

radar2024.sau.ac.ir

نهمین کنفرانس ملی رادار و سامانه های مراقبتی ایران

9th Iranian National Conference on
Radar and Surveillance Systems



An Introduction to mmWave 4D Imaging Massive MIMO Radars



Mohammad Alaee
University of Luxembourg, SnT, SPARC

25 February 2025

mohammad.alae@uni.lu

Luxembourg

Capital and largest city

Luxembourg
49°36'38"N 6°07'58"E

Official Languages

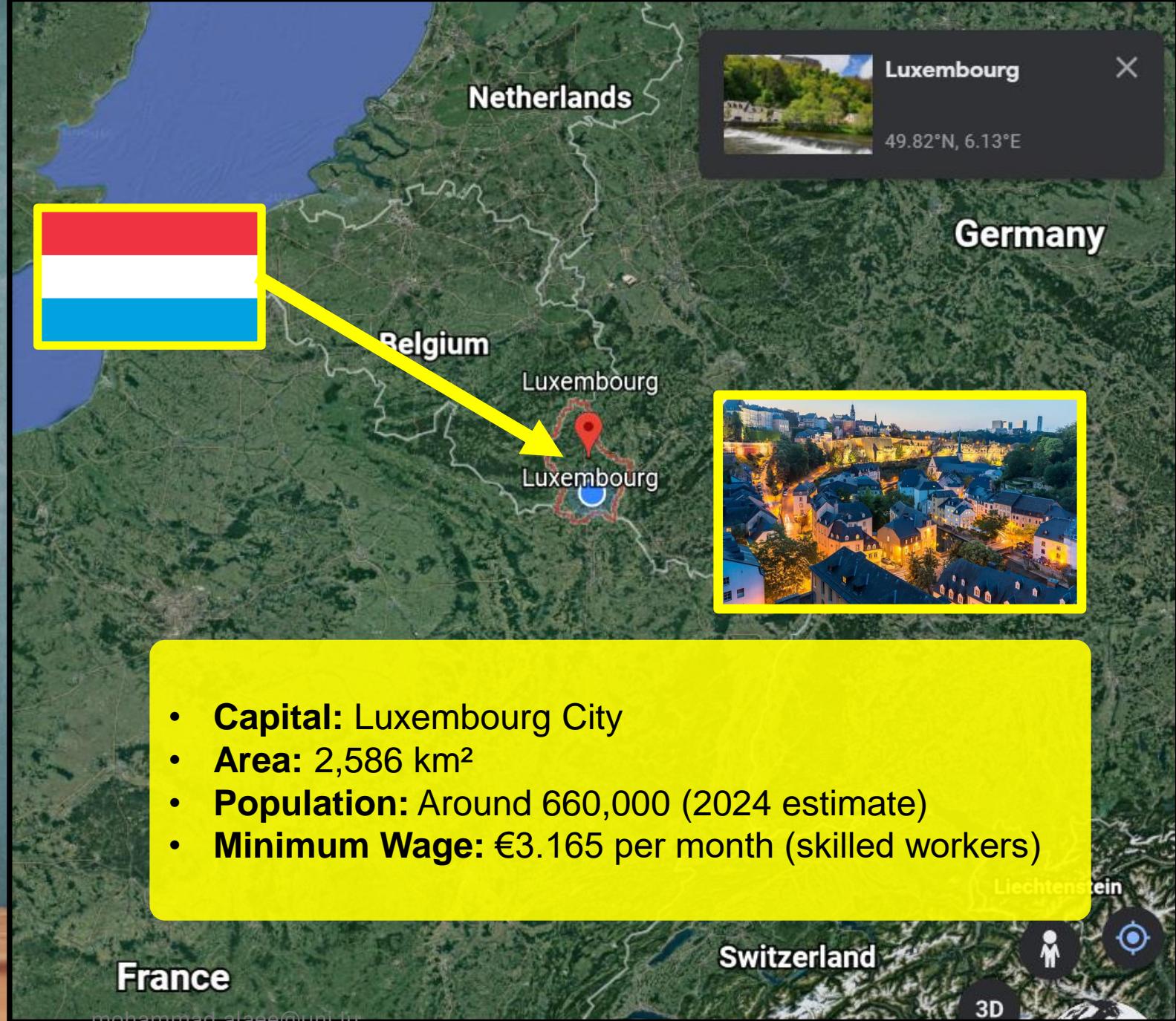
languages:

- Luxembourgish
- German
- French

Nationality (2023)

- 52.8% Luxembourgers
- 14.5% Portuguese
- 7.6% French
- 3.7% Italians
- 21.4% other

Luxembourg is the wealthiest country in the European Union, per capita, and its citizens enjoy a high **standard of living**.



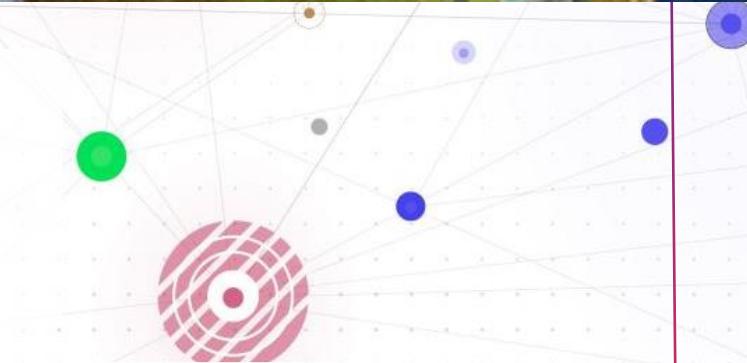
University of Luxembourg



7000
students

300
faculty members
130
nationalities

60%
international
students



World University Ranking by subject 2024

- 68 in Law
- 126-150 in Computer Science
- 151-175 in Engineering
- 151-175 in Education
- 176-200 in Psychology
- 201-250 in Life Sciences
- 201-250 in Arts and Humanities



20th Young University

worldwide and #3 worldwide
for its “international outlook” in
the Times Higher Education
(THE) World University
Rankings 2024

Founded in 2003

3 Faculties



Faculty of Science,
Technology
and Medicine



Faculty of Humanities,
Education
and Social Sciences



Faculty of Law,
Economics
and Finance

4 Interdisciplinary Centres



SnT

PEOPLE



500+
Workforce



65+
Nationalities



31%
Alumni who stay
in Luxembourg



50%
Doctoral
Candidates on
Industrial Projects

PARTNERSHIPS & INNOVATION



65+
Partners



8M
Partners annual
contribution in Euros



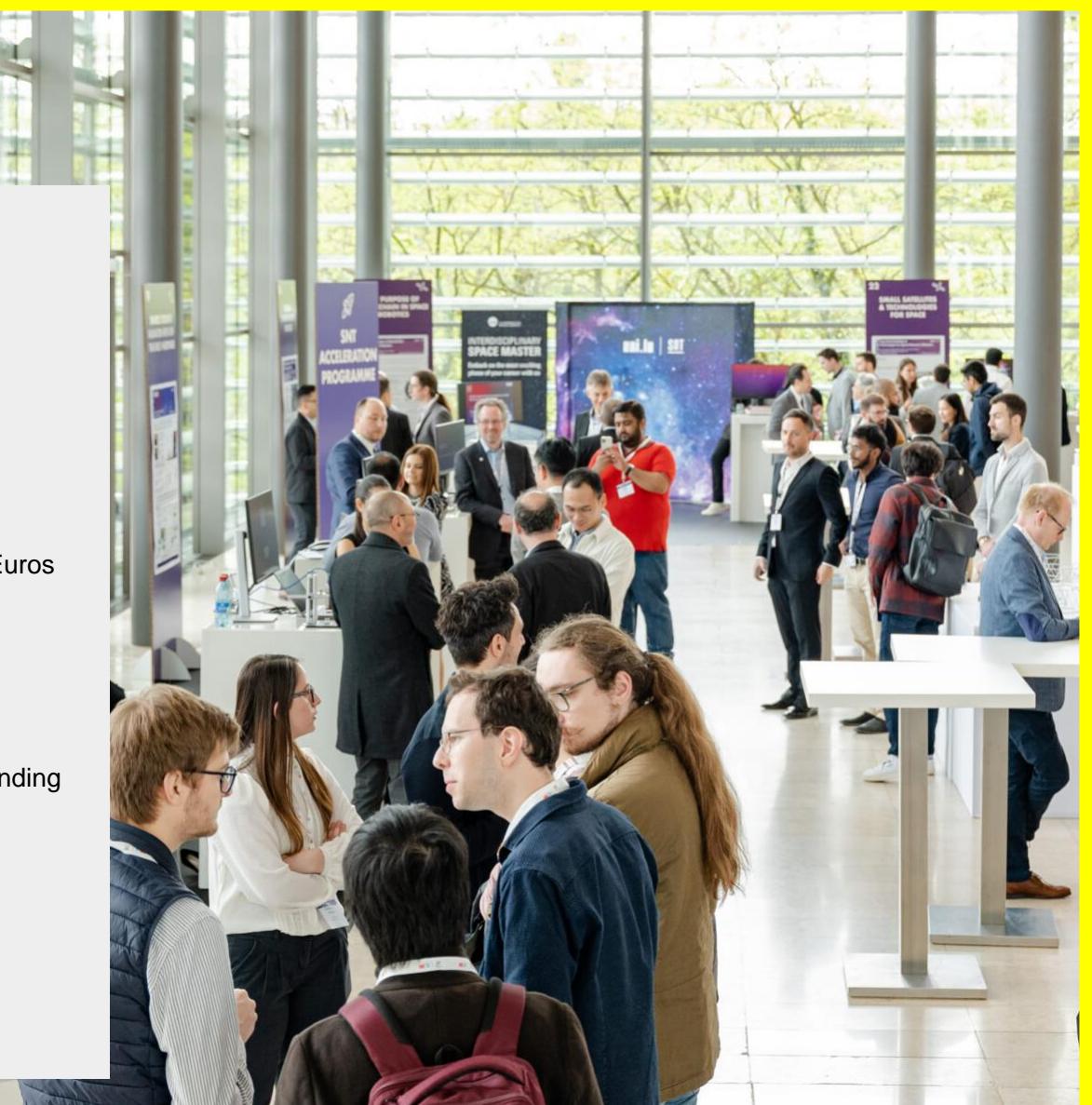
70%
External project funding



6
Spin-offs

mohammad.alaeed@uni.lu

uni.lu
UNIVERSITY OF
LUXEMBOURG





Applied Security and Information Assurance Group
(APSIA)



Automation & Robotics (ARG)



Critical and Extreme Security and Dependability
(CritiX)



CryptoLUX



Computer Vision, Imaging and Machine Intelligence
(CVI2)



Entrepreneurship, Innovation and New Technology
Research Group (EINT)



Digital Financial Services and Cross-Organisational
Digital Transformations (FINATRAX)



Sociotechnical Cybersecurity (IRiSC)



Parallel Computing & Optimisation (PCOG)



Services and Data Management



Security Design and Validation



Signal Processing and Communications



Space Robotics (SpaceR)



Signal Processing Applications in Radar and
Communications (SPARC)



Space Systems Engineering (SpaSys)



Trustworthy Software (TruX)



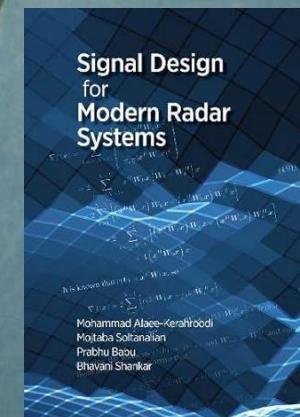
Software Verification and Validation (SVV)



Ubiquitous and Intelligent Systems (UBIX)



mohammad.alaeen@uni.lu



Alae-Kerahroodi,
Mohammad, et al. *Signal
design for modern radar
systems*. Artech House, 2022.



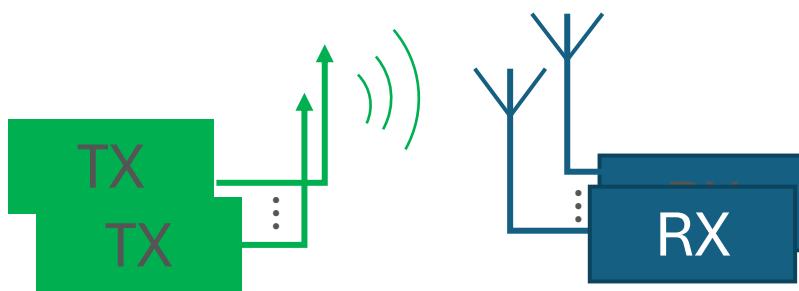
UNIVERSITY OF
LUXEMBOURG

An Introduction to **mmWave 4D** Imaging Massive MIMO Radars

mohammad.alae@uni.lu

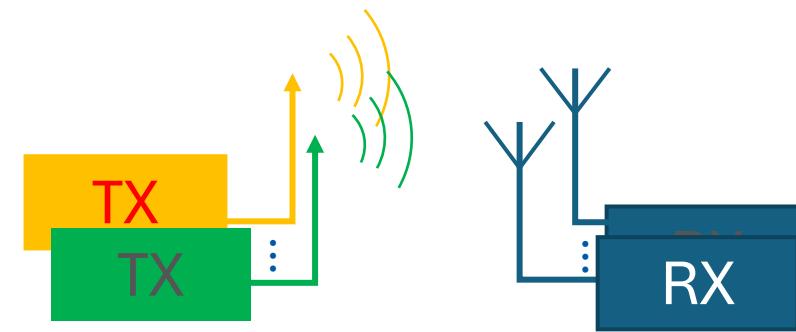
- ❑ What is a MIMO Radar?
- ❑ Array Sparsity in MIMO radar
- ❑ 4D imaging MIMO Radars
- ❑ Transmit waveform in mmWave and MIMO radars
- ❑ Radar Sensors and Radar on Chip (RoC)
- ❑ Massive MIMO 4D imaging
- ❑ Questions and Discussion

