Advancement of AI and Simulation Intersecting mmWave Radar

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Agenda

- Application domains of mmWave sensing
- Introduce today's challenge
- Bio-Inspired mmWave sensing and perception
- Pyramid of mmWave perception simulation environment
- Case studies
- Conclusion & Q&A

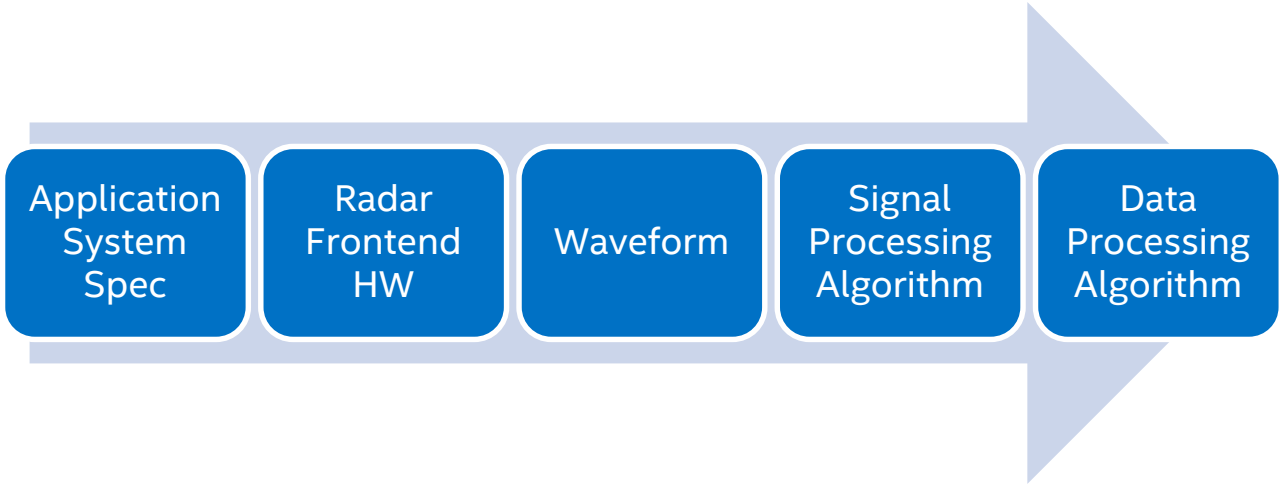
Application domains of mmWave sensing

- Less privacy sensitivity
- Robustness to weather and lighting conditions
- New sensing dimensions and modality

Privacy Sensitive	All weather & lighting	Modality/Redundancy
Elderly Care	Intrusion Detection	Human-machine Interface
Patient Monitoring	Industrial/Mining Monitoring	Automotive
Home Monitoring	Automotive	Robotics

Challenge

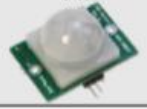
- Application specific design of hardware and software



- Artificial Neural Network (ANN) provides a promising solution
- How to efficiently generate dataset and train?

Case 1: Efficient CNN + FMCW Radar for Gesture Recognition [2] (I)

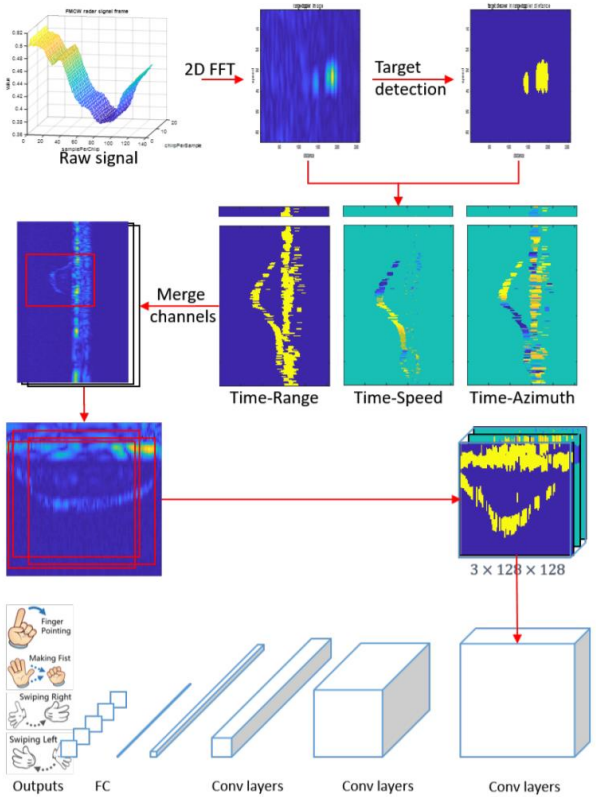
- Radar is near-perfect sensor for gesture recognition

