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Successive Pose Estimation and Beam Tracking for mmWave Vehicular Communication Systems

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

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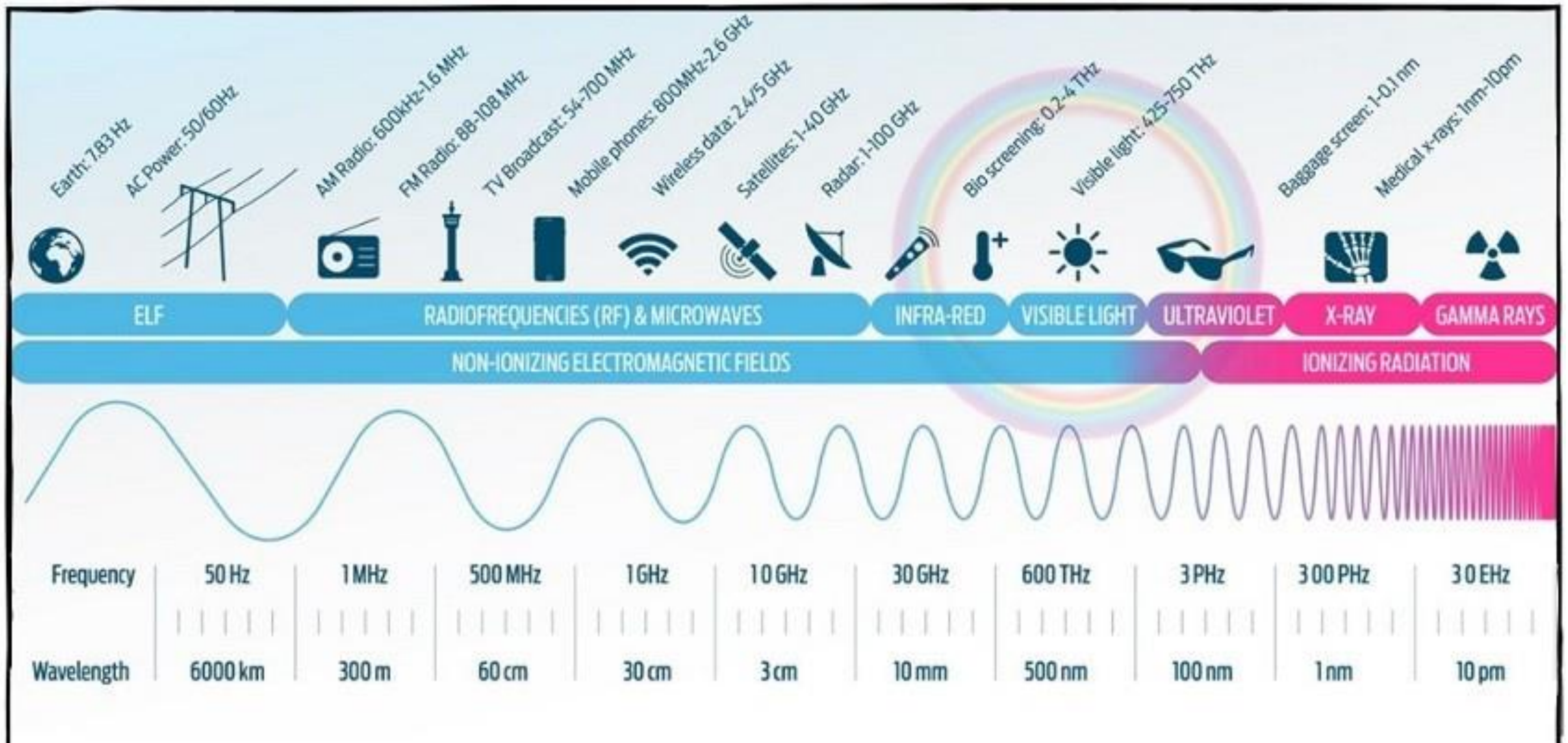
Outline