Phased Array



Single Input Multi Output

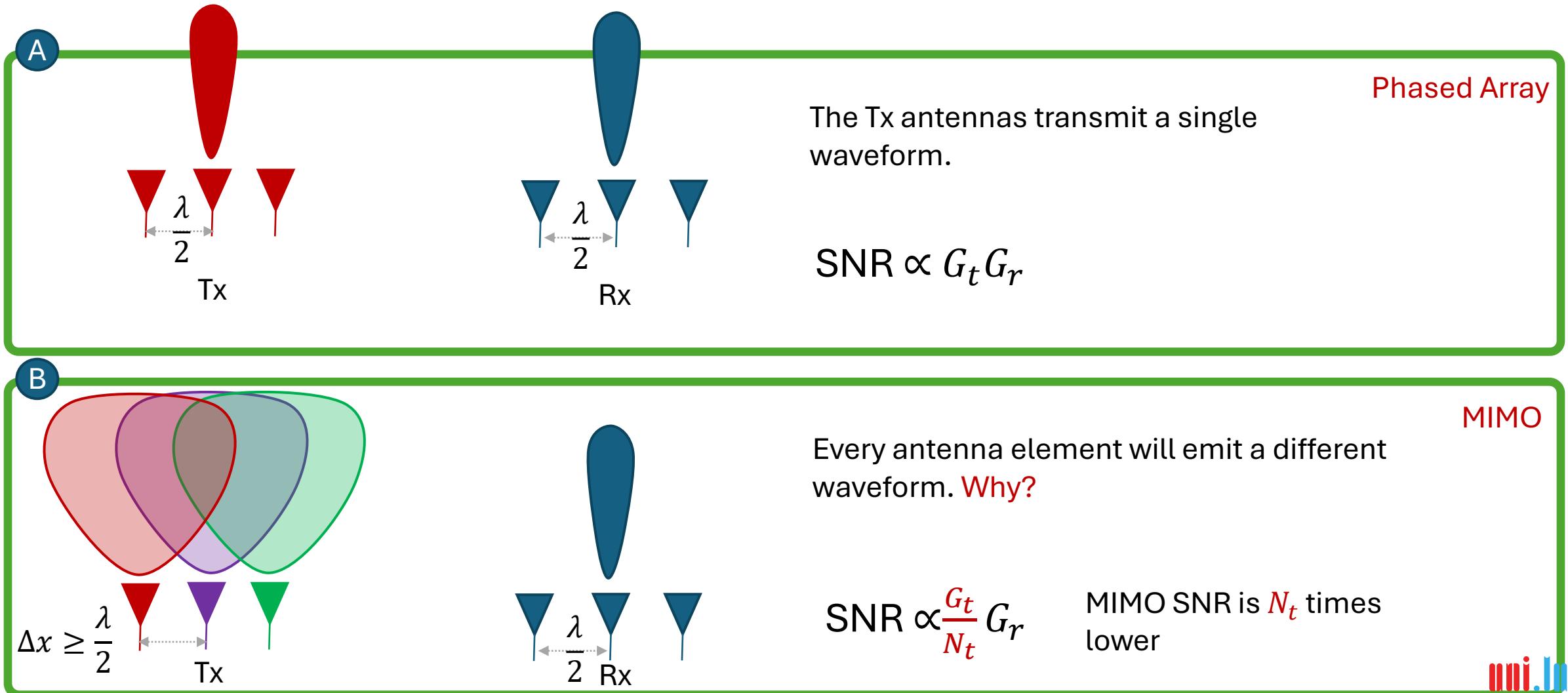
MIMO



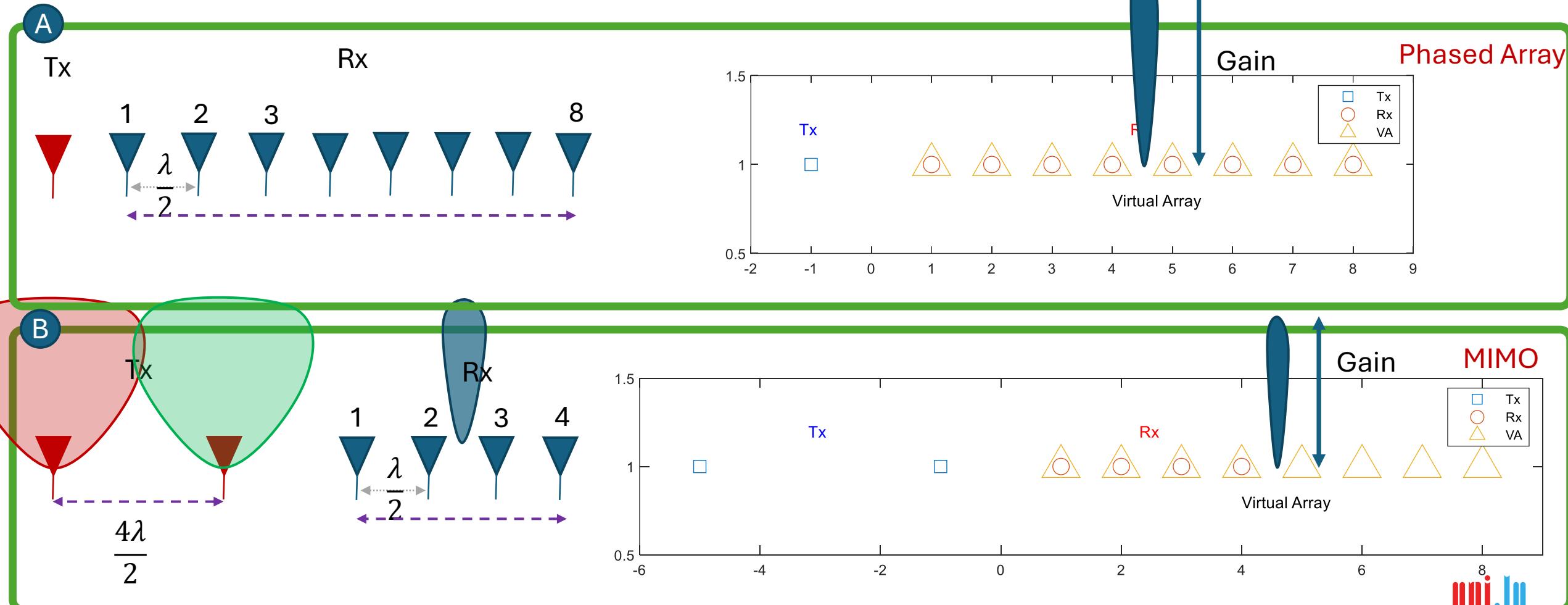
Multi Input Multi Output

Waveform diversity

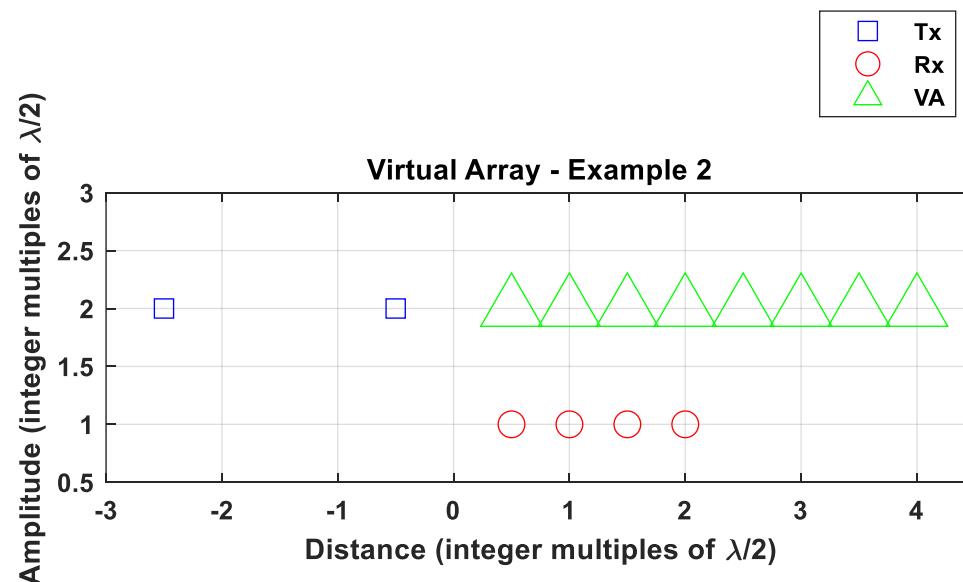
Phase Array and MIMO Radars



Array Sparsity in MIMO Radars

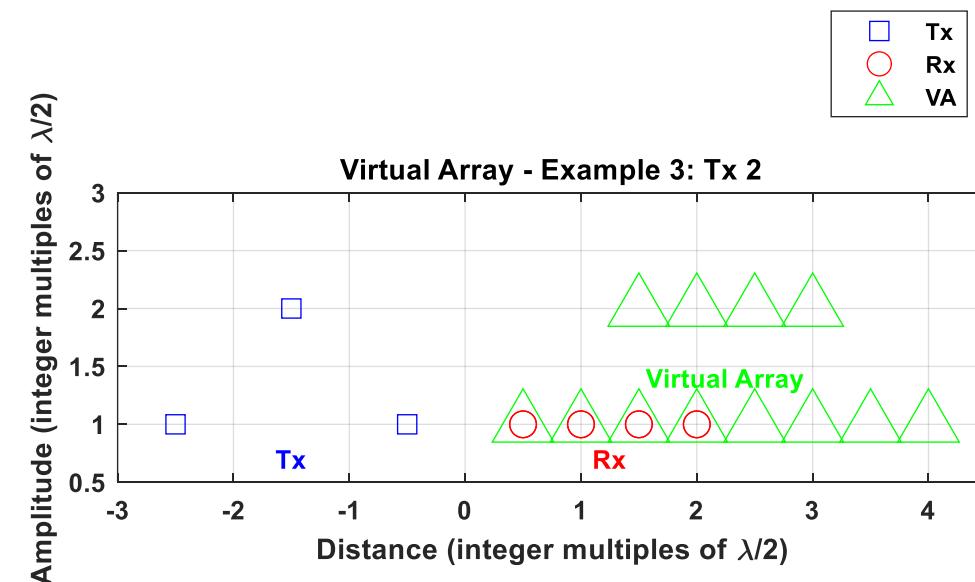


Virtual Array in MIMO Radars



$2 + 4 = 6 \Rightarrow$ physical elements

$2 \times 4 = 8 \Rightarrow$ virtual elements



$3 + 4 = 7 \Rightarrow$ physical elements

$3 \times 4 = 12 \Rightarrow$ virtual elements



<https://radarmimo.com/download-center/>

<https://github.com/radarmimo/Download-Center>

Virtual Array in MIMO Radars

$24 + 24 = 48 \Rightarrow$ physical elements

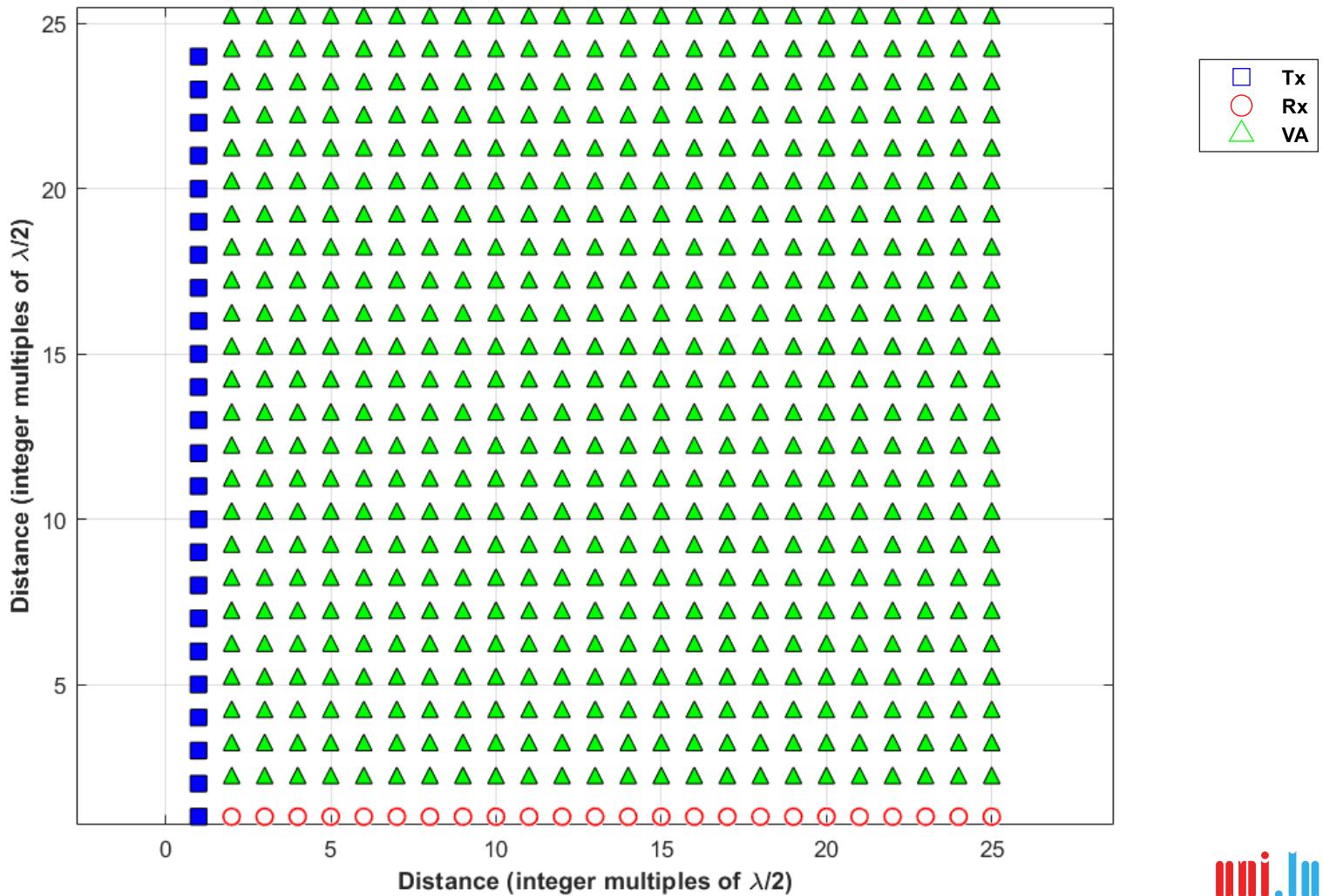
$24 \times 24 = 576 \Rightarrow$ virtual elements

576
Antenna array

4D – imaging MIMO Radar

Range + Azimuth + Elevation +
Doppler

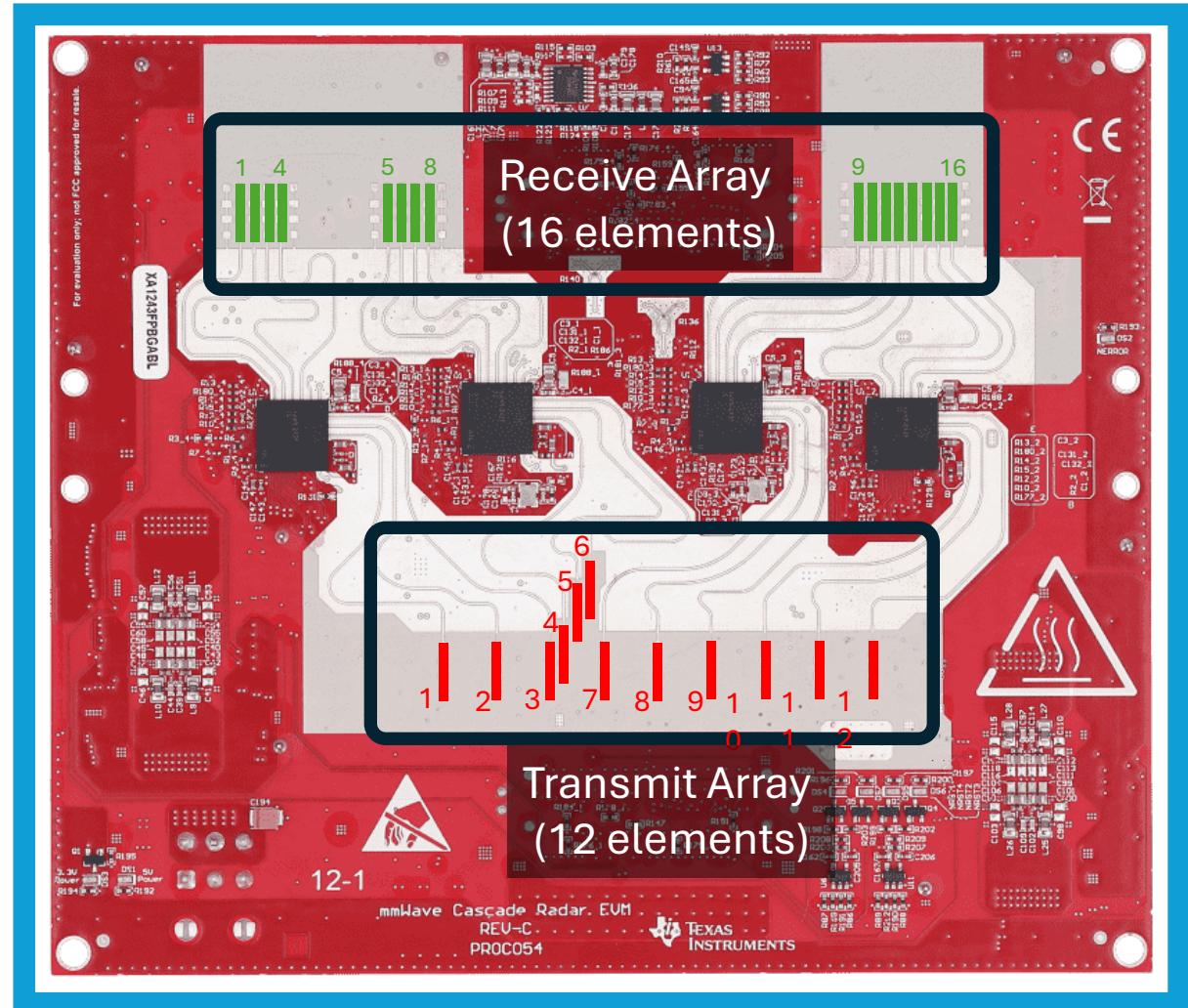
Conventional radars provide range,
velocity, and azimuth but lack height
information.



