mmBox: mmWave Bounding Box for Vehicle and Pedestrian Detection under Outdoor Environment

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Objective, Motivation, and Challenges

Objective

- mmBox aims to design a mmWave-based object detection system, which can effectively predict bounding box for vehicle and pedestrian under extreme outdoor environment

Motivation

- The high resolution, low-cost, and ability to penetrate small obstacles of mmWave enable the feasibility to be applied in adverse environment
- Existing works have limited performance, *e.g.*, RODNet[1] only predicts a likelihood cluster on the heatmap, and Radatron[2] lacks distance and height details of objects

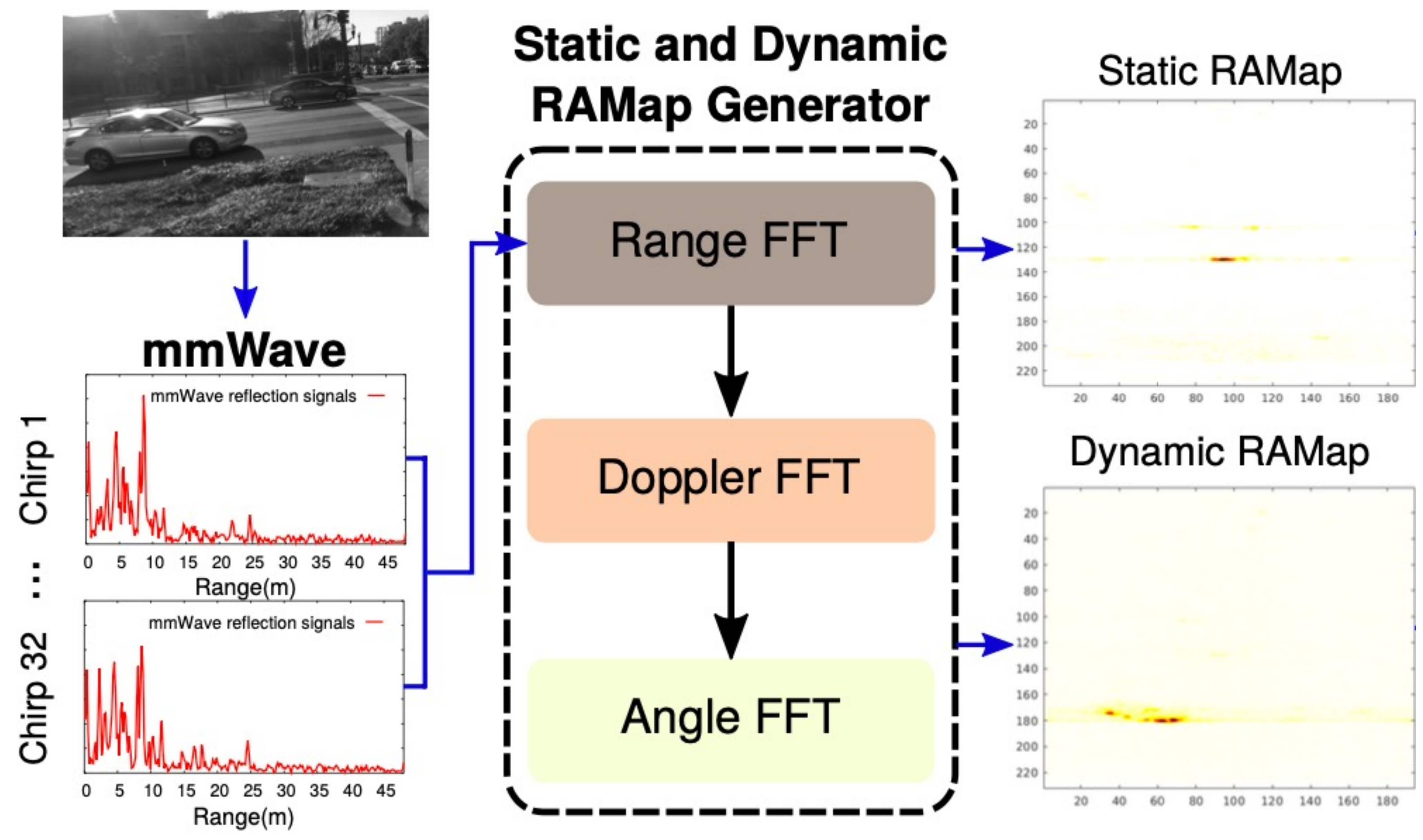
Challenges

- **Noise and Sparsity.** Only a few parts of transmitted signals are correctly reflected to receivers due to specularity, and the strong reflectors will generate noise
- **Complex Outdoor Environment.** More complicated objects and surroundings further increase the difficulty of extracting enough features of targets from the sparse and noisy mmWave reflections

Data Processing

Static and Dynamic RAMap Generator

- **Range FFT** is applied to convert time domain signals to the frequency domain, capturing distance details
- **Doppler FFT** is applied on varying chirps in a frame to differentiate between stationary and moving entities
- **Angle FFT** is applied on signals from non-overlapping virtual antennas to derive the azimuth angle from Range-Doppler data



