On the Road to 6G: NTN, Coexistence & Integrated Sensing

Prof. F. Rodrigo Porto Cavalcanti & GTEL Team

Federal University of Ceara

rodrigo@gtel.ufc.br

Organized by:

xGMobile Inatel FAPEMIG EMBRAPII GOVERNO DE MINAS AQUI O TREM PROSPERA. MINISTÉRIO DA CIÊNCIA, TECNOLOGIA E INOVAÇÃO GOVERNO DO BRASIL DO LADO DO POVO BRASILEIRO

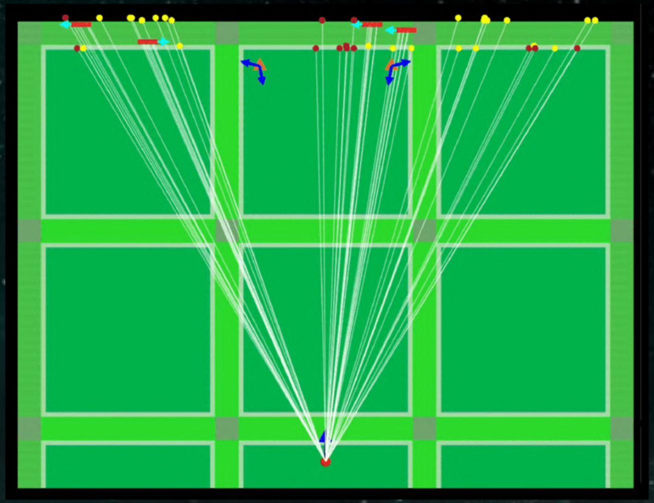
GTEL/UFC & Ericsson: 25 Years of Cooperation

- 30+ projects
- 500+ peer reviewed papers
- 3 Books
- 80+ Patents
- Best EE PhD Thesis
- 100+ MSc and PhD thesis funded
- Technology contributions to 3G, 4G and 5G systems
- Graduate internships at Ericsson Research sites