Example 1: AWR2243 - MMWCAS-RF-EVM

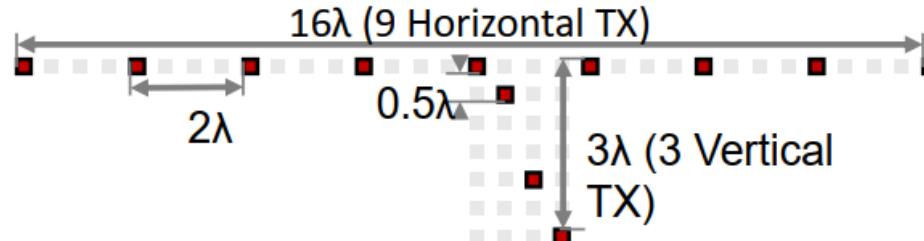
mmWave cascade imaging radar RF evaluation module

4x AWRx 76-81GHz Radar SoC	Integrated VCO, LO distribution, PA, LNA, ADC, 3 TX and 4 RX ARM MCU R4 Controller
12x TX, 16x RX Antennas	<ul style="list-style-type: none">• 12 total transmitters across all 4 AWRx devices• 16 total receivers across all 4 AWRx devices• 86 non-overlapping Azimuth virtual array ($\lambda/2$)• 4 minimum redundancy array (MRA) Elevation
Embedded Antenna	<ul style="list-style-type: none">• 4-element series-fed patch antenna, 12dBi• ± 60 deg Azimuth 3dB• ± 30 deg Elevation 3dB

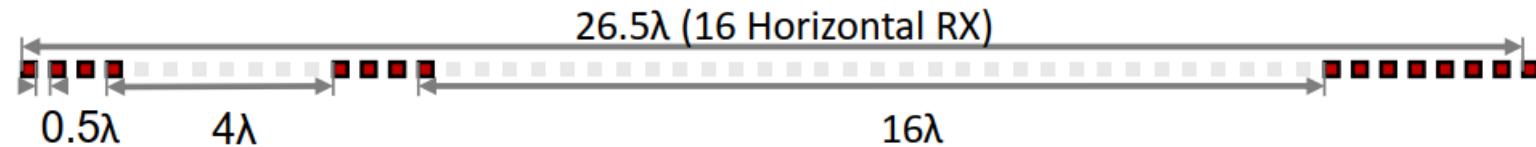


Example 1: AWR2243 - MMWCAS-RF-EVM mmWave cascade imaging radar RF evaluation module

Transmit Array
(12 elements)



Receive Array
(16 elements)



$$16\lambda + 26.5\lambda = 42.5\lambda$$

86-element array 1.8° horizontal resolution

Virtual Array (192 elements)

42.5λ (86 Horizontal Virtual Antennas)

3λ (16 \times 3=48 Vertical Virtual Antennas)

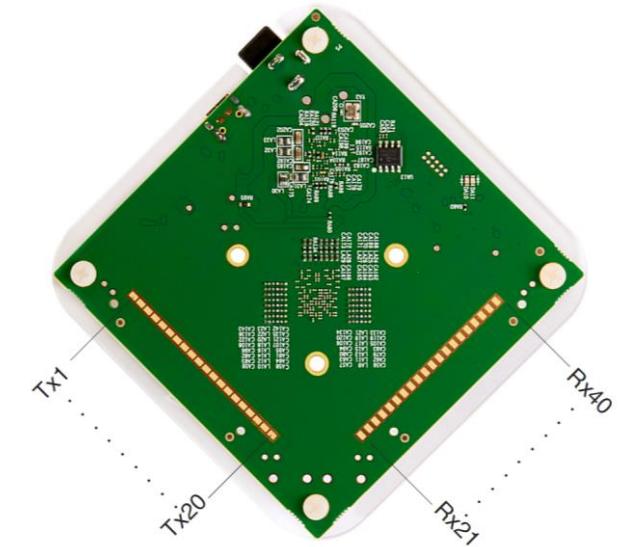
18° elevation resolution

$N \times M$ virtual elements with $N + M$ physical antennas

Example 2: Vayyar (VTRIG-74)



Parameter	Specification	Notes
Transceivers	40 Tx/Rx	Up to 20TX and 20 RX
Frequency Band	62 - 69 GHz	
Field of View (FoV)	Refer to Antenna and RF Characteristics	
RBW	10-800 KHz	
# of points	2-151 Frequency points	
Stop-Start min step	150MHz	
EIRP (Typ.)	-5 dBm	
Max Range Resolution	$\frac{C}{2BW} = \frac{3e^8}{2 \cdot 7e^9} = 2.14\text{cm}$	BW dependent
Range Accuracy	<< Range Resolution	Depends on the target strength and shape
Max Angular Resolution	$\Delta\theta \approx \frac{\lambda}{D} \approx \frac{3e^8}{64e^9 \cdot 0.04} \approx 0.117\text{rad} \approx 6.7\text{deg}$	– Wavelength [@64GHz] D – Length of the array [0.04m] Profile dependent
Angular Accuracy	<< Angular Resolution	Depends on the target strength and shape
Dimensions	PCB: 80 mm x 80 mm Perspex Cover: 90 mm x 90 mm	



Example 3: Phoenix

Perception Radar



Antenna

48 x 48 patch antenna

Array

2X24 TX x 4x12 RX

Frequency

76–81 GHz

Bandwidth

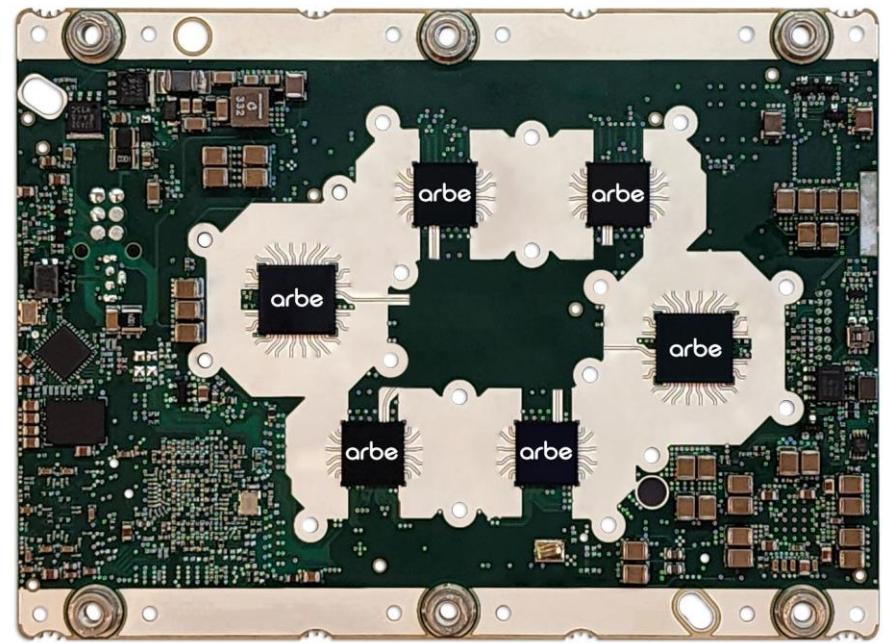
<2 GHz

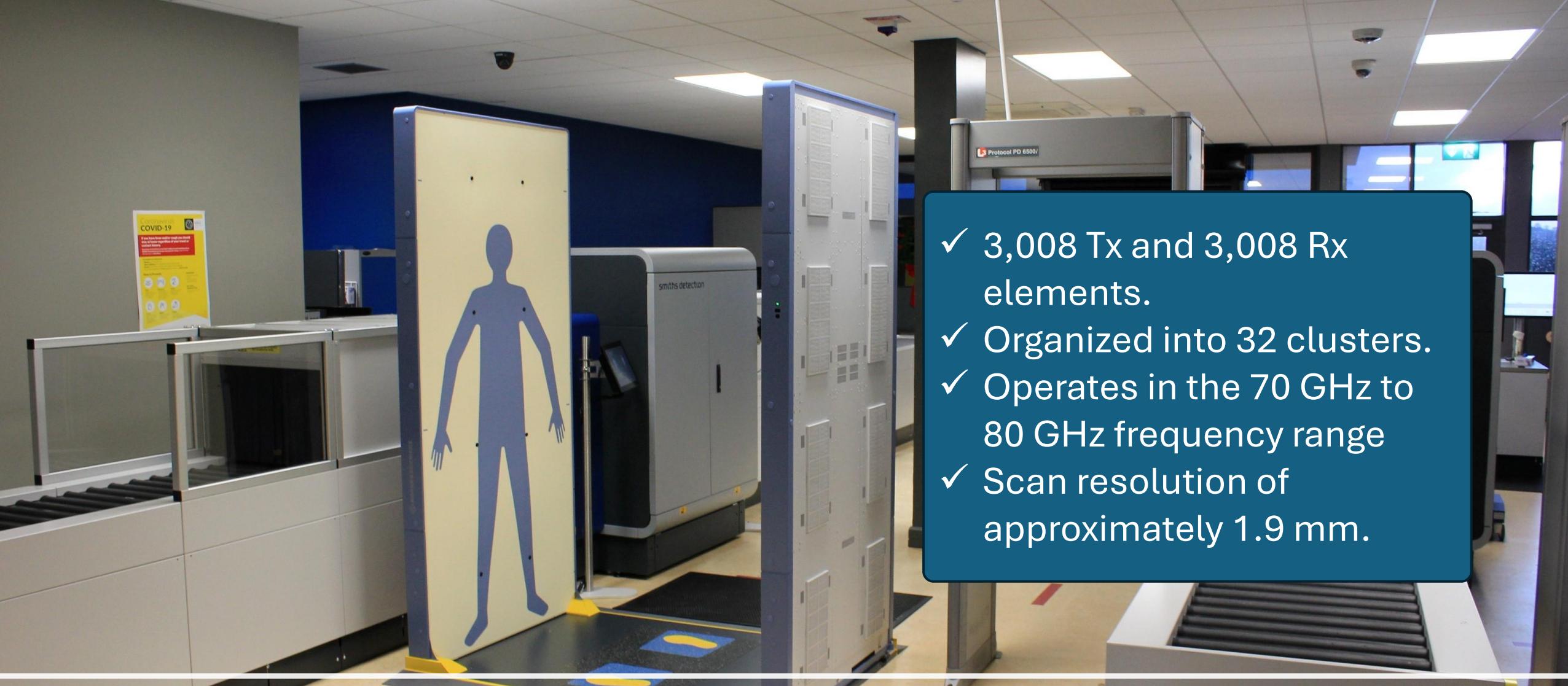
Frame rate

<30 FPS



48 Tx × 48 Rx =
2034 virtual
antennas





- ✓ 3,008 Tx and 3,008 Rx elements.
- ✓ Organized into 32 clusters.
- ✓ Operates in the 70 GHz to 80 GHz frequency range
- ✓ Scan resolution of approximately 1.9 mm.

