نهمین کنفرانس ملی
رادار و سامانه‌های
مراقبتی ایران

radar2024.ssau.ac.ir

9th Iranian National Conference on Radar and Surveillance Systems

An Introduction to mmWave 4D Imaging Massive MIMO Radars

UNIVERSITY OF LUXEMBOURG

Mohammad Alaee
University of Luxembourg, SnT, SPARC

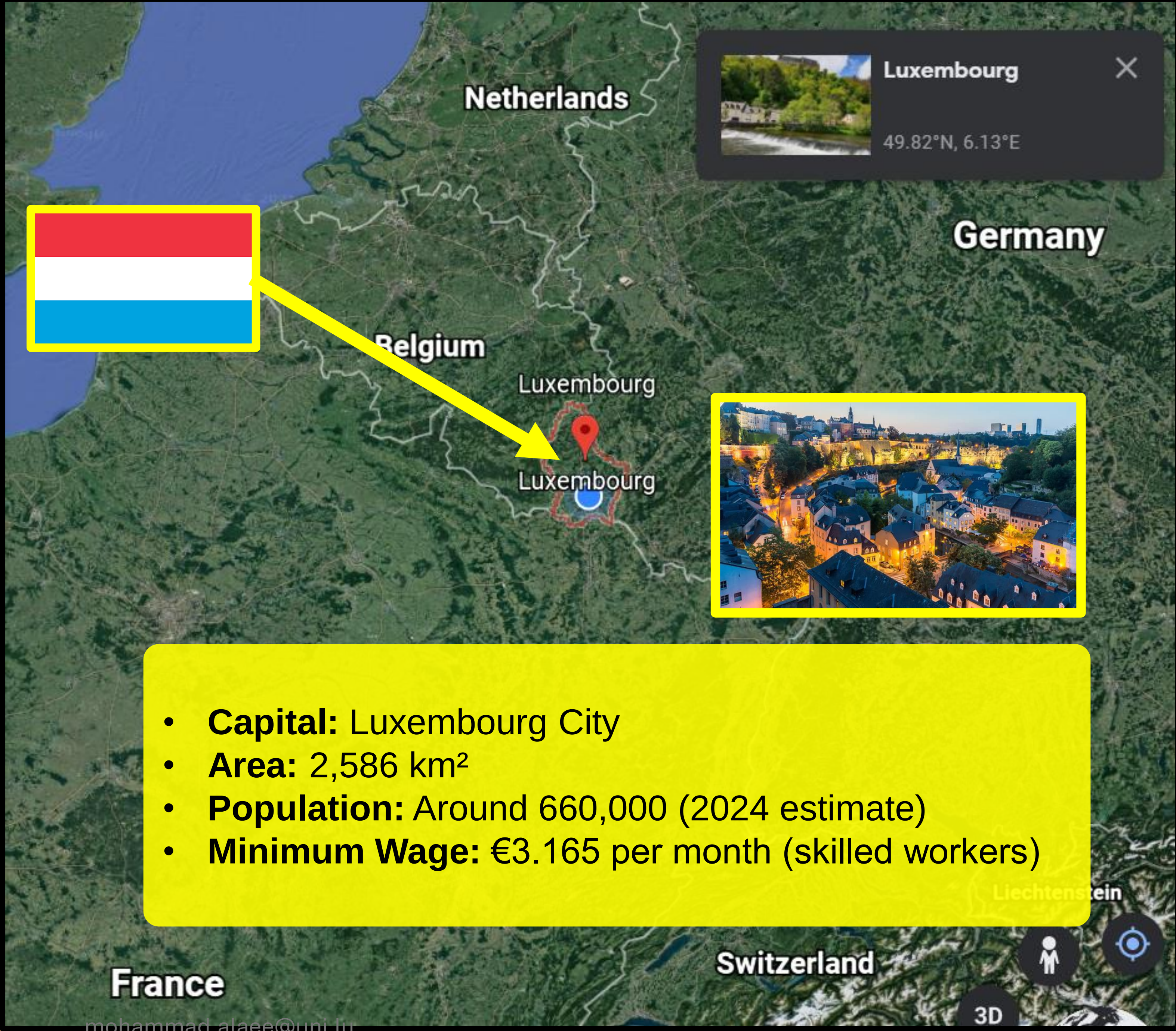
25 February 2025

mohammad.alaee@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.



- **Capital:** Luxembourg City
- **Area:** 2,586 km²
- **Population:** Around 660,000 (2024 estimate)
- **Minimum Wage:** €3.165 per month (skilled workers)

mohammad.alaee@uni.lu

Who we are

University of Luxembourg

Founded in 2003

3 Faculties

Faculty of Science, Technology and Medicine

Faculty of Humanities, Education and Social Sciences

Faculty of Law, Economics and Finance

7000 students

300 faculty members

60% international students

1000+ PhDs

130 nationalities

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

4 Interdisciplinary Centres

SnT

LCSB

C²DH

LCEL

SnT

UNIVERSITY OF LUXEMBOURG

PEOPLE

500+
Workforce

65+
Nationalities

31%
Alumni who stay in Luxembourg

50%
Doctoral Candidates on Industrial Projects

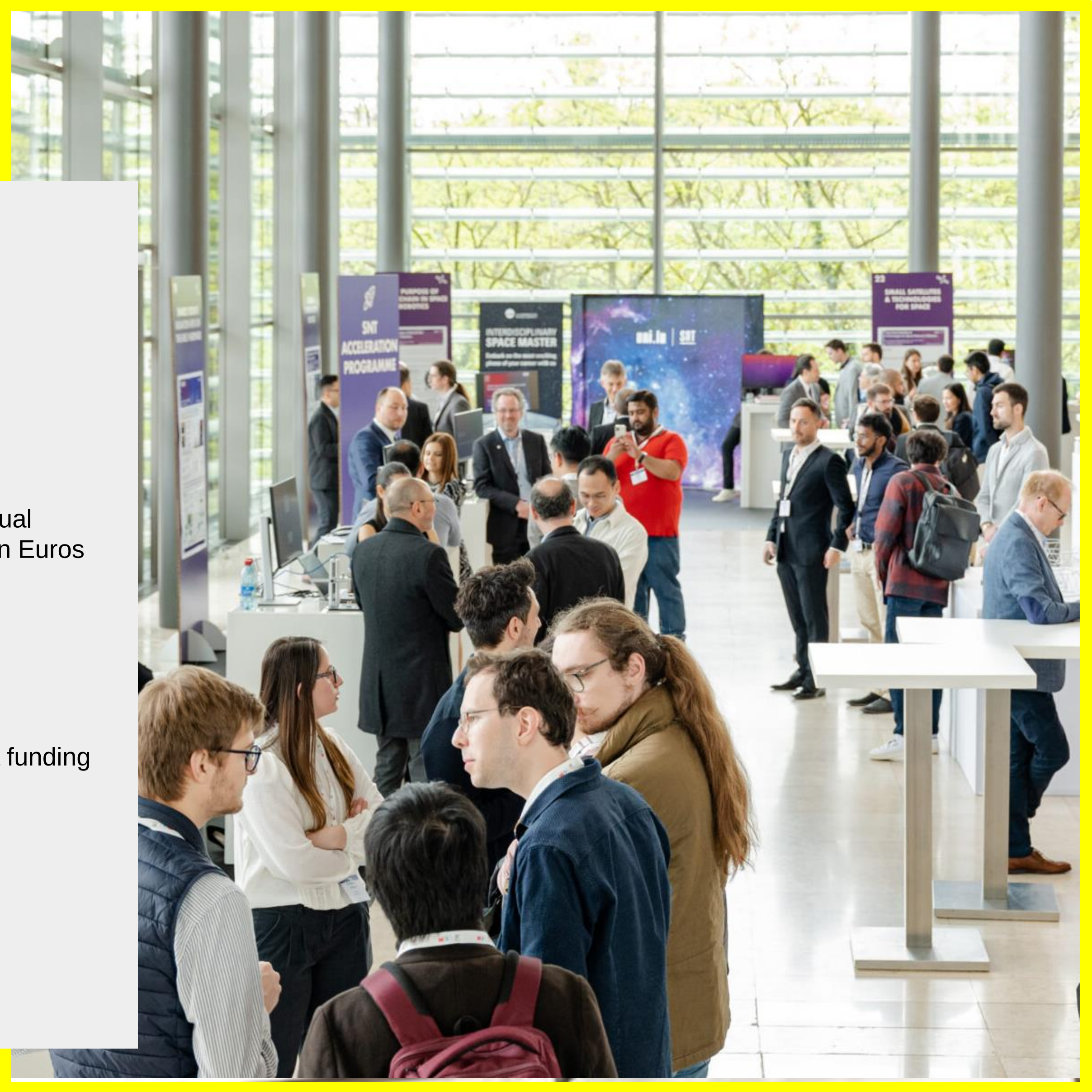
PARTNERSHIPS & INNOVATION

65+
Partners

8M
Partners annual contribution in Euros

70%
External project funding

6
Spin-offs



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 Manage

Security Design and Valida

Signal Processing and Com

Space Robotics (SpaceR)

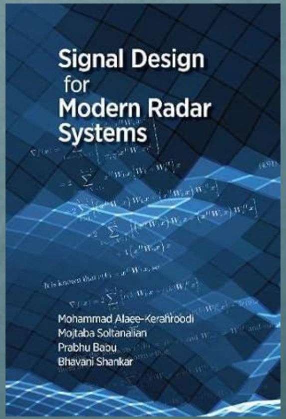
Signal Processing Applications in Radar and Communications (SPARC)

Space Systems Engineering (SpaSys)

Trustworthy Software (TruX)

Software Verification and Validation (SVV)

Ubiquitous and Intelligent Systems (UBIX)



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

An Introduction to mmWave 4D Imaging Massive MIMO Radars

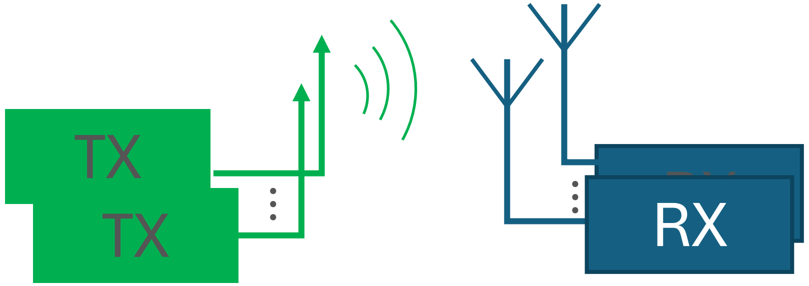
mohammad.alaee@uni.lu

UNIVERSITY OF LUXEMBOURG

- ❑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

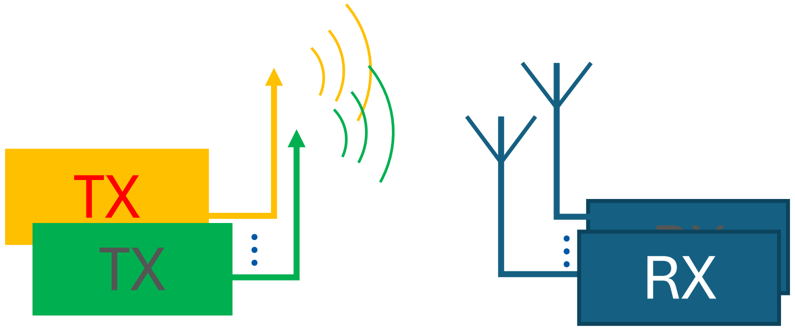
mohammad.alaee@uni.lu

Phased Array



Single Input Multi Output

MIMO

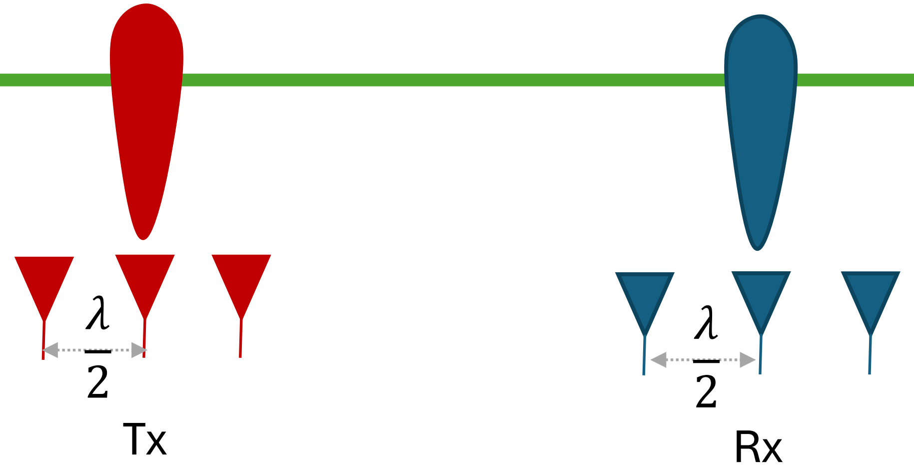


Multi Input Multi Output

Waveform diversity

Phase Array and MIMO Radars

A

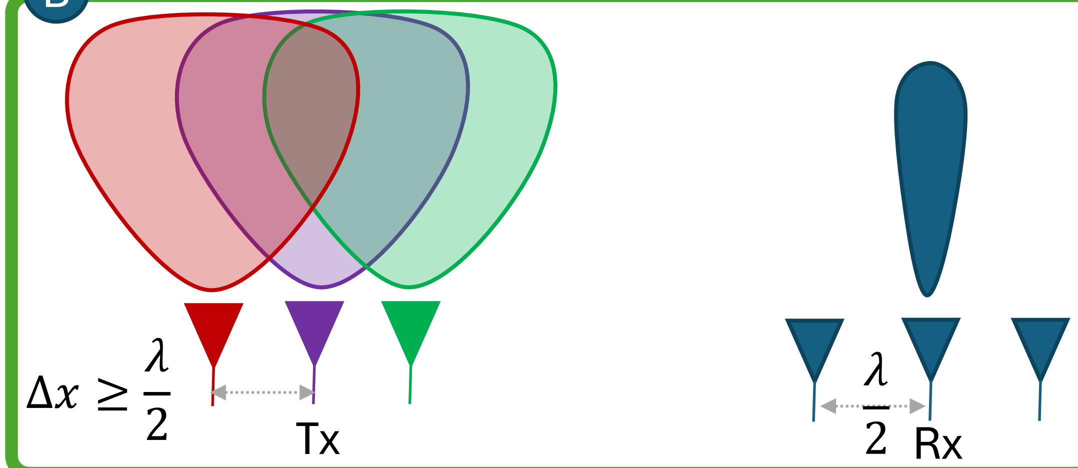


Phased Array

The Tx antennas transmit a single waveform.

$$\text{SNR} \propto G_t G_r$$

B



MIMO

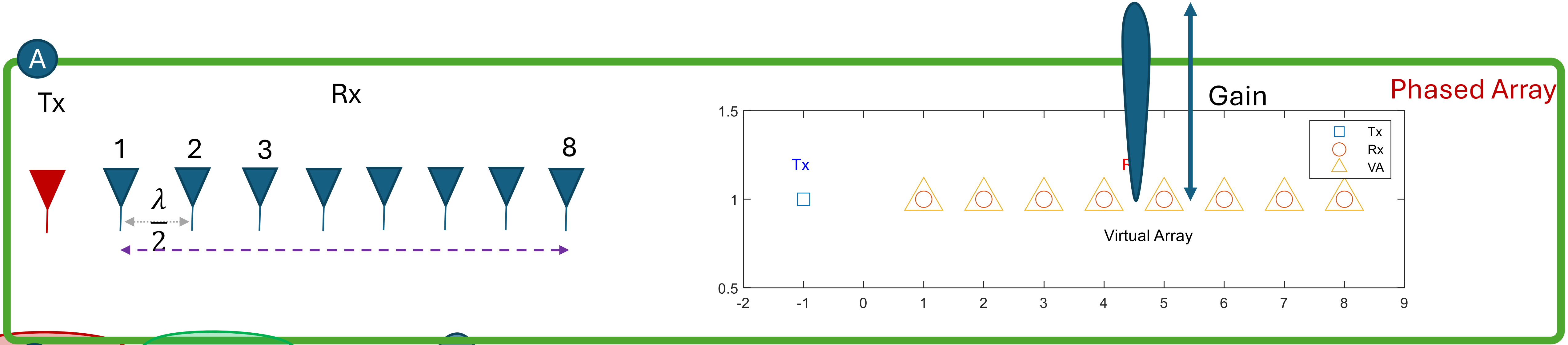
Every antenna element will emit a different waveform. Why?

