Announcements

Reminders:

- Lab 2 checkpoint extended to Thursday
- Must submit discussion questions for Thomas today!
    - Auditors can email me to submit questions
- Lab submissions can be revised to receive credit, up to 1 week after all feedback (i.e., for all students) has been posted

Carnegie Mellon University

L9: Radar Systems

18-848 RadarML

Tianshu Huang

Outline

1. Radar Industry
2. Silicon & Radar Devices
3. Radar Sensor Systems
4. Modulation Design
5. Radar Perception Systems

Outline

1. **Radar Industry**
2. Silicon & Radar Devices
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The Radar Supply Chain

Silicon vendors

- Texas Instruments
- Infineon
- Analog Devices — AHEAD OF WHAT'S POSSIBLE™
- NXP

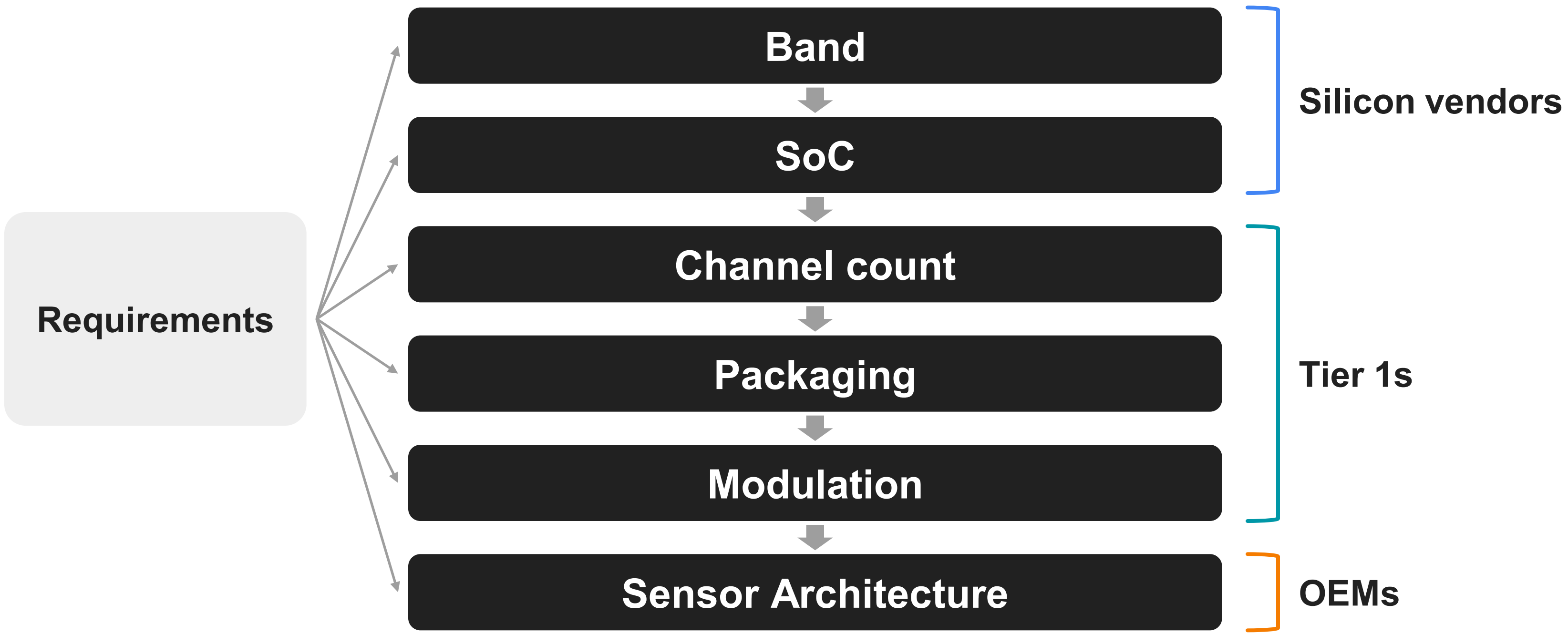
Tier 1s

- BOSCH
- Continental
- DENSO
- APTIV
- ZF
- Valeo

OEMs

- WAYMO
- TESLA
- VW
- TOYOTA
- Ford

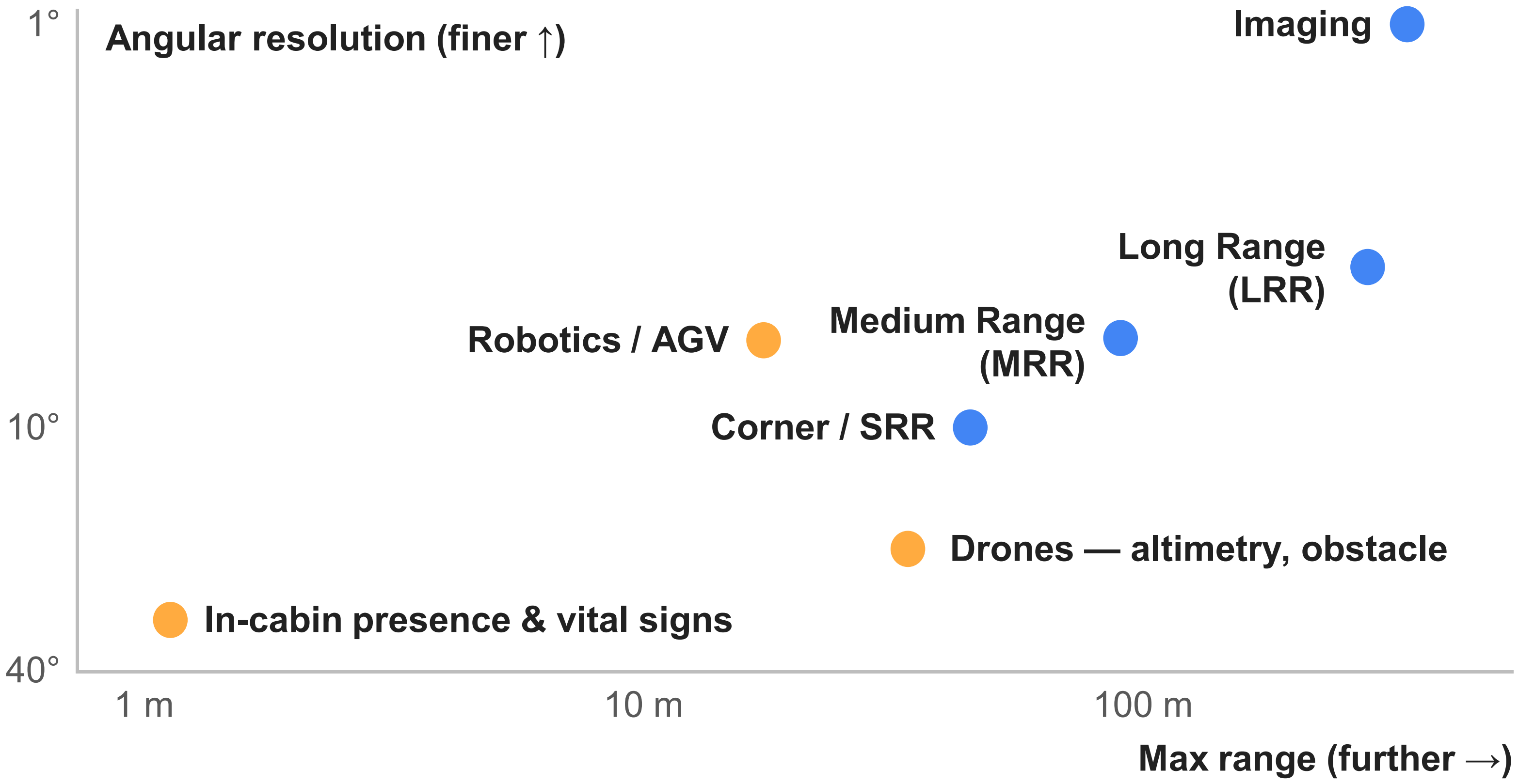
Designing Hardware



Requirements → physics → hardware

Requirement	Physics	Hardware
Range resolution	$\Delta R = c / 2B$	Chirp bandwidth
Max range	$R^4 \propto P_t G^2 \lambda^2 \sigma / SNR_{min}$	Power and antenna gain
Field of view	Element pattern; $d \le \lambda/2$	Element design and spacing
Velocity resolution	$\Delta v = \lambda / 2T_{frame}$	Frame duration (chirps per frame)
Max unambiguous velocity	$v_{max} = \lambda / 4T_{chirp}$	Chirp repetition time
Angular resolution	$\theta_{res} \approx \lambda / (N d \cos\theta)$	Virtual array size

Radar Classes



Outline

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UNITED STATES FREQUENCY ALLOCATIONS

THE RADIO SPECTRUM

RADIO SERVICES COLOR LEGEND

- AERONAUTICAL MOBILE
- AERONAUTICAL MOBILE SATELLITE
- AERONAUTICAL RADIONAVIGATION
- AMATEUR
- AMATEUR SATELLITE
- BROADCASTING
- BROADCASTING SATELLITE
- EARTH EXPLORATION SATELLITE
- FIXED
- FIXED SATELLITE
- INTER-SATELLITE
- LAND MOBILE
- LAND MOBILE SATELLITE
- MARITIME MOBILE
- MARITIME MOBILE SATELLITE
- MARITIME RADIONAVIGATION
- METEOROLOGICAL
- METEOROLOGICAL SATELLITE
- MOBILE
- MOBILE SATELLITE
- RADIO ASTRONOMY
- RADIODETERMINATION SATELLITE
- RADIOLOCATION
- RADIOLOCATION SATELLITE
- RADIONAVIGATION
- RADIONAVIGATION SATELLITE
- SPACE OPERATION
- SPACE RESEARCH
- STANDARD FREQUENCY AND TIME SIGNAL
- STANDARD FREQUENCY AND TIME SIGNAL SATELLITE

ACTIVITY CODE

- FEDERAL EXCLUSIVE
- FEDERAL/NON-FEDERAL SHARED
- NON-FEDERAL EXCLUSIVE

ALLOCATION USAGE DESIGNATION

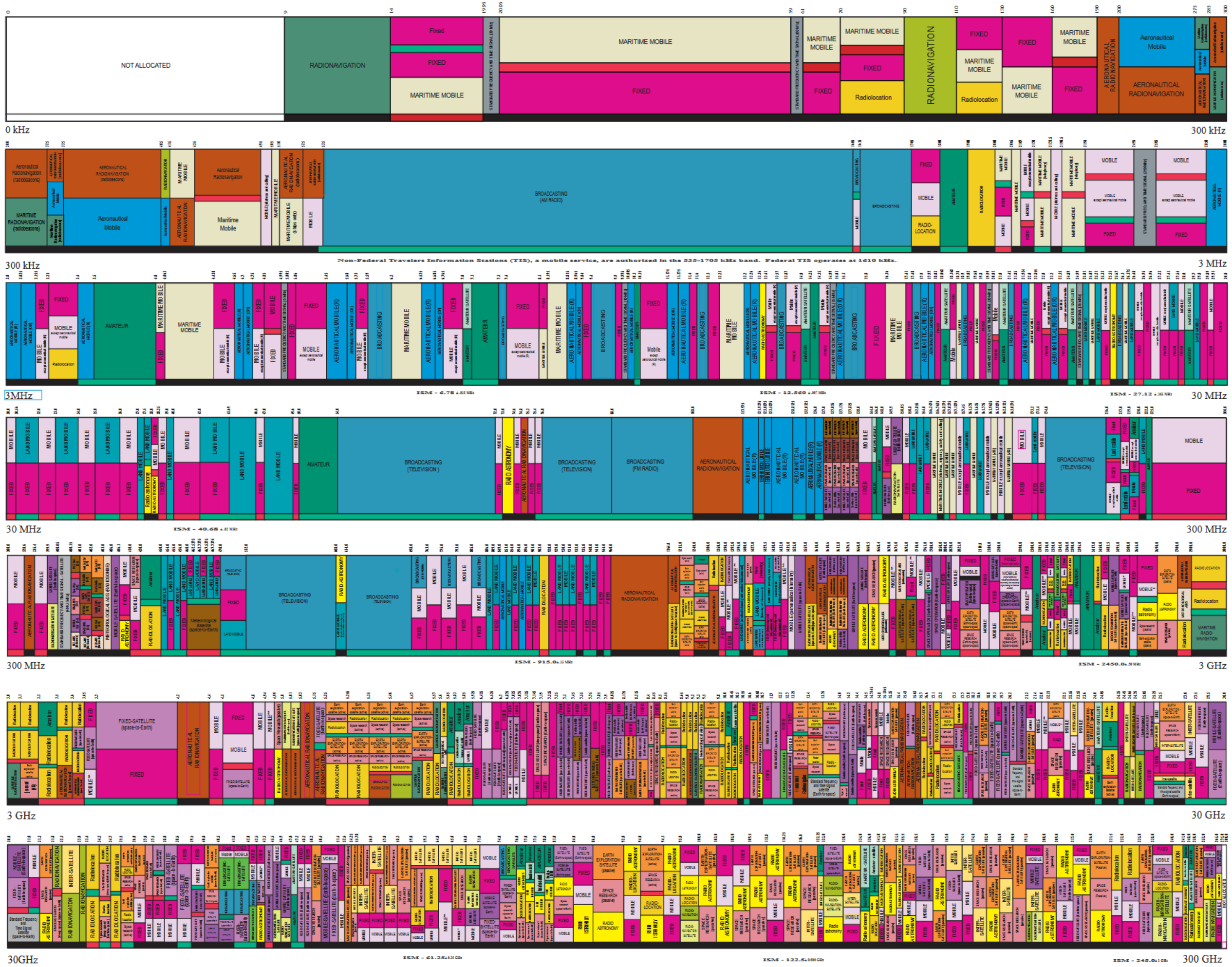
SERVICE	EXAMPLE	DESCRIPTION
Primary	FIXED	Capital Letters
Secondary	Mobile	1st Capital with lower case letters

This chart is a graphic single-point-in-time portrayal of the Table of Frequency Allocations used by the FCC and NTIA. As such, it may not completely reflect all aspects, i.e. footnotes and recent changes made to the Table of Frequency Allocations. Therefore, for complete information, users should consult the Table to determine the current status of U.S. allocations.