MINISTÉRIO DA CIÊNCIA, TECNOLOGIA E INOVAÇÃO

GOVERNO DO BRASIL
DO LADO DO POVO BRASILEIRO

Research Agenda in Previous Years



Toolbox graphical user interface (GUI) illustrating UEs and their serving nodes

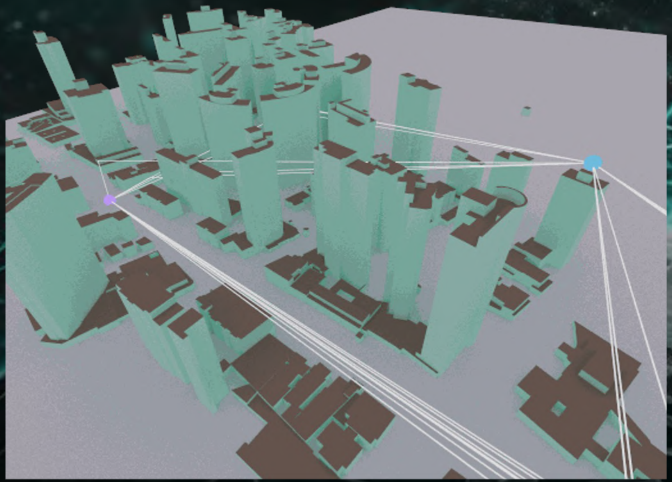


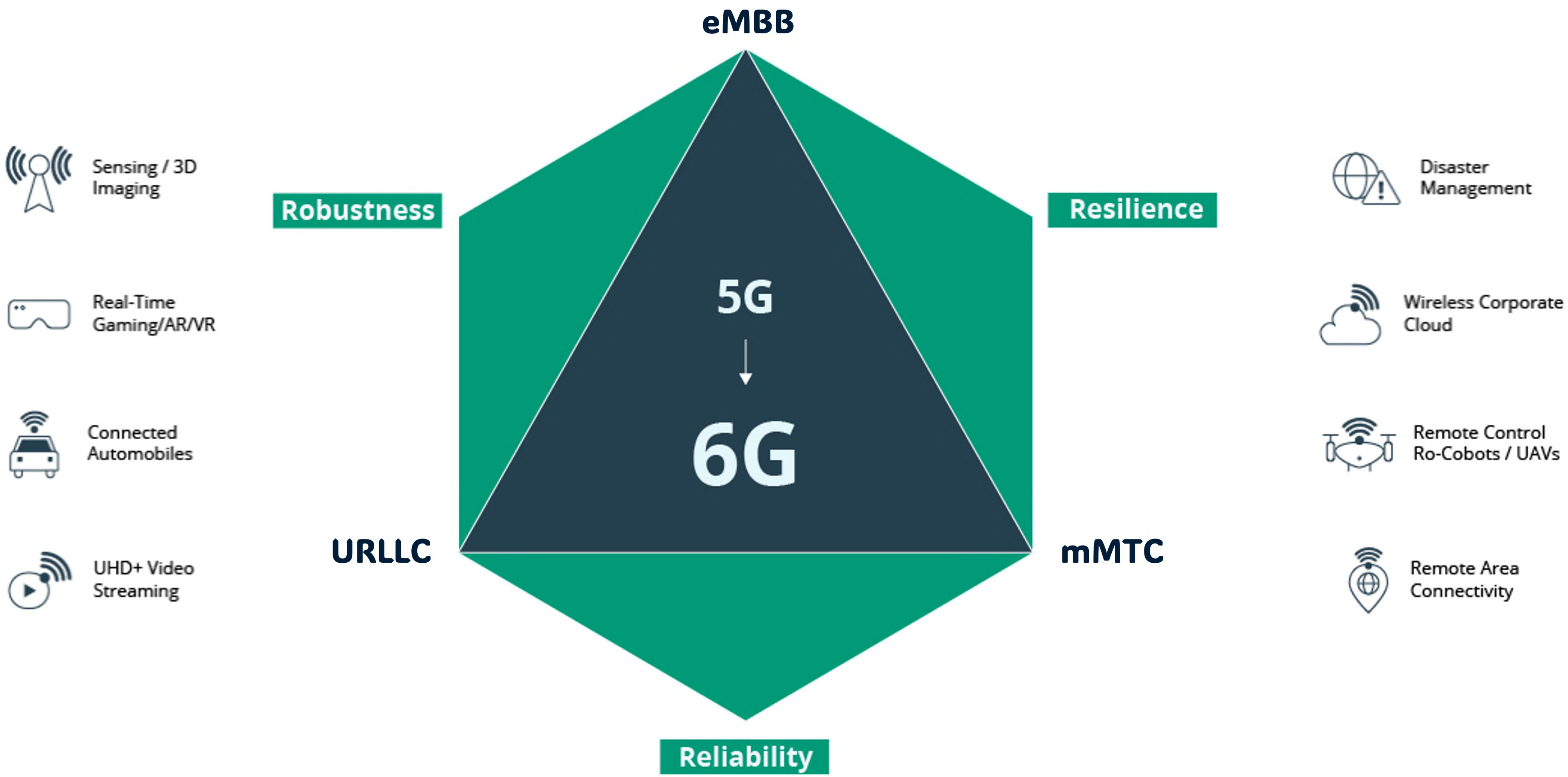
Illustration of Ray-Tracing in Fortaleza with real gNB position

- **Advanced Antenna Systems**
  - Massive & Distributed MIMO
  - CSI Acquisition
  - Pilot Management
- **Radio Resource Management**
  - Packet Scheduling
  - Handover
  - Beam Management
  - Power Control
- **Advanced Simulators**
  - 3D Channel Modelling, e.g. for UAVs
  - Physical-Layers (LTE, New Radio)
  - Mobility, Traffic modelling

Organized by:

xGMobile Inatel FAPEMIG EMBRAPII GOVERNO DE MINAS AQUI O TREM PROSPERA. MINISTÉRIO DA CIÊNCIA, TECNOLOGIA E INOVAÇÃO GOVERNO DO BRASIL DO LADO DO POVO BRASILEIRO

Rationale for 6G



Non-Terrestrial Networks

Challenges for Satellite Direct-to-Device (3GPP NTN)

