

# Successive Pose Estimation and Beam Tracking for mmWave Vehicular Communication Systems

WS01: 4th Workshop on Emerging Topics in 6G Communications

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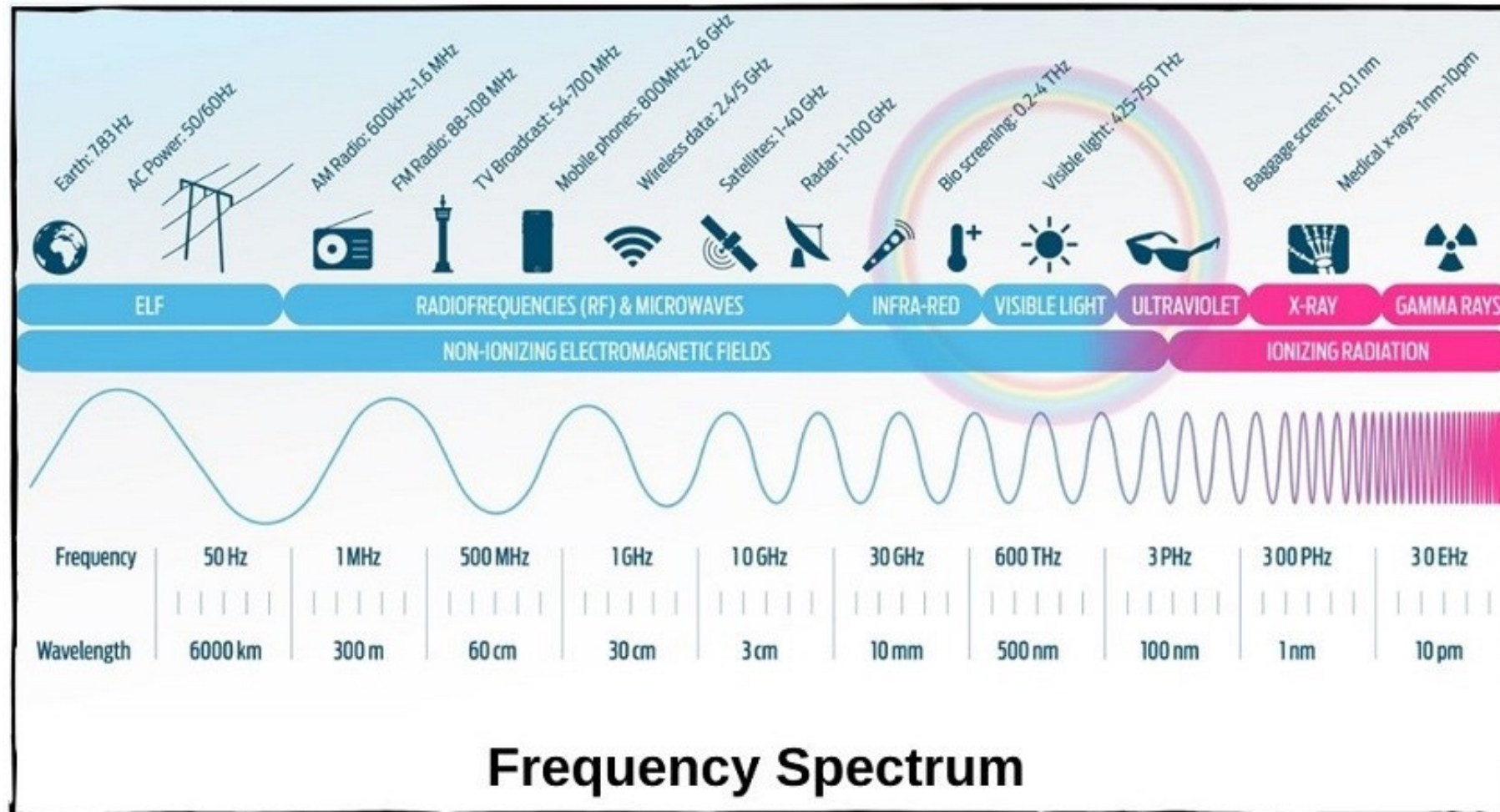


# Outline

- **I. Introduction**
- II. mmWave Sensing & Communications Model
- III. Successive Pose Estimation and Beam Tracking (SPEBT)
- IV. Simulations and Conclusions

