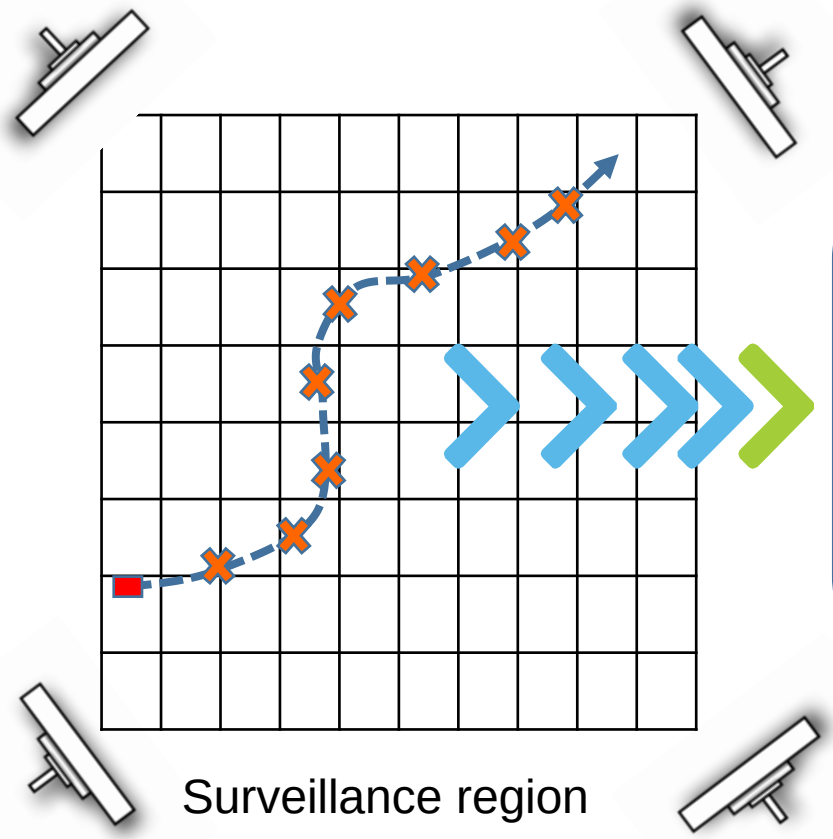
# COTS RFID Reader

**0.0015 radians (4096 bits)**

*Impinj Reader*

**$\approx 0.038mm$ accuracy**

# Problem definition



Surveillance region

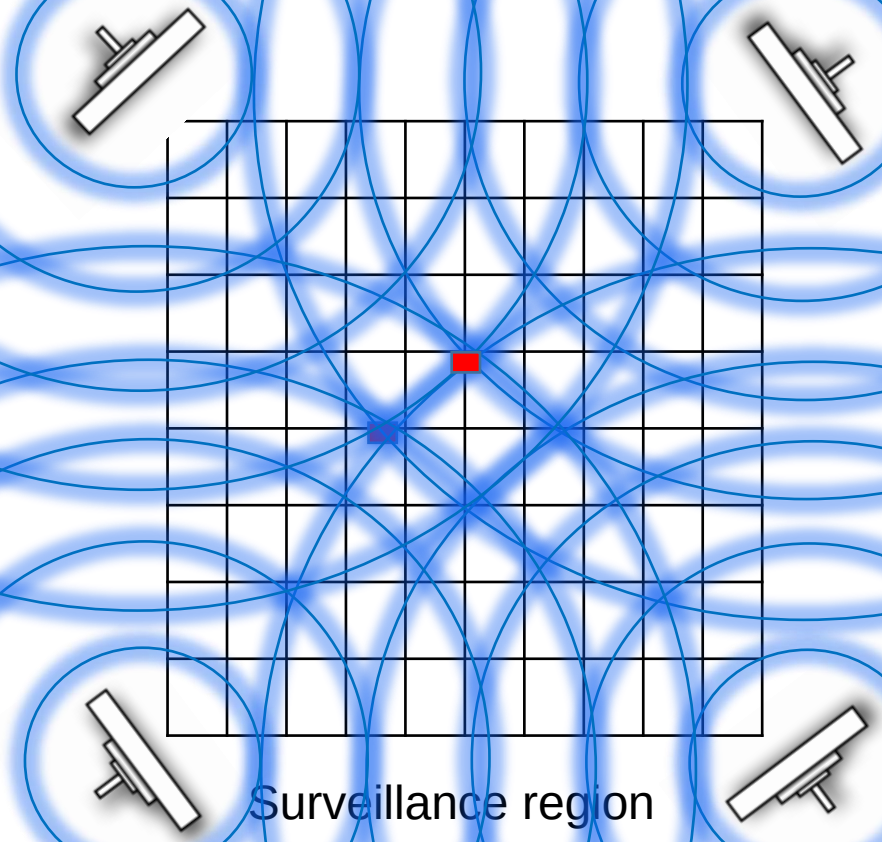
Reader antenna

$$M \times N$$

$$\{(\theta_{1,1}, t_{1,1}), (\theta_{1,2}, t_{1,2}) \cdots, (\theta_{1,N}, t_{1,N})\}$$
$$\{(\theta_{2,1}, t_{2,1}), (\theta_{2,2}, t_{2,2}) \cdots, (\theta_{2,N}, t_{2,N})\}$$
$$\vdots \qquad \vdots \qquad \vdots$$
$$\{(\theta_{M,1}, t_{M,1}), (\theta_{M,2}, t_{M,2}) \cdots, (\theta_{M,N}, t_{M,N})\}$$

**Utilizing antennas' locations, sampled phase values and timestamps to find out the tag's trajectory $f(t)$?**

# Bird's Eye View of Tagoram



# Tagoram

Case 1. Controllable Case

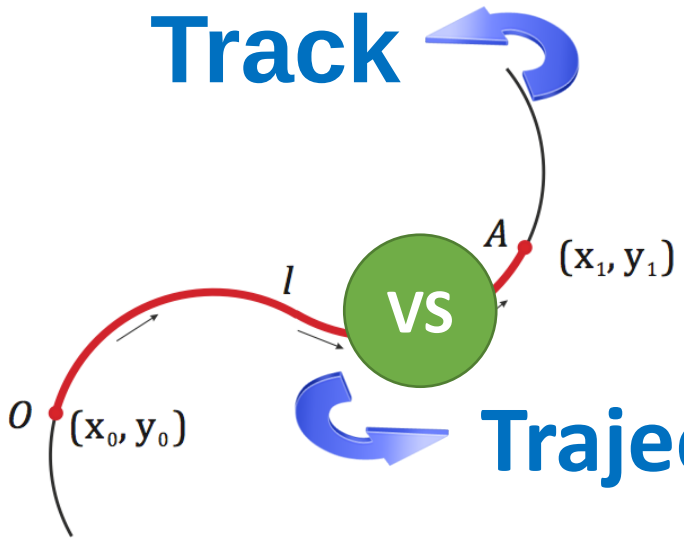
Case 2. Uncontrollable Case

# 4 Movement with Known Track

## Controllable case

# Track vs. Trajectory

**A function of geometric relationships**

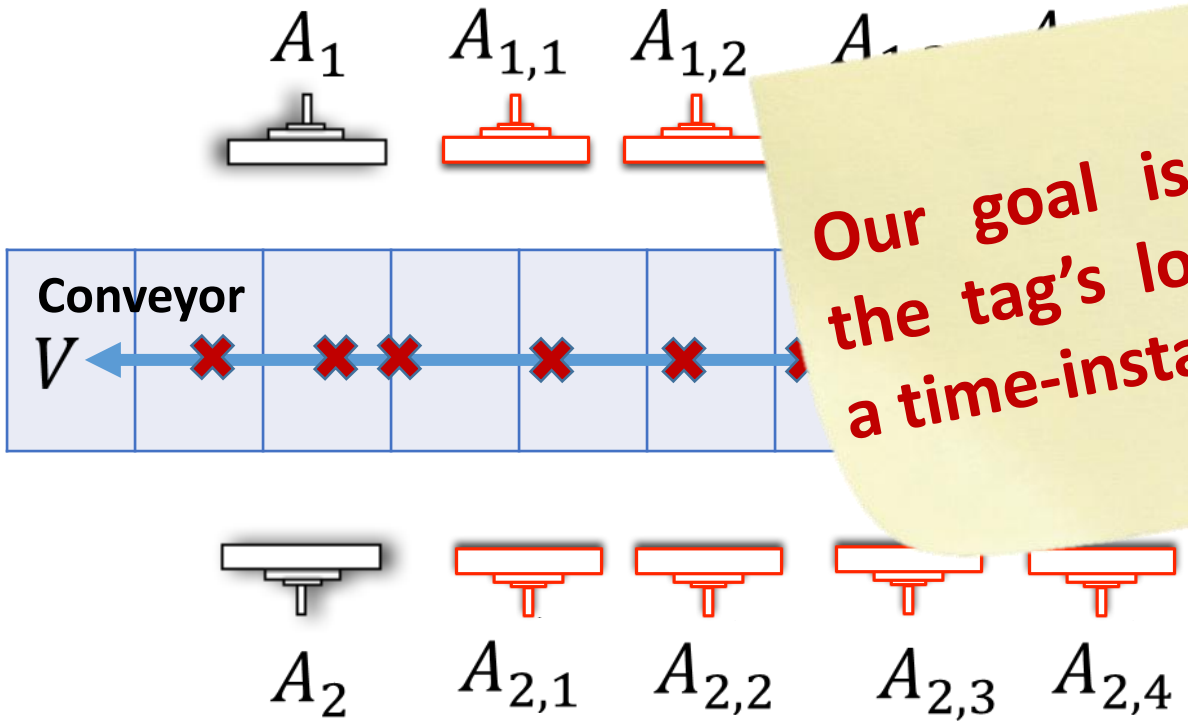



Our goal is to find the tag's trajectory with a known track.

**A function of time–space relationships**

# Virtual Antenna Array

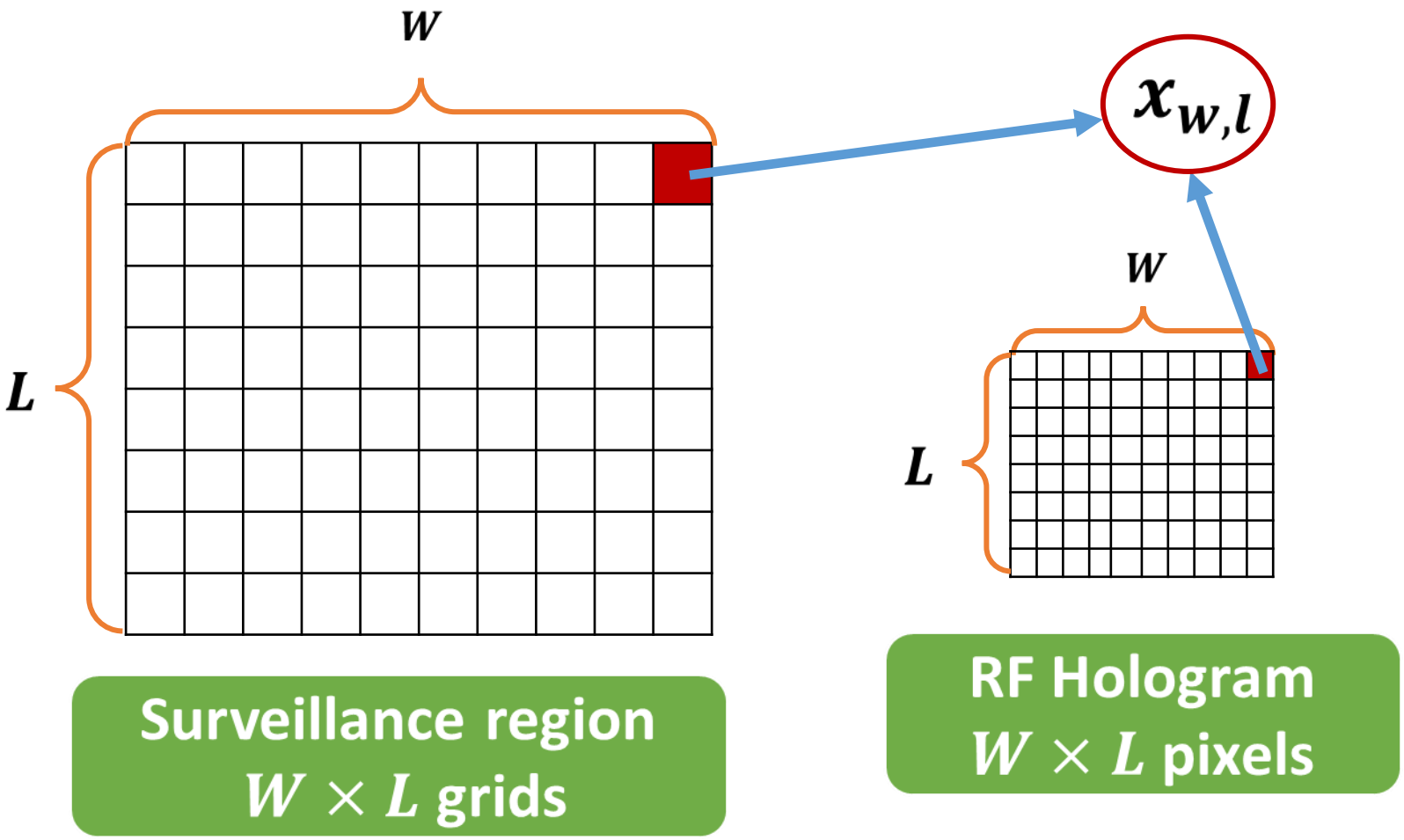
**Inverse Synthetic Aperture Radar**




Our goal is to find the tag's location at a time-instance $t_0$

**Initial position**

# RF Hologram


W
L
$x_{w,l}$
W
L
Surveillance region
$W \times L$ grids
RF Hologram
$W \times L$ pixels