U.S. DEPARTMENT OF COMMERCE
National Telecommunications and Information Administration
Office of Spectrum Management

JANUARY 2016

For sale by the Superintendent of Documents, U.S. Government Printing Office

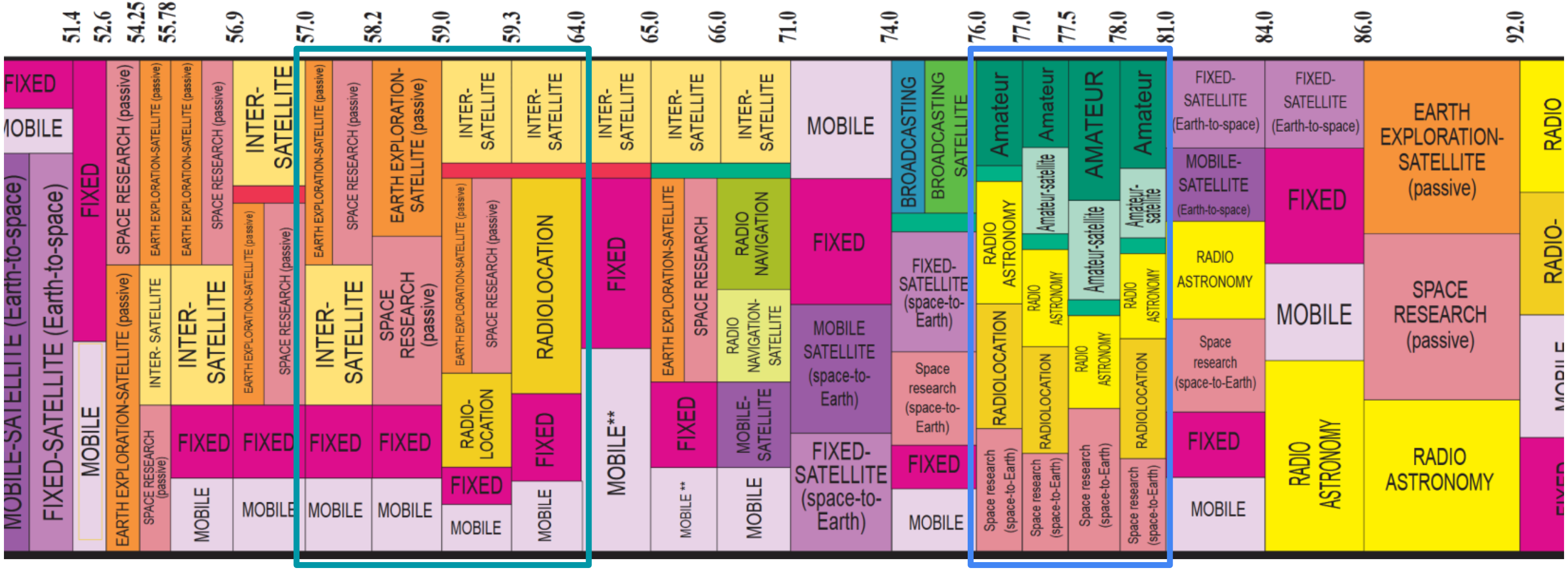


* EXCEPT AERONAUTICAL MOBILE (R)

** EXCEPT AERONAUTICAL MOBILE

PLEASE NOTE: THE SPACING ALLOTTED THE SERVICES IN THE SPECTRUM SEGMENTS SHOWN IS NOT PROPORTIONAL TO THE ACTUAL AMOUNT OF SPECTRUM OCCUPIED.

Spectrum is crowded!



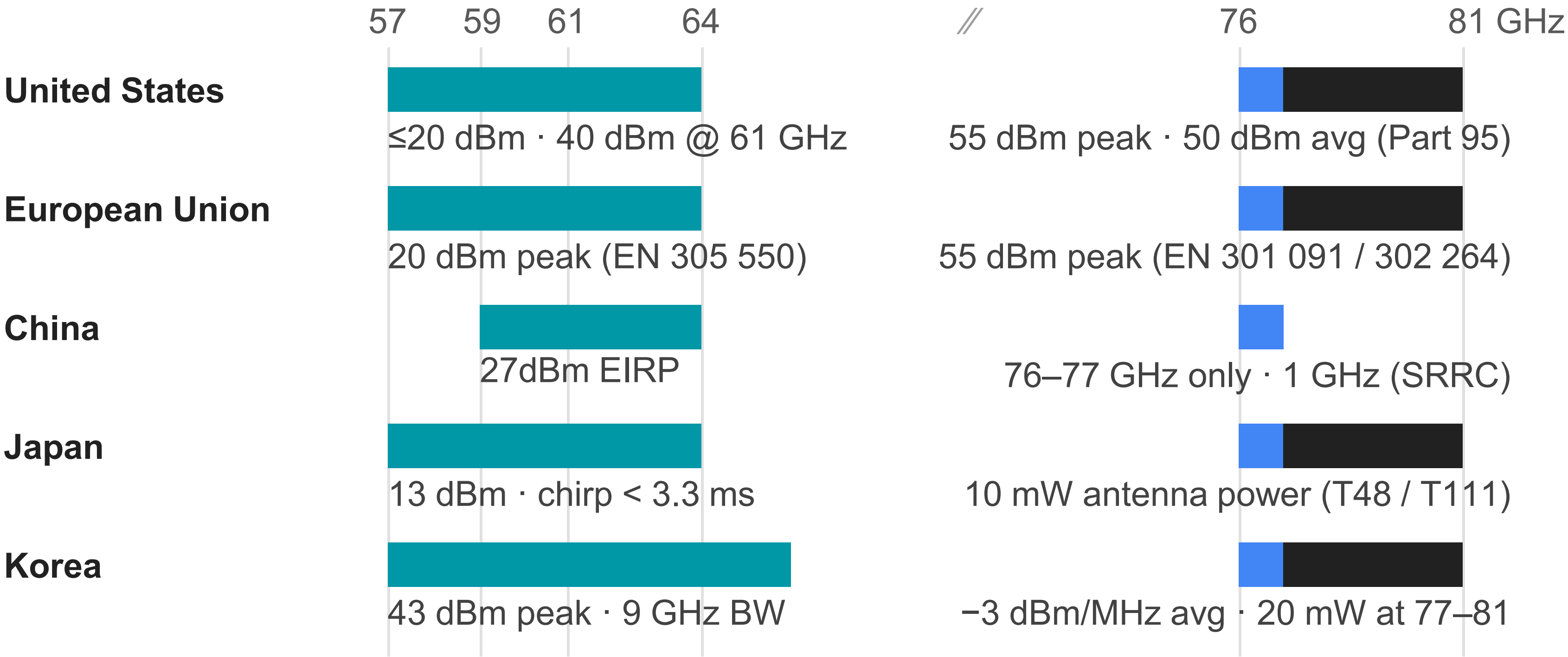
57–64 GHz

Unlicensed · in-cabin, robotics

76–81 GHz

Vehicular radar allocation

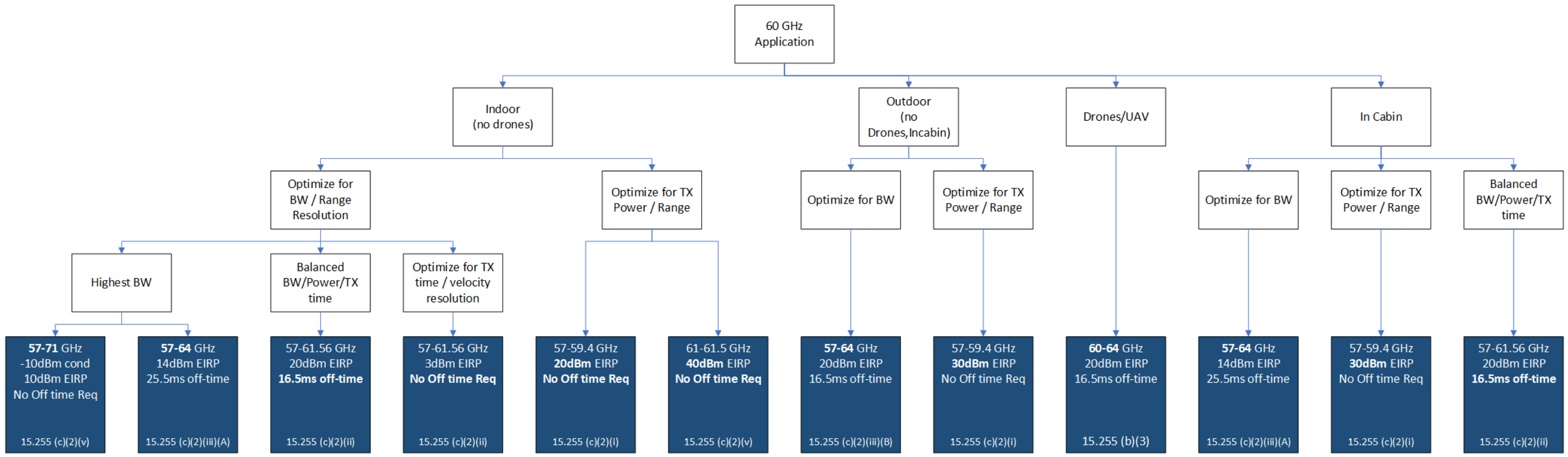
Spectrum is a regulatory mess



60 or 77 GHz?

Decision axis	57–64 GHz	76–81 GHz
Bandwidth	Up to 7 GHz, but unlicensed	1 GHz (76–77) + 4 GHz (77–81)
Permitted Power	≈ 20–30 dBm	55 dBm peak / 50 dBm mean
Licensing	Unlicensed, fragmented by region	(Mostly) Harmonised
Use cases	Indoor, in-cabin	Outside
Verdict by class	**Presence, vital signs, gesture**	**Corner, MRR, LRR, imaging**

60 GHz



60 GHz Application
Indoor (no drones)
Outdoor (no Drones,Incabin)
Drones/UAV
In Cabin
Optimize for BW / Range Resolution
Optimize for TX Power / Range
Optimize for BW
Optimize for TX Power / Range
Optimize for BW
Optimize for TX Power / Range
Balanced BW/Power/TX time
Highest BW
Balanced BW/Power/TX time
Optimize for TX time / velocity resolution
57-71 GHz -10dBm cond 10dBm EIRP No Off time Req 15.255 (c)(2)(v)
57-64 GHz 14dBm EIRP 25.5ms off-time 15.255 (c)(2)(iii)(A)
57-61.56 GHz 20dBm EIRP 16.5ms off-time 15.255 (c)(2)(ii)
57-61.56 GHz 3dBm EIRP No Off time Req 15.255 (c)(2)(ii)
57-59.4 GHz 20dBm EIRP No Off time Req 15.255 (c)(2)(i)
61-61.5 GHz 40dBm EIRP No Off time Req 15.255 (c)(2)(v)
57-64 GHz 20dBm EIRP 16.5ms off-time 15.255 (c)(2)(iii)(B)
57-59.4 GHz 30dBm EIRP No Off time Req 15.255 (c)(2)(i)
60-64 GHz 20dBm EIRP 16.5ms off-time 15.255 (b)(3)
57-64 GHz 14dBm EIRP 25.5ms off-time 15.255 (c)(2)(iii)(A)
57-59.4 GHz 30dBm EIRP No Off time Req 15.255 (c)(2)(i)
57-61.56 GHz 20dBm EIRP 16.5ms off-time 15.255 (c)(2)(ii)

