Radio Positioning in 6G Communication Systems

Cooperative Multi-Monostatic Sensing

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Outline

• Introduction to ICaS
• Preliminaries on sensing
• Multi-Monostatic Sensing
• Results
• Conclusion
Introduction

6G is expected to provide high data rate, minimal latency, and cm-level positioning accuracy [1].

- e.g., in autonomous driving, extended reality (XR), and digital twins.

Positioning is the process of estimating the location and speed of a device/object from radio measurements

- It could be active or passive

Active Sensing: included in 3GPP.

- In the cellular network, there are the PRS (Positioning reference signal) and SRS (sounding reference signal).

Passive Sensing: not yet included.

- Monostatic, Bistatic, Multistatic Sensing

Fig. 1: Localization accuracies for different radio technologies in different environments [2].


ICaS: two functions one system

• Enablers
  – More bandwidth at mmWave frequencies
  – Hardware, signal and radio resource re-use
  – Massive MIMO
  – AI-based designs and algorithms

• Challenges
  – Hardware impairments
  – Power consumption
  – Deployment cost
  – Satisfying accuracy for plethora of use cases
  – Trade-off between coms and sensing KPIs

<table>
<thead>
<tr>
<th>Sensing Perspective</th>
<th>Communication Perspective</th>
</tr>
</thead>
<tbody>
<tr>
<td>Probability of Detection</td>
<td>Throughput</td>
</tr>
<tr>
<td>Range Resolution</td>
<td>Latency</td>
</tr>
<tr>
<td>Velocity Resolution</td>
<td>Spectral Efficiency</td>
</tr>
<tr>
<td>Maximum Unambiguous Range</td>
<td>Energy Efficiency</td>
</tr>
<tr>
<td>Maximum Unambiguous Velocity</td>
<td>Number of Served Users</td>
</tr>
<tr>
<td>Estimation Accuracy</td>
<td>Bit Error Rate</td>
</tr>
</tbody>
</table>
Types of Sensing

- **Monostatic Sensing**
  - Coherent Signal Processing

- **Bistatic Sensing**
  - Large angles of observation
  - Coherent operation difficult

- **Multistatic Sensing**
  - Increased target information
  - Increased probability of detection
  - Coherent operation difficult
Resource sharing
OFDM Radar Use Case

Analyzed KPIs:
• Range resolution
• Velocity resolution
• Maximum Unambiguous Range/Velocity

System model
• Single BS used as a monostatic radar.
• Two targets being detected.
• No clutter and no interference was assumed.

Radar receiver

**Simulation Parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Band</strong></td>
<td>Sub-6GHz</td>
</tr>
<tr>
<td><strong>MonteCarlo No</strong></td>
<td>1000</td>
</tr>
<tr>
<td>$f_c$ (MHz)</td>
<td>3500 28000</td>
</tr>
<tr>
<td>$\Delta f$ (kHz)</td>
<td>{15, 30, 60} {60, 120}</td>
</tr>
<tr>
<td><strong>OFDM Numerology</strong></td>
<td>3GPP 38.211</td>
</tr>
<tr>
<td><strong>Field Dimensions</strong>*</td>
<td>$35 \leq R \leq 200$ (m), $-30^\circ \leq \theta \leq 30^\circ$</td>
</tr>
<tr>
<td><strong>AP Position</strong></td>
<td>$(X, Y) = (0, 0), h = 7m$</td>
</tr>
<tr>
<td><strong>AP antenna gain (dBi)</strong></td>
<td>17.5 24</td>
</tr>
<tr>
<td><strong>Channel model</strong></td>
<td>LOS Channel (open field)</td>
</tr>
<tr>
<td><strong>Noise power (dBm)</strong></td>
<td>$-174 + 10 \log_{10}(\Delta f N_{sc}) + 7$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Radar type</strong></td>
<td>OFDM Radar (QPSK)</td>
</tr>
<tr>
<td><strong>Total BS power</strong></td>
<td>43dBm</td>
</tr>
<tr>
<td>$P_{sensing}$</td>
<td>0.1</td>
</tr>
<tr>
<td><strong>Detection method</strong></td>
<td>Periodogram + peak detection</td>
</tr>
<tr>
<td><strong>No. of targets</strong></td>
<td>2</td>
</tr>
<tr>
<td><strong>Target max velocity</strong>**</td>
<td>$\min(150 \text{kph}, v_{IC}, v_{mig})$</td>
</tr>
<tr>
<td><strong>Target RCS</strong></td>
<td>$1m^2$</td>
</tr>
</tbody>
</table>

