SpotFi: Decimeter Level Localization using WiFi

Manikanta Kotaru, Kiran Joshi, Dinesh Bharadia, Sachin Katti

Stanford University
Applications of Indoor Localization

Targeted Location Based Advertising

Indoor Navigation (e.g. Airport Terminals)

Real Life Analytics (Gym, Office, etc..)

Indoor localization platform providing decimeter-level accuracy could enable a host of applications
Easily Deployable

- Commercial WiFi chips
Easily Deployable

- Commercial WiFi chips
- No hardware or firmware change
Easily Deployable

- Commercial WiFi chips
- No hardware or firmware change
- No User Intervention
Easily Deployable, Universal

- Localize any WiFi device
- No specialized sensors
Easily Deployable, Universal, Accurate

- Error of few tens of centimeters
## State-of-the-art

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System Overview
Localization - Overview
Localization - Overview
Challenge - Multipath
Solving The Multipath Problem

State-of-the-art
Model signal on antennas alone

SpotFi
Model signal on both antennas and subcarriers

Antennas

Subcarriers
$f_1$
$f_2$
$f_3$
$f_4$
Step 1: Resolve Multipath
Signal Modeling

Equal Distance Line
Phase

Distance travelled by the WiFi signal

Phase

1/ frequency
Signal Modeling – AoA (Angle of Arrival)
Signal Modeling - AoA

Define \( \Phi_1 = e^{-\frac{j2\pi dsin\theta_1 f}{c}} \)

Phase at the antenna 1: \( x_1 = \Gamma_1 \)
Phase at the antenna 2: \( x_2 = \Gamma_1 \Phi_1 \)
Phase at the antenna 3: \( x_3 = \Gamma_1 \Phi_1^2 \)

\( \Gamma_1 \) is complex attenuation of the path.
\( \Phi_1 \) depends on AoA
Say There Are Two Paths...
Say There Are Two Paths...

\[ x_1 = \Gamma_1 \]
\[ x_2 = \Gamma_1 \Phi_1 \]
\[ x_3 = \Gamma_1 \Phi_1^2 \]
Say There Are Two Paths...

\[ x_1 = \Gamma_1 + \Gamma_2 \]
\[ x_2 = \Gamma_1 \Phi_1 + \Gamma_2 \Phi_2 \]
\[ x_3 = \Gamma_1 \Phi_1^2 + \Gamma_2 \Phi_2^2 \]
Problem Statement

\[
x_1 = \Gamma_1 + \Gamma_2
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CSI - Known
Problem Statement

\[ x_1 = \Gamma_1 + \Gamma_2 \]
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\[ x_3 = \Gamma_1 \Phi_1^2 + \Gamma_2 \Phi_2^2 \]

Parameters - Unknown
Problem Statement

Number of paths (or AoAs) $< \text{Number of antennas (or equations)}$

\[
\begin{align*}
x_1 &= \Gamma_1 + \Gamma_2 \\
x_2 &= \Gamma_1 \Phi_1 + \Gamma_2 \Phi_2 \\
x_3 &= \Gamma_1 \Phi_1^2 + \Gamma_2 \Phi_2^2
\end{align*}
\]
Typical Indoor Multipath
That’s A Problem

State-of-the-art

Commodity WiFi chips

Number of antennas/equations should be at least 5
How To Obtain More Equations?

Model signal on both antennas and subcarriers

Antennas

Subcarriers

\[ f_1 \]
\[ f_2 \]
\[ f_3 \]
\[ f_4 \]
Each Subcarrier Gives New Equations
Define \( \Omega_1 = e^{-j2\pi(f_2-f_1)\tau_1} \)

Phase at first subcarrier: \( x_1 = \Gamma_1 \)

Phase at second subcarrier: \( x_2 = \Gamma_1 \Omega_1 \)

\( \Gamma_1 \) is complex attenuation of the path. \( \Omega_1 \) depends on incoming signal ToF
Estimate both AoA and ToF

More number of equations in terms of parameter of our interest
Say There Are Two Paths...

At first subcarrier, for 3 antennas

\[ x_1 = \Gamma_1 \]
\[ x_2 = \Gamma_1 \Phi_1 \]
\[ x_3 = \Gamma_1 \Phi_1^2 \]

At second subcarrier, for 3 antennas

\[ y_1 = \Gamma_1 \Omega_1 \]
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Say There Are Two Paths...