77 GHz

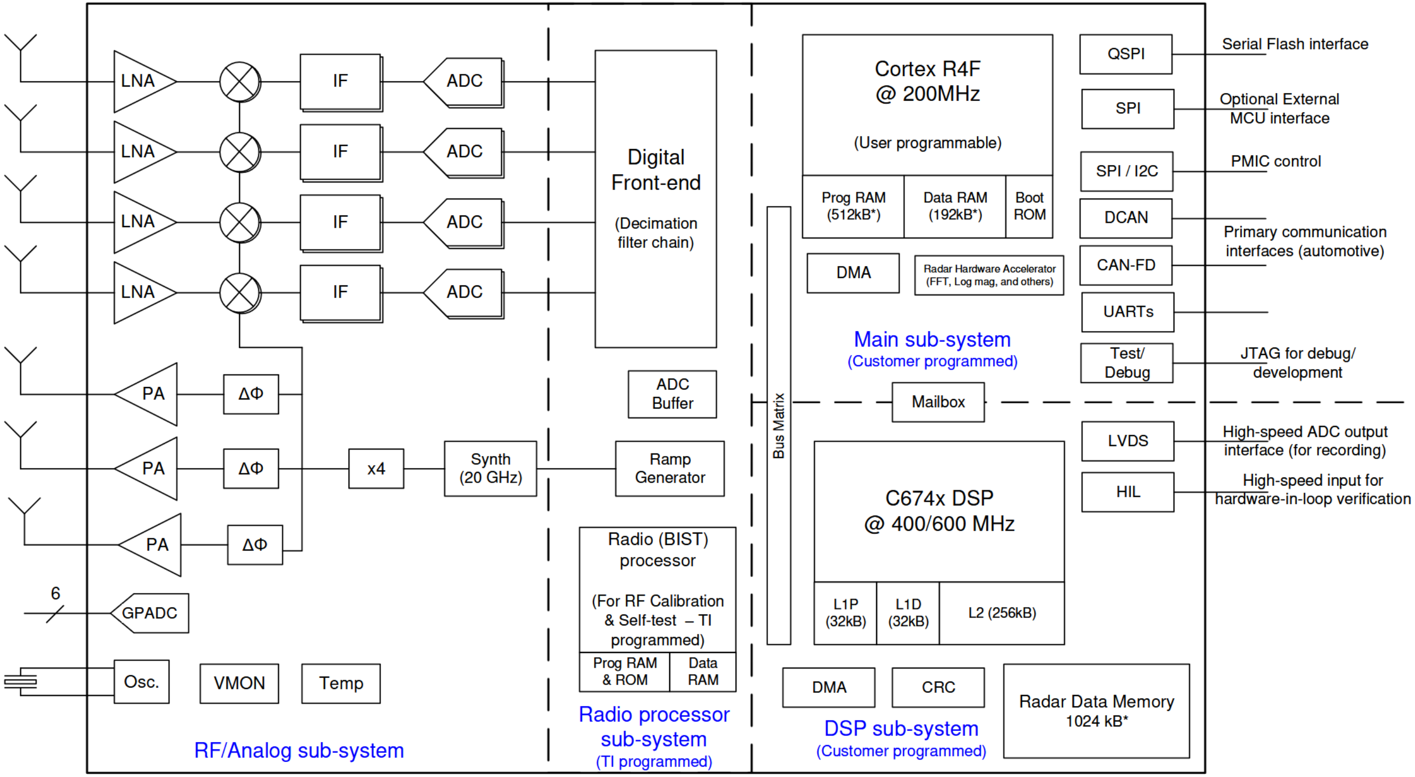
76–77 GHz

1 GHz bandwidth
Peak 55 / mean 50 dBm EIRP
$\Delta R = c / 2B = 15$ cm

77–81 GHz

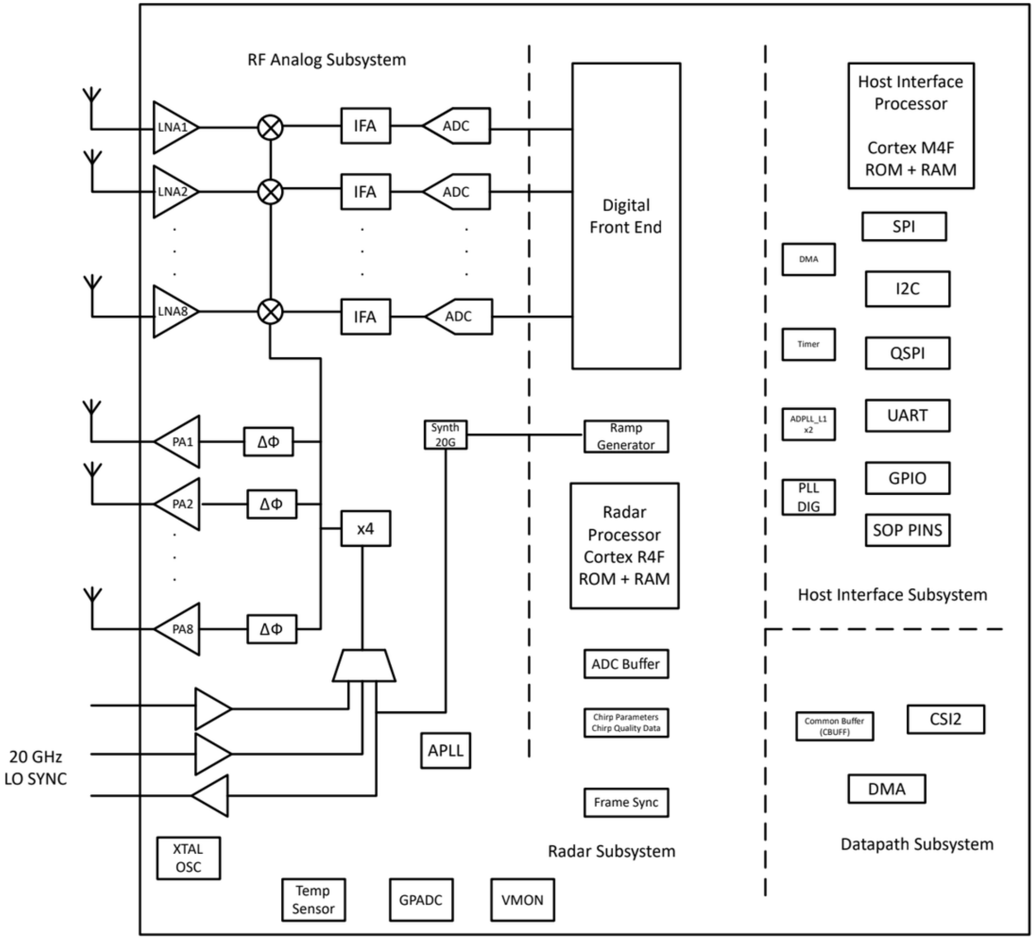
4 GHz bandwidth
Peak 55 dBm · −3 dBm/MHz mean
$\Delta R = c / 2B = 3.75$ cm

TI AWR1843



* Up to 512kB of Radar Data Memory can be switched to the Main R4F program and data RAMs

TI AWR2188

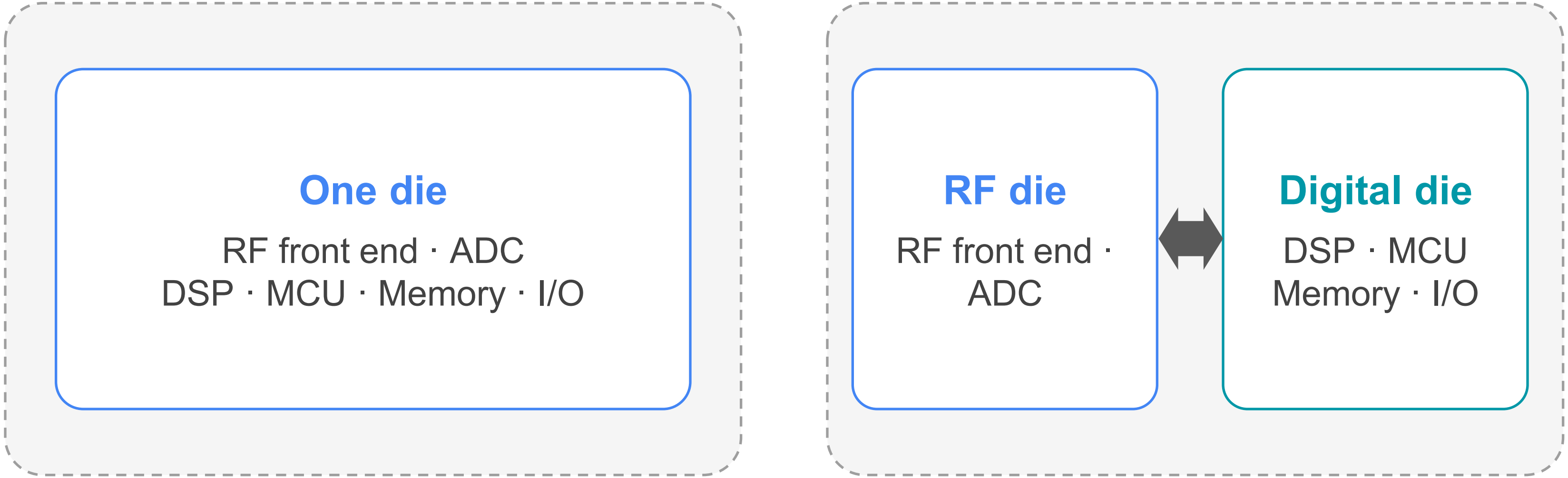


A. Multi-chip cascading feature is available in AWR2188

B. Internal temperature sensor accuracy is ± 3 °C.

Monolithic vs chiplets

Monolithic | **Chiplets**



one die / one package · one process node

multiple dies / one package · multiple nodes

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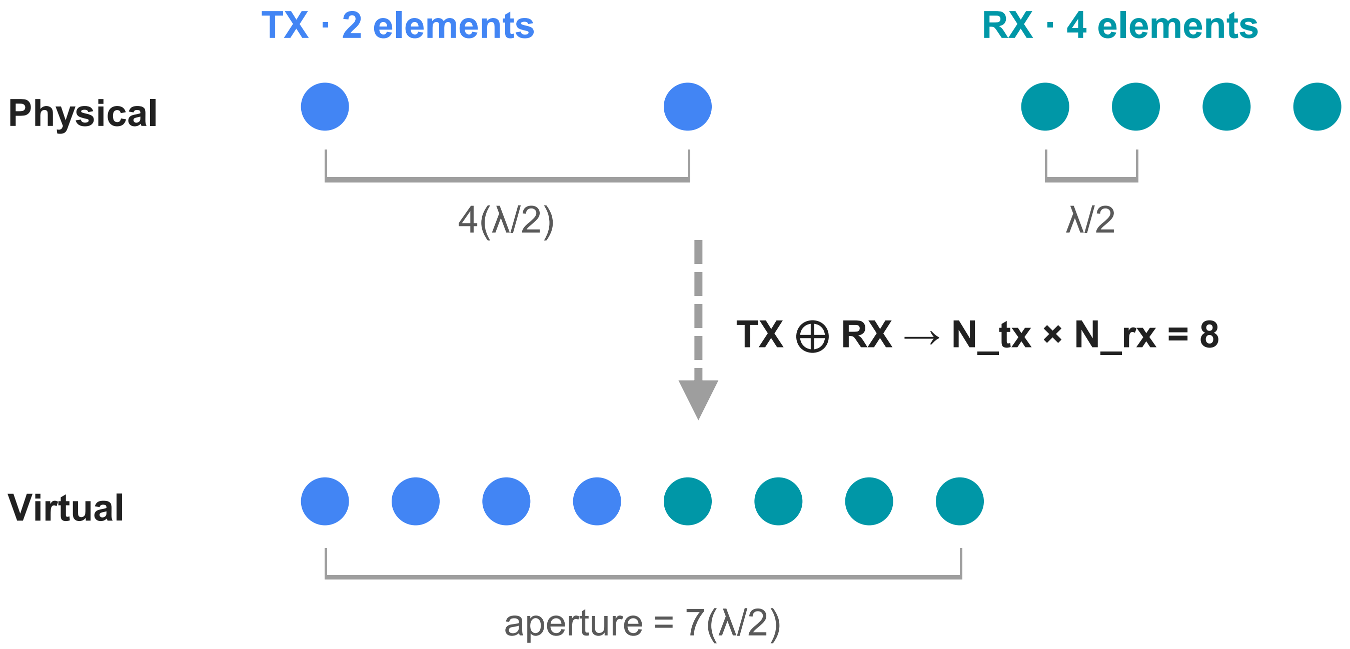
Virtual arrays, reviewed