Example 4: Rohde & Schwarz R&S QPS201 security scanner

LFM Transmit waveform

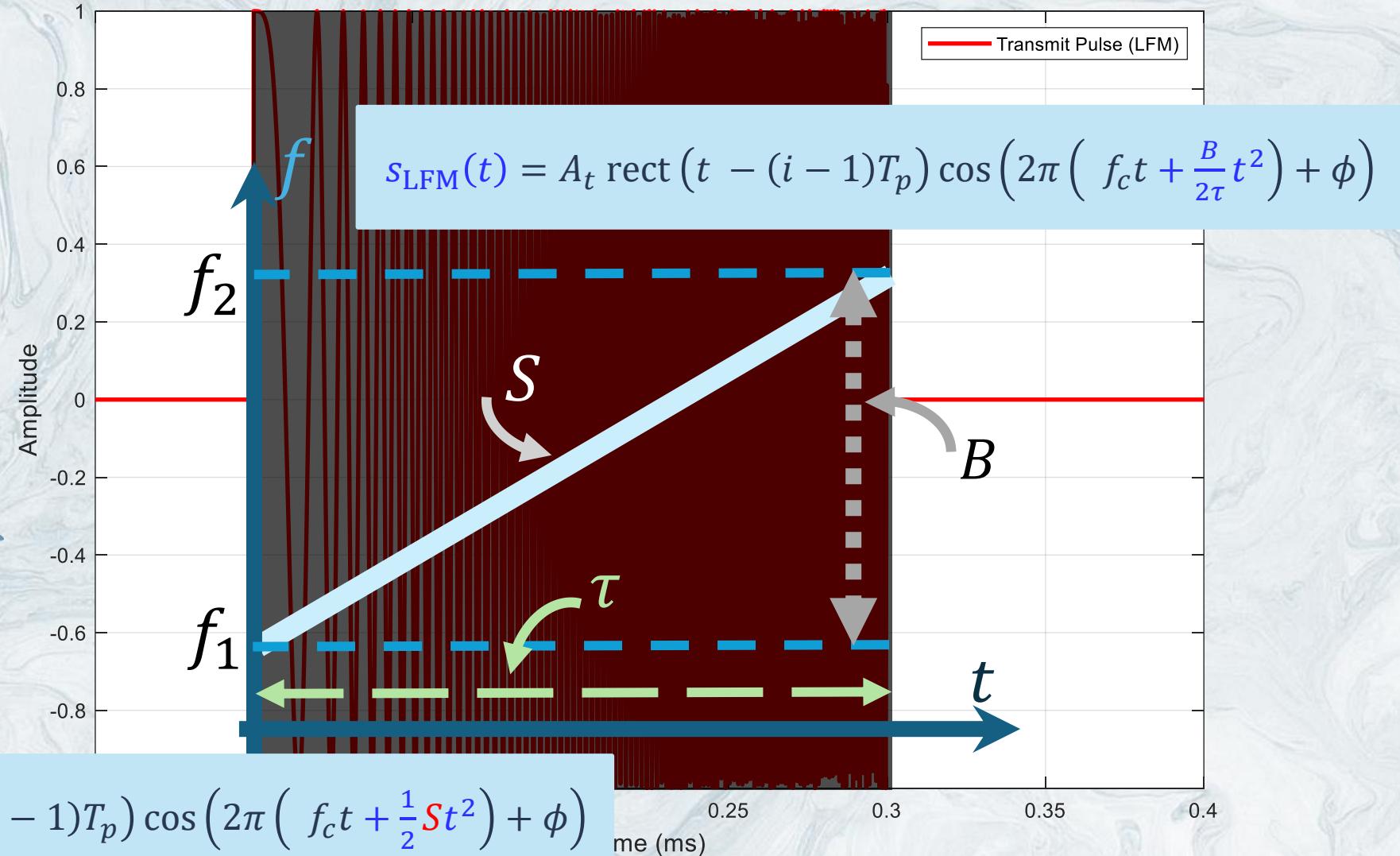
$$B = 1 \text{ MHz}$$

$$\Delta R = \frac{c}{2B} = 150 \text{ m}$$

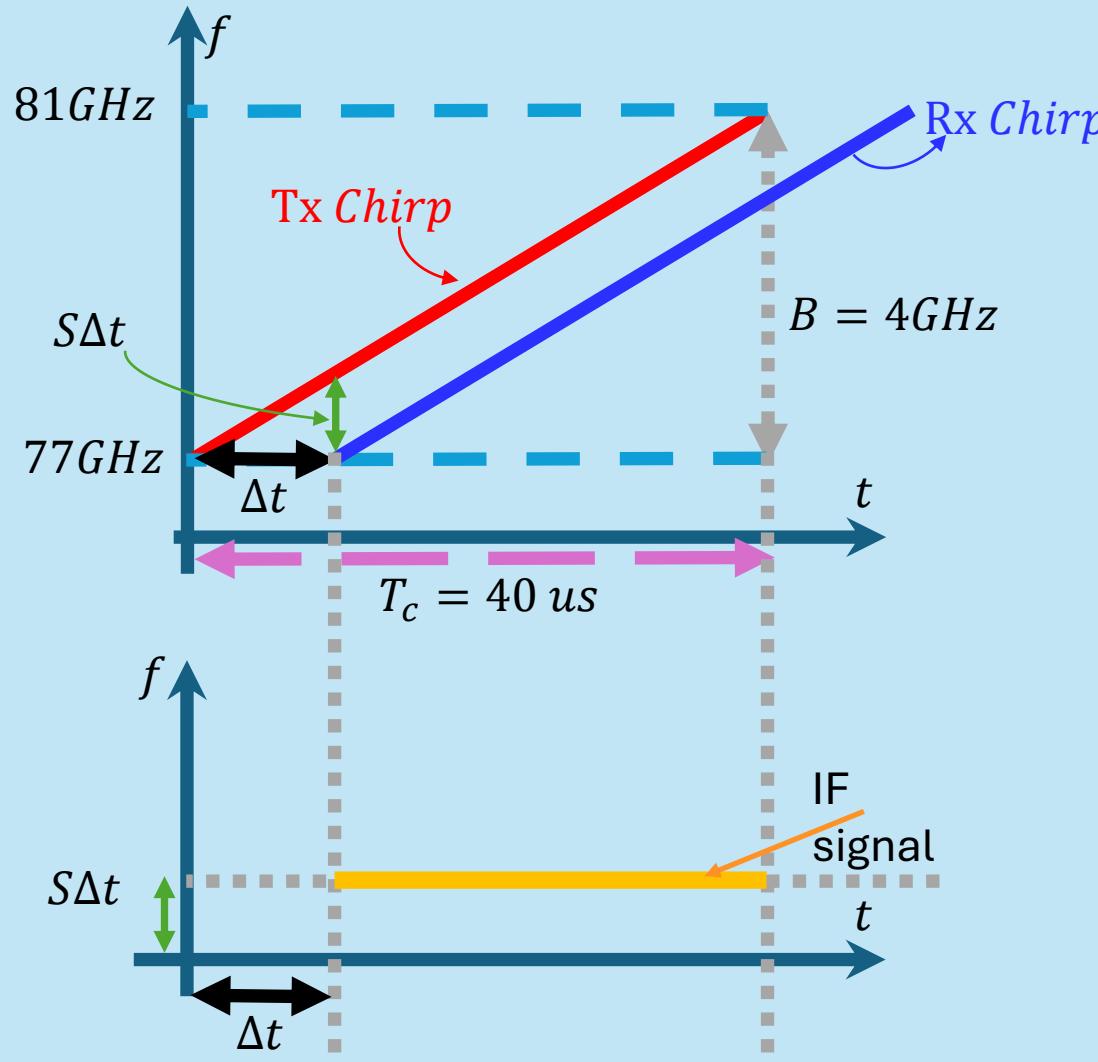
$$S = \frac{B}{\tau}$$



$$s_{\text{LFM}}(t) = A_t \text{rect}(t - (i - 1)T_p) \cos\left(2\pi\left(f_c t + \frac{1}{2} S t^2\right) + \phi\right)$$



Transmit waveform in mmWave radars - FMCW



Example

$$S = \frac{B}{T_c} = \frac{4 \text{ GHz}}{40 \text{ } \mu\text{s}} = 100 \frac{\text{MHz}}{\mu\text{s}}$$

$\Delta t = 0.1 \mu\text{s}$ (object at range of 15 m)

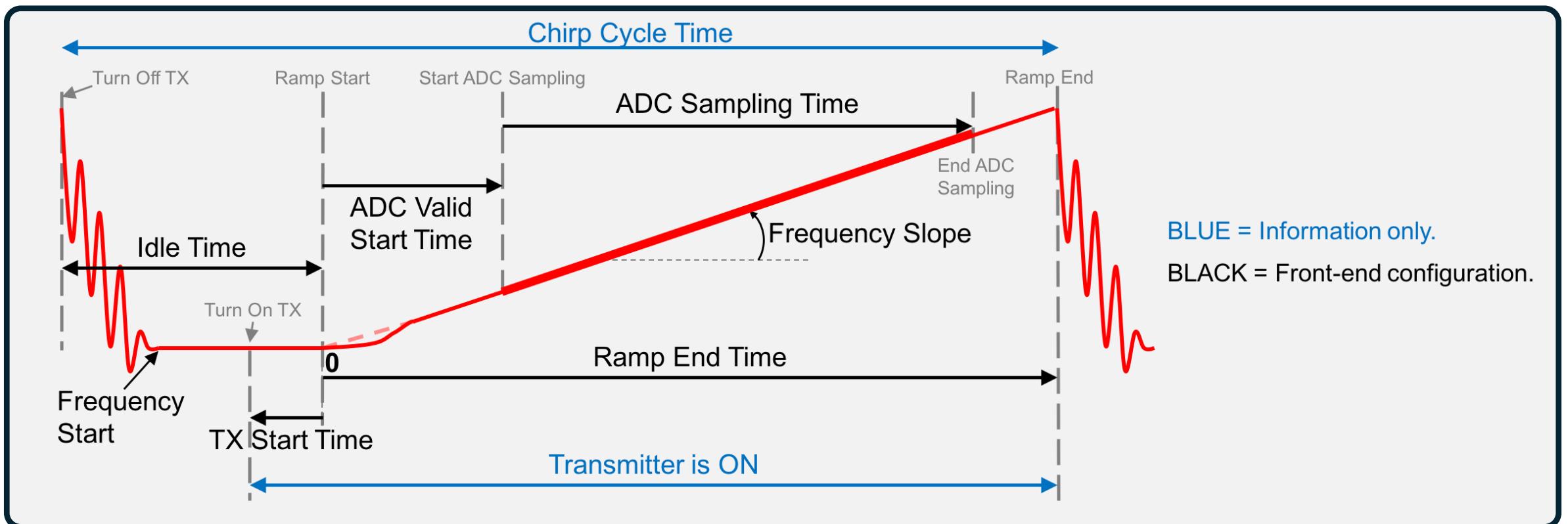
$$f_{\text{IF}} = S\Delta t = 100 \frac{\text{MHz}}{\mu\text{s}} \times 0.1 \mu\text{s} = 10 \text{ MHz}$$

$f_s = 10 \text{ MHz}$ (complex sampling ADCs) instead of 4 GHz (complex sampling ADCs)

This is called “de-chirp”

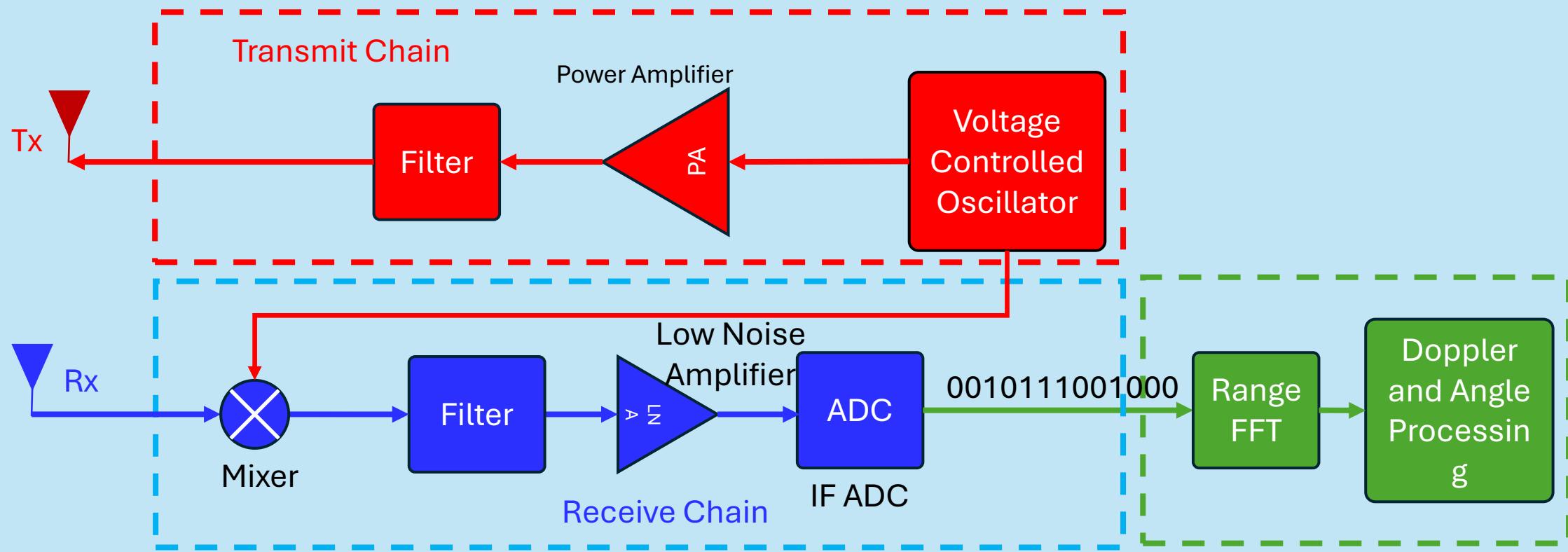
FMCW in Practice

➤ Slow-Chirp and Fast-Chirp

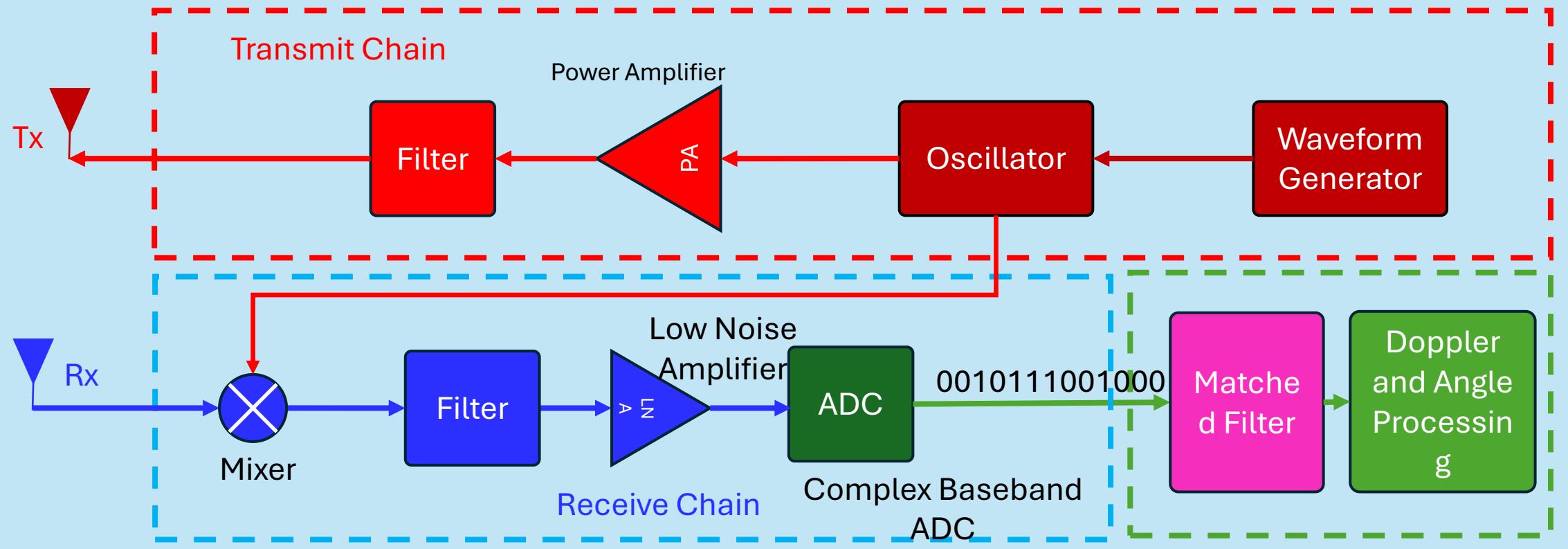


- **Fast Chirp:** each chirp is typically 10's of μs in duration (Typically Range-Doppler Coupling is neglectable)
- **Slow Chirp:** Old FMCW Radars with huge Range-Doppler Coupling

