Part 2

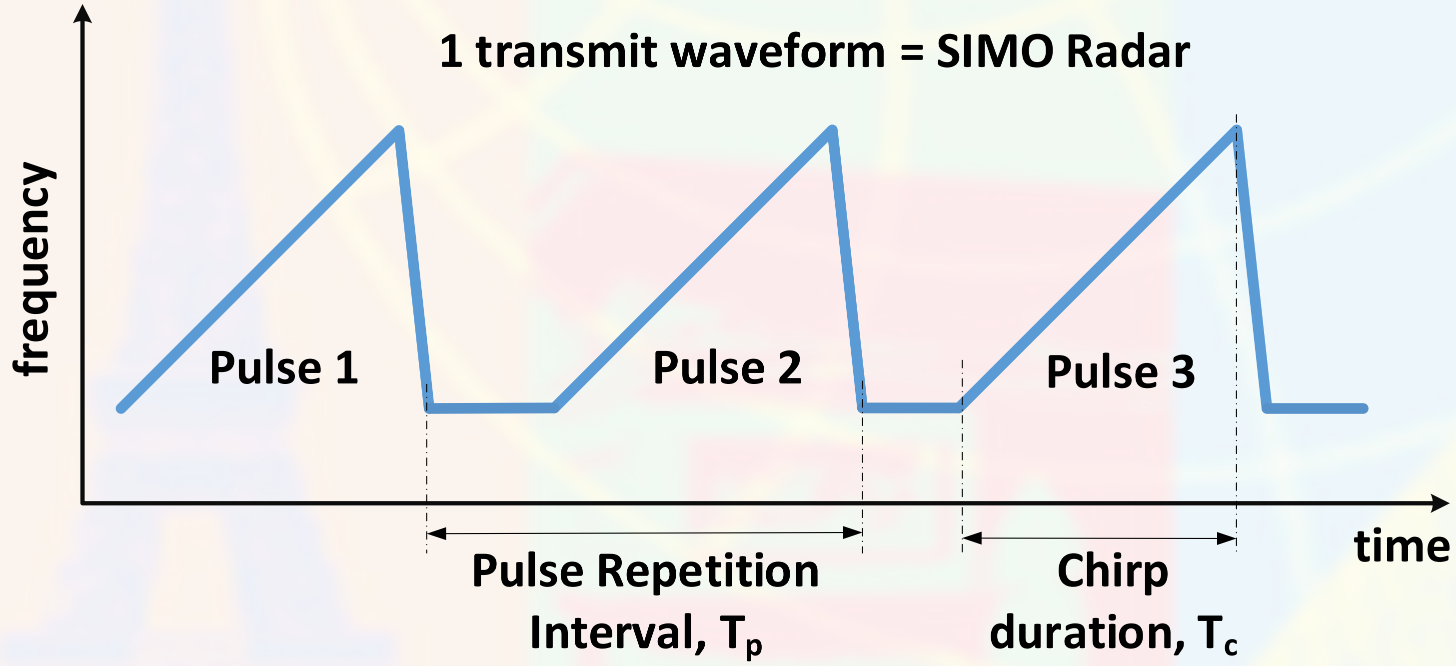
Inter-chirp Waveform Modulation Techniques

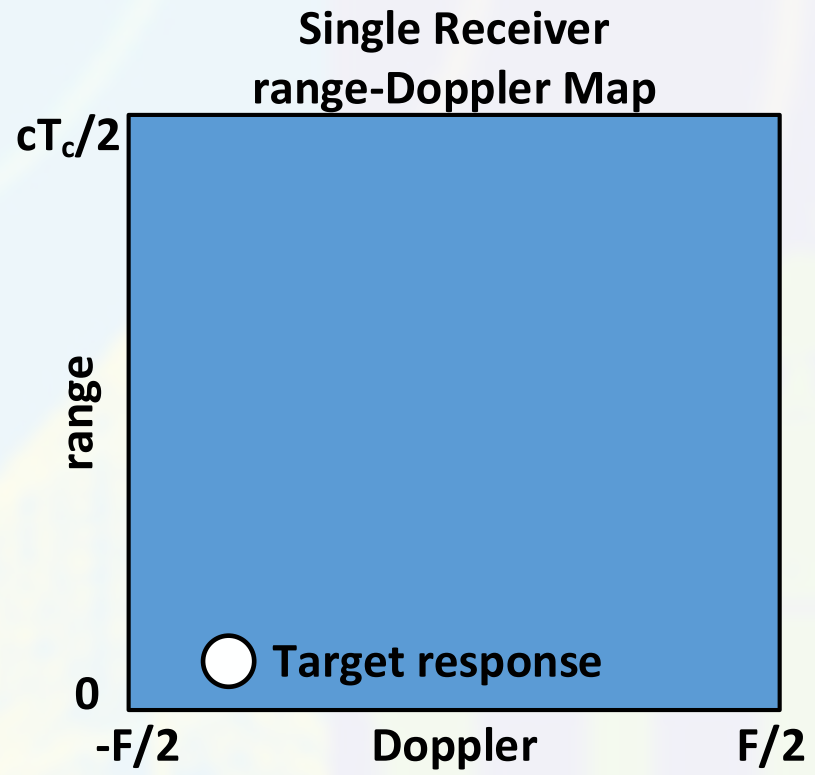
Agenda

- Inter-Pulse Modulation Techniques
  - Time Division Multiplexing (TDM)
  - Frequency Division Multiplexing (FDM)
  - Doppler Division Multiplexing (DDM)
  - Binary Phase Modulation (BPM)
  - Code Division Multiplexing (CDM)

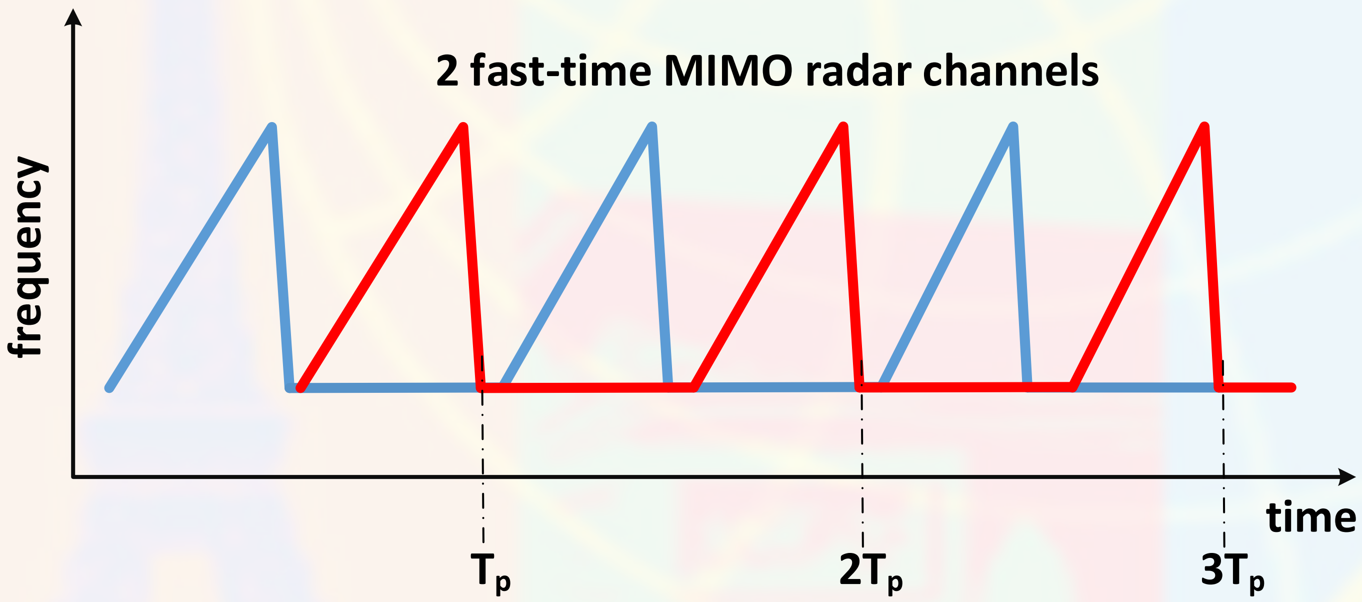
Time Division Multiplexing (TDM)