The key is

# How to define the likelihood?

# RF Hologram

**Naïve Hologram**

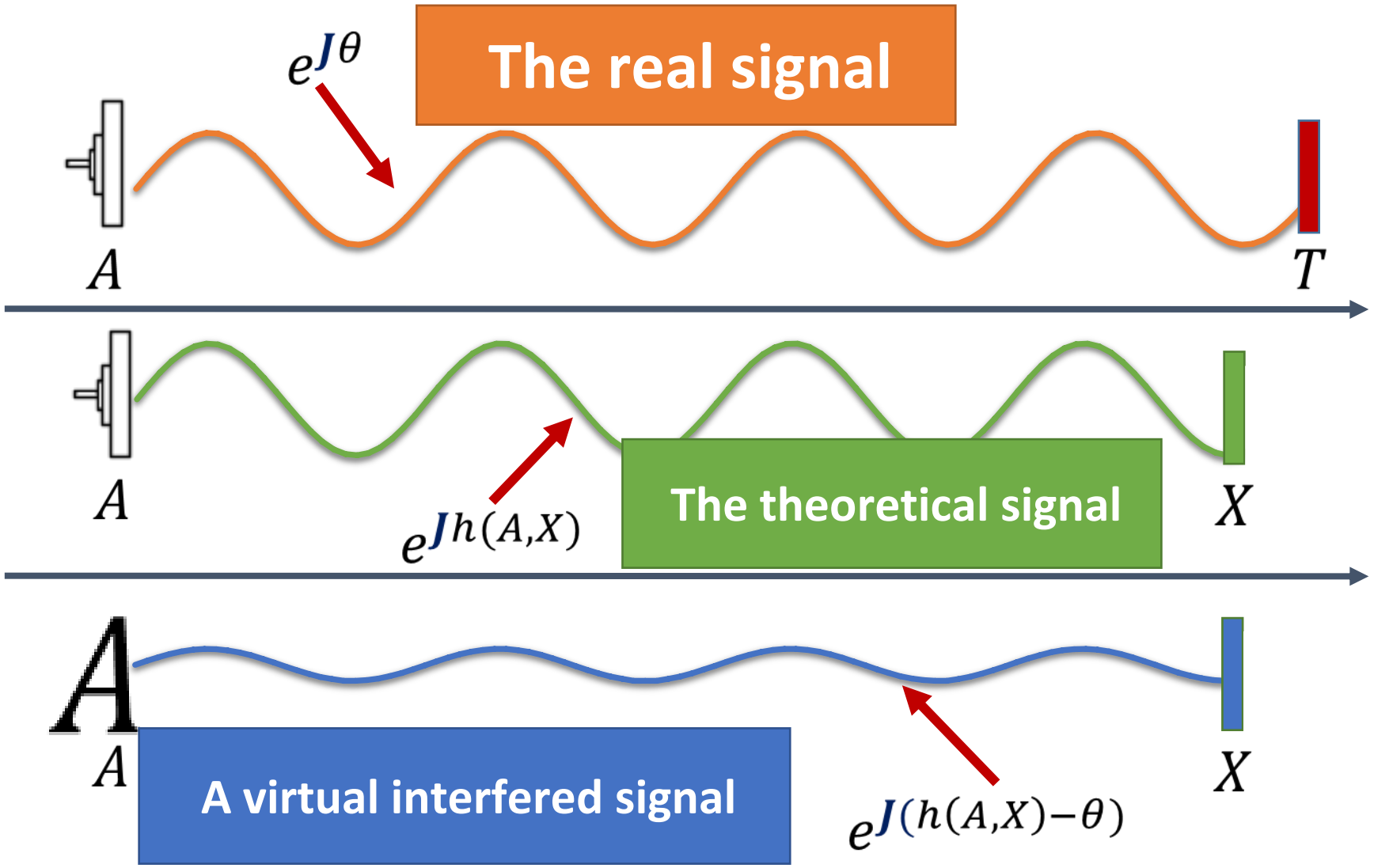
**Augmented Hologram**

**Thermal noise**

**Device diversity**

**Differential Augmented Hologram**

# Naïve Hologram



# Naïve Hologram

Sum of all signals

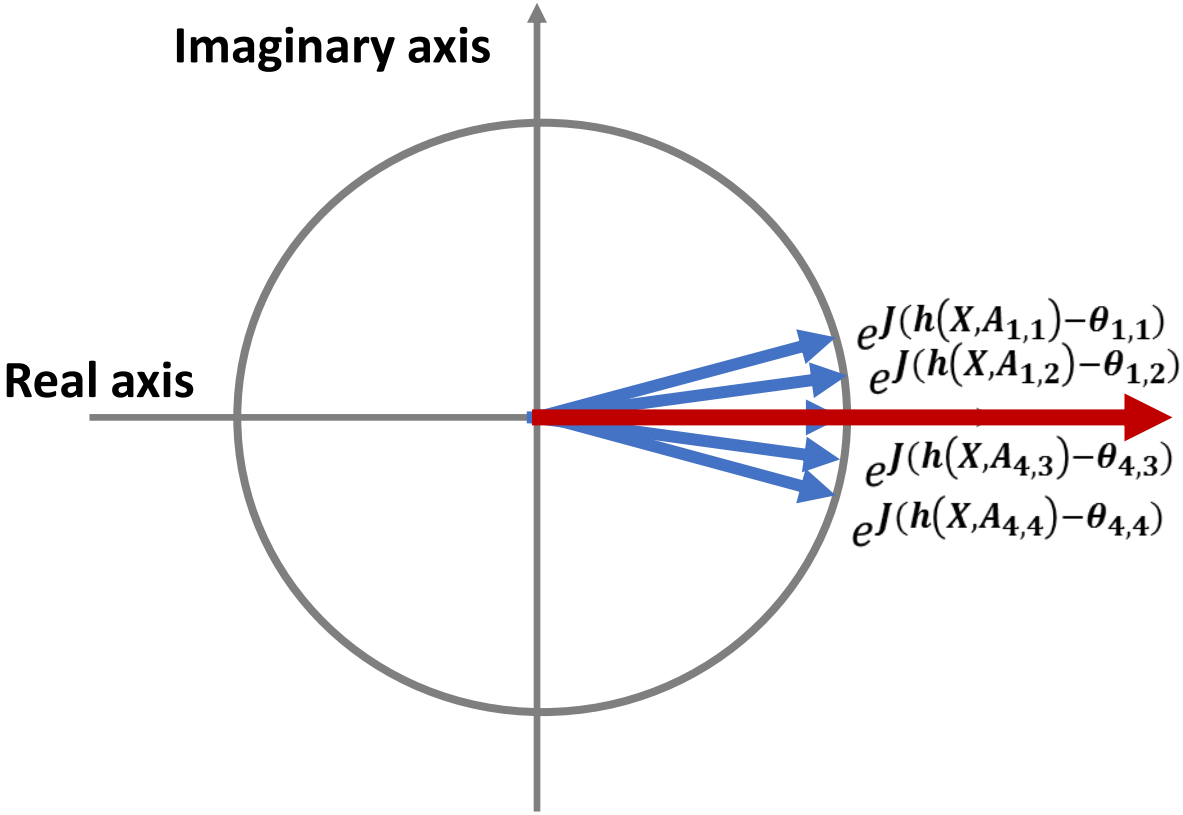
DEFINIT ). *The naive holo-gram is an image in which the pixel value* $x_{w,l}$, *indicating the likelihood that the corresponding grid* $X_{w,i}$ *is the initial position, is calculated by*

$$x_{w,l} = \left| \sum_{m=1}^{M} \sum_{n=1}^{N} S(X_{w,l}, A_{m,n}, \theta_{m,n}) \right| \tag{9}$$

*where* $S(X, A, \theta) = e^{\mathbf{J}(h(X,A)-\theta)}$. *The term* $\mathbf{J}$ *denotes the imaginary number and the term* $e^{\mathbf{J}\theta}$ *represents a complex exponential*

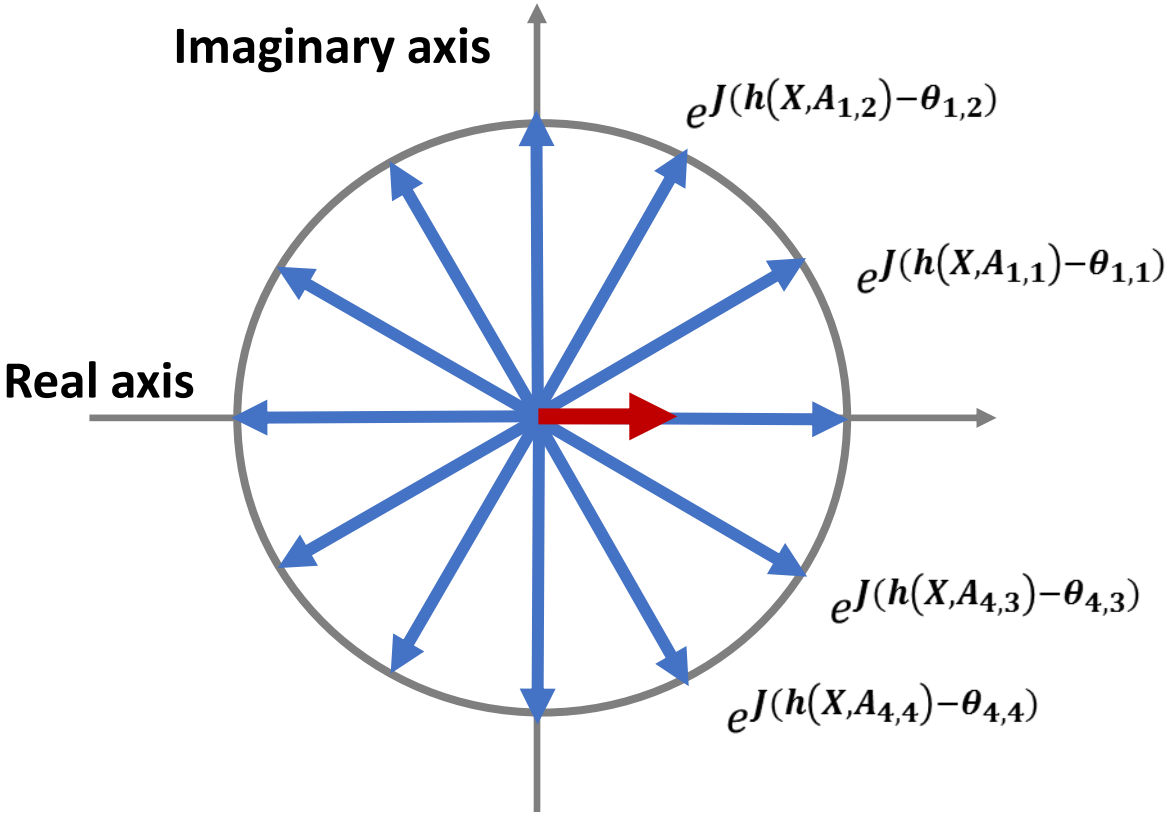
Virtual interfered signal

# Naïve Hologram



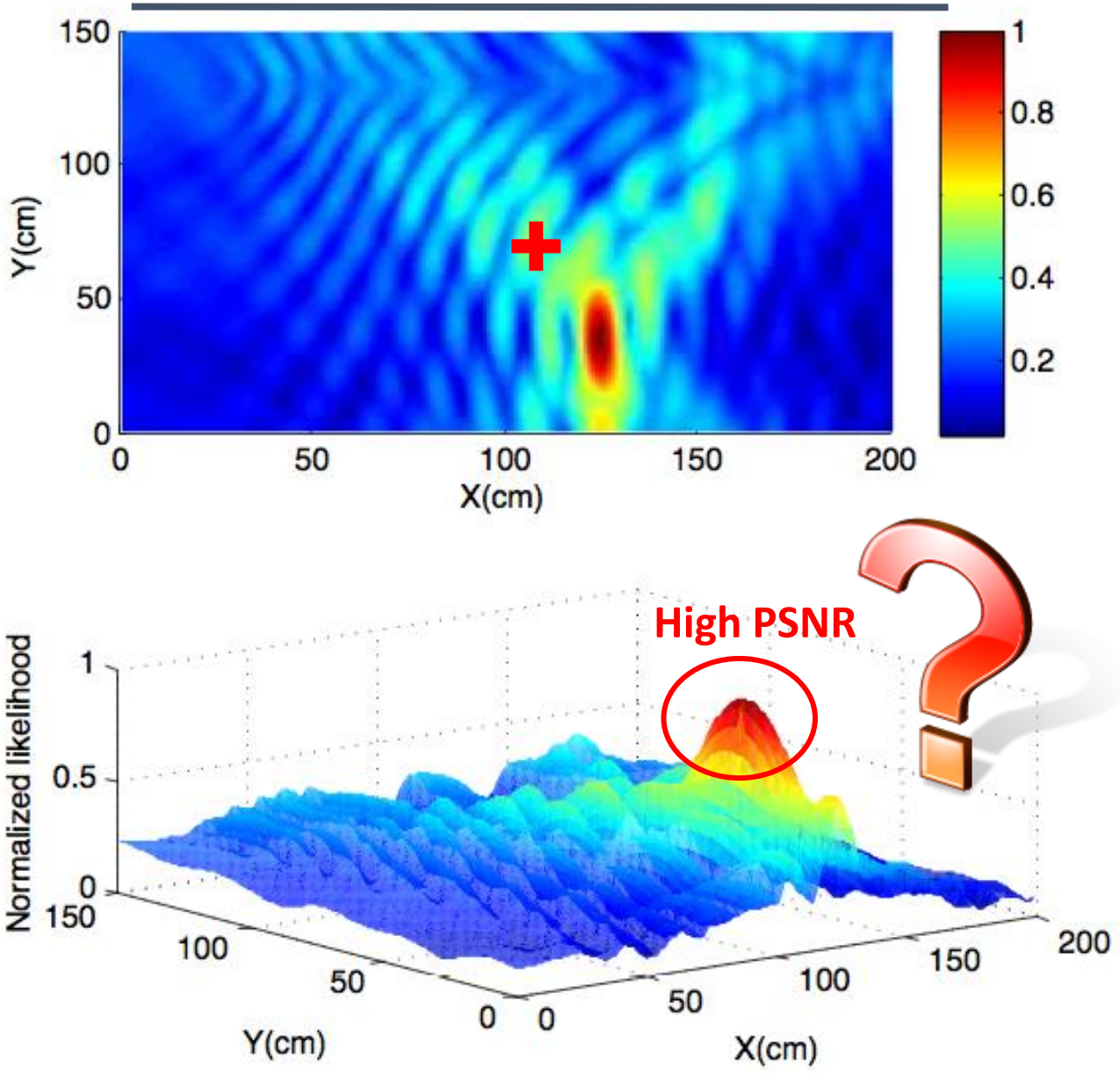

**If $X$ is the initial location, the waves add up constructively.**

# Naïve Hologram




**If $X$ is not the initial location, the waves canceled out.**

# Naïve Hologram



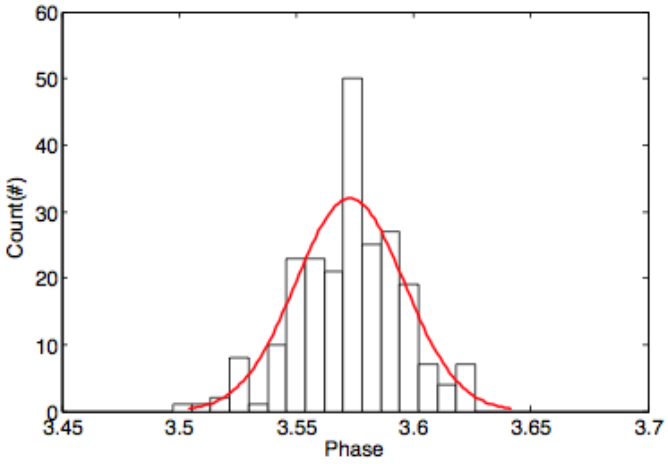
# Influence from Thermal Noise

100 tags

$0° \sim 40°$

$920 \sim 926\ MHz$

$-70 \sim -30dbm$




**Experiment** | **Observations**

**Modeling** | **CDF**

$$\theta \sim \mathcal{N}(\mu, \sigma)$$

$$F(\theta; \mu, \sigma)$$

varying with $d$

$\sigma = 0.1$

# How to deal with thermal noise?

## Augmented Hologram

# Augmented Hologram

A probabilistic weight

$(h(X,A) - \theta) \sim \mathcal{N}(0, 0.1)$

DEFINITION 2 (AH). *The augmented hologram is an image in which the pixel value* $x_{w,l}$ *is*

$$x_{w,l} = \left| \sum_{m=1}^{M} \sum_{n=1}^{N} \|S(X_{w,l}, A_{m,n}, \theta_{m,n})\| S(X_{w,l}, A_{m,n}, \theta_{m,n}) \right| \quad (10)$$