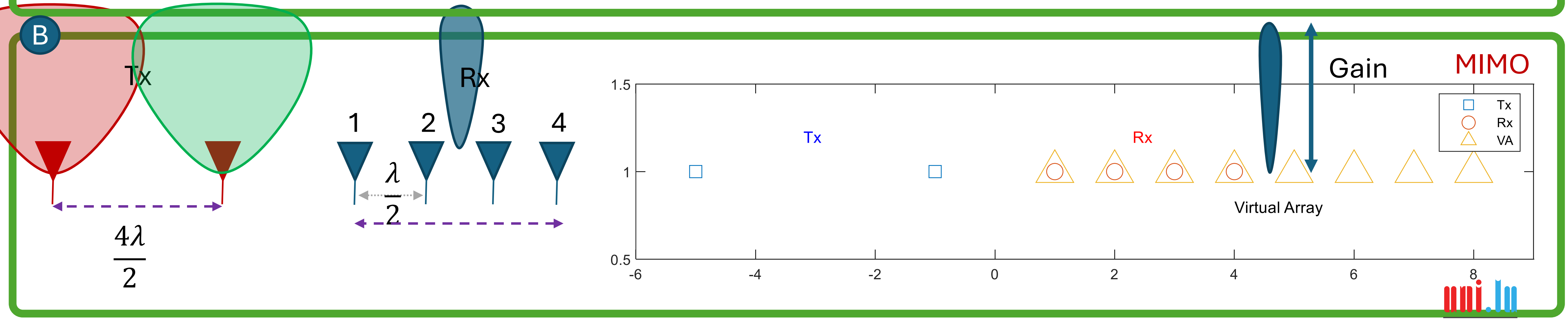
$$\text{SNR} \propto \frac{G_t}{N_t} G_r$$

MIMO SNR is N_t times lower

mohammad.alaee@uni.lu

Array Sparsity in MIMO Radars

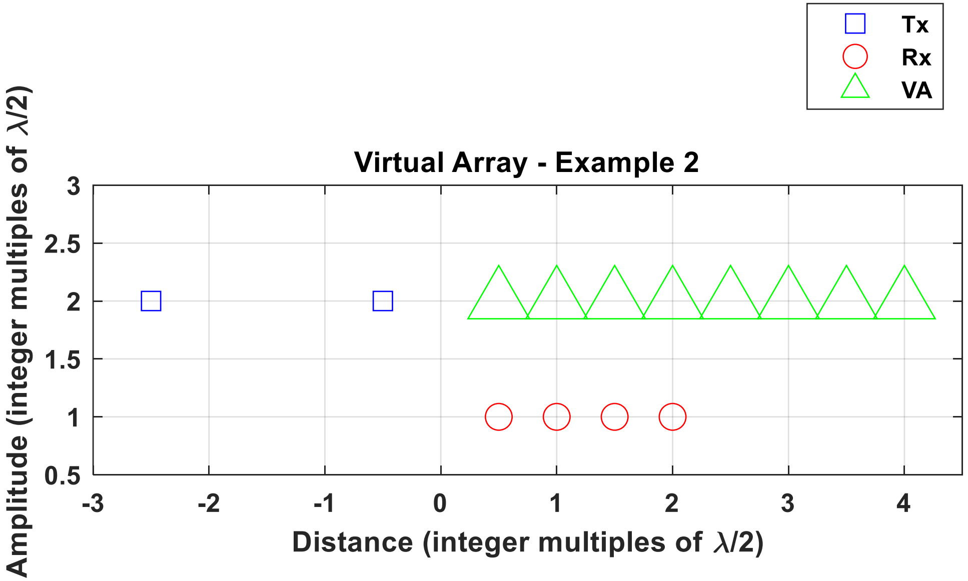


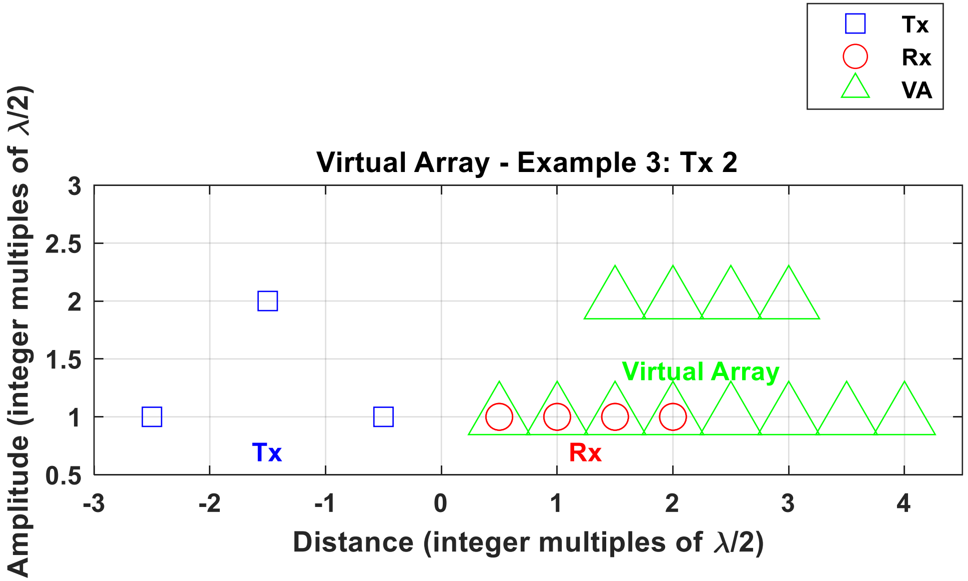


mohammad.alaee@uni.lu

UNIVERSITY OF LUXEMBOURG

Virtual Array in MIMO Radars





2 + 4 = 6 => physical elements

2 × 4 = 8 => virtual elements

3 + 4 = 7 => physical elements

3 × 4 = 12 => virtual elements

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

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

mohammad.alaee@uni.lu

Virtual Array in MIMO Radars

24 + 24 = 48 => physical elements

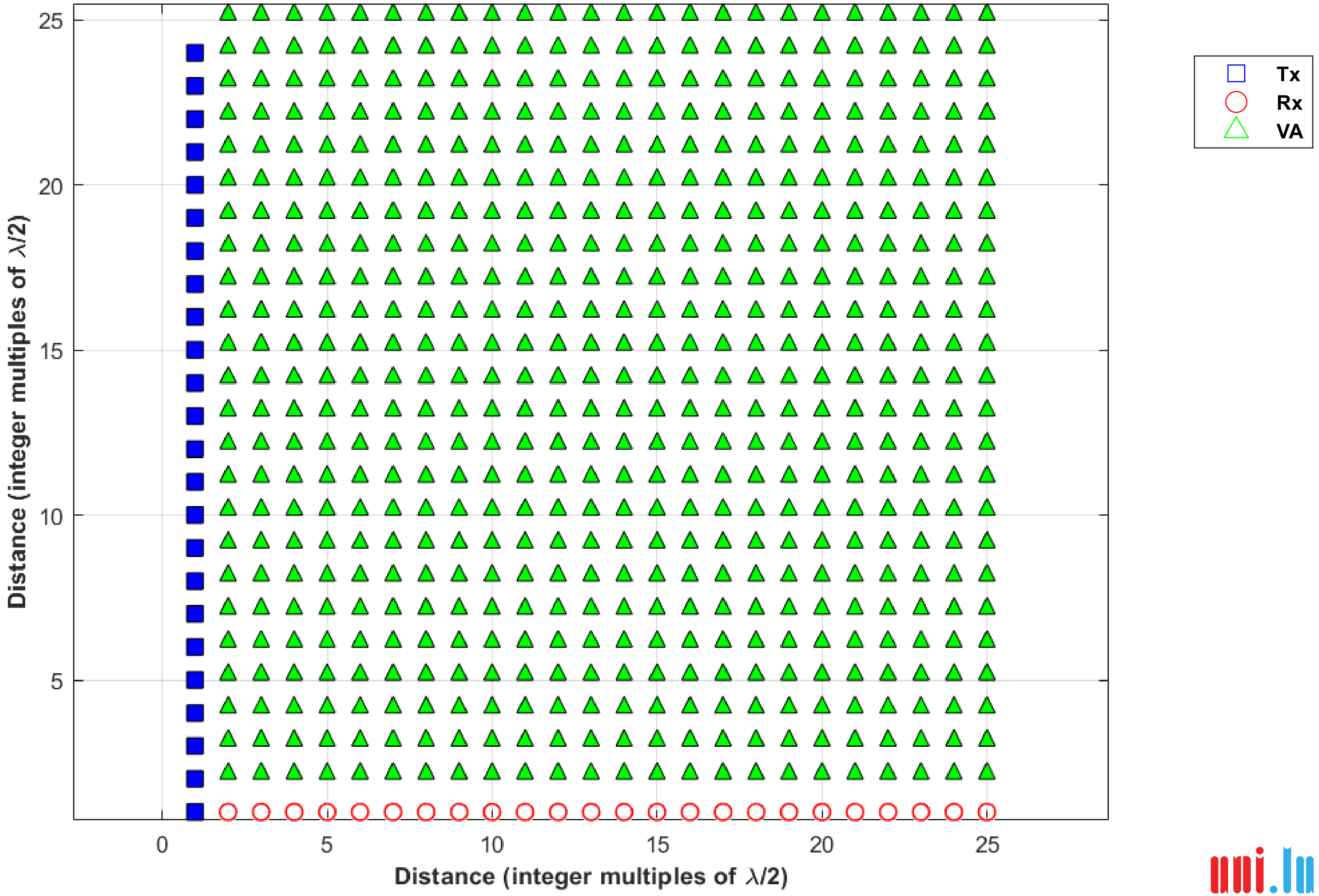
24 × 24 = 576 => virtual elements

576
Antenna array

4D – imaging MIMO Radar

Range + Azimuth + Elevation + Doppler

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

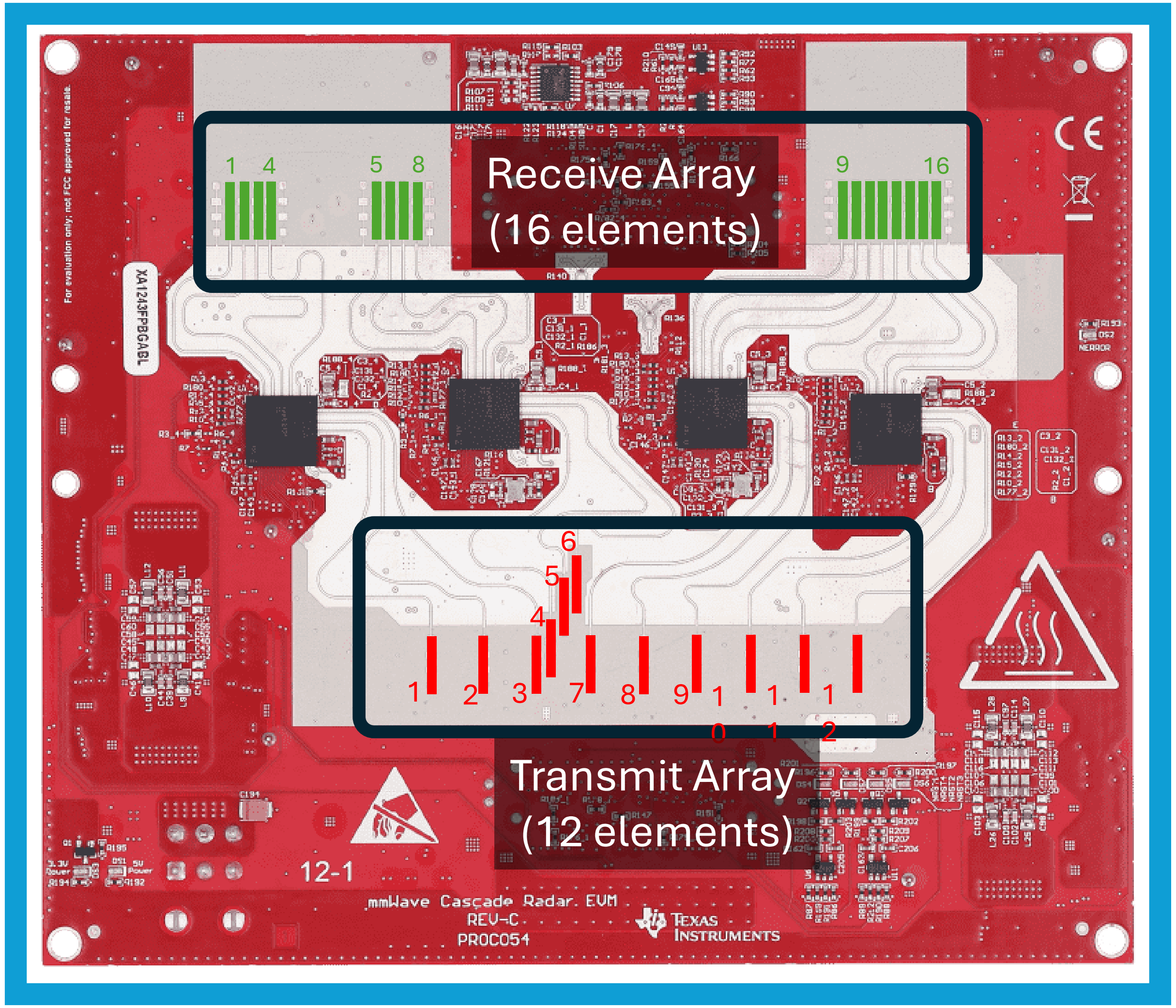


mohammad.alaee@uni.lu

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

UNIVERSITY OF LUXEMBOURG

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	• 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	• 4-element series-fed patch antenna, 12dBi• ± 60 deg Azimuth 3dB• ± 30 deg Elevation 3dB