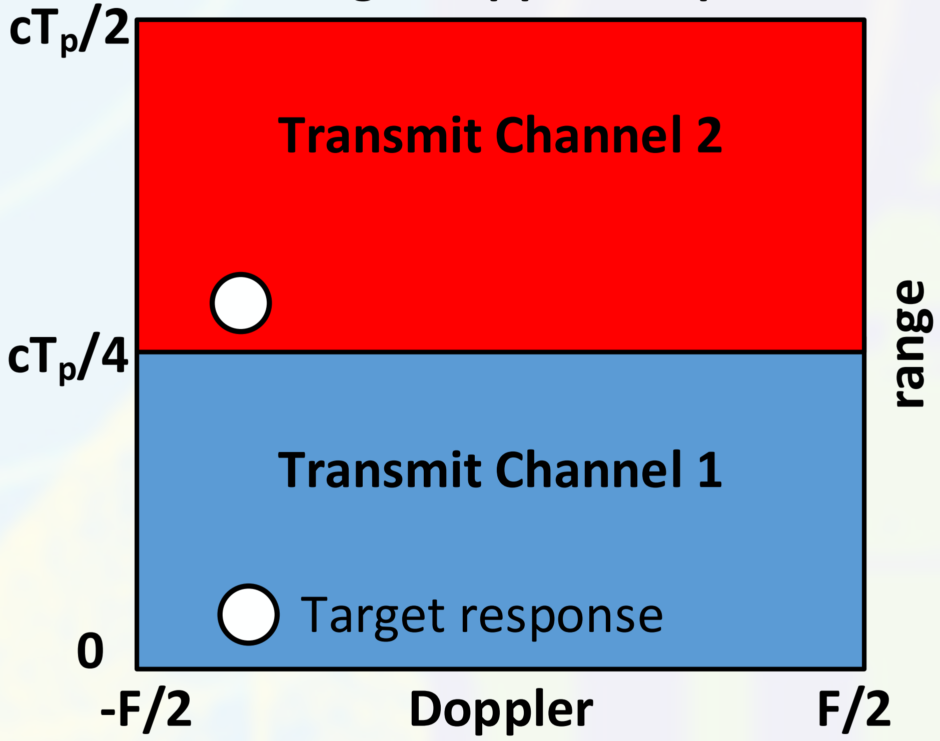
$$F = \frac{1}{T_p}$$



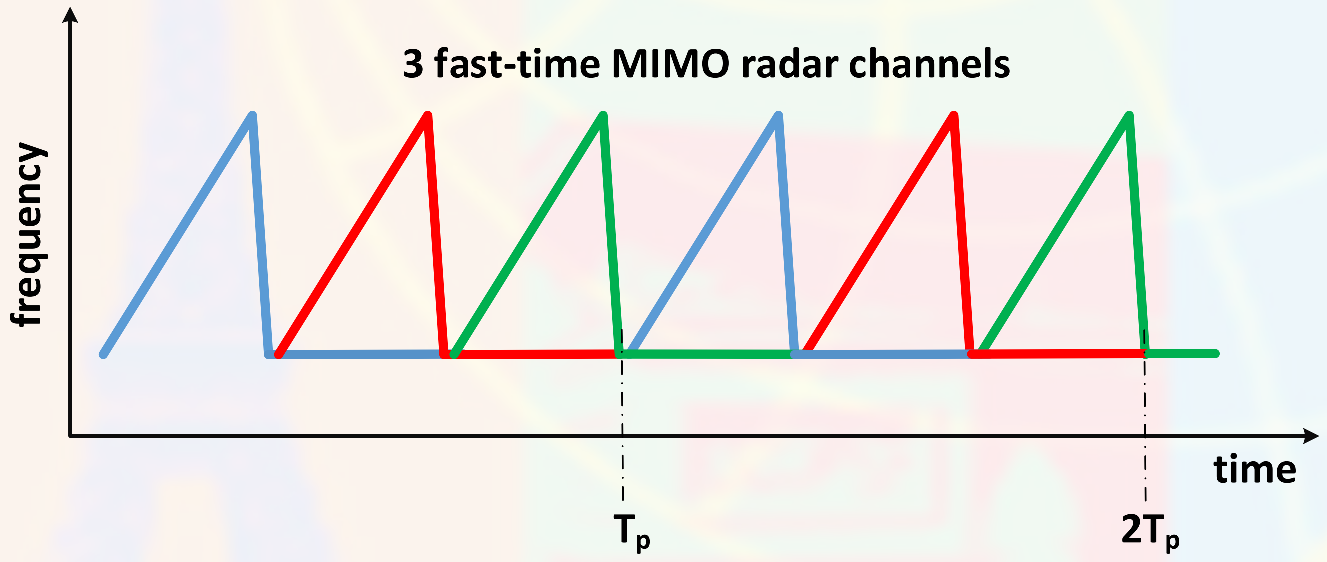


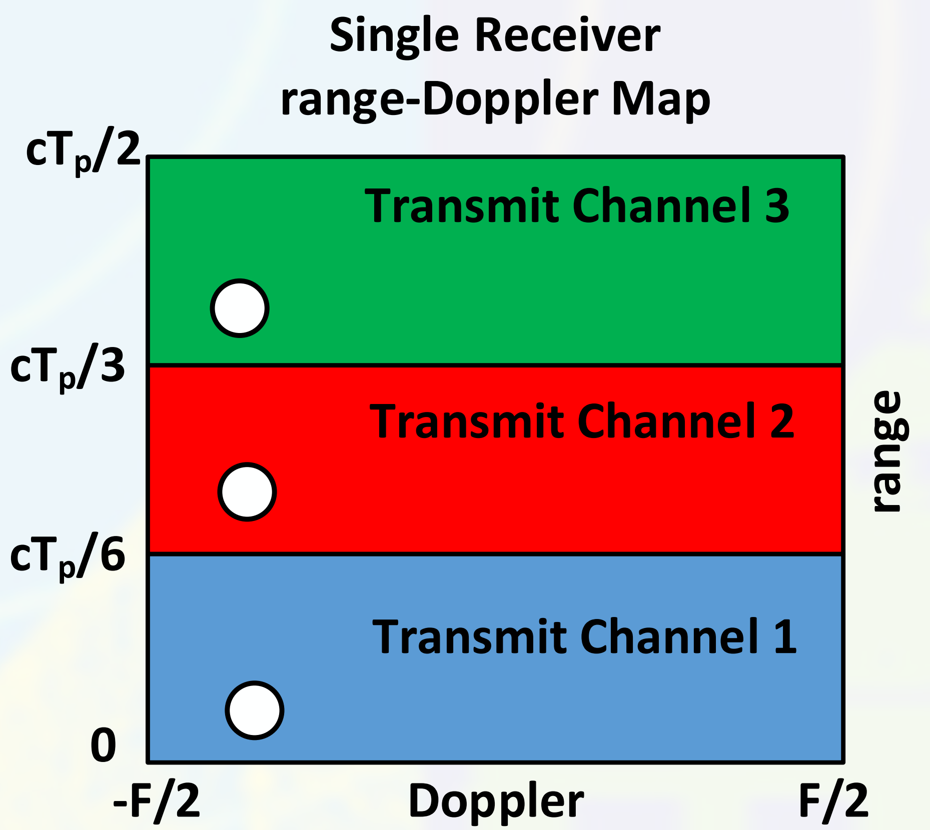
Time Division Multiplexing (TDM)





Time Division Multiplexing (TDM)





Time Division Multiplexing (TDM)

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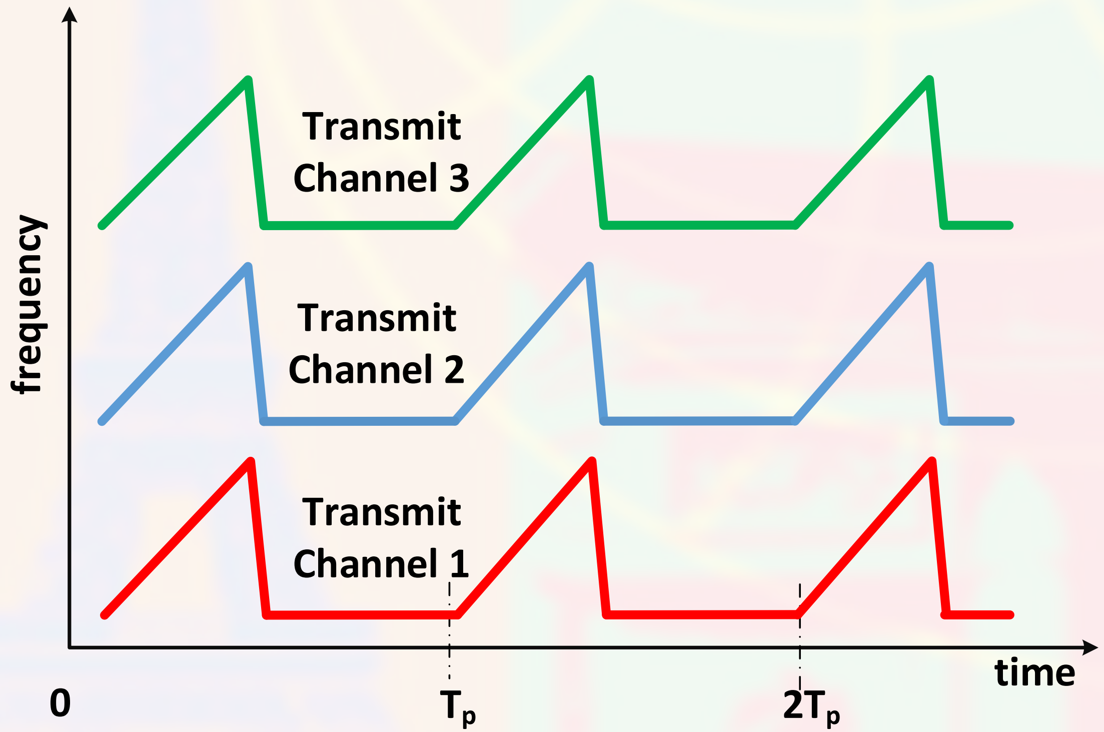
- TDM scheme requires least demanding hardware
- Transmission switches from one antenna to another sequentially within a pulse
- Simple radars with mass manufacturing requirement need to be cost efficient and majorly apply TDM scheme

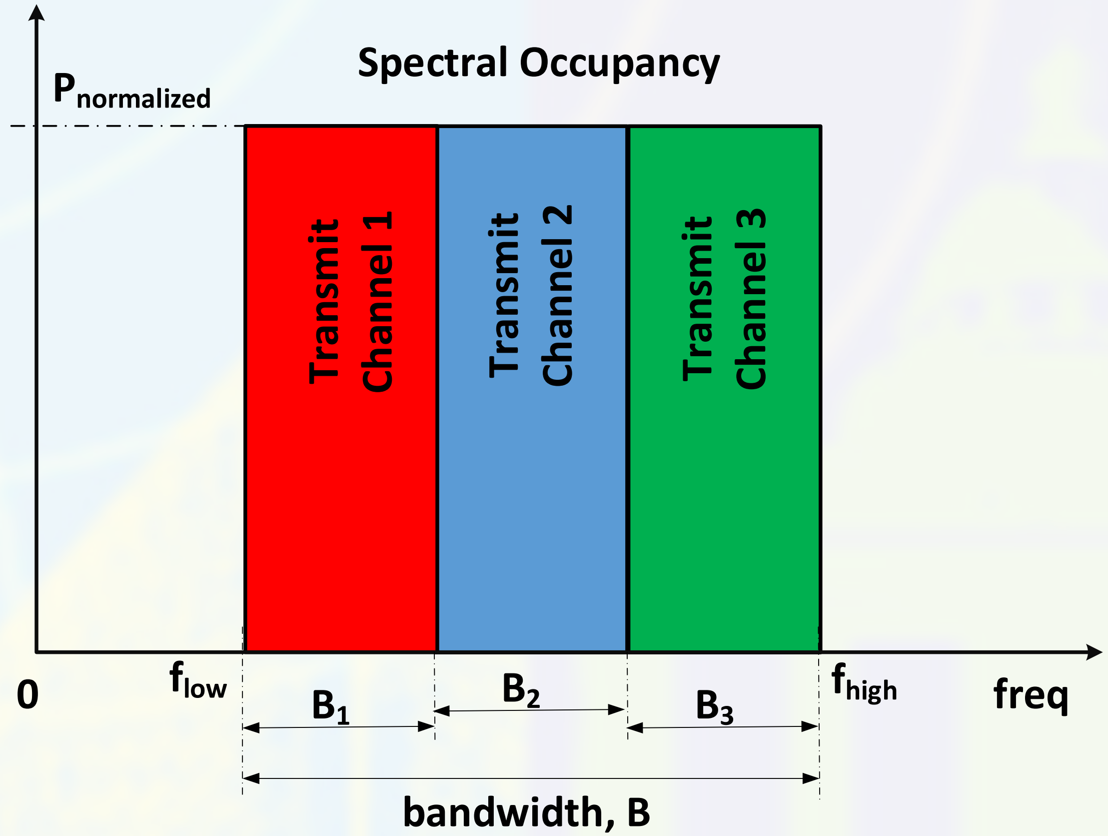
Frequency Division Multiplexing (FDM)

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

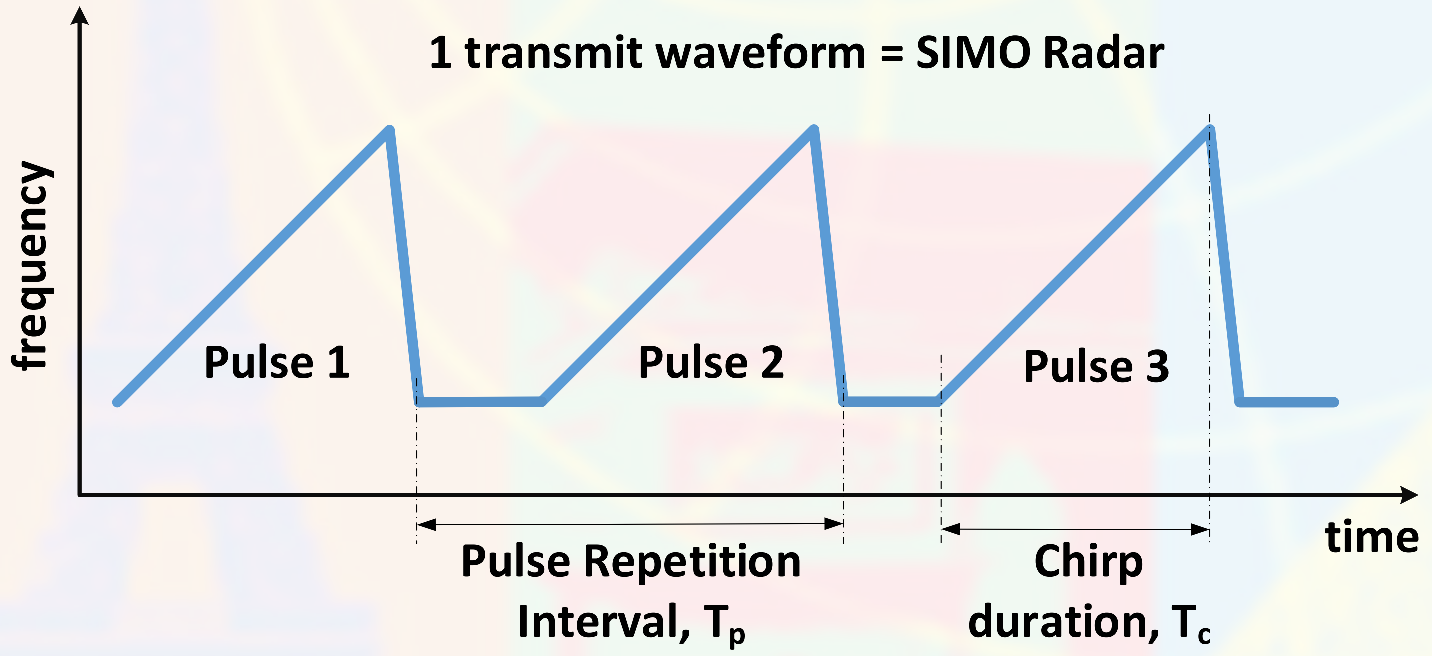
$$\text{range resolution} = \frac{c}{2B},$$

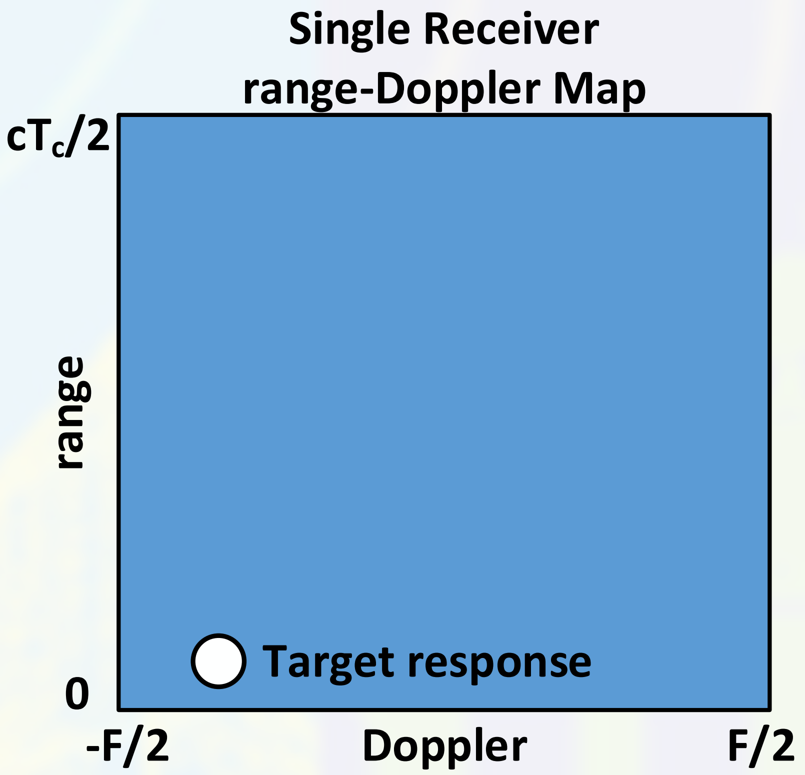
$$\text{where } c = \text{speed of light}, \ B = \text{bandwidth}.$$