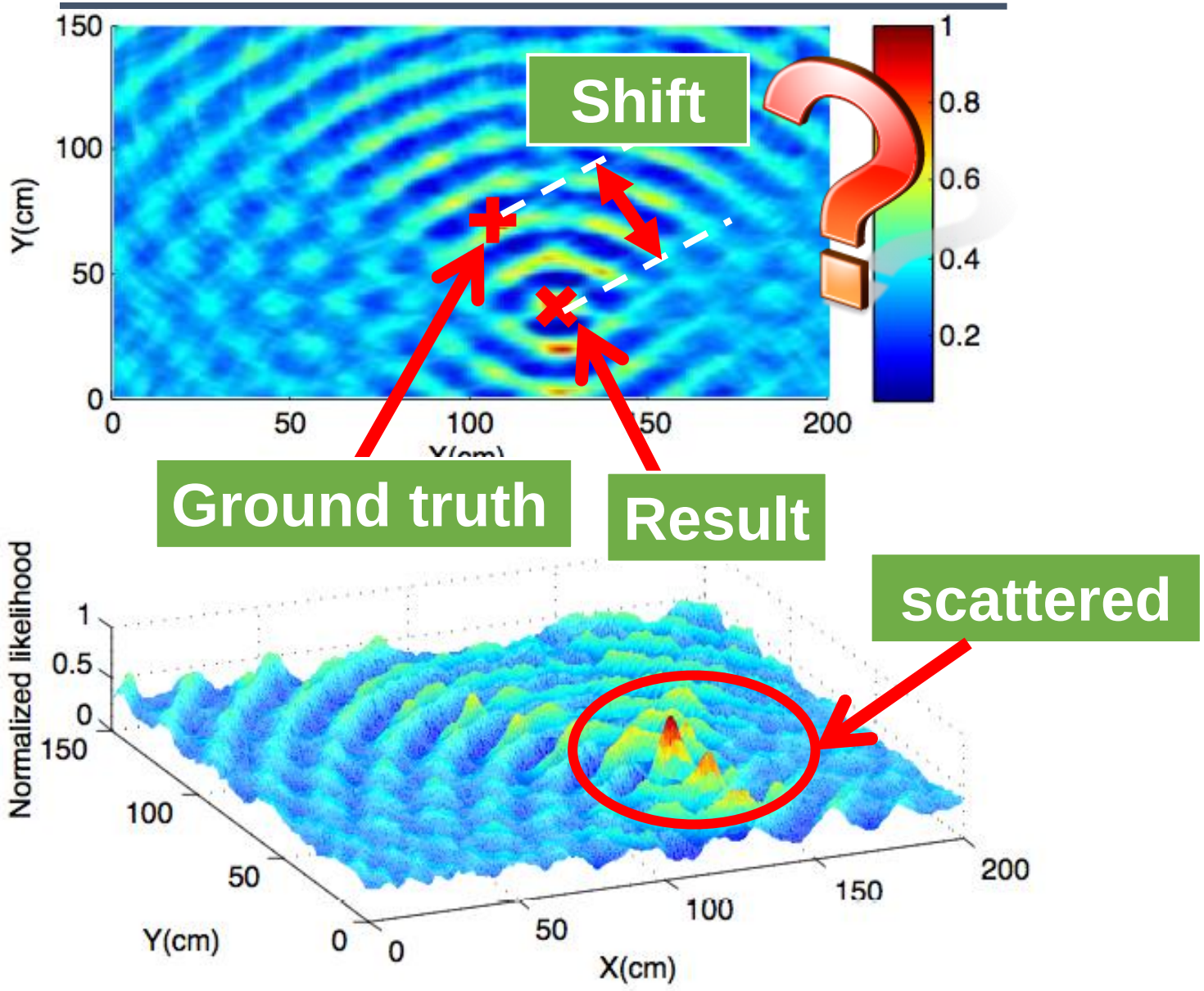
*where*

$$\begin{cases} \|S(X, A, \theta)\| = 2 \times F(|h(X, A) - \theta|; 0, 0.1) \\ F(x; \mu, \sigma) = \dfrac{1}{\sigma\sqrt{2\pi}} \displaystyle\int_{x}^{\infty} \exp\left(-\frac{(t-\mu)^2}{2\sigma^2}\right) dt \end{cases}$$

*and* $F(x; \mu, \sigma)$ *is the cumulative probability function of Gaussian distribution* $\mathcal{N}(\mu, \sigma)$.

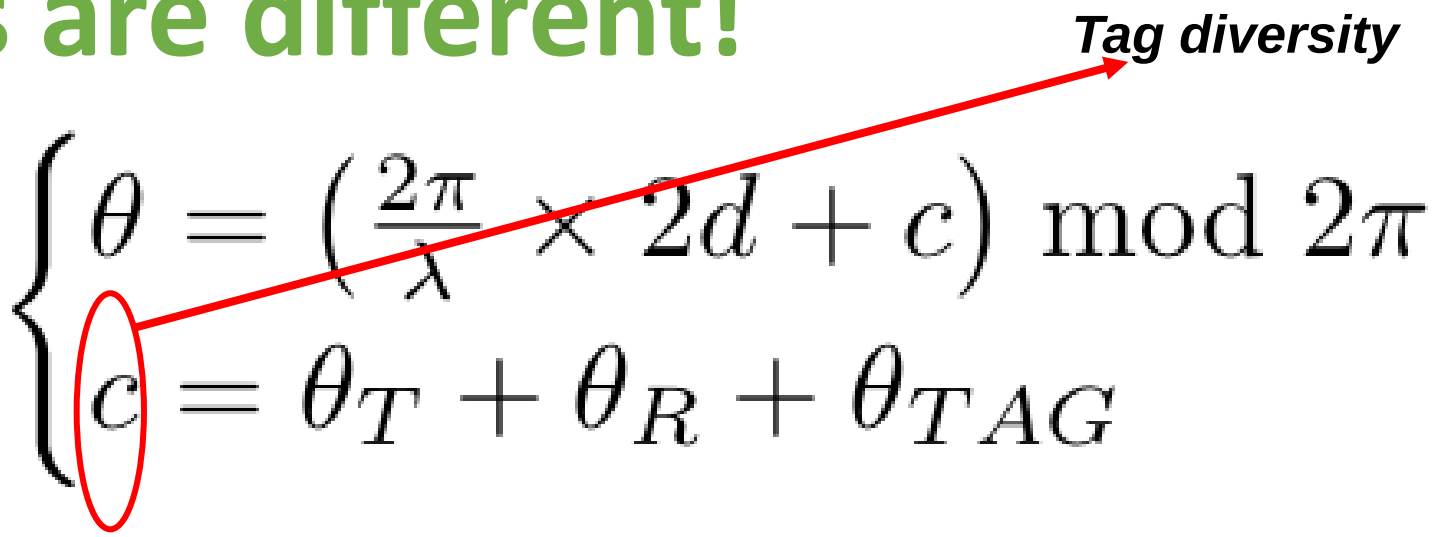
Probability of $T \rightarrow A$

# Augmented Hologram



# What is missing again?

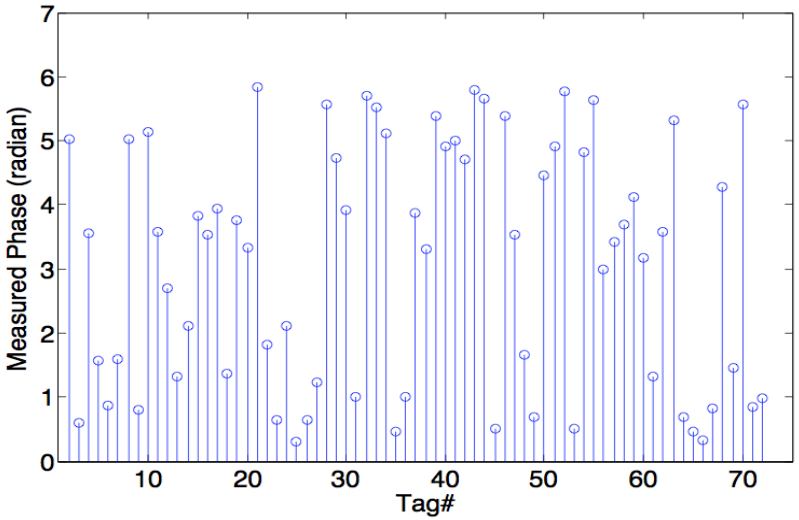
## Tags are different!



# Influence from Tag Diversity

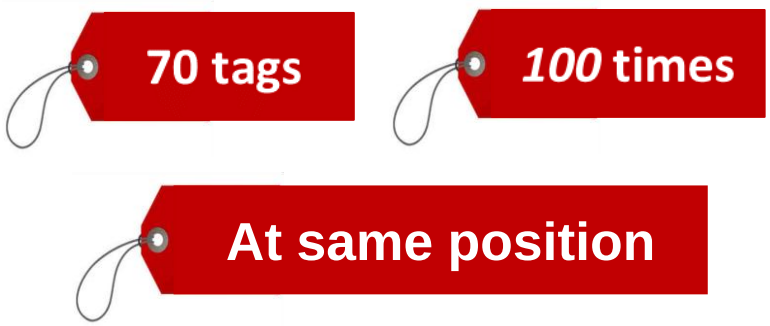
$$\begin{cases} \theta = \left(\frac{2\pi}{\lambda} \times 2d + c\right) \bmod 2\pi \\ c = \theta_T + \theta_R + \theta_{TAG} \end{cases}$$

***Tag diversity***




**Modeling** | **Observations**

**Experiment** | **Random test**




**Pass *KS-test* to be verified over a *uniform distribution* with 0.5 significant level.**

# How to eliminate tag diversity?

## Differential Augmented Hologram

# Differential Augmented Hologram

DEFINITION 3 (DAH). *The differential augmented hologram is an image in which the pixel value is calculated by*

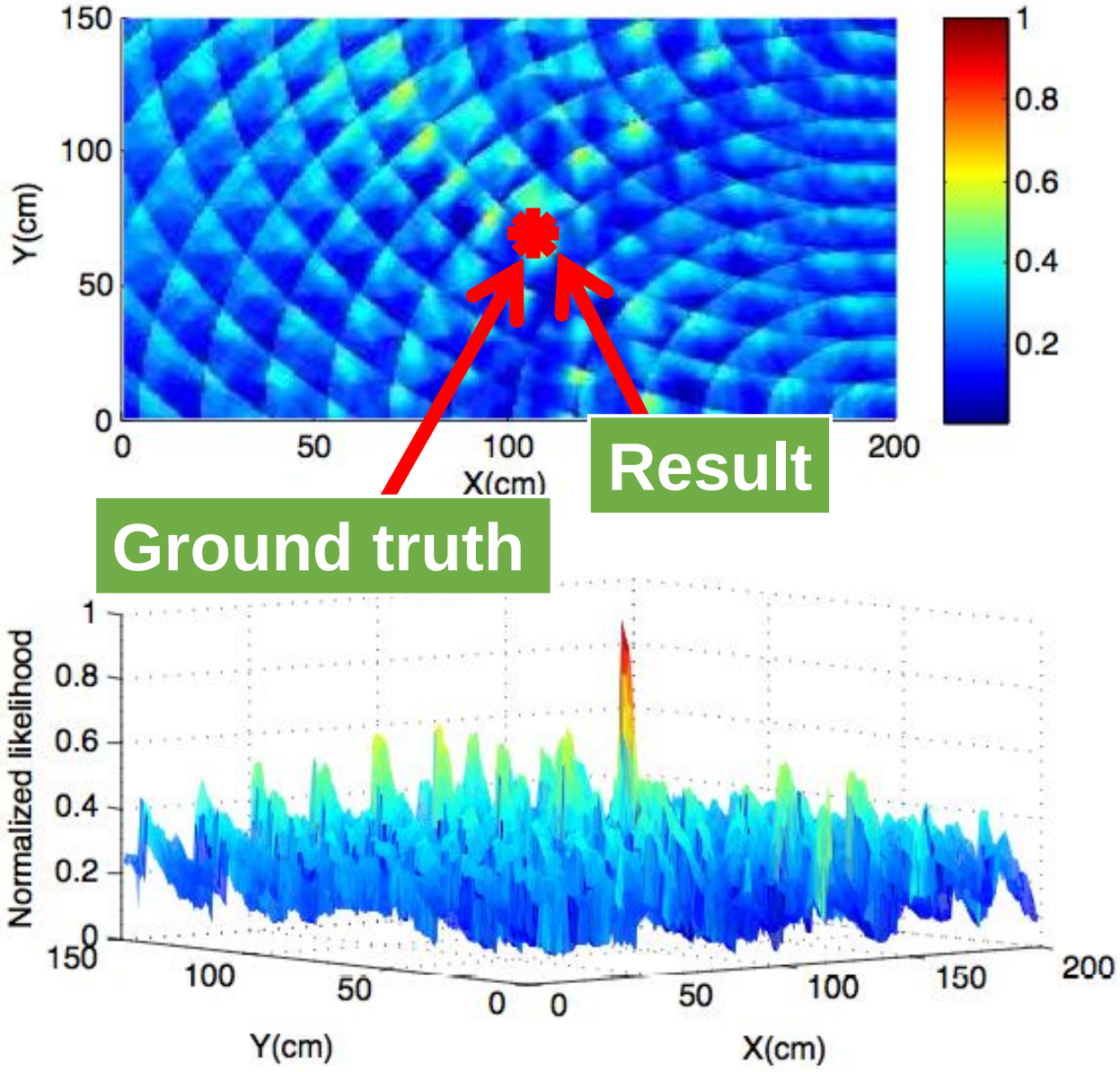
$$x_{w,l} = \left| \sum_{m=1}^{M} \sum_{n=1}^{N} \|\mathbb{S}(X_{w,l}, A_{m,n}, \theta_{m,n})\| \mathbb{S}(X_{w,l}, A_{m,n}, \theta_{m,n}) \right| \tag{11}$$