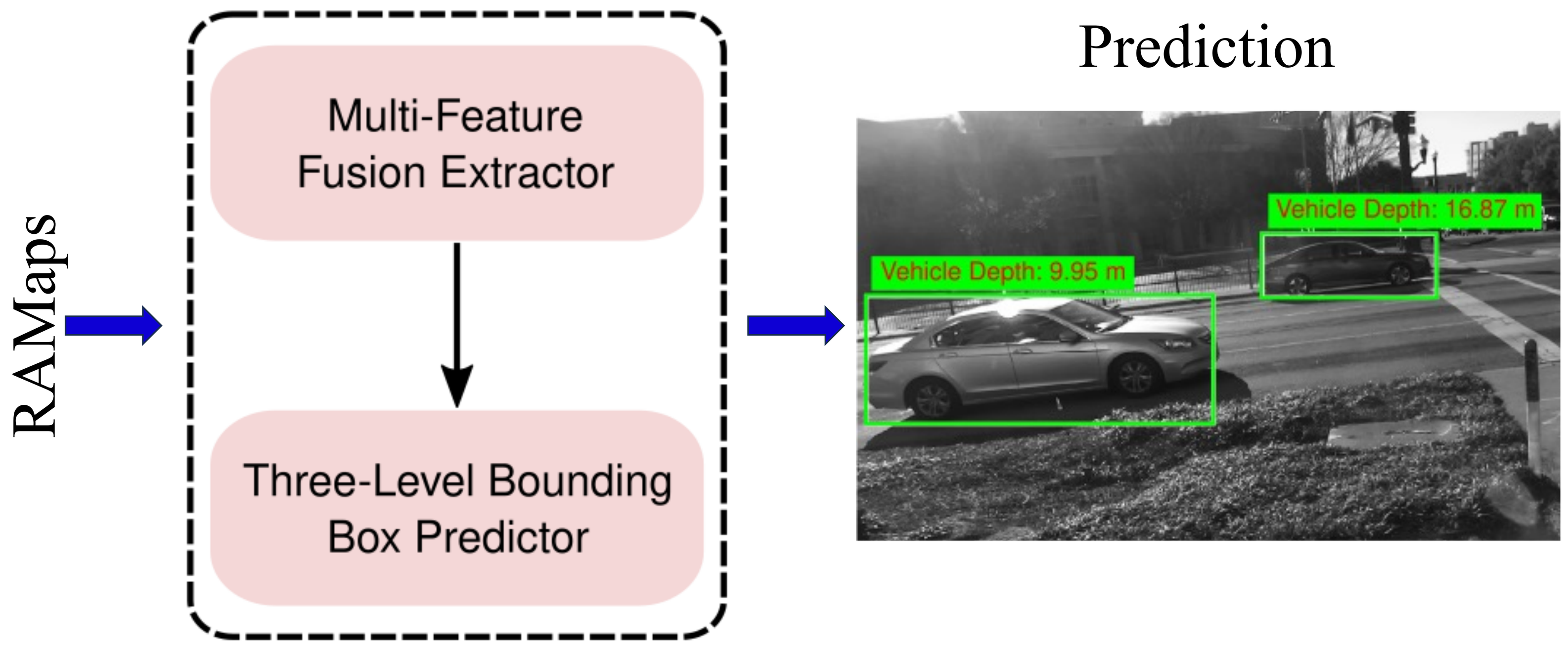
[1] Wang, Yizhou, et al. "RODNet: A real-time radar object detection network cross-supervised by camera-radar fused object 3D localization." *IEEE Journal of Selected Topics in Signal Processing* 15.4 (2021): 954-967.
[2] Madani, Sohrab, et al. "Radatron: Accurate detection using multi-resolution cascaded mimo radar." European Conference on Computer Vision. Cham: Springer Nature Switzerland, 2022..

Model Architecture

Multi-Scale Bounding Box Generator

- **Feature Extractor.** This module fuses features from both static and dynamic RAMaps across multiple scales.
- **Three-Level Bounding Box Predictor.** This module outputs 3 scale predictions. The small size predictions mainly focus on the large bounding boxes, while large-scale predictions consider large ones more.
- **Predefined Anchors.** These 3x3 anchors are matched with 3-level prediction in 3 different sizes to improve the performance.
- **Loss Function:**

$$L_{EIOU} = 1 - IOU + \frac{\rho^2(b, b^{gt})}{(w^c)^2 + (h^c)^2} + \frac{\rho^2(w, w^{gt})}{(w^c)^2} + \frac{\rho^2(h, h^{gt})}{(h^c)^2}$$



Results

Dataset

- We collected mmWave reflections, gray-scale images, and depth images in outdoor street scenes.
- In total, we got 10,440 samples for training and 2,280 samples for testing

Results

- mmBox showcases remarkable precision on various, metrics including Average Precision (AP) and Classification Accuracy (CA), Average Center Distance (ACD), Average Height/Width Ratio (AWR/AHR), and Average Depth Difference (ADD).

	CA	AP_{50}	ACD	AHR	AWR	ADD (m)
Vehicle	100%	42%	20 pix.	0.998	1.009	0.80
Pedestrian	100%	24%	11 pix.	0.995	1.007	0.51

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