

SpotFi: Decimeter Level Localization Using WiFi

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Kotaru, Manikanta, Kiran Joshi, Dinesh Bharadia, and Sachin Katti. "SpotFi: Decimeter Level Localization Using WiFi." In Proceedings of the 2015 ACM Conference on Special Interest Group on Data Communication, pp. 269-282. ACM, 2015.

WiFi Indoor Localization System

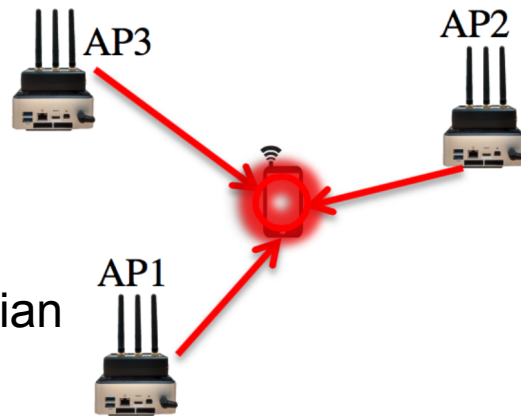
We want it to be:

- **Deployable** on existing WiFi Infrastructure
- **Universal**, should be able to localize any target device that has a commodity WiFi Chip
- **Accurate**, as accurate as the best known localization systems that use WiFi

SpotFi

An indoor localization system that can be deployed on commodity WiFi infrastructure

- Requires no hardware change, calibration or fingerprinting
- Uses RSSI and CSI exposed by access points (APs)
- As accurate as the state of the art methods (median accuracy: 40 cm)



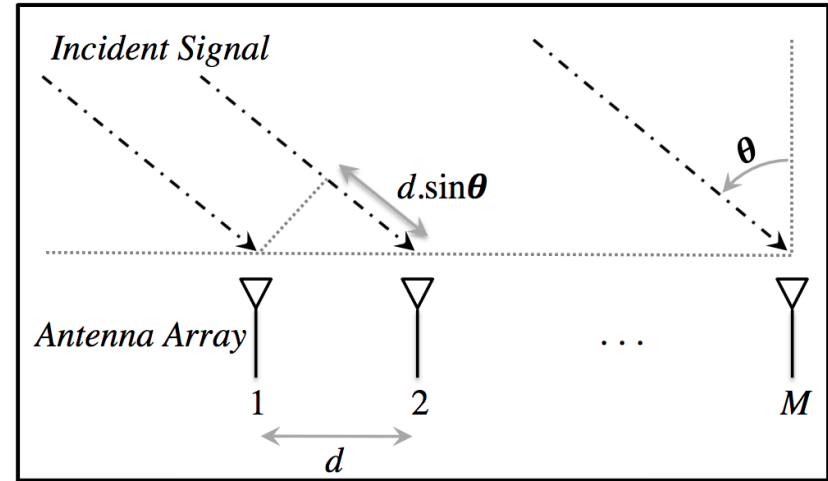
Terminology

- Received signal strength indicator (**RSSI**)
 - A number indicating the power of a signal received by an antenna.
- Channel state information (**CSI**)
 - A complex number specifying the attenuation and phase shift of the signal path between an antenna pair [1].

[1] <http://dhalperi.github.io/linux-80211n-csitool/>

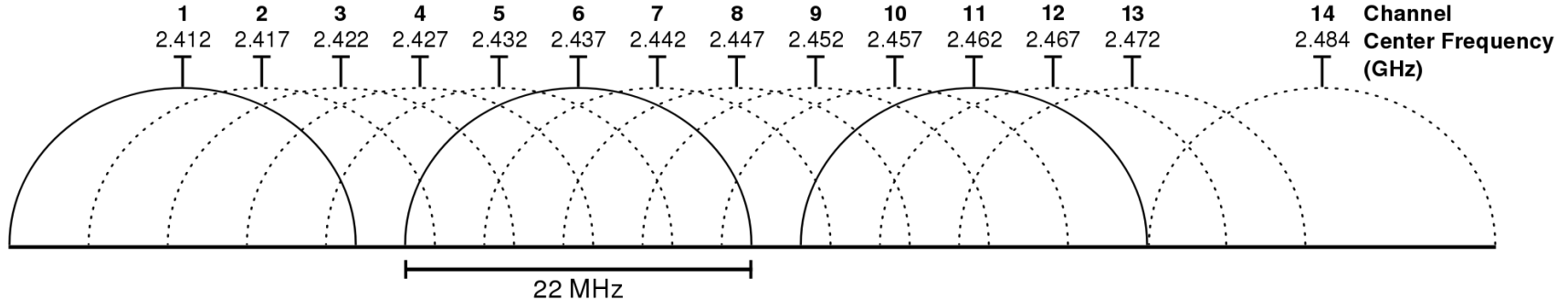
More Terminology

- Angle of Arrival (**AoA**)
 - Direction of a signal incident on an antenna array
 - Determined by measuring the time difference of arrival at individual elements of the array
- Time of Flight (**ToF**)
 - Time taken by a signal to reach to a receiver from a transmitter