FMCW radar



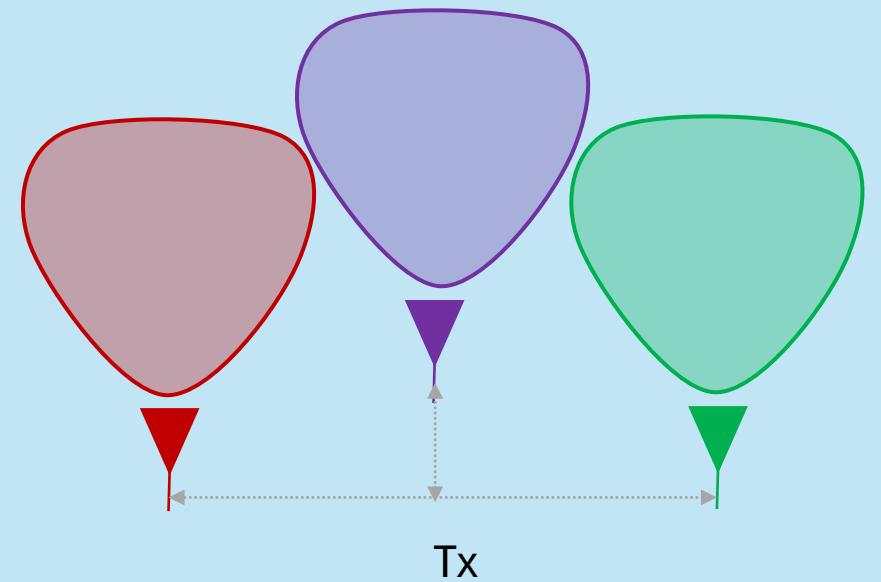
PMCW radar



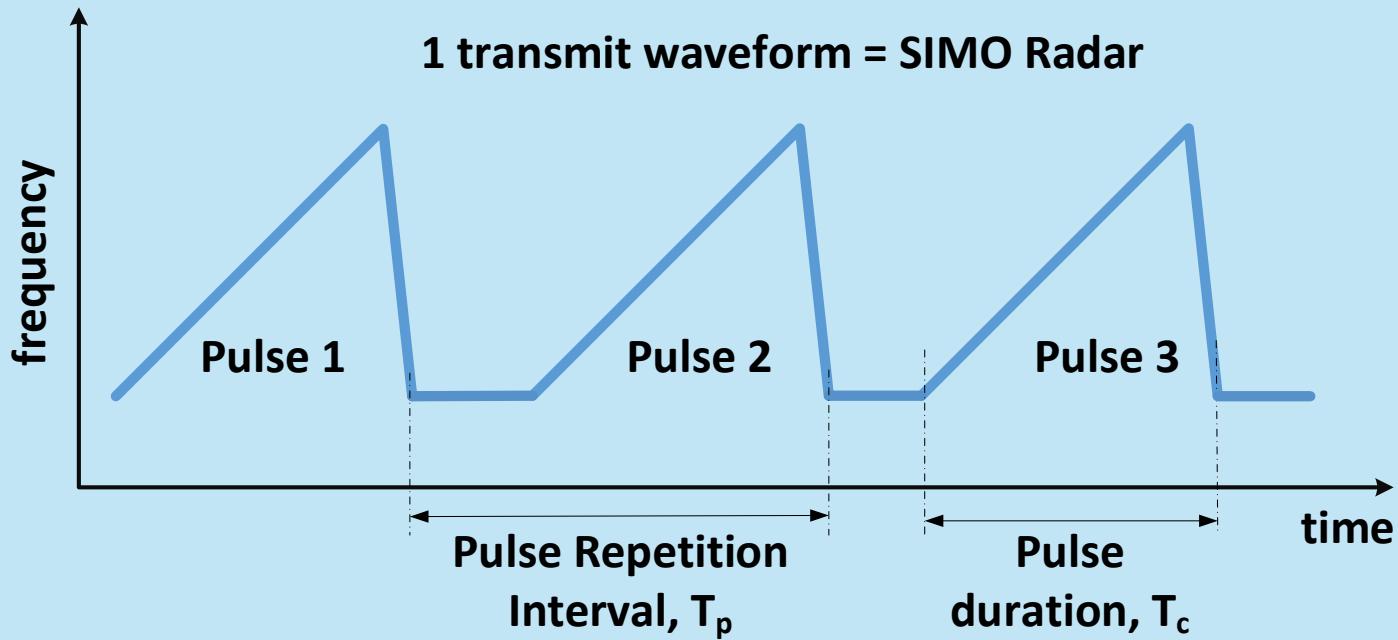
Transmit waveform in MIMO radars

Inter-Pulse Modulation Techniques

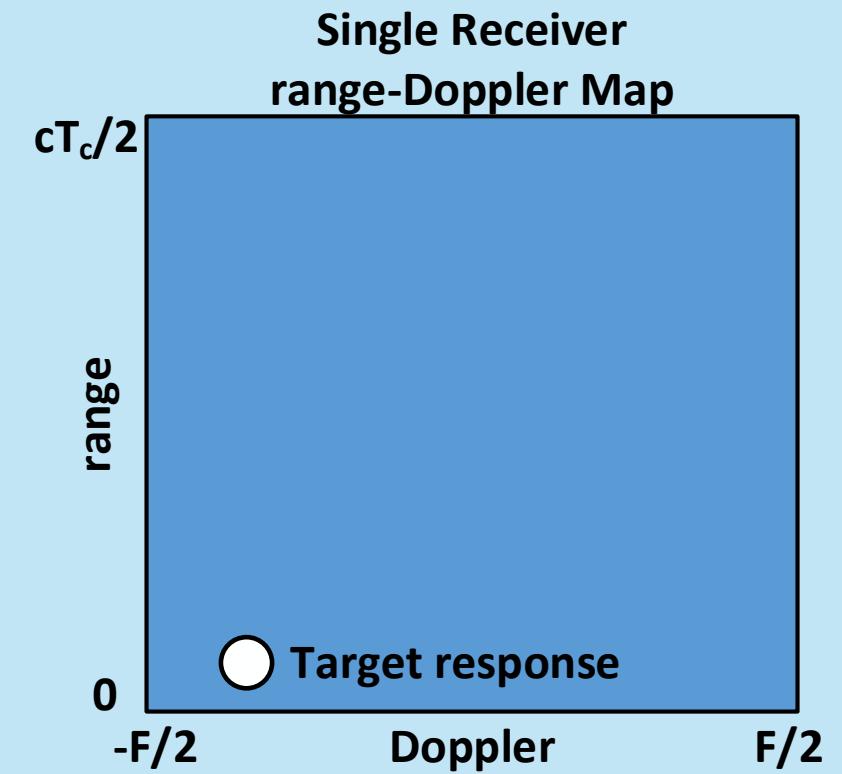
- Time Division Multiplexing (TDM)
- Frequency Division Multiplexing (FDM)
- Doppler Division Multiplexing (DDM)
- Binary Phase Modulation (BPM)



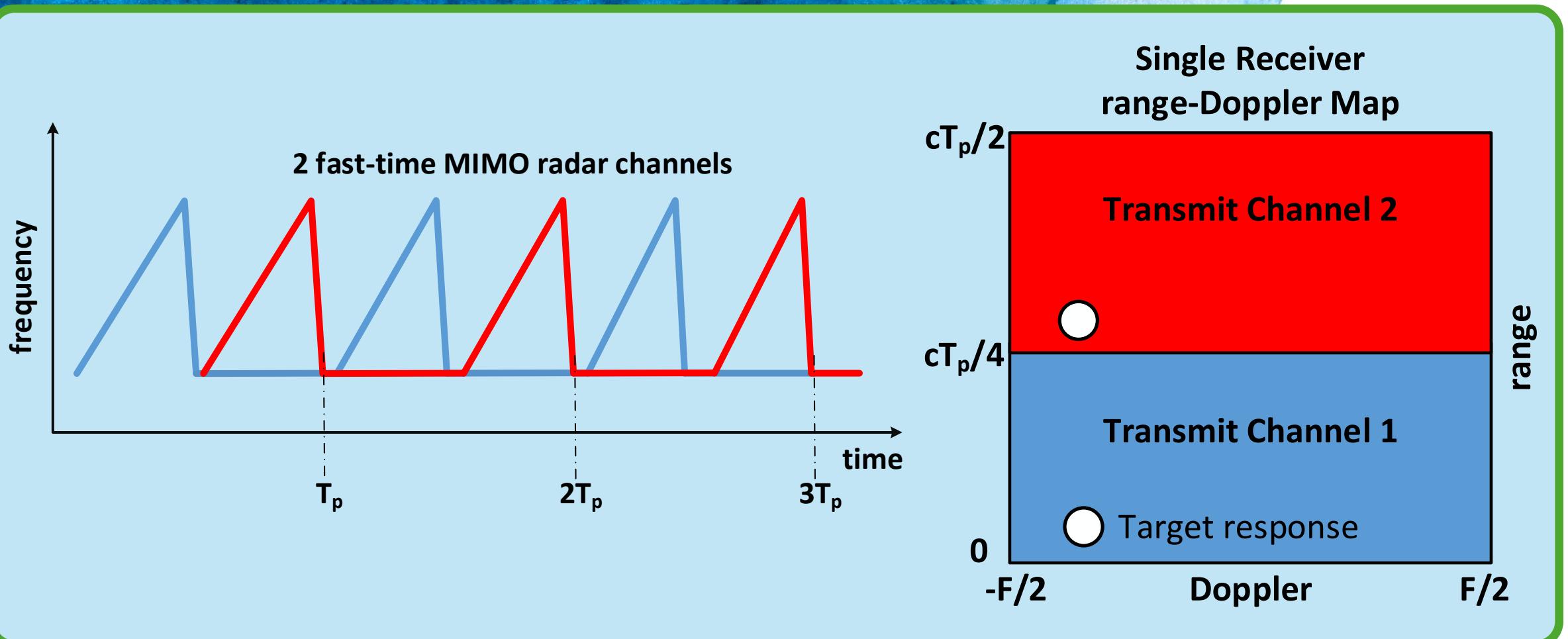
Time Division Multiplexing (TDM)