- 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 



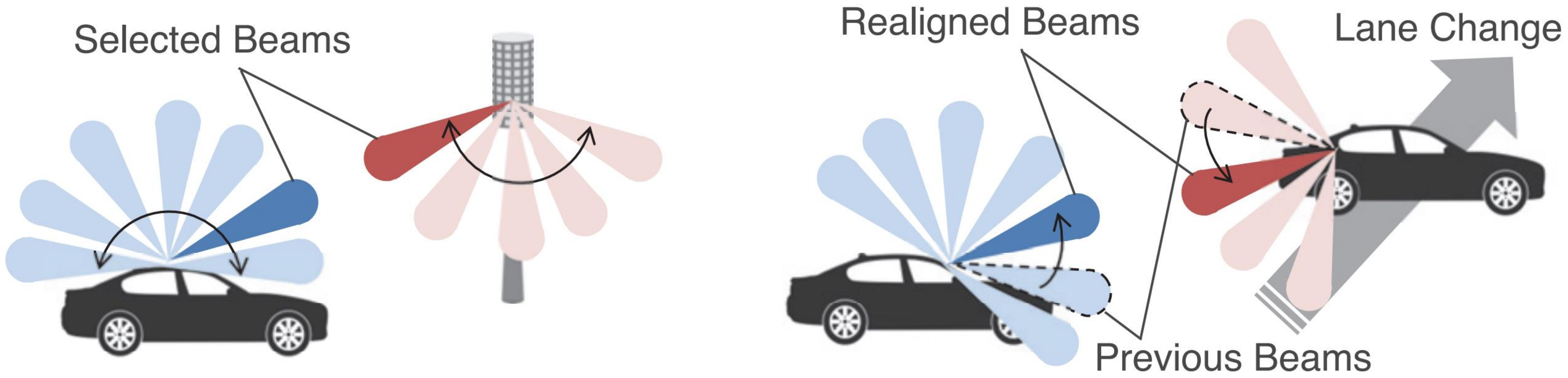
Frequency Spectrum

I. Background

- mmWave Communications: MIMO Beamforming

High Mobility Vehicular Communications

- Beam Training Overhead → Solution: Beam Tracking



(a) Initial Beam Alignment. (b) Beam Tracking.

Fig. 1. Overview of mmWave V2X beam management [1].

[1] T. Shimizu, V. Va, G. Bansal and R. W. Heath, "Millimeter Wave V2X Communications: Use Cases and Design Considerations of Beam Management," 2018 Asia-Pacific Microwave Conference (APMC), Kyoto, Japan, 2018, pp. 183-185.

I. Motivation

- mmWave Radar Sensing → Pose Estimation → mmWave Communications

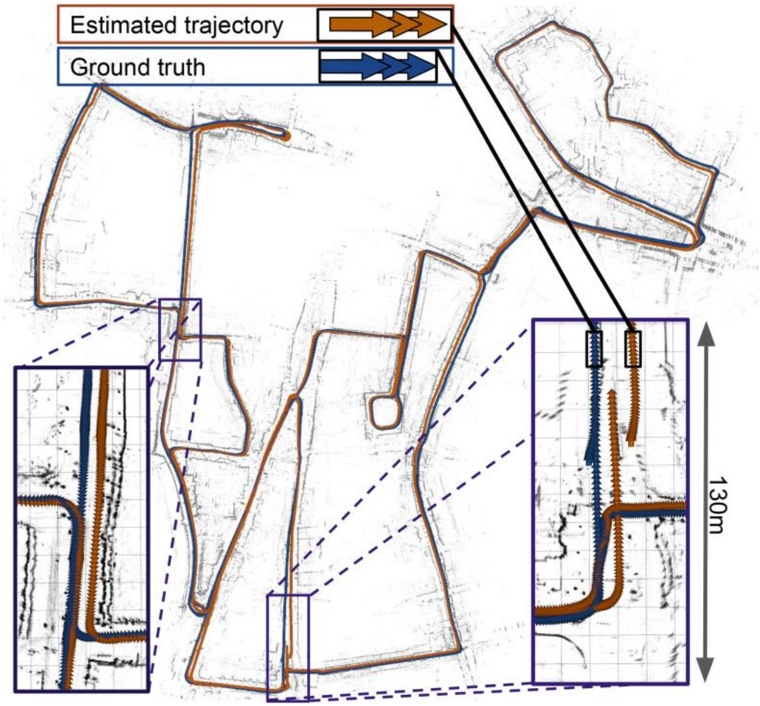


Fig. 2. Pose Estimation via mmWave Radar [2].

