WiZoom: Accurate Multipath Profiling using Commodity WiFi Devices with Limited Bandwidth

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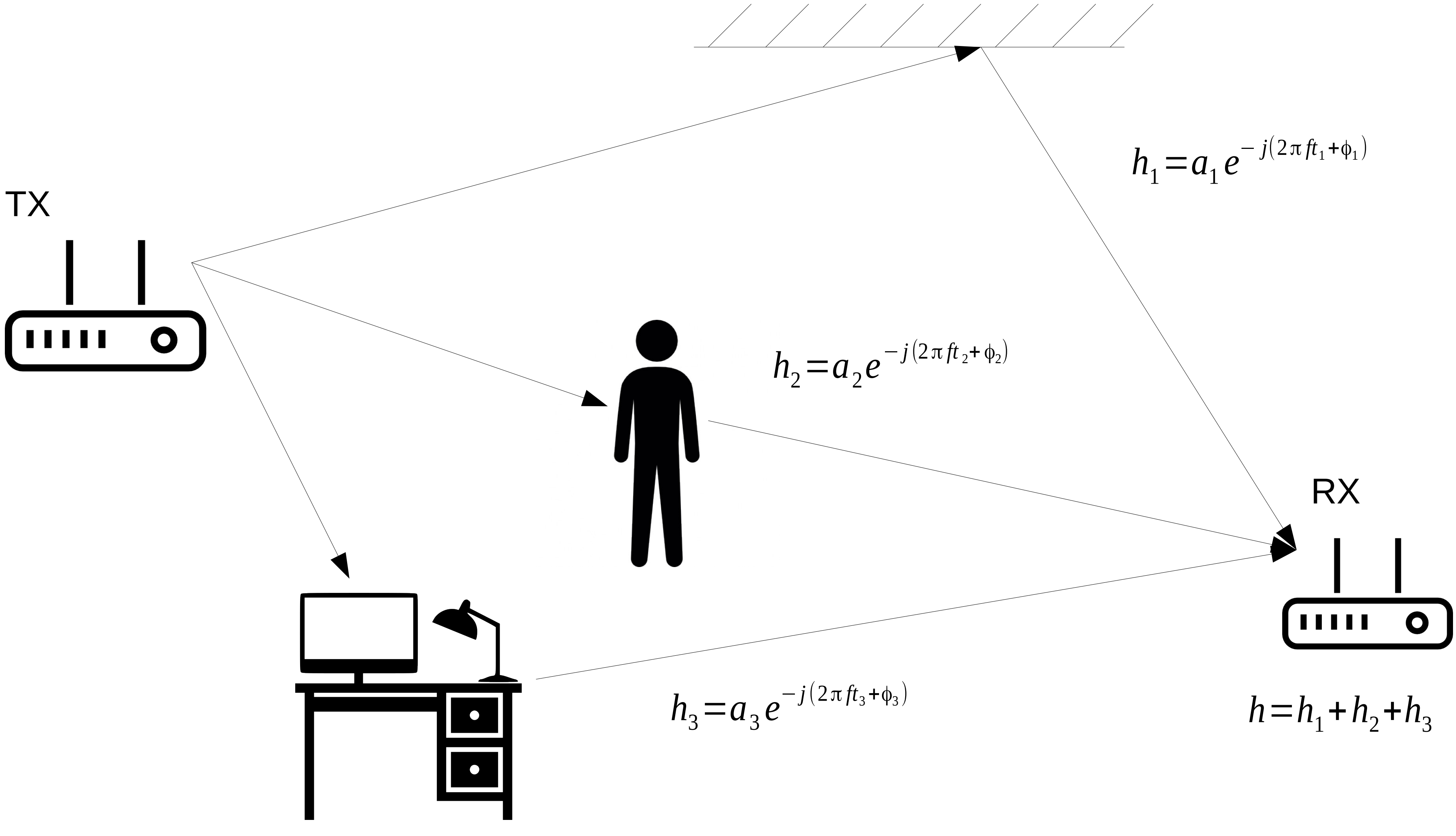
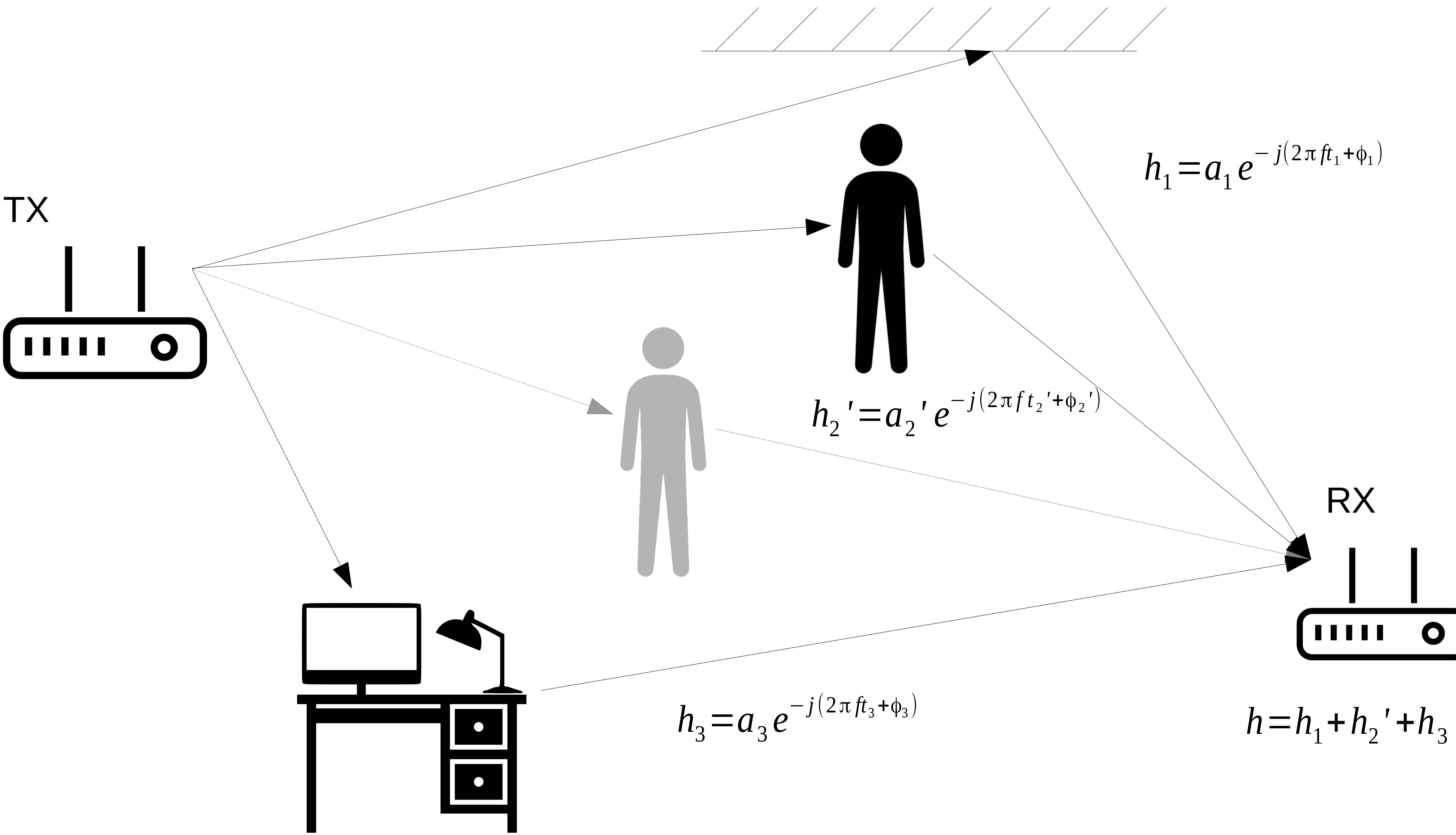
Motivation