Organized by:

xGMobile · Inatel · FAPEMIG · EMBRAPII · GOVERNO DE MINAS AQUI O TREM PROSPERA. · MINISTÉRIO DA CIÊNCIA, TECNOLOGIA E INOVAÇÃO · GOVERNO DO BRASIL DO LADO DO POVO BRASILEIRO

D2D & NTN in 6G

Digital Inclusion with NTN in 6G

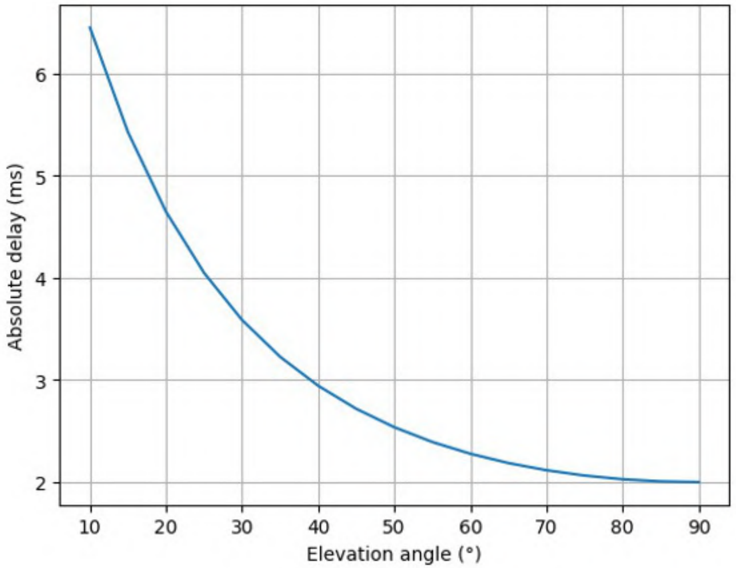
- Connect underserved and remote areas
- TN/NTN integration: key enabler
- LEO satellites “mega-cells”: bridging the digital divide
- Technical innovation with social impact

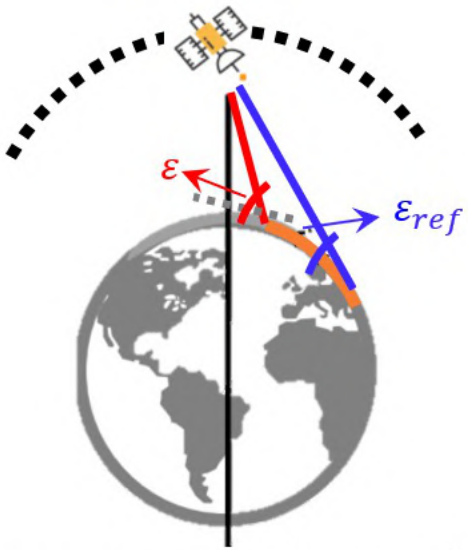
Technological Challenges

- Limited Power Budget
- Synchronization and mobility issues
- UEs geographically far apart
  - Large delay spread → misaligned UL/DL
- LEO satellite moves at ~7 km/s
  - High Doppler effect

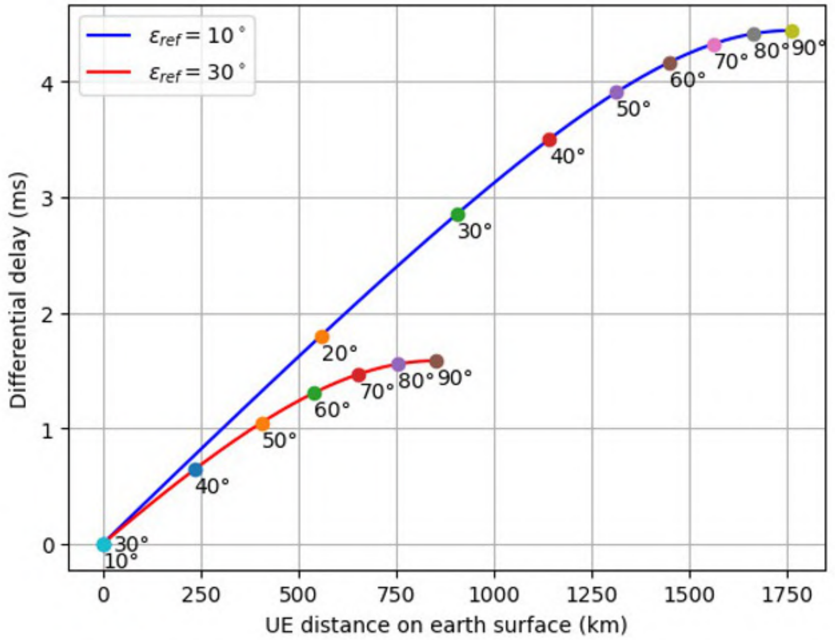
Propagation Delay Spread in LEO Satellite Mega-Cells