*where*

$$\begin{cases} \mathbb{S}(X_{w,l}, A_{m,n}, \theta_{m,n}) = e^{\mathbf{J}\theta_{dif}} \\ \|\mathbb{S}(X_{w,l}, A_{m,n}, \theta_{m,n})\| = 2 \times F(|\theta_{dif}|; 0, 0.1 \times \sqrt{2}) \\ \theta_{dif} = (h(X_{w,l}, A_{m,n}) - \theta_{m,n}) - (h(X_{w,l}, A_{m,1}) - \theta_{m,1})) \end{cases}$$

**Using difference of difference of phase values**

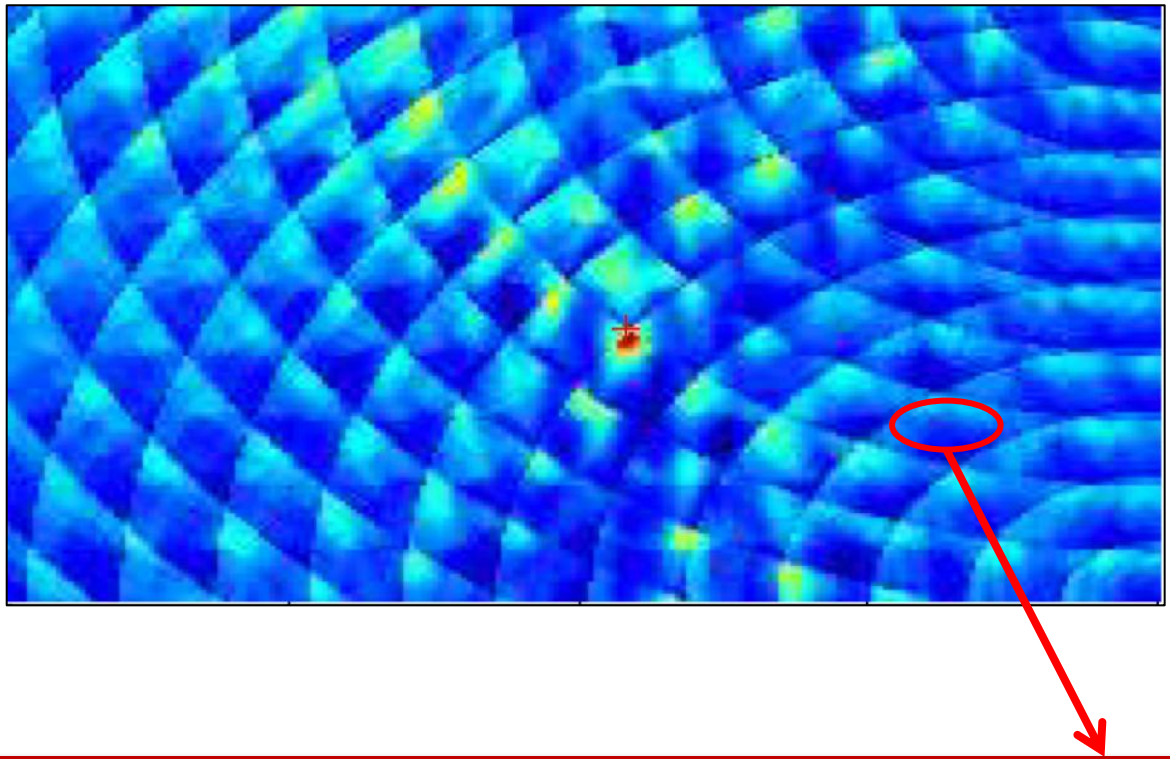
# Differential Augmented Hologram



# How to achieve the real-time?

## Incremental computations

# Saving Computations in Spatial Domain



**Observation: The computations on blue pixel (low level PSNR) are totally wasted**

# 5 Movement with Unknown Track

## Uncontrollable case

# Overview

1. Estimating Speeds, Fitting tag's trajectory
2. Selecting the optimal trajectory

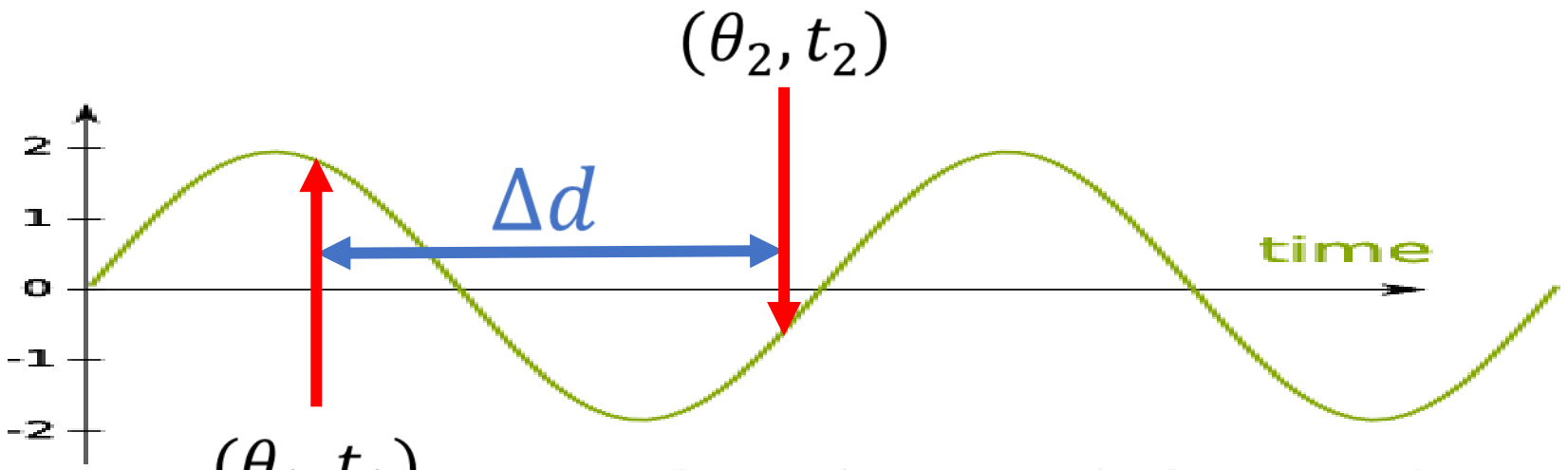
# Observations

- **Observation 1**: The maximum velocity of conveyor system $< 300mm/s$

- **Observation 2**: The time interval between two consecutive reads is about $30ms$

# Fitting tag's trajectory

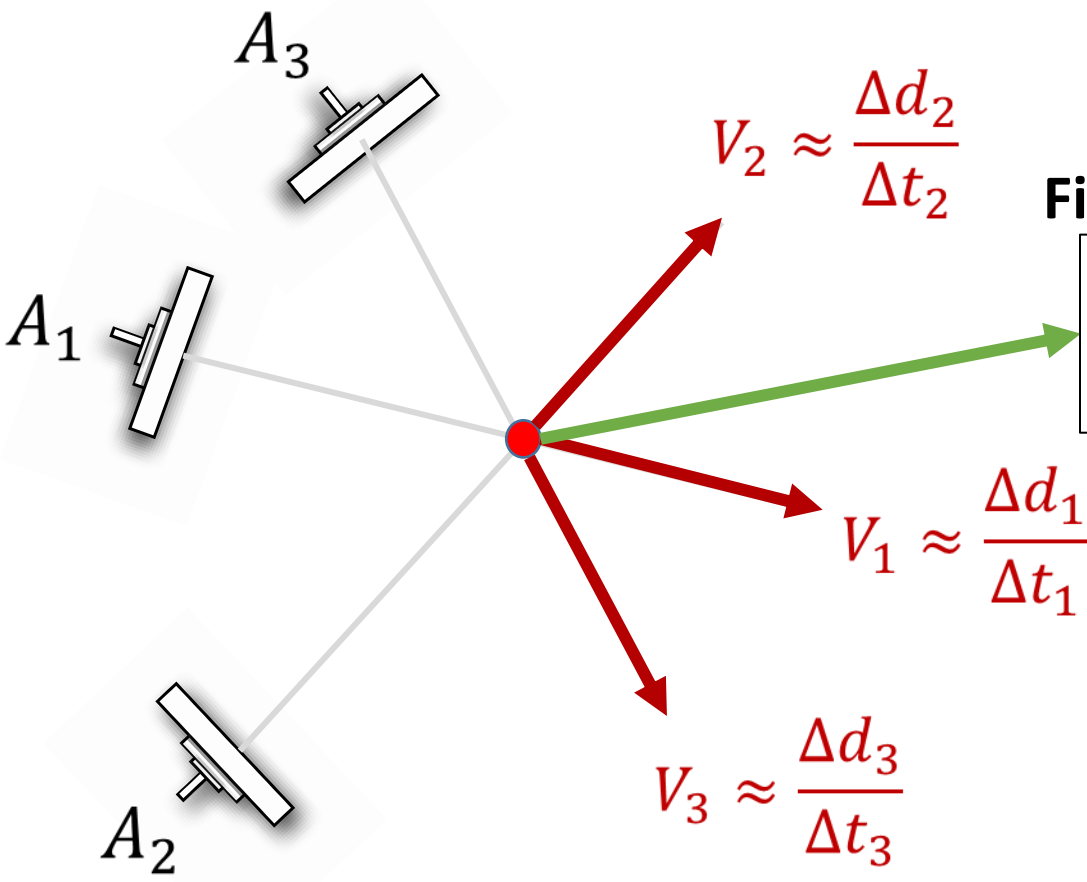
**The displacement $\Delta d$ between two reads is less than half a wavelength.**




$$\Delta d = (\theta_2 - \theta_1)/4\pi \times \lambda$$

*More complicate cases are discussed in our paper.*

# Fitting Tag's Trajectory




**Fitting the speed using NLS**

$$\begin{cases} \widetilde{V}_{m,n} \approx \frac{\Delta d}{t_{m,n+1} - t_{m,n}} \\ \angle \widetilde{V}_{m,n} \approx \angle (f(t_n) - A_m) \end{cases}$$

# Fitting Tag's Trajectory

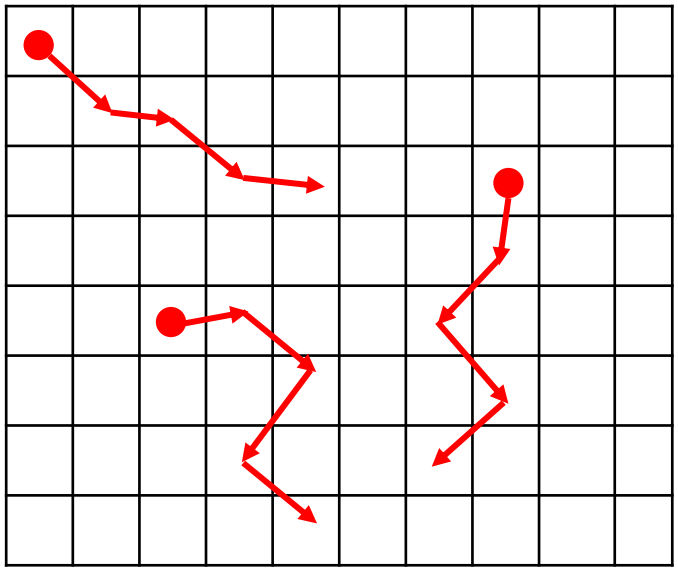
$v$ — Speed Chain → $V = \{V_1, \cdots, V_N\}$

$f(t_n)$ — Trajectory →

$$f(t_n) = f(t_{n-1}) + f(t_n - t_{n-1}) \cdot \vec{V}_n$$

$$= f(t_0) + \sum_{k=1}^{n} (t_k - t_{k-1}) \cdot \vec{V}_k$$

# Selecting the Optimal Trajectory



$$f(t_n) = f(t_0) + \sum_{k=1}^{n} (t_k - t_{k-1}) \cdot \vec{V}_k$$

***Unknown!***

# 6 Implementation & Evaluation

Purely based on COTS devices

# Hardware & Software Introduction

## Reader

ImpinJ R420 reader.