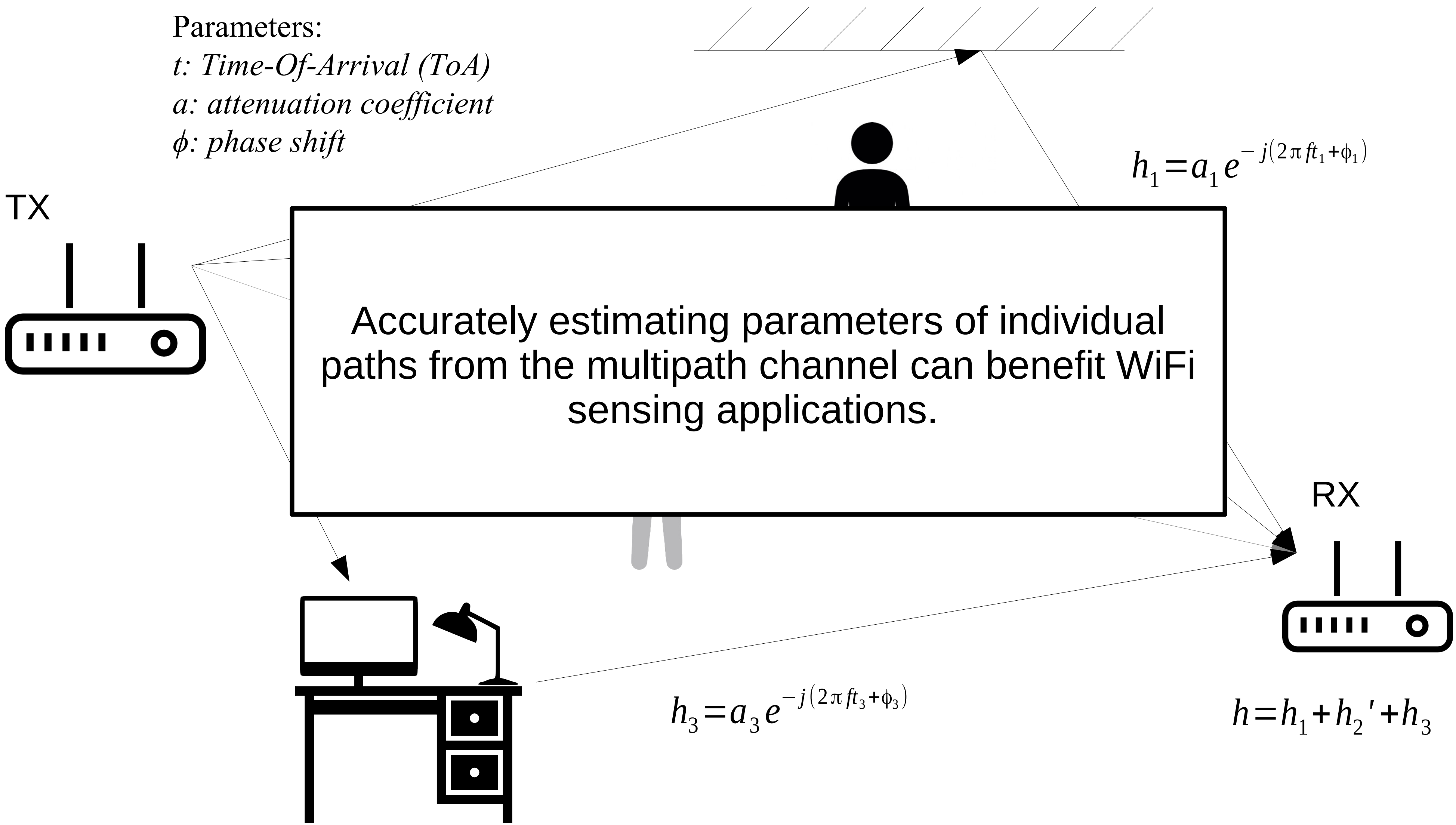


TX
RX
$h_1 = a_1 e^{-j(2\pi f t_1 + \phi_1)}$
$h_2 = a_2 e^{-j(2\pi f t_2 + \phi_2)}$
$h_3 = a_3 e^{-j(2\pi f t_3 + \phi_3)}$
$h = h_1 + h_2 + h_3$