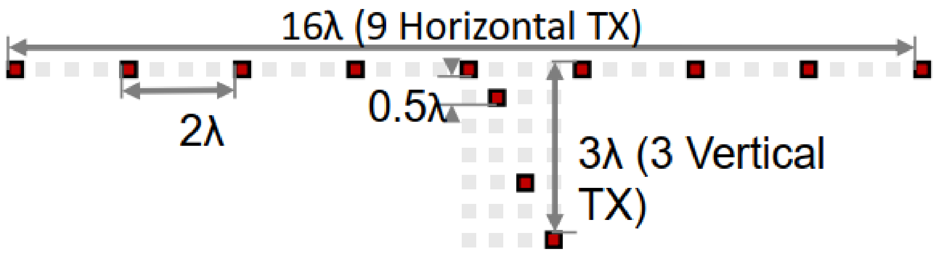


TEXAS INSTRUMENTS

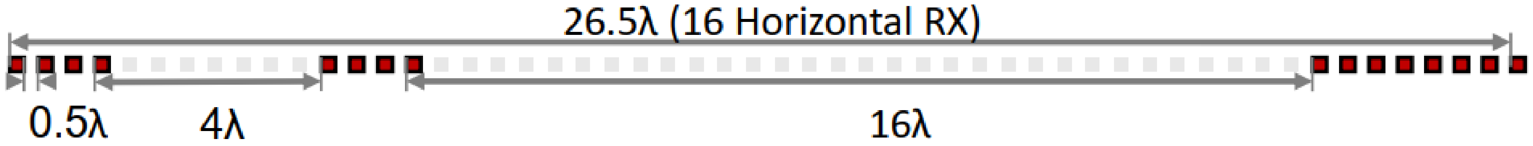
https://www.ti.com/

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

Transmit Array (12 elements)



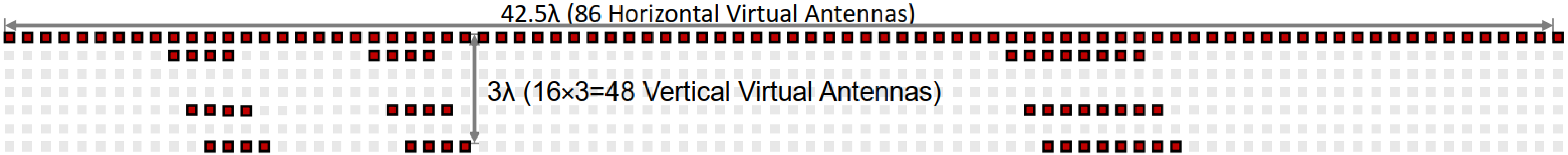
Receive Array (16 elements)



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

86-element array 1.8° horizontal resolution

Virtual Array (192 elements)



18° elevation resolution

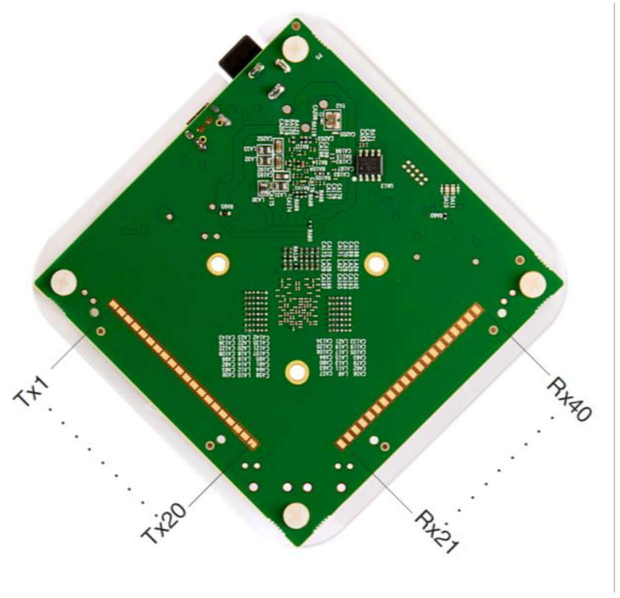
$N \times M$ virtual elements with $N + M$ physical antennas

mohammad.alaee@uni.lu

Example 2: Vayyar (VTRIG-74)

vayyar™

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	$\Delta\theta \approx \frac{\lambda}{D} \approx \frac{3e^8}{64e^9 \cdot 0.04} \approx 0.117rad \approx 6.7deg$	– 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	