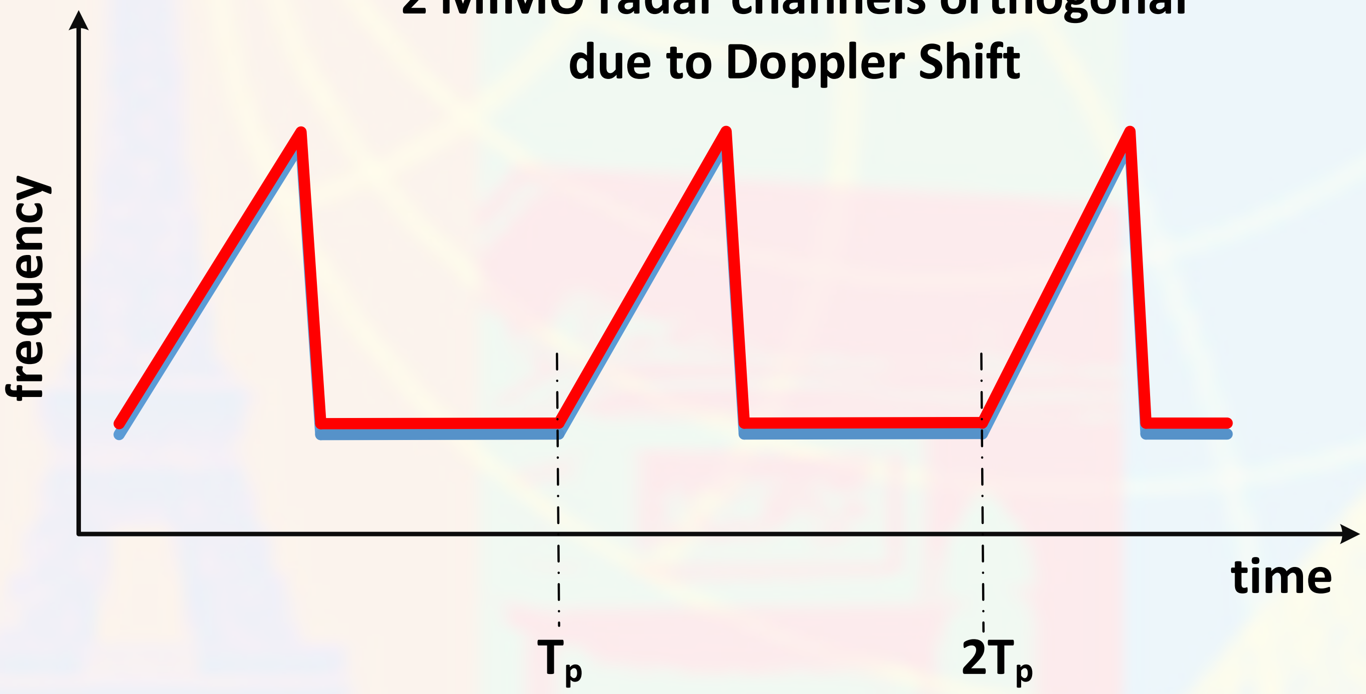
Doppler Division Multiplexing (DDM)



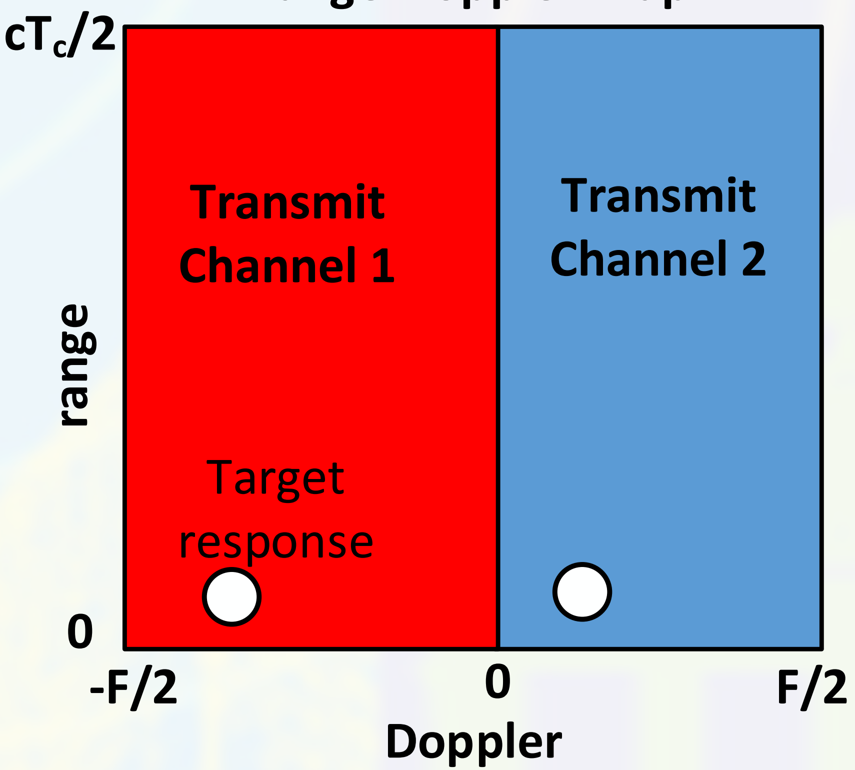


Doppler Division Multiplexing (DDM)

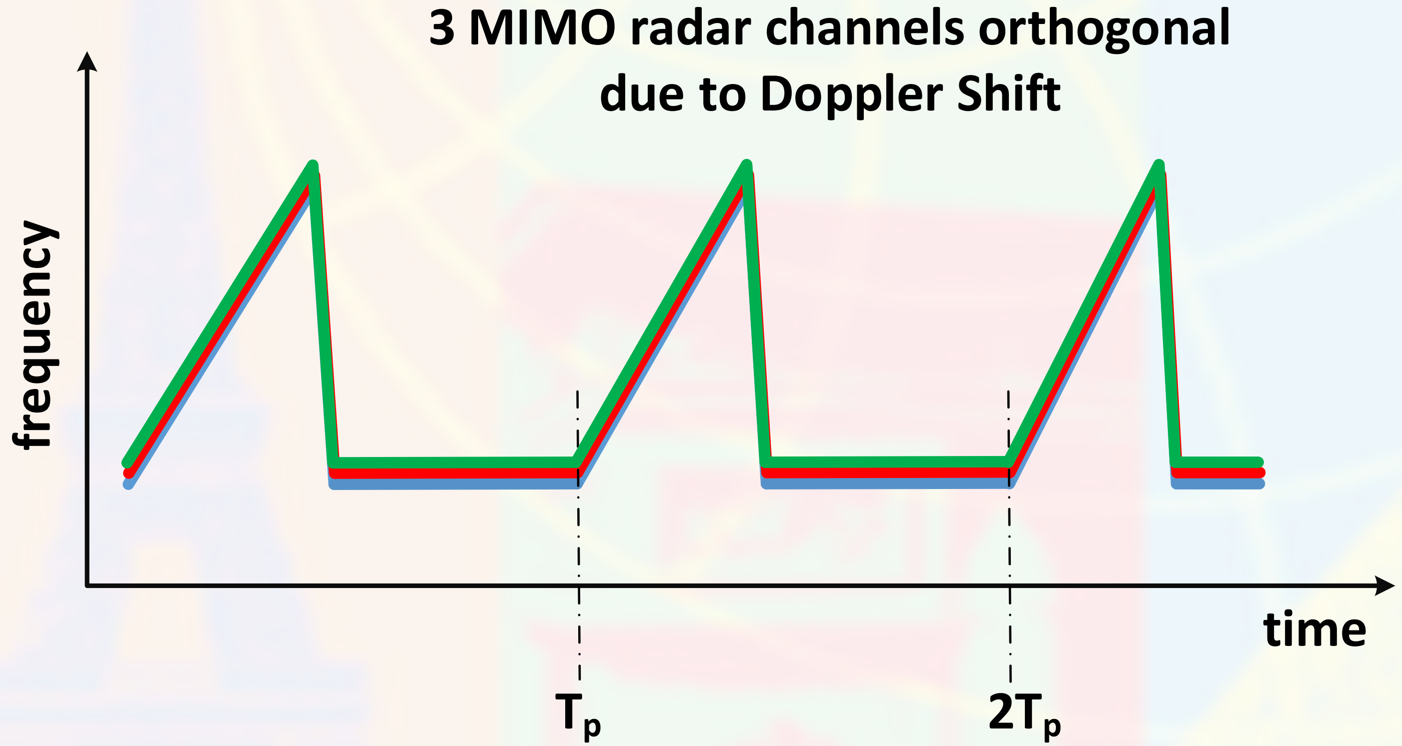
2 MIMO radar channels orthogonal due to Doppler Shift