WiFi Channels

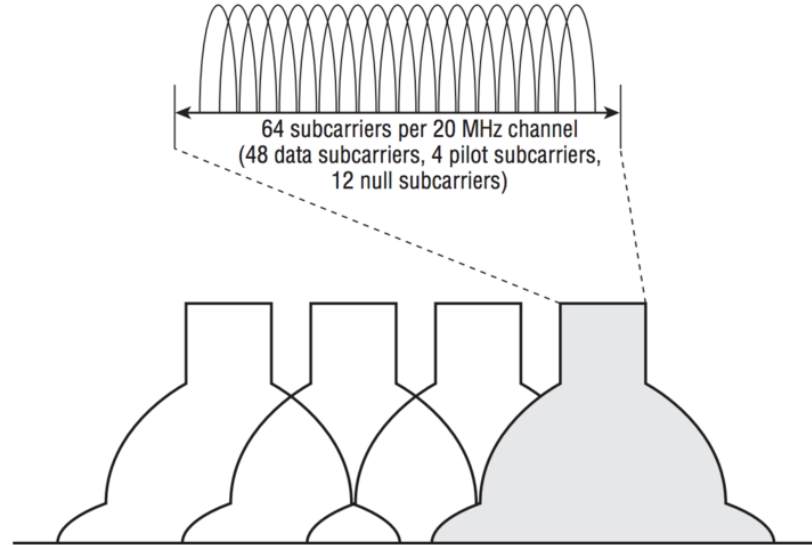
2.4 GHz band channels



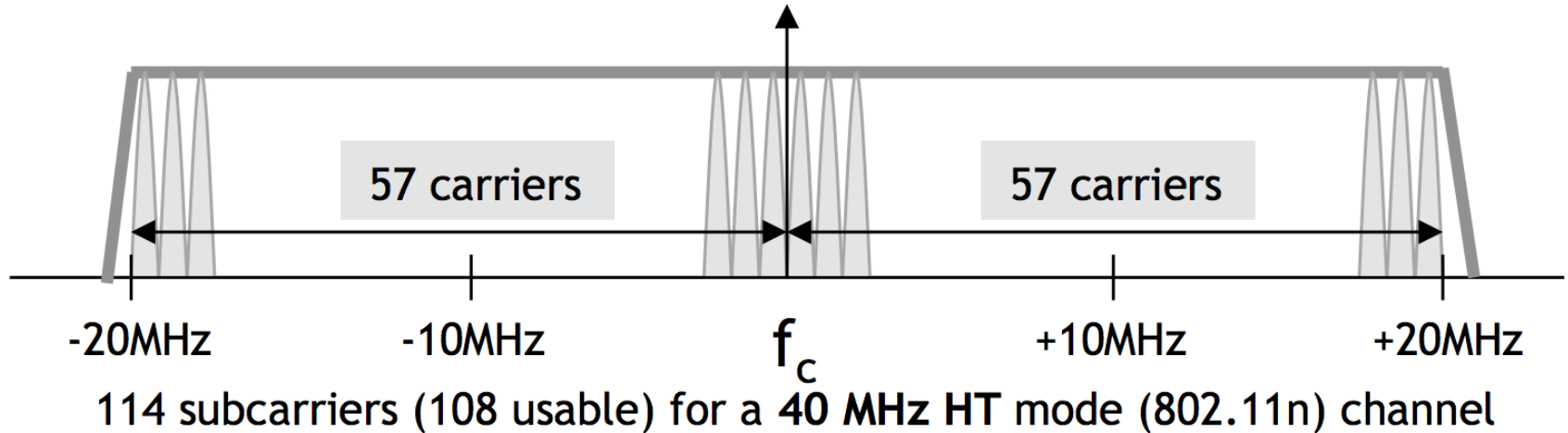
In SpotFi experiments WiFi client and all APs are configured to use the same channel with a 40 MHz bandwidth in the 5GHz band.

OFDM Subcarriers

Orthogonal frequency-division multiplexing (OFDM) divides a channel into narrower orthogonal subcarriers:



114 OFDM Subcarriers for 40 MHz



In SpotFi experiments a channel with 40 MHz bandwidth is used. However, the firmware of the NIC provides CSI for only 30 of the subcarriers.

Custom-made WiFi Client

- Intel 5300 WiFi NIC on top of a small PC (Intel NUC).
- CSI extraction software is available for the NIC. PC is used to extract and report CSI values, timestamps and MAC addresses to a central server.
- Other WiFi chip families (Broadcom, Intel, Atheros and Marvell) also expose the CSI per subcarrier per antenna. Only software is needed to report to a server.