4 directional antennas

## Tag

Alien 2 × 2 Inlay

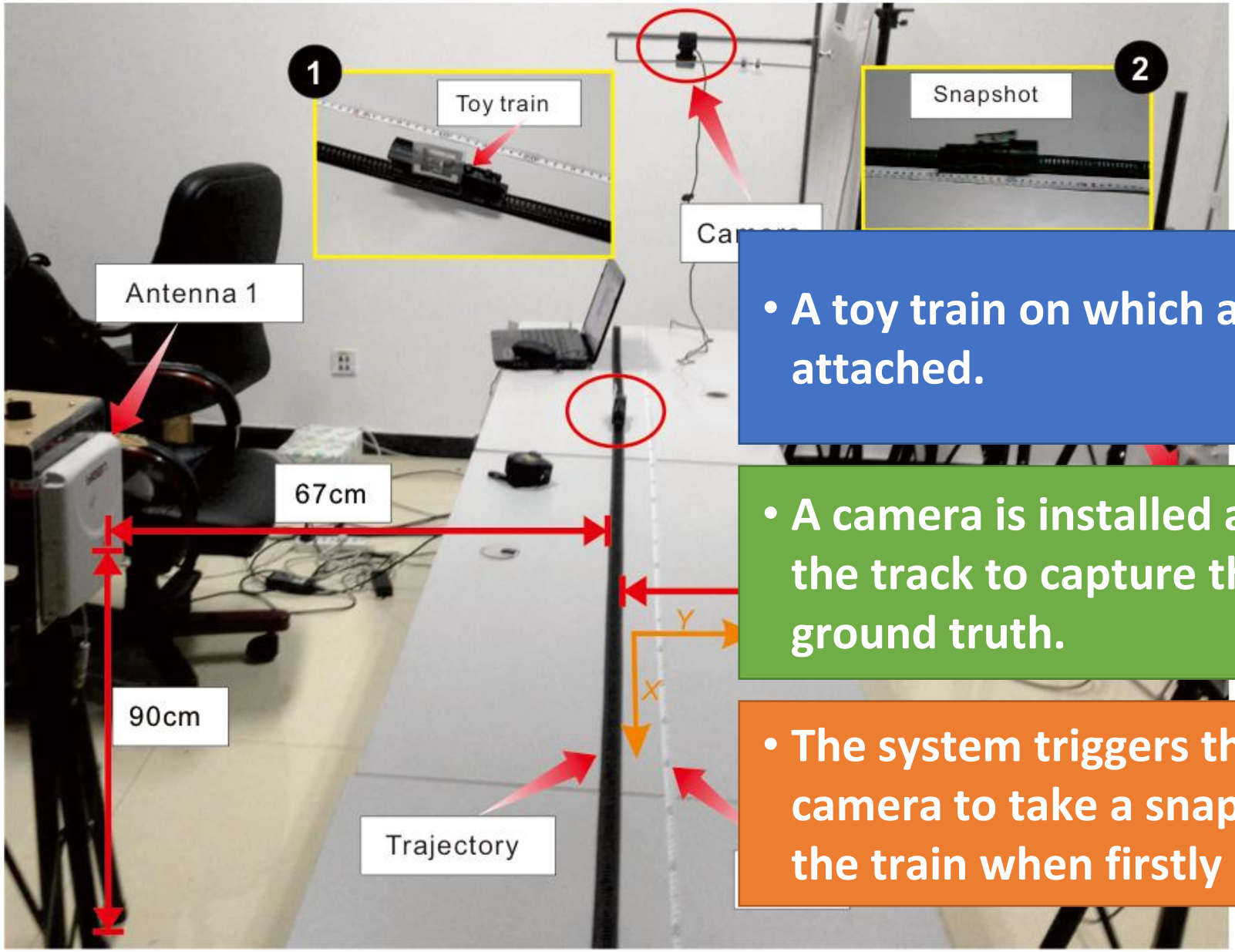
Alien Squiggle Inlay

## Software

EPCglobal LLRP

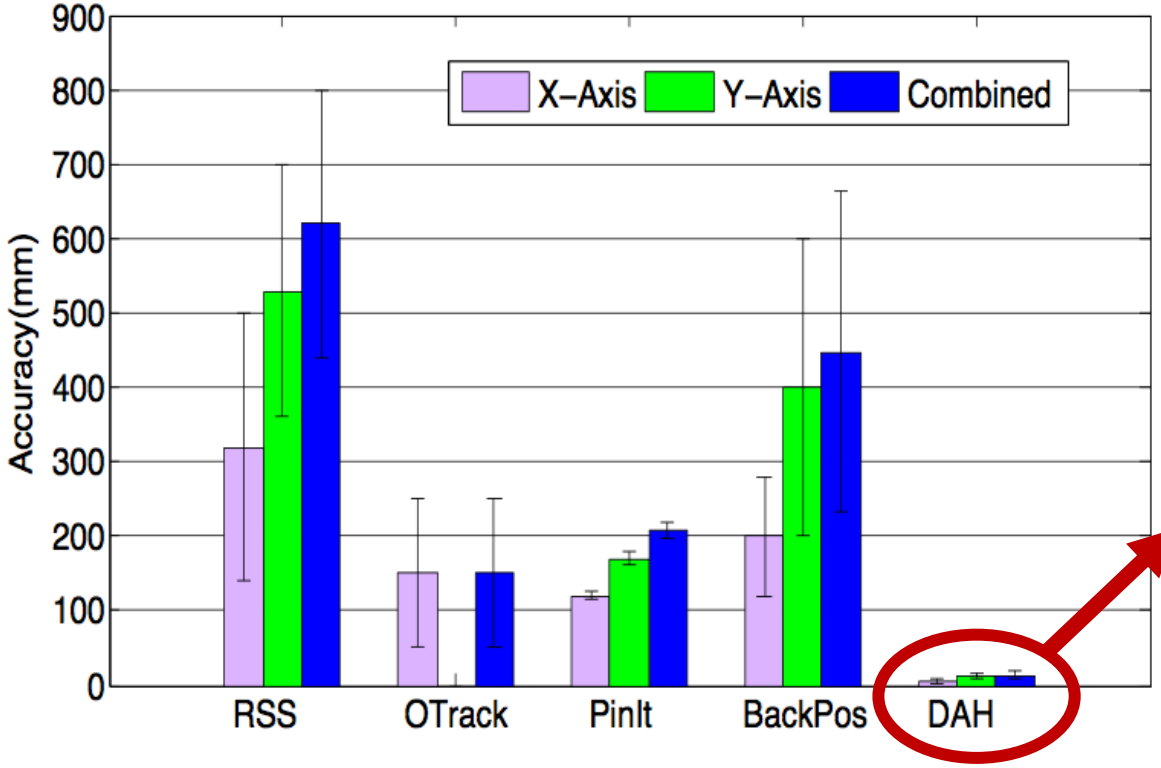
Java

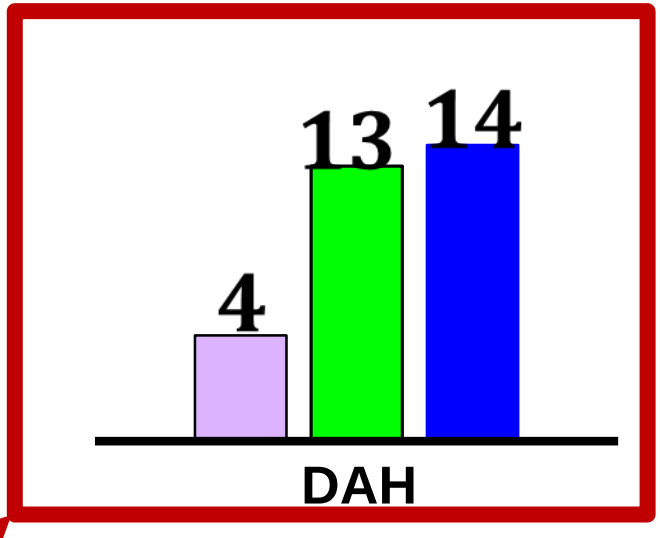
# Linear Track




- A toy train on which a tag is attached.
- A camera is installed above the track to capture the ground truth.
- The system triggers the camera to take a snapshot on the train when firstly read.

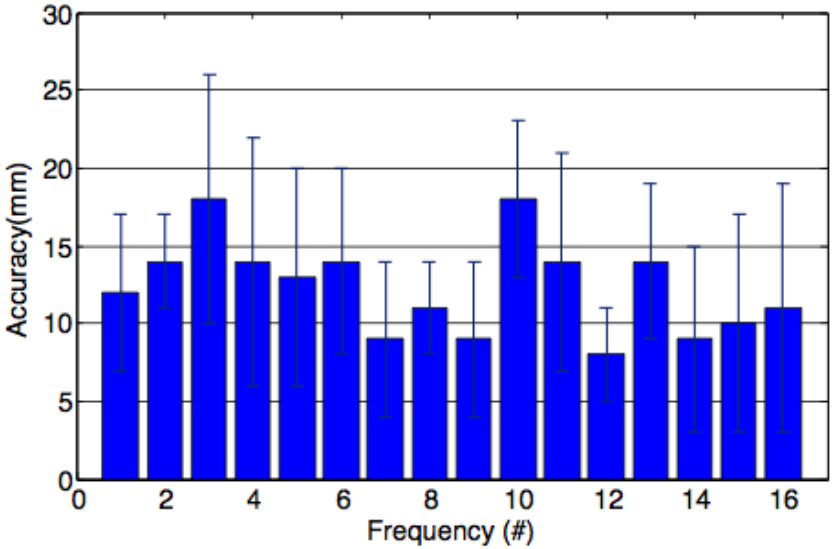
# Tracking Accuracy in Linear Track



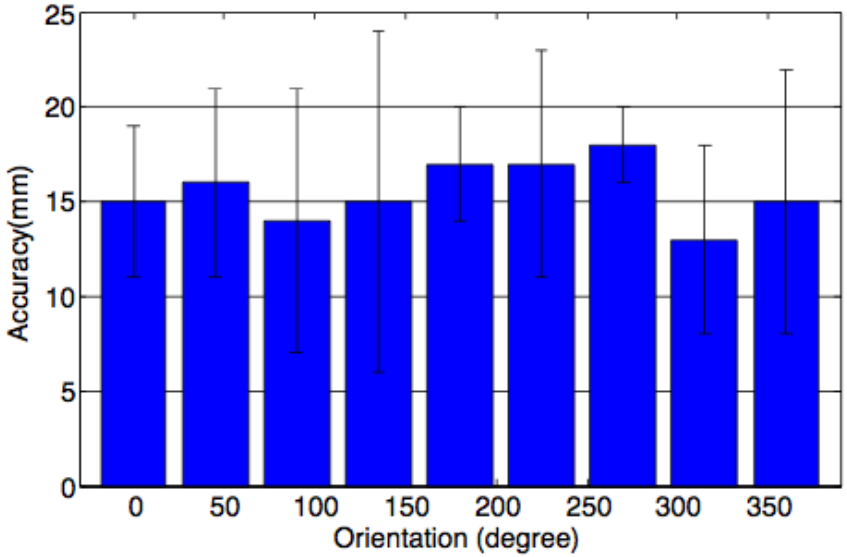




**Improve the accuracy by $48\times, 30\times, 28\times$ *and* $8.5\times$ in comparison to RSS, OTrack, PinIt and BackPos.**