mohammad.alaee@uni.lu

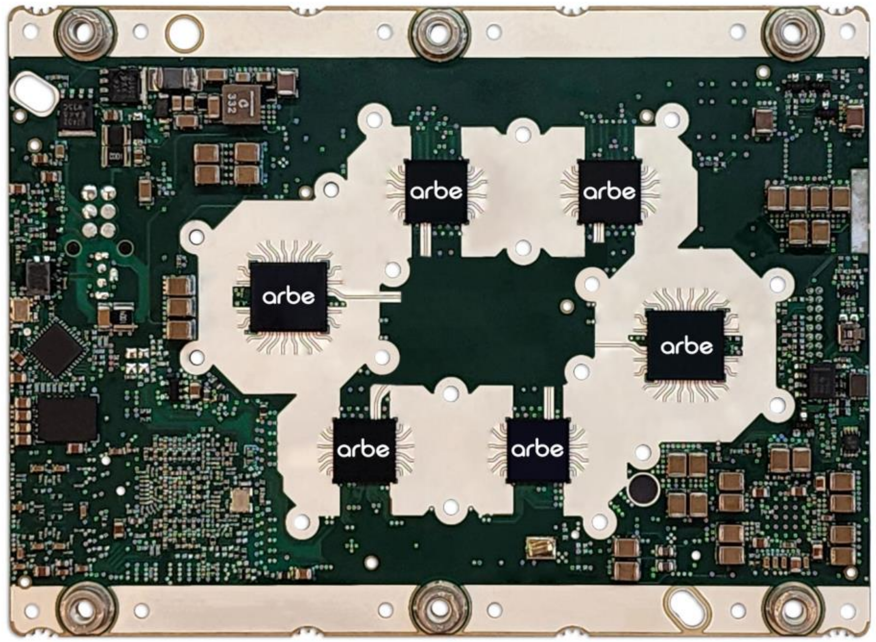
uni.lu UNIVERSITY OF LUXEMBOURG

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

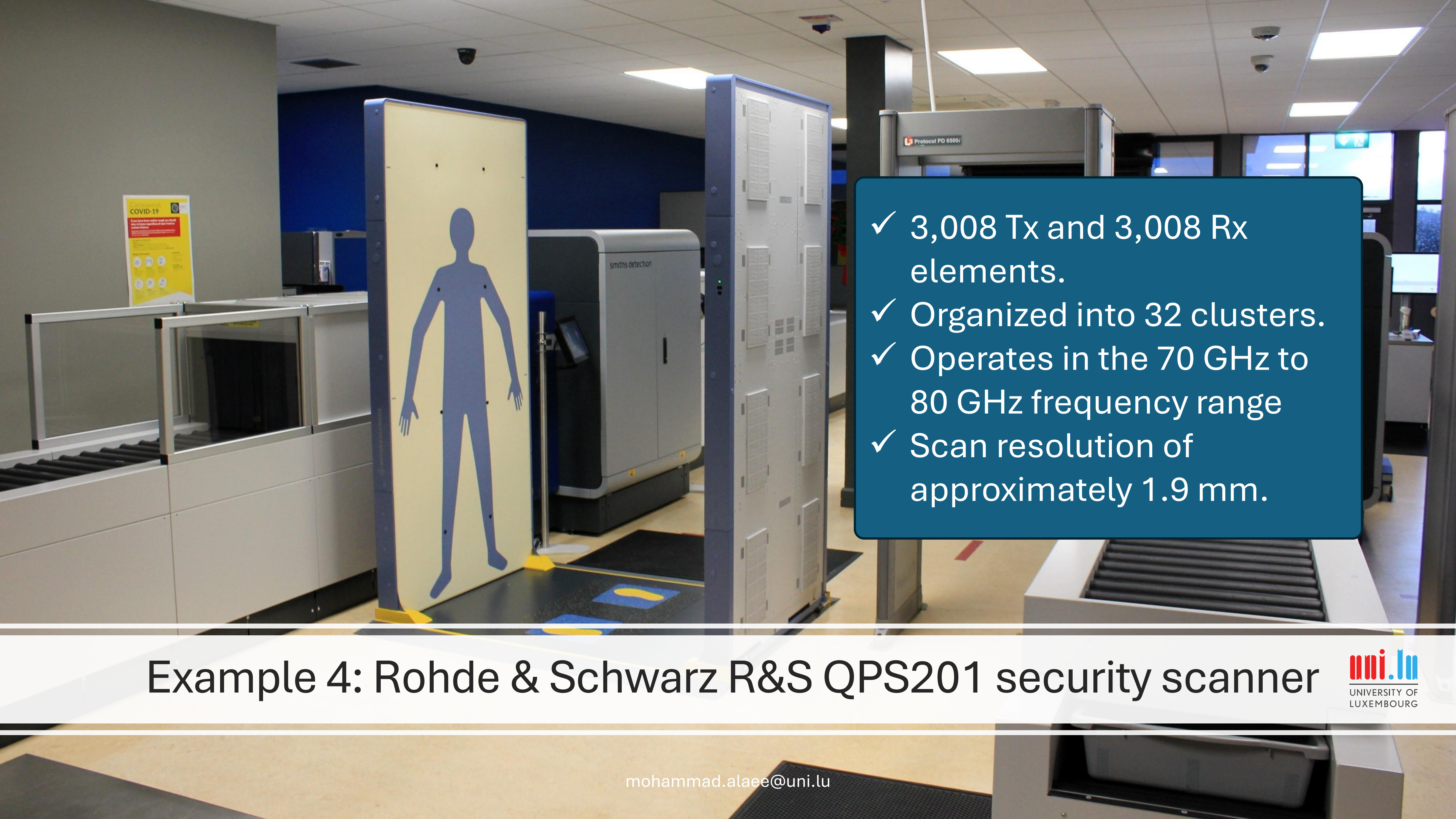
arbe

48 Tx × 48 Rx =
2034 virtual
antennas



mohammad.alaee@uni.lu

UNIVERSITY OF LUXEMBOURG



- ✓ 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

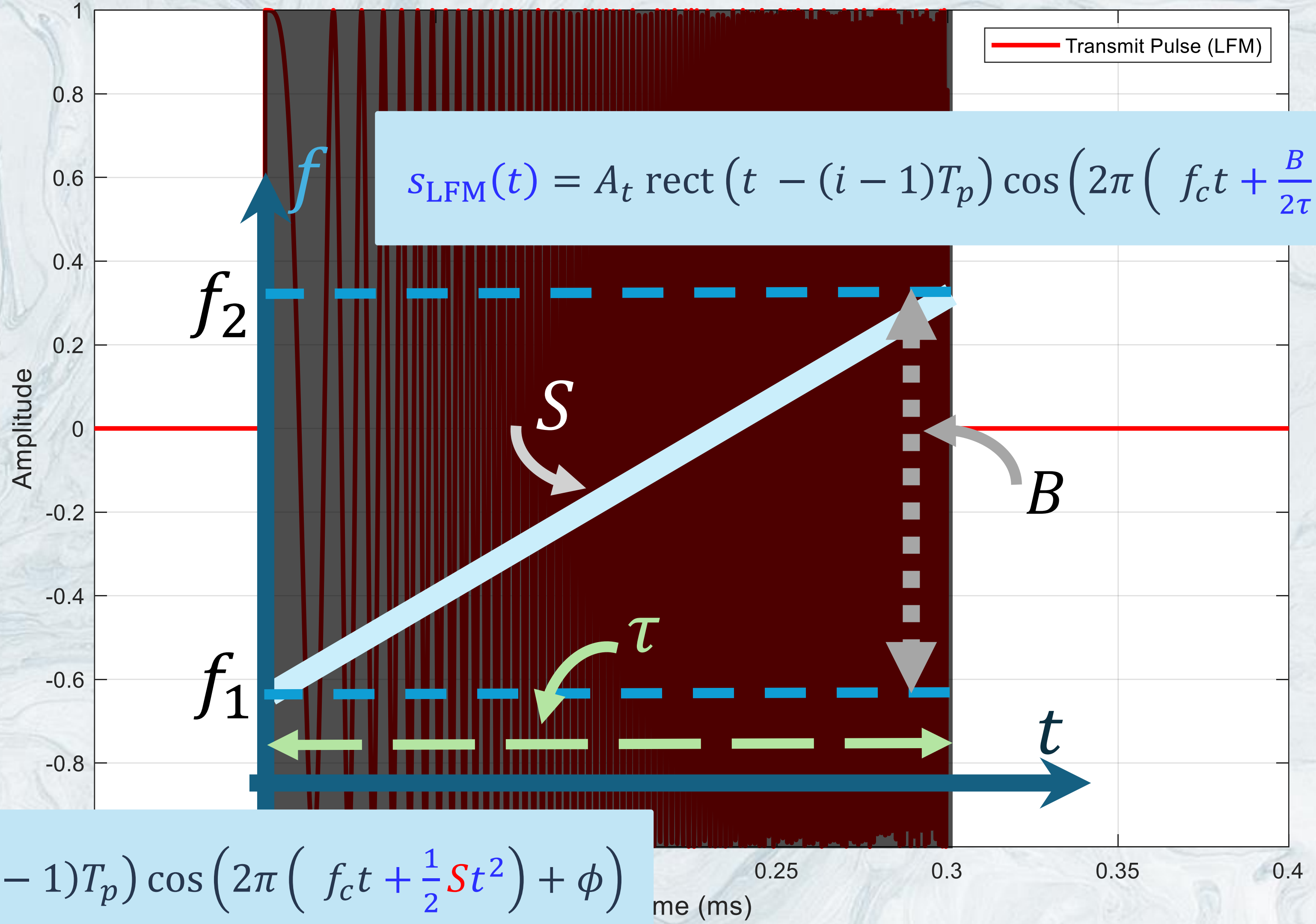
UNIVERSITY OF LUXEMBOURG

LFM Transmit waveform

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

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

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

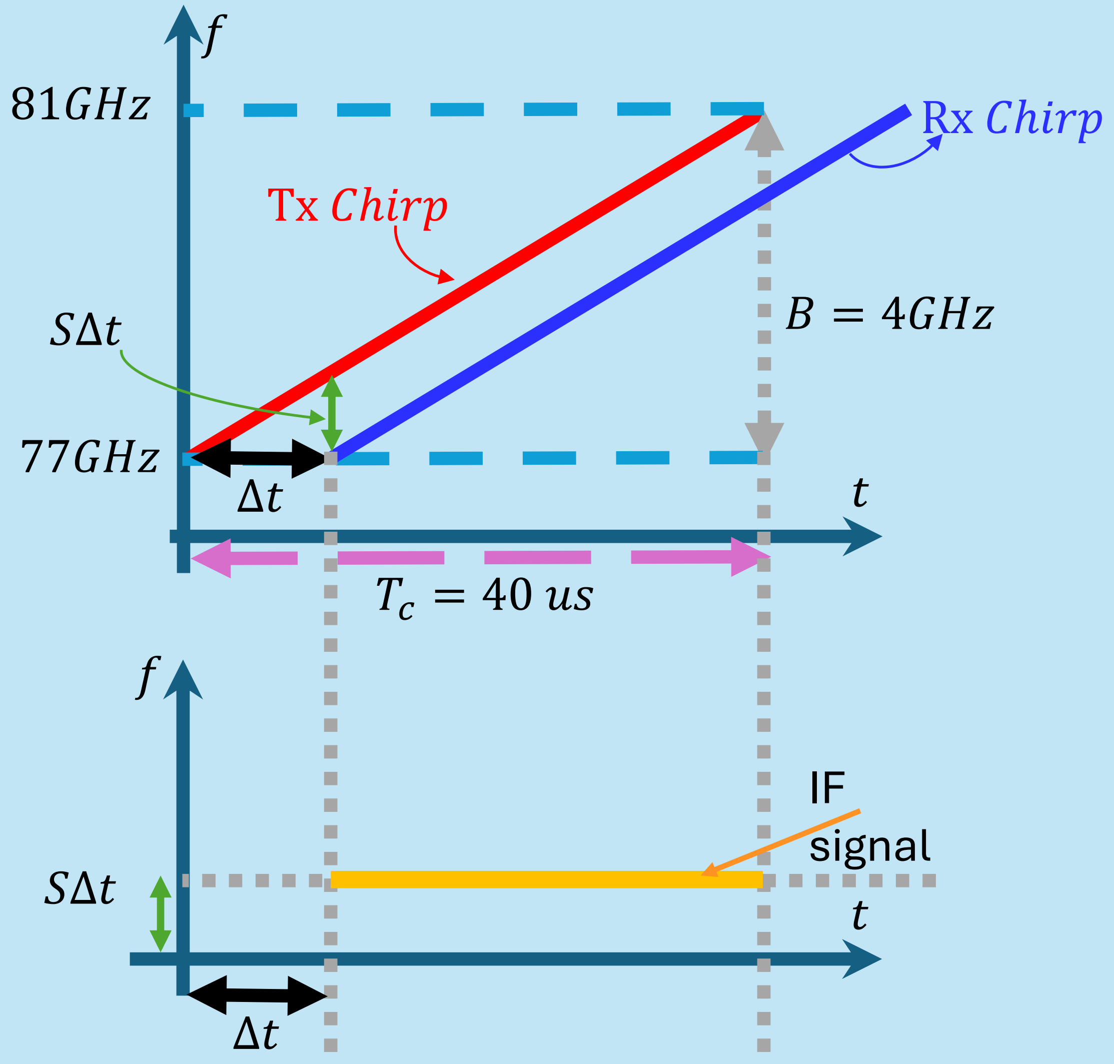


$$s_{\text{LFM}}(t) = A_t \operatorname{rect}\left(t - (i-1)T_p\right) \cos\left(2\pi\left(f_c t + \frac{B}{2\tau} t^2\right) + \phi\right)$$

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

mohammad.alaee@uni.lu

Transmit waveform in mmWave radars - FMCW



Example

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

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

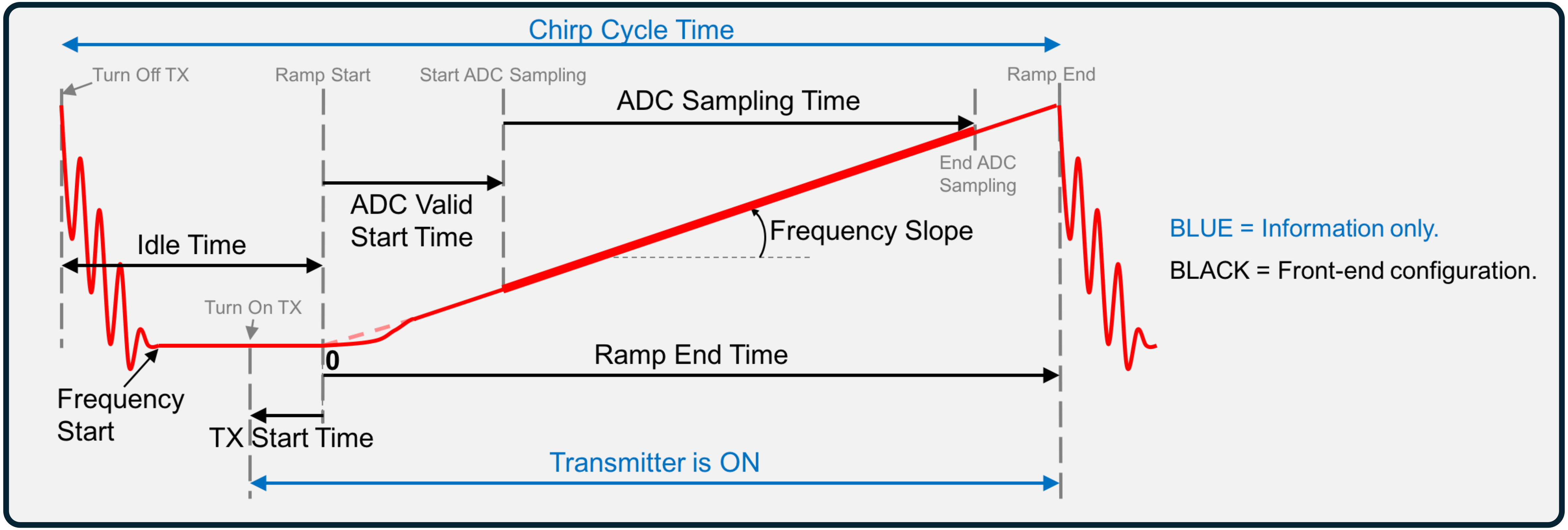
$$f_{\text{IF}} = S\Delta t = 100\,\frac{\text{MHz}}{\mu\text{s}} \times 0.1\ \mu\text{s} = 10\text{ MHz}$$

$f_s = 10$ MHz (complex sampling ADCs) instead of 4 GHz (complex sampling ADCs)

This is called "de-chirp"

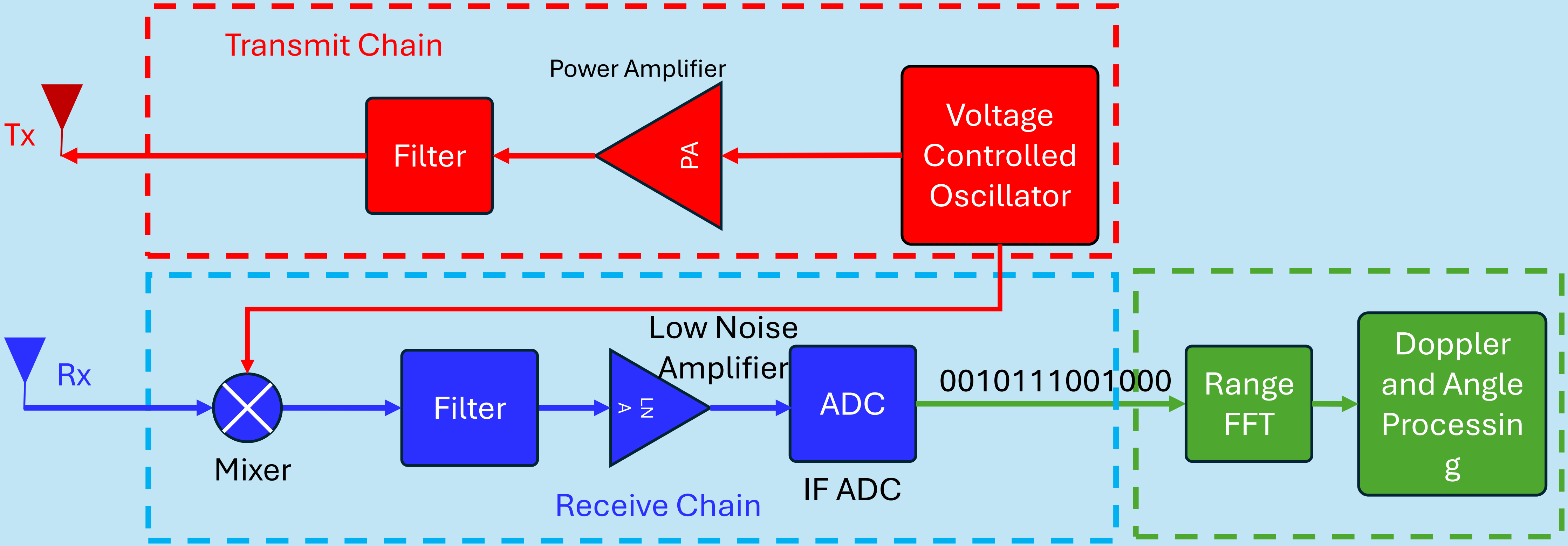
FMCW in Practice

➢ Slow-Chirp and Fast-Chirp



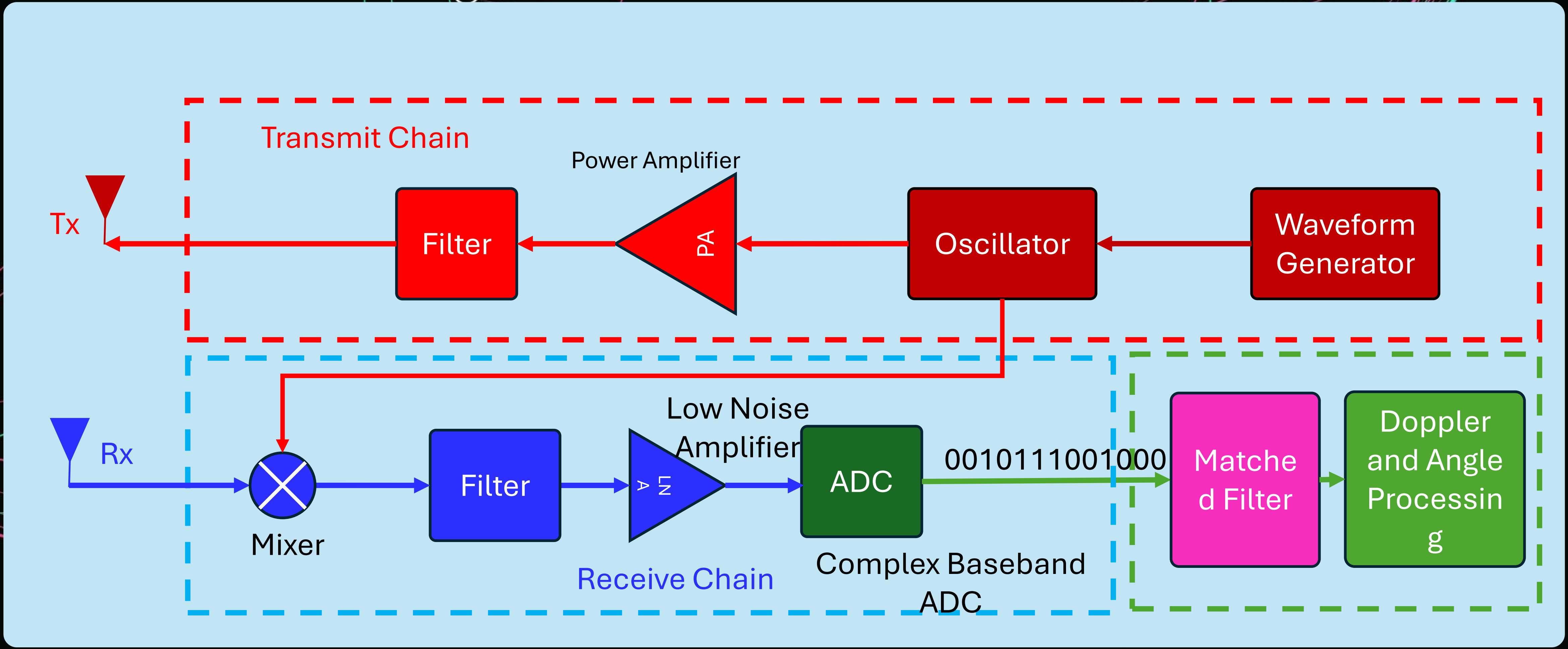
- **Fast Chirp**: each chirp is typically 10's of μs in duration (Typically Range-Doppler Coupling is neglectable)
- **Slow Chirp**: Old FMCW Radars with huge Range-Doppler Coupling