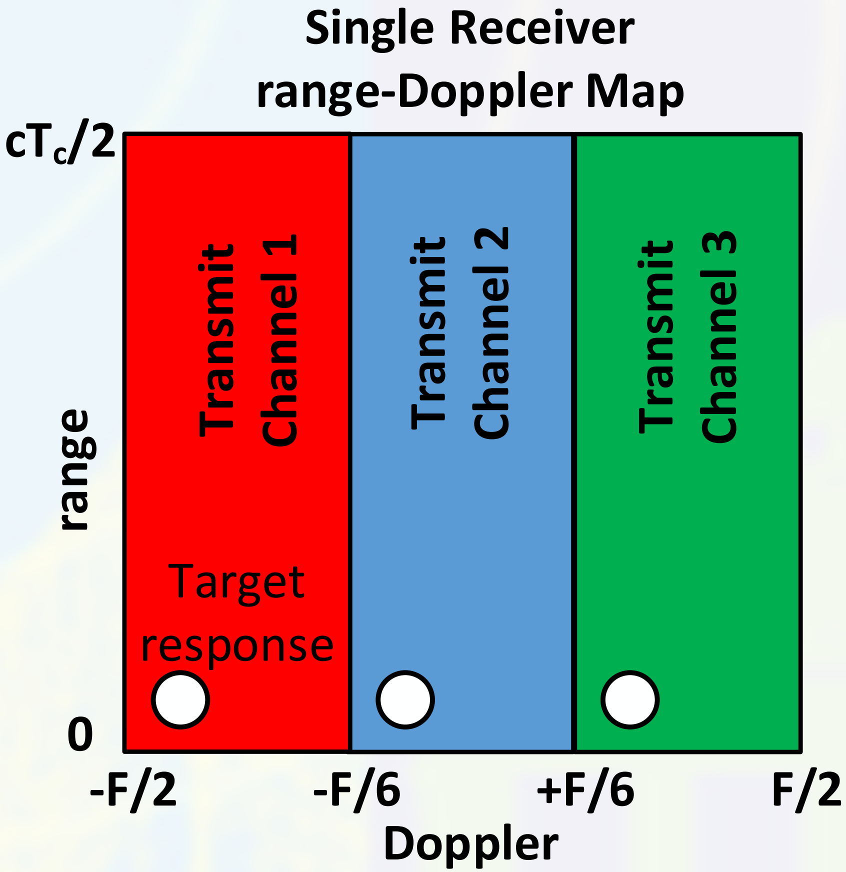


Single Receiver range-Doppler Map

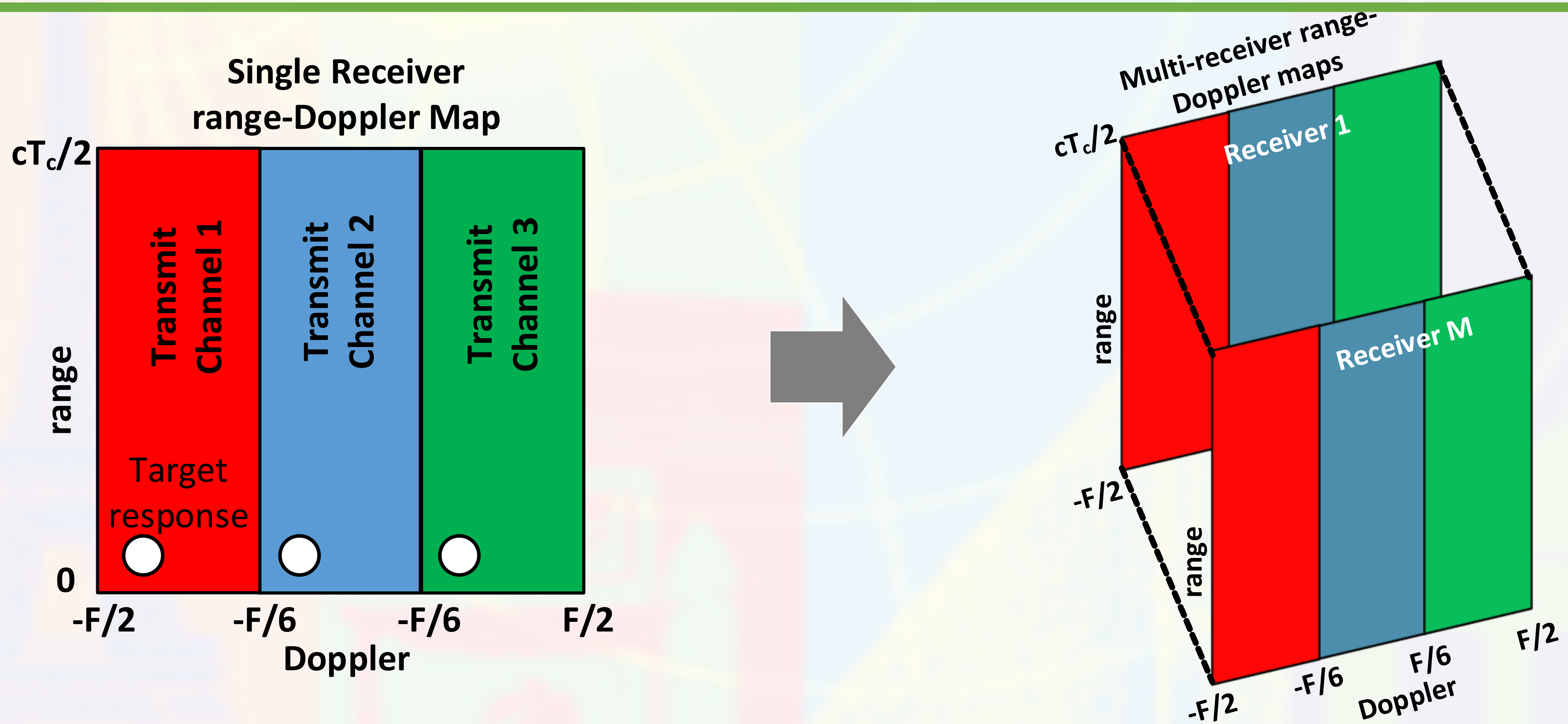


Doppler Division Multiplexing (DDM)





Doppler Division Multiplexing (DDM)



Doppler Division Multiplexing (DDM)

- DDM scheme requires advanced transmission hardware
- Consists of dedicated phase shifters with defined alphabet size at every transmit antenna
- Automotive radars have vastly applied this transmission scheme
- Requires identification of the peak corresponding to the real Doppler from the available aliased peaks
- Additional processing steps involved at the receiver

General Transmit Signal Model

$$\mathbf{u}_{m,q}(t) = w_{m,q} e^{j\phi(t)} \frac{1}{T_c} \text{rect}\left(\frac{2t}{T_c}\right)$$

$$\text{where} \quad \phi(t) = 2\pi(f_c t + \frac{1}{2} S t^2),$$

$$m = 1, \ldots, M, \quad q = 1, \ldots, Q, \text{ and}$$

$$w_{m,q} = \begin{cases} \delta[m - \text{mod}(q-1, M) - 1], & \text{TDM}^{\#} \\ e^{-j2\pi mq/M}, & \text{DDM} \\ \text{Had}[m, \text{mod}(q-1, M) + 1], & \text{BPM} \end{cases}$$

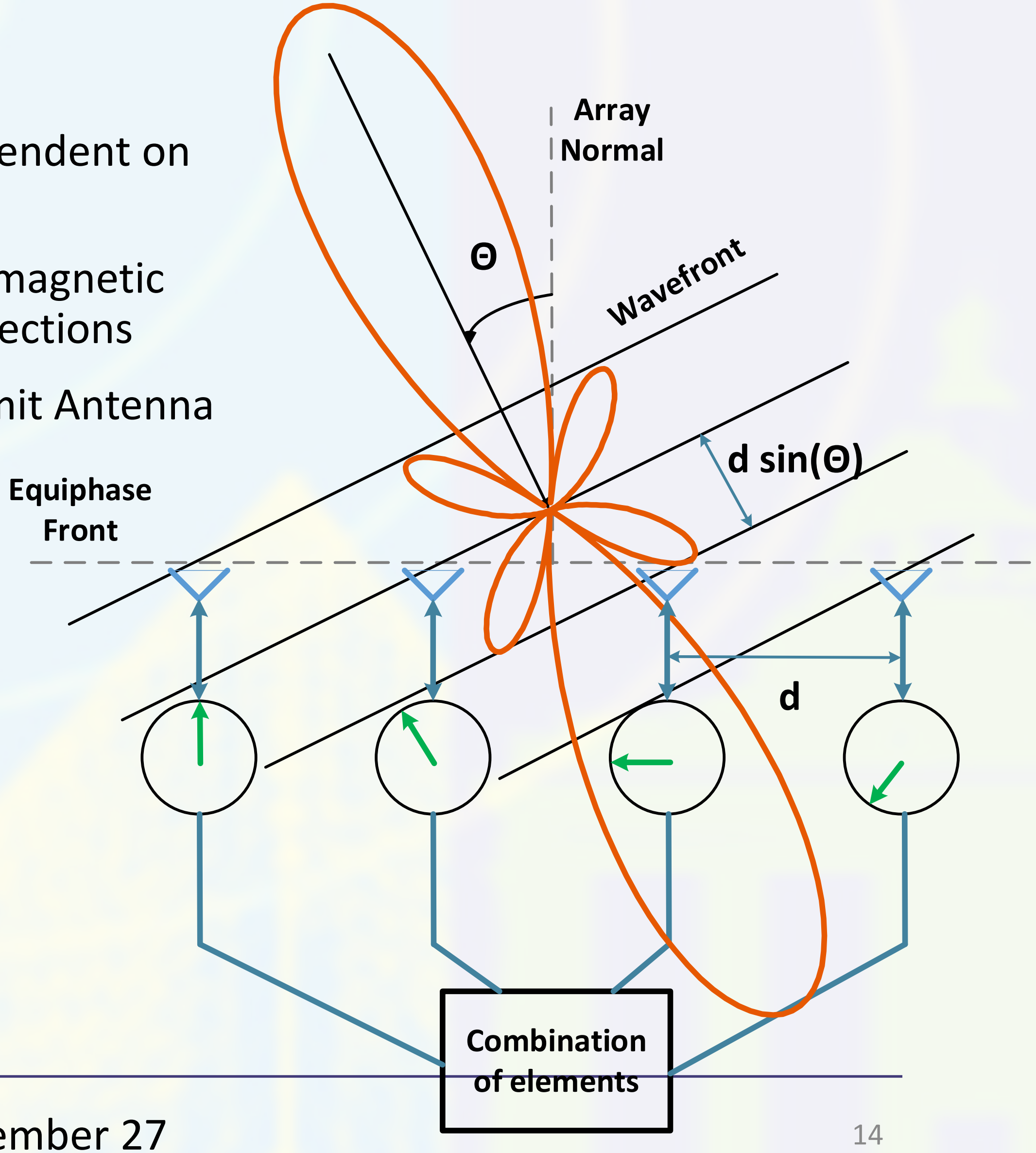
M: transmit antenna elements
T_c: transmit chirp duration
f_c: center frequency
S: chirp slope
Q: transmit pulses
Had: Hadamard Matrix
δ: Dirac delta function
mod: modulo operation

[#] N. K. Sichani et al., "Waveform Selection for FMCW and PMCW 4D-Imaging Automotive Radar Sensors," 2023 IEEE Radar Conference (RadarConf23), San Antonio, TX, USA, 2023, pp. 1-6, doi: 10.1109/RadarConf2351548.2023.10149733.

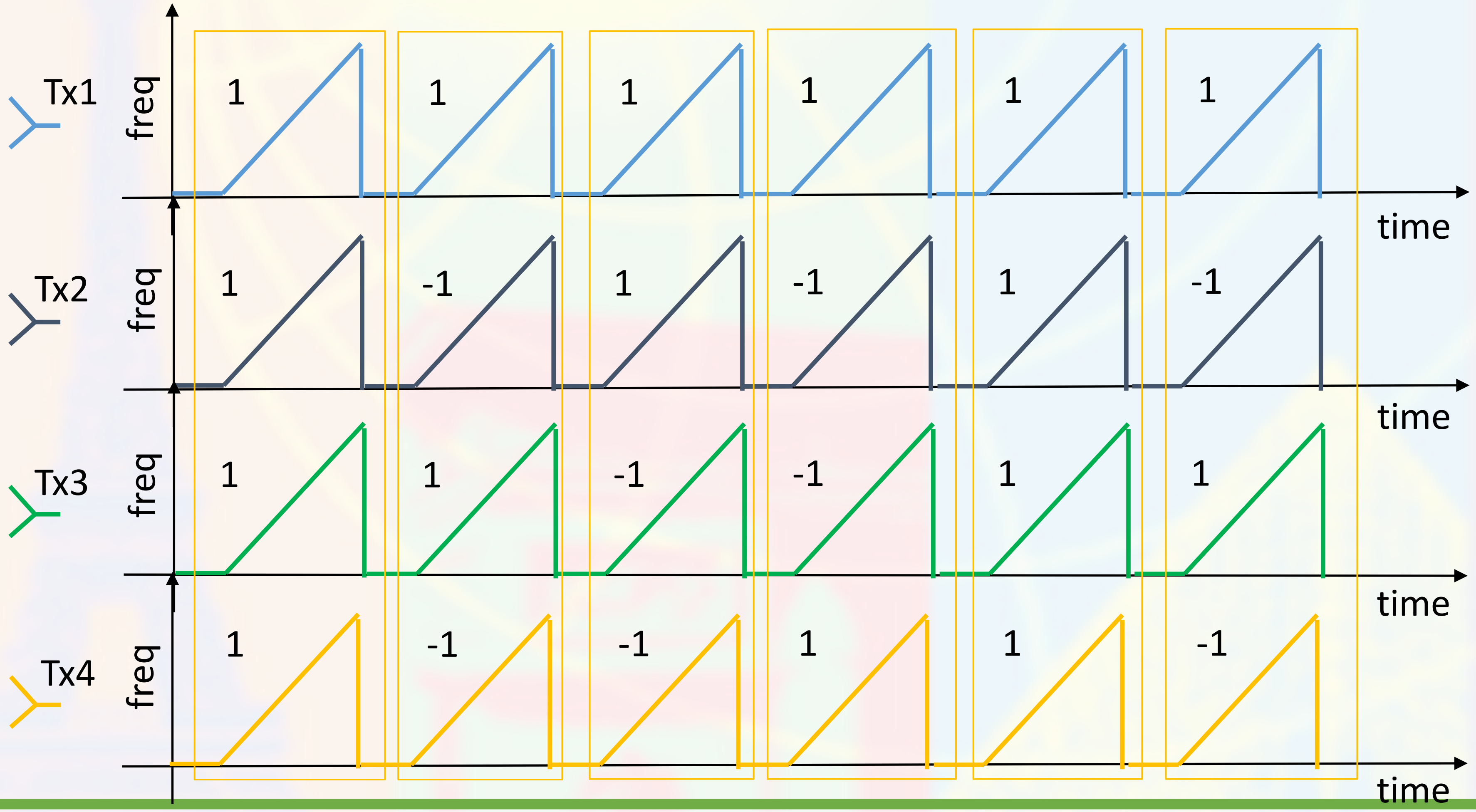
Directivity / Beampattern and ULA

- Radiated/received energy from/at radar antenna array is dependent on angle
- Beampattern is a visual representation of intensity of electromagnetic energy transmitted/received by the antenna in all angular directions
- An antenna with Uniform Linear Array layout with one Transmit Antenna and four Receive antennas (Figs) has a steering vector as

$$\mathbf{a}(\theta) \triangleq \begin{bmatrix} a_1(\theta) \\ \vdots \\ a_m(\theta) \\ \vdots \\ a_M(\theta) \end{bmatrix} = \begin{bmatrix} 1 \\ \vdots \\ e^{-j\frac{2\pi}{\lambda} m d \sin(\theta)} \\ \vdots \\ e^{-j\frac{2\pi}{\lambda} M d \sin(\theta)} \end{bmatrix}.$$



Binary Phase Modulation (BPM)



Hadamard Code

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

Binary Phase Modulation (BPM)