Motivation

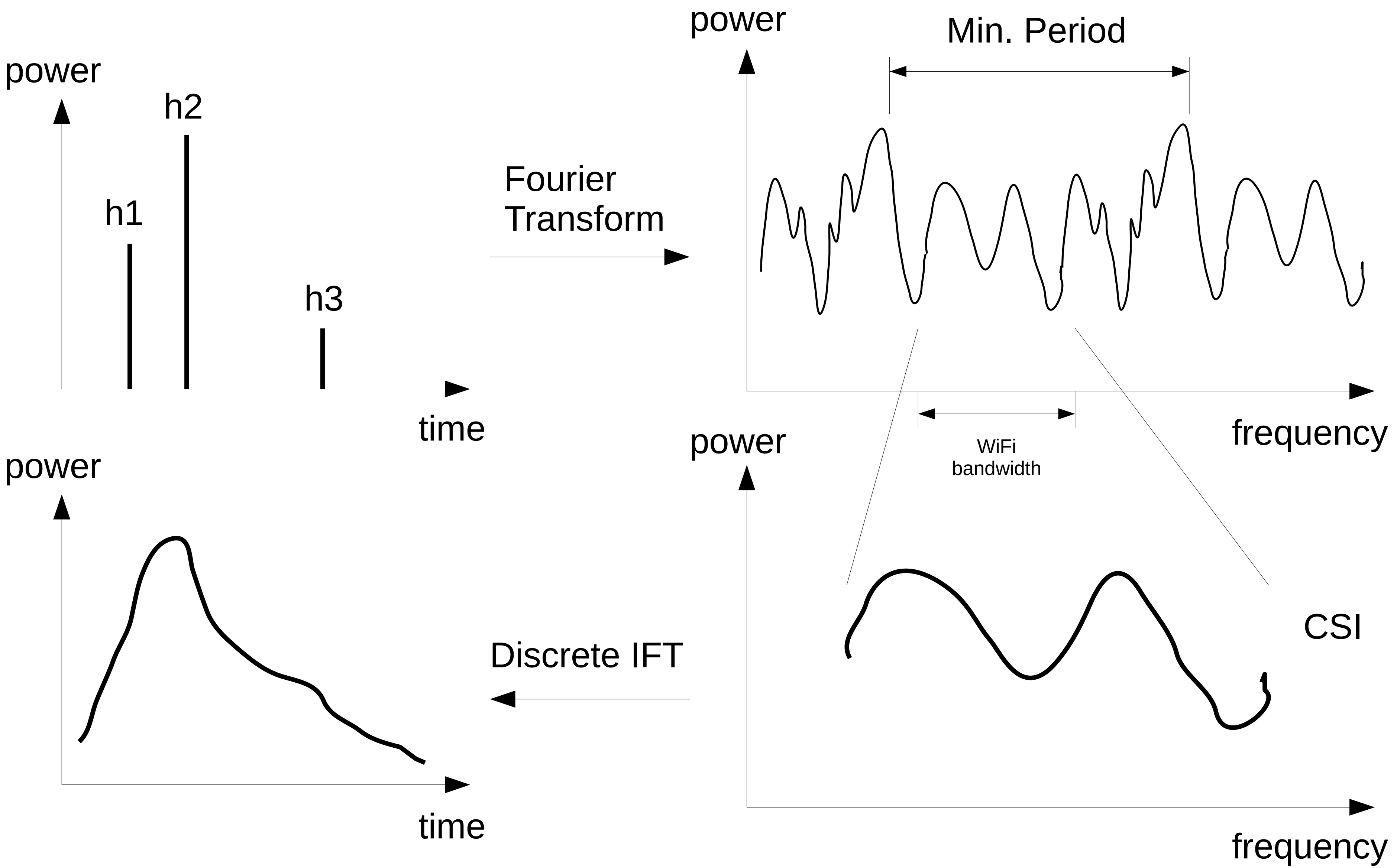

TX
$h_1 = a_1 e^{-j(2\pi f t_1 + \phi_1)}$
$h_2' = a_2' e^{-j(2\pi f t_2' + \phi_2')}$
RX
$h_3 = a_3 e^{-j(2\pi f t_3 + \phi_3)}$
$h = h_1 + h_2' + h_3$

Motivation

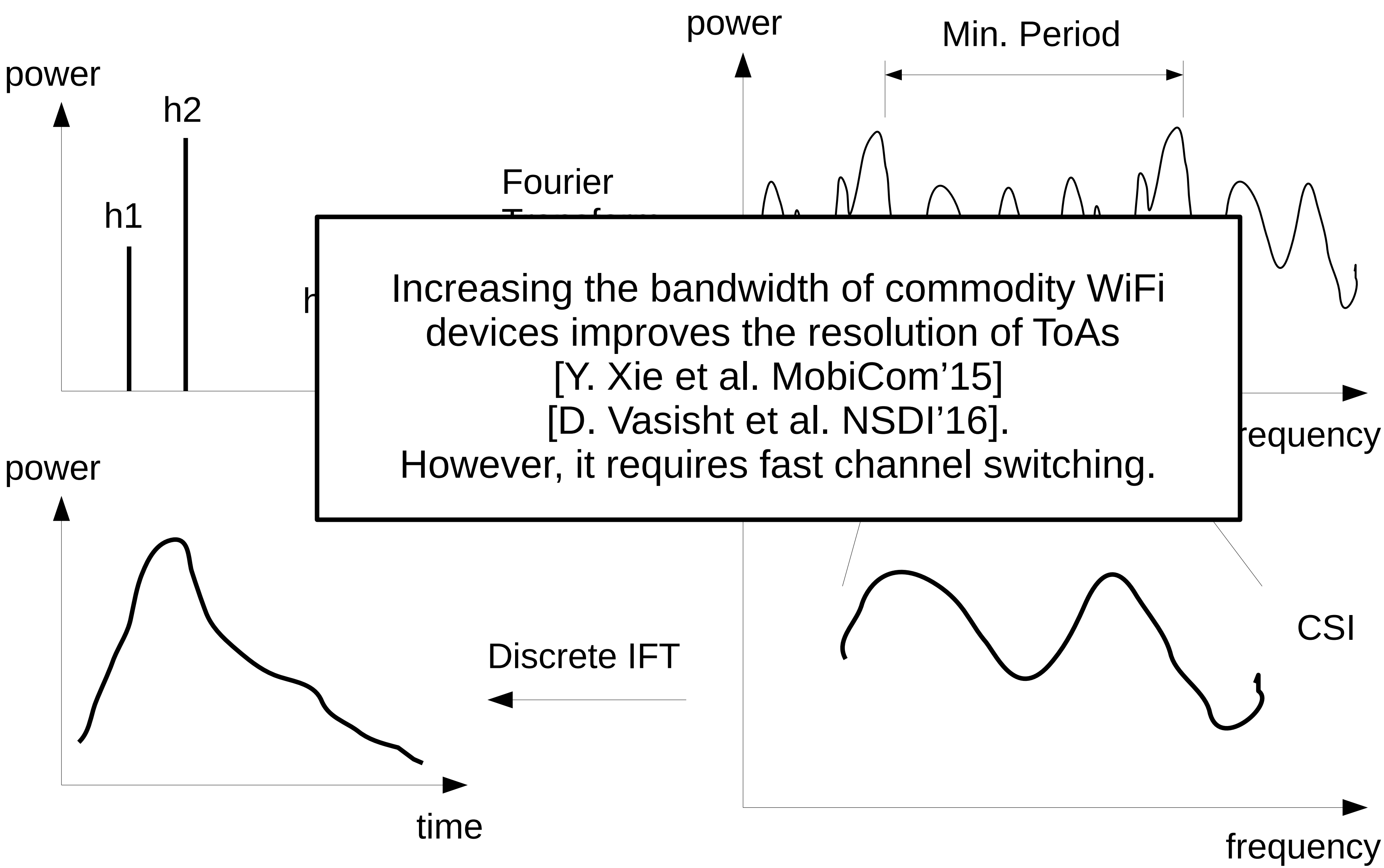


Accurately estimating parameters of individual paths from the multipath channel can benefit WiFi sensing applications.