FMCW radar



mohammad.alaee@uni.lu

PMCW radar

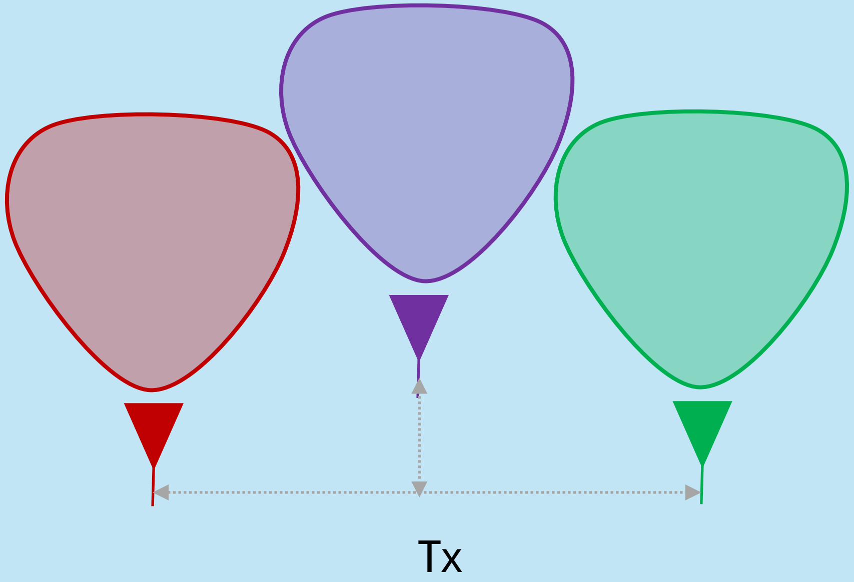


mohammad.alaee@uni.lu

Transmit waveform in MIMO radars

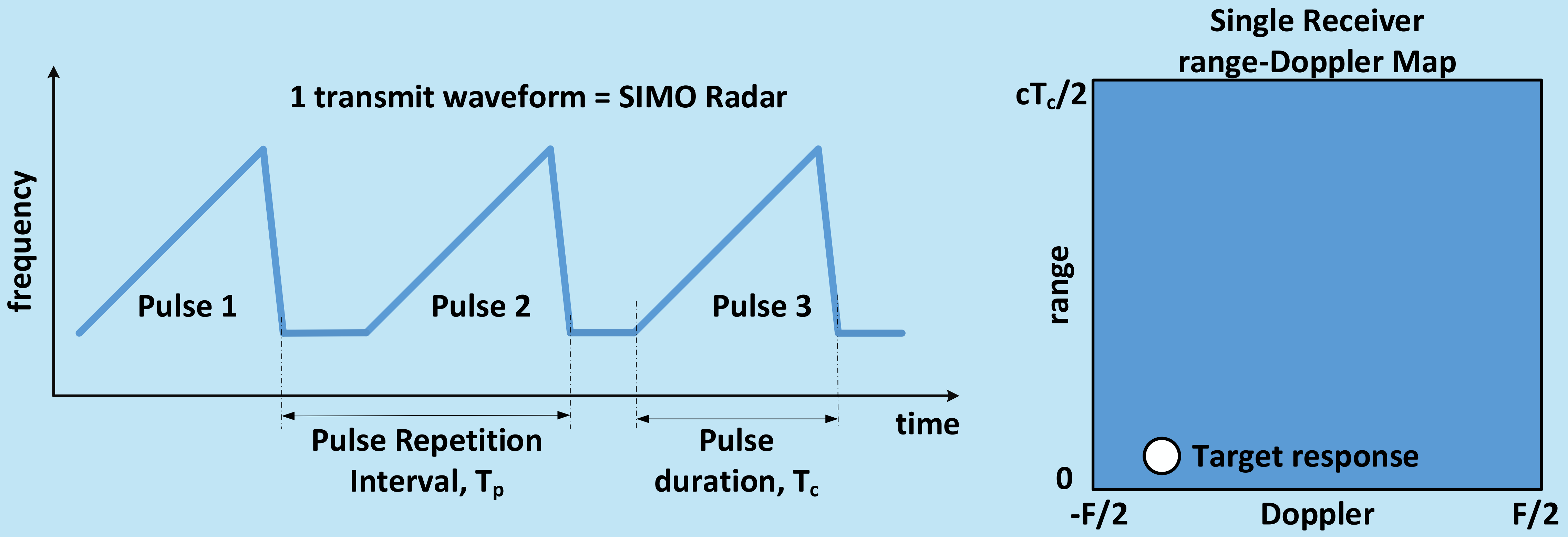
Inter-Pulse Modulation Techniques

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



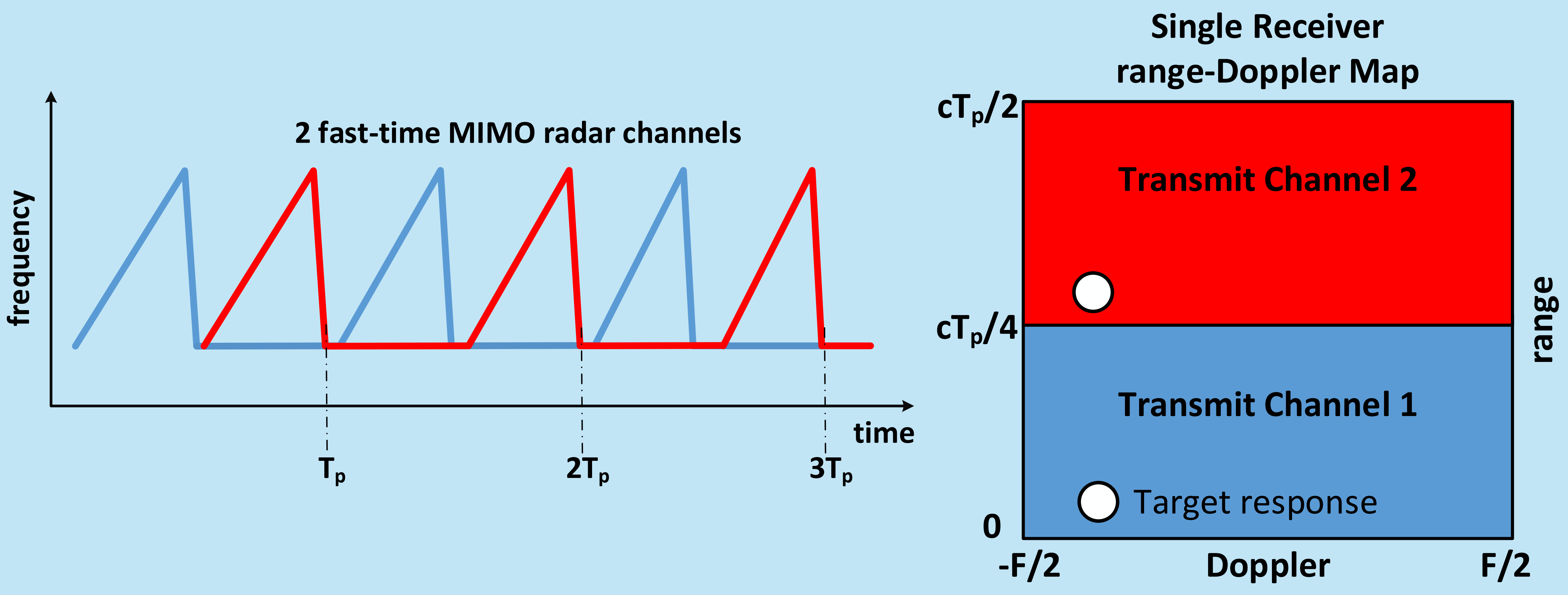
Time Division Multiplexing (TDM)

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



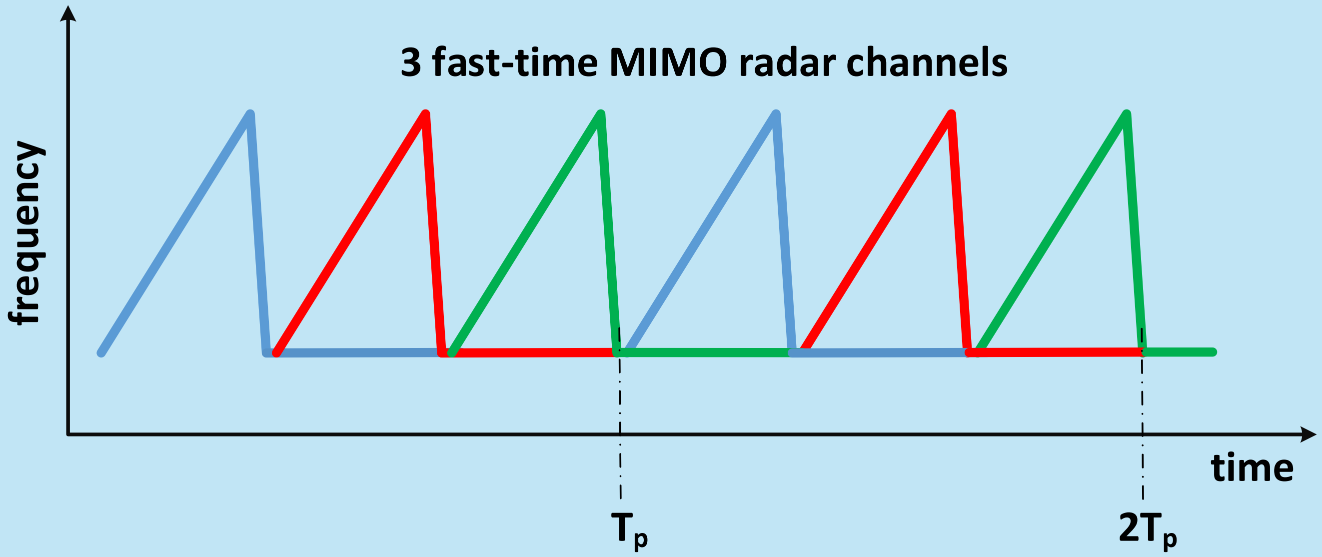
mohammad.alaee@uni.lu

TDM-MIMO

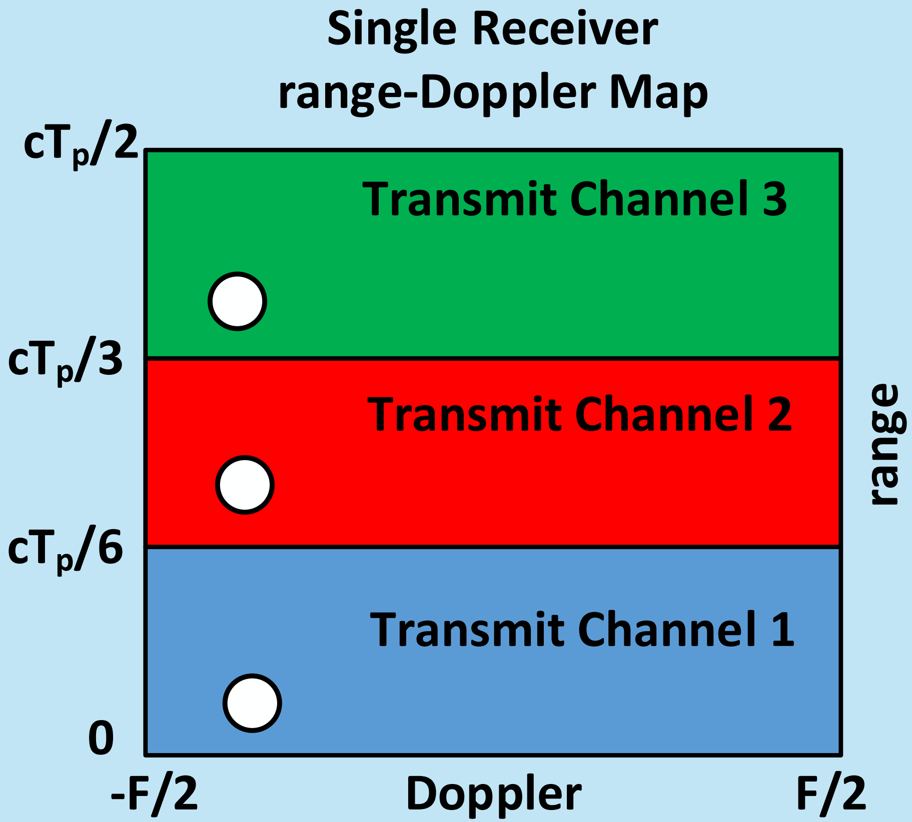


2 fast-time MIMO radar channels
frequency
time
T_p
$2T_p$
$3T_p$
Single Receiver
range-Doppler Map
$cT_p/2$
$cT_p/4$
0
Transmit Channel 2
Transmit Channel 1
Target response
range
-F/2
Doppler
F/2

TDM-MIMO



3 fast-time MIMO radar channels
frequency
time
T_p
$2T_p$



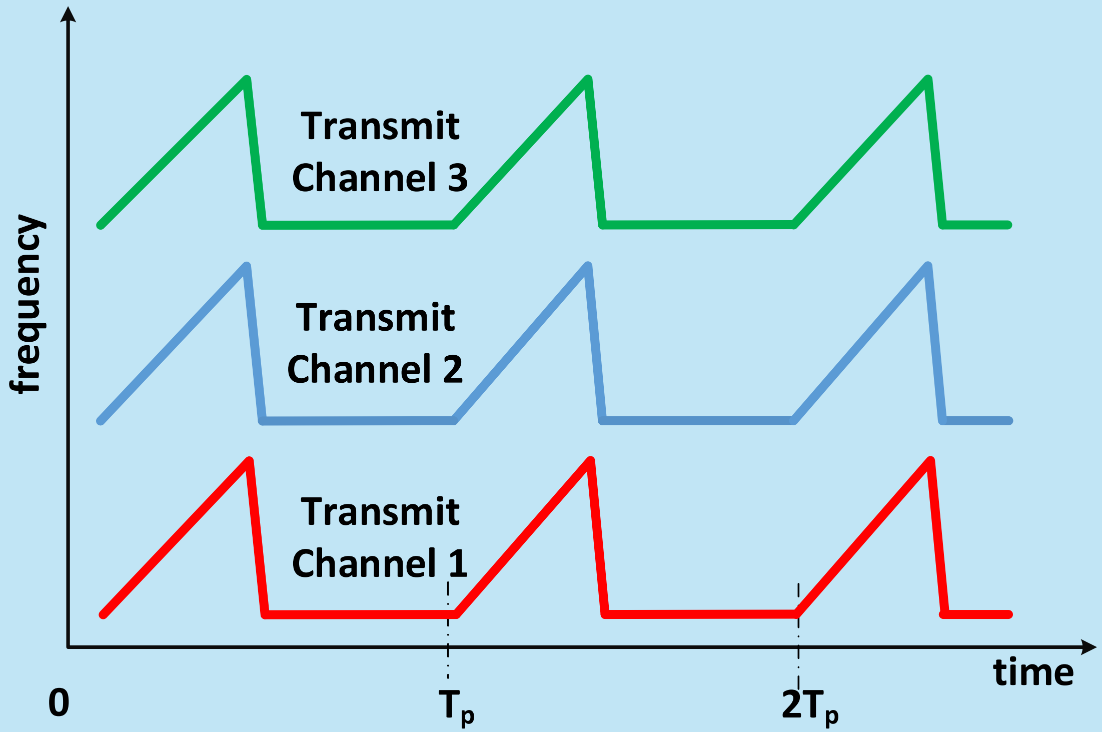
Single Receiver
range-Doppler Map
$cT_p/2$
$cT_p/3$
$cT_p/6$
0
Transmit Channel 3
Transmit Channel 2
Transmit Channel 1
range
-F/2
Doppler
F/2