# Impacts of frequency and orientation



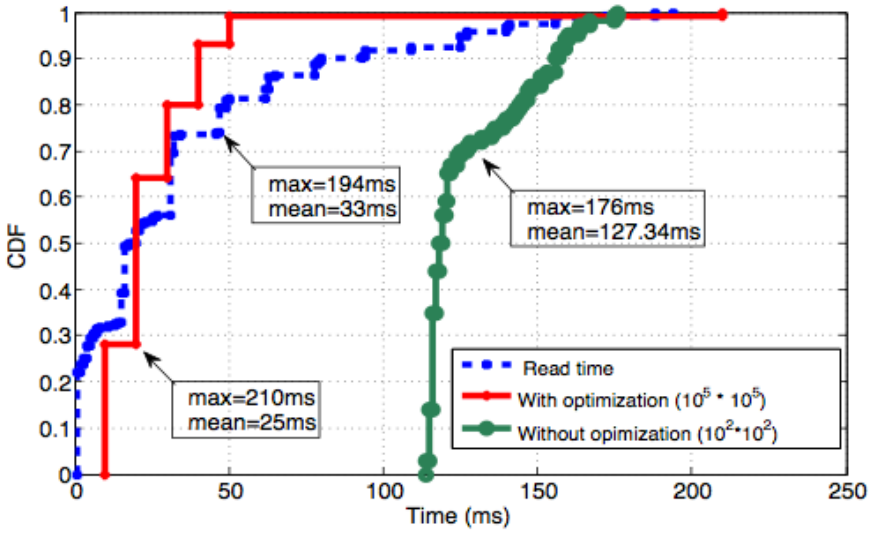

Impact of frequency



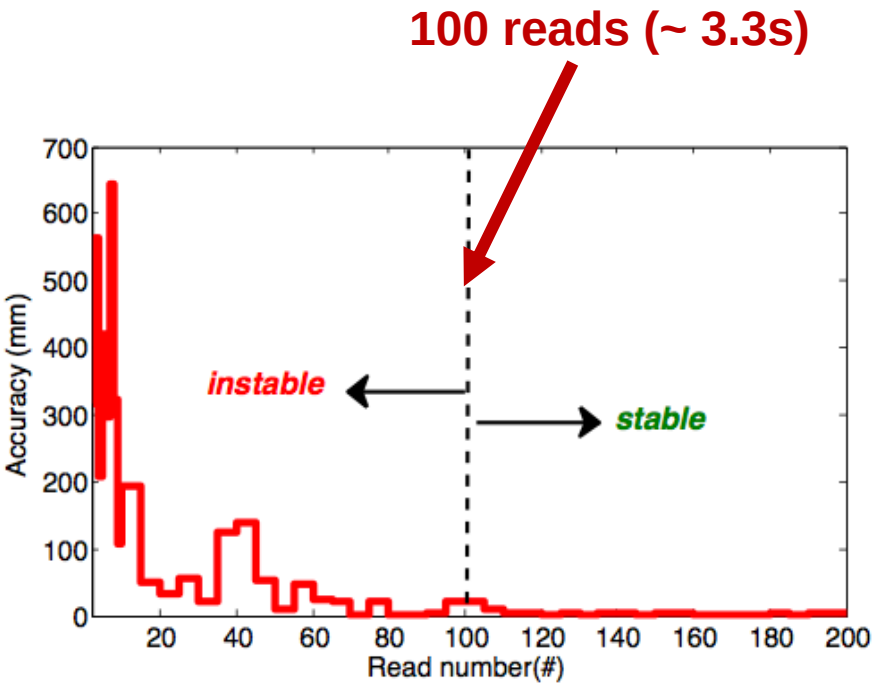

Impact of orientation

**Both frequency and orientation take limited impacts on tracking accuracy.**

# Real-time evaluation

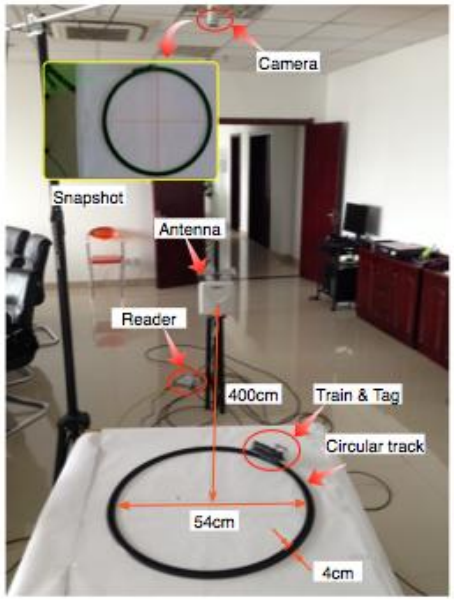



**Read-time**

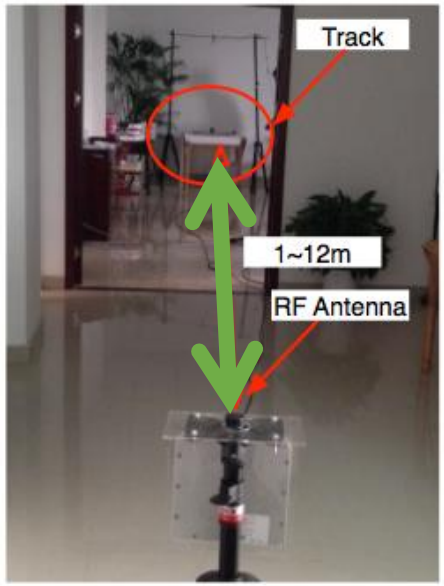



**Accuracy vs. Real-time**

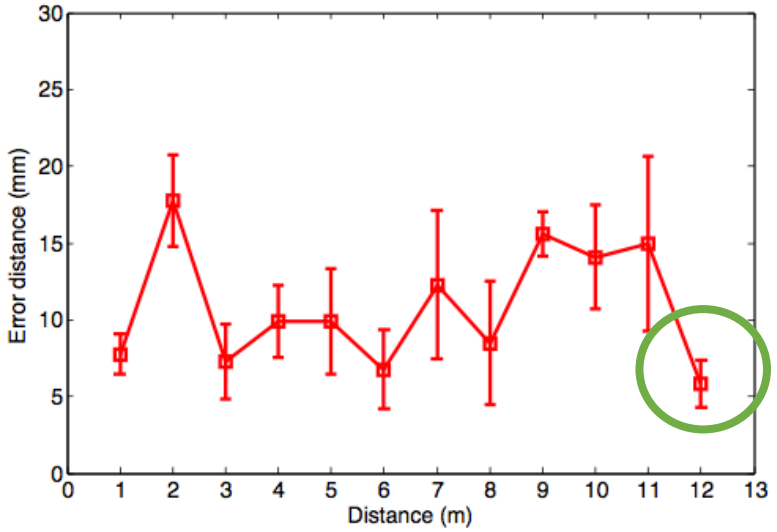
# Impact of distance




(a) Circular track

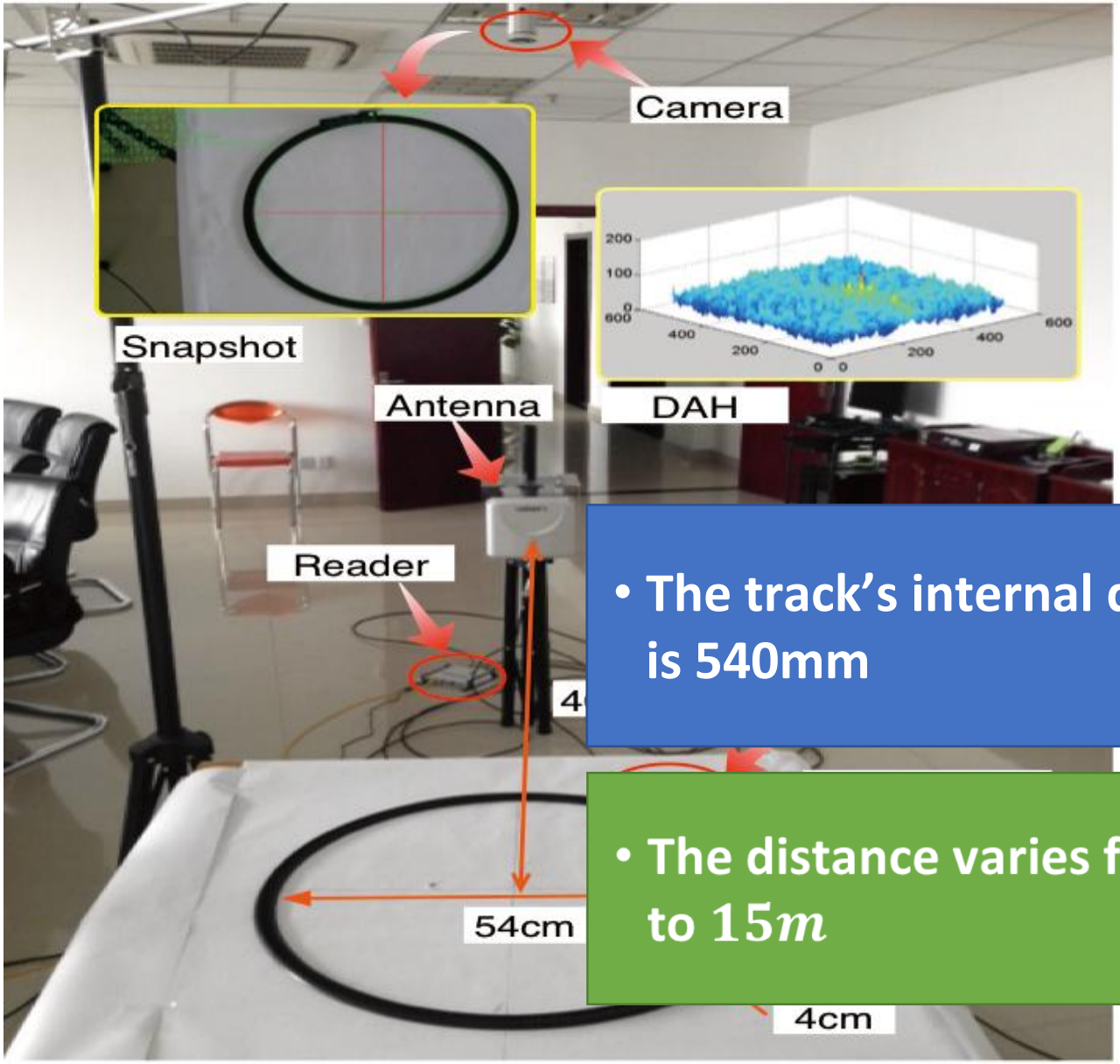



(b) Experiment setup



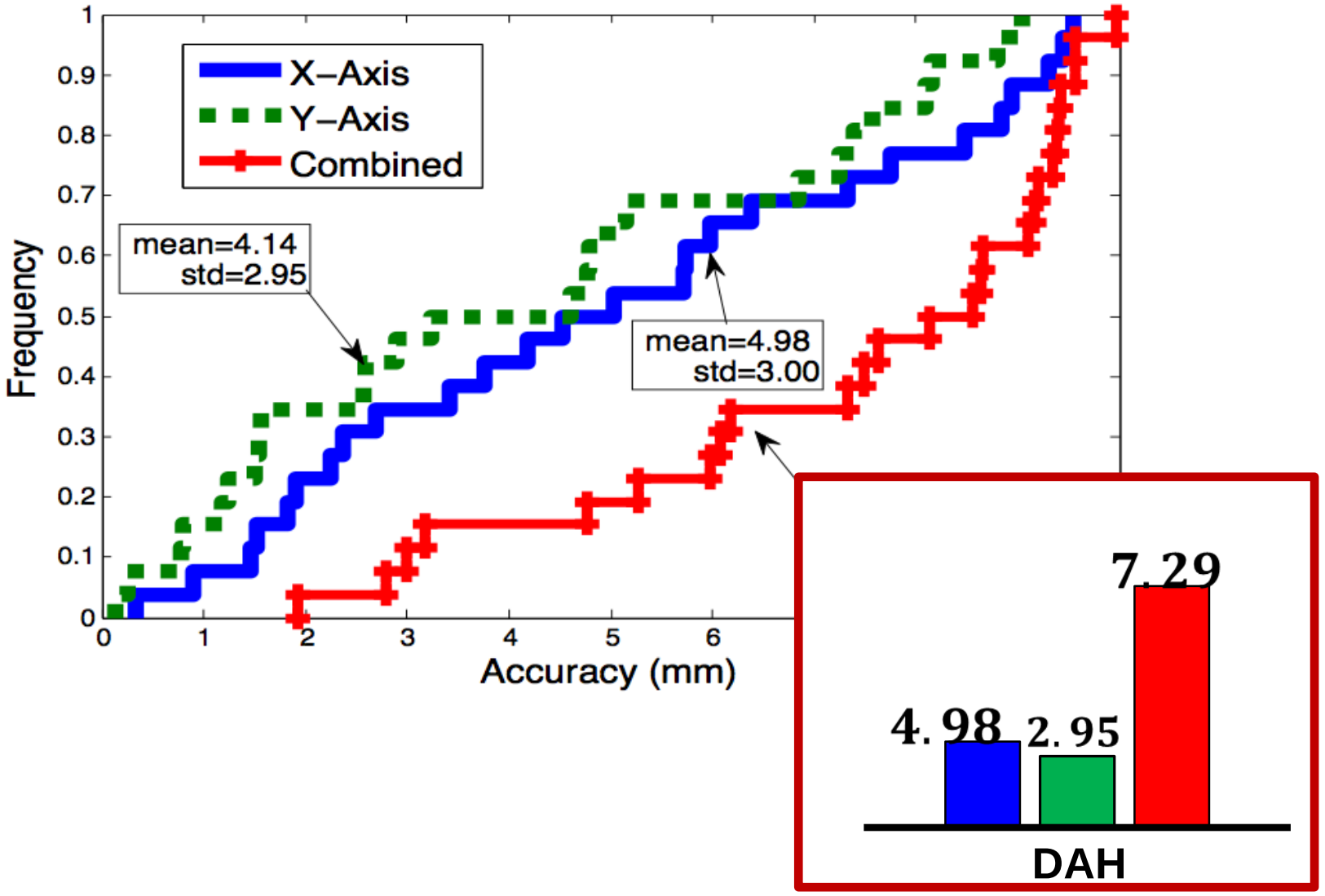

**No obvious pattern between distance and accuracy**

# Controllable Case with Nonlinear Track

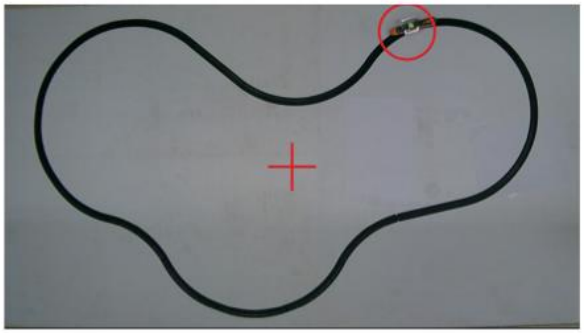



- The track's internal diameter is 540mm
- The distance varies from $1m$ to $15m$

# Nonlinear track



# Under Uncontrollable Case



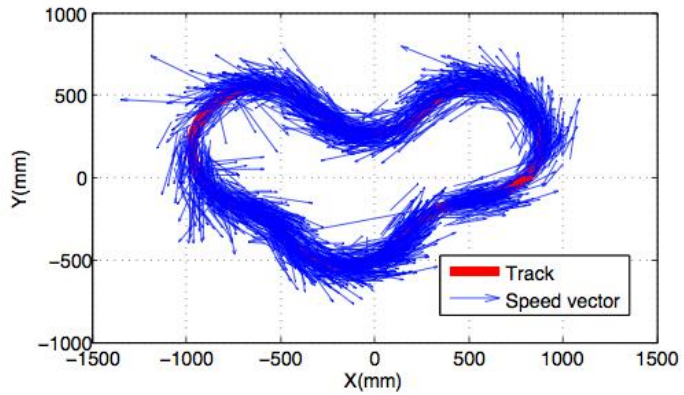



Figure 16: Estimated speed

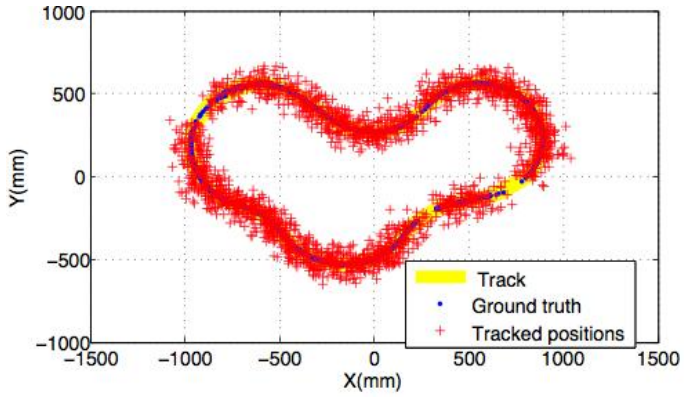


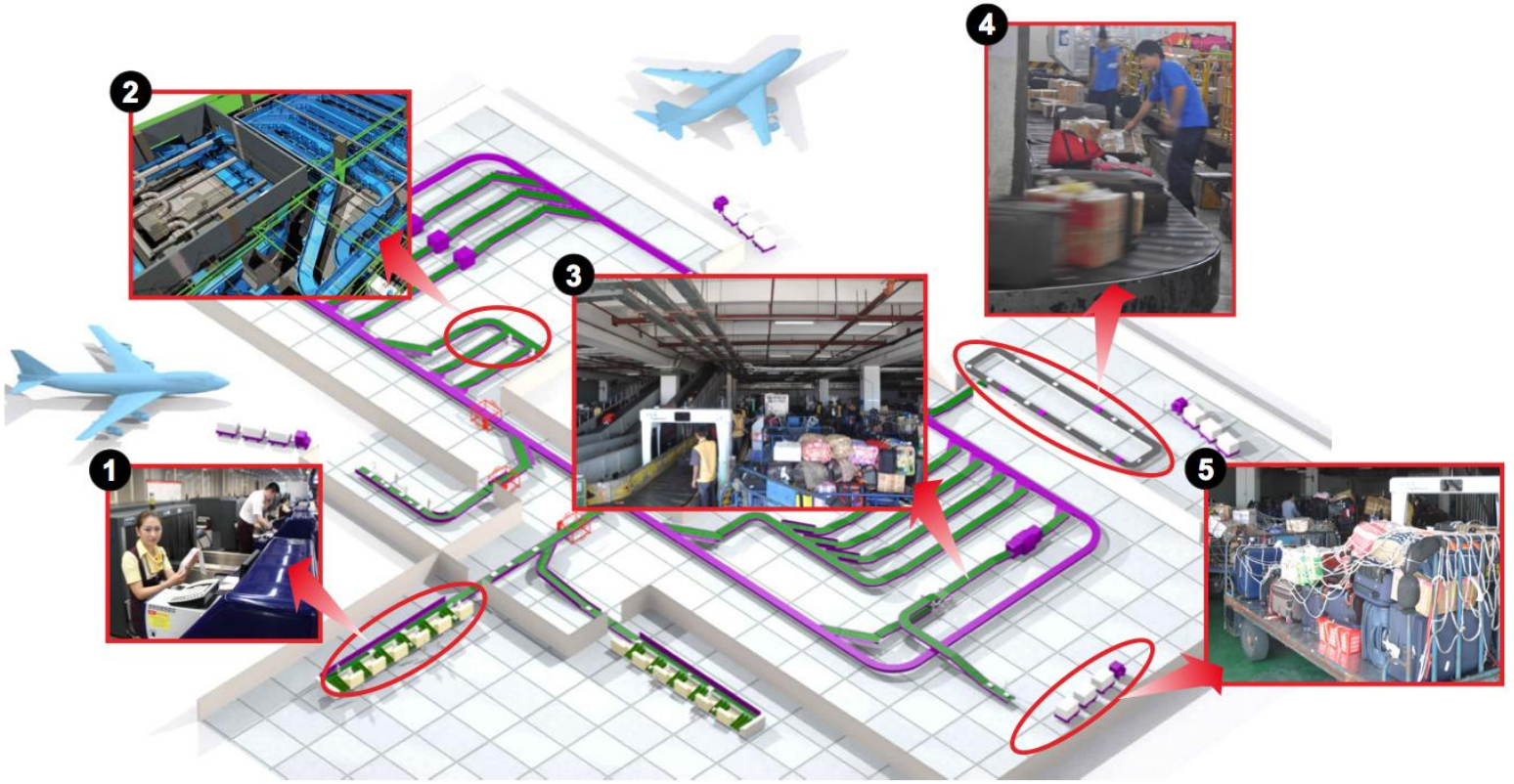

Figure 17: Fitted trajectory

**A median of 12.3cm accuracy with a standard deviation of 5cm ---- better method proposed later, with about 1cm accuracy**