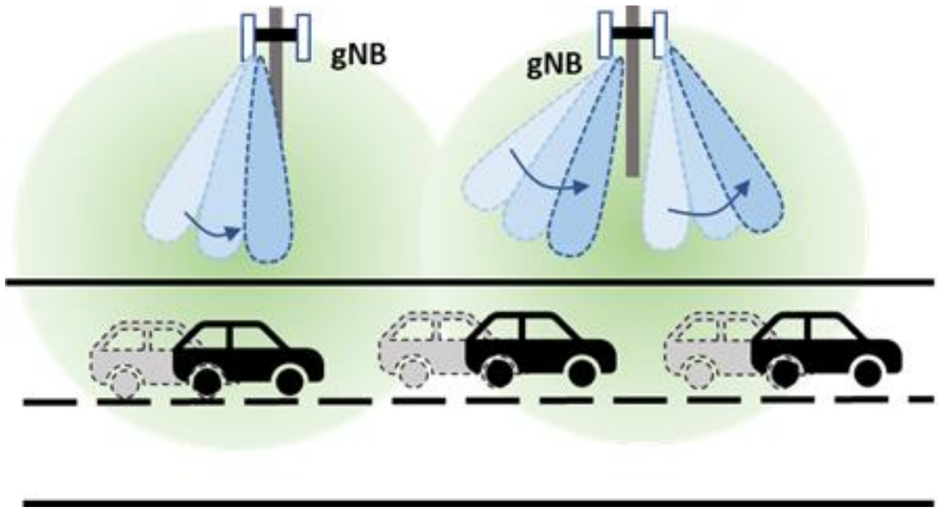


Fig. 3. mmWave Vehicular Communications.

[2] Adolfsson D, Magnusson M, Alhashimi A, et al. Lidar-level localization with radar? The CFEAR approach to accurate, fast, and robust large-scale radar odometry in diverse environments[J]. IEEE Transactions on robotics, 2022, 39(2): 1476-1495.

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II. System Model

- **Communications Model**

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

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

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

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

AoD: $\boldsymbol{\phi}$
AoA: $\boldsymbol{\psi}$

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

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

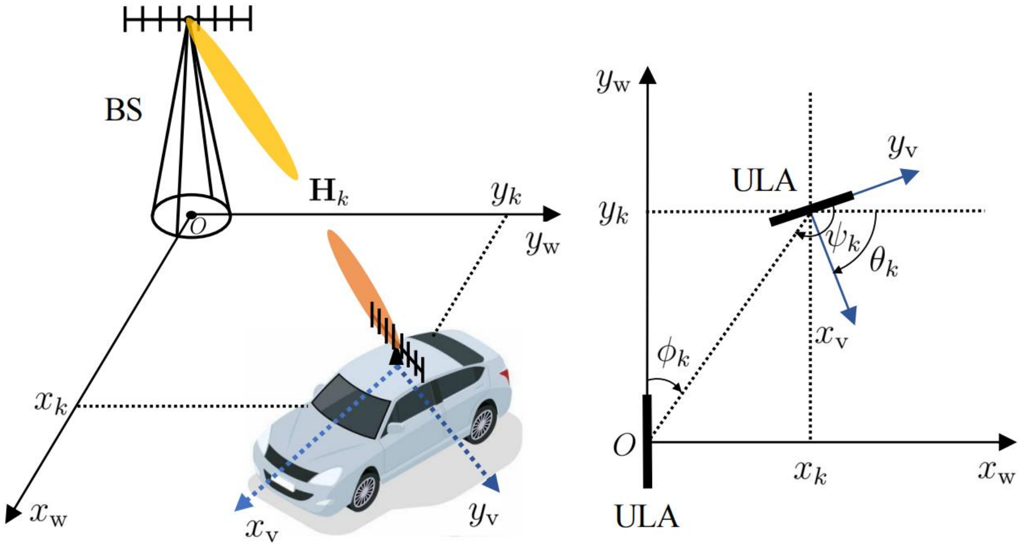

Fig. 4. 3D view and 2D bird's eye view of MIMO system.