Challenge: Resolution

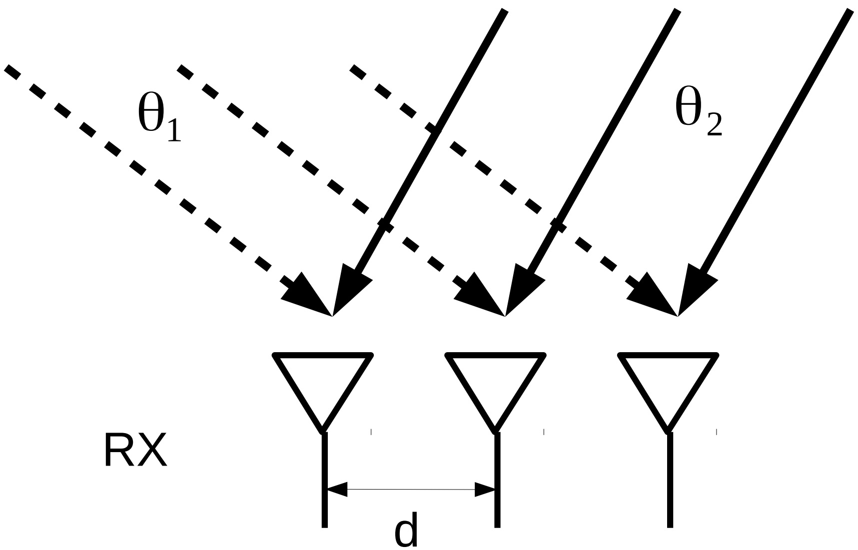


Challenge: Resolution



Increasing the bandwidth of commodity WiFi devices improves the resolution of ToAs [Y. Xie et al. MobiCom’15] [D. Vasisht et al. NSDI’16].
However, it requires fast channel switching.

Remind: Resolution of AoA



Mode vectors:

$$a(\theta_1)=[1\ \ e^{j2\pi d\cos\theta_1/\lambda}\ \ e^{j2\pi 2d\cos\theta_1/\lambda}]$$

$$a(\theta_2)=[1\ \ e^{j2\pi d\cos\theta_2/\lambda}\ \ e^{j2\pi 2d\cos\theta_2/\lambda}]$$

MUSIC for AoA:

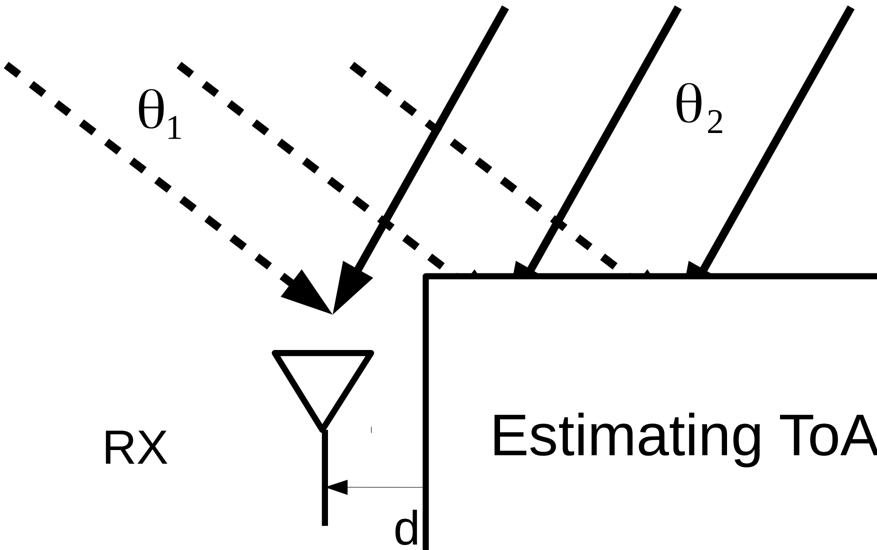
$$X=AF+W \qquad A=[a(\theta_1)'\ \ a(\theta_2)']$$

Increasing the length of mode vectors can improve the resolution of AoA.

[M. Kataru et al. SIGCOMM'15] increases the length of mode vectors by incorporating different subcarriers:

$$A=\begin{bmatrix} 1 & 1 \\ e^{j2\pi\Delta_f t_1} & e^{j2\pi\Delta_f t_2} \\ e^{j2\pi 2\Delta_f t_1} & e^{j2\pi 2\Delta_f t_2} \\ \vdots & \vdots \\ e^{j2\pi d\cos\theta_1/\lambda} & e^{j2\pi d\cos\theta_2/\lambda} \\ e^{j2\pi(d\cos\theta_1/\lambda+\Delta_f t_1)} & e^{j2\pi(d\cos\theta_2/\lambda+\Delta_f t_2)} \\ e^{j2\pi(d\cos\theta_1/\lambda+2\Delta_f t_1)} & e^{j2\pi(d\cos\theta_2/\lambda+2\Delta_f t_2)} \\ \vdots & \vdots \\ e^{j2\pi 2d\cos\theta_1/\lambda} & e^{j2\pi 2d\cos\theta_2/\lambda} \\ e^{j2\pi(2d\cos\theta_1/\lambda+\Delta_f t_1)} & e^{j2\pi(2d\cos\theta_2/\lambda+\Delta_f t_2)} \\ e^{j2\pi(2d\cos\theta_1/\lambda+2\Delta_f t_1)} & e^{j2\pi(2d\cos\theta_2/\lambda+2\Delta_f t_2)} \\ \vdots & \vdots \end{bmatrix}$$

Remind: Resolution of AoA



Estimating ToA is similar to estimating AoA!

Mode vectors:

$a(\theta_1)=[1\ e^{j2\pi \cdots}\ \cdots]$

$a(\theta_2)=[1\ e^{j2\pi d\cos\theta_2/\lambda}\ e^{j2\pi 2d\cos\theta_2/\lambda}]$

MUSIC for AoA:

$$X = AF + W \qquad A=[a(\theta_1)'\ a(\theta_2)']$$

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The Analogy

- AoA estimation
  - AoA introduces phase shift across different **antennas**.
  - Apply MUSIC using **antennas** as sensors.
  - Improve resolution:

    Increase the number of sensors by incorporating **subcarriers**.