Kotaru, Manikanta, Kiran Joshi, Dinesh Bharadia, and Sachin Katti.
"SpotOn: Indoor localization using commercial off-the-shelf WiFi NICs."
(indoorlocompetition2015)

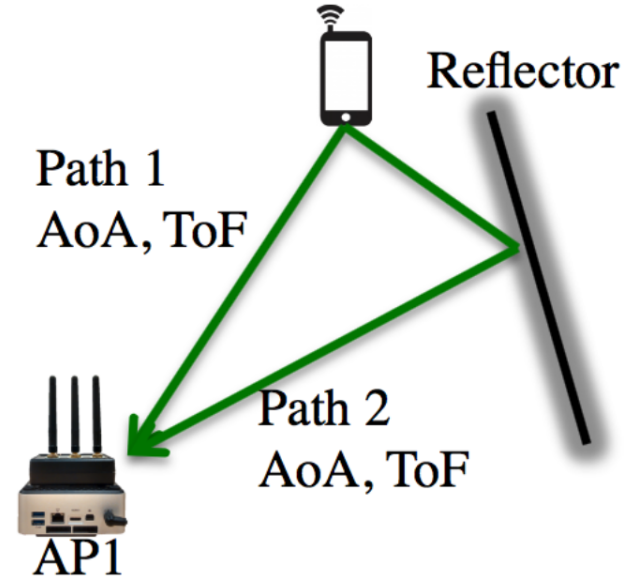
Back to SpotFi

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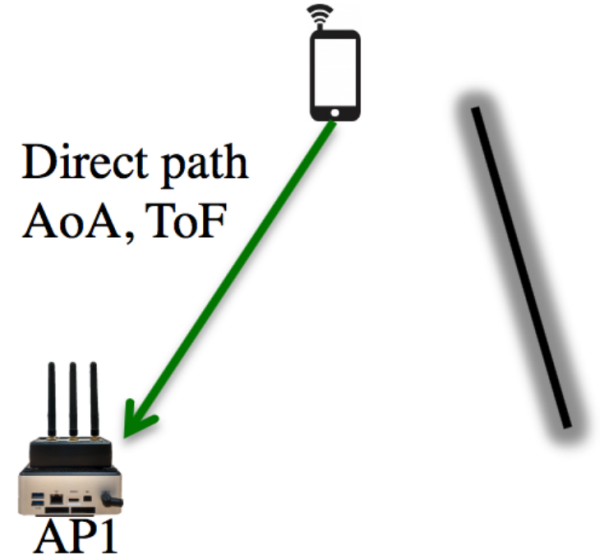
SpotFi

1. Estimates the AoA and ToF of multipath components using CSI values



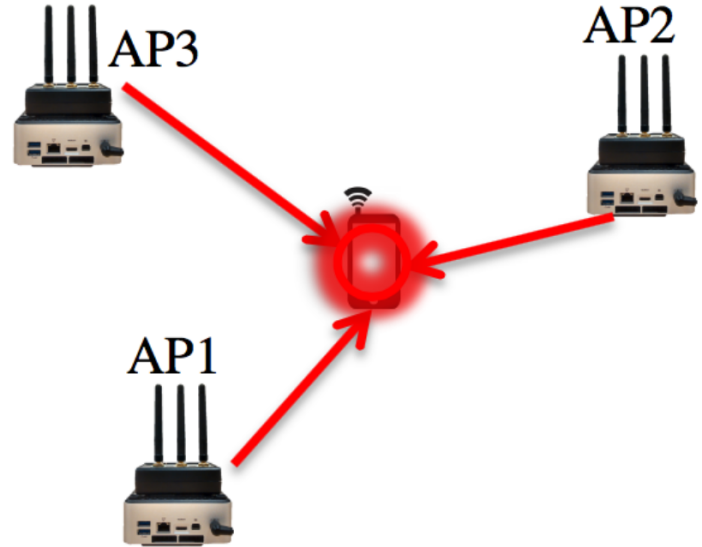
SpotFi

1. Estimates the AoA and ToF of multipath components using CSI values
2. Identifies the AoA and ToF pair belonging to the direct path



SpotFi

1. Estimates the AoA and ToF of multipath components using CSI values
2. Identifies the AoA and ToF pair belonging to the direct path
3. Combines the AoA and RSSI from all APs to localize target

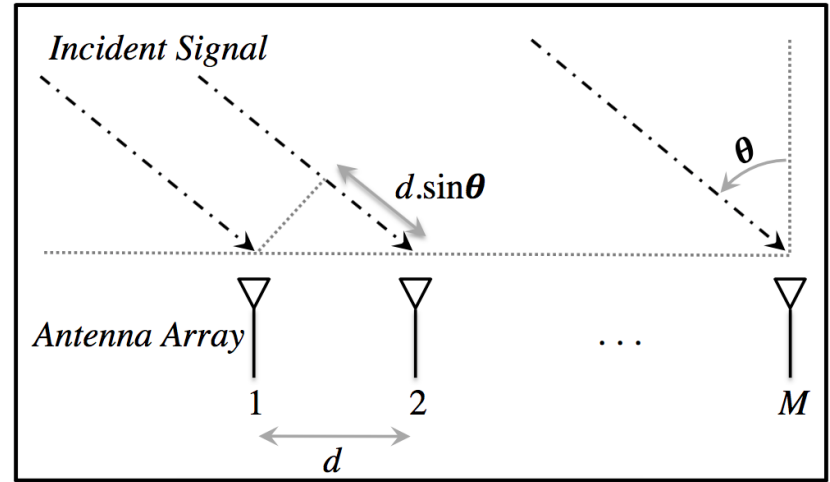


Estimating AoA

- Typically there are 6-8 significant reflectors in an indoor environment (shown in previous studies)
- How to estimate AoA of each path when AP has only three antennas?