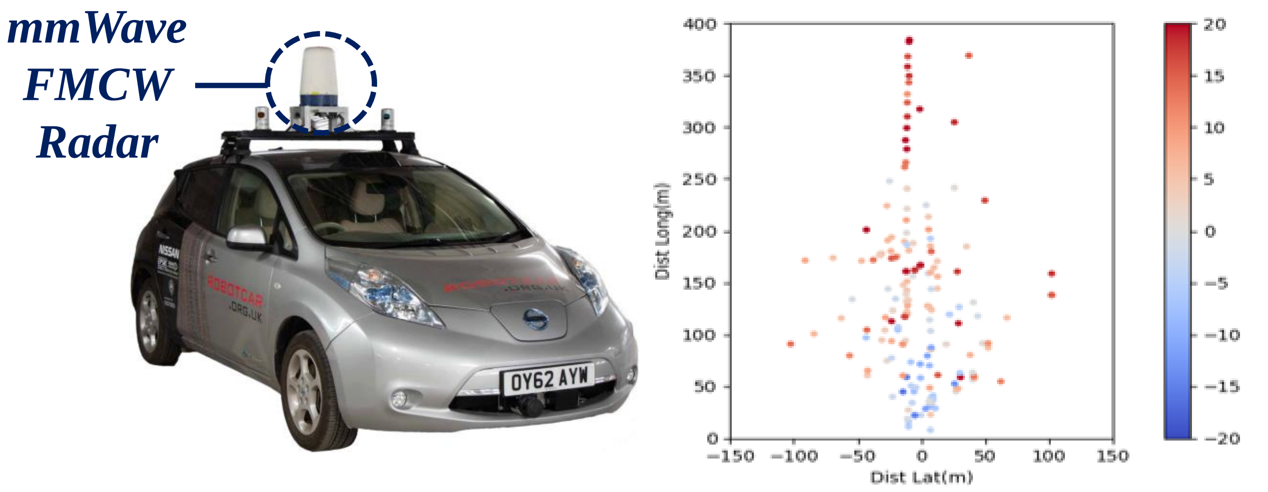

Fig. 5. mmWave vehicular sensing platform [3] and radar point cloud.

[3] D. Barnes, M. Gadd, P. Murcutt, P. Newman and I. Posner, "The Oxford Radar RobotCar Dataset: A Radar Extension to the Oxford RobotCar Dataset," 2020 IEEE International Conference on Robotics and Automation (ICRA), Paris, France, 2020, pp. 6433-6438.

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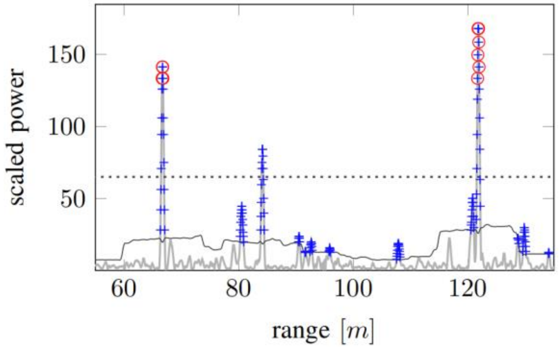
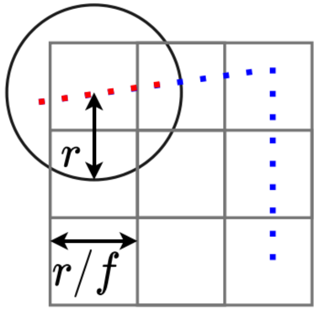
III. SPEBT

Fast –CFEAR [1]

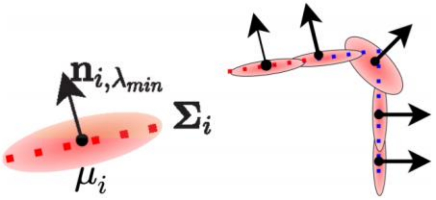
- K-Strongest Conservative Filtering



- Downsampling



- Estimating Oriented Surface Points



- Point Cloud Registration

$$\min_{\mathbf{T}_k} f_{\mathrm{P2L}}(\mathbf{T}_k | \mathbf{T}_{k-1}, \mathcal{M}_{k-1}, \mathcal{M}_k)$$

$$\Leftrightarrow \min_{\mathbf{r}_k, \theta_k} \sum_{\forall i \in \mathcal{M}_k} \mathcal{L}_\delta \left(\mathbf{n}_j^\mathsf{T} \left(\Delta \mathbf{R}_k \boldsymbol{\mu}_i + \Delta \mathbf{r}_k - \boldsymbol{\mu}_j \right) \right)$$

