Decimeter-Level Localization with a Single WiFi Access Point

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Indoor Localization is Cool!

SpotFi [SIGCOMM’ 15], ToneTrack [Mobicom’ 15], Phaser [Mobicom’ 14], Tagoram [Mobicom’ 14], LTEye [SIGCOMM’ 14], ArrayTrack [NSDI’13], PinPoint [NSDI’13], PinIt [SIGCOMM’13], Zee [MobiCom’12], PinLoc [MobySys’12], EZ [MobiCom’10], ....

• Locate **off-the-shelf devices**

• **Accuracy of tens of cm**
But... They Need 4-5 Access Points

Homes and small businesses have **ONE** access point (AP)
Application: Control heating based on occupancy
Application: WiFi Geo-Fencing
Application: Device-to-device Localization

Enable device-to-device localization without infrastructure support
Chronos

• Enables decimeter-accurate localization using a single off-the-shelf WiFi card

• A novel algorithm to estimate propagation time to sub-nanosecond accuracy using a WiFi card

• Implemented and evaluated in practical settings
Why past work needs multiple AP’s?
Single Access Point?

distance

θ
Measuring Distance

Distance = speed of light \times \text{propagation delay}
Measuring Distance

How do we measure propagation delay?
Propagation Delay

Phase of the signal ($\phi$) = $2\pi ft \ mod \ 2\pi$
Propagation Delay: Example

\[ \phi = 2\pi ft \mod 2\pi \]
Propagation Delay: Example

- 5.8 GHz
- 5.18 GHz
- 2.48 GHz
- 2.41 GHz

Graph showing the propagation delay with time (t (ns)) on the x-axis and frequency on the y-axis.
Mathematically

\[ \phi_1 = 2\pi f_1 t \mod 2\pi \]
\[ \phi_2 = 2\pi f_2 t \mod 2\pi \]
\[ \vdots \]
\[ \phi_N = 2\pi f_N t \mod 2\pi \]
Mathematically

\[ \phi_1 = 2\pi f_1 t \mod 2\pi \]

\[ \phi_2 = 2\pi f_2 t \mod 2\pi \]

Use Chinese Remainder Theorem to get the propagation delay
Can’t measure propagation delay without detection delay

Distance = speed of light x propagation delay
Measured delay = propagation delay + detection delay
Packet Detection Delay

Detection Delay

Detection

Decoding

How do we eliminate detection delay?
**Problem:** Separate detection delay from propagation delay

**Solution:** Leverage that propagation delay and detection delay happen at different frequencies
Propagation Delay ($t$)  

Detection Delay ($t'$)  

\[ \phi = 2\pi ft \mod 2\pi \]

\[ \phi = 2\pi ft + 2\pi (f - f_c)t' \mod 2\pi \]
Idea: Use OFDM to measure phase at $f=f_c$.
But WiFi does not transmit at $f=f_c$
Solution: Leverage OFDM

\[ \phi = 2\pi ft + 2\pi (f - f_c)t' \mod 2\pi \]
\[ \phi_c = 2\pi f_c t + 0 \mod 2\pi \]
Mathematically

\[ \phi_{c,1} = 2\pi f_{c,1} t \mod 2\pi \]
\[ \phi_{c,2} = 2\pi f_{c,2} t \mod 2\pi \]

Chronos eliminates packet detection delay by leveraging OFDM properties
Additional System Components

• Initial Phase Offset Compensation

• Multipath resolution
Additional System Components

- Initial Phase Offset Compensation
- Multipath resolution
Initial Phase Offsets

\[ \phi = 2\pi ft \mod 2\pi \]

\[ \phi = 2\pi ft + \Delta\phi \mod 2\pi \]
Idea: Use Acknowledgements

\[
\begin{align*}
\phi_1 &= 2\pi f t + \Delta \phi \mod 2\pi \\
\phi_2 &= 2\pi f t - \Delta \phi \mod 2\pi \\
\phi_1 + \phi_2 &= 4\pi f t \mod 2\pi
\end{align*}
\]
Idea: Use Acknowledgements

Chronos eliminates phase offsets by using acknowledgements

\[ \phi_1 = 2\pi ft + \Delta\phi \mod 2\pi \]
Additional System Components

• Initial Phase offset Compensation

• Multipath resolution
Problem: Multipath Effect
Solution: Find delays for each path

Distance to source corresponds to the smallest delay.

- 5.2 ns
- 10 ns
- 16 ns
Experimental Evaluation
Implementation

• Evaluation with off-the-shelf Intel WiFi 5300 cards

• Kernel modifications to the iwlwifi driver in the Ubuntu kernel

• Ground truth measurements using laser distance measurement device (1mm accurate)
Evaluation Testbed: Office Environment
Distance Measurement Accuracy

- **CDF**

- **Error (m)**
  - LOS
  - NLOS

- **14 cm**
- **21 cm**
Localization Accuracy

CDF

Error (m)

LOS

NLOS

SpotFi (SIGCOMM’15)

3 AP’s

4 AP’s

5 AP’s

190 cm

80 cm

60 cm

65 cm

98 cm

65 cm

0

0.2

0.4

0.6

0.8

1

0

2

4

blue line

red line

LOS

NLOS

3 AP’s

4 AP’s

5 AP’s

190 cm

80 cm

60 cm
Chronos can achieve state-of-the-art localization accuracy with a single AP.

SpotFi (SIGCOMM ’15)

<table>
<thead>
<tr>
<th>Number of APs</th>
<th>Error (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>190 cm</td>
</tr>
<tr>
<td>4</td>
<td>80 cm</td>
</tr>
<tr>
<td>5</td>
<td>60 cm</td>
</tr>
</tbody>
</table>
Applications

Smart Homes

WiFi Geo-fencing

Device to Device localization
Applications

Smart Homes

WiFi Geo-fencing

Device to Device localization
Application: Smart Homes

- Living room
- Bedroom1
- Bedroom2
- Kitchen
- Bath

9 m
13 m
Application: Smart Homes

Chronos detects the correct room with accuracy 94%.
Applications

Smart Homes

WiFi Geo-fencing

Device to Device localization
Application: GeoFencing

Coffee Station

9 m

7 m
Application: GeoFencing

Chronos can accurately authenticate WiFi users with 97% accuracy.
Applications

- Smart Homes
- WiFi Geo-fencing
- Device to Device localization
Application: TakeMyPicture Drone
Application: TakeMyPicture Drone

Drone

User

1.4 m

x (m)

y (m)
Application: TakeMyPicture Drone

CDF

Error (cm)

4.2 cm
Application: TakeMyPicture Drone

Chronos enables a drone to follow the user with no infrastructure support.

CDF

Error (cm)

4.2 cm
Related Work

• WiFi Localization: SpotFi [SIGCOMM’ 15], ToneTrack [Mobicom’ 15], Phaser [Mobicom’ 14], Tagoram [Mobicom’ 14], ....
• Closest Work: SAIL [MobiSys’ 14]
Conclusion

• Chronos is the first system to enable accurate localization on off-the-shelf WiFi cards

• Its key enabler is a novel algorithm that can estimate accurate propagation delay, by eliminating the detection delay