# 7 Pilot Study

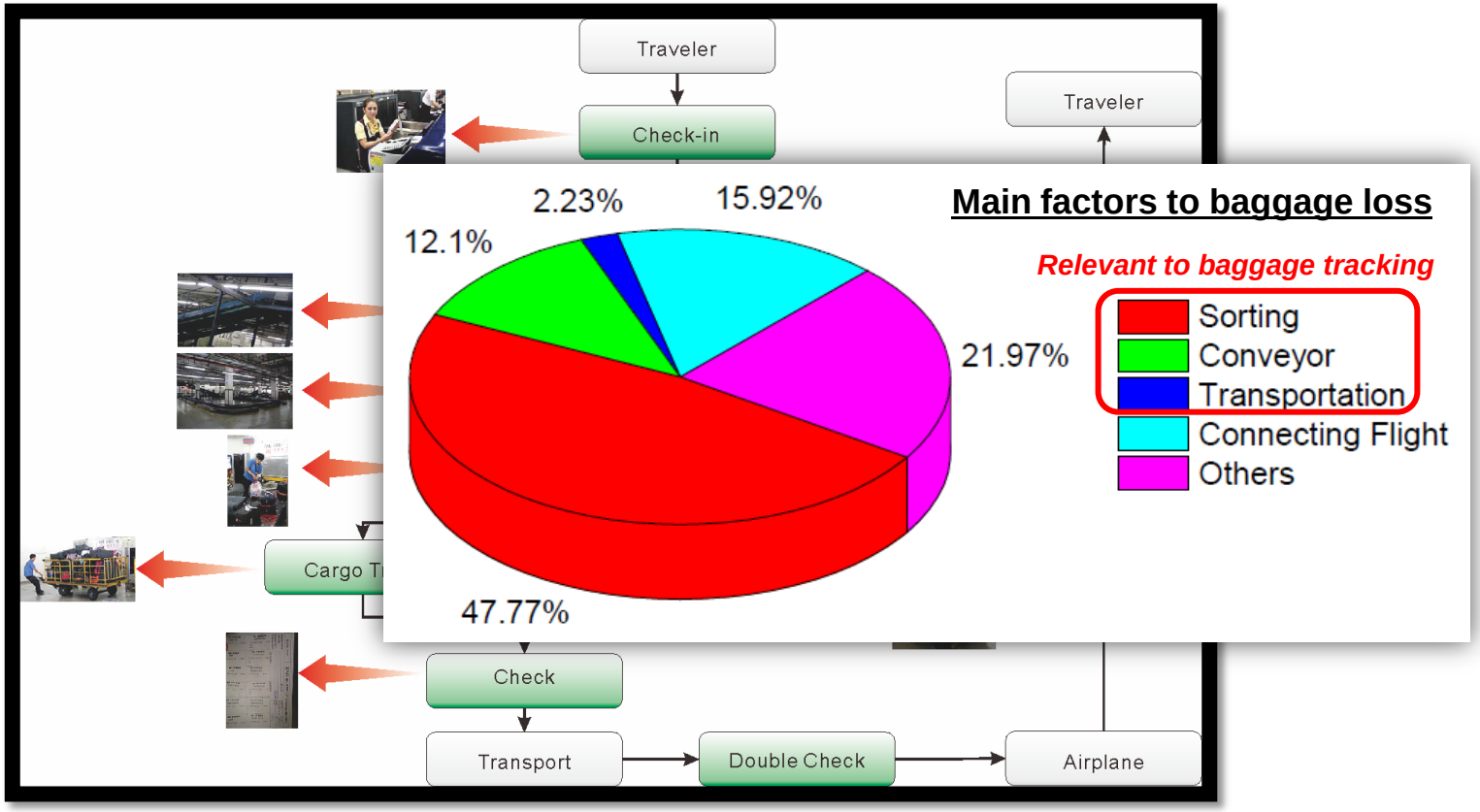
In two airports

# TagAssist: RFID assisted baggage sortation




## Automatic Track & Check Service
## Collaborated with Hainan Airline

# Where baggage lost?



# Current workflow – Manual sortation

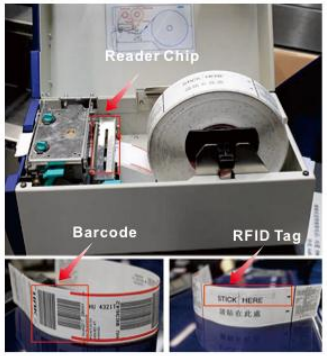

**It is error-prone step to find the baggage from the carousel in manual sortation.**

**Sortation carousel**

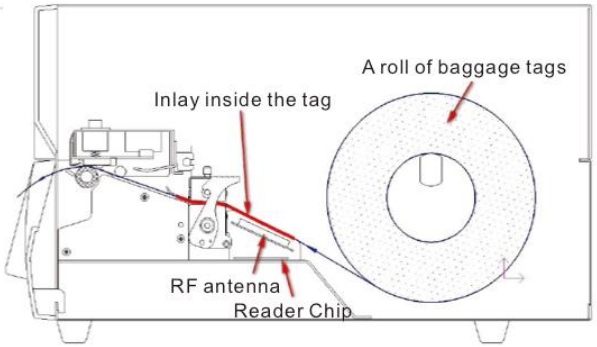
**Sorting baggage**

# How to assist sorter quickly find and sort baggage?

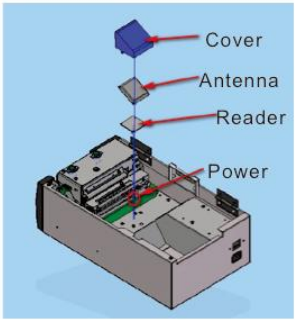
# Step 1: Upgrade Printer




(a) Internal structure



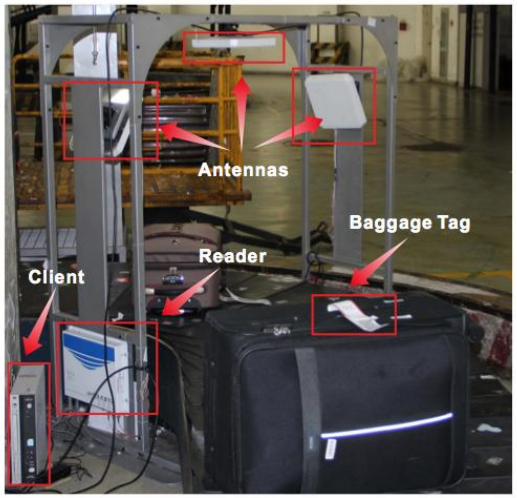

(b) Schematic diagram




(c) Working scenario

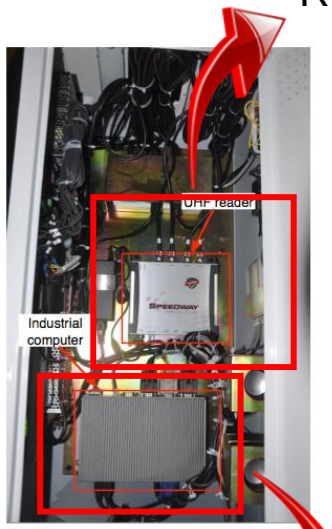
**We upgraded the tag printer by embedding a module of RFID reader in printer and an inlay inside each baggage tag.**

# Step 2: TrackPoint




(a) Version 1.0


(b) Version 2.0




(c) Internal structure

(a) Two TrackPoints


(b) Version 2.0

# Step 3: Visualization

(a) TrackPoint & Visualization


(b) Display screen


(c) Screenshot


(d) TrackPoint & Visualization

# Pilot site

Beijing Capital International Airport


Sanya Phoenix International Airport

# Setup

- Each airport contains 5 TrackPoints, 4 visualization screens, and 22 RFID Printers.

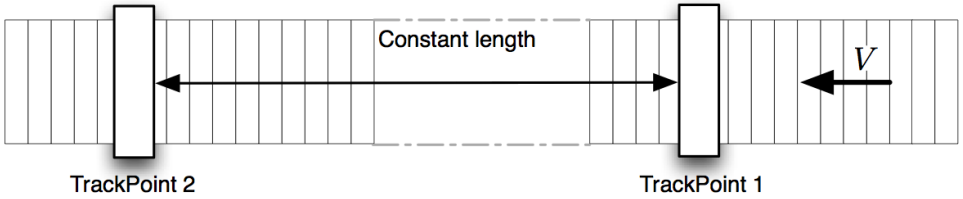
- The two-year pilot study totally spent more than $600,000

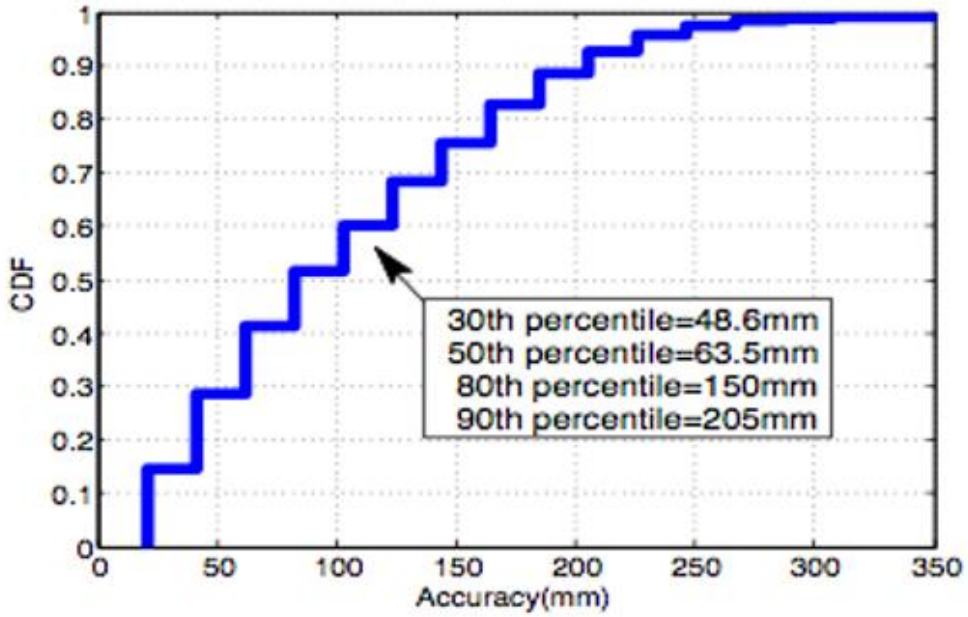
# Setup

- Consumed 110,000 RFID tags.

- Involved 53 destination airports, 93 air lines, and 1,094 flights.