1. Conservative Filtering for Efficient and Accurate Radar odometry

III. SPEBT

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EKF[1]-based Beam Tracking

- State Evolution Model:
  - Channel state vector: $\mathbf{s}_k = \left[|\alpha_k|,\ \arg\alpha_k,\ \phi_k,\ \psi_k\right]^{\mathsf{T}}$
  - Channel state evolution model: $\mathbf{s}_k \approx \hat{\mathbf{F}}_k\mathbf{s}_{k-1} + \hat{\mathbf{u}}_k + \mathbf{w}_k$
    - **F**: evolution matrix
    - ***u***: control input → **Modelled by the pose estimation**
    - ***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

EKF → **Channel Calibration**

1. Extended Kalman Filter

III. SPEBT

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- 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

input: $\mathbf{r}_0,\ \theta_0,\ \mathcal{M}_0$

output: $\bar{\mathbf{s}}_{k|k} = [|\alpha_k|,\ \phi_k,\ \psi_k]^\mathsf{T}$

initialization: Set timeslot $k = 0$. Initialize channel state vector $\bar{\mathbf{s}}_\mathrm{I}$ via mmWave initial access techniques. Set $\bar{\mathbf{s}}_{0|0} = \bar{\mathbf{s}}_\mathrm{I}$ and $\mathbf{P}_{0|0} = \bar{\mathbf{Q}}_0$. Set thresholds $\tilde{\alpha},\ \tilde{\phi},\ \tilde{\psi} > 0$.

repeat $k \leftarrow k+1$

// Fast-CFEAR Based Pose Estimation

The latest radar point cloud is available at timeslot k.

Obtain a sparse representation $\mathcal{M}_k$ by performing the first three stages of Fast-CFEAR approach.

Estimate the vehicle pose $(\hat{\mathbf{r}}_k, \hat{\theta}_k)$ via point cloud registration.

// EKF Based Beam Tracking

Beam tracking via configuring the analog precoder $\mathbf{f}_k = \mathbf{a}_\mathrm{t}(\phi_{k-1})$ and the analog combiner $\mathbf{g}_k = \mathbf{a}_\mathrm{r}(\psi_{k-1})$.

– Channel Prediction Stage:

A Priori Channel State Vector:

$\bar{\mathbf{s}}_{k|k-1} = \bar{\mathbf{F}}_k \bar{\mathbf{s}}_{k-1|k-1} + \bar{\mathbf{u}}_k$

A Priori Channel Covariance Matrix:

$\mathbf{P}_{k|k-1} = \bar{\mathbf{F}}_k \mathbf{P}_{k-1|k-1} \bar{\mathbf{F}}_k^\mathsf{T} + \bar{\mathbf{Q}}_k$

– Channel Update Stage:

Kalman Gain:

$\mathbf{K}_k = \frac{\mathbf{P}_{k|k-1}\nabla\bar{h}(\bar{\mathbf{s}}_{k|k-1})}{\nabla^\mathsf{T}\bar{h}(\bar{\mathbf{s}}_{k|k-1})\mathbf{P}_{k|k-1}\nabla\bar{h}(\bar{\mathbf{s}}_{k|k-1}) + \sigma^2_{\bar{v}_k}}$

A Posteriori Channel State Vector:

$\bar{\mathbf{s}}_{k|k} = \bar{\mathbf{s}}_{k|k-1} + \mathbf{K}_k(\bar{z}_k - \nabla^\mathsf{T}\bar{h}(\bar{\mathbf{s}}_{k|k-1})\bar{\mathbf{s}}_{k|k-1})$

A Posteriori Channel Covariance Matrix:

$\mathbf{P}_{k|k} = (\mathbf{I} - \mathbf{K}_k \nabla^\mathsf{T}\bar{h}(\bar{\mathbf{s}}_{k|k-1}))\mathbf{P}_{k|k-1}$