Sensor	Field of View	Range resolution	Information captured	Anonymity	Bad weather	Price	Computation
radar 	★★★☆☆ 90°	★★★★★ 2mm	★★★☆☆ Distance, velocity, angle	★★★★★ Yes	★★★★★ Good in fog, dust, smoke	★★★☆☆ $5	★★★★☆ Medium
IR TOF Camera 	★★★☆☆ 60°	★★★★☆ 2cm	★★★★★ Texture, RGB, IR	☆☆☆☆☆ No	★★★☆☆ Sensitive to light	★★★☆☆ $5	★☆☆☆☆ High
PIR 	★★★☆☆ 100°	☆☆☆☆☆ N/A	★☆☆☆☆ Human in motion	★★★★★ Yes	★★★☆☆ Sensitive to light, heat	★★★★☆ $1	★★★★★ Low
ultrasonic 	★★★★☆ 100°	★★★★★ 3mm	★☆☆☆☆ distance	★★★★★ Yes	★★☆☆☆ Bad in smoke, dust	★★★★☆ $1	★★★★★ Low

[1] Cai, Xiaodong, Jingyi Ma, Wei Liu, Hemin Han, and Lili Ma. "Efficient convolutional neural network for FMCW radar based hand gesture recognition." In *Adjunct Proceedings of the 2019 ACM International Joint Conference on Pervasive and Ubiquitous Computing and Proceedings of the 2019 ACM International Symposium on Wearable Computers*, pp. 17-20. 2019.

Case 1: Efficient CNN + FMCW Radar for Gesture Recognition (II)

- Three-channel input frames
  - Range-time trajectory
  - Speed-time trajectory
  - Azimuth-time trajectory
- Efficient DNN architecture
  - VGG-10
  - VGG-10 with Residual layers



Case 1: Efficient CNN + FMCW Radar for Gesture Recognition (III)

- FMCW radar with speed-spatial-angular resolution
- VGG-10+Resnet DNN architecture
- 96% real-time accuracy

Table 3: Accuracy comparison among models

Network Architecture	Avg. Acc.	LEFT	RIGHT	CLICK	WRIST
VGG-10	91.0%	94.9%	80.7%	95.5%	97.0%
ResNet-20	98.7%	99.1%	99.0%	97.9%	98.9%
CNN+LSTM	78.0%	69.0%	49.5%	84.6%	90.1%

Confusion matrix on Test set		gesture prediction					
		none	left	right	click	wrist	prec
Gesture ground truth	none	2189	18	5	6	5	98.5%
	left	9	2118	10	0	0	99.1%
	right	1	19	2055	0	0	99.0%
	click	1	5	0	2150	40	97.9%
	wrist	10	0	0	14	2215	98.9%
	recall	99.0%	98.1%	99.3%	99.1%	98.0%	98.7%

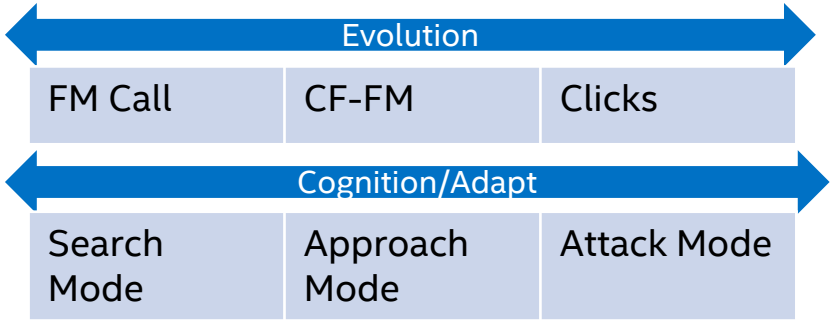
Figure 9: Confusion matrix on test set

Question: Could the nature does it better?

Bio-Inspired mmWave sensing and perception

Coherent ranging and perception

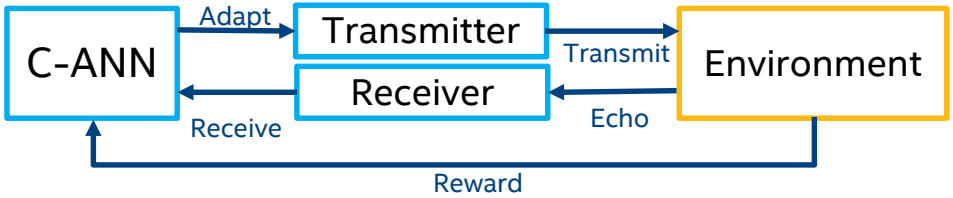
- High range resolution (10ns) and angular accuracy (up to 0.7°)
- Doppler shifts/modulation analysis
- Target detection, object recognition, collision avoidance
- Adaptation and cognitive behavior