# I. Background

- mmWave for both **Sensing**  and **Communications** 



# I. Background

- mmWave Communications: **MIMO Beamforming**

**High Mobility Vehicular Communications**

- Beam Training Overhead → Solution: **Beam Tracking**

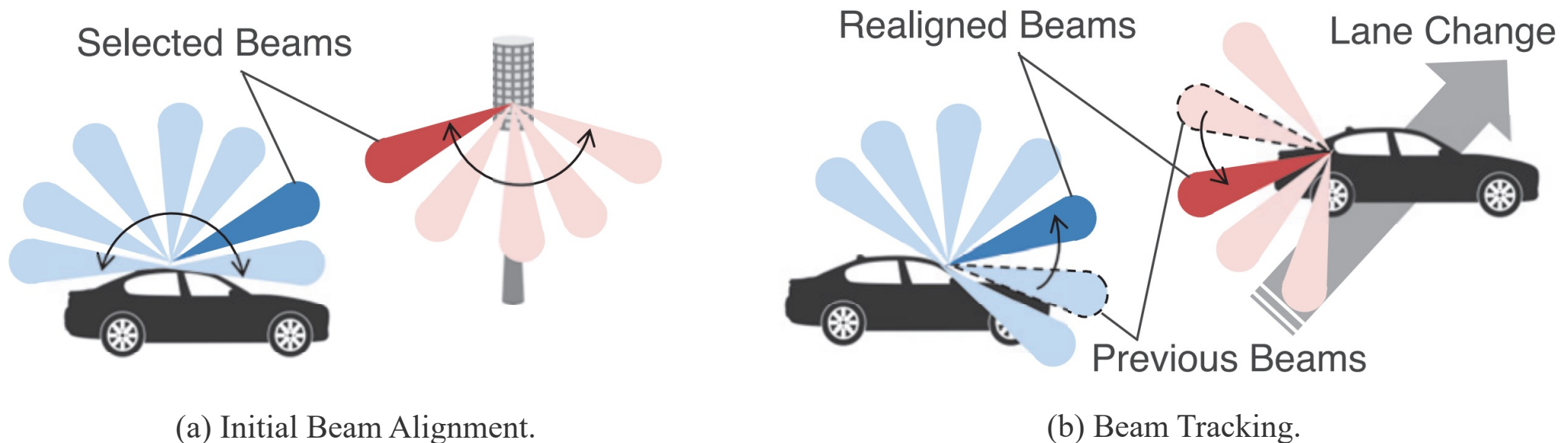


Fig. 1. Overview of mmWave V2X beam management <sup>[1]</sup>.

# I. Motivation

- mmWave Radar Sensing → Pose Estimation → mmWave Communications

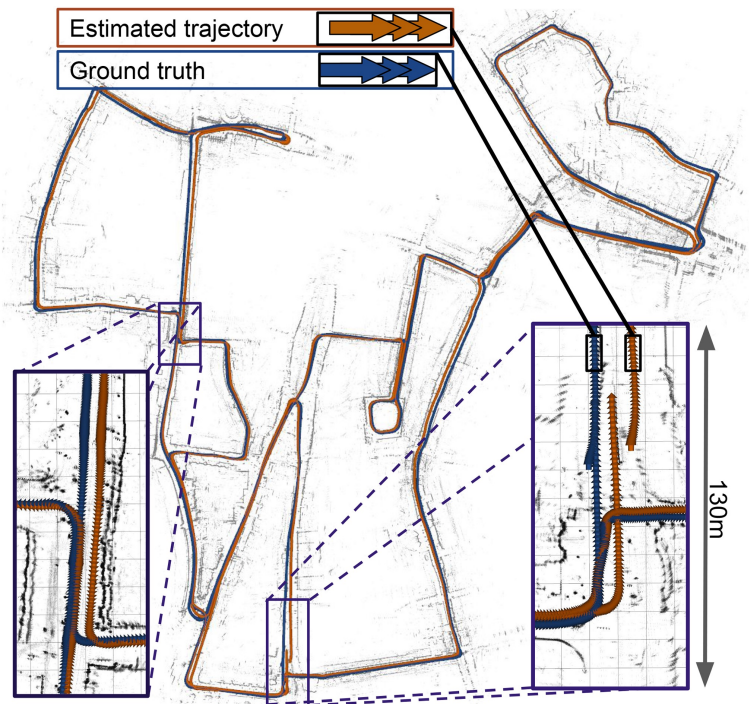


Fig. 2. Pose Estimation via mmWave Radar [2].

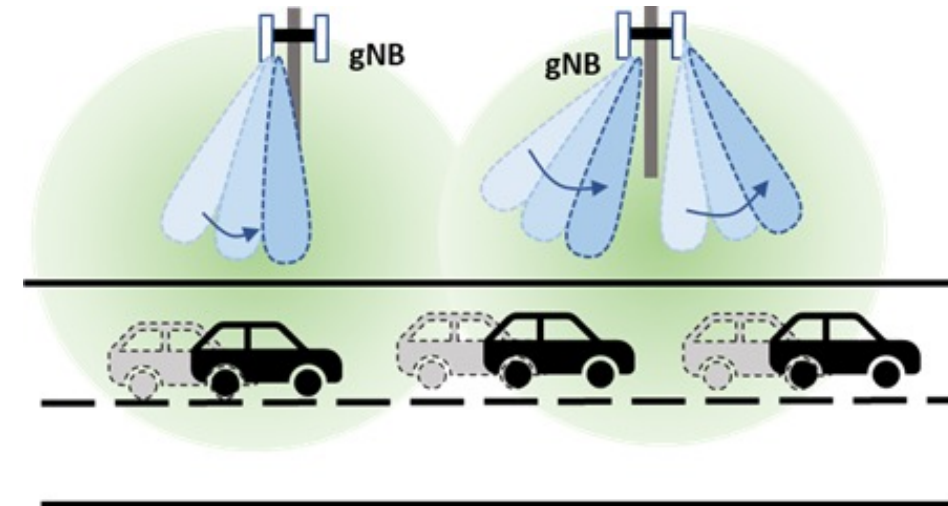


Fig. 3. mmWave Vehicular Communications.

