Synchronicity: Pushing the Envelope of Fine-Grained Localization with Distributed MIMO

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Precise location services are important

- **Outdoors:** GPS
  - Accurate enough for navigation
  - Signals fade in indoor environments

- Precise indoor location enables:
  - Augmented reality on smart devices
  - Localization in huge spaces

**WiFi!**
MIMO technology is popular

- Increasing number of antennas on an access point
- Higher bandwidth

**MIMO 802.11n**

**MU-MIMO 802.11ac**

**Distributed MIMO 802.11xx ?**

**Channelization**

- 5.17 GHz
- 5.33 GHz
- 20 MHz
- 40 MHz
- 80 MHz
- 160 MHz

New with 802.11ac

**AoA localization (ArrayTrack [NSDI’13])**

**ToA (SAIL [Mobisys’14])**

**TDoA localization**
Time difference of arrival (TDoA)

\[ d_3 - d_1 = d_{31} \text{ (hyperbola 1)} \]

\[ d_2 - d_1 = d_{21} \text{(hyperbola 2)} \]
TDoA: New opportunities

Previous disadvantageous:
- APs were not time synchronized
- Limited bandwidth (20MHz)

New opportunities for TDoA:
- Larger bandwidth: upto 160MHz for 802.11ac
- Distributed MIMO: APs achieve precise time synchronization (SourceSync [SIGCOMM’10], Clock Sync [MobiCom’14 poster])
- Channel State Information available for each sub-carrier
Challenge: TDoA resolution is limited

<table>
<thead>
<tr>
<th>Physical Layer</th>
<th>Bandwidth</th>
<th>Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>802.11g</td>
<td>20 MHz</td>
<td>15 m</td>
</tr>
<tr>
<td>802.11n</td>
<td>40 MHz</td>
<td>7.6 m</td>
</tr>
<tr>
<td>802.11ac</td>
<td>&lt;160 MHz</td>
<td>&gt;1.9 m</td>
</tr>
</tbody>
</table>

Super resolution schemes can improve the naïve resolution above to some extent
MUSIC’s resolution limit

Naïve: 15m resolution (20MHz sampling rate)

MUSIC: around 8m resolution

When two paths get closer, MUSIC fails to resolve them correctly

The two peaks merged into one eventually
Synchronicity: key observation

When the sampling rate is not high enough to resolve all the signals correctly, the stronger peak is more accurate!
Key observation verification

- Stronger peak has less error
- The error becomes smaller with larger signal strength difference
Merged peak can still be accurate

As long as the LOS path is stronger

- The larger signal strength difference, the smaller the peak error
Synchronicity step outline

- Spectrum identification (SI) on a single AP

- Triangle inequality (TI) across multiple APs

- Clustering and outlier rejection across multiple APs
Spectrum identification (SI)

- Compare the peak distance with the threshold: verify whether the spectrum falls in the inaccurate zone.
- Compare the amplitudes of the peaks: discard the spectrum with weaker first peak.
Spectrum identification (SI) of merged peak

- Identify whether the first peak is a single signal peak or merged peak
- If it’s a merged peak, check the skewness of the peak: discard the spectrum with forward skewness
Synchronicity step outline

- Spectrum identification (SI) on a single AP
- Triangle inequality (TI) across multiple APs
- Clustering and outlier rejection across multiple APs
Multi-AP processing for LOS path blockage: triangle inequality (TI)

The LOS path difference is always smaller than the AP distance $dc$.

If $dr - d1 > dc$ is detected, $dr$ is NLOS path and should be discarded.
Synchronicity step outline

- Spectrum identification (SI) on a single AP
- Triangle inequality (TI) across multiple APs
- Clustering and outlier rejection across multiple APs
Multi-AP processing for LOS path blockage: clustering and outlier rejection

The LOS-path blocked AP localizes client to random positions while LOS AP estimates are clustered.

A5 is blocked for NLOS

E125 is far away from other location estimates
Combines MUSIC and Matrix Pencil

- MP: Matrix Pencil on raw data
- MUSIC: MUSIC on noise space data
- Synchronicity: (1) MUSIC to divide data (2) Apply Matrix Pencil on signal-space data
Experimental setup

• Each of the 6 antennas on WARP emulates one AP

• Soekris boxes equipped with 802.11 radios as clients
Overall performance

Synchronicity improves the median accuracy from 3.6m (MUSIC) to 1.7m

CDF of location error in cm for Synchronicity and MUSIC.
Performance/w time synchronization error

*We borrow time synchronization error data from SourceSync*
Conclusion and future work

• Synchronicity: 1.7 m accuracy from just TDoA
  – Single antenna APs; 20MHz channel bandwidth

• Can augment other schemes including AoA

• Significant accuracy improvement on higher bandwidth

• Merge adjacent channel data for more accurate localization

Thank you!