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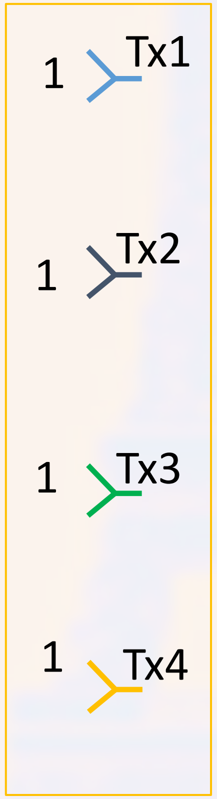
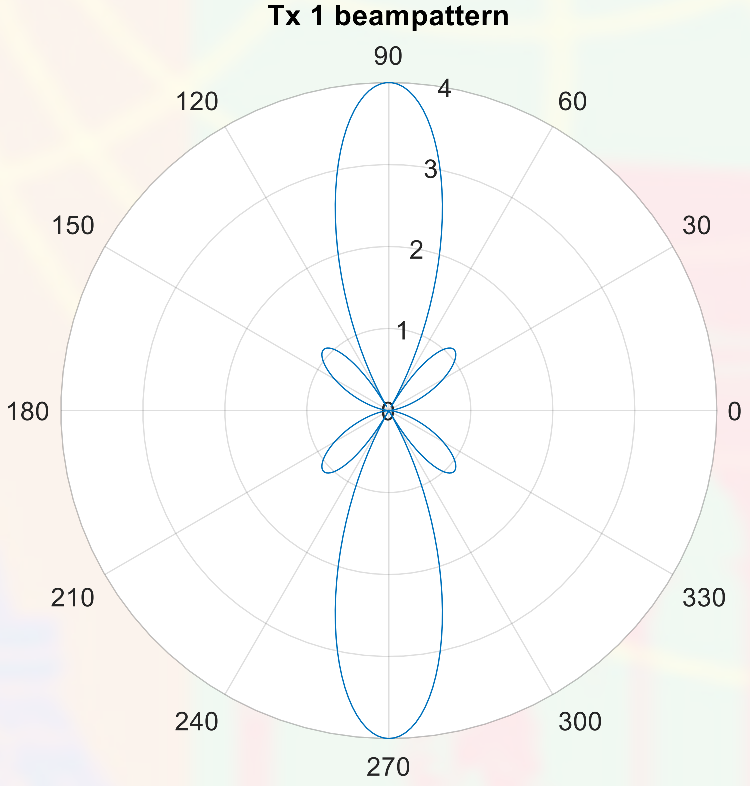
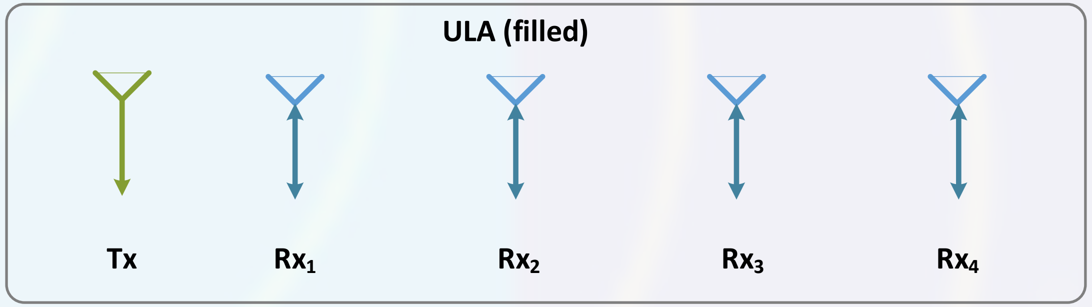
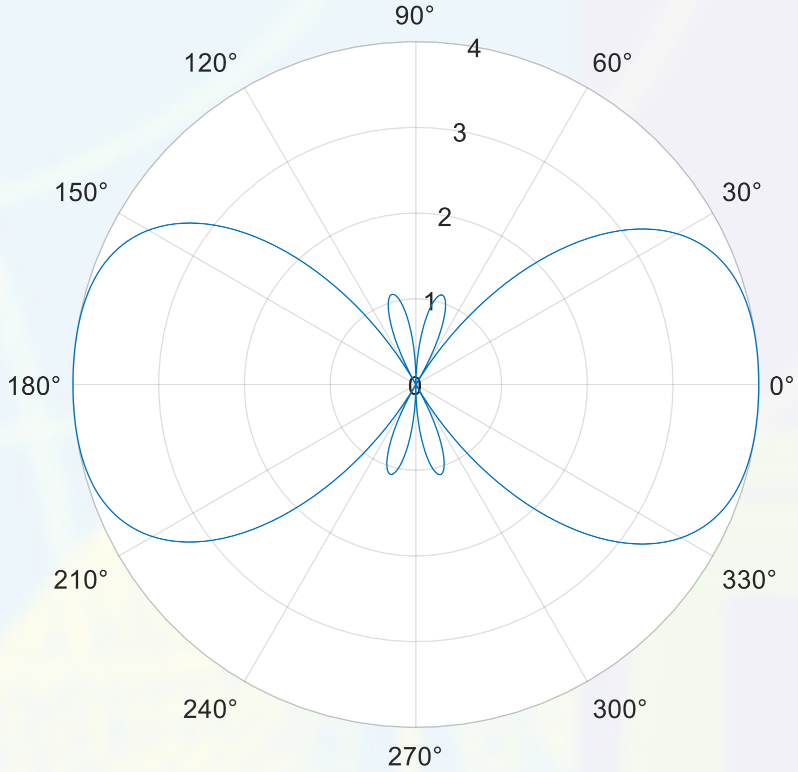
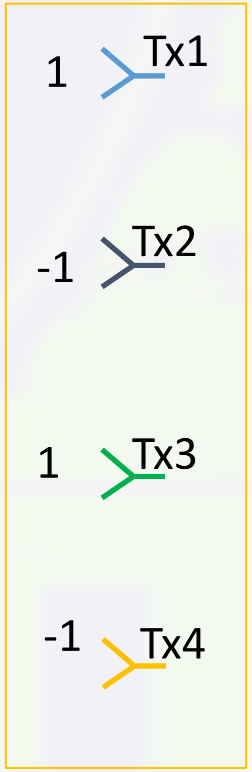
Filled Array



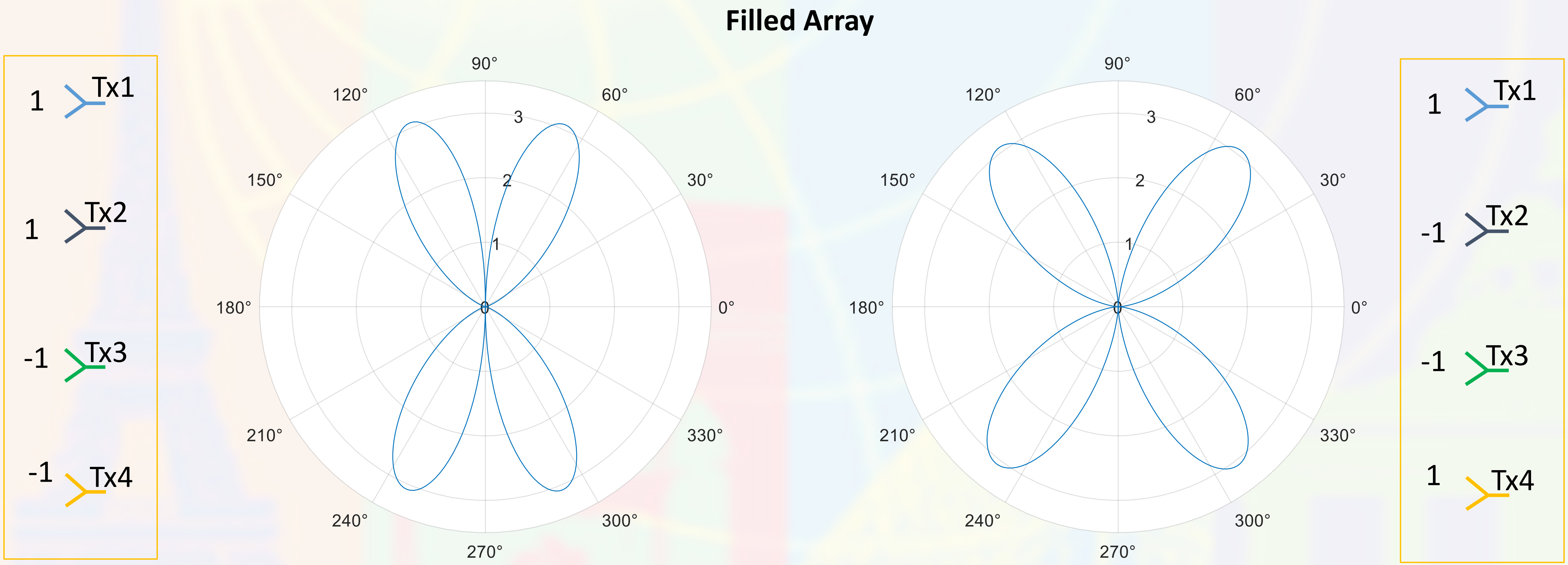






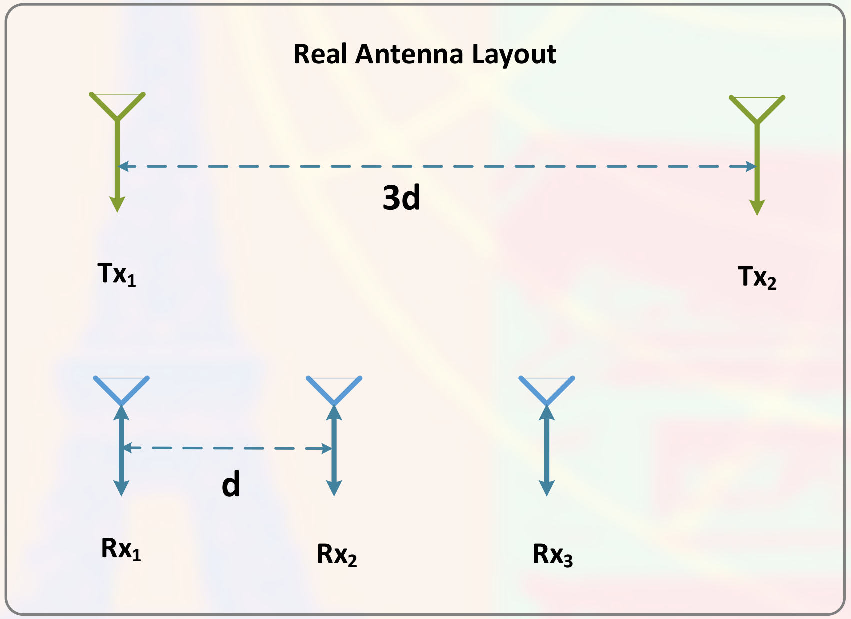


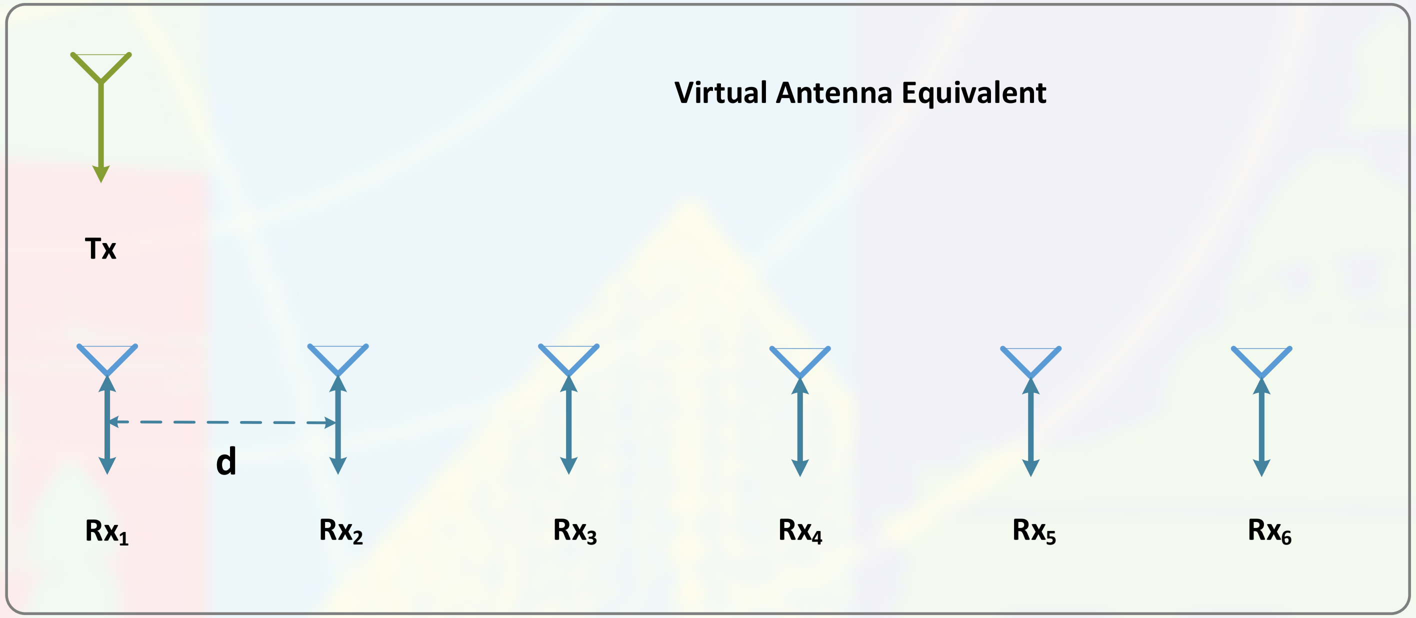
Binary Phase Modulation (BPM)



Magic of MIMO in Radars

- MIMO radar: it probes a channel by transmitting multiple signals (separated temporally, spectrally or spatially) and received with some similar multiplicity*.