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# II. System Model

## • Communications Model

$$z_k = \mathbf{g}_k^H \mathbf{H}_k \mathbf{f}_k b_k + v_k$$

$$\mathbf{H}_k \triangleq \mathbf{G}_k^{\text{LoS}} = \alpha_k \mathbf{a}_r(\psi_k) \mathbf{a}_t^H(\phi_k)$$

$$\mathbf{a}_t(\phi) = \frac{1}{\sqrt{N}} \left[ 1, e^{-j \frac{2\pi d}{\lambda} \cos \phi}, \dots, e^{-j(N-1) \frac{2\pi d}{\lambda} \cos \phi} \right]^T$$

$$\mathbf{a}_r(\psi) = \frac{1}{\sqrt{M}} \left[ 1, e^{-j \frac{2\pi d}{\lambda} \cos \psi}, \dots, e^{-j(M-1) \frac{2\pi d}{\lambda} \cos \psi} \right]^T$$

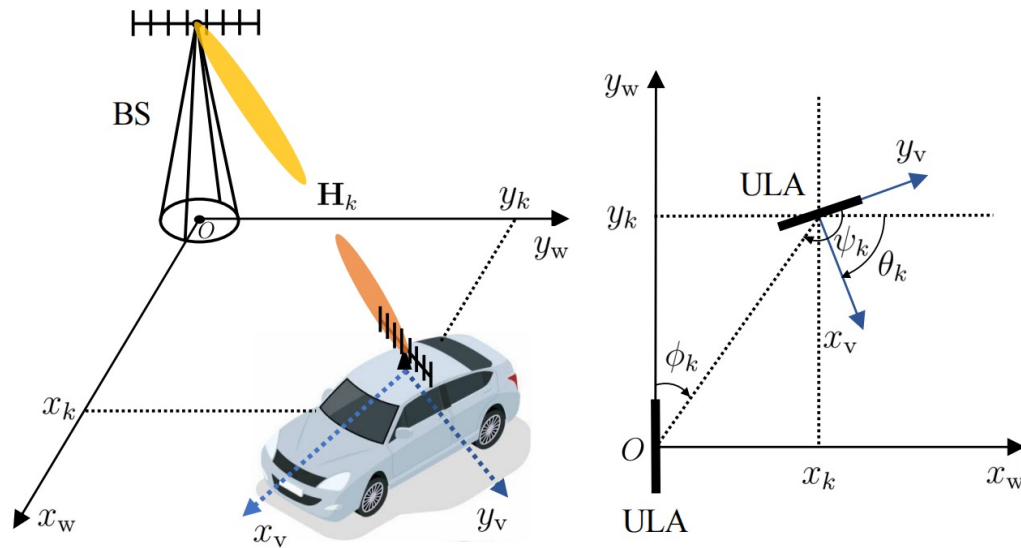


Fig. 4. 3D view and 2D bird's eye view of MIMO system.

## • Sensing Model

- Emit mmWave and detect reflected powers. By processing the collected radar point cloud, estimate the vehicle pose:

**AoD:  $\phi$**   
**AoA:  $\psi$**

**Position:  $(\hat{x}, \hat{y})$**   
**Yaw:  $\hat{\theta}$**

*mmWave  
FMCW  
Radar*

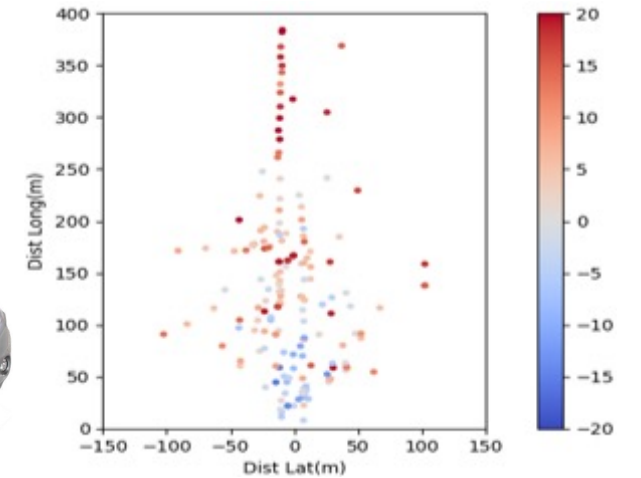


Fig. 5. mmWave vehicular sensing platform<sup>[3]</sup> and radar point cloud.