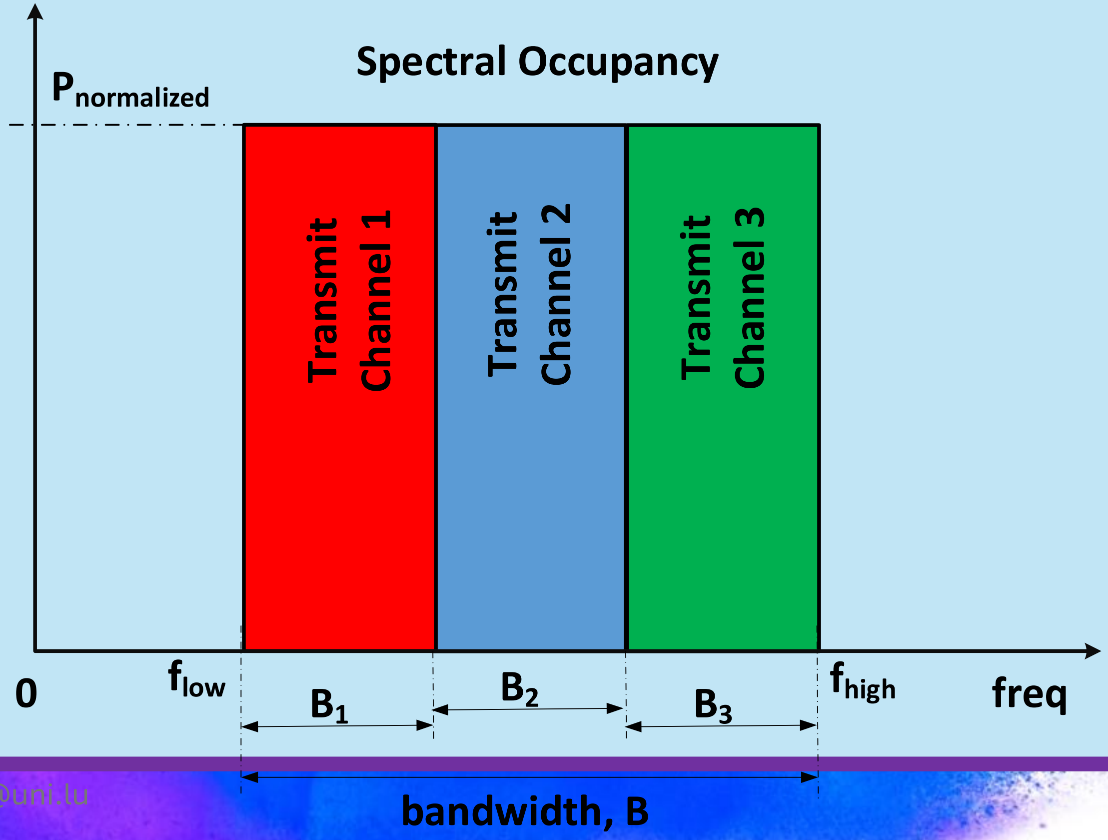
Frequency Division Multiplexing (FDM)

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

$$\text{range resolution} = \frac{c}{2B},$$

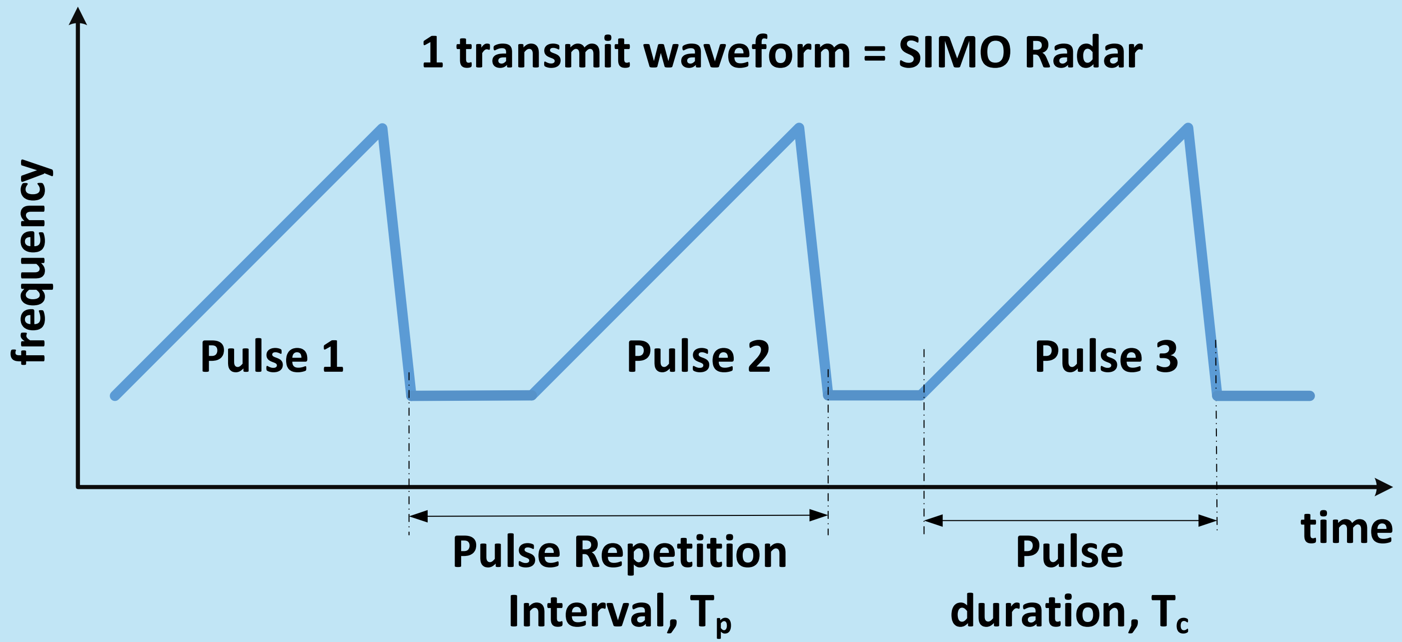
$$\text{where } c = \text{speed of light}, \ B = \text{bandwidth}.$$

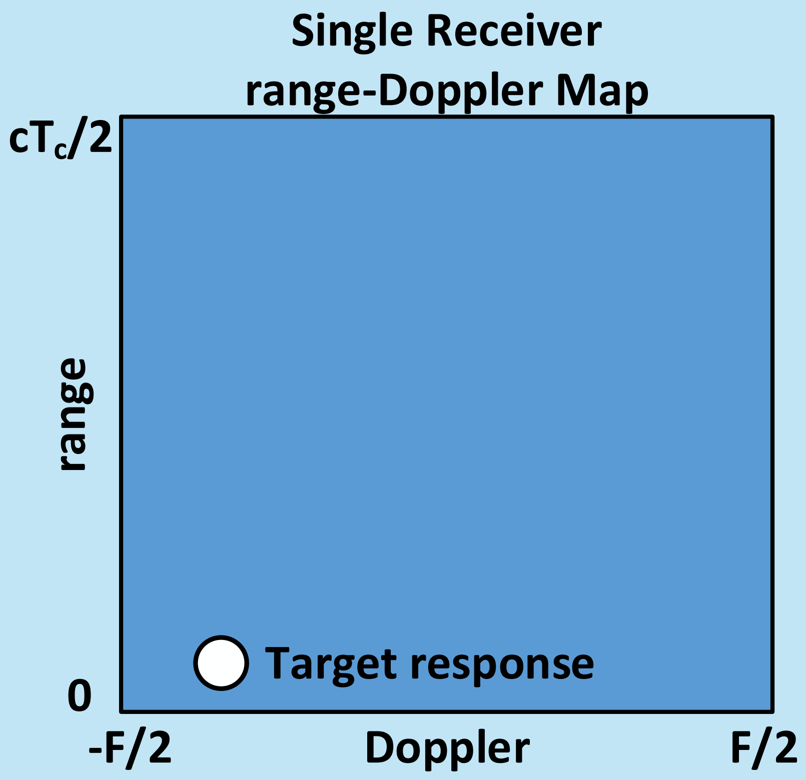




mohammad.alaee@uni.lu

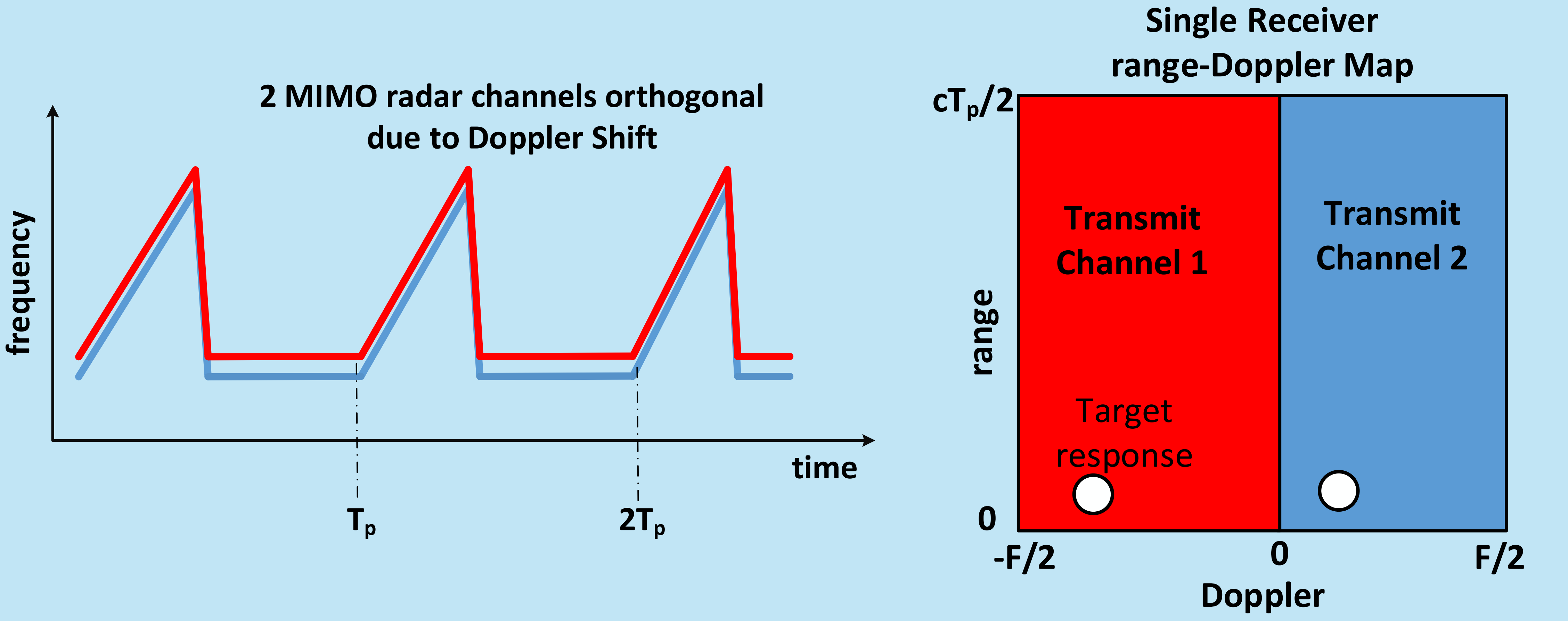
Doppler Division Multiplexing (DDM)