AWR2944EVM

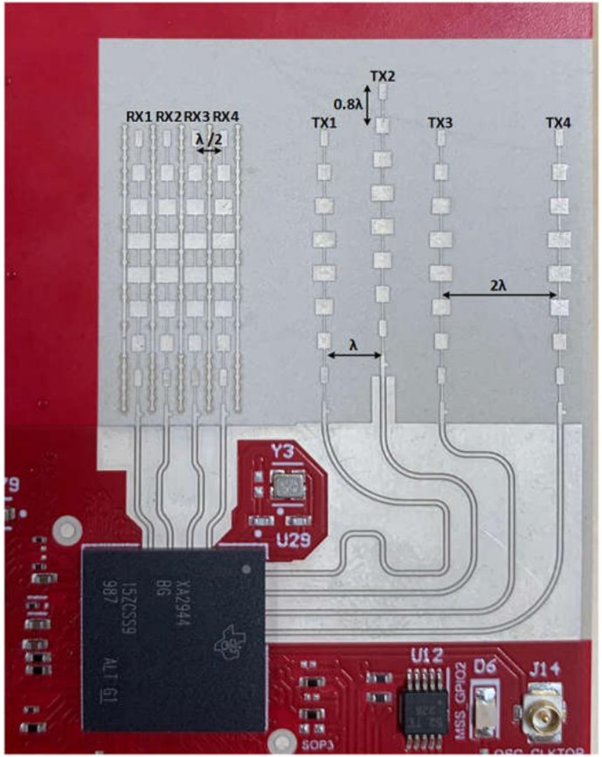


Figure 2-17. AWR2944EVM Antenna Design

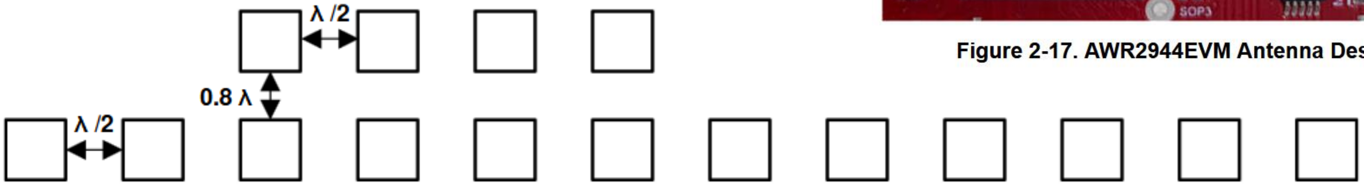


Figure 2-18. Virtual Antenna Array

AWR2544LOPEVM

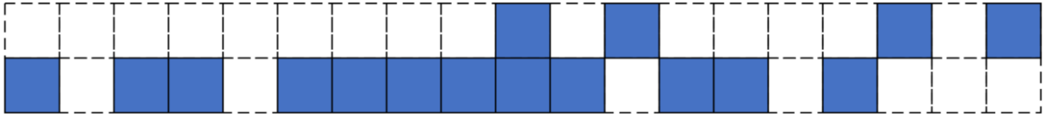


Figure 2-14. Virtual Antenna Array

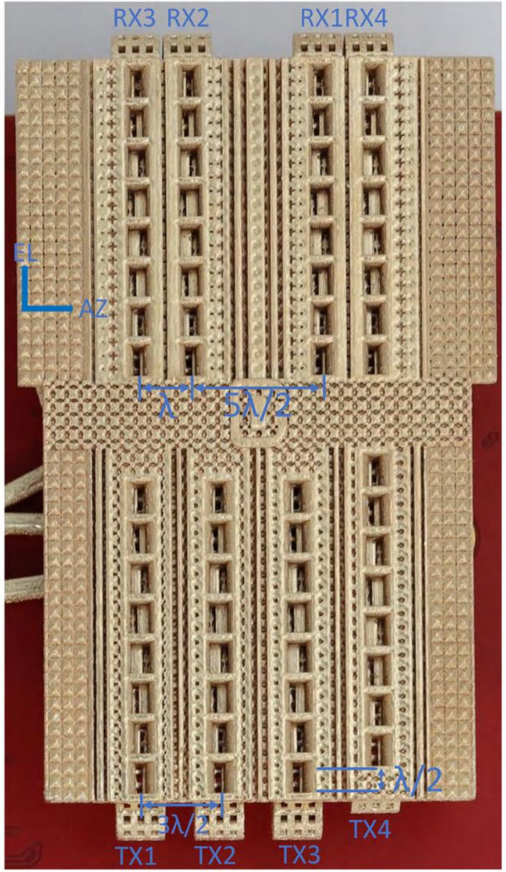
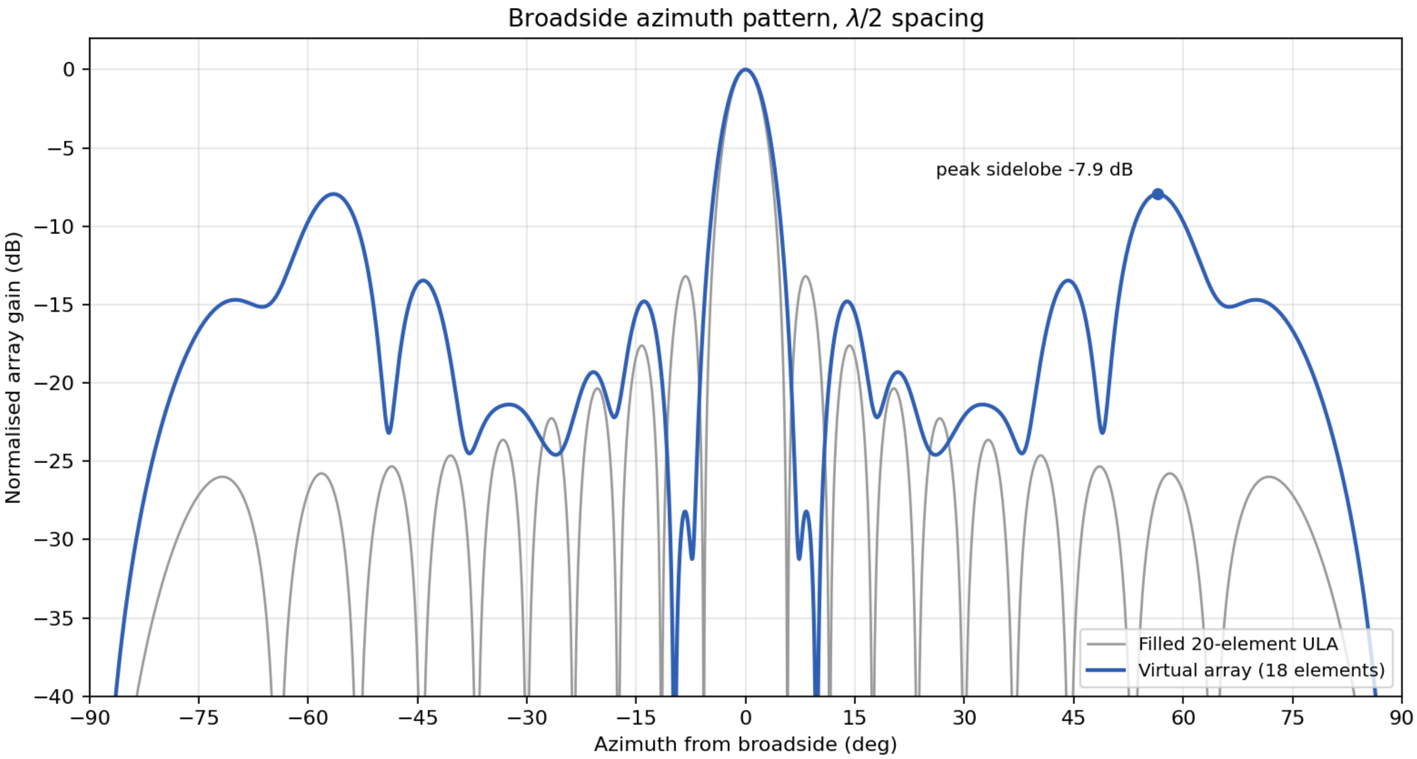
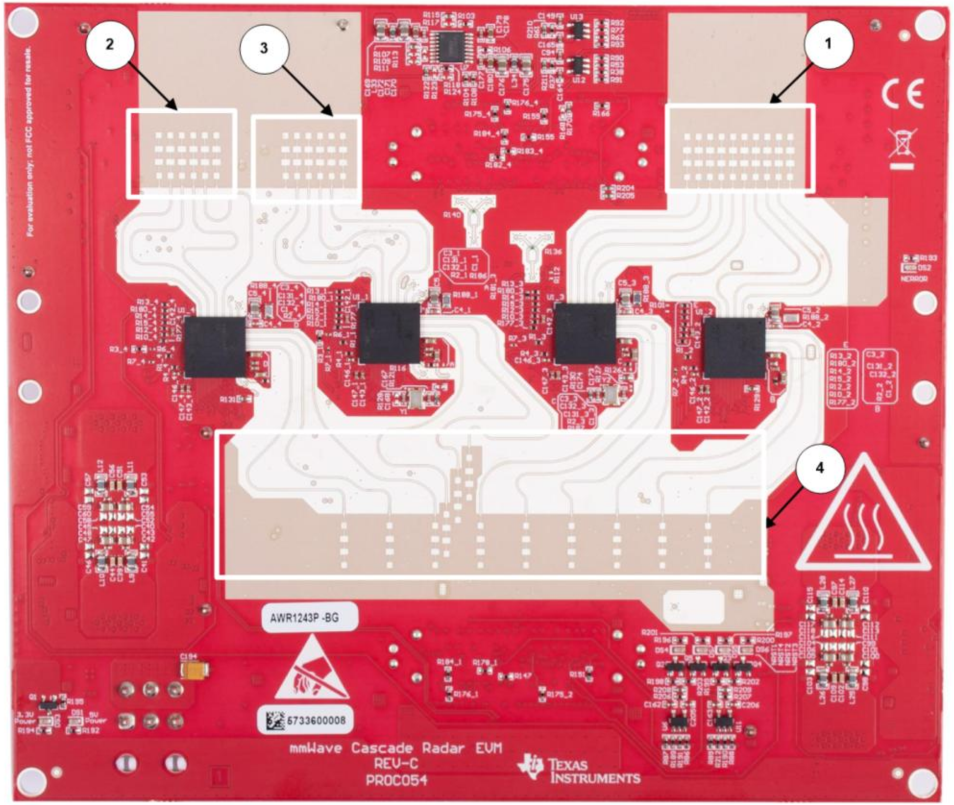


Figure 2-13. AWR2544LOPEVM Antenna Design

Sparse arrays



4x (3x4) Cascade: TI MMWCAS-RF-EVM



4x (3x4) Cascade: TI MMWCAS-RF-EVM

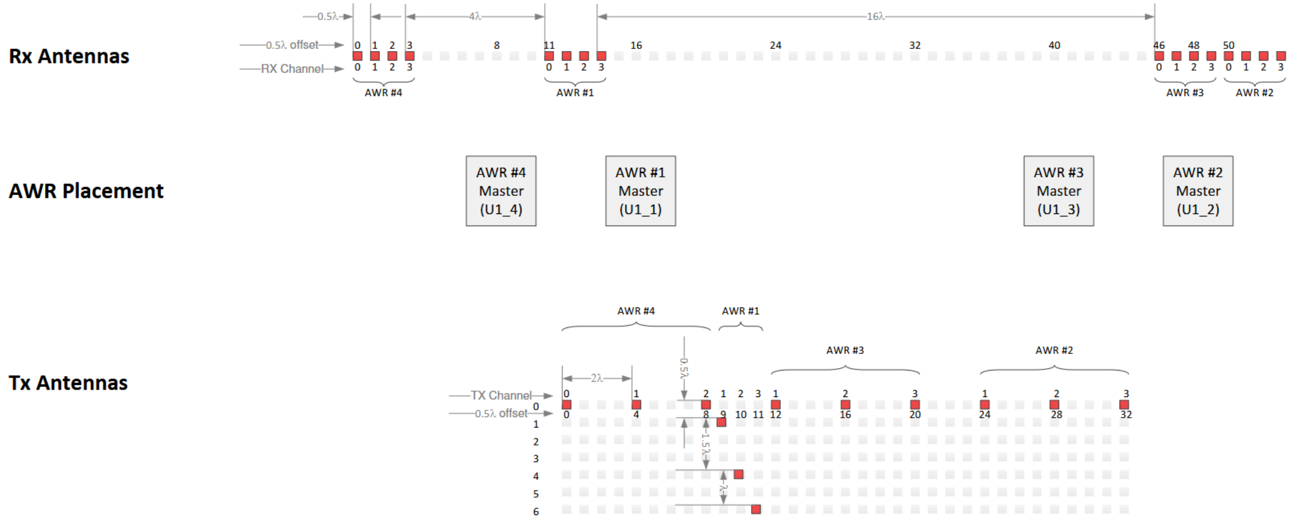


Figure 26. RX/TX Antenna Offsets

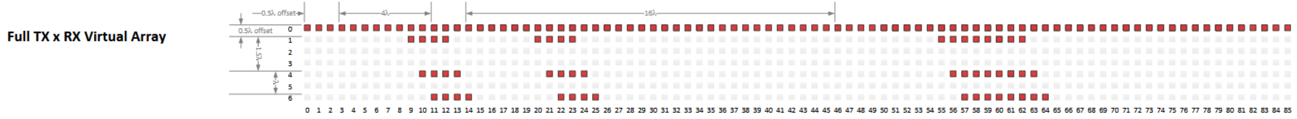
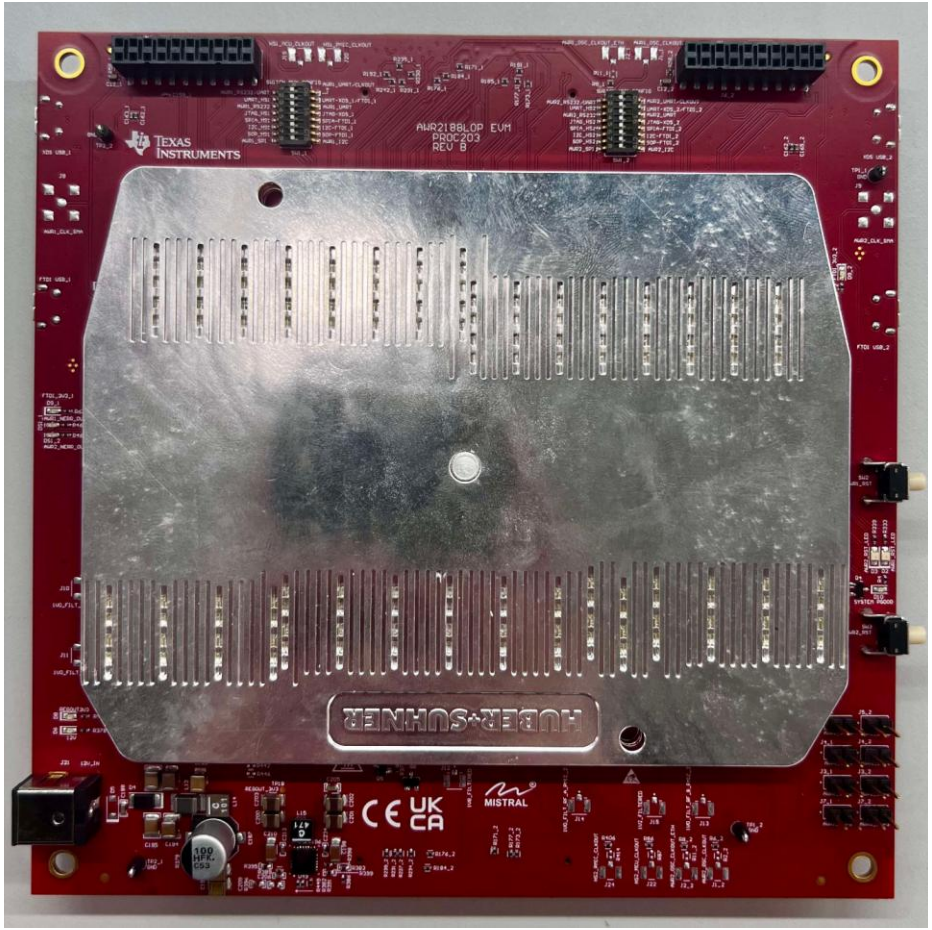