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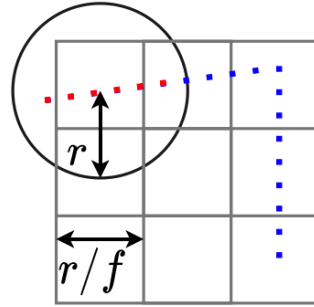


# III. SPEBT

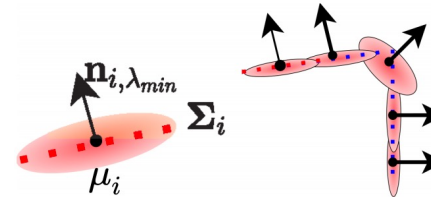
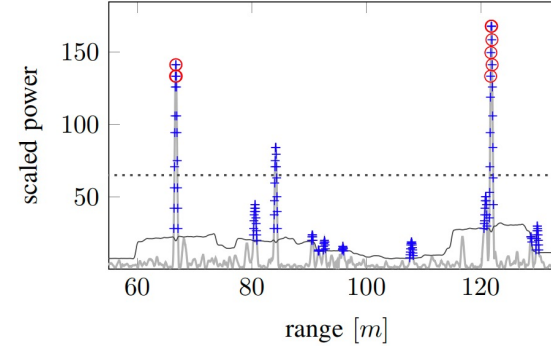
## *Fast -CFEAR<sup>1</sup>*

- $K$ -Strongest Conservative Filtering

- Downsampling



- Estimating Oriented Surface Points



- Point Cloud Registration

$$\begin{aligned} & \min_{\mathbf{T}_k} f_{\text{P2L}}(\mathbf{T}_k | \mathbf{T}_{k-1}, \mathcal{M}_{k-1}, \mathcal{M}_k) \\ \Leftrightarrow & \min_{\mathbf{r}_k, \theta_k} \sum_{\forall i \in \mathcal{M}_k} \mathcal{L}_\delta(\mathbf{n}_j^\top (\Delta \mathbf{R}_k \boldsymbol{\mu}_i + \Delta \mathbf{r}_k - \boldsymbol{\mu}_j)) \end{aligned}$$

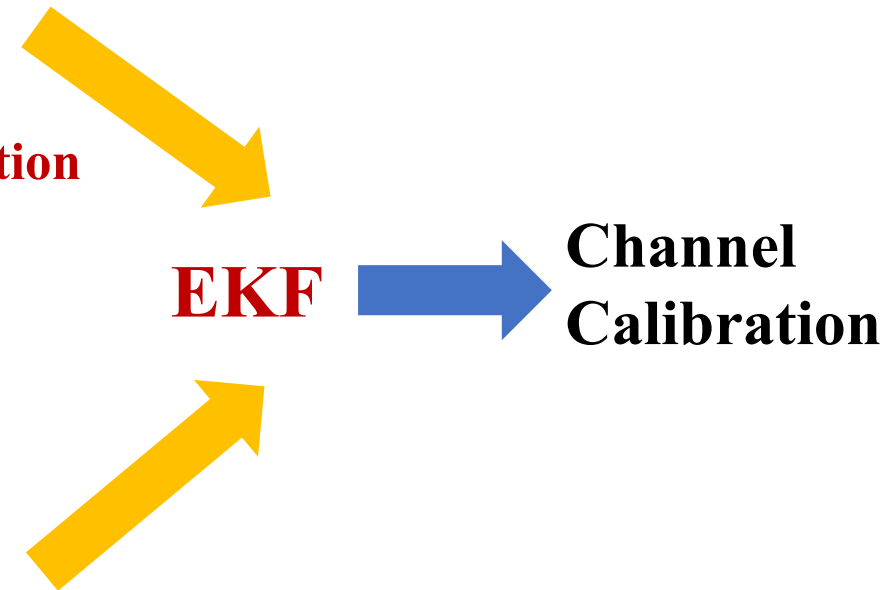
## *EKF<sup>2</sup>-based Beam Tracking*

- State Evolution Model:

- Channel state vector:  $\mathbf{s}_k = [|\alpha_k|, \arg \alpha_k, \phi_k, \psi_k]^T$
- Channel state evolution model:  $\mathbf{s}_k \approx \hat{\mathbf{F}}_k \mathbf{s}_{k-1} + \hat{\mathbf{u}}_k + \mathbf{w}_k$ 
  - $\mathbf{F}$ : evolution matrix
  - $\mathbf{u}$ : control input  $\longrightarrow$  **Modelled by the pose estimation**
  - $\mathbf{w}$ : Gaussian process noise

- Measurement Model:

- Pilot symbol  $b_k$  (from BS to vehicle)
- Channel measurement model:  $z_k = h(\mathbf{s}_k) + v_k$ 
  - $h(\cdot)$ : channel measurement function
  - $v$ : Gaussian measurement noise



# III. SPEBT

## • SPEBT Scheme

- Considering phase information is inessential and hard to be evaluated by pose estimation, adjust the channel state vector by excluding  $\arg(\alpha_k)$ . Change the channel measurement model from complexed-valued to real-valued for the ease of deploying EKF algorithm.
- To guarantee the accuracy and timeliness of the tracked channel, the algorithm should re-initialize the channel state vector once the deviation between the tracked channel and the initial channel are greater than the given thresholds.