- ToA estimation
  - ToA introduces phase shift across different **subcarriers**.
  - Apply MUSIC using **subcarriers** as sensors.
  - Improve resolution:

    Increase the number of sensors by incorporating **antennas**.

The Analogy

- AoA estimation
  - AoA introduces phase shift across different **antenn**
  - Apply M **antenn**
  - Improv

    Increase the number of sensors by incorporating **subcarriers**.

- ToA estimation
  - ToA introduces phase shift across different
  - sing sensors.
  - on:

    Increase the number of sensors by incorporating **antennas**.

WiZoom uses this analogy and allocates all the resolution power to ToA estimation.

Estimate ToA

Signal model:

$$X = AF + W$$

$$A = \begin{bmatrix} 1 & 1 & .. & 1 \\ e^{j2\pi\Delta_f t_1} & e^{j2\pi\Delta_f t_2} & .. & e^{j2\pi\Delta_f t_k} \\ e^{j2\pi 2\Delta_f t_1} & e^{j2\pi 2\Delta_f t_2} & .. & e^{j2\pi 2\Delta_f t_k} \\ : & : & .. & : \\ e^{j2\pi n\Delta_f t_1} & e^{j2\pi n\Delta_f t_2} & .. & e^{j2\pi n\Delta_f t_k} \end{bmatrix} \quad N$$

$$\overset{M}{\longleftrightarrow}$$

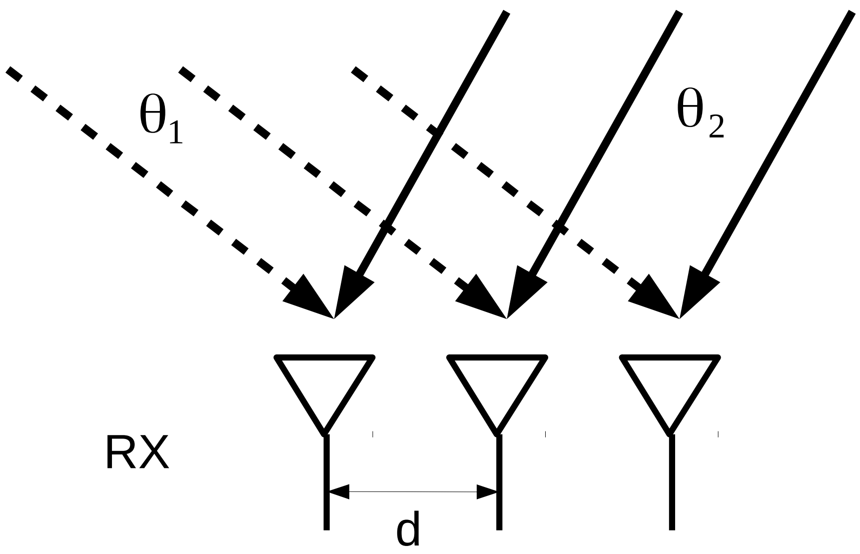
$$X = \begin{bmatrix} h(f_1) & h(f_2) & .. & h(f_M) \\ h(f_{M+1}) & h(f_{M+2}) & .. & h(f_{2M}) \\ h(f_{2M+1}) & h(f_{2M+2}) & .. & h(f_{3M}) \\ : & : & .. & : \\ h(f_{NM}) & h(f_{(N-1)M+1}) & .. & h(f_{NM}) \end{bmatrix} \quad N$$

#Subcarriers = N * M

MUSIC is applied to estimate (t_1, …, t_k)

Estimate ToA

Combine multiple antennas to improve resolution



$$h_{antenna\,1} = h_1 + h_2$$

$$h_{antenna\,2} = h_1 e^{j 2\pi\, d\cos\theta_1/\lambda} + h_2 e^{j 2\pi\, d\cos\theta_2/\lambda}$$

$$h_{antenna\,2} = h_1 e^{j 2\pi\, 2 d\cos\theta_1/\lambda} + h_2 e^{j 2\pi\, 2 d\cos\theta_2/\lambda}$$

Channels of different antennas are **uncorrelated linear combinations** of multipath components.

The difference of ToAs between different antennas can be ignored.

Estimate ToA

Combine multiple antennas to improve resolution

M * #antennas

$$X = \begin{bmatrix} h_1(f_1) & .. & h_1(f_M) & h_2(f_1) & .. & h_2(f_M) & .. \\ h_1(f_{M+1}) & .. & h_1(f_{2M}) & h_2(f_{M+1}) & .. & h_2(f_{2M}) & .. \\ h_1(f_{2M+1}) & .. & h_1(f_{3M}) & h_2(f_{2M+1}) & .. & h_2(f_{3M}) & .. \\ \vdots & .. & \vdots & \vdots & .. & \vdots & .. \\ h_1(f_{NM}) & .. & h_1(f_{NM}) & h_2(f_{NM}) & .. & h_2(f_{NM}) & .. \end{bmatrix}$$

N

(Total # of Elements) = (# of Subcarriers) * (# of Antennas)

This means we can further increase N to improve resolution.

Estimate other path-related parameters

Channel model:

$$h(f)=\sum_{i=1}^{N} a_i e^{-j(2\pi f t_i+\phi_i)}$$

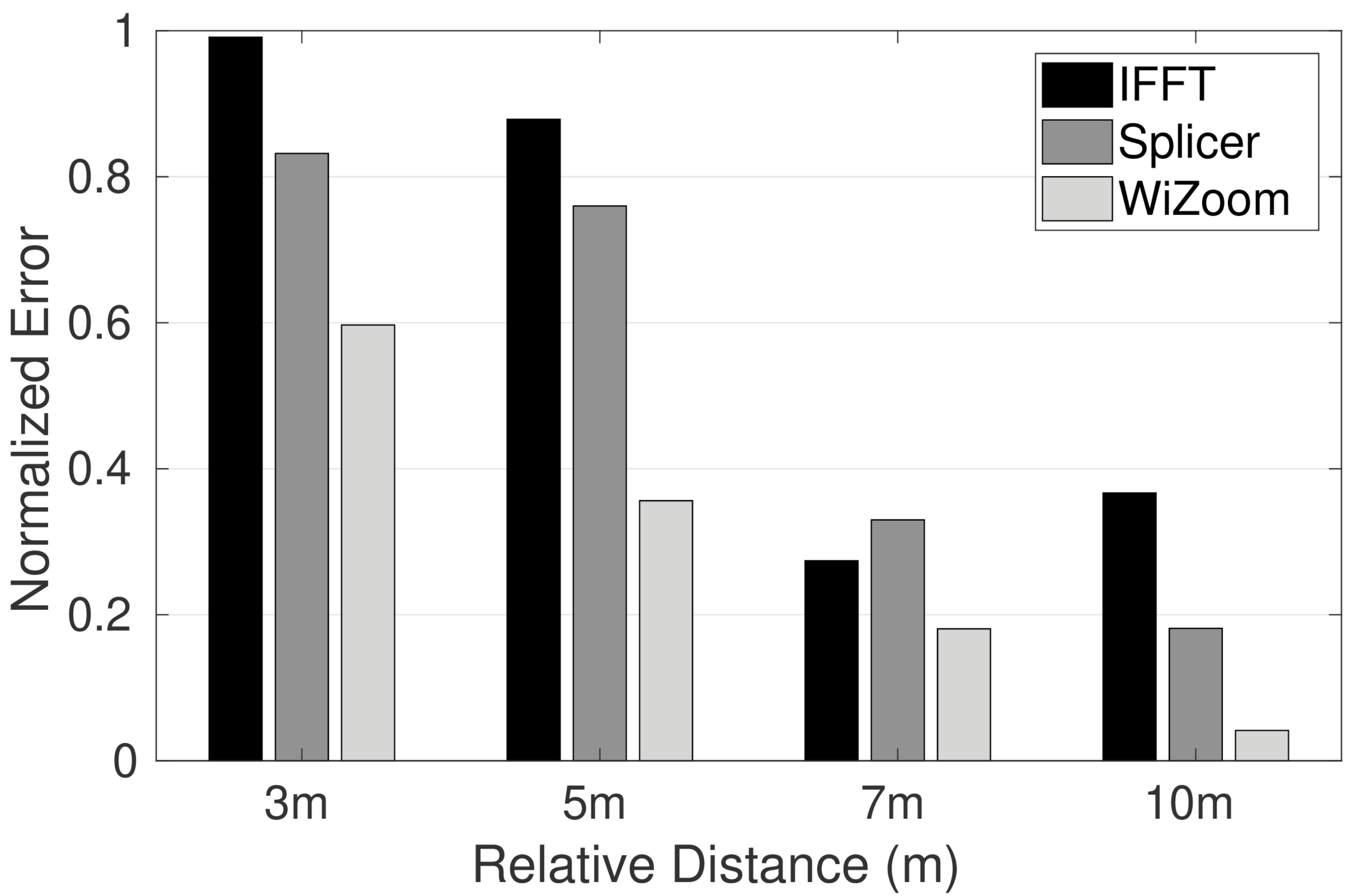
# of equations = # of subcarriers
# of unknowns = # of multipath components

Solve this linear system using Least Square.

Evaluation

- Ideal case benchmark
  - Use RF cables, attenuators and splitters to emulate multipath channels of WiFi signal.
  - Different length of RF cables emulate different signal propagation paths, which induces different ToAs
- Real environment evaluation
  - Lab: 13*13m, 200 locations, distance of [1,12]m
  - Corridor: 3*50m, 200 locations, distance of [1,50]m
  - Meeting room: 3*5m, 20 locations, distance of 3m

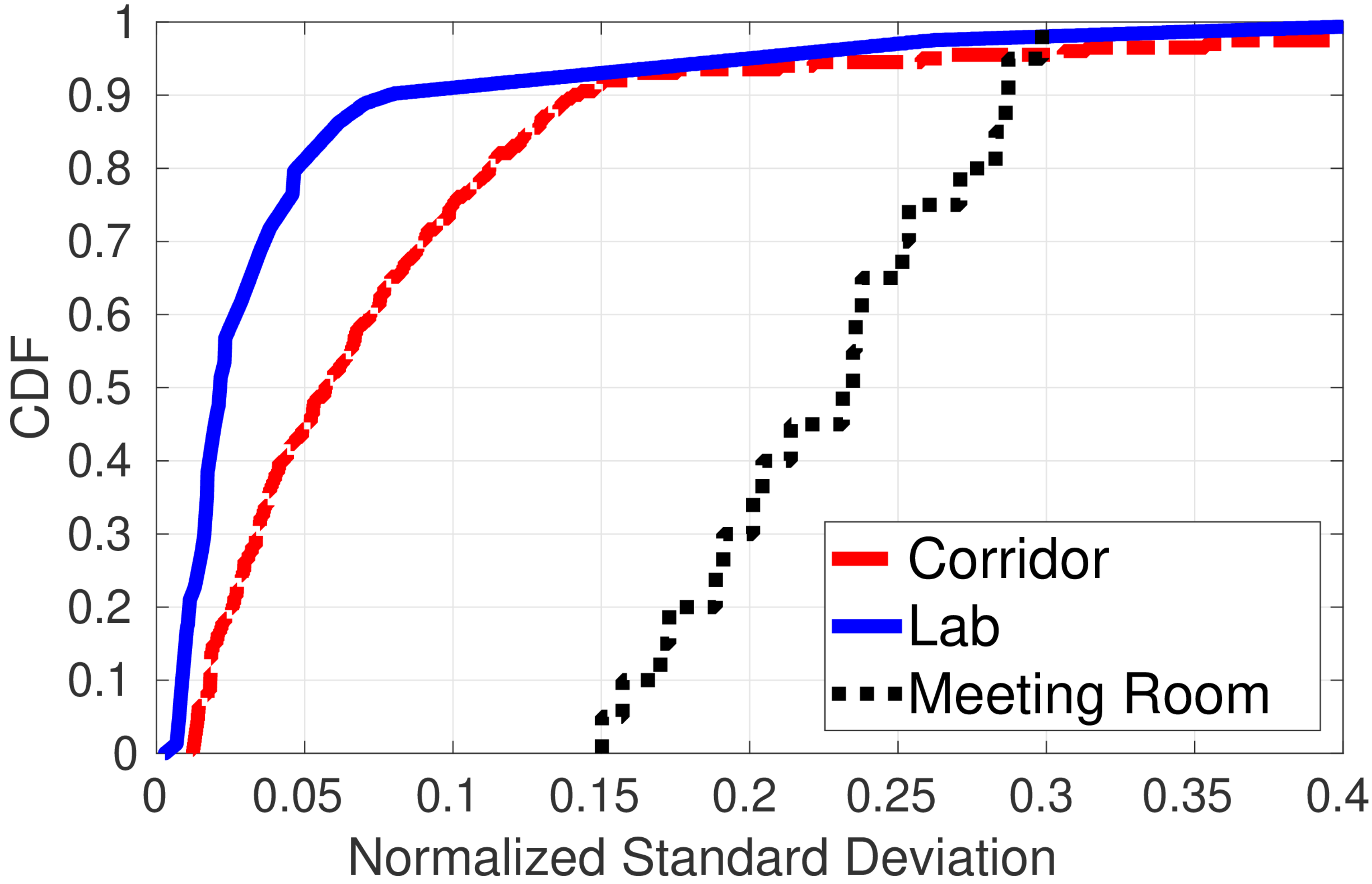
Ideal case



IFFT
Splicer
WiZoom
Normalized Error
0
0.2
0.4
0.6
0.8
1
3m
5m
7m
10m
Relative Distance (m)