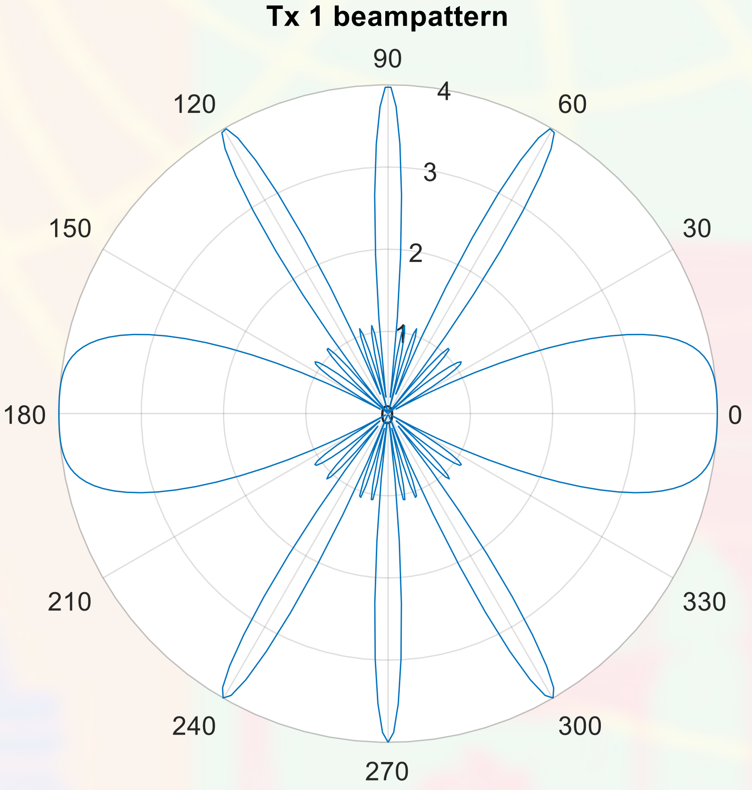


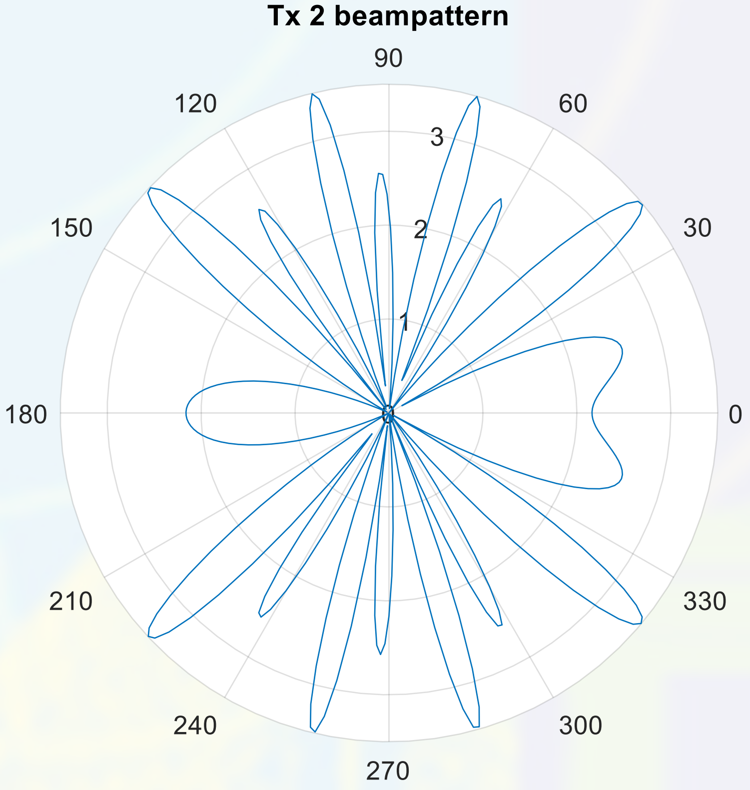
* D. W. Bliss and K. W. Forsythe, "Multiple-input multiple-output (MIMO) radar and imaging: degrees of freedom and resolution," *The Thirty-Seventh Asilomar Conference on Signals, Systems & Computers, 2003*, Pacific Grove, CA, USA, 2003, pp. 54-59 Vol.1, doi: 10.1109/ACSSC.2003.1291865.

Binary Phase Modulation (BPM)

Sparse Array

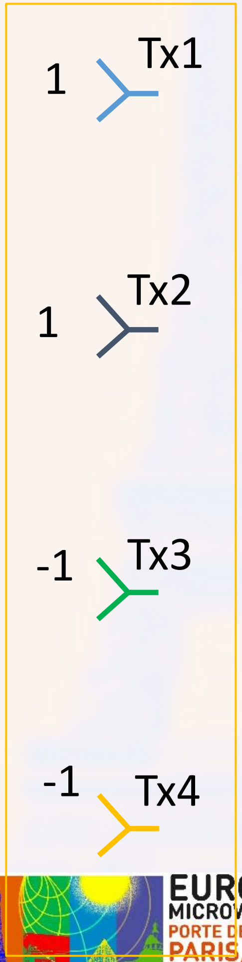
1	Tx1
1	Tx2
1	Tx3
1	Tx4



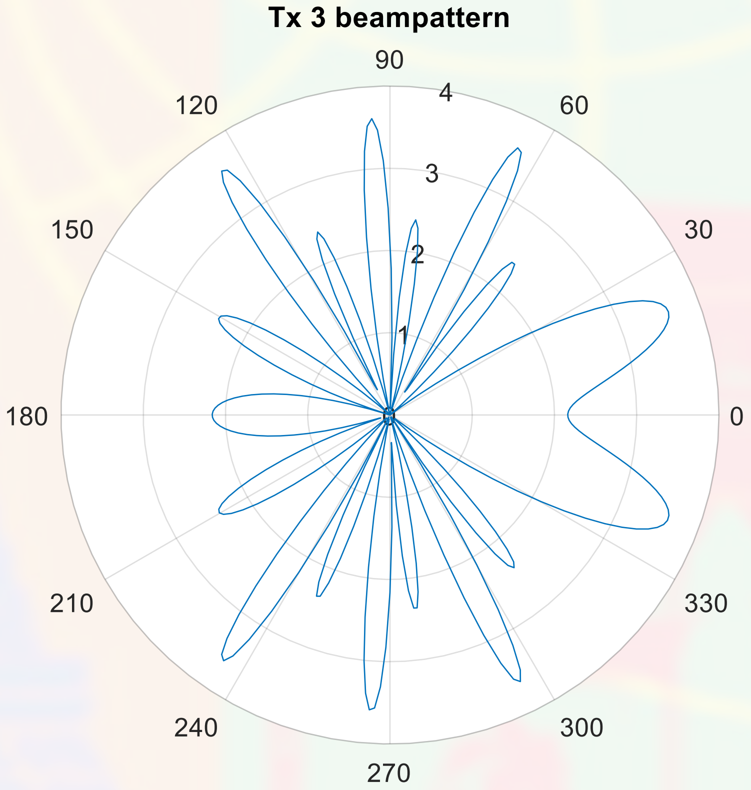


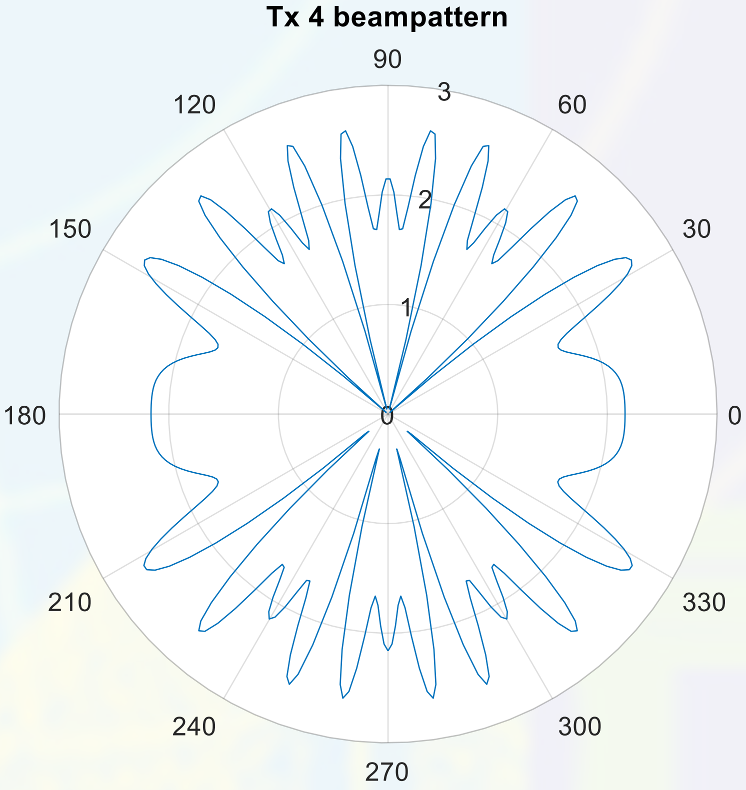
1	Tx1
-1	Tx2
1	Tx3
-1	Tx4

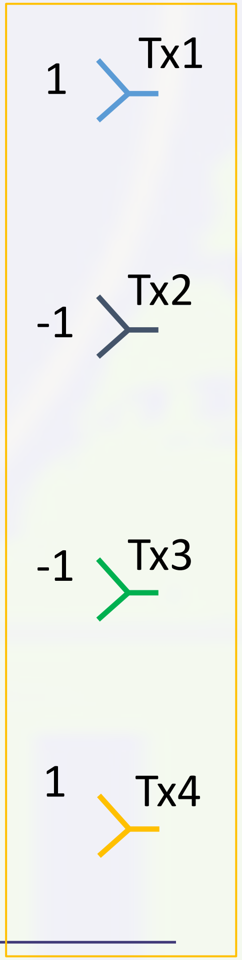
Binary Phase Modulation (BPM)