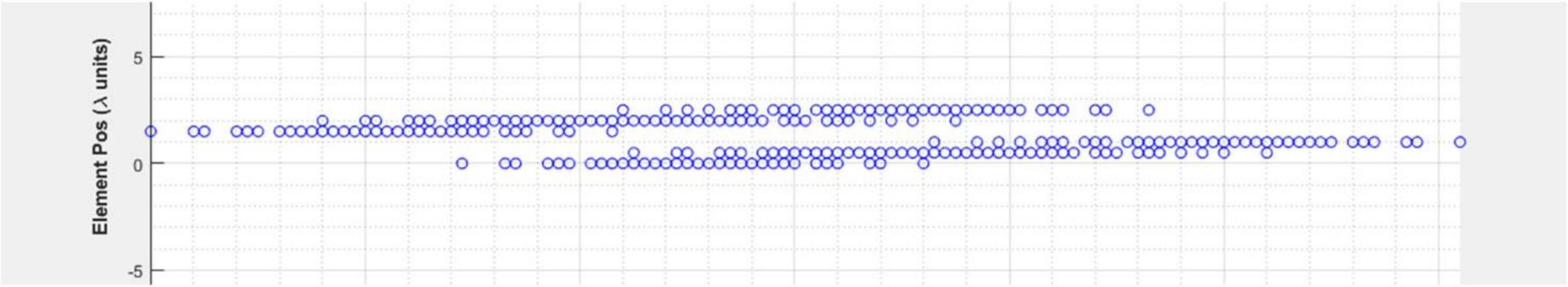
Figure 27. Resulting Virtual Antenna Array

2x (8x8) Cascade: TI AWR2188EVM



2x (8x8) Cascade: TI AWR2188EVM

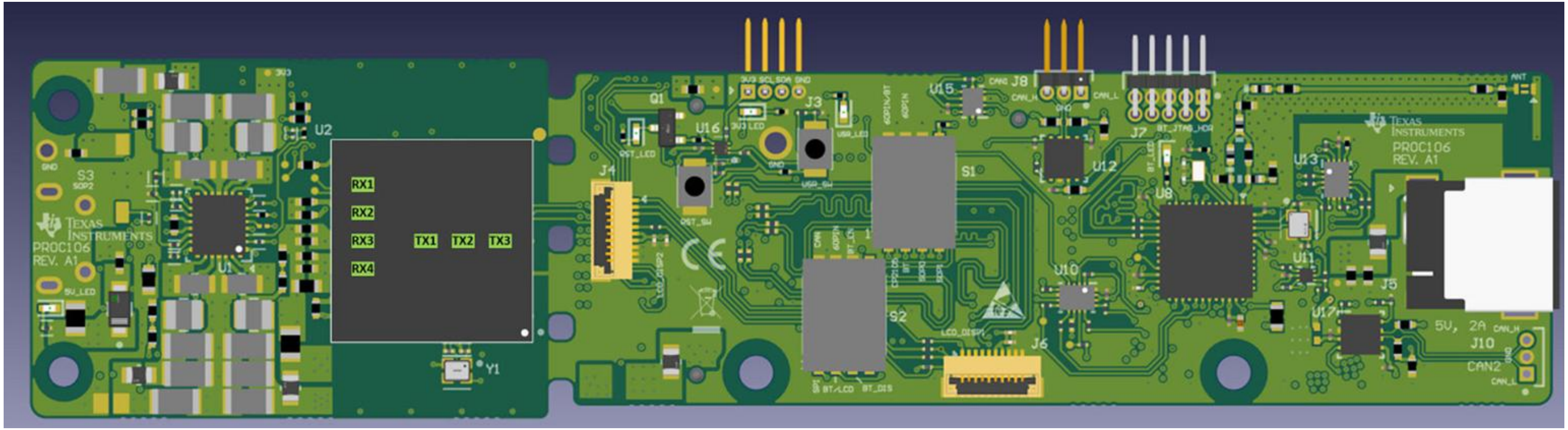
The total resulting virtual array of the 16x16 combined elements is shown in the Antenna Near-Regular Array Configuration figure.



Single-chip vs cascade

	Single chip	Cascade
Channels	2×4 to 8×8	**12×16 and beyond**
Angular resolution	a few degrees	**about a degree**
LO distribution	on-die	**fan-out on PCB**
Sync and calibration	one device	**frame sync and per-chip calibration**
Thermal	single die	**drift between dies**
Board area and power	fairly small	**scales with device count**
Data volume	100s of mbps	**scales with channel count**

Antenna-on-package



Launch-on-package

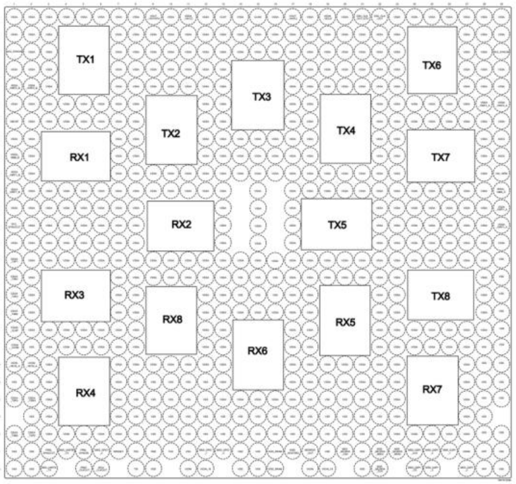
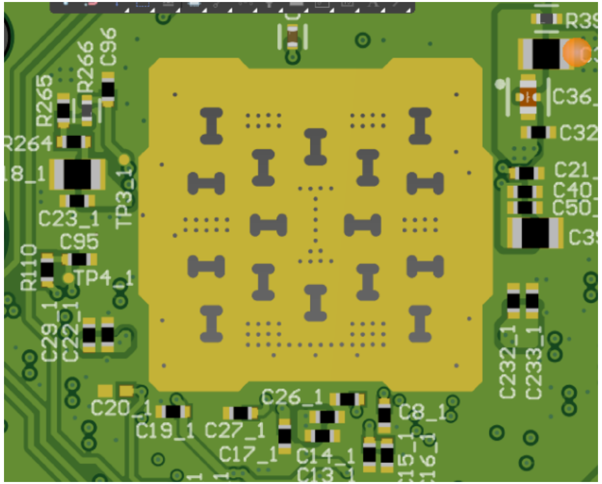
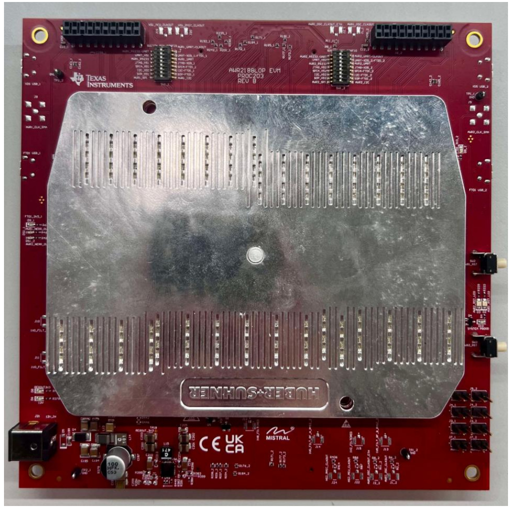


Figure 6-1. Pin Diagram





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Review: Chirp Design

- **Target range resolution ⇒ bandwidth**
  - Tradeoff: bandwidth & adc buffer size are limited
- **Max doppler ⇒ chirp rate**
  - Tradeoff: limited by ADC sample rate, chirp slope
- **Doppler resolution ⇒ # chirps per frame**
  - Tradeoff: lower framerate, blurring

Range (fast-time FFT)

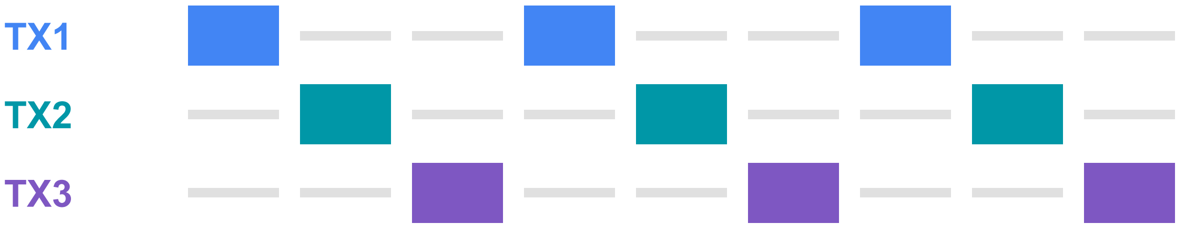
- Beat frequency: $f_b = S t_d = \frac{2Sr}{c} \Rightarrow r = \frac{f_b c}{2S}$
- Resolution: $\Delta r = \frac{c}{2B}$
- Max range: $R_{\max} = N\,\Delta r = \frac{F_s c}{2S}$
- Real-valued ADC (no I/Q): only $N/2$ usable bins, $f_{b,\max} = F_s/2$, so $R_{\max} = \frac{F_s c}{4S}$

Doppler (slow-time FFT)

- Round-trip phase: $\phi \approx 2\pi f_0 t_d = 4\pi r/\lambda$
- Per-chirp advance: $\Delta\phi_{dop} = \frac{4\pi v}{\lambda} T_c \Rightarrow v = \frac{\Delta\phi_{dop}\,\lambda}{4\pi T_c}$
- Doppler shift: $f_d = 2v/\lambda$
- Resolution: $\Delta v = \frac{\lambda}{2 N_d T_c}$
- Max unambiguous: $|v| \le v_{\max} = \frac{\lambda}{4T_c}$ (from $|f_d| \le \frac{1}{2T_c}$, or $|\Delta\phi_{dop}| < \pi$)

Time Division Multiplexing (TDM)

Round robin, N_tx = 3



	N_tx = 3
SNR loss $-10 \log_{10}$ N_tx	−4.8 dB
Max unambiguous velocity v_max ÷ N_tx	÷ 3
Angle bias from Doppler phase drifts between TX slots	small (at low speeds)

Time Division Multiplexing (TDM)

	N_tx = 3	N_tx = 16
SNR loss $-10 \log_{10}$ N_tx	−4.8 dB	**−12 dB**
Max unambiguous velocity v_max ÷ N_tx	÷ 3	**÷ 16**
Angle bias from Doppler phase drifts between TX slots	small (at low speeds)	**grows with N_tx**

Doppler Division Multiplexing (DDM)