Observations

- AoA introduces a phase shift across antennas
- Phase shift is a function of distance between antennas and the AoA



Phase shift at m^{th} antenna:

$$-2 \times \pi \times d \times (m - 1) \times \sin(\theta_k) \times f / c$$

The MUSIC Algorithm

The MUSIC algorithm estimates the transmitter location.

Steering matrix construction:

1. **Phase shift at m^{th} antenna:** $-2 \times \pi \times d \times (m - 1) \times \sin(\theta_k) \times f / c$
2. **For simplicity of representation take exponential:** $\Phi(\theta_k) = e^{-j2\pi \times d \times \sin(\theta_k) \times f / c}$
3. **Vector of phase shifts in antenna array:** $\vec{a}(\theta_k) = [1 \ \Phi(\theta_k) \ \dots \ \Phi(\theta_k)^{(M-1)}]^\top$
4. **Steering matrix:** $\mathbf{A} = [\vec{a}(\theta_1), \dots, \vec{a}(\theta_L)]$

The MUSIC Algorithm

Let \mathbf{X} be the CSI matrix reported by WiFi card:

$$\text{CSI matrix} = \begin{bmatrix} \text{csi}_{1,1} & \text{csi}_{1,2} & \dots & \text{csi}_{1,30} \\ \text{csi}_{2,1} & \text{csi}_{2,2} & \dots & \text{csi}_{2,30} \\ \text{csi}_{3,1} & \text{csi}_{3,2} & \dots & \text{csi}_{3,30} \end{bmatrix}$$

We know from the literature that eigenvectors of $\mathbf{X}\mathbf{X}^H$ corresponding to the eigenvalue zero, if they exist, are orthogonal to the columns of \mathbf{A}

To compute AoA values:

1. Compute the eigenvectors of $\mathbf{X}\mathbf{X}^H$ that correspond to eigenvalue zero
2. Compute the steering vectors orthogonal to the eigenvectors. AoA values are found since steering vectors are parametrized using AoA values.

The MUSIC Algorithm

In order for eigenvectors of \mathbf{XX}^H that correspond to eigenvalue zero to exist:

- Number of antennas has to be larger than the number of propagation paths
- Past work either used more than three antennas or rotating antennas to simulate a larger array of antennas
- **How can we use MUSIC algorithm with three antennas?**

Super-Resolution AoA Estimation

- We can get CSI measurements from each of the OFDM subcarriers
- They can be leveraged as new sensors (antennas)
- Intel 5300 WiFi has 30 subcarriers per antenna and has 3 antennas = 90 sensors

Problem

- Phase shift due to AoA is negligible across all the subcarriers of an antenna.
- There are only 2 distinct phase shifts (second and third antenna w.r.t first one)
- We are still limited with the number of antennas

Solution

- Instead of just estimating AoA, also estimate ToF for each path
- ToF introduces measurable phase shifts across subcarriers
- Introduce phase shifts to each of the sensors due to both AoA and ToF. New steering vector:

$$\vec{a}(\theta, \tau) = \left[\overbrace{1, \dots, \Omega_{\tau}^{N-1}}^{\text{antenna 1}}, \underbrace{\Phi_{\theta}, \dots, \Omega_{\tau}^{N-1} \Phi_{\theta}}_{\text{antenna 2}}, \dots, \overbrace{\Phi_{\theta}^{M-1}, \dots, \Omega_{\tau}^{N-1} \Phi_{\theta}^{M-1}}^{\text{antenna M}} \right]^{\top}$$

Super-Resolution AoA Estimation

- New measurement matrix **X** is constructed using CSI values at different shifted subarrays of sensors
- Music algorithm can now be applied to **X** (**Smoothed CSI**)

$$\begin{array}{c}
 \begin{bmatrix} \text{csi}_{1,1} \\ \vdots \\ \text{csi}_{1,30} \\ \text{csi}_{2,1} \\ \vdots \\ \text{csi}_{2,30} \\ \text{csi}_{3,1} \\ \vdots \\ \text{csi}_{3,30} \end{bmatrix}
 \end{array}
 \xrightarrow{\quad}
 \begin{array}{c}
 \begin{bmatrix}
 \text{csi}_{1,1} & \text{csi}_{1,2} & \cdots & \text{csi}_{1,16} & \text{csi}_{2,1} & \cdots & \text{csi}_{2,16} \\
 \text{csi}_{1,2} & \text{csi}_{1,3} & \cdots & \text{csi}_{1,17} & \text{csi}_{2,2} & \cdots & \text{csi}_{2,17} \\
 \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\
 \text{csi}_{1,15} & \text{csi}_{1,16} & \cdots & \text{csi}_{1,30} & \text{csi}_{2,15} & \cdots & \text{csi}_{2,30} \\
 \text{csi}_{2,1} & \text{csi}_{2,2} & \cdots & \text{csi}_{2,16} & \text{csi}_{3,1} & \cdots & \text{csi}_{3,16} \\
 \text{csi}_{2,2} & \text{csi}_{2,3} & \cdots & \text{csi}_{2,17} & \text{csi}_{3,2} & \cdots & \text{csi}_{3,17} \\
 \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\
 \text{csi}_{2,15} & \text{csi}_{2,16} & \cdots & \text{csi}_{2,30} & \text{csi}_{3,15} & \cdots & \text{csi}_{3,30}
 \end{bmatrix}
 \end{array}$$