[2] Nachum Ulanovsky, Cynthia F. Moss, *What the bat's voice tells the bat's brain*, Proceedings of the National Academy of Sciences Jun 2008, 105 (25) 8491-8498; DOI: 10.1073/pnas.0703550105

ANN driven architecture

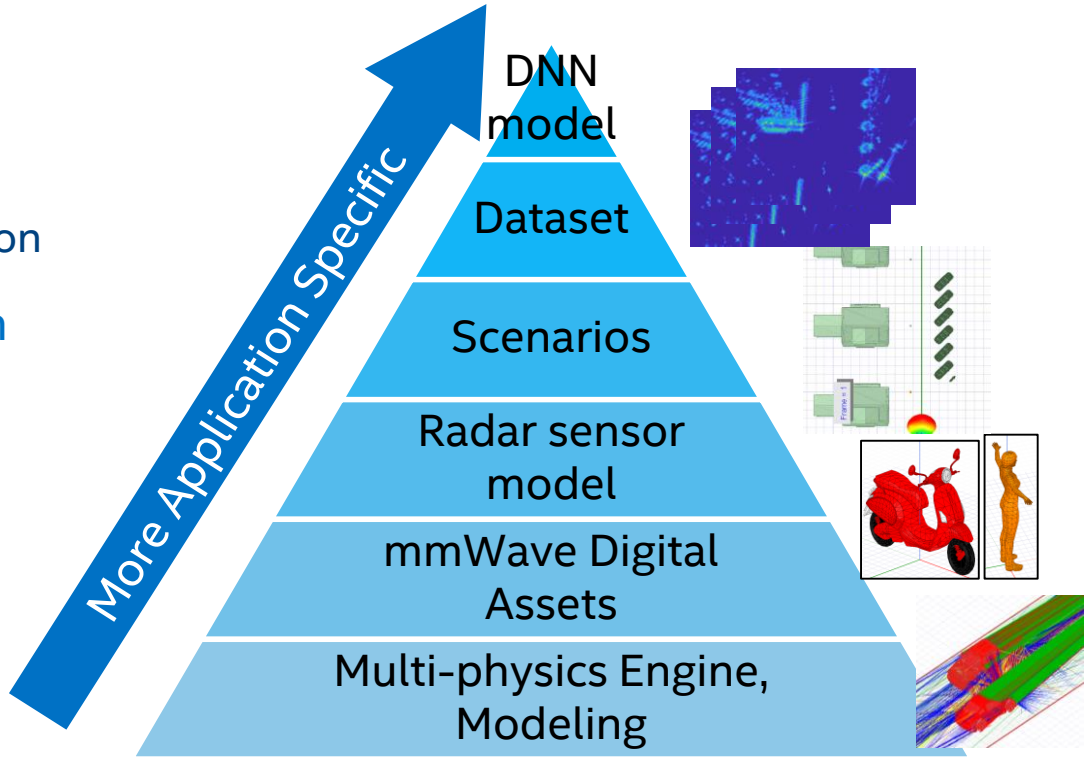
- ✓ Co-optimization of waveform and radio front-end design
- ✓ Deep Reinforcement Learning based waveform, modulation adaptation
- ✓ Coherent ANN optimized for I/Q input
- × Costly to find training environment