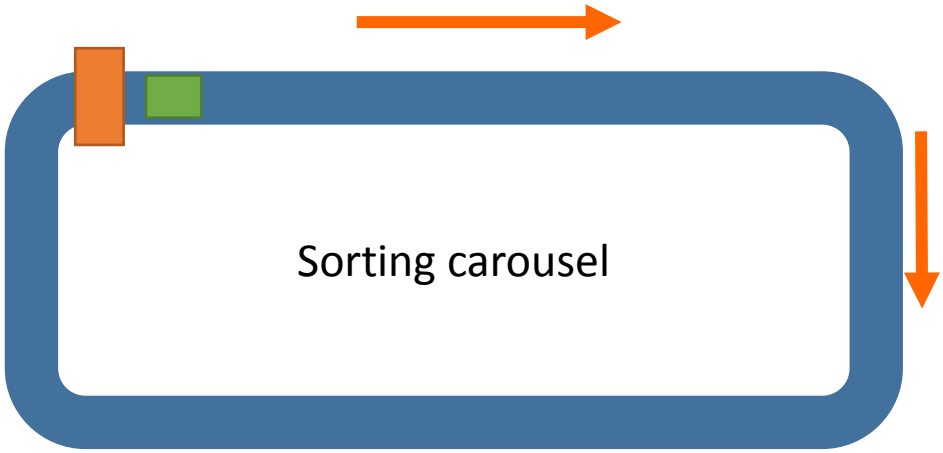
# Tracking Accuracy

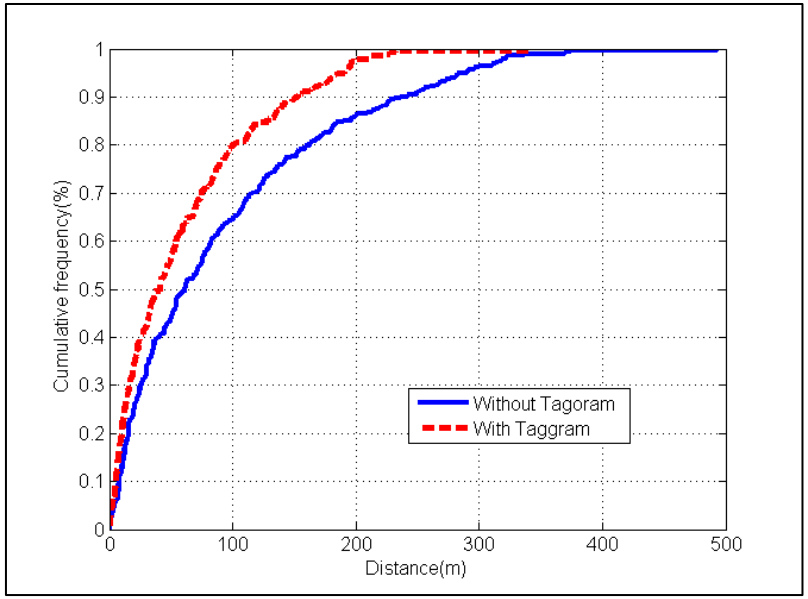



**Tagoram achieves a median accuracy of 6.35cm in practice.**

# Efficiency Improvement

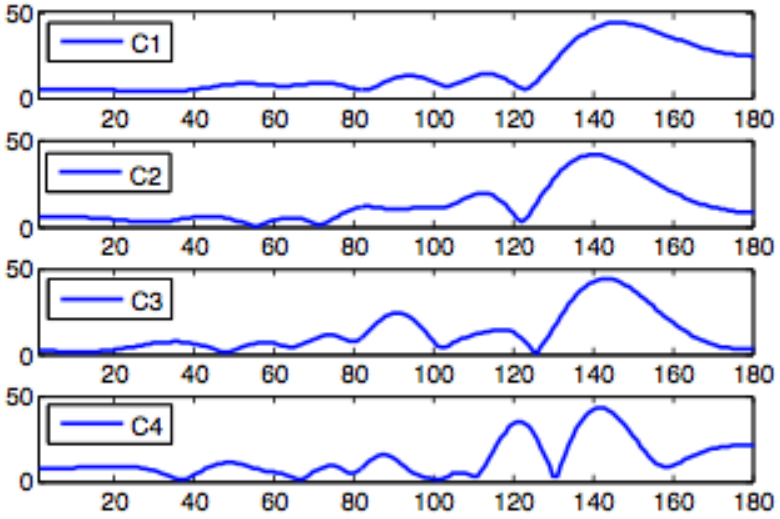


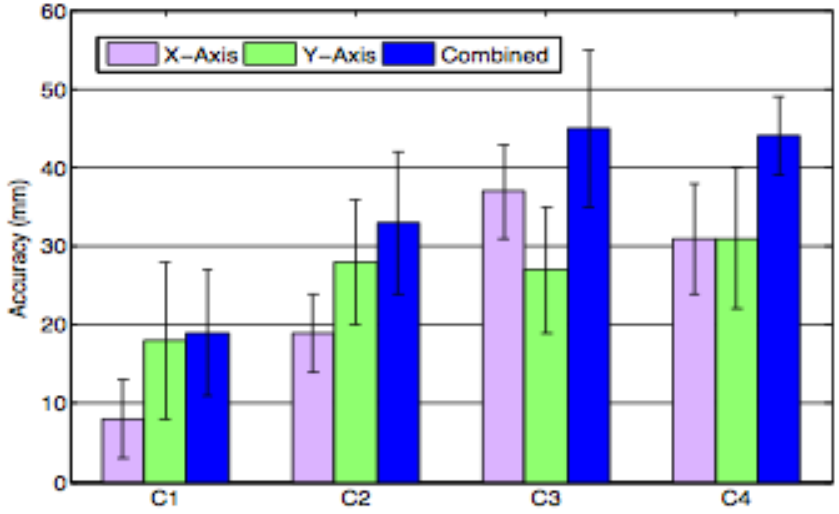

**Tagoram decreases the mean distance by 30%.**

# Tolerance to multipath

*Top four multipath cases*




*Tracking accuracies*



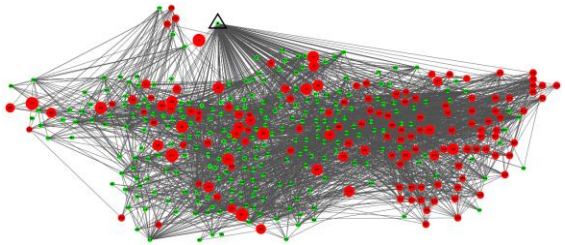

**Tagoram has strong tolerance to multipath effect**

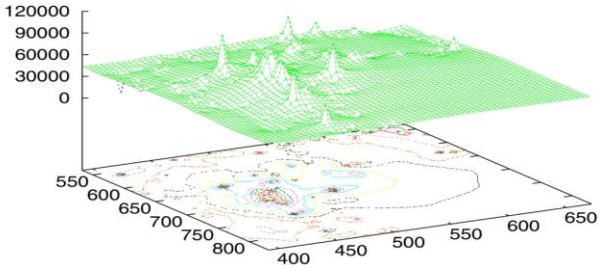
# Other Research

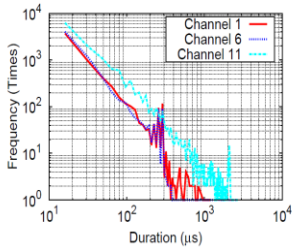
OceanSense

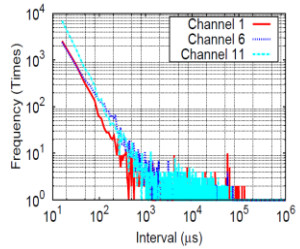

GreenOrbs

CitySee





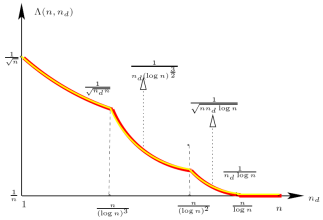



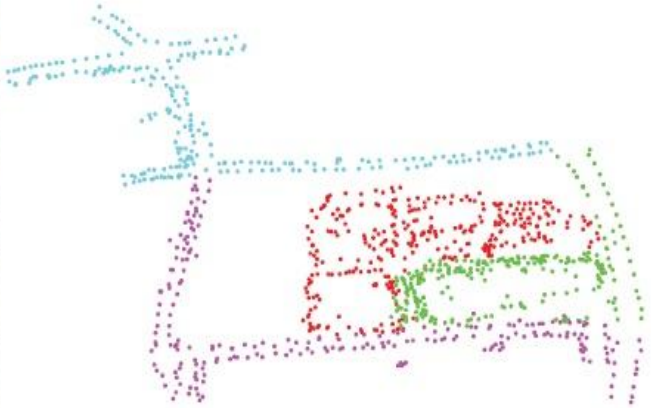

Networking observations

ZIMO: Coexistence

Capacity: Large scale



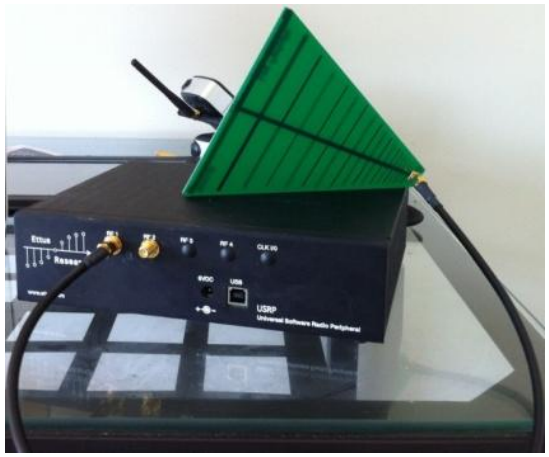
# CitySee System (2011--)



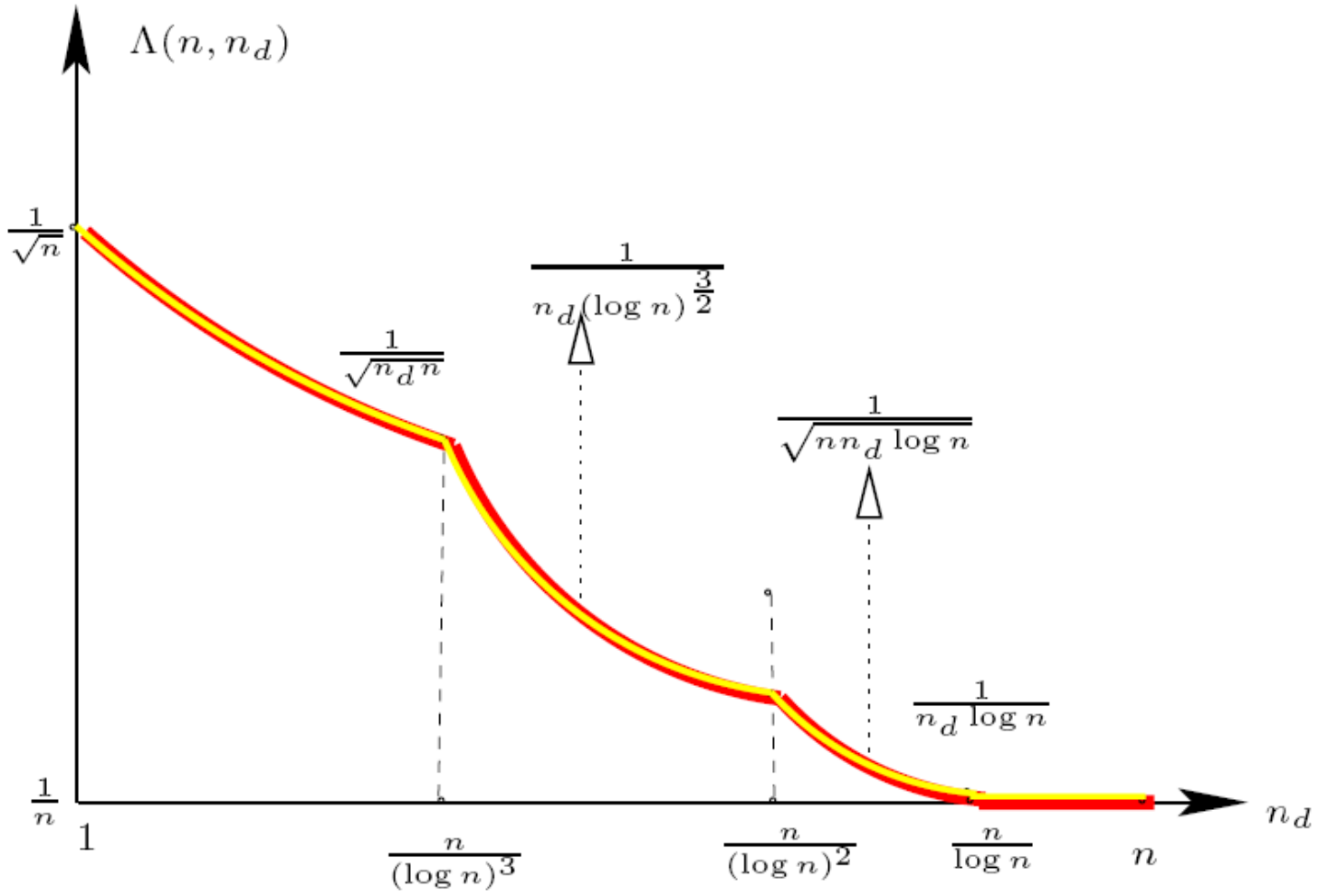
# Sensor nodes, mesh routers

# Cyber Physical Systems

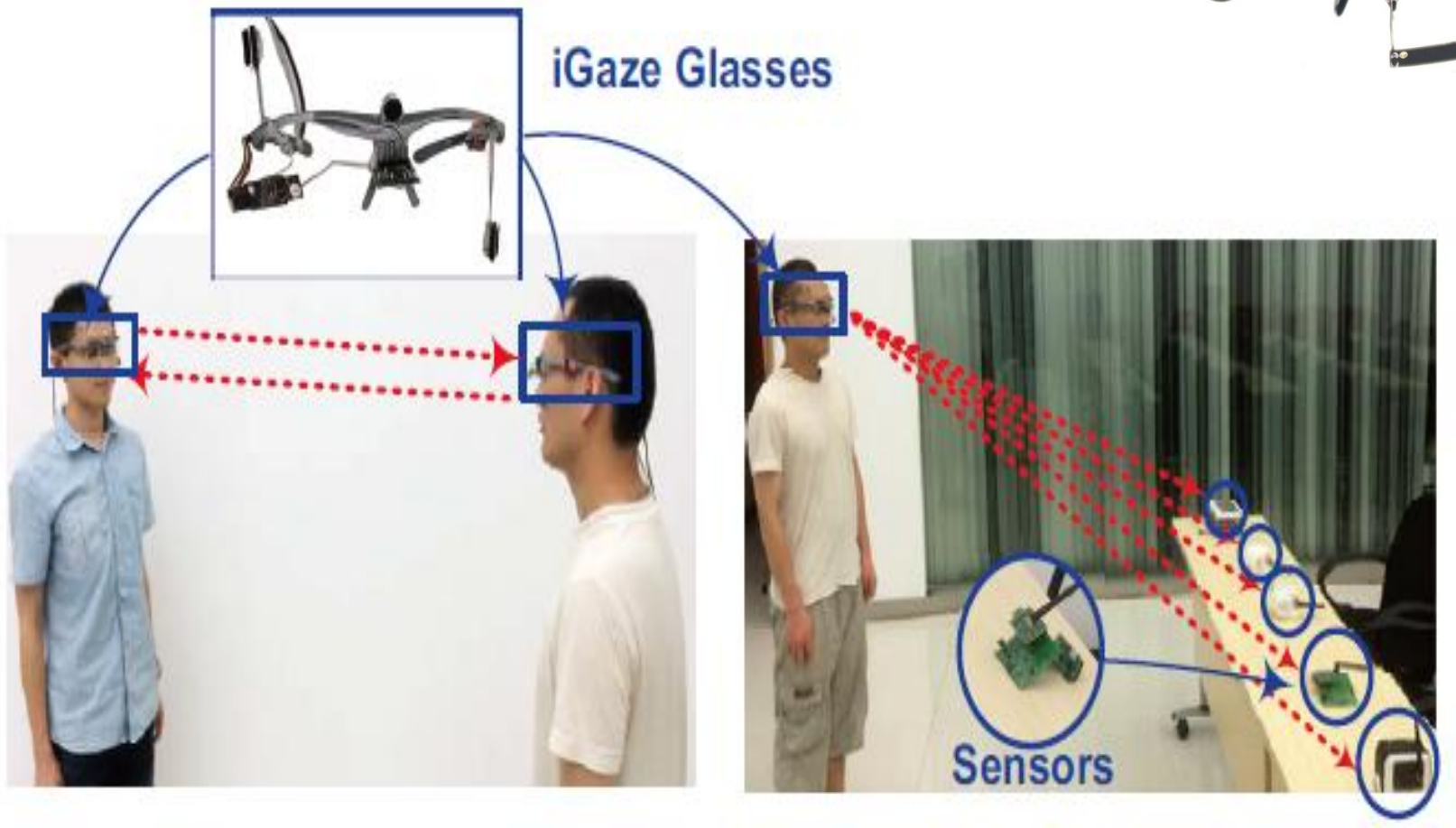

# Cognitive Radio Networks




# Capacity of Large Scale Networks



# Our iGaze Glasses



# Acknowledgments




Research Grants Council 研究資助局

# PhD Students (alumni 10)

UNCC

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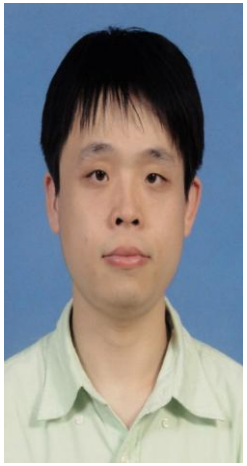
financial

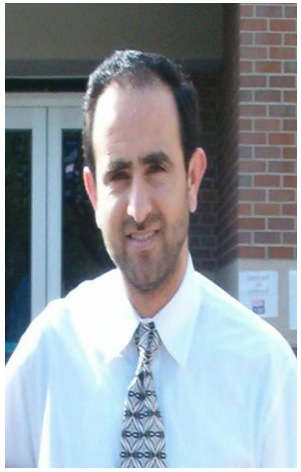
Google

W. Oregon

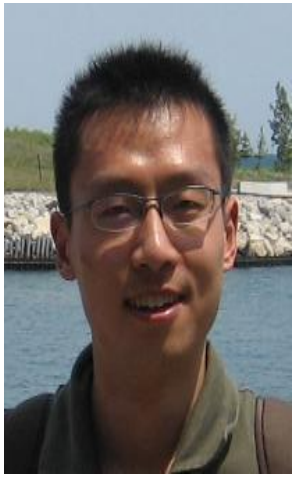
Tsinghua



financial



Motorola



UT Dallas

Toledo

# Current PhD Students


adidas
GAP


JACK
Columbia

# Demo Video

# Airport Video

# Thank you !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Professor, IIT, USA

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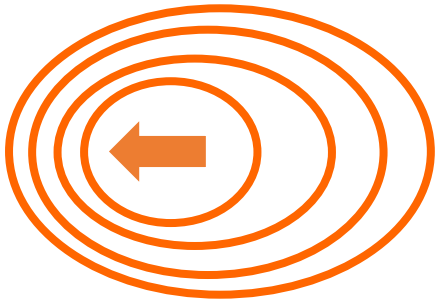
xli@cs.iit.edu

# Influences from other factors

## 1 Why tolerate Doppler effect?



## 2 Why tolerate NLOS?