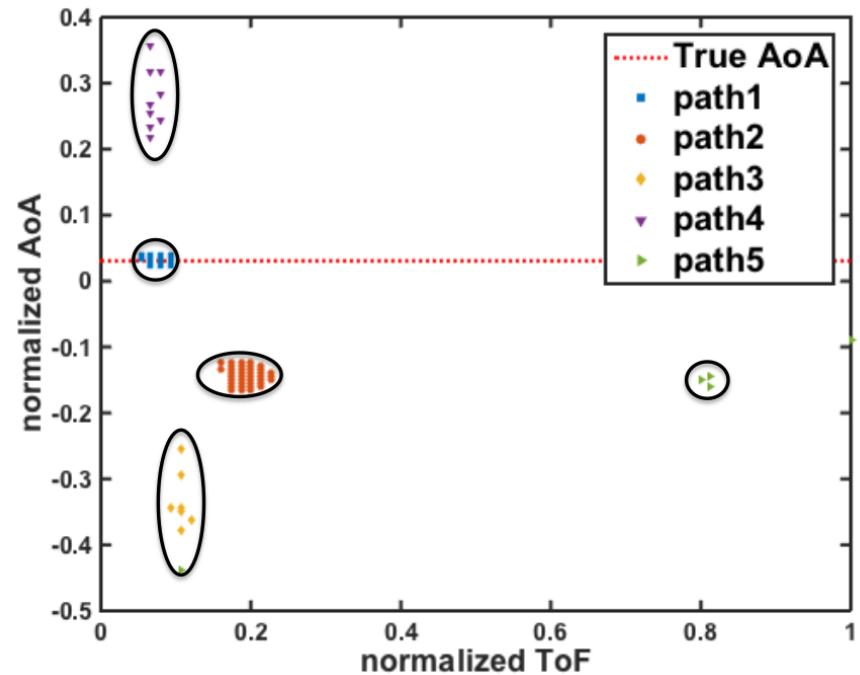
$\text{CSI}_{90 \times 1}$
 $\text{Smoothed CSI}_{30 \times 30}$

Identifying Direct Path AoA

- The path with smallest ToF is likely to be the direct one (heuristics fail!)
- Key idea: look for the path with much smaller variation between consecutive packets
- Assign a likelihood to each path inversely proportional to their variation
- Declare the path with highest likelihood metric as the direct path

Estimating Direct Path Likelihoods

- AoA and ToF estimates are plotted in 2D and clustered
- Number of clusters is chosen as five (typically five significant paths are seen)
- If a cluster corresponds to a direct path it should contain many packets and variances should be low. Design a likelihood function to reflect these insights.



path1 is chosen as the direct path

Localizing the Target

- Find the location that best explains the AoA estimates and RSSI measurements at different APs
- Use a path loss model to relate RSSI to distance

Localizing the Target

Minimize:

$$\sum_{i=1}^R l_i [(\bar{p}_i - p_i)^2 + (\bar{\theta}_i - \theta_i)^2]$$

where

l_i : likelihood value of most likely candidate for the direct path from i^{th} AP

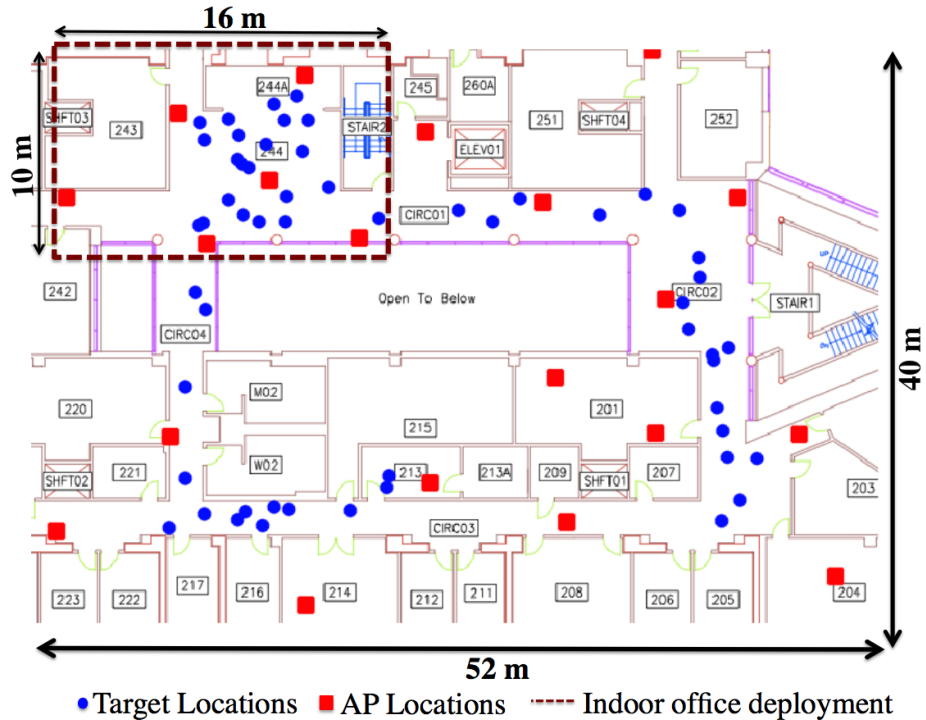
θ_i, p_i : direct path estimate of AoA and observed RSSI of the i^{th} AP