– Deviation Checking for Re-initialization:

if $||\alpha_k| - |\alpha_\mathrm{I}|| > \tilde{\alpha}$ or $|\phi_k - \phi_\mathrm{I}| > \tilde{\phi}$ or $|\psi_k - \psi_\mathrm{I}| > \tilde{\psi}$

Re-initialize $\bar{\mathbf{s}}_\mathrm{I}$ and set $\bar{\mathbf{s}}_{k|k} = \bar{\mathbf{s}}_\mathrm{I}$.

end

until The vehicle arrives at destination.

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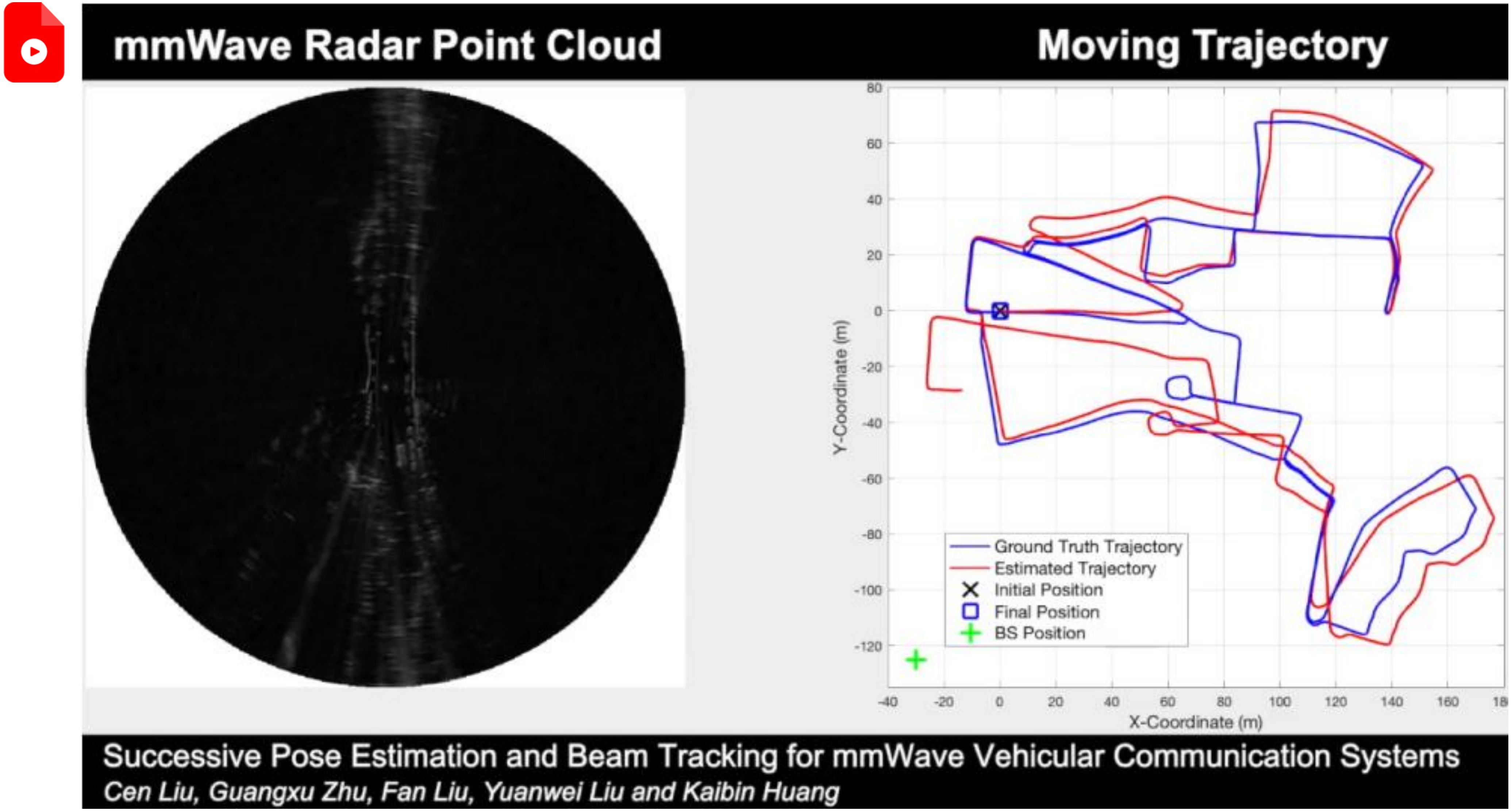
IV. Simulations