- UEs in different locations experience highly unequal delays (ms-level)
- UL/DL signals arrive misaligned, requiring extended guard periods
- Impact: Reduced spectral efficiency and wasted resources
- Insight: New frame designs and adaptive timing strategies are needed for efficient TN/NTN integration



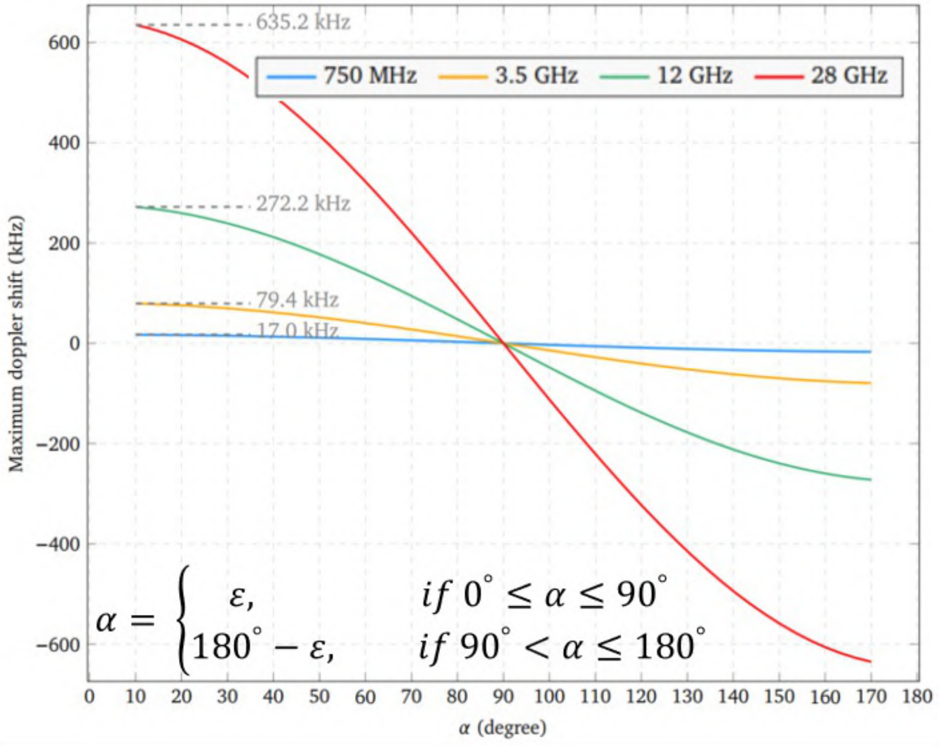


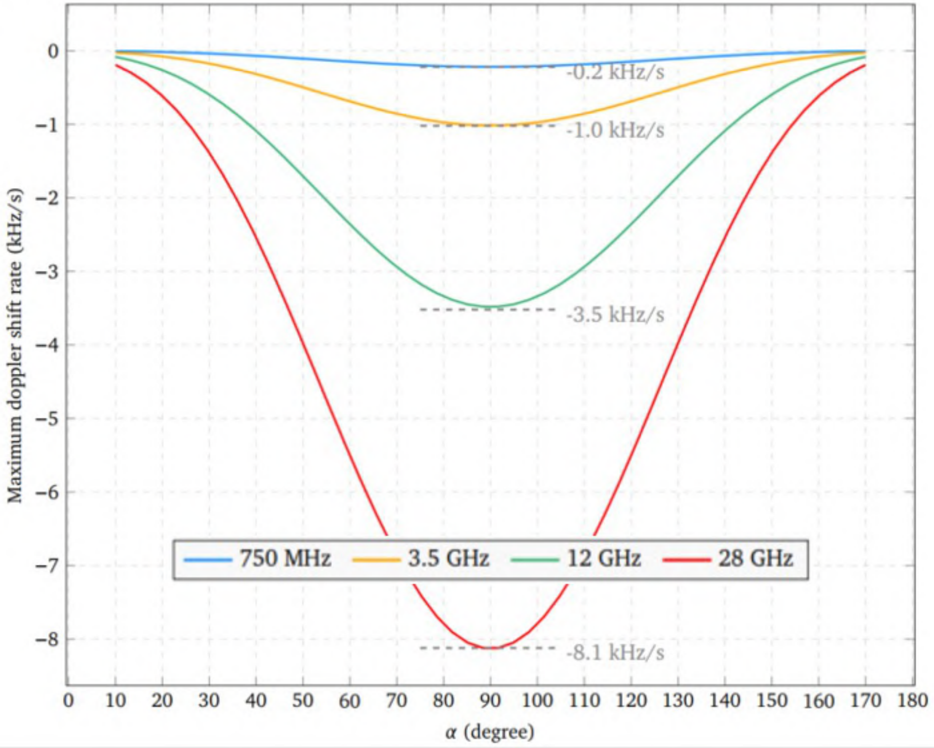
- One UE fixed at cell edge with $\varepsilon_{ref} = \{10^\circ, 30^\circ\}$
- Other moving from $\varepsilon = \varepsilon_{ref}$ until $\varepsilon = 90^\circ$