$\bar{\theta}_i, \bar{p}_i$: AoA and RSSI if the target was transmitting from that location. The search space is the all points inside the floor plan.

Solution: Apply sequential convex optimization techniques to piece-wise convexify the objective function and obtain the target location that minimizes it

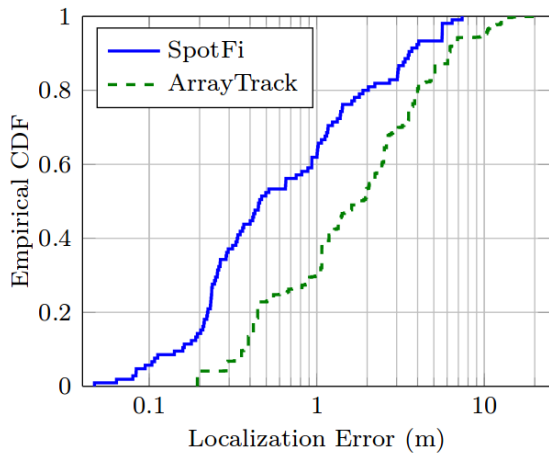
Experiments - Testbed

- APs are in monitor mode with 40 MHz bandwidth in the 5 GHz band
- A custom-made AP is placed at every target location and configured to the same channel with APs
- Ground truth locations of the client are measured using lasers
- The CSI, MAC addresses and timestamps are sent to the server from each of the APs

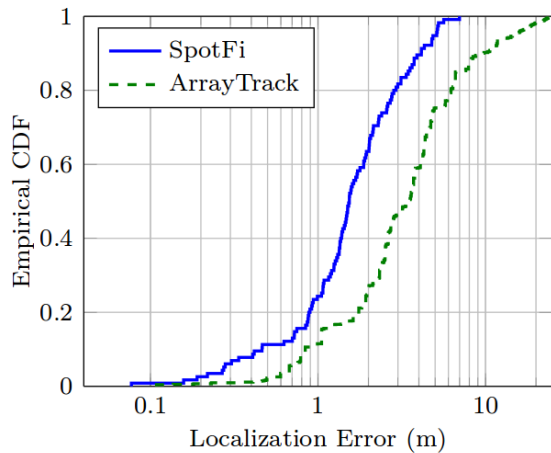


SpotFi's Localization Accuracy

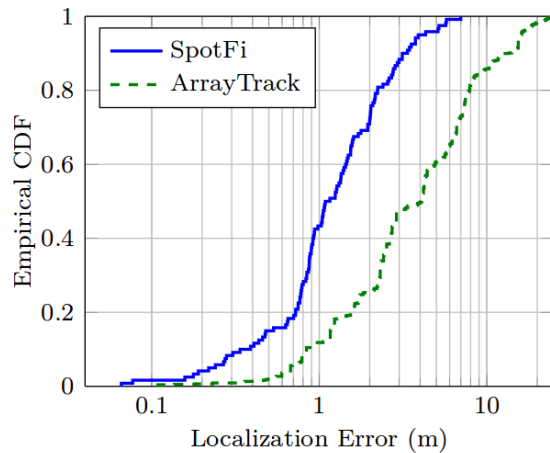
- 0.4 m median localization error for SpotFi (vs 1.8 m for ArrayTrack) in indoor office
- ArrayTrack degrades to 3.5 m (vs 1.6 m for SpotFi) in high NLoS deployment