- 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	$5\text{m} \sim 100\text{m}$
K-strongest filtering	$K = 3$
Pixel value threshold (integer: $0 \sim 255$)	$\kappa_{\min} = 55$
Side length of downsampling grid cell	$d_{\mathrm{D}} = 3.5\text{m}$
Resampling factor	$f_{\mathrm{D}} = 1.0$
Angle tolerance	$\Theta = 30°$
Huber loss $\mathcal{L}_\delta$	$\delta = 0.1$

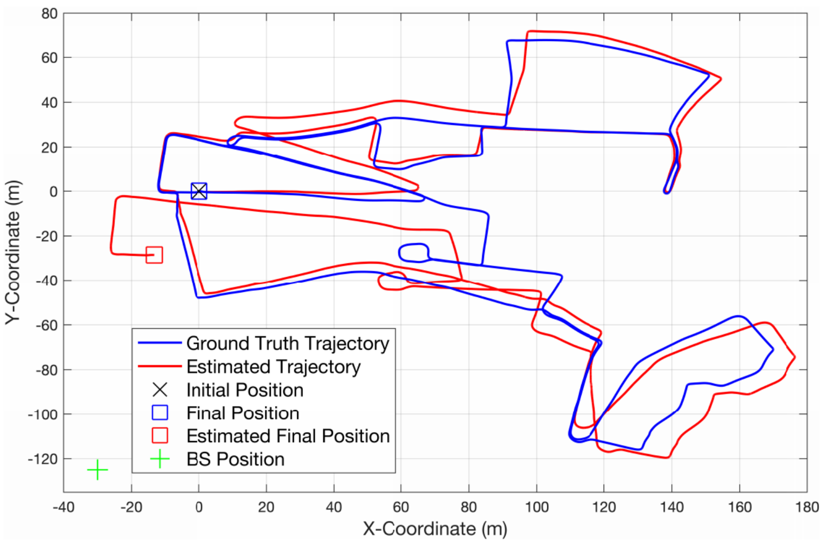


Fig. 6. The estimated vehicle moving trajectory compared to ground truth. Both trajectories are aligned by the initial position marked with ×, and the final positions are marked with □. The position of BS is marked with +.