At first subcarrier, for 3 antennas

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At second subcarrier, for 3 antennas

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CSI - Known

Subcarrier 1
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Subcarrier 2
\[
\begin{align*}
y_1 &= \Gamma_1 \Omega_1 + \Gamma_2 \\
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Parameters - Unknown

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\end{align*}
\]
Problem Statement

Number of equations = Number of Subcarriers \times Number of Antennas

Subcarrier 1
\[
\begin{align*}
x_1 &= \Gamma_1 + \Gamma_2 \\
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\]
AoA, ToF Estimates
Step 2: Identify Direct Path
AoA, ToF Estimates
Use Multiple Packets
Use Multiple Packets

![Graph showing normalized AoA vs. normalized ToF](image-url)
Use Multiple Packets
Use Multiple Packets
Direct Path Likelihood

- Smaller ToF
Direct Path Likelihood

- Smaller ToF
- Tighter Cluster
Direct Path Likelihood

- Smaller ToF
- Tighter Cluster
- More Packets
Highest Direct Path Likelihood
Step 3: Localize The Target
Use Multiple APs

Direct Path AoA = 45 degrees
Signal Strength = 10 dB

Direct Path AoA = 10 degrees
Signal Strength = 30 dB

Direct Path AoA = -45 degrees
Signal Strength = 20 dB

Find location that best explains the AoA and Signal Strength at all the APs
Use Different Weights

Direct Path AoA = 45 degrees
Signal Strength = 10 dB
Direct Path Likelihood

Direct Path AoA = 10 degrees
Signal Strength = 30 dB
Direct Path Likelihood

Direct Path AoA = -45 degrees
Signal Strength = 20 dB
Direct Path Likelihood

Use different weights for different APs
Evaluation
Indoor Office Deployment

<table>
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<tr>
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<th>Localization Error (m)</th>
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<td>0.3 m</td>
</tr>
<tr>
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Empirical CDF

Localization Error (m)

Target Locations

AP Locations
Stress Test – Obstacles Blocking The Direct Path
Stress Test – Obstacles Blocking The Direct Path

Empirical CDF

Localization Error (m)

AP Locations
Target Locations

1.3 m

Localization Error (m)

Empirical CDF
Effect of WiFi AP Deployment Density

![Graph showing empirical CDF for localization error with different AP densities]
Conclusion

• **Deployable:** Indoor Localization with commercial WiFi chips

• **Accurate:** Accuracy comparable to state-of-the-art localization systems which are not suitable for wide deployments

• **Universal:** Simple localization targets with only a WiFi chip
References

• J. Xiong and K. Jamieson, “Arraytrack: A fine-grained indoor location system,” NSDI ’13.
• M. Youssef and A. Agrawala, “The horus wlan location determination system,” MobiSys ’05.
• All the icons are from the Noun Project https://thenounproject.com/
BackFi: High Throughput WiFi Backscatter for IoT

Dinesh Bharadia*, Kiran Joshi*, Manikanta Kotaru, Sachin Katti
Stanford University
*co-primary authors
The Internet of Things (IoT) Vision
The Internet of Things (IoT) Vision

Sense
The Internet of Things (IoT) Vision

Sense

Collect & Analyze
The Internet of Things (IoT) Vision

Sense

Collect & Analyze

Control
The Internet of Things (IoT) Vision

Sense  Collect & Analyze  Control

BackFi
What do we need for IoT Connectivity?

Sense
What do we need for IoT Connectivity?

Sense

Ubiquitous connectivity
What do we need for IoT Connectivity?

Sense

Ubiquitous connectivity
Low power
What do we need for IoT Connectivity?

- Ubiquitous connectivity
- Low power
- High uplink rate
What do we need for IoT Connectivity?