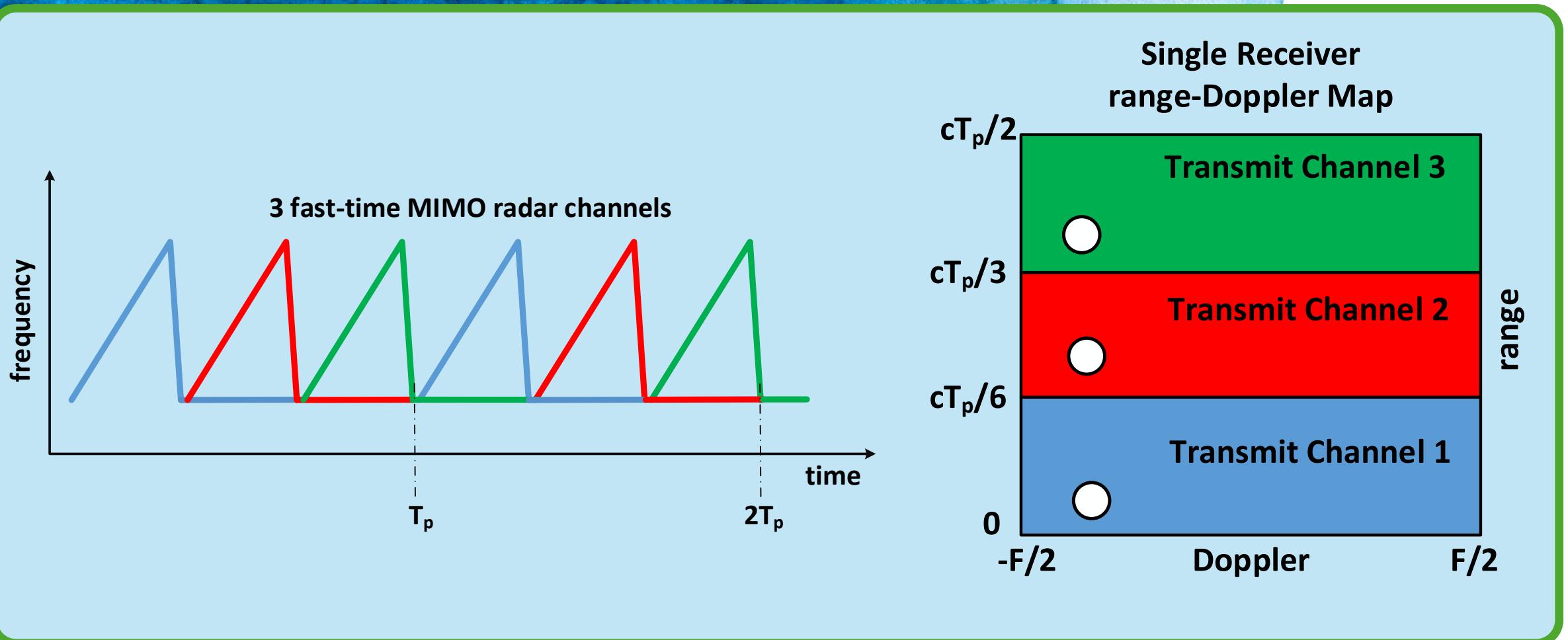
$$F = \frac{1}{T_R}$$



TDM-MIMO

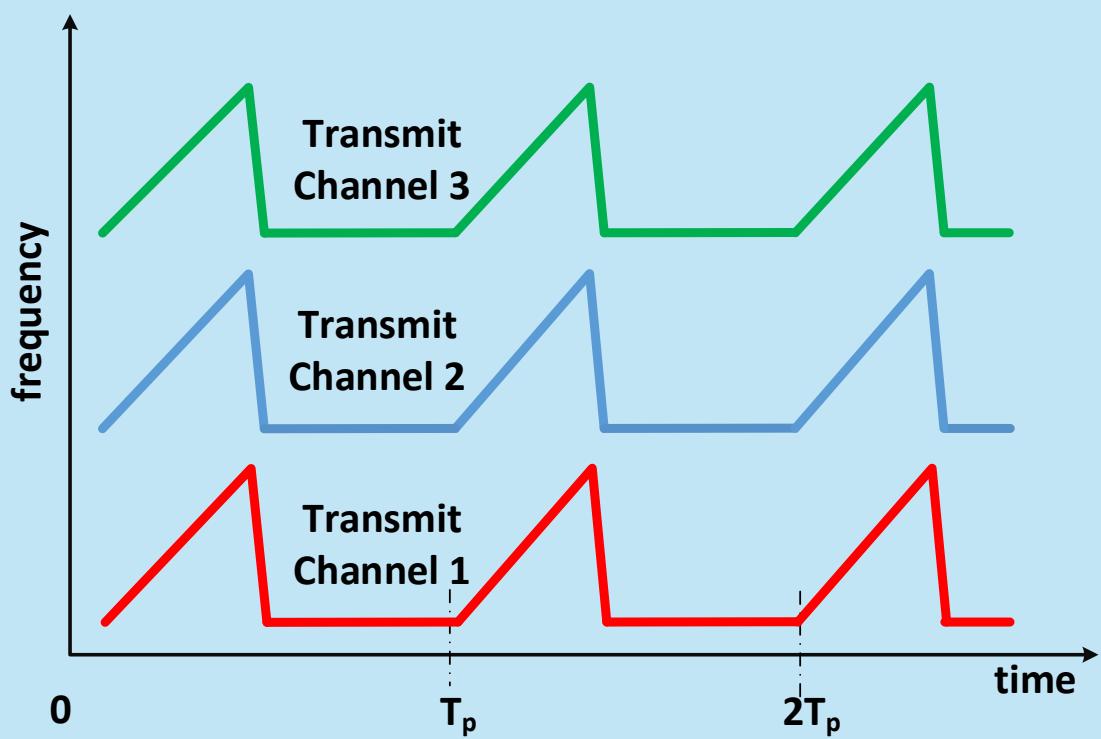


TDM-MIMO

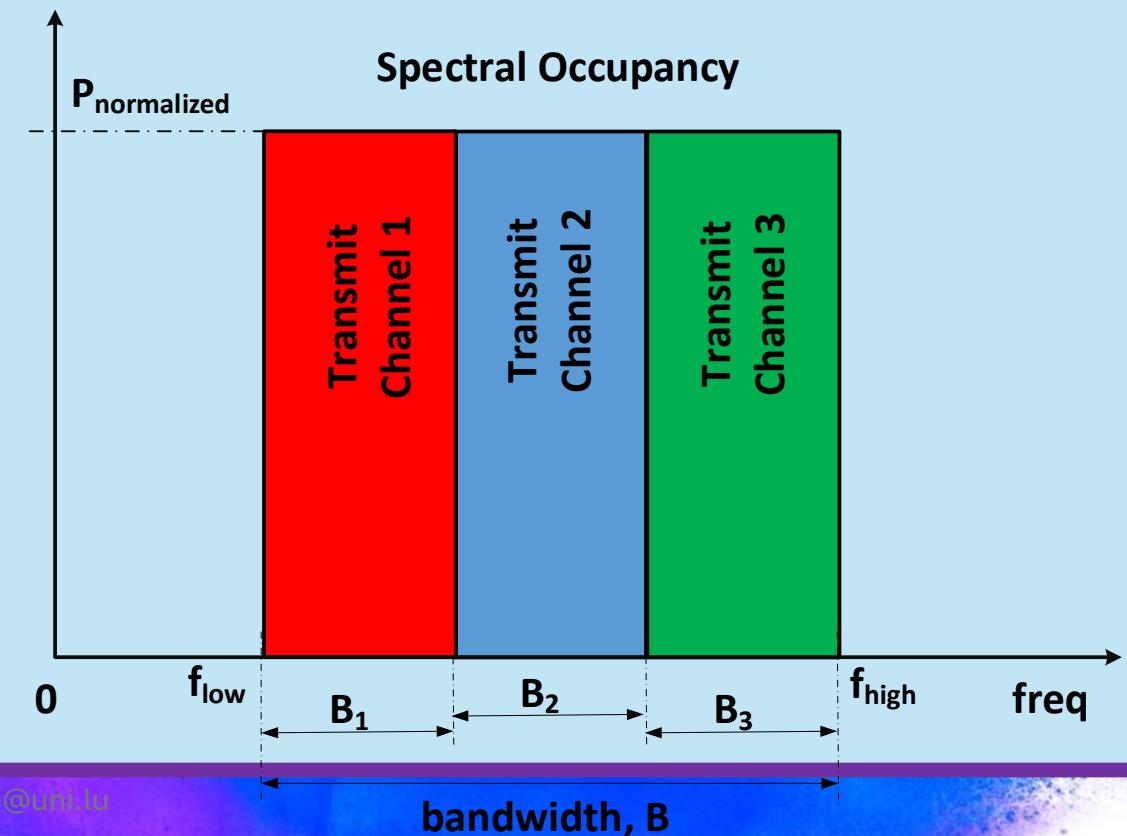


Frequency Division Multiplexing (FDM)

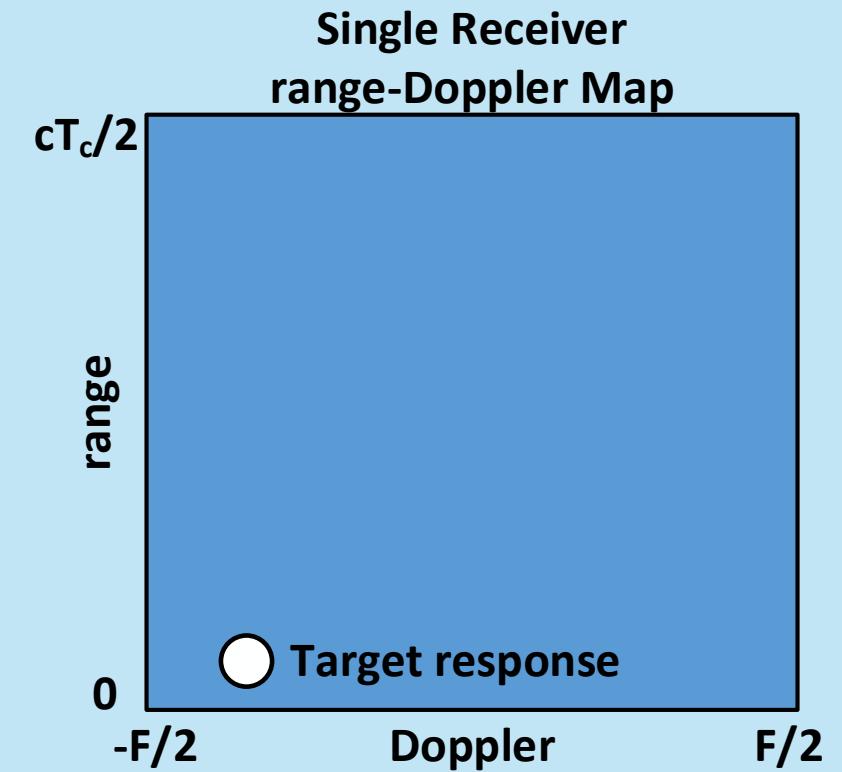
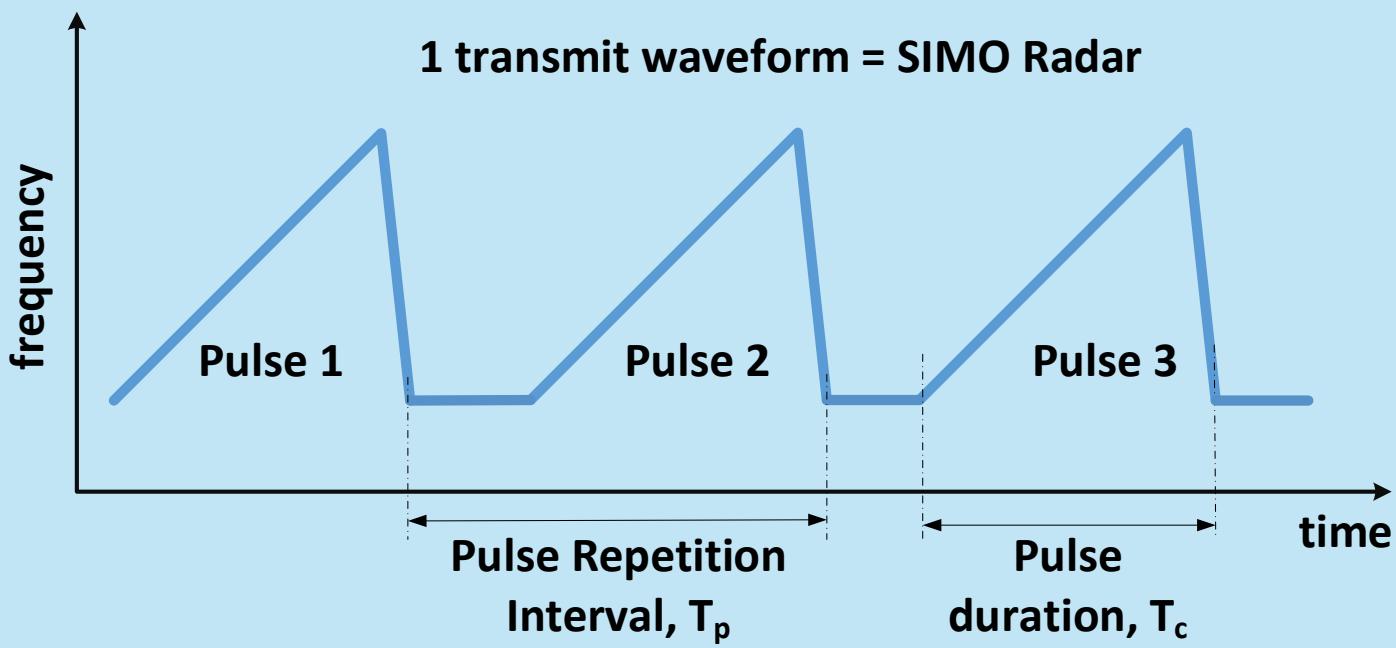
- Easy to implement with minimal hardware complexity
- range resolution compromised for more channels



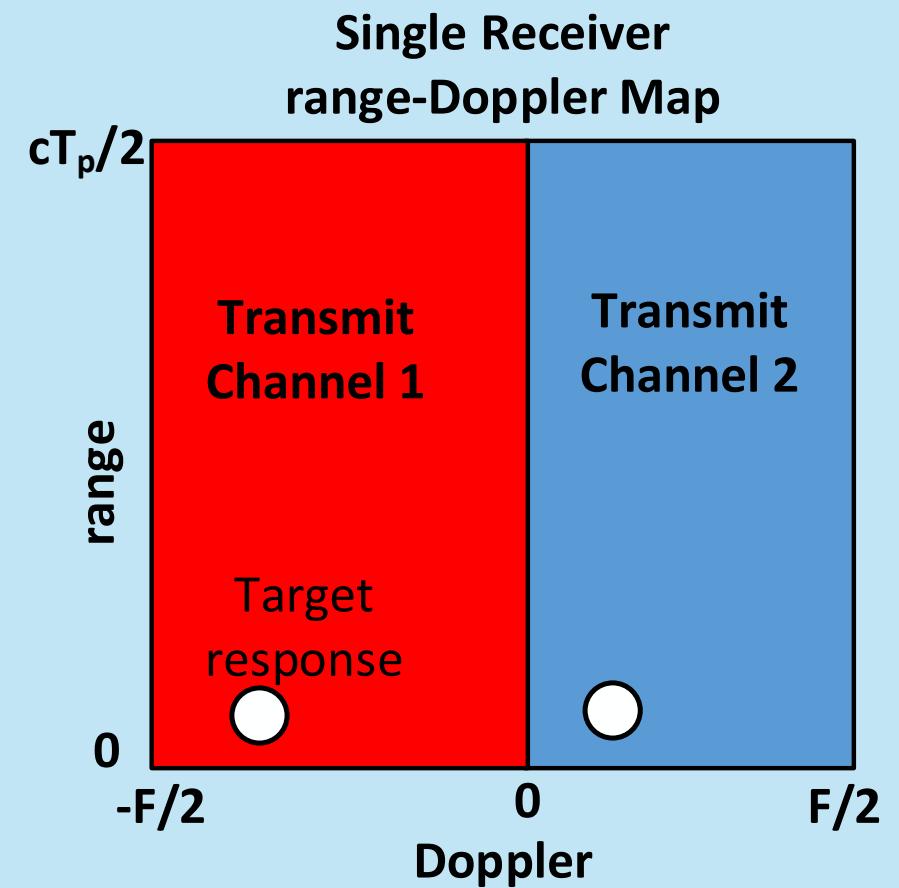
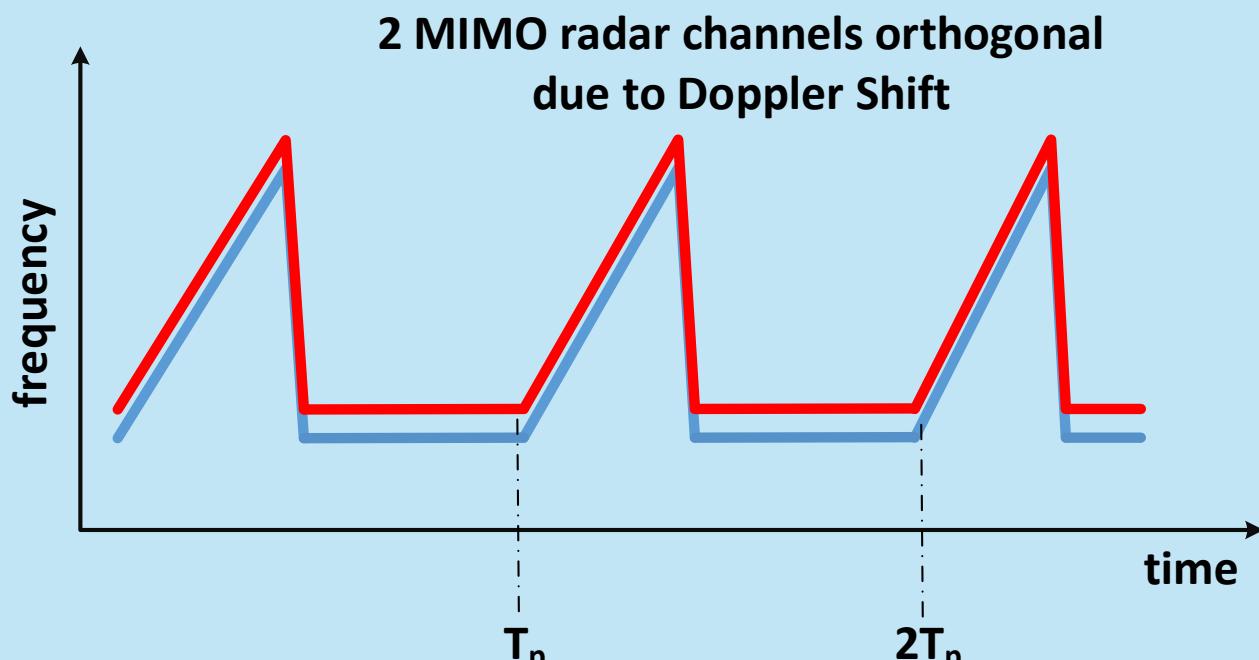
range resolution = $\frac{c}{2B}$,
where c = speed of light, B = bandwidth.