(a) Indoor office deployment



(b) High NLoS deployment



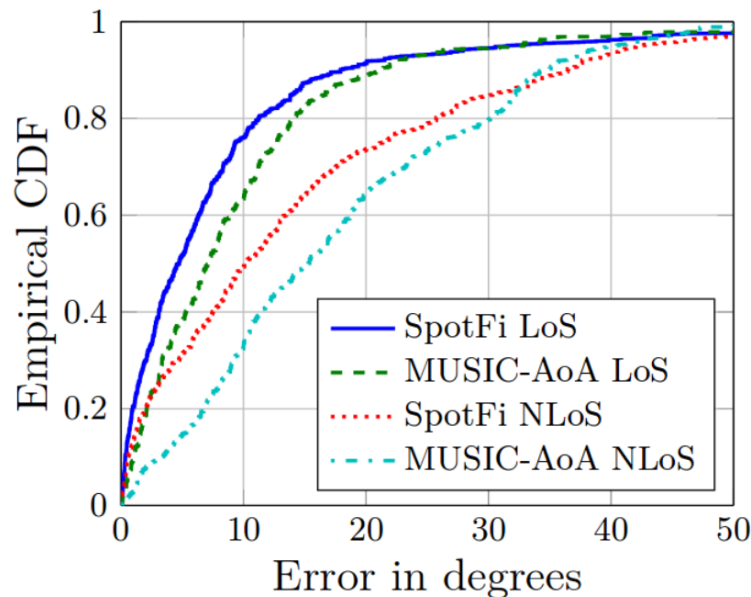
(c) Corridors

AoA Estimation Error

- Difference between ground truth direct path AoA and estimated AoA that is closest to this ground truth (This way effect of direct path selection is removed)

Result:

SpotFi is better. Improvement in NLoS scenario is greater (5.2 vs 2.4 degrees better median accuracy).



Direct Path AoA Selection Accuracy

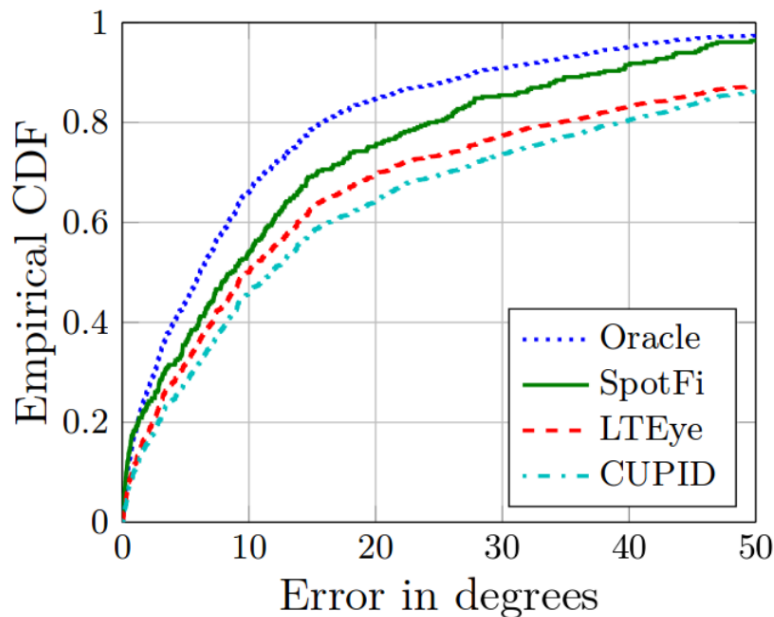
All schemes are using the AoA estimates from SpotFi

AoA Selection Heuristics:

- **LTeye**: one with the smallest ToF
- **CUPID**: one with the largest value in the MUSIC spectrum
- **Oracle**: one that is closest to the ground truth

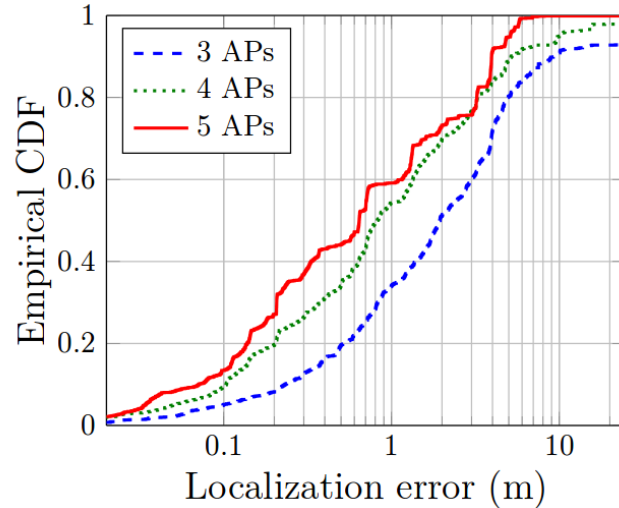
Result:

SpotFi is the best relative to the Oracle



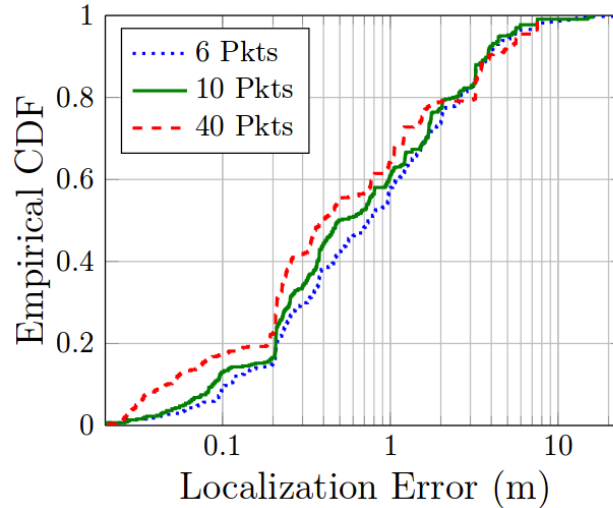
Effect of AP Density and Number of Packets

Big improvement from 3 to 4 APs.