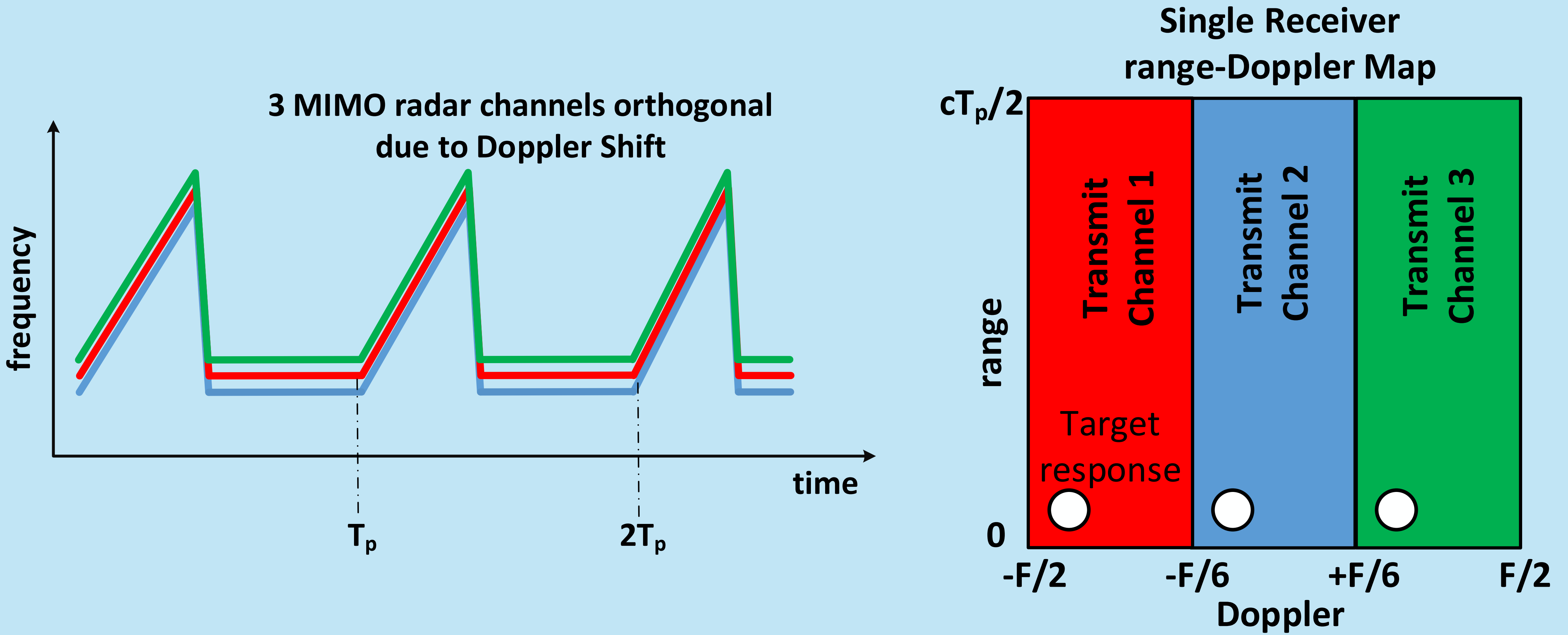
mohammad.alaee@uni.lu

DDM - MIMO

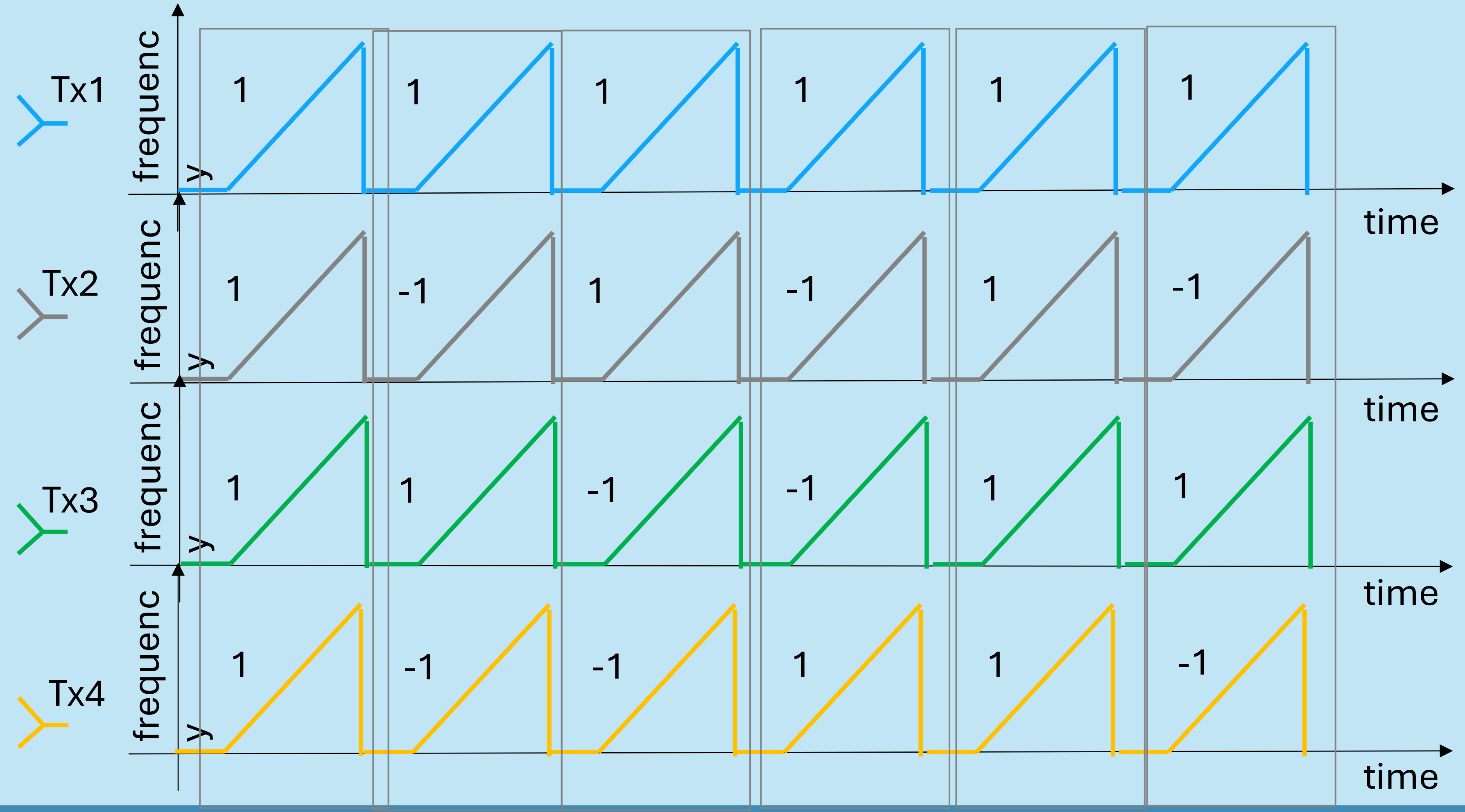


2 MIMO radar channels orthogonal due to Doppler Shift
frequency
time
Tp
2Tp
Single Receiver range-Doppler Map
cTp/2
range
0
Transmit Channel 1
Target response
Transmit Channel 2
-F/2
0
F/2
Doppler

DDM - MIMO


3 MIMO radar channels orthogonal due to Doppler Shift
frequency
time
T_p
$2T_p$
Single Receiver range-Doppler Map
$cT_p/2$
range
0
Transmit Channel 1
Transmit Channel 2
Transmit Channel 3
Target response
-F/2
-F/6
+F/6
F/2
Doppler

Binary Phase Modulation (BPM)

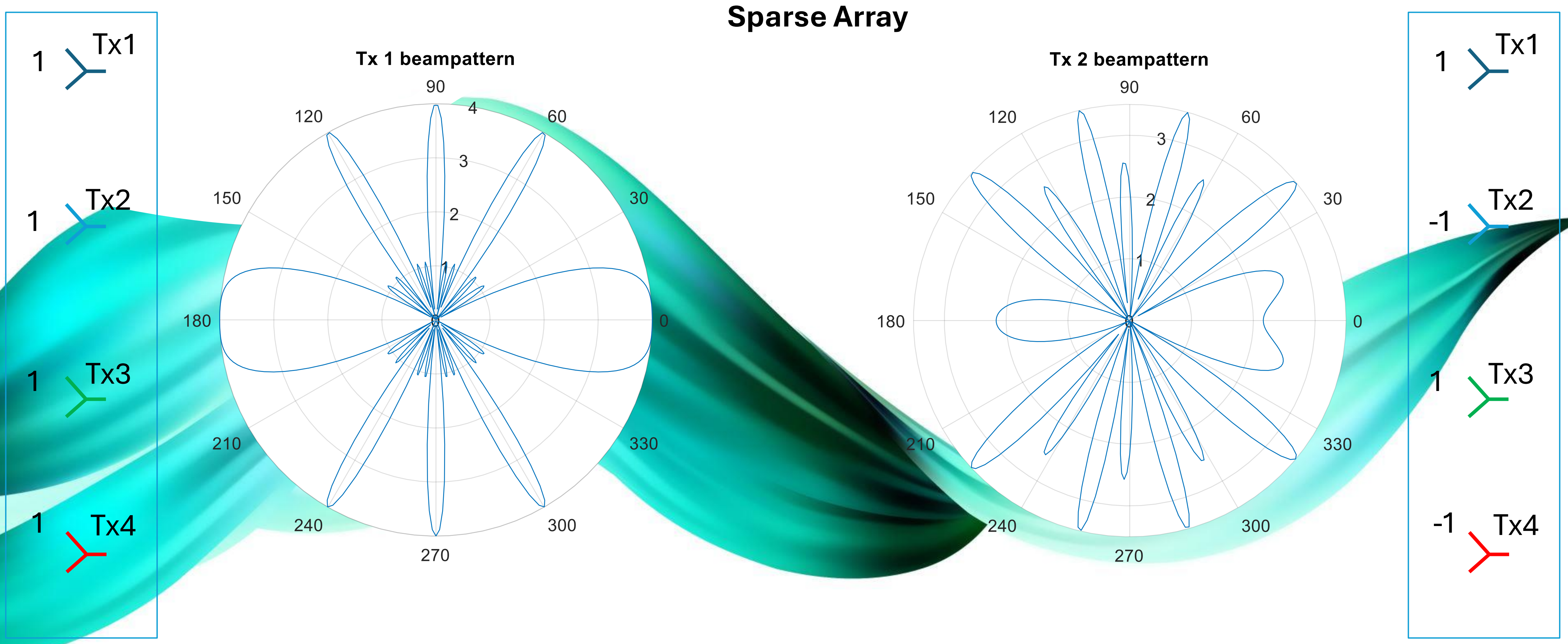


Hadamard Code

$$\begin{matrix} 1 & 1 & 1 & 1 \\ 1 & -1 & 1 & -1 \\ 1 & 1 & -1 & -1 \\ 1 & -1 & -1 & 1 \end{matrix}$$

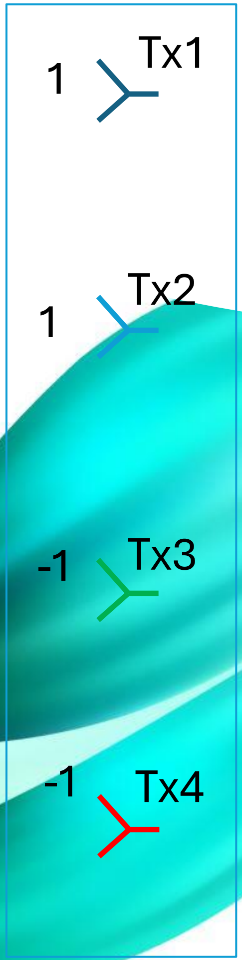
mohammad.alaee@uni.lu

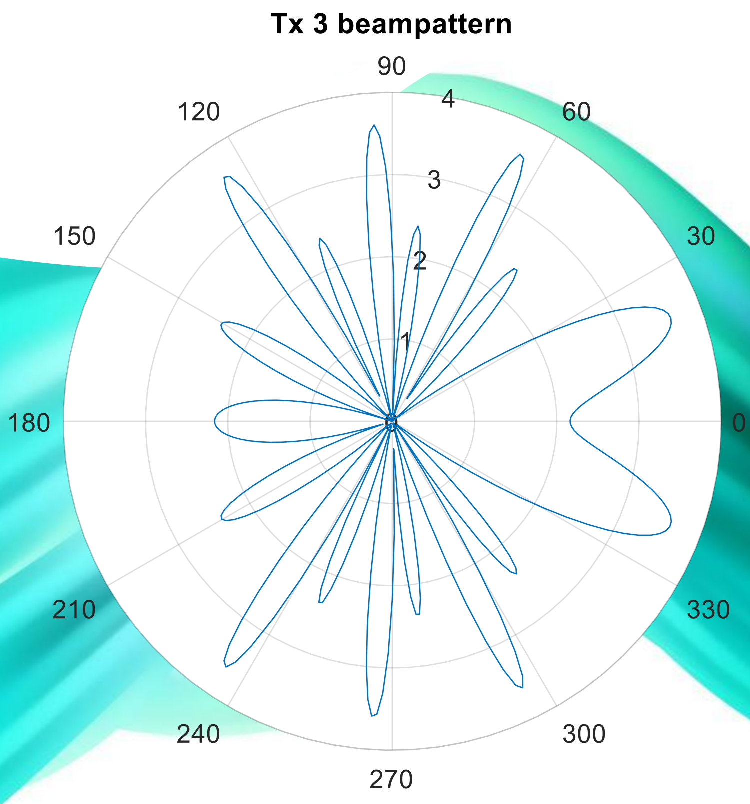
BPM-MIMO

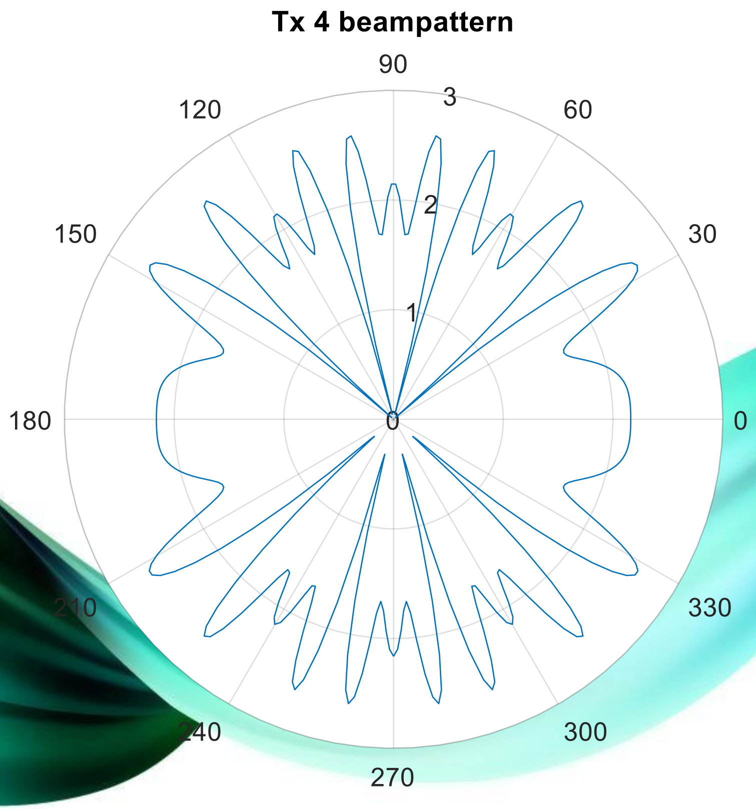

Sparse Array
1 Tx1
1 Tx2
1 Tx3
1 Tx4
Tx 1 beampattern
90
120
60
150
30
180
0
210
330
240
300
270
1
2
3
4
Tx 2 beampattern
90
120
60
150
30
180
0
210
330
240
300
270
1
2
3
1 Tx1
-1 Tx2
1 Tx3
-1 Tx4