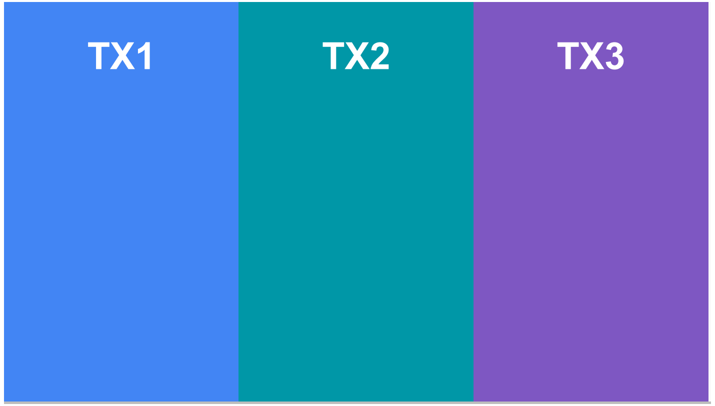
Every TX on every chirp

TX1	0	0	0	0	0	0	0
TX2	0	⅓	⅔	0	⅓	⅔	0
TX3	0	⅔	⅓	0	⅔	⅓	0

phase increment in units of 2π

$\Delta\varphi_k = 2\pi k / N\_tx$ per chirp, per TX

After the Doppler FFT



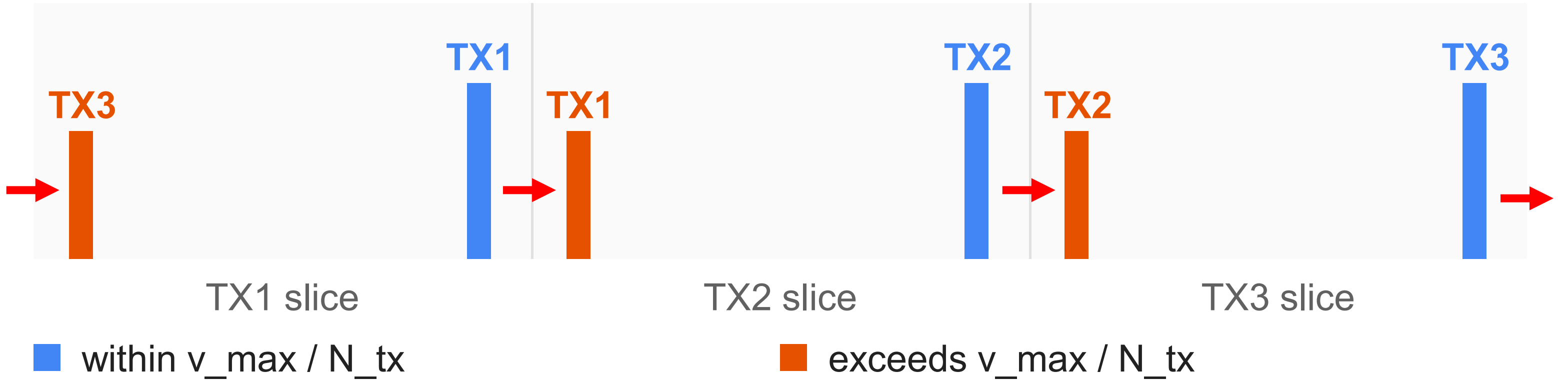
DDM: Velocity Ambiguity

Gain

Full TX duty cycle; no lost gain

Cost

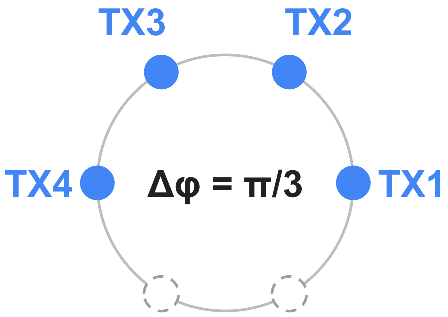
v_max still ÷ N_tx

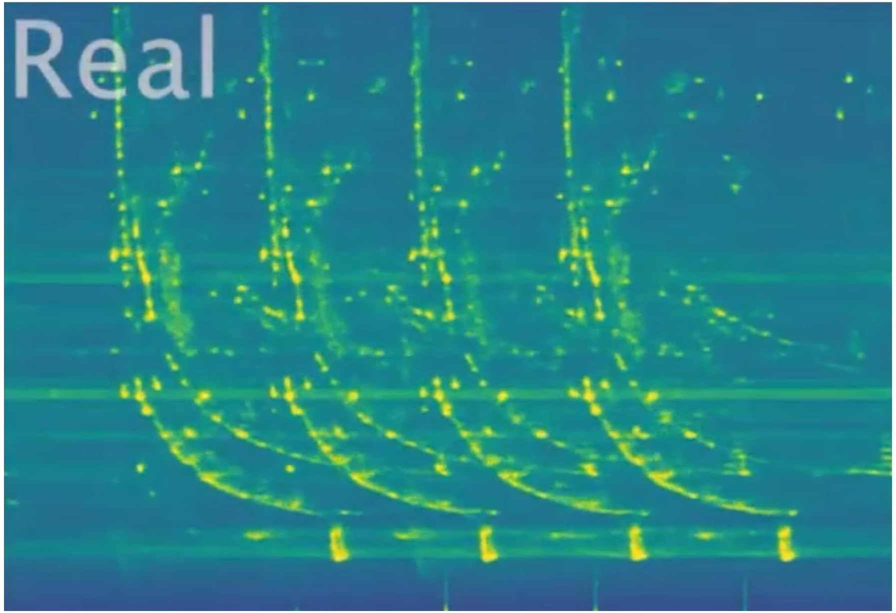


DDM: Velocity Ambiguity Resolution (VAR)

"Empty band" DDM VAR:

- Reserve empty slot(s)
- Each target appears once for each slot
- The first appearance after the "empty" slot is TX1



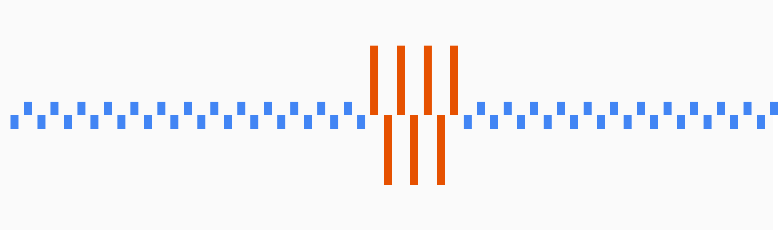


Other VAR Methods

- Make virtual elements from different TX coincide
  - More advanced version: compute angular spectrum for each TX and evaluate where they coincide
- Use coded doppler shifts
- …

Interference mitigation

Time domain



interferer crossing → burst

After the range FFT

noise floor rises — no false target

Toolkit

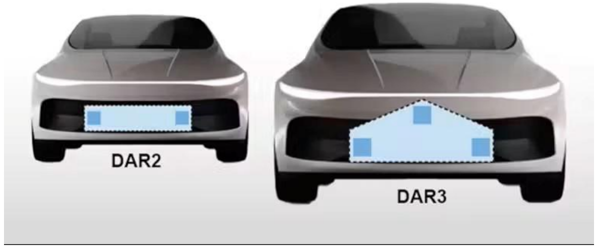
Chirp randomisation
signed slope and start frequency vary

Frequency hopping
between frames

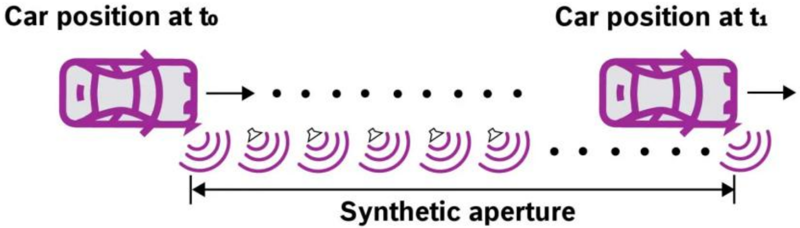
Detect and repair
blanking → reconstruction

Beyond single-radar, range-Doppler

Distributed aperture radar



Synthetic aperture radar



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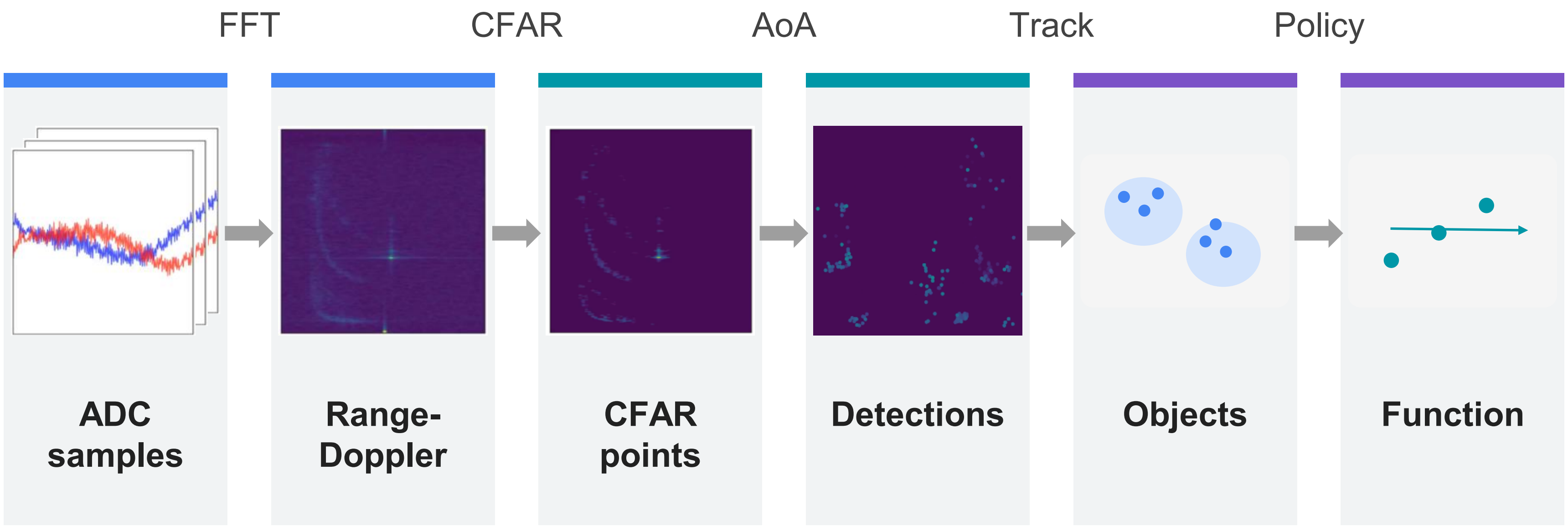
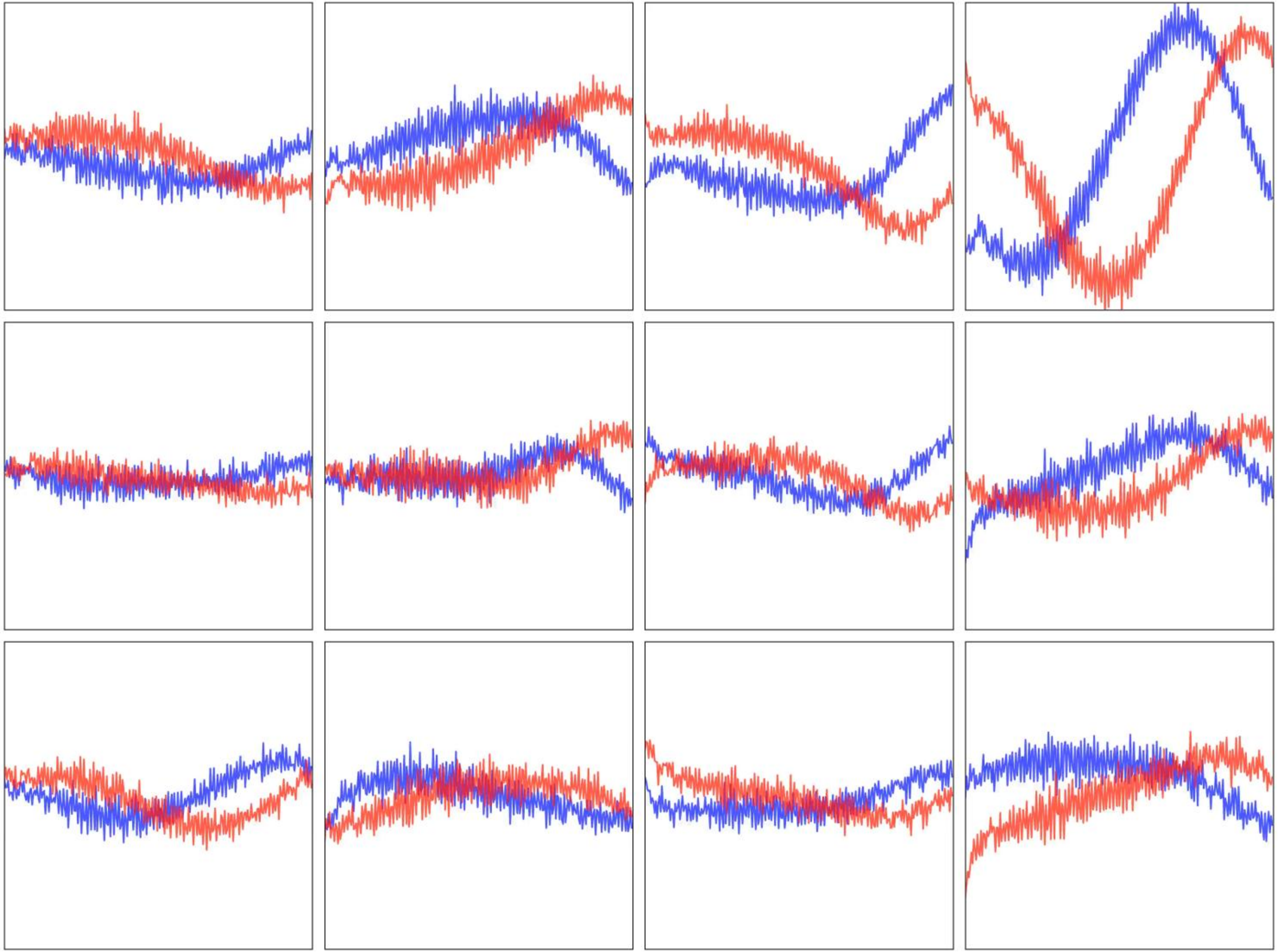
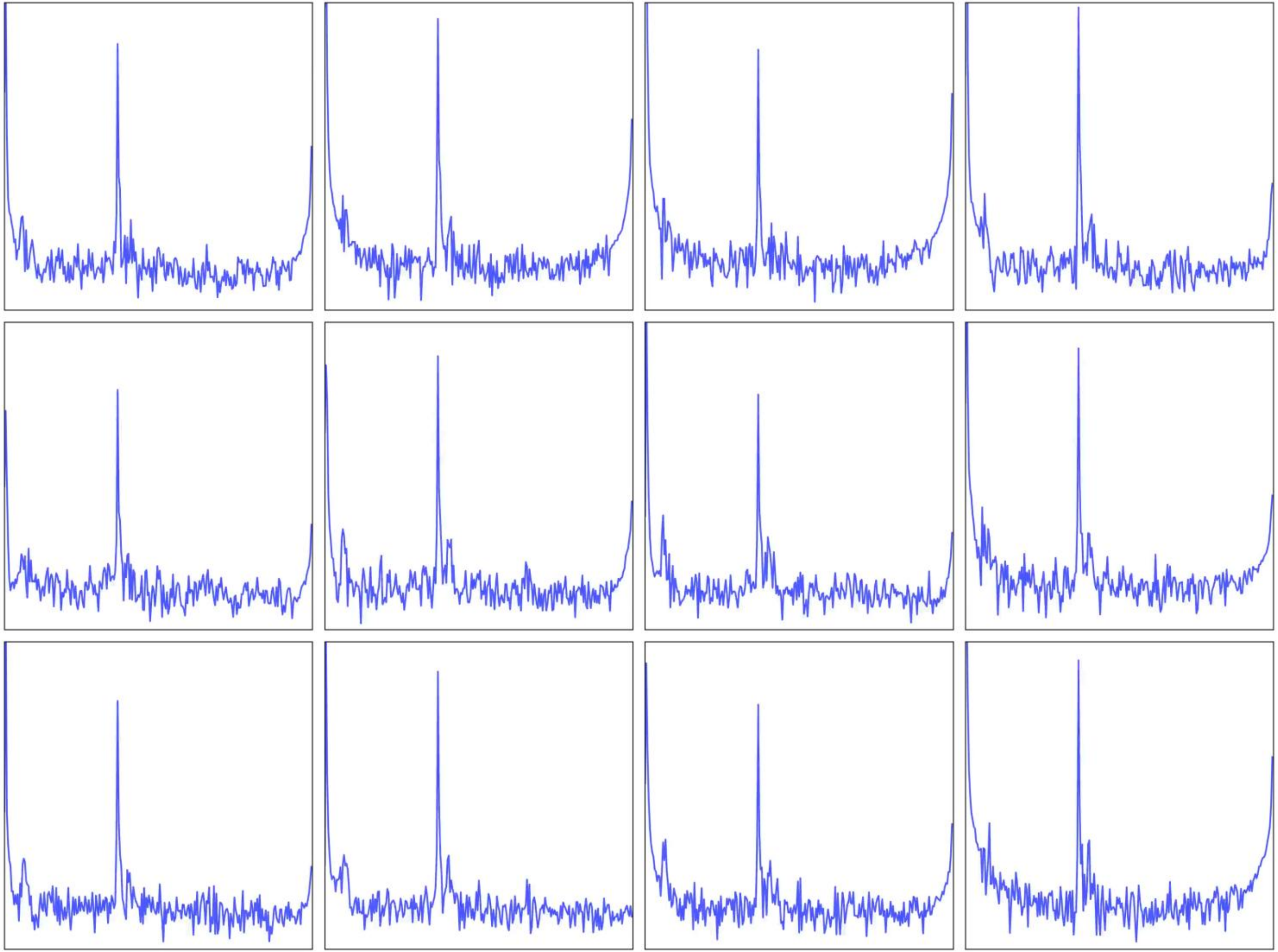
Classical Radar Signal Processing Pipeline