Sparse Array

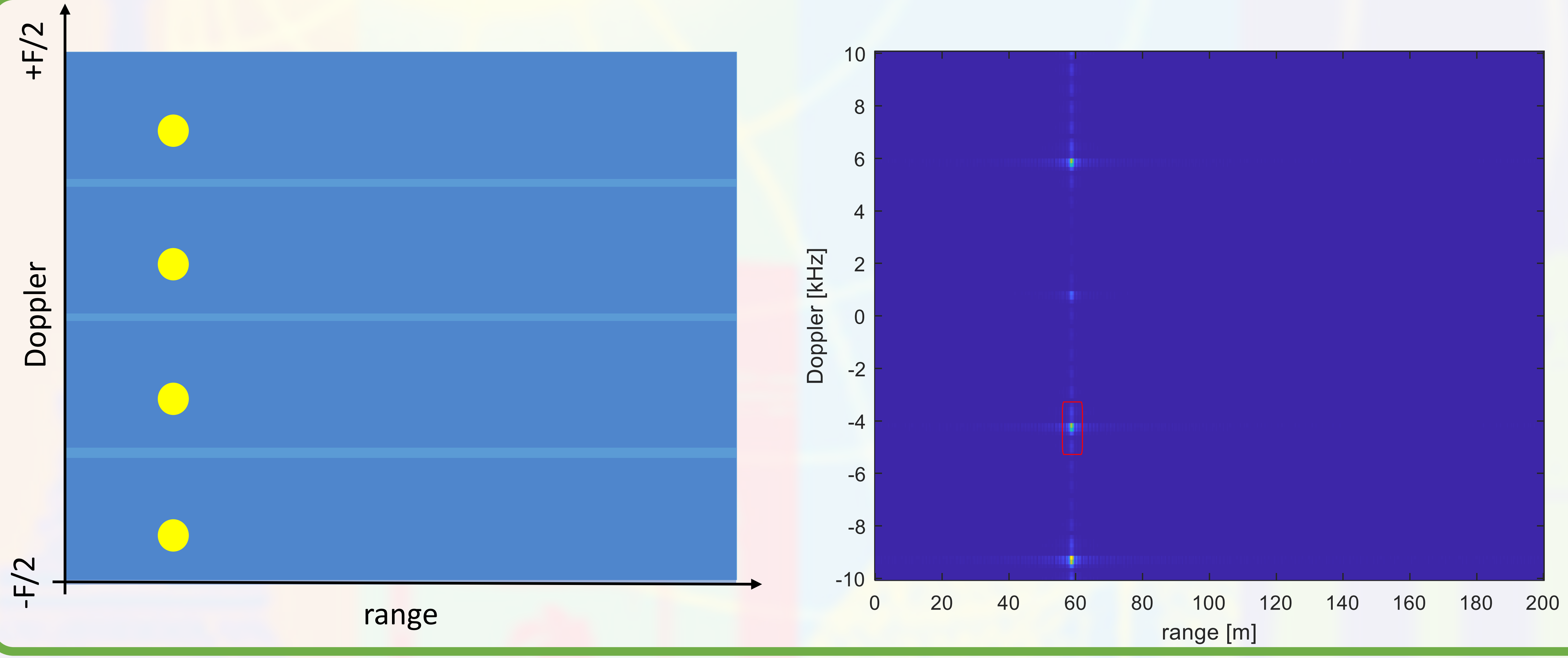




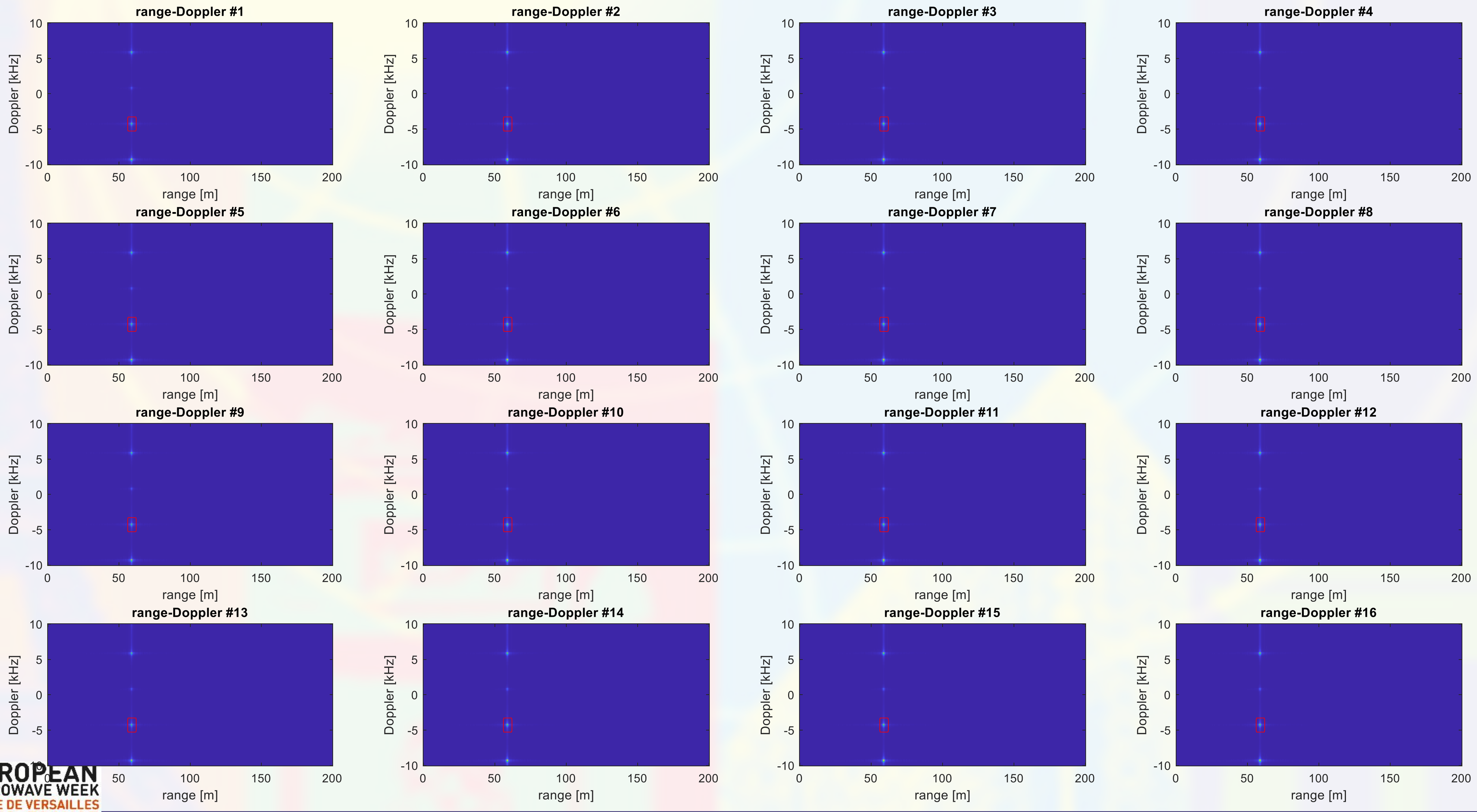


Binary Phase Modulation (BPM)

Doppler aliased clutter and targets appear in other channels



Binary Phase Modulation (BPM)



Binary Phase Modulation (BPM)

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- BPM-MIMO makes use of the device's full transmission capabilities (because all the transmitters are active at any time)
- BPM-MIMO may not achieve perfect orthogonality between channels. As a result, when BPM-MIMO is used, more sidelobes are expected.
- BPM-MIMO reduces the unambiguous Doppler range

Inter-Pulse Code Division Multiplexing (CDM)

$$\mathbf{u}_{m,q}(t) = w_{m,q} e^{j\phi(t)} \frac{1}{T} \mathrm{rect}\left(\frac{2t}{T}\right)$$

where $\phi(t) = 2\pi f_c t,$

$m = 1, \ldots, M, \quad q = 1, \ldots, Q,$ and

$w_{m,q} = Z(r, n),$ Zadoff-Chu Sequence Set

Further, $Z(r,n) = e^{-j\frac{\pi r n(n+1)}{N}},$

where $n = 0, 1, \ldots, N-1,$ and

r is the root of the sequence coprime with N.

N: chips of duration T_{cp}

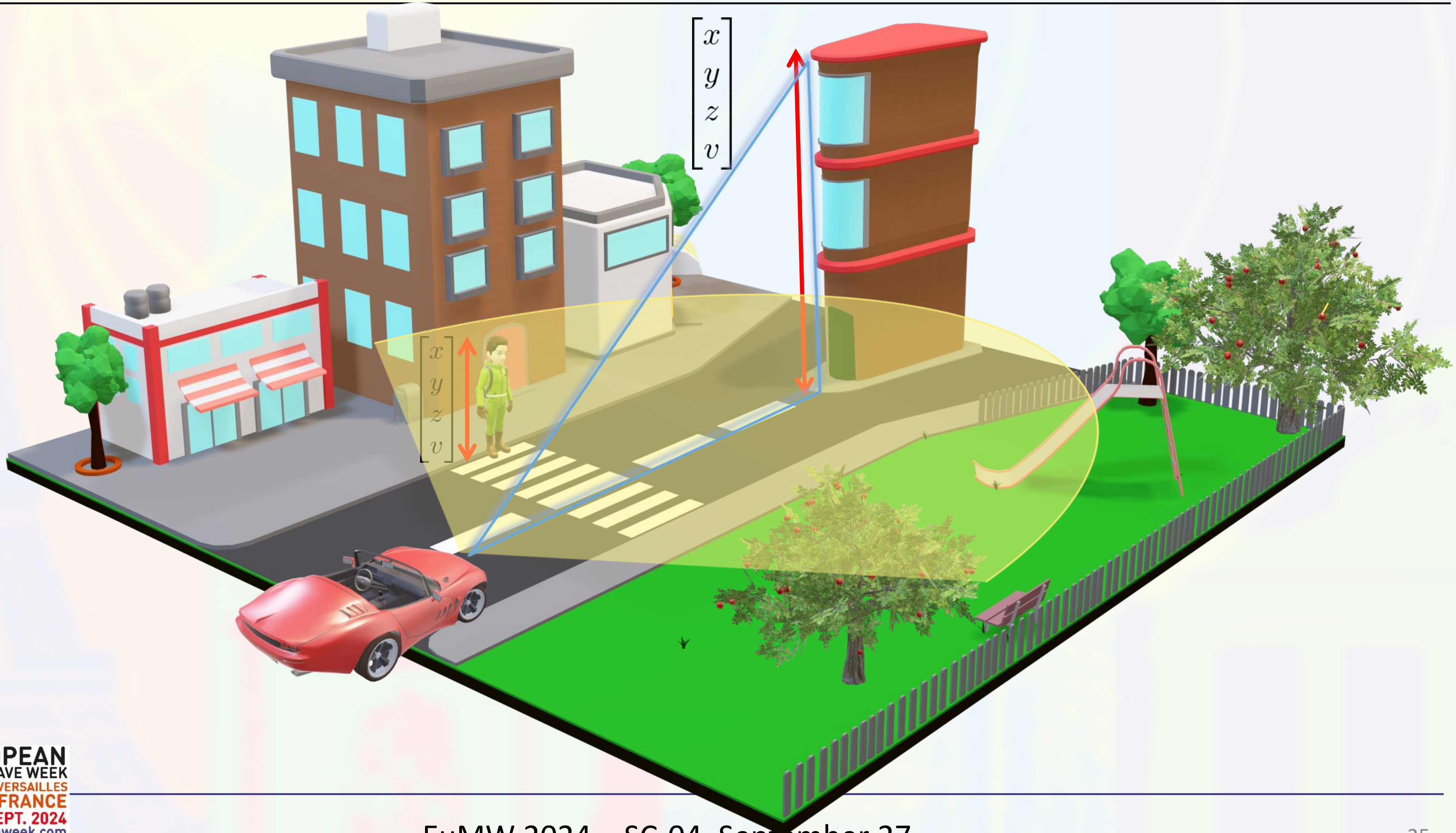
M: transmit sequences

T: transmit pulse duration

Q: transmit pulses

Z: Zadoff Chu Matrix

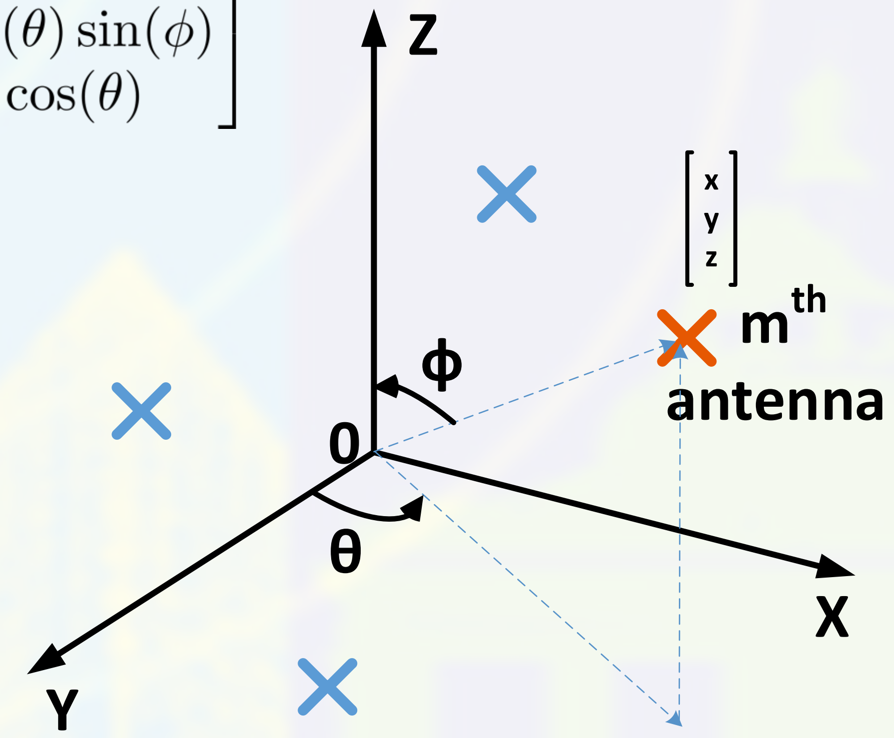
4D MIMO Radars



Beampattern for Generic Antenna Layout

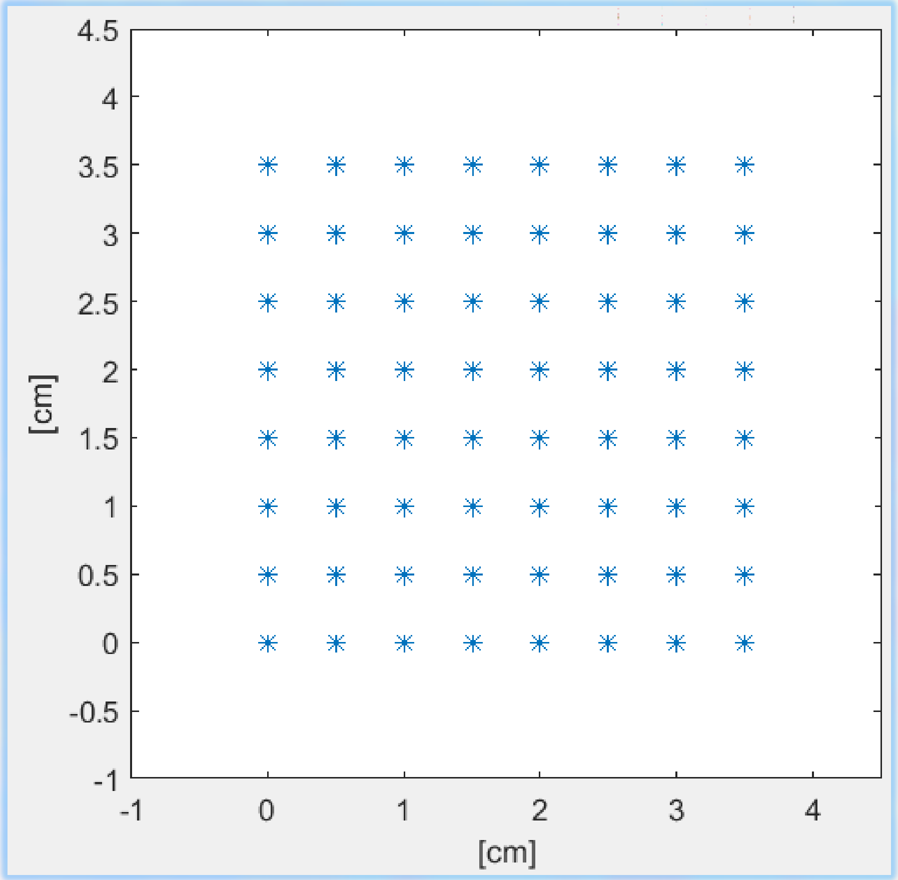
- Arbitrary position vector for the m[th] antenna, $\mathbf{p} = \begin{bmatrix} x \\ y \\ z \end{bmatrix}, \mathbf{r} \triangleq \begin{bmatrix} \sin(\theta)\cos(\phi) \\ \sin(\theta)\sin(\phi) \\ \cos(\theta) \end{bmatrix}$
- Steering vector for the m[th] antenna is