(a) localization error with different AP densities

10 packets is required for accurate localization.



(b) localization error with different number of packets used for localization

Conclusion

SpotFi achieves state of the art indoor localization accuracy using commodity WiFi infrastructure.

Related Work

RSSI Based Approaches

- Measure RSSI at multiple APs, use triangulation along with a propagation model
- Median accuracy: 2-4 m, 80th percentile error: 5m

Pros : easy to deploy

Cons: not accurate due to insufficient propagation model

Related Work

Fingerprinting Based Approaches

- Collect vector of RSSIs, create fingerprints for locations
- Median accuracy: 0.6 m, tail accuracy: 1.3 m

Pros : **accurate**

Cons: difficult to deploy, recurring fingerprinting operation (e.g., when the furniture is moved)

Related Work

AoA Based Approaches

- Find the AoA of the direct path to the target from each AP and use triangulation
- Median accuracy: 0.4 m

Pros : accurate

Cons: Difficult to deploy, require hardware changes (e.g., adding more antennas)

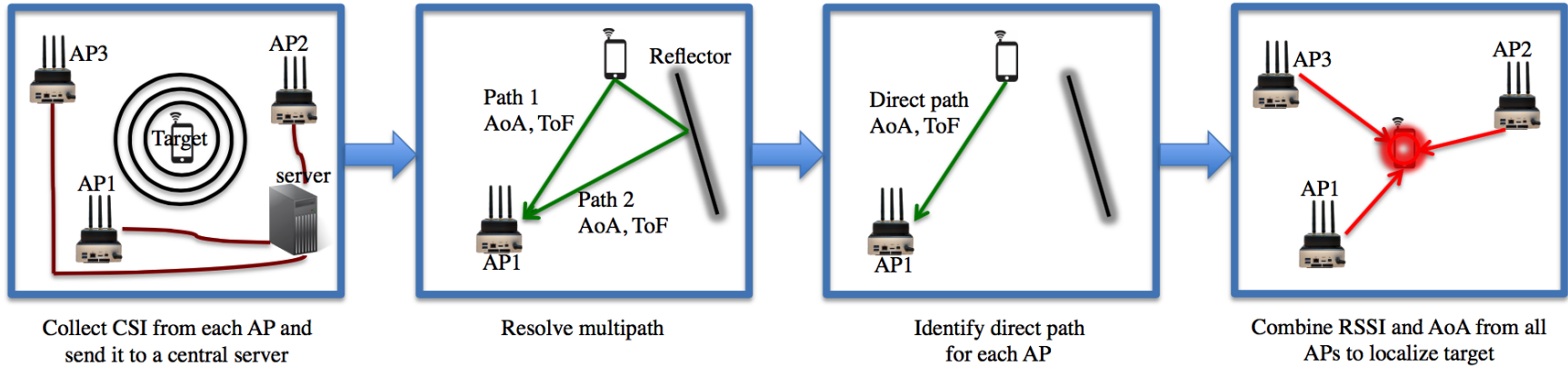
Related Work

Other Approaches

- Use sensors such as gyroscope, accelerometer along with AoA information: **not all devices have these sensors**
- Use time of flight at a granularity of nanoseconds: **requires all APs to be synchronized**
- RFIDs, ultrasound, visible light or beacons: **not ubiquitous as WiFi**

Questions?

SpotFi: Decimeter Level Localization Using WiFi



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3. **Vector of phase shifts in antenna array:** $\vec{a}(\theta_k) = [1 \ \Phi(\theta_k) \ \dots \ \Phi(\theta_k)^{(M-1)}]^\top$
4. **Array of received signals at the antennas due to k^{th} path:** $\vec{a}(\theta_k) \gamma_k$
 where γ_k is the attenuation in the first antenna
5. **Steering matrix:** $\mathbf{A} = [\vec{a}(\theta_1), \ \dots, \ \vec{a}(\theta_L)]$
6. **Measurement matrix:** $\vec{\Gamma} = [\gamma_1 \ \dots \ \gamma_L]^\top$
 $\mathbf{X} = [\vec{x}_1 \ \dots \ \vec{x}_N] = \mathbf{A}[\vec{\Gamma}_1 \ \dots \ \vec{\Gamma}_N] = \mathbf{A}\mathbf{F}$
 $\vec{x} = \mathbf{A}\vec{\Gamma}$: received signal vector at a subcarrier

The MUSIC Algorithm

Measurement matrix:

$$\mathbf{X} = [\vec{x}_1 \ \dots \ \vec{x}_N] = \mathbf{A}[\vec{\Gamma}_1 \ \dots \ \vec{\Gamma}_N] = \mathbf{A}\mathbf{F}$$

$$\vec{\Gamma} = [\gamma_1 \ \dots \ \gamma_L]^\top$$
$$\vec{x} = \mathbf{A}\vec{\Gamma}$$

\mathbf{X} corresponds to CSI matrix reported by WiFi card:

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