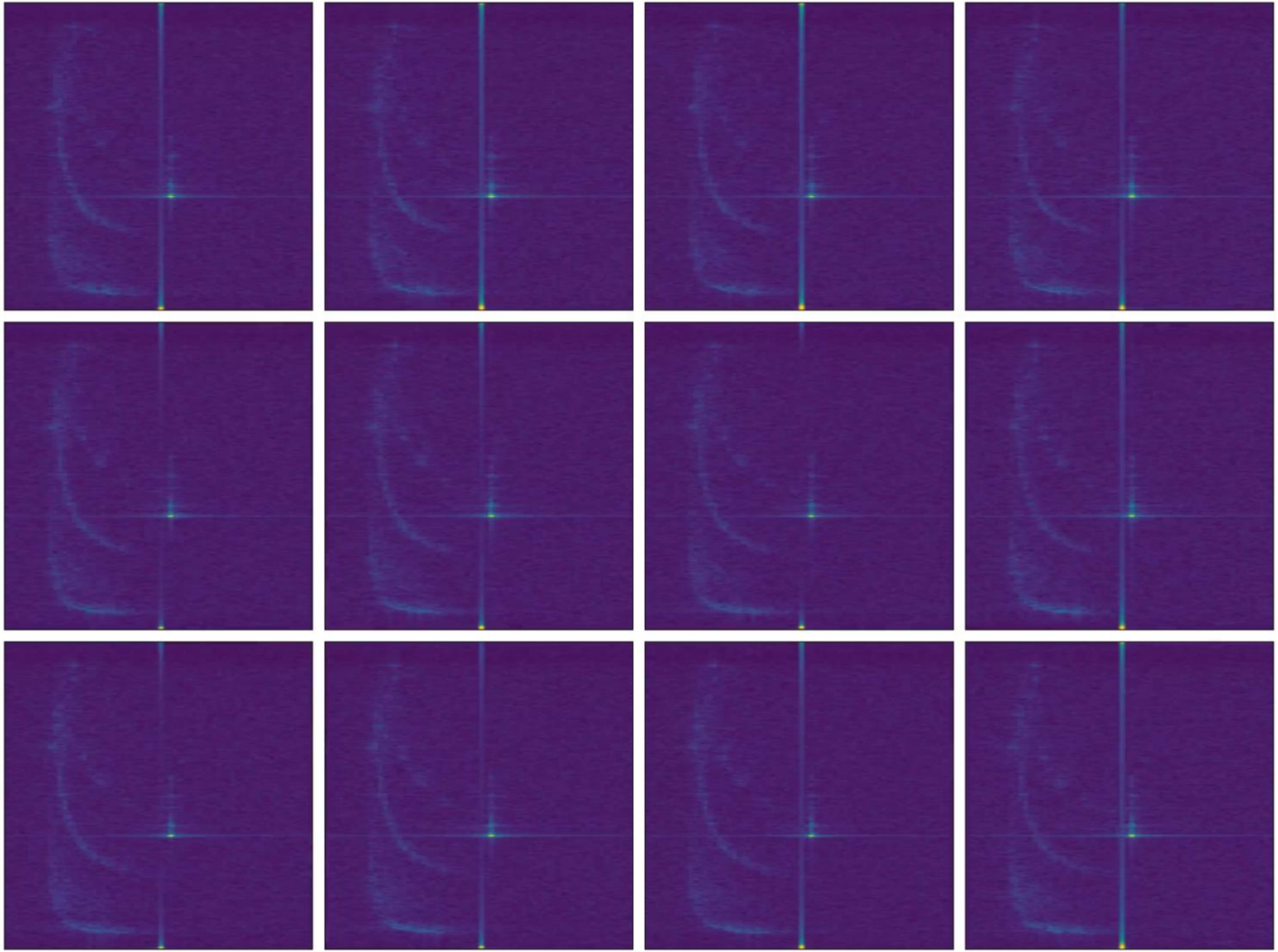
Time
Signal



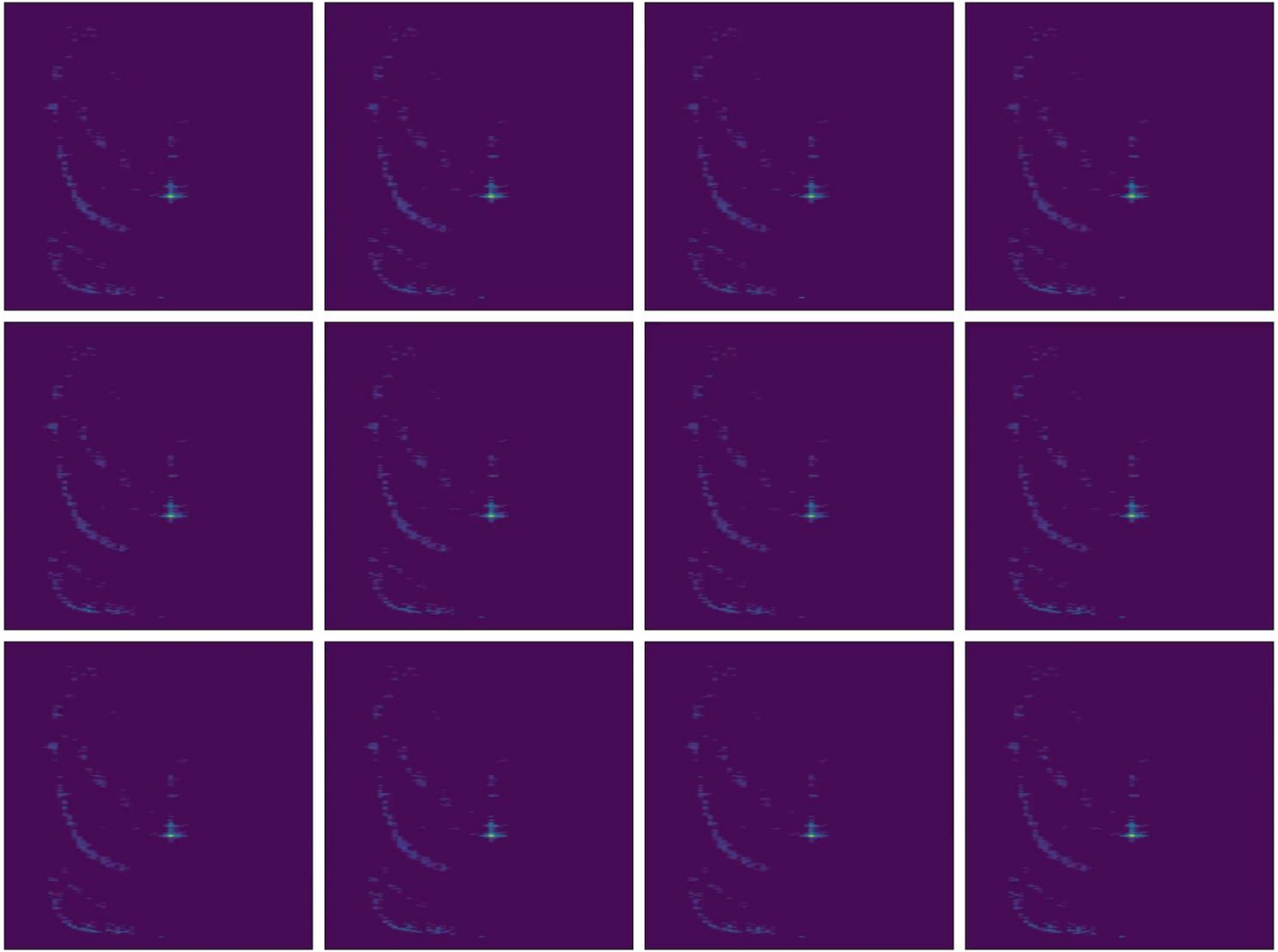
Range Spectrum



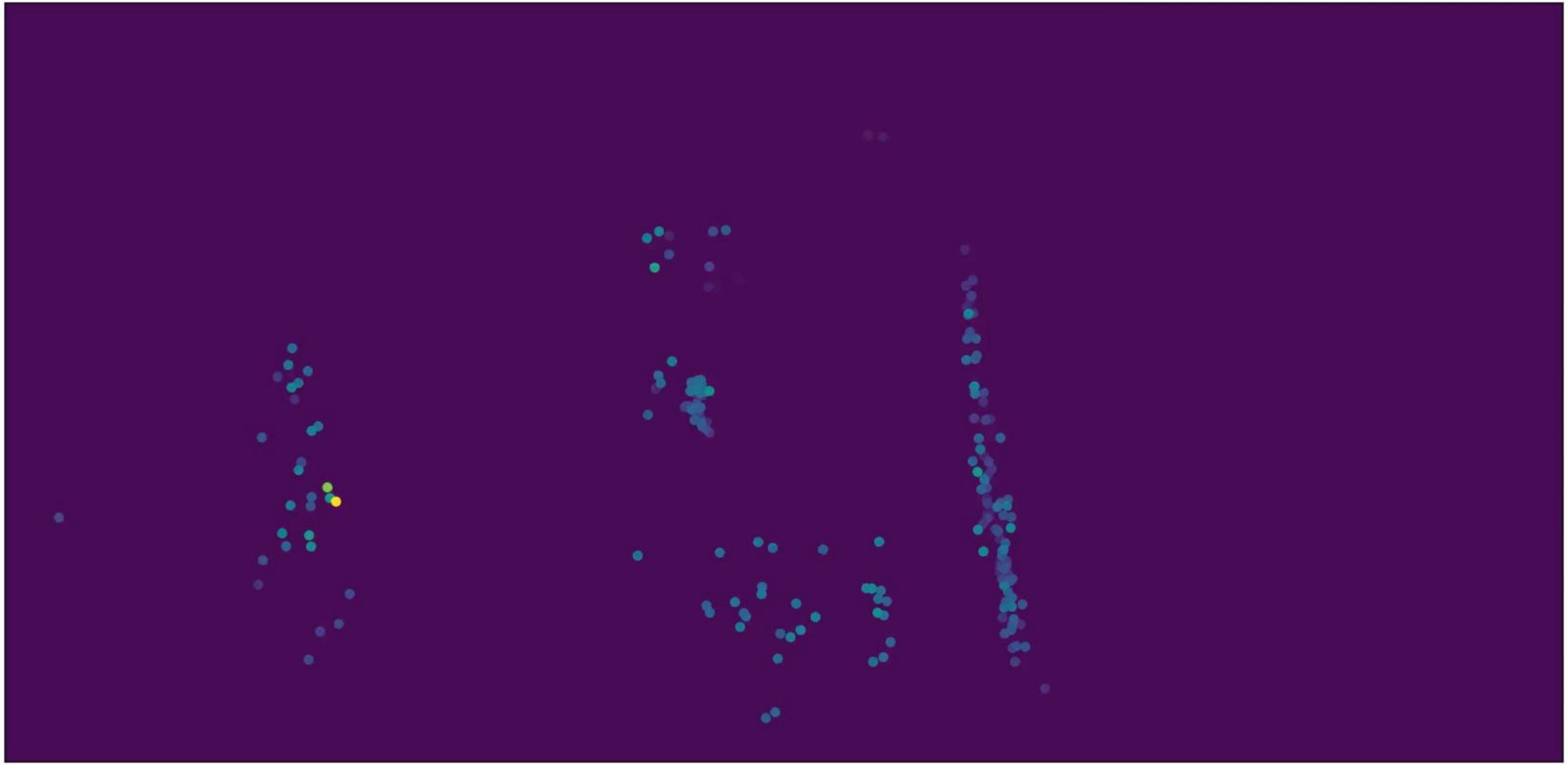
Range-Doppler



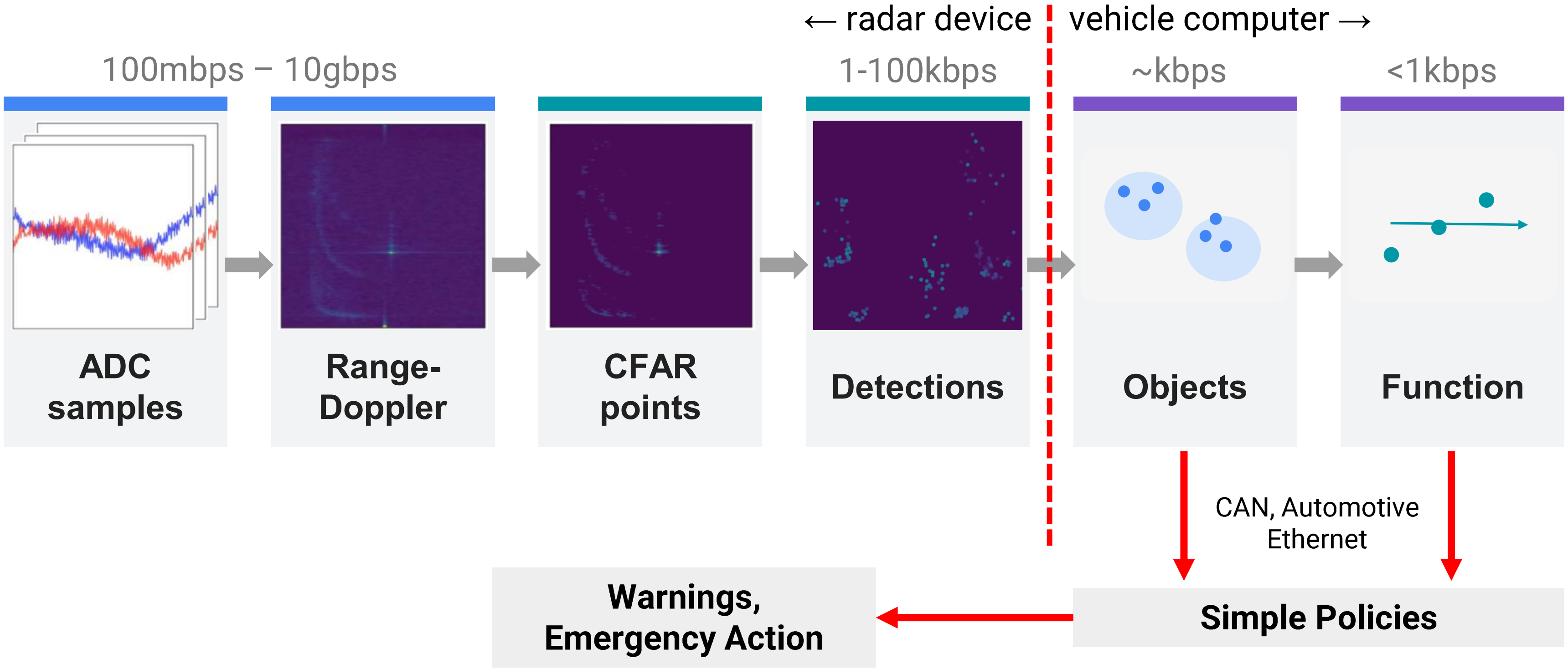
CFAR



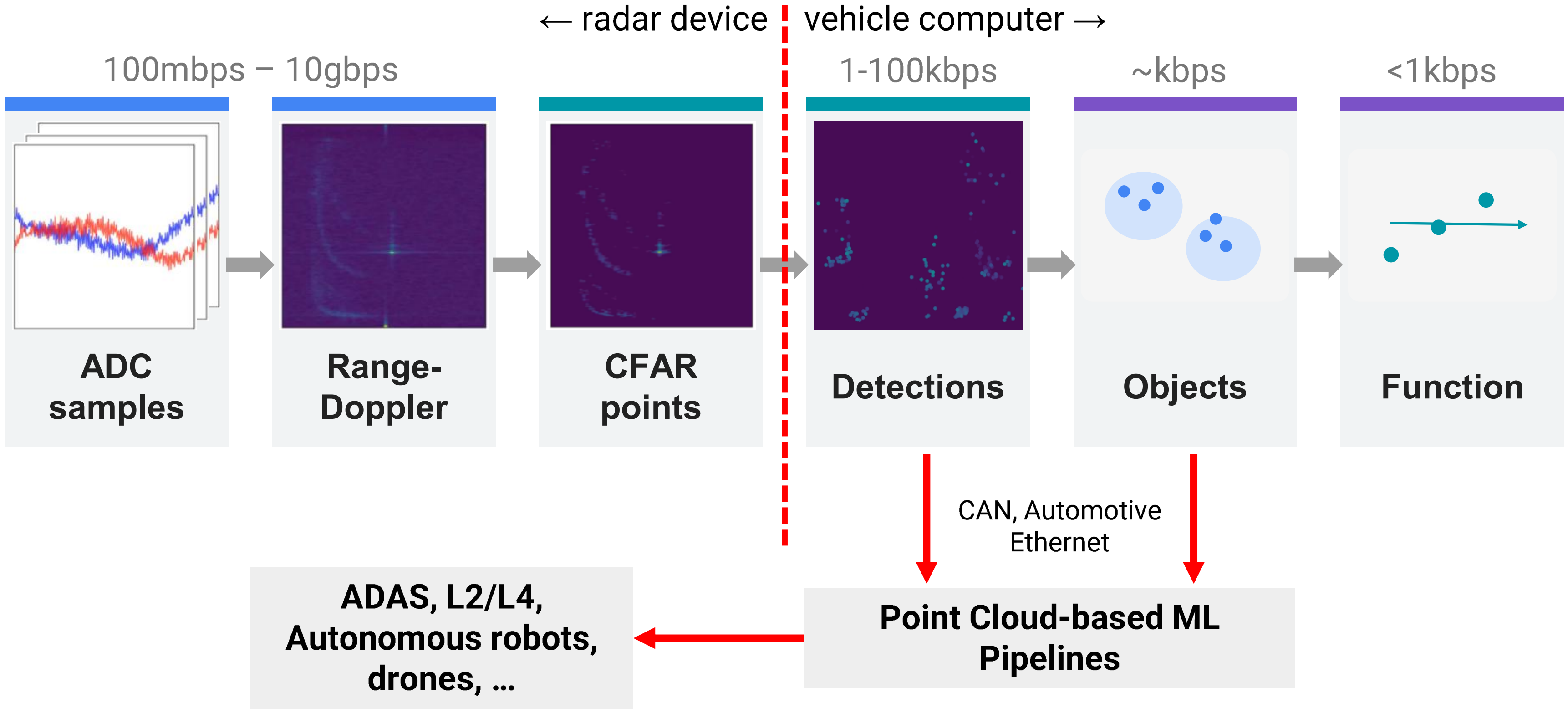
AoA Estimation



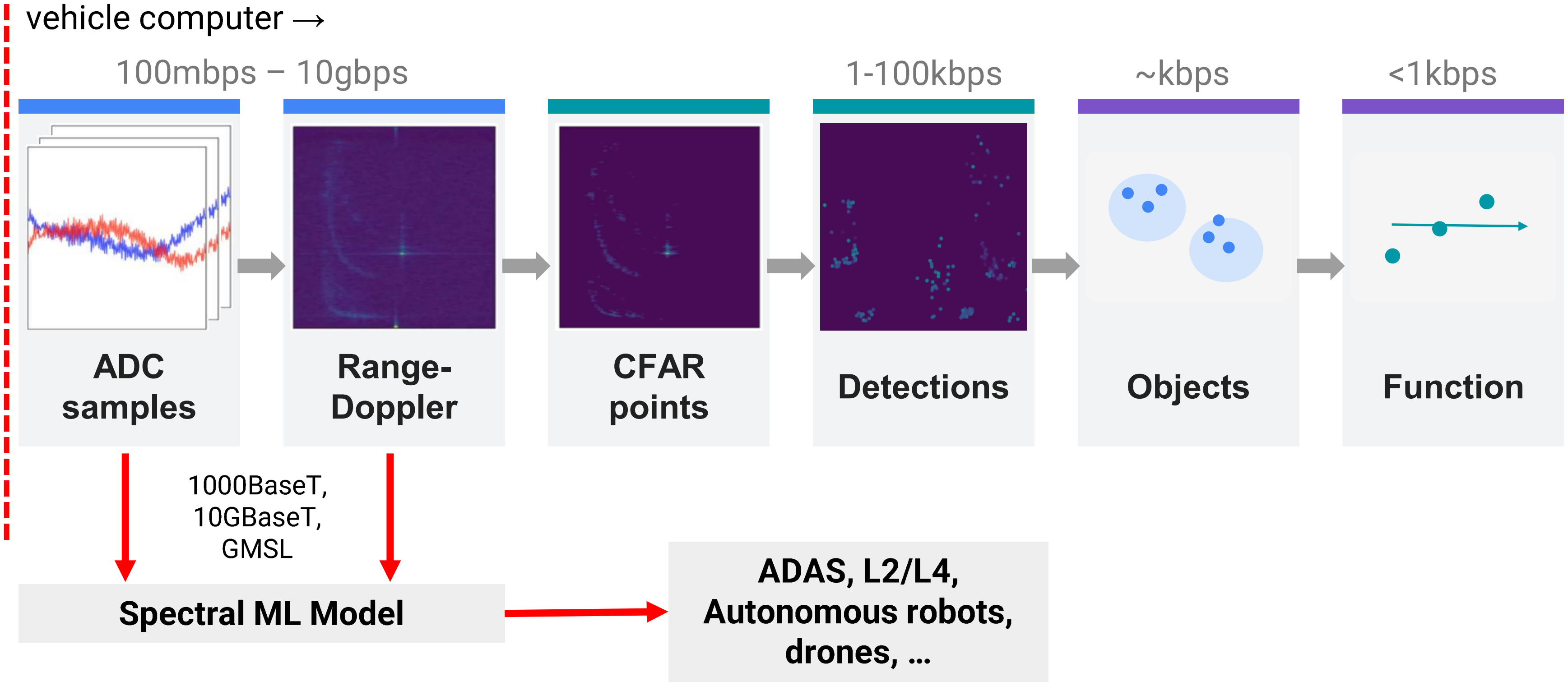
Traditional Systems



Point Cloud Perception



Spectral Radar Perception



Edge vs Central Architectures

	Edge	Central
Data Rate	Negligible (~kbps)	**High (>100mbps)**
Data Density	Low (100-1000 points)	**High (dense data cube)**
Vehicle Computer	No special requirements	**Requires powerful accelerator**
R&D Cost for OEMs	Low to None	**Requires ML expertise**
Flexibility to Change	Low	**High (easy OTA updates)**

Summary

Requirement	Hardware	Design Decision
Range resolution	Chirp bandwidth	Frequency band (60 vs 76 vs 77 GHz)
Max range	Power and antenna gain	Frequency band, antenna design, packaging
Field of view	Element design and spacing	
Velocity resolution	Frame duration (chirps per frame)	Modulation and signal processing pipeline
Max unambiguous velocity	Chirp repetition time	
Angular resolution	Virtual array size	Radar silicon, single-chip vs cascade
Perception Pipeline	Data rate and compute capability	Edge vs central

Next Time

From Blips to Bounding Boxes:
The Evolution of Automotive Radar Perception

Michael Ulrich

Senior Expert, AI Perception & Signal Processing, Bosch