Ubiquitous connectivity
Low power
High uplink rate
Sufficient range
**BackFi**: Ubiquitous, low power, high throughput connectivity for IoT sensors using ambient WiFi
**BackFi:** Ubiquitous, low power, high throughput connectivity for IoT sensors using ambient WiFi

Sense

![Diagram of Sense with various icons and a bar graph](image)
**BackFi**: Ubiquitous, low power, high throughput connectivity for IoT sensors using ambient WiFi
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- **Technical spec**: BackFi’s contributions include ubiquitous connectivity, low power, high uplink rate, and sufficient range.
- **Key enabling technique**: These features are enabled by the same technique as WiFi – backscatter ubiquitous ambient signals.
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Related Work
Related Work

- Ubiquitous connectivity
- Low power
- High uplink rate
- Sufficient range
Related Work

| WiFi-Backscatter | Ubiquitous connectivity | Low power | High uplink rate | Sufficient range |

WiFi Backscatter:
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IoT Sensor
BackFi’s Overview

IoT Sensor  BackFi AP
BackFi’s Overview

IoT Sensor  BackFi AP
IoT Sensor Design
IoT Sensor Design
IoT Sensor Design

Sense

Sensor data

...10101010...
IoT Sensor Design

Sensor data

...10101010...
IoT Sensor Design

Sensor data

...10101010...

Data modulation

0 to -1
1 to +1
IoT Sensor Design

Sensor data: $\ldots 10101010 \ldots$

Data modulation:

-0 to -1
0 to +1

1 → Data modulation
-1 →
IoT Sensor Design

Sense

Sensor data

...10101010...

Data modulation

0 to -1
1 to +1
BackFi AP Design
BackFi AP Design
BackFi AP Design
BackFi AP Design

Received signal $= \text{Sensor backscatter} + \text{Environmental reflections}$
Challenge 1: Strong Environmental Reflections
Challenge 1: Strong Environmental Reflections

Power in dBm

-100 -80 -60 -40 -20 0 20

Frequency in GHz

2.45 GHz

40 MHz
Challenge 1: Strong Environmental Reflections
Challenge 1: Strong Environmental Reflections

Power in dBm

20

10

0

-10

-20

-30

-40

-50

-60

-70

-80

-90

-100

Frequency in GHz

2.45

40 MHz
Challenge 1: Strong Environmental Reflections

Received signal = \text{Sensor backscatter} + \text{Environmental reflections}
Challenge 1: Strong Environmental Reflections

Received signal = Sensor backscatter + Environmental reflections
Why not use Self-Interference Cancelation?
Why not use Self-Interference Cancelation?
Why not use Self-Interference Cancelation?
Why not use Self-Interference Cancelation?

Transmitted signal: $\Sigma A ftre & canc$ 

Received signal: 

Cancelation filter: $\Sigma$ 

After cancelation: $= 0$
Why not use Self-Interference Cancelation?

Received signal = Sensor backscatter + Environmental reflections
Why not use Self-Interference Cancelation?

Received signal = \text{Sensor backscatter} + \text{Environmental reflections}

After cancelation = 0
Eliminating environmental reflections

Received signal = Sensor backscatter + Environmental reflections
Eliminating environmental reflections

Received signal = **Sensor backscatter** + **Environmental reflections**
Eliminating environmental reflections

Sense

Turn off the backscatter

Received signal = \text{Sensor backscatter} + \text{Environmental reflections}
Eliminating environmental reflections

Turn off the backscatter

Received signal = Sensor backscatter + Environmental reflections

Estimate the environmental reflections

Transmitted signal

Received signal

Σ

After cancelation = 0

Cancelation filter
Eliminating environmental reflections

Received signal = Sensor backscatter + Environmental reflections

After cancellation = Sensor backscatter

Turn on the backscatter

Sense

Estimate the environmental reflections
Challenge 2: Inferring IoT Sensor Data
Challenge 2: Inferring IoT Sensor Data

Sensor backscatter is function of:
Challenge 2: Inferring IoT Sensor Data

Sensor backscatter is function of:
• Transmitted signal
Challenge 2: Inferring IoT Sensor Data

Sensor backscatter is function of:
• Transmitted signal
• IoT sensor data
Challenge 2: Inferring IoT Sensor Data

Sensor backscatter is function of:
• Transmitted signal
• IoT sensor data
• Wireless channel distortions
Challenge 2: Inferring IoT Sensor Data

Sensor backscatter is function of:

- Transmitted signal
- IoT sensor data
- Wireless channel distortions
Modeling Sensor Backscatter
Modeling Sensor Backscatter

Transmitted signal = x
Modeling Sensor Backscatter

\[\text{Transmitted signal} = x\]
Modeling Sensor Backscatter

\[ x \ast h \]