### Algorithm 1 The Proposed SPEBT Scheme

```

1: input:  $\mathbf{r}_0, \theta_0, \mathcal{M}_0$ 
2: output:  $\bar{\mathbf{s}}_{k|k} = [|\alpha_k|, \phi_k, \psi_k]^\top$ 
3: initialization: Set timeslot  $k = 0$ . Initialize channel state vector  $\bar{\mathbf{s}}_1$  via mmWave initial access techniques. Set  $\bar{\mathbf{s}}_{0|0} = \bar{\mathbf{s}}_1$  and  $\mathbf{P}_{0|0} = \bar{\mathbf{Q}}_0$ . Set thresholds  $\tilde{\alpha}, \tilde{\phi}, \tilde{\psi} > 0$ .
4: repeat  $k \leftarrow k + 1$ 
    // Fast-CFEAR Based Pose Estimation
5:   The latest radar point cloud is available at timeslot  $k$ .
6:   Obtain a sparse representation  $\mathcal{M}_k$  by performing the first three stages of Fast-CFEAR approach.
7:   Estimate the vehicle pose  $(\hat{\mathbf{r}}_k, \hat{\theta}_k)$  via point cloud registration.
    // EKF Based Beam Tracking
8:   Beam tracking via configuring the analog precoder  $\mathbf{f}_k = \mathbf{a}_t(\phi_{k-1})$  and the analog combiner  $\mathbf{g}_k = \mathbf{a}_r(\psi_{k-1})$ 
    - Channel Prediction Stage:
9:   A Priori Channel State Vector:
 $\bar{\mathbf{s}}_{k|k-1} = \bar{\mathbf{F}}_k \bar{\mathbf{s}}_{k-1|k-1} + \bar{\mathbf{u}}_k$ 
10:  A Priori Channel Covariance Matrix:
 $\mathbf{P}_{k|k-1} = \bar{\mathbf{F}}_k \mathbf{P}_{k-1|k-1} \bar{\mathbf{F}}_k^\top + \bar{\mathbf{Q}}_k$ 
    - Channel Update Stage:
11:  Kalman Gain:
 $\mathbf{K}_k = \frac{\mathbf{P}_{k|k-1} \nabla \bar{h}(\bar{\mathbf{s}}_{k|k-1})}{\nabla^\top \bar{h}(\bar{\mathbf{s}}_{k|k-1}) \mathbf{P}_{k|k-1} \nabla \bar{h}(\bar{\mathbf{s}}_{k|k-1}) + \sigma_{\bar{v}_k}^2}$ 
12:  A Posteriori Channel State Vector:
 $\bar{\mathbf{s}}_{k|k} = \bar{\mathbf{s}}_{k|k-1} + \mathbf{K}_k (\bar{z}_k - \nabla \bar{h}(\bar{\mathbf{s}}_{k|k-1}) \bar{\mathbf{s}}_{k|k-1})$ 
13:  A Posteriori Channel Covariance Matrix:
 $\mathbf{P}_{k|k} = (\mathbf{I} - \mathbf{K}_k \nabla \bar{h}(\bar{\mathbf{s}}_{k|k-1})) \mathbf{P}_{k|k-1}$ 
    - Deviation Checking for Re-initialization:
14:  if  $||\alpha_k| - |\alpha_1|| > \tilde{\alpha}$  or  $|\phi_k - \phi_1| > \tilde{\phi}$  or  $|\psi_k - \psi_1| > \tilde{\psi}$ 
15:    Re-initialize  $\bar{\mathbf{s}}_1$  and set  $\bar{\mathbf{s}}_{k|k} = \bar{\mathbf{s}}_1$ .
16:  end
17: until The vehicle arrives at destination.