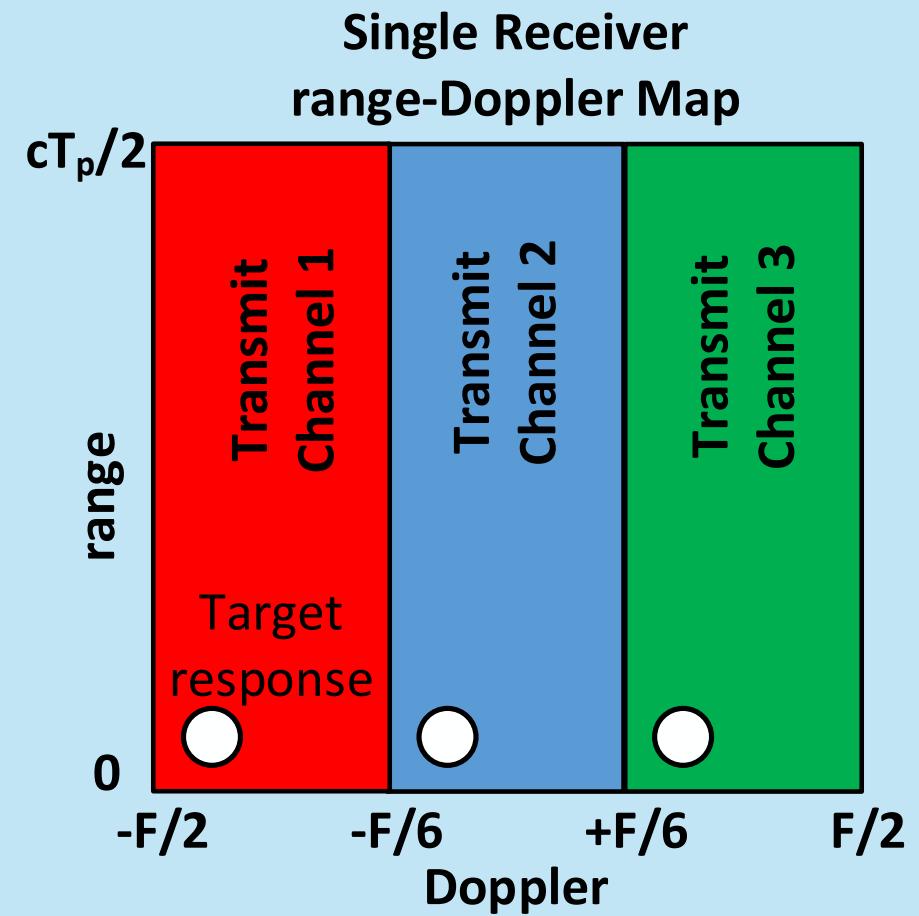
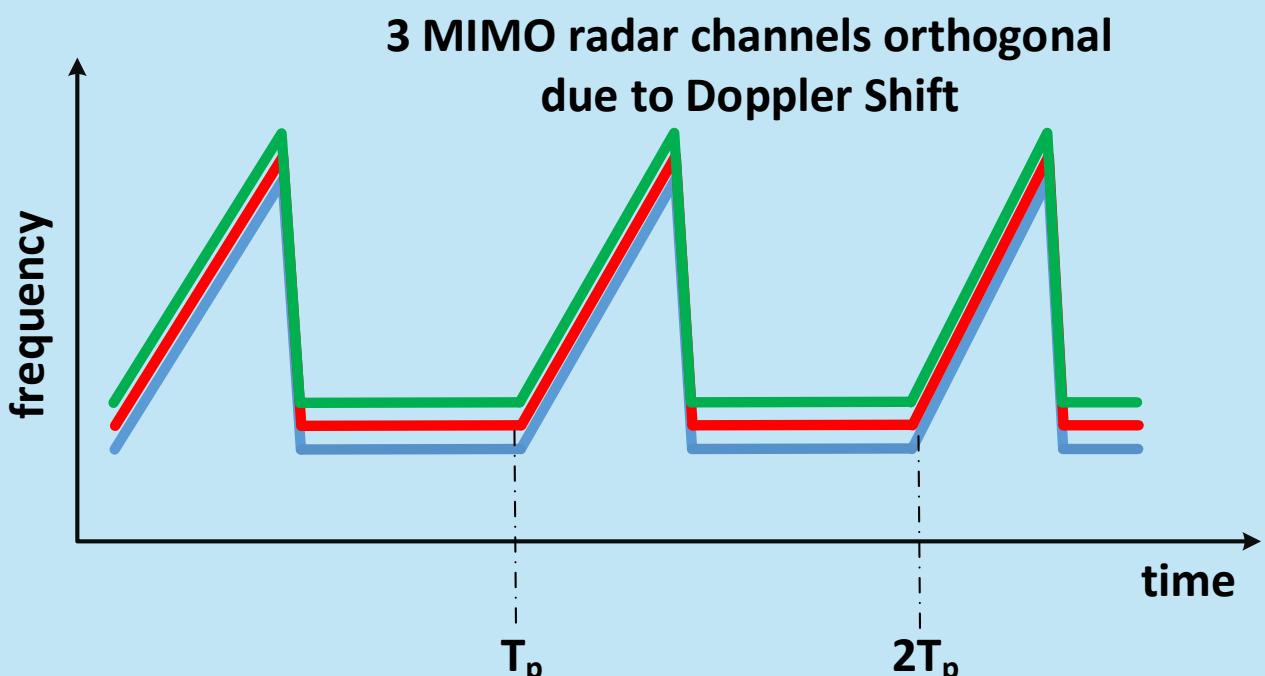
Doppler Division Multiplexing (DDM)



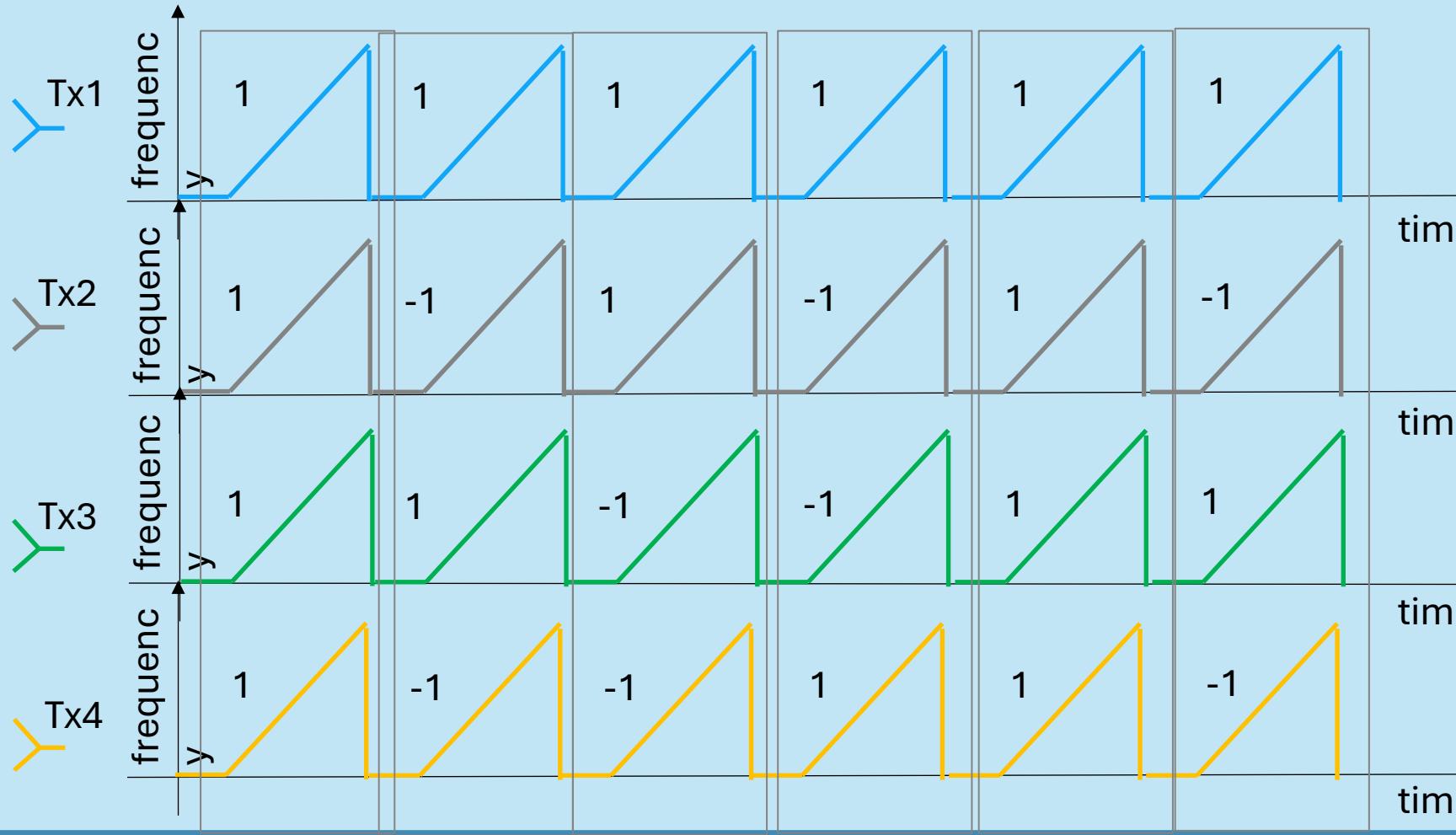
DDM - MIMO



DDM - MIMO



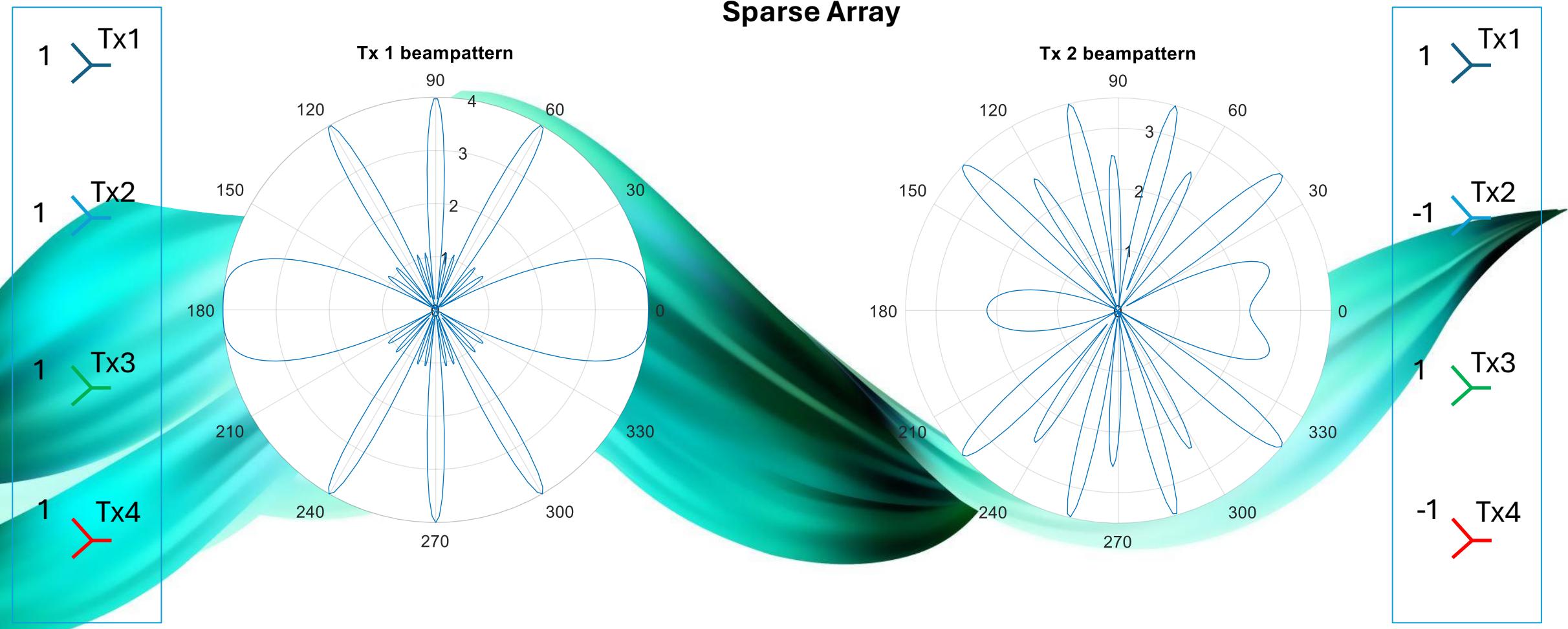
Binary Phase Modulation (BPM)