Transmitted signal = \( x \)
Modeling Sensor Backscatter

Sensor data $= \theta$

Transmitted signal $= x$

$\times \star h$
Modeling Sensor Backscatter

\[(x \ast h). \theta \]

Sensor data = \[\theta \]
Modeling Sensor Backscatter

\[
(x \ast h) \cdot \theta = x \ast h
\]

Sensor data = \( \theta \)

Transmitted signal = \( x \)
Modeling Sensor Backscatter

\[
\text{Rx} = \text{sensor backscatter} = ((x \ast h). \theta) \ast h
\]
Modeling Sensor Backscatter

\[
\text{Rx} = \text{sensor backscatter} = ((x \ast h) \cdot \theta) \ast h
\]

\[
\text{Transmitted signal} = x
\]

\[
\text{Sensor data} \rightarrow \theta \rightarrow (x \ast h) \cdot \theta \rightarrow x \ast h
\]
Estimating Backscatter Channel

\[ x \ast h \] Transmitted signal = \( x \)
Estimating Backscatter Channel

Use predefined sequence of sensor data $\theta$ to estimate channel

$\mathbf{h}$

$\mathbf{x} \ast \mathbf{h}$

Transmitted signal $= \mathbf{x}$
Estimating Backscatter Channel

Use predefined sequence of sensor data $\theta$ to estimate channel

Sensor data $= 1$

$\quad x \ast h$

Transmitted signal $= x$
Estimating Backscatter Channel

Use predefined sequence of sensor data $\theta$ to estimate channel

$\text{Transmitted signal} = x$

$\text{Sensor data} = 1$

$\text{Rx} = (x \ast h) \ast h$
Estimating Backscatter Channel

Use predefined sequence of sensor data $\theta$ to estimate channel

Transmitted signal $= x$

Sensor data $= 1$

$Rx = (x \ast h) \ast h$

$Rx = \text{sensor backscatter} = x \ast (h \ast h)$
Estimating Backscatter Channel

Use predefined sequence of sensor data $\theta$ to estimate channel

$$Rx = (x * h) * h$$

$$Rx = \text{sensor backscatter} = x * (h * h)$$

Estimate $h$
Modeling Sensor Backscatter

\[ \text{Sensor data} = \theta \rightarrow \ast \rightarrow x \star h \rightarrow \theta \rightarrow \times \rightarrow \text{Transmitted signal} = x \]

\[ \text{Rx} = ((x \star h) \cdot \theta) \ast h \]

\[ \text{Rx} = \text{sensor backscatter} = \]
Modeling Sensor Backscatter

\[ \text{Rx} = \text{sensor backscatter} = ((x \ast h) \ast \theta) \ast h \]

\[ \text{Rx} = ((x \ast h) \ast \theta) \ast h \]

Transmitted signal = \( x \)

Sensor data = \( \theta \)

\[ (x \ast h) \ast \theta \]

\[ x \ast h \]
Modeling Sensor Backscatter

\[ \text{Sensor data} = \theta \rightarrow \times \]

Transmitted signal = \(x\)

\[ \text{Rx} = ((x \ast h) \cdot \theta) \ast h \]

\[ \text{Rx} = \text{sensor backscatter} = ((x \ast h) \cdot \theta) \ast h \]

\[
\begin{align*}
\checkmark & \checkmark & \checkmark & \checkmark
\end{align*}
\]
Modeling Sensor Backscatter

\[ (x \ast h) \cdot \theta \]

Transmitted signal = \( x \)

\[ Rx = ((x \ast h) \cdot \theta) \ast h \]

Rx = sensor backscatter = \( (x \ast h) \cdot \theta) \ast h \)

\[ \checkmark \checkmark \ ? \ \checkmark \]

Incoming signal \( z = (x \ast h) \)
Modeling Sensor Backscatter

\[ \text{Rx} = \text{sensor backscatter} = (x \ast h, \theta) \ast h \]

Incoming signal \( z = (x \ast h) \)

Sensor backscatter \( = (z \ast \theta) \ast h \)
Demodulating $\theta$ from Sensor Backscatter

Sensor Backscatter = $\{z. \theta\} * h$
Demodulating $\theta$ from Sensor Backscatter

Sensor Backscatter = $\{z, \theta\} \ast h$

Incoming $z$
Demodulating $\theta$ from Sensor Backscatter

$$\text{Sensor Backscatter} = \{z, \theta\} \ast h$$
Demodulating $\theta$ from Sensor Backscatter