```

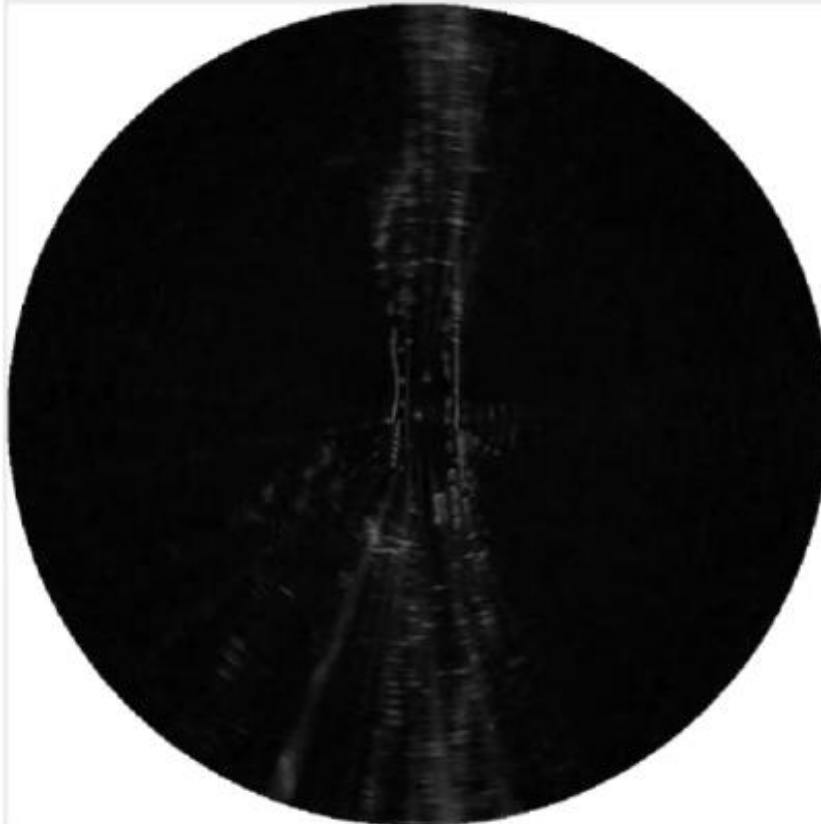
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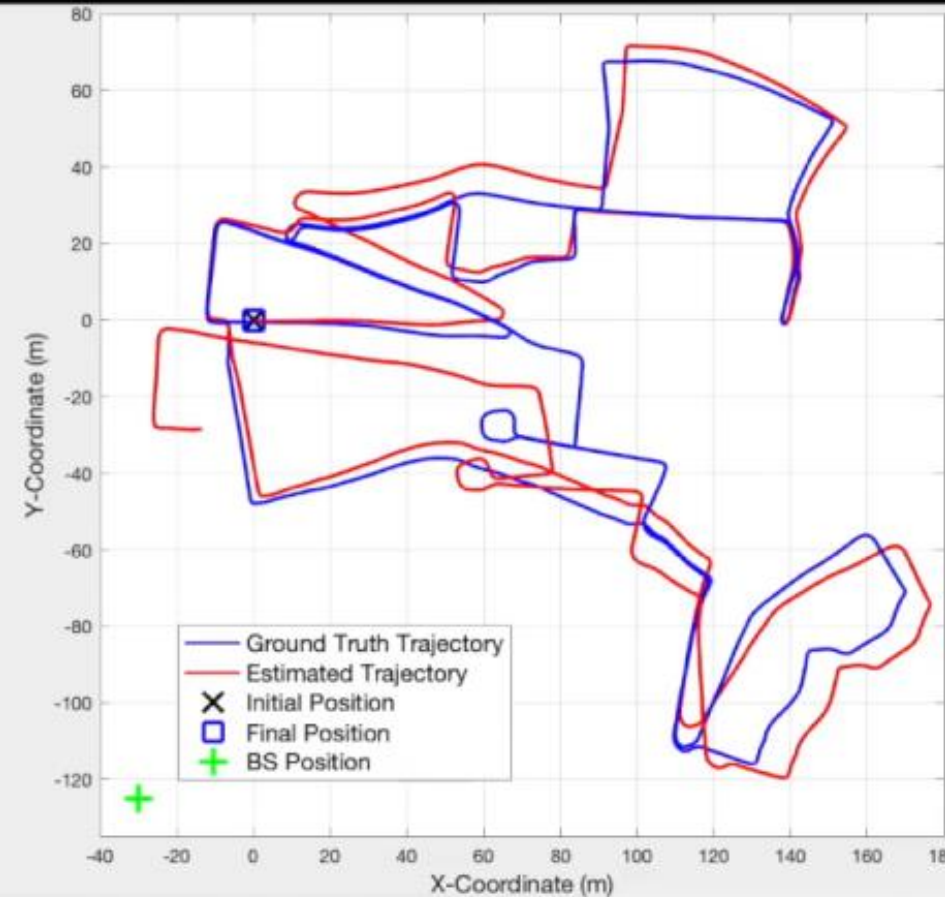
# IV. Simulations



mmWave Radar Point Cloud



Moving Trajectory



**Successive Pose Estimation and Beam Tracking for mmWave Vehicular Communication Systems**  
*Gen Liu, Guangxu Zhu, Fan Liu, Yuanwei Liu and Kaibin Huang*

- Dataset: Oxford Radar RobotCar dataset. Sequence: 2019-01-15-14-24-38. Sensor: Navtech CTS350-X mmWave FMCW radar.
- Implemented by C++ in Visual Studio 2022 and visualized in MATLAB R2023a.