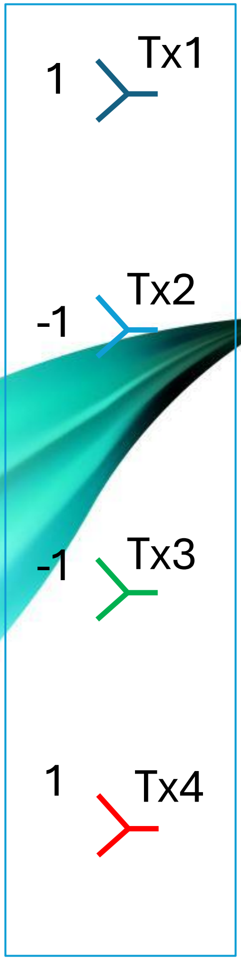
BPM-MIMO

Sparse Array





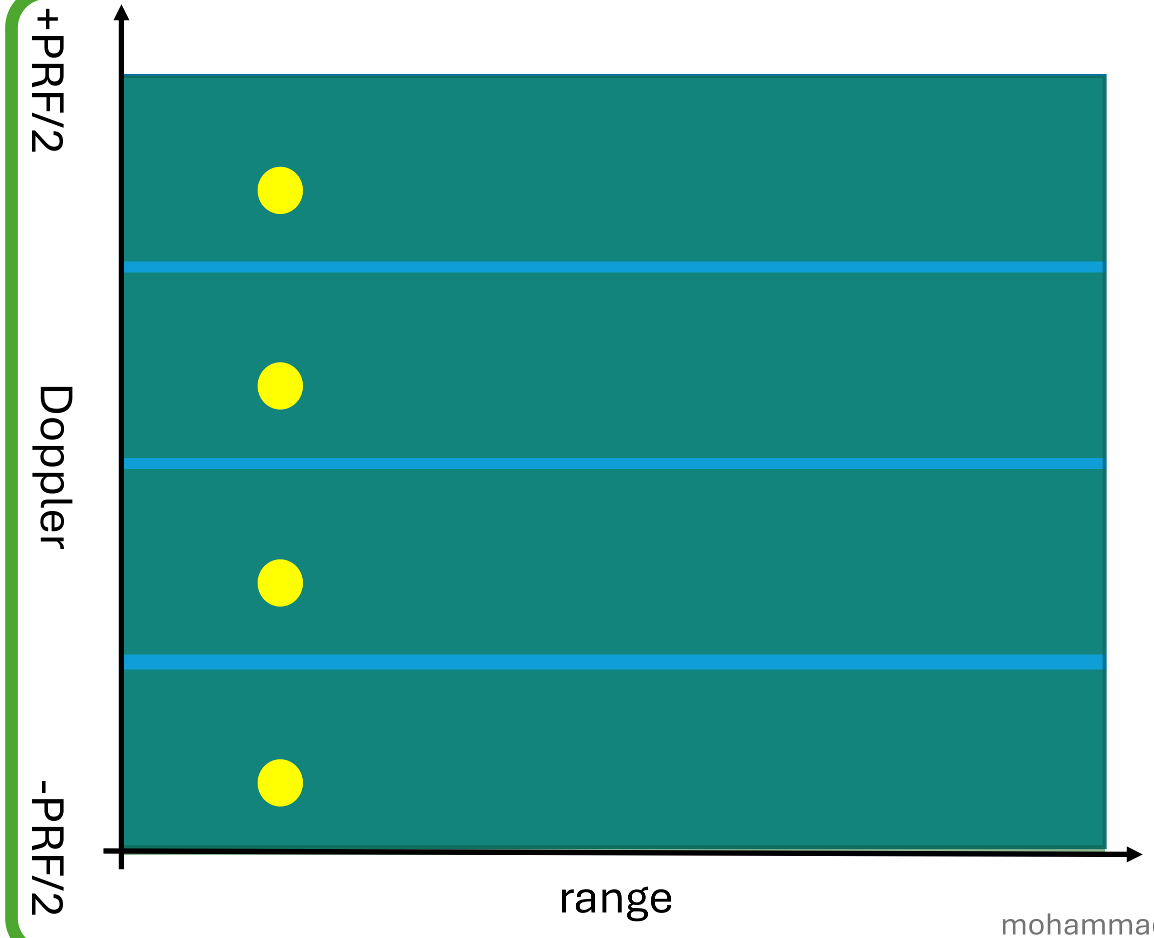


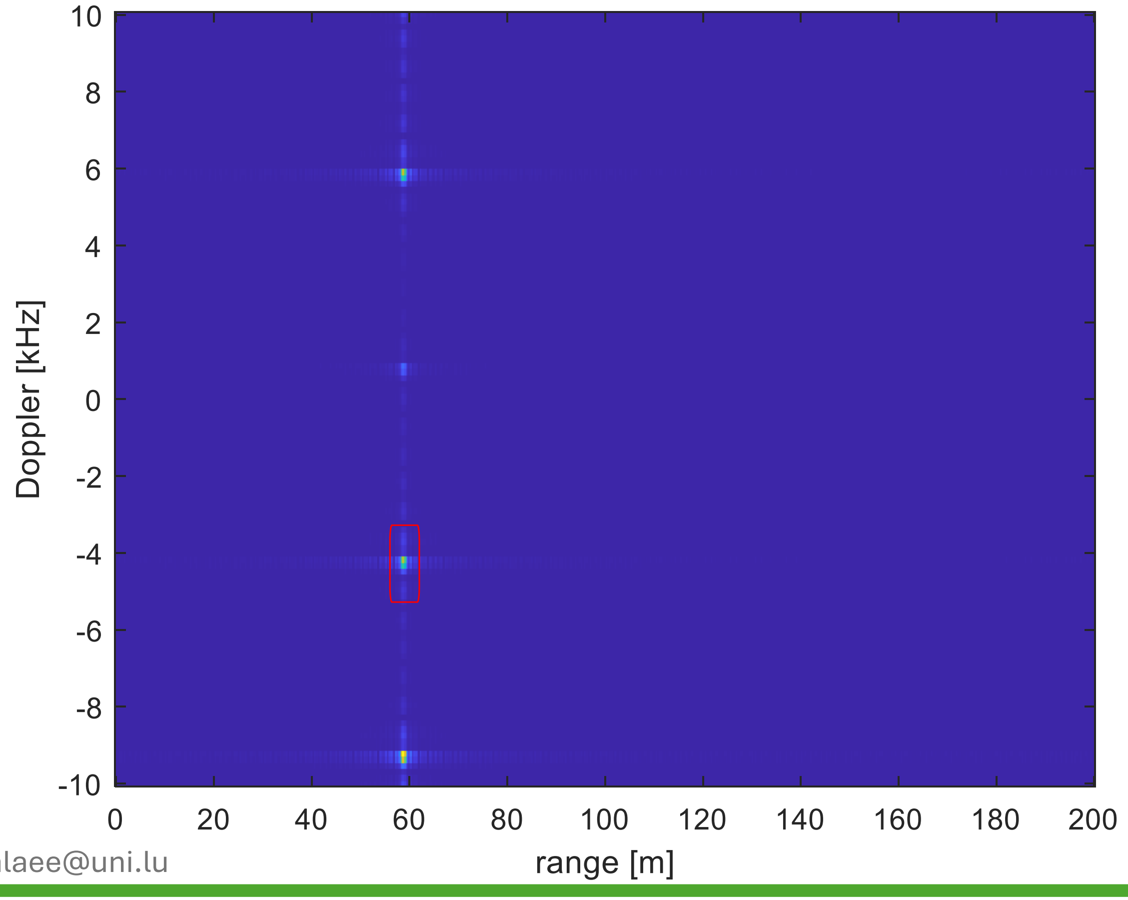


mohammad.alaee@uni.lu

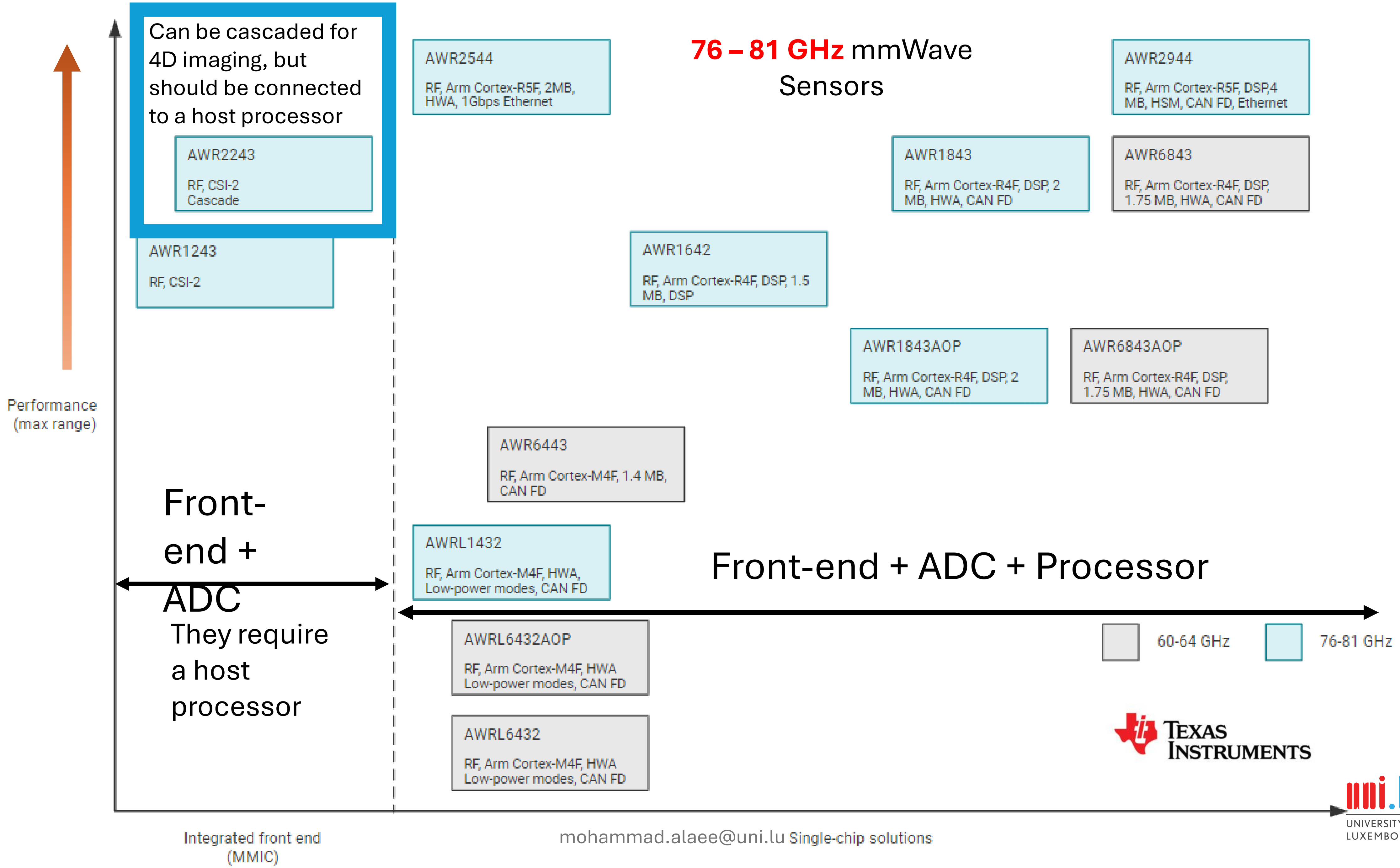
BPM-MIMO

Doppler aliased clutter and targets appear in other channels



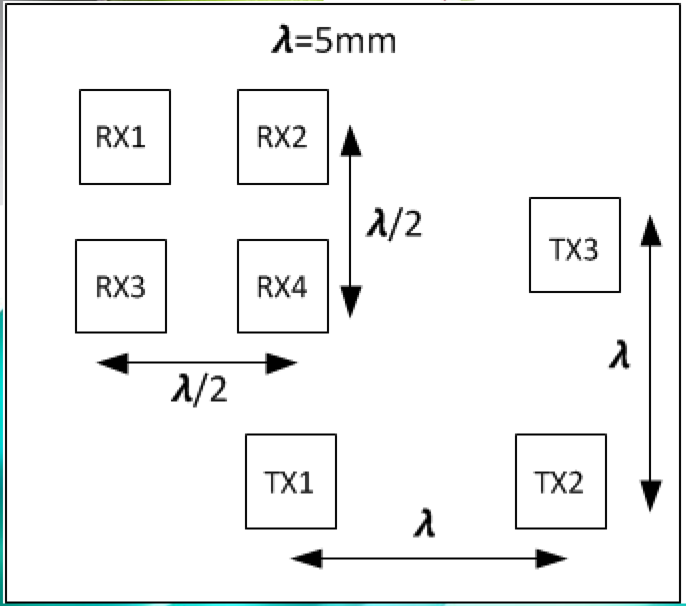


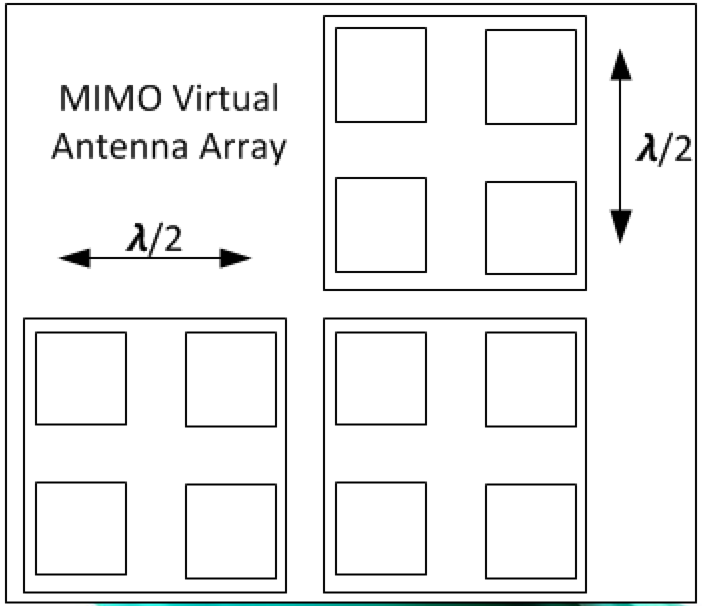
Radar Sensors and Radar on Chip (RoC)



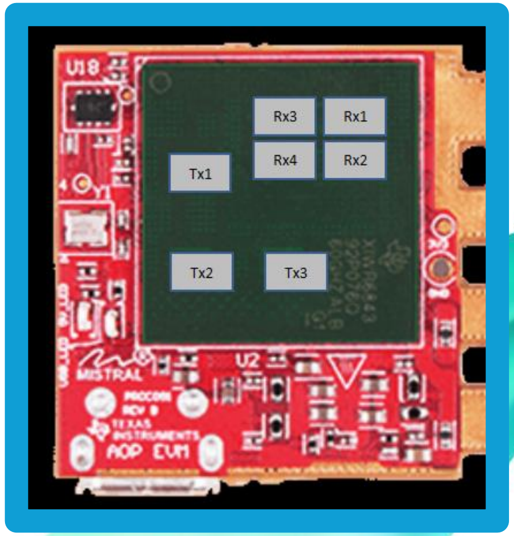
UNIVERSITY OF LUXEMBOURG

IWR6843 Antenna-on-Package (AoP)





IWR6843 AoP



mohammad.alaee@uni.lu

Massive MIMO 4D radar

UNIVERSITY OF LUXEMBOURG

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)

- Blind-spot detection
- Adaptive cruise control
- In-cabin monitoring

Smart Cities & Surveillance

- Traffic monitoring
- Perimeter security
- Crowd analytics

Healthcare & Vital Sign Monitoring

- Non-contact heart rate and respiration
- Fall detection
- Sleep monitoring

Consumer Electronics & Smart Homes

- Gesture control
- Presence detection
- Smart appliances

Aerospace & Defense

- Aircraft navigation
- Surveillance and reconnaissance

Space & Environmental Monitoring

- Satellite-based earth observation
- Climate monitoring

Drones & Urban Air Mobility (UAM)

- Autonomous Navigation
- Terrain mapping
- Autonomous delivery
- Obstacle detection

Robotics & Industrial Automation

- Precision navigation
- Obstacle avoidance
- Worker safety

Thank You!

and Questions