Bio-Inspired mmWave sensing and perception framework

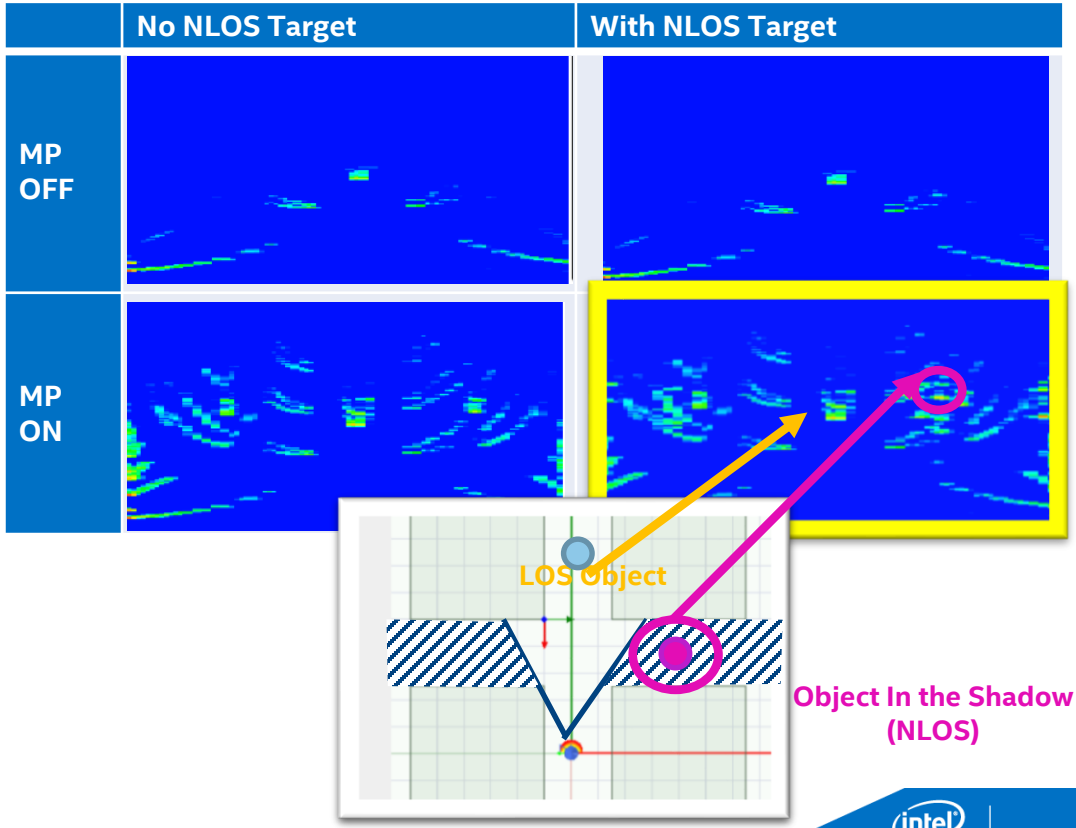
Pyramid of mmWave perception simulation environment

- Multi-physics simulation
  - Physics engine
  - Ray-tracing based EM simulation
- Build application dataset with
  - mmWave digital assets
  - Radar sensor model
  - Scenario definition
- Train DNN with synthetic dataset



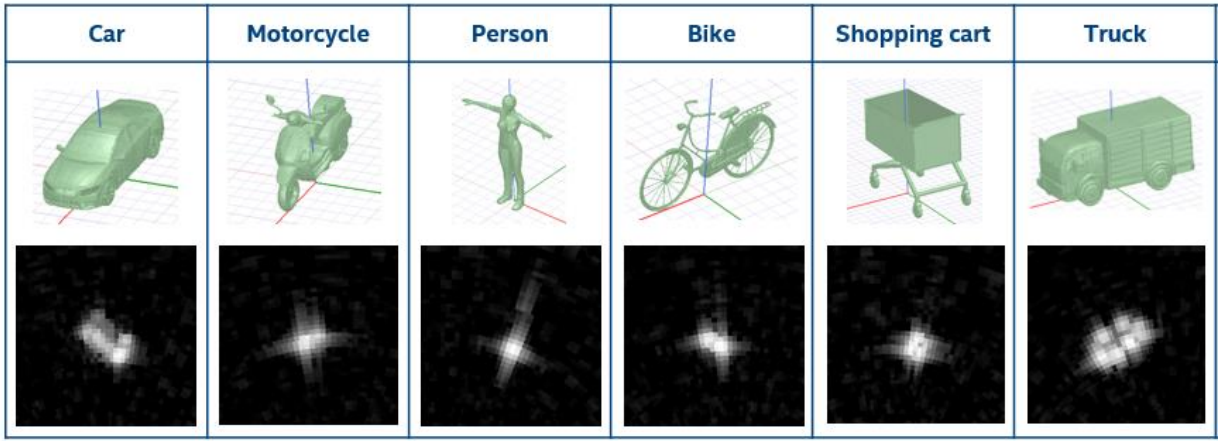
Case 2: Feasibility for simulation based Radar Dataset generation: Multi-path

- Multipath mitigation
- Turn enemies into friends – NLOS detection
- DL approach paired with simulation:
  - High complexity with conventional model-based approach
  - Can turn off multipath in simulation
  - Easy access to ground truth

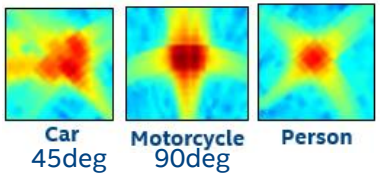


Case 3: DNN for Object Class Estimation

- Synthetic dataset generated with multi physics simulation



- Optimized DNN learned from MF-FFT processed 3D voxel dataset
  - > 99% classification accuracy,
  - < 7 deg orientation RMSE



Conclusion and Open Challenges

- Bootstrap R&D on mmWave sensing pipeline with simulation
  - Synthetic data generation
  - Readily available ground truth
  - Hand-craft/expand corner cases
  - Verification/validation
- Open Challenges:
  - Transfer trained models to field deployment
  - Find detailed simulation with highly dynamic scenarios
  - EM simulation in mmWave still need acceleration

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