# IV. Simulations

## • Pose Estimation Performance

TABLE I. Simulation Parameters.

Pose Estimation Subsystem	Parameter Value
Selected sensing range	5m ~ 100m
$K$ -strongest filtering	$K = 3$
Pixel value threshold (integer: 0 ~ 255)	$\kappa_{\min} = 55$
Side length of downsampling grid cell	$d_D = 3.5\text{m}$
Resampling factor	$f_D = 1.0$
Angle tolerance	$\Theta = 30^\circ$
Huber loss $\mathcal{L}_\delta$	$\delta = 0.1$

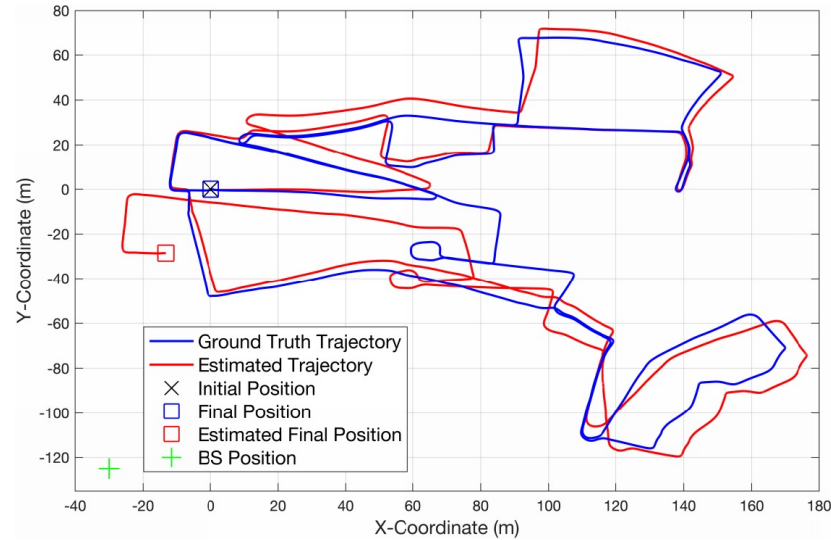


Fig. 6. The estimated vehicle moving trajectory compared to ground truth. Both trajectories are aligned by the initial position marked with  $\times$ , and the final positions are marked with  $\square$ . The position of BS is marked with  $+$ .

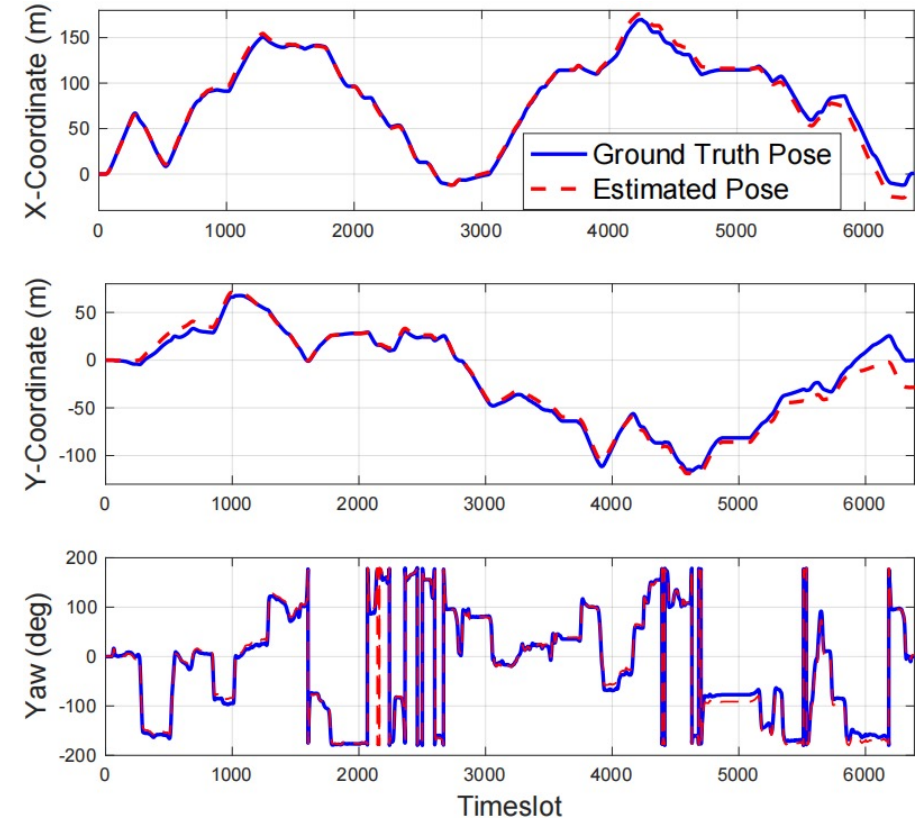


Fig. 7. The estimated pose compared to ground truth pose on coordinate  $(x_k, y_k)$  and yaw  $\theta_k$  against timeslot  $k$ .