Sensor Backscatter = $\{z, \theta\} \ast h$
Demodulating $\theta$ from Sensor Backscatter

Sensor Backscatter = \{z, \theta\} \ast h

WiFi AP
Sampling rate
40 Msps

IoT sensor
Information switching rate
2 Msps
Demodulating $\theta$ from Sensor Backscatter

Sensor Backscatter = $\{z, \theta\} \ast h$
Demodulating $\theta$ from Sensor Backscatter

Sensor Backscatter = $\{z, \theta\} \ast h$
Demodulating $\theta$ from Sensor Backscatter

Sensor Backscatter = \{z. \theta\} \ast h
Demodulating $\theta$ from Sensor Backscatter

Sensor Backscatter = \{z, \theta\} \ast h

Maximal Ratio Combining = \sum \text{weights} \ast \text{samples} = \sum w_i \ast s_i
Demodulating $\theta$ from Sensor Backscatter

Sensor Backscatter = \{z, \theta\} \ast h

Maximal Ratio Combining = \sum \text{weights} \ast \text{samples} = \sum w_i \ast s_i
Demodulating $\theta$ from Sensor Backscatter

Sensor Backscatter = \{z, \theta\} \ast h

Maximal Ratio Combining = \sum \text{weights} \ast \text{samples} = \sum w_i \ast s_i
BackFi Prototype
BackFi Prototype
BackFi Prototype

Antenna

Modulator

Digital control board
BackFi Prototype

Antenna

Modulator

Digital control board

WiFi Backscatter radio with BPSK, QPSK & 16 PSK
BackFi Prototype

Antenna

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WiFi Backscatter radio with BPSK, QPSK & 16 PSK
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WiFi Backscatter radio with BPSK, QPSK & 16 PSK

Built using WARP SDR platform, designed for 802.11, BW 20MHz, 20dBm TX power
BackFi Prototype

WiFi Backscatter radio with BPSK, QPSK & 16 PSK

Built using WARP SDR platform, designed for 802.11, BW 20MHz, 20dBm TX power
BackFi Prototype
Testbed & Performance Metrics
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Indoor office environment:
• AP and IoT sensor are placed in LOS
Testbed & Performance Metrics

Indoor office environment:
• AP and IoT sensor are placed in LOS
• WiFi clients are placed nearby
Testbed & Performance Metrics

Indoor office environment:
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• Varied the placement of IoT device, client and WiFi AP.
Testbed & Performance Metrics

Indoor office environment:
• AP and IoT sensor are placed in LOS
• WiFi clients are placed nearby
• Varied the placement of IoT device, client and WiFi AP.

Performance metrics
• Throughput
• Energy per bit
What is the range and throughput?

Throughput of IoT sensor with distance from AP

Throughput in Mbps

Range in meters

- 0.5
- 1
- 2
- 4
- 5
- 6
- 7
What is the range and throughput?

Throughput of IoT sensor with distance from AP

- **Throughput in Mbps**
- **Range in meters**

Throughput decreases as the distance from the AP increases.
What is the range and throughput?

Throughput of IoT sensor with distance from AP

Throughput in Mbps vs Range in meters

Three order of magnitude better throughput than prior WiFi backscatter.
What is the power consumption of BackFi?

<table>
<thead>
<tr>
<th>Throughput in Mbps</th>
<th>EPB in pJ/bit</th>
<th>Total Power Consumption in uW for continuous mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>.1</td>
<td>12.66</td>
<td>1.27</td>
</tr>
<tr>
<td>.5</td>
<td>5.04</td>
<td>2.52</td>
</tr>
<tr>
<td>1</td>
<td>4.10</td>
<td>4.10</td>
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Two order magnitude better EPB than prior work
Conclusion
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BackFi provides high throughput, low power, ubiquitous connectivity using ambient WiFi signals
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- Not restricted to WiFi, can use other ambient signals such as LTE, Bluetooth
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• Vision: Build a pervading layer of connectivity over all ambient communication signals
Conclusion

BackFi provides high throughput, low power, ubiquitous connectivity using ambient WiFi signals

• Not restricted to WiFi, can use other ambient signals such as LTE, Bluetooth

• Vision: Build a pervading layer of connectivity over all ambient communication signals

• Next step: go from a link to a network