$$\mathbf{a}(\theta,\phi) = \begin{bmatrix} a_1(\theta,\phi) \\ \vdots \\ a_m(\theta,\phi) \\ \vdots \\ a_M(\theta,\phi) \end{bmatrix}, \text{where } a_m(\theta,\phi) \triangleq e^{-j\frac{2\pi}{\lambda}\mathbf{p}_m^T\mathbf{r}(\theta,\phi)}.$$

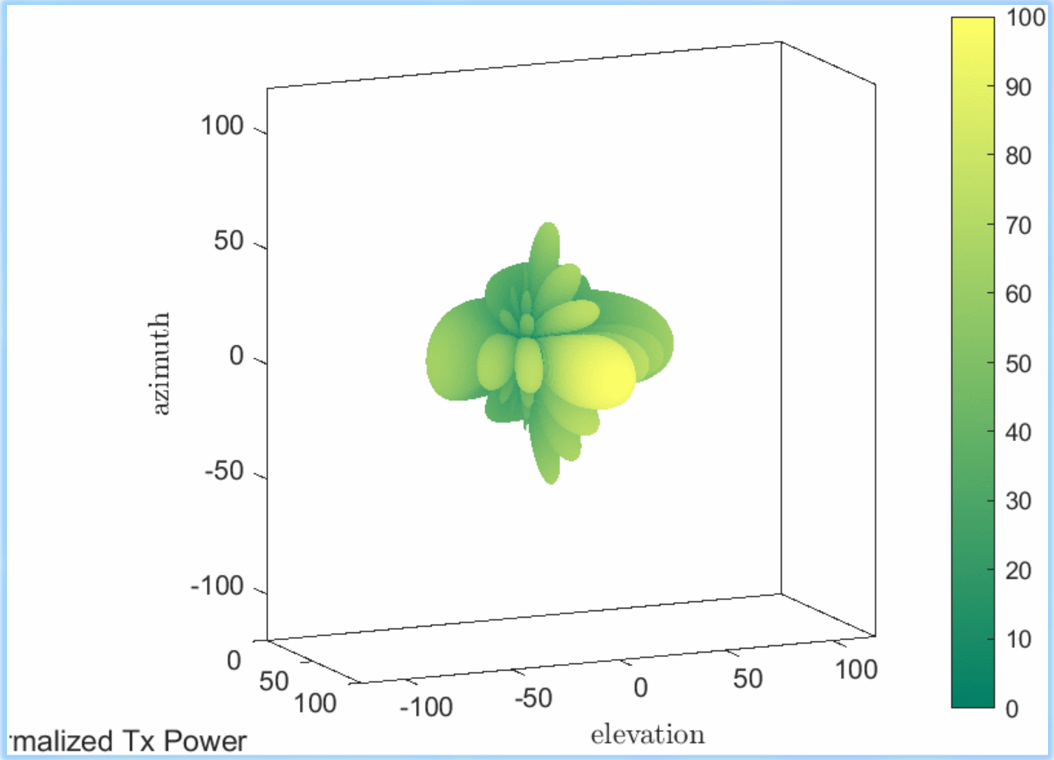


Binary Phase Modulation (BPM)

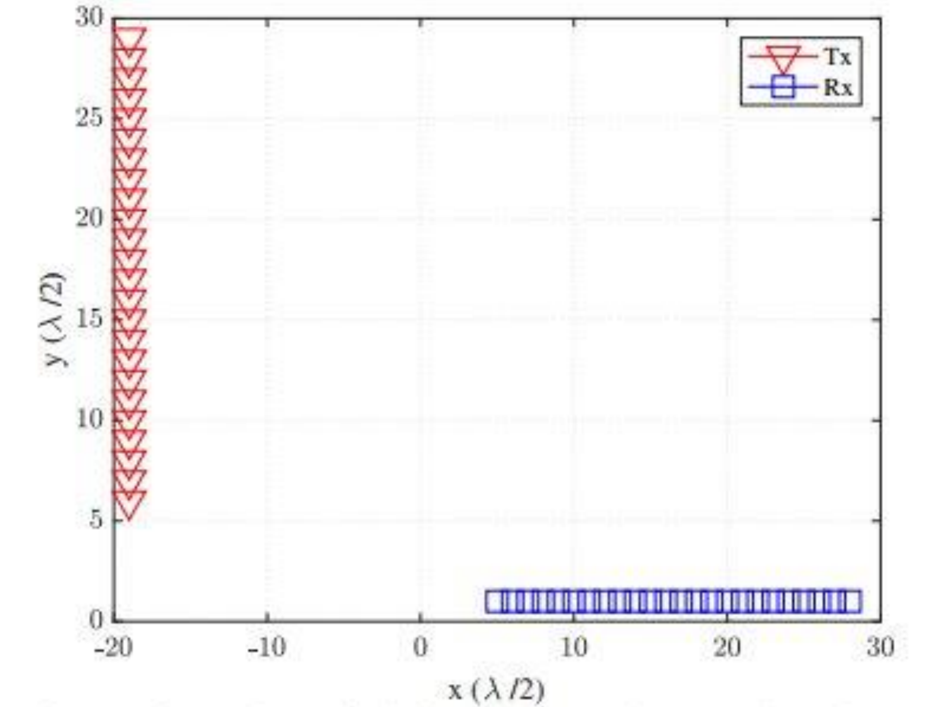
Antenna Layout



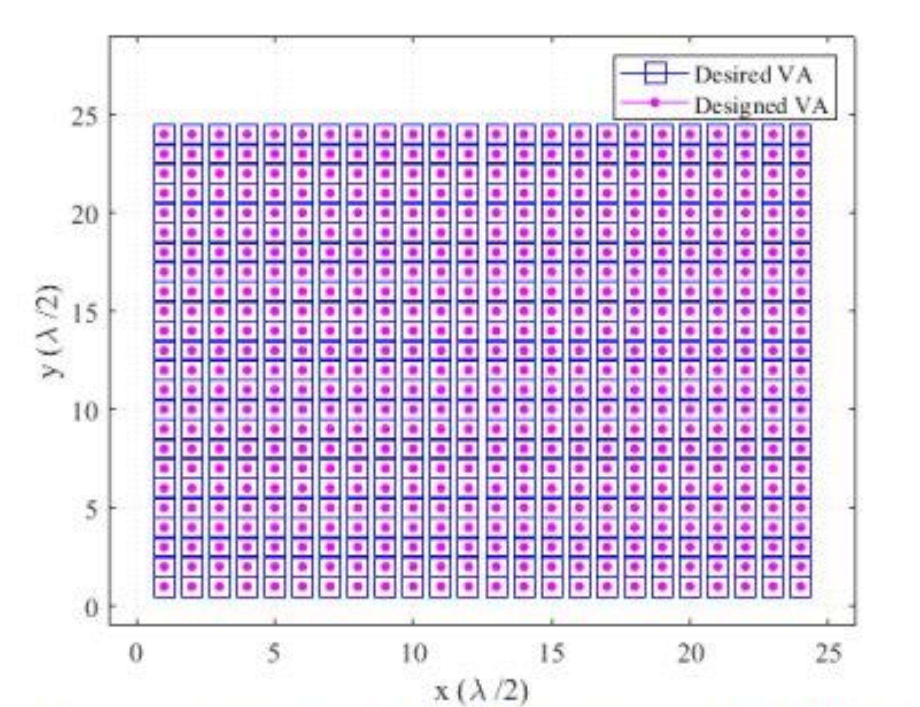
Beam Pattern GIF for Azimuth-Elevation



Antenna Layouts (Real and Virtual)



2D configuration of designed transmitter and receiver antenna array positions.



Dense configuration of desired and designed 2D MIMO virtual array.

Real Antenna Position for Virtual array layout

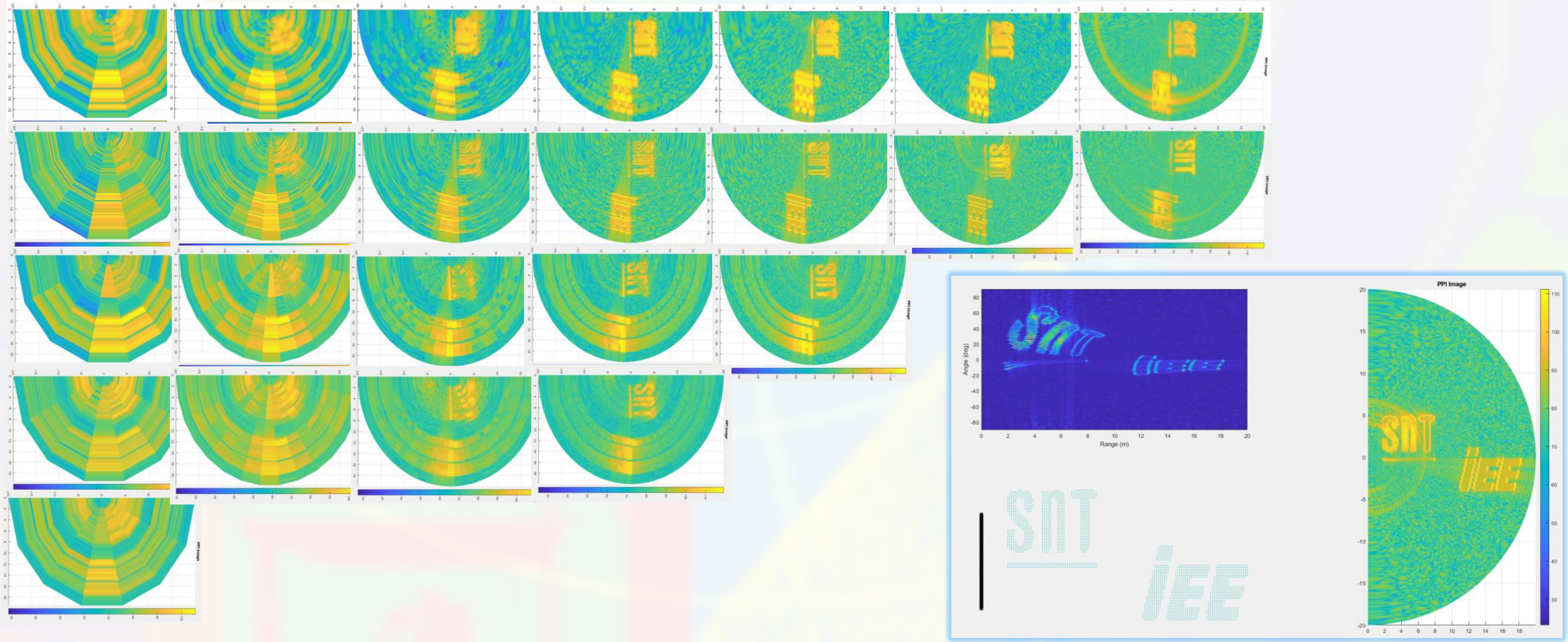
Angular Resolution Enhancement with Virtual Aperture

MIMO Radar Virtual Array Length (Half wavelength)

4 | 8 | 20 | 50 | 100 | 200 | 500

Radar Bandwidth (GHz)

0.3 | 1 | 2 | 4 | 8



Enhancement in angular resolution by increasing the Virtual aperture

Thanks!