**Range Resolution Estimation**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_{subcarriers}$</td>
<td>{25 50 100: 100: 3300}</td>
</tr>
<tr>
<td><strong>Measurement duration</strong></td>
<td>1 slot ($N_{sym}$ symbols)</td>
</tr>
<tr>
<td>FFT size</td>
<td>$4N_{subcarriers}$</td>
</tr>
</tbody>
</table>

**Velocity Resolution Estimation**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_{sc}$</td>
<td>120 (10 Resource Blocks)</td>
</tr>
<tr>
<td><strong>Measurement duration</strong></td>
<td>{5 10 15 20 25: 25: 500} OFDM symbols</td>
</tr>
<tr>
<td>FFT size</td>
<td>$4N_{OFDM\text{symbols}}$</td>
</tr>
</tbody>
</table>

\* $R \geq d_{ISI} = \frac{cT_{CP}}{2}$ was not considered.

\*\* $v_{IC} = \frac{(0.1S\text{CS})c}{2f_c}$, $v_{mig} = \frac{c}{4N_{sc}N_{OFDM\text{sym}}\Delta f_{sym}}$
With lower subcarrier spacing, we need higher number of subcarriers to achieve the desired range resolution. To achieve $\Delta r = 1 \text{ m}$, $BW = 150 \text{ MHz}$ is needed.

FR2 spectrum band is better than FR1 for stringent range resolution scenarios.
• With lower subcarrier spacing, higher number of OFDM symbols are need to achieve the desired velocity resolution.
# Maximum Unambiguous Velocity and Range

**Table 1:** Maximum unambiguous range for different numerologies.

<table>
<thead>
<tr>
<th>Band</th>
<th>$\Delta f$ (kHz)</th>
<th>$T_{CP}$ (μs)</th>
<th>$R_{max}$ (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FR1</td>
<td>15</td>
<td>4.7</td>
<td>700</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>2.3</td>
<td>345</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>1.2</td>
<td>180</td>
</tr>
<tr>
<td></td>
<td>60 (Ext. CP)</td>
<td>4.1</td>
<td>620</td>
</tr>
<tr>
<td>FR2</td>
<td>60</td>
<td>1.2</td>
<td>180</td>
</tr>
<tr>
<td></td>
<td>120</td>
<td>0.6</td>
<td>90</td>
</tr>
</tbody>
</table>

**Table 2:** Maximum unambiguous velocity for different numerologies.

<table>
<thead>
<tr>
<th>Band</th>
<th>$\Delta f$ (kHz)</th>
<th>$f_{D,max}$ (Hz)</th>
<th>$\Delta f/f_c$</th>
<th>$v_{max}$ (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FR1</td>
<td>15</td>
<td>1500</td>
<td>$4.3e-6$</td>
<td>64</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>3000</td>
<td>$8.6e-6$</td>
<td>129</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>6000</td>
<td>$17.1e-6$</td>
<td>257</td>
</tr>
<tr>
<td>FR2</td>
<td>60</td>
<td>6000</td>
<td>$2.1e-6$</td>
<td>32</td>
</tr>
<tr>
<td></td>
<td>120</td>
<td>12000</td>
<td>$4.3e-6$</td>
<td>64</td>
</tr>
</tbody>
</table>
Monostatic sensing: challenges

• In passive sensing there are some challenges to address

1. There is a bias in the estimation due to the multipath components.

2. The accuracy of the measurements depend on the number of non-line-of-sight components.

3. It is challenging to distinguish between multiple targets and “false” targets created by multipath.

• One possible solution is by taking advantage of the network densification in 6G and using multiple BSs cooperatively, where each BS acts as a monostatic radar, building the called multi-monostatic sensing.
System Model

- **K base stations**
  - All synchronized
  - Connected to a Central Processing Unit (CPU)

- **OFDM waveform under 5G NR**
  - M OFDM symbols
  - N active subcarriers

- Single target moving throughout the street

- Distance and position estimation
Monostatic Sensing: Channel Model

- Ray Tracing MATLAB simulator
- Section of Berlin (.osm file):
  - Red: BS
  - Blue: Target
- The number of reflections ($N_R$) can be set.
  - Figure 2: $N_R \leq 1$

Fig. 3: Ray Tracing Simulator
Monostatic Sensing: Periodogram

- Periodogram algorithm used to estimate distance:

\[ A(n, m) = \left| \sum_{r=0}^{N'-1} \sum_{l=0}^{M'-1} (D_{r,l} e^{-j2\pi l m/M'}) e^{j2\pi r n/N'} \right| \]