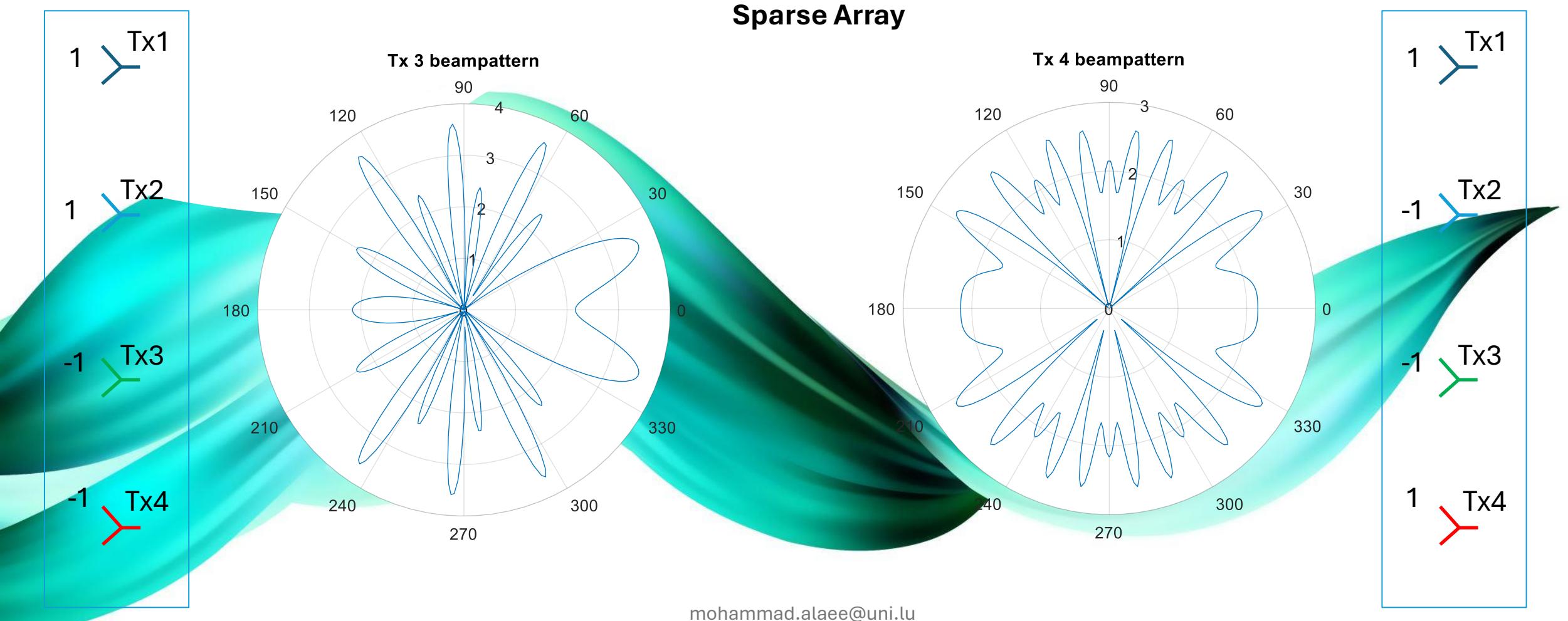
Hadamard Code

1	1	1	1
1	-1	1	-1
1	1	-1	-1
1	-1	-1	1

BPM-MIMO

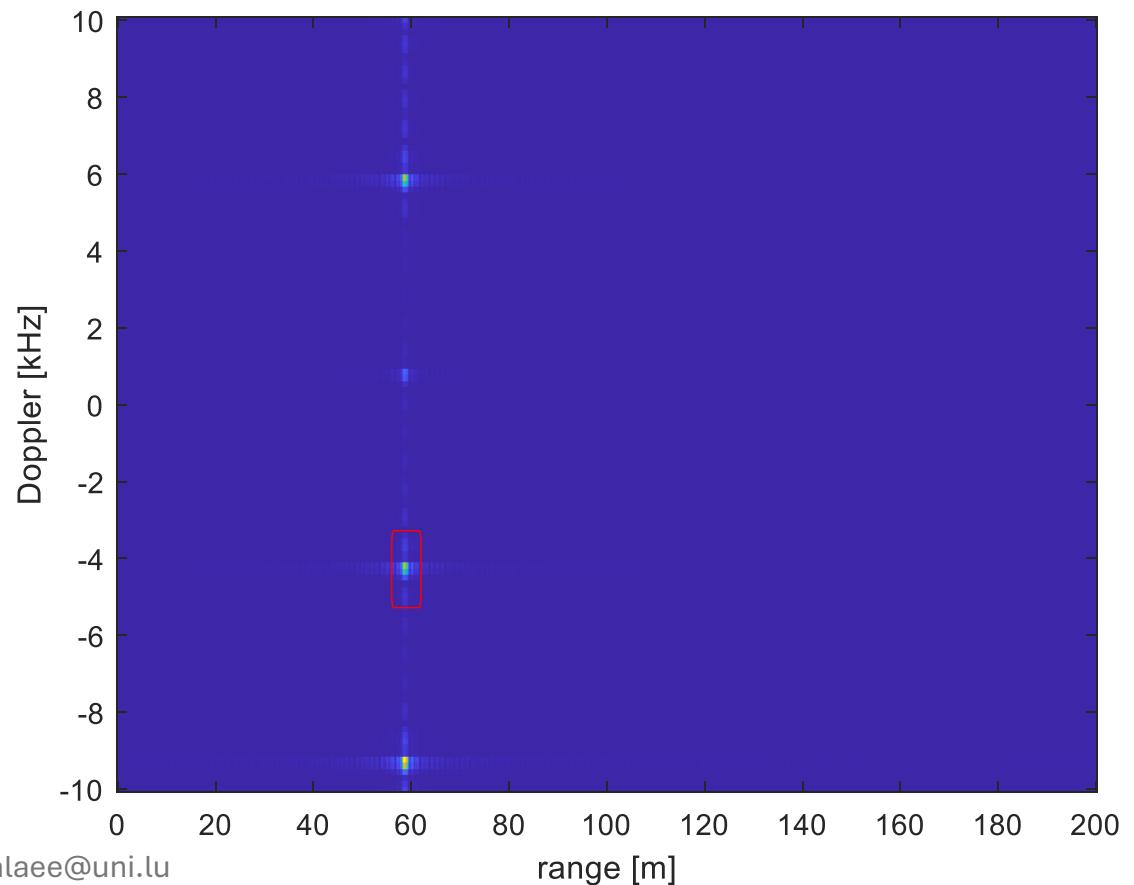
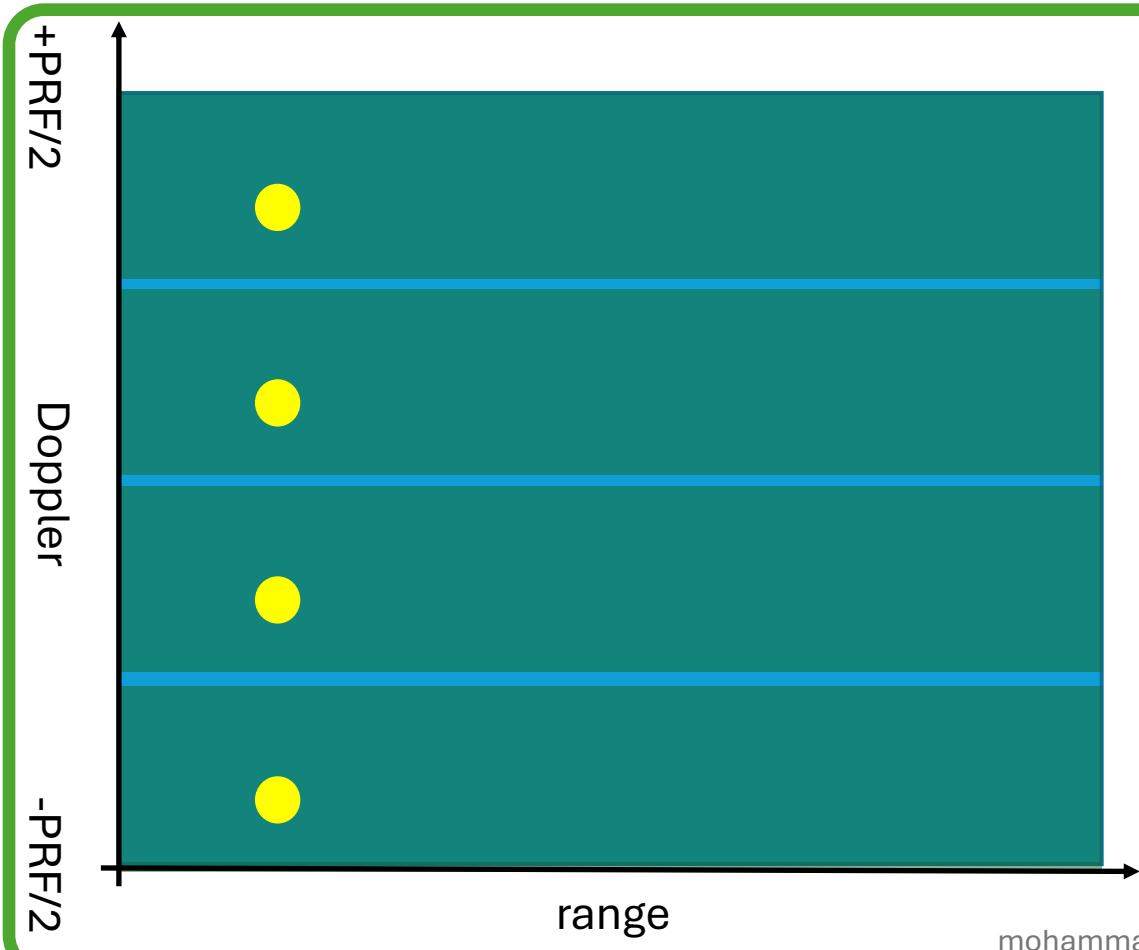


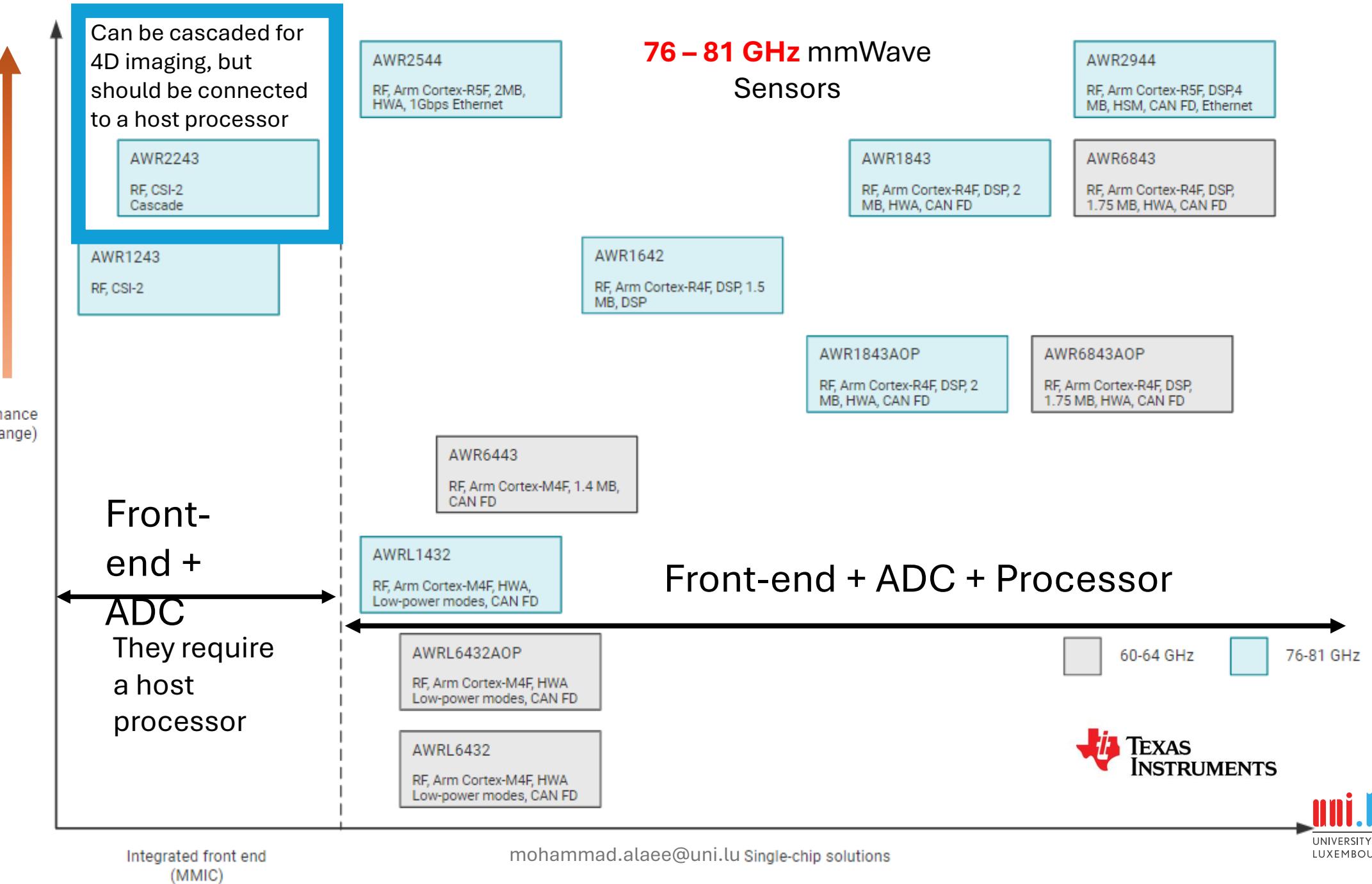
BPM-MIMO



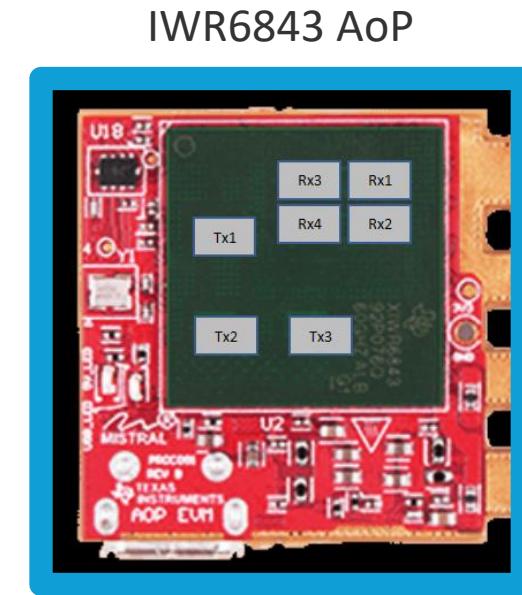
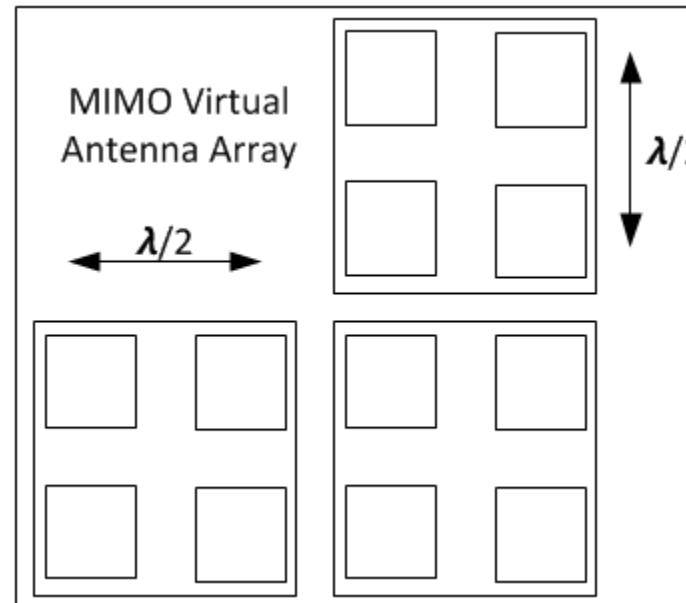
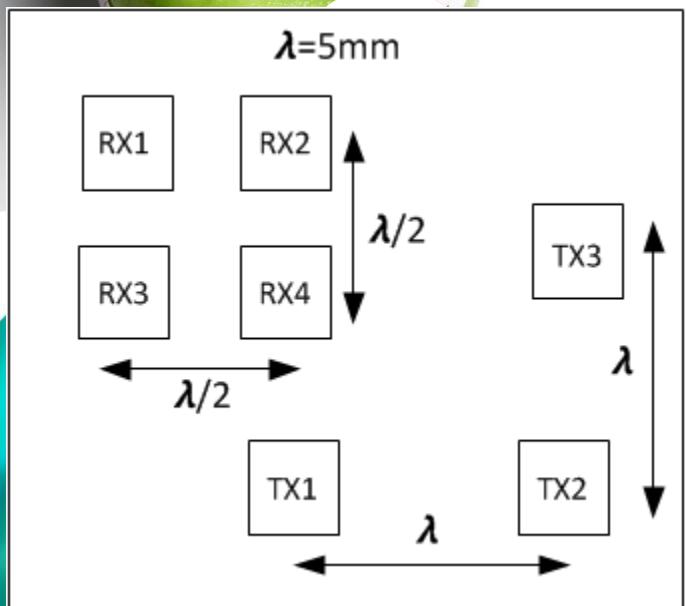
BPM-MIMO

Doppler aliased clutter and targets appear in other channels





IWR6843 Antenna-on-Package (AoP)



Massive MIMO 4D radar

High Angular Resolution:

Massive MIMO creates a dense virtual array, enabling **fine angular resolution** in both azimuth and elevation. This allows detection of small objects and separation of closely spaced targets.

Wide Field of View (FoV):

Larger arrays provide an expanded field of view, crucial for automotive, drone navigation, and surveillance applications.

Improved Detection in Clutter:

The high number of independent beams enhances target detection even in environments with heavy clutter.

Enhanced Object Classification:

With precise 3D localization, the radar can classify objects based on their shape, size, and height.

Robust Performance in All Conditions:

Like other radars, it works in fog, rain, snow, and darkness, unlike cameras and LiDAR.

Applications



Autonomous driving (ADAS)

Smart Cities & Surveillance

Healthcare & Vital Sign Monitoring

Consumer Electronics & Smart Homes

Aerospace & Defense

Space & Environmental Monitoring

Drones & Urban Air Mobility (UAM)

Robotics & Industrial Automation

Blind-spot detection

Traffic monitoring

Non-contact heart rate and respiration

Gesture control

Aircraft navigation

Satellite-based earth observation

Autonomous Navigation

Precision navigation

Adaptive cruise control

Perimeter security

Fall detection

Presence detection

Surveillance and reconnaissance

Climate monitoring

Terrain mapping

Obstacle avoidance

In-cabin monitoring

Crowd analytics

Sleep monitoring

Smart appliances

Reconnaissance

Monitoring

Autonomous delivery

Worker safety

Obstacle detection

Thank You!
and Questions