\* In order to ensure that our system can work on mmWave radar, the tracking data is appropriately scaled.



# IV. Simulations

## • Beam Tracking Performance

TABLE II. Simulation Parameters.

Beam Tracking Subsystem	Parameter Value
Carrier frequency and wavelength	$f = 50\text{GHz}, \lambda = 6\text{mm}$
Number of transmit/receive antennas	$N = M = 4$
Antenna spacing	$d = \lambda/2$
Path loss exponent	$\gamma = 2.2$
Magnitude of path gain at $d_0 = 1\text{m}$	$ \alpha_{\text{ref}}  = 5 \times 10^{-4}$
Noise power	$\sigma_v^2 = -90\text{dBm}$
Standard deviation of estimation error	$\sigma_r = 1.0\text{m}, \sigma_\theta = 3^\circ$
Channel re-initialization thresholds	$\tilde{\alpha} = 5 \times 10^{-7}$ $\tilde{\phi} = \tilde{\psi} = 7.5^\circ$
Coordinate of vehicle initial position	$(0\text{m}, 0\text{m})$
Coordinate of BS position	$(-30\text{m}, -125\text{m})$

TABLE III. Beam tracking RMSE.

Channel	Path Gain Mag. (%)	AoD (deg)	AoA (deg)
RMSE	1.580	0.220	4.616

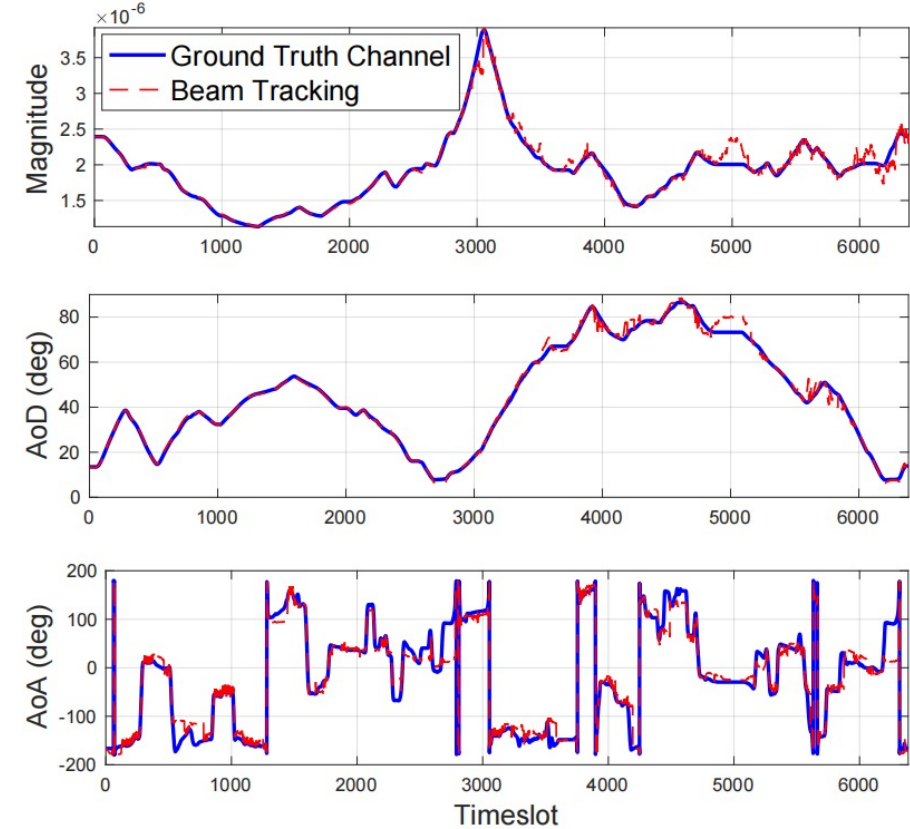


Fig. 8. A beam tracking realization generated by SPEBT scheme compared to ground truth channel on magnitude, AoD and AoA against timeslot  $k$ .

# IV. Conclusions

- We studied the mmWave radar sensing-aided mmWave communications aiming at **reducing beam training overhead** in highly mobile vehicular communication systems.
- A *Successive Pose Estimation and Beam Tracking* (SPEBT) scheme is proposed to achieve this goal, and simulations on an open-source **real-world sensing dataset** are conducted to verify its feasibility and effectiveness.
- A **potential future direction** is to extend the proposed scheme on **3-dimensional (3D)** sensing dataset so as to generate precise 3D pose estimation results and accurate 3D beam tracking output.

# Successive Pose Estimation and Beam Tracking for mmWave Vehicular Communication Systems

- Thanks for listening!
- If you have any questions, kindly contact us via email address [liucen@u.nus.edu](mailto:liucen@u.nus.edu).