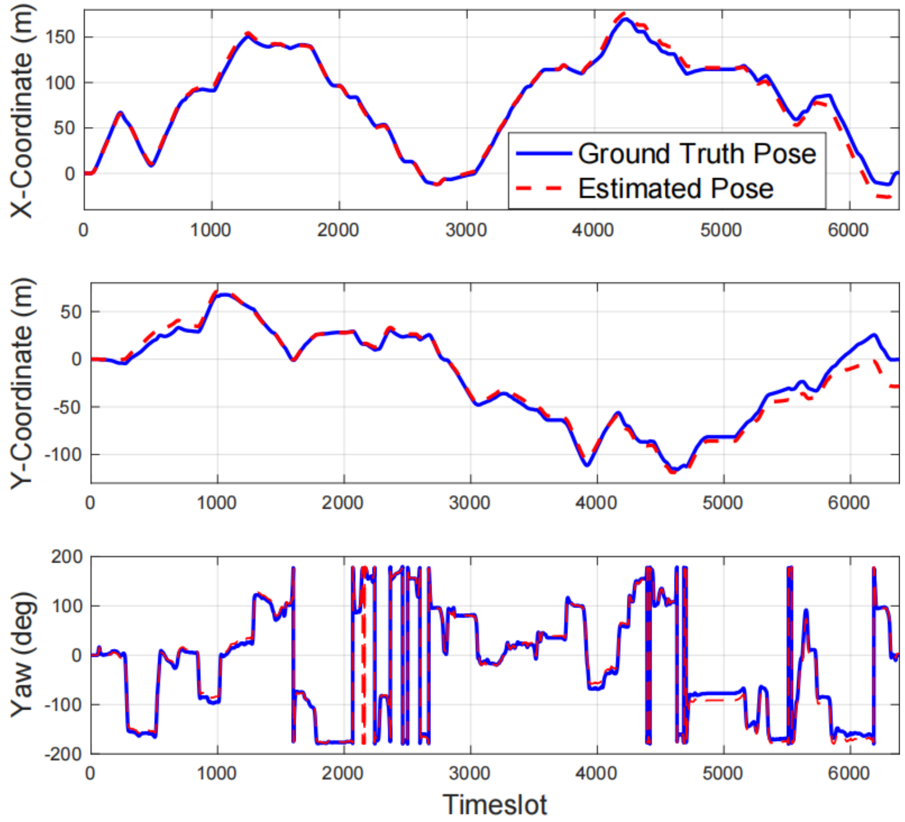


Fig. 7. The estimated pose compared to ground truth pose on coordinate (x_k, y_k) and yaw θ_k against timeslot k.

* 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 $d_0 = 1\text{m}$	$\lvert\alpha_{\text{ref}}\rvert = 5 \times 10^{-4}$
Noise power	$\sigma_v^2 = -90\text{dBm}$
Standard deviation of estimation error	$\sigma_r = 1.0\text{m}, \sigma_\theta = 3°$
Channel re-initialization thresholds	$\tilde{\alpha} = 5 \times 10^{-7}$ $\tilde{\phi} = \tilde{\psi} = 7.5°$
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

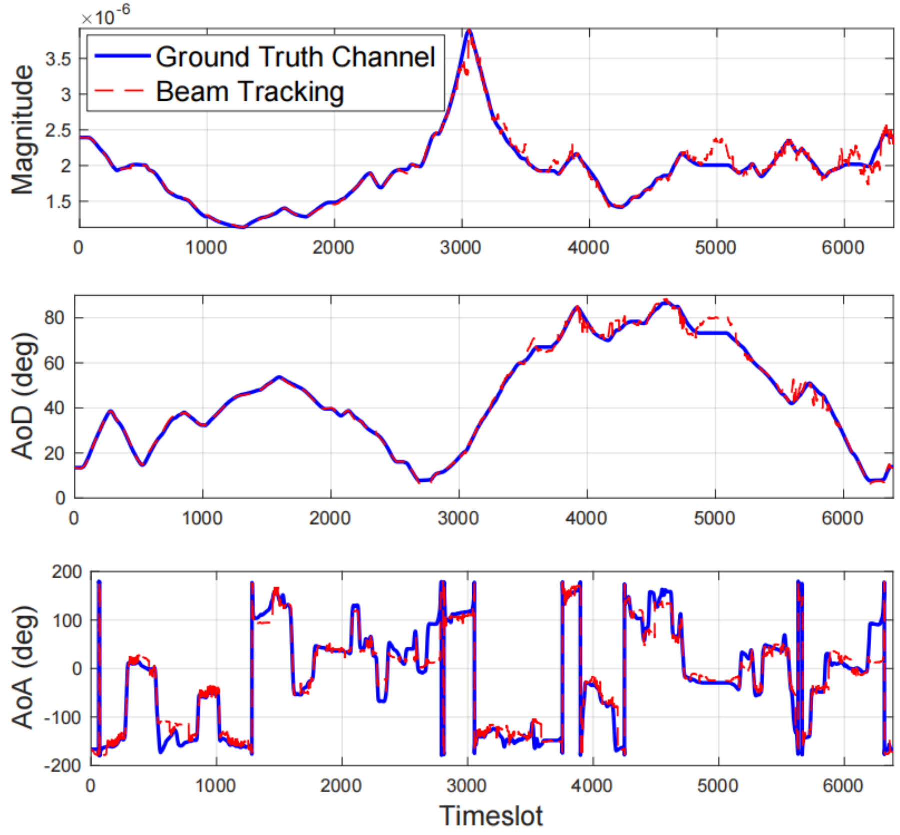


Fig. 8. A beam tracking realization generated by SPEBT scheme compared to ground truth channel on magnitude, AoD and AoA against timeslot *k*.

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 .