- Estimated distance and speed are given by:

\[
\hat{d} = \frac{\hat{\n} c_0}{2 \Delta f N'}, \quad \hat{v} = \frac{\hat{\n} c_0}{2 f_C T M'}
\]

where \( \hat{n}, \hat{m} \) are estimated as:

\[
(\hat{n}, \hat{m}) = \arg \max_{n, m} A(n, m)
\]

\begin{itemize}
  \item \( D_{r,l} \): Received signal after zero-forcing
  \item \( M' \geq M \) (M OFDM symbols)
  \item \( N' \geq N \) (N active subcarriers)
  \item \( \Delta f \): Subcarrier spacing
  \item \( f_C \): Carrier frequency
  \item \( T \): Overall OFDM symbol duration
\end{itemize}
Monostatic Sensing: Effect of Multipath

Fig. 4: Delay profile comparison between a LOS-only and a multipath-rich environment

- From the figure, the error $|\hat{d} - d^*|$ increases for multipath-rich environment, where
  - $\hat{d}$ is the estimated distance
  - $d^*$ is the true distance

- The more paths considered, the more difficult to detect the real target.
Multi-monostatic Sensing [2]

- K base stations
  - All synchronized
  - Connected to a Central Processing Unit (CPU)

- Each BS estimate the distance

- A fusion method is run in a CPU:
  - The estimated distances $\hat{d}_k$ are fused.
  - The position of the target $x$ is obtained.

- Three fusion algorithms are studied:
  - Maximum Likelihood
  - Maximum A Posteriori
  - Non-linear Least Square

Multi-monostatic Sensing: Fusion Algorithms

- Maximum Likelihood (ML)
  \[
  \hat{x}_{\text{LL}} = \arg\max_x \sum_{k \in \mathcal{K}} w_k \cdot \ln \left( \frac{1}{\sqrt{2\pi}} \cdot \exp \left( -\frac{(d_k - |x_k - x|)^2}{2\sigma_k^2} \right) \right) = \arg\max_x \sum_{k \in \mathcal{K}} w_k \cdot \ln(p_k(x))
  \]

- Maximum a Posteriori (MAP)
  \[
  \hat{x}_{\text{MAP}} = \arg\max_x \sum_{k \in \mathcal{K}} w_k \left[ \ln(p_k(x)) + \ln \left( \frac{1}{|x - x_k| + \epsilon} \right) \right]
  \]

- Non-linear Least Square (NLLS)
  \[
  \hat{x}_{\text{NLLS}} = \arg\min_x \sum_{k \in \mathcal{K}} w_k \left( d_k - |x_k - x| \right)^2
  \]
  - \(\sigma_k^2\): Gaussian component of the k-th BS.
  - \(w_k\): weight for the k-th BS.
  - \(d_k\): estimated distance of the k-th BS.
Multi-monostatic Sensing: Fusion

- The parameters are estimated by doing a Gaussian fit over the periodogram output:
  - The mean is used for $\hat{d}_k$
  - The variance is used for $\sigma_k^2$
  - The amplitude is used for $w_k$
## Simulation Parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bandwidth</td>
<td>20 and 100 MHz</td>
</tr>
<tr>
<td>Carrier Frequency</td>
<td>3.5 GHz</td>
</tr>
<tr>
<td>Radar Transmit Power</td>
<td>$p_T = 23$ dBm</td>
</tr>
<tr>
<td>Antennas (Rx, Tx)</td>
<td>Omnidirectional</td>
</tr>
<tr>
<td>SCS</td>
<td>30 kHz</td>
</tr>
<tr>
<td>Vehicle speed</td>
<td>$\approx 50$ km/h</td>
</tr>
<tr>
<td>Number of subcarriers</td>
<td>666 and 3333</td>
</tr>
<tr>
<td>Number of Symbols</td>
<td>500 ($\approx$2 frames)</td>
</tr>
<tr>
<td>Number of BSs</td>
<td>Up to 3</td>
</tr>
<tr>
<td>Vehicle height</td>
<td>1 m</td>
</tr>
<tr>
<td>Target RCS</td>
<td>7 dBsm</td>
</tr>
</tbody>
</table>

- Range resolution: 1.5 m
- Velocity resolution: 2.4 m/s
Results: 2 BSs Case

- Depending on the BS location, there is different gain in the fusion output.
Results: Comparison of fusion for 2 and 3 BSs

- There is a considerable gain under limited BW.
- However, there is no gain under 100 MHz, as BS3 is not giving accurate estimates due to multipath.
Findings

- Multi-monostatic sensing increases the accuracy of the estimation by combining the individual estimates of each BSs.

- Increasing the BW leads to less accuracy error in distance and positioning error.

- Under low resolution, the fusion of BSs' estimates can result in higher accuracy.

- Under higher resolution, the gain in the accuracy is dependent on the location of the BSs, where based on the multipath condition, each BS contributes more or less to the fusion gain.
Monostatic Sensing: Effect of Multipath (ToA + AoA)

- Adding an antenna array gives the AoA information.