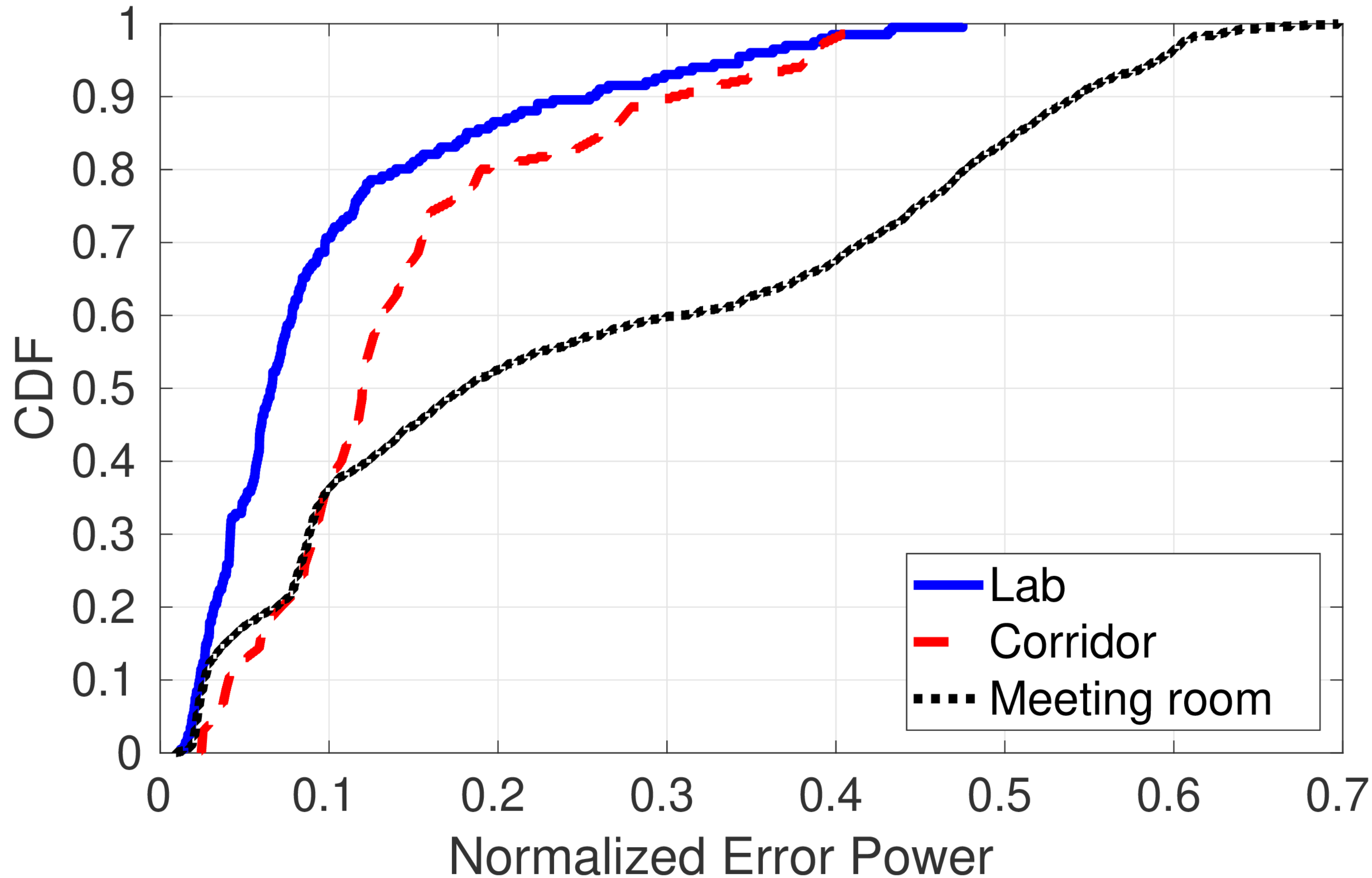
Real Environment

- Stability of direct path attenuation



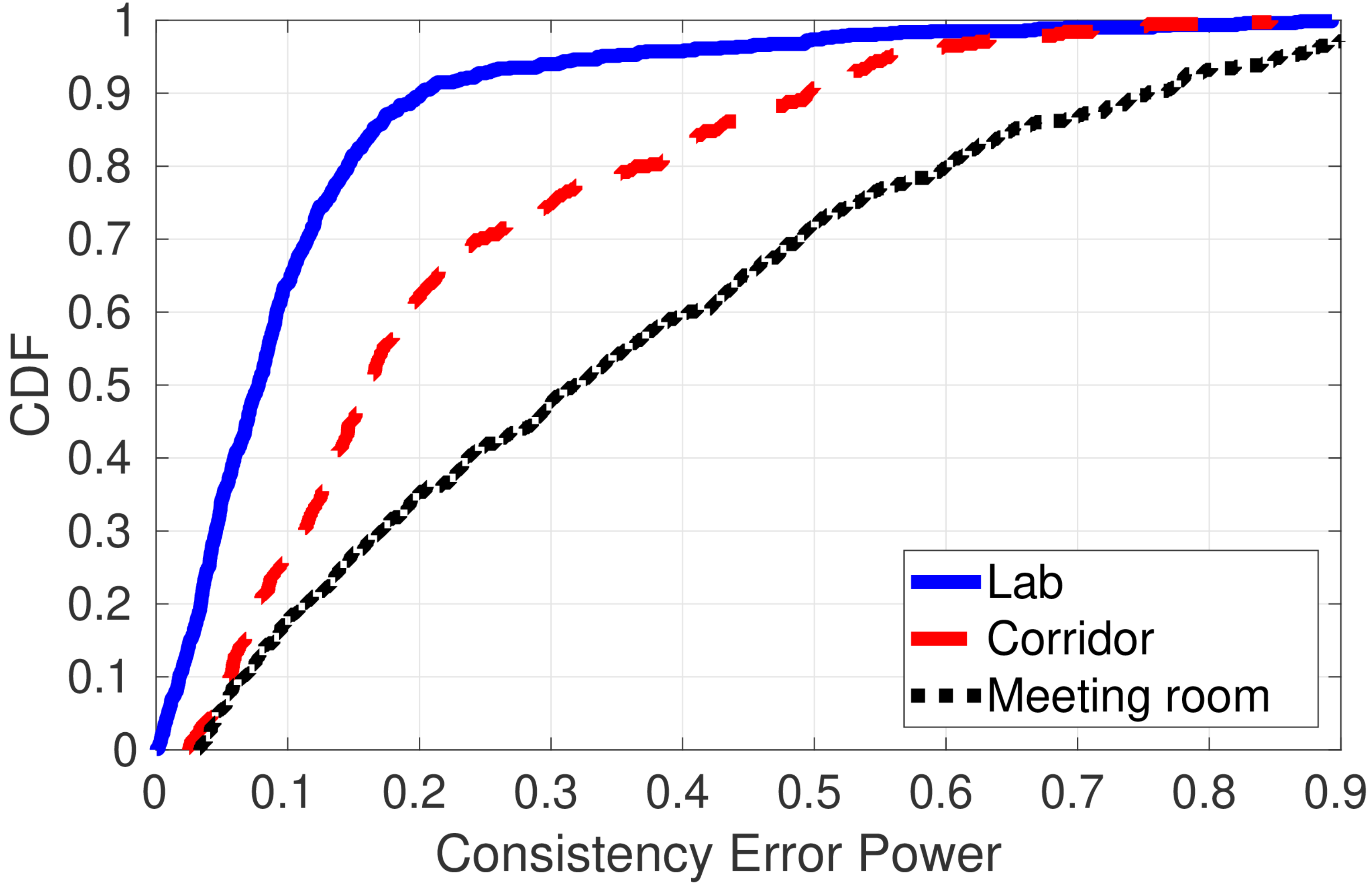
Real Environment

- CSI fitting performance



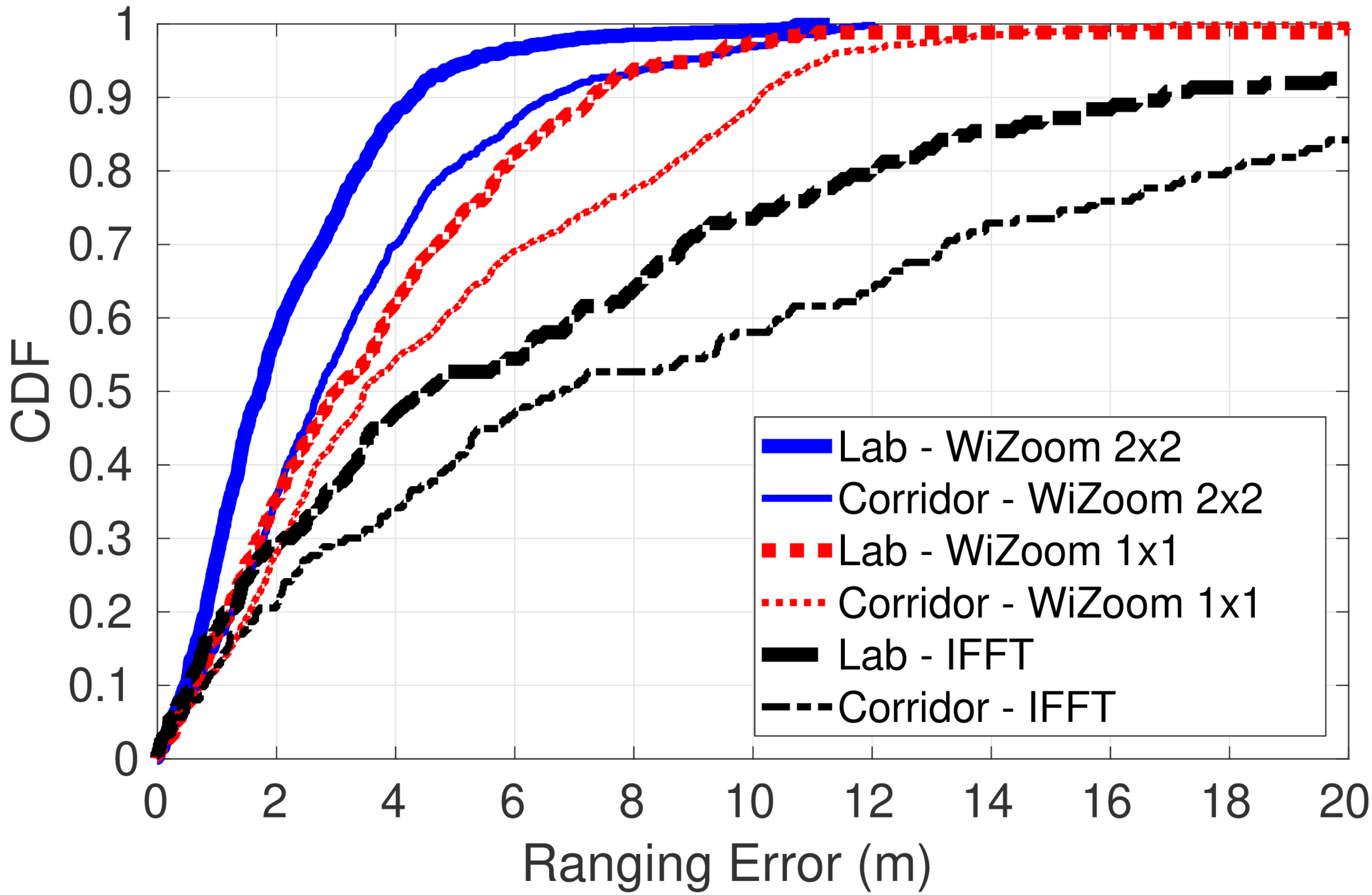
Real Environment

- Consistency across different antennas



Real Environment

- Ranging error



Conclusion

- We tackle the problem of multipath profiling using commodity WiFi devices with limited bandwidth.
- We design a scheme called WiZoom, which uses a MUSIC-based algorithm and combines multiple antennas to estimate ToAs with high resolution.
- WiZoom also estimates other path-related parameters to form the complete multipath profile.
- We evaluate the performance of WiZoom and the results show that WiZoom outperforms existed methods.

Thank you all!

Further question? Hua Xue: howardsid@sjtu.edu.cn

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