- We use a uniform rectangular array of 8x8 antennas with FoV of $[-60^\circ, 60^\circ]$.
  - Beamwidth of 12°
  - Gain of 22 dBi

- We can do beam scanning to sense the entire environment.

- By performing the periodogram on each angle of the beam scanning phase, we can estimate the position of the target (figure 4).

![Figure 4: Periodogram map of distance and angle information.](image)
Monostatic Sensing: Effect of Multipath (ToA + AoA)

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- We use a uniform rectangular array of 8x8 antennas with FoV of $[-60^\circ, 60^\circ]$.
  - Beamwidth of $12^\circ$
  - Gain of 22 dBi
- We can do beam scanning to sense the entire environment.
- By performing the periodogram on each angle of the beam scanning phase, we can estimate the position of the target (figure 4).

- How do we know which peak correspond to a target or is it just multipath?

Figure 4: Periodogram map of distance and angle information.
Monostatic Sensing: Effect of Multipath (ToA + AoA)

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  - Beamwidth of $12^\circ$
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- We can do beam scanning to sense the entire environment.

- By performing the periodogram on each angle of the beam scanning phase, we can estimate the position of the target (figure 4).

- Is the current peak selection method used still valid?

---

Figure 4: Periodogram map of distance and angle information.
Monostatic Sensing: Effect of Multipath (ToA + AoA)

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• By performing the periodogram on each angle of the beam scanning phase, we can estimate the position of the target (figure 4).

Figure 4: Periodogram map of distance and angle information.
Scenario and Proposed Algorithm

- In order to estimate the target and overcome multipath, a 3-stage algorithm is proposed:

BS level

1. Beamforming Stage of i-th BS
   - $i \in [1, 2, 3]$
   - Estimated peaks of each BS

2. Pruning Stage
   - Feasible peaks

CPU level

3. Classification Stage
   - Number of targets
   - Peaks related to a target

Figure 6: Scenario for the simulations. The three BSs build a convex-hull for the sensing coverage, given by the field of view of the antenna arrays.
Scenario and Proposed Algorithm

• In order to estimate the target and overcome multipath, a 3-stage algorithm is proposed:

1. Beamforming Stage
   - Each BS sense the environment over a range of $[\theta_{\text{min}}, \theta_{\text{max}}]$ and computes the periodogram for each angle step.
   - All the peaks found on the map (AoA - Range) are shared to a CPU.

2. Pruning Stage
   - All infeasible peaks are removed from the map.

3. Classification Stage
   - All the peaks are classified and assigned.
   - The number of targets is estimated.

Figure 6: Scenario for the simulations. The three BSs build a convex-hull for the sensing coverage, given by the field of view of the antenna arrays.
## Simulation Parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bandwidth</td>
<td>100 MHz</td>
</tr>
<tr>
<td>Carrier Frequency</td>
<td>3.5 GHz</td>
</tr>
<tr>
<td>Transmit Power</td>
<td>$P_T = 49$ dBm</td>
</tr>
<tr>
<td>Antennas (Rx, Tx)</td>
<td>URA 8x8</td>
</tr>
<tr>
<td>Field of View</td>
<td>$[-60^\circ, 60^\circ]$</td>
</tr>
<tr>
<td>SCS</td>
<td>30 kHz</td>
</tr>
<tr>
<td>Number of BSs</td>
<td>Up to 3</td>
</tr>
<tr>
<td>Target height</td>
<td>1 m</td>
</tr>
<tr>
<td>Target RCS</td>
<td>7 dBsm</td>
</tr>
</tbody>
</table>

Figure 7: Scenario for the simulations. Vincent Square, London, is used.
Beamforming Phase

- Each BS perform a beam scanning.
- At each AoA, the periodogram is compute.
- All the peaks above a threshold are sent to the CPU.
- The CPU map all the peaks to the absolute positions.
Pruning Phase

- The CPU removes all the peaks that are outside of the convex hull.
Classification Phase

• The CPU uses DBSCAN in order to classify the peaks.

• The cluster are defined as a set of 3 points.

• The separation of the peaks is up to 5 m

• DBSCAN gives the number of targets and the clusters.
Future work and open questions

• How can we combine the estimates of AoA and ToA in order to enhance the estimation accuracy?

• How fast the beam scanning phase needs to be so that all BSs can see the same target in the same position?

• Will these approach work for multiple object detection?
Radio Positioning in 6G Communication Systems

Cooperative Multi-Monostatic Sensing

Prof. Marina Petrova

May 2, 2024
Vielen Dank
für Ihre Aufmerksamkeit