High Doppler Effect

- LEO mobility introduces large Doppler shifts (kHz scale)
- Rapid Doppler shift rate causes fast-changing frequency offsets
- Channel estimation and synchronization break down → degraded QoS
- Besides, might interfere with neighboring systems
- Compensation schemes are critical for stable NTN performance





Spectrum Coexistence

A Roadmap for Spectrum Sharing in the Centimeter Wave Band (3GPP FR3)

Organized by:

Spectrum for 6G

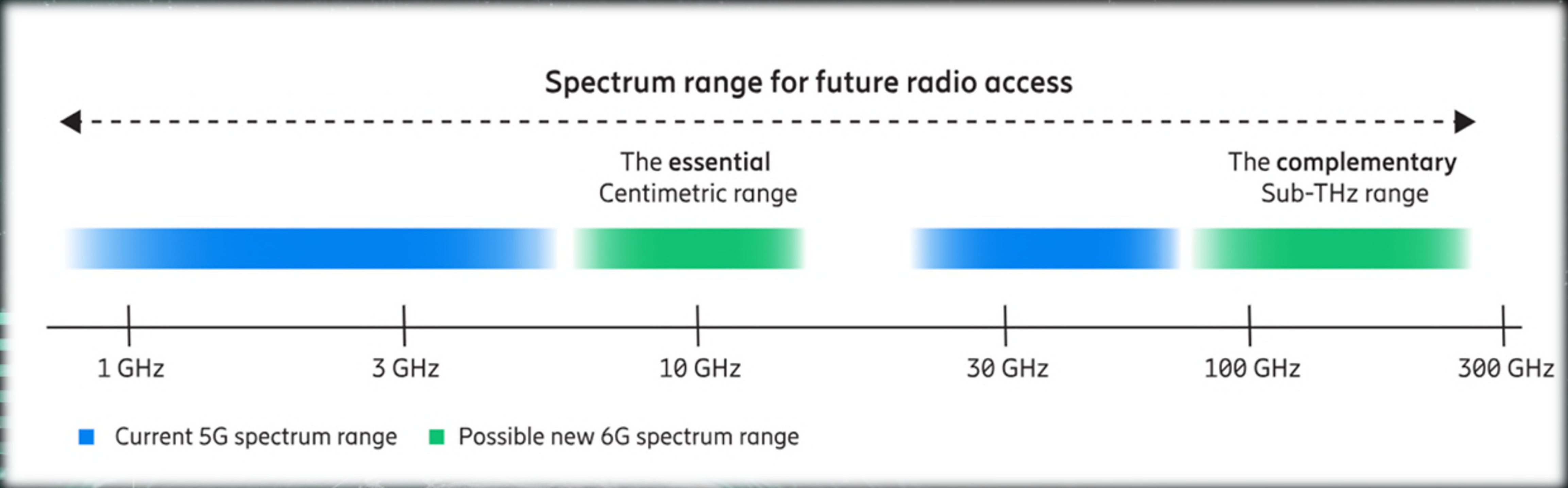


Figure Source: Ericsson

Organized by:

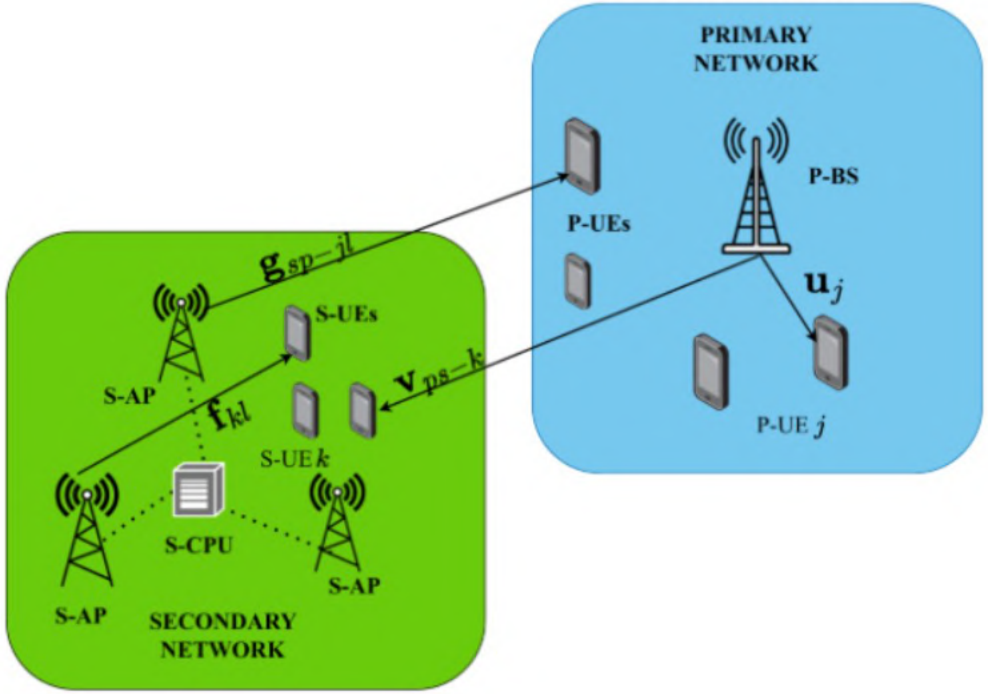
xGMobile Inatel FAPEMIG EMBRAPII GOVERNO DE MINAS AQUI O TREM PROSPERA. MINISTÉRIO DA CIÊNCIA, TECNOLOGIA E INOVAÇÃO GOVERNO DO BRASIL DO LADO DO POVO BRASILEIRO

MIMO Precoding strategies for network coexistence

Interference mitigation strategies

- Maximum Ratio (MR):
  - Aligns transmission with the user's channel but does not cancel interference.
- MMSE-based approaches:
  - Centralized (at the PN)
  - Distributed variants L-MMSE and LP-MMSE (at the SN)
- AP scheduling:
  - To reduce inter-system interference, the S-APs nearest to the PN are not scheduled to serve the S-UEs. Only requires spatial information about the S-APs relative to the PN.

Massive MIMO BS



CF-mMIMO system

Performance evaluation

- Primary Network (PN):
  - BS with M = 40 antennas.
  - Serves K_p = 15 single-antenna P-UEs.
- Secondary Network (SN):
  - L = 10 distributed S-APs, each with N = 4 antennas.
  - Jointly serves K_s = 15 single-antenna S-UEs.

Table I: Simulation Parameters

Parameter	Value
Communication bandwidth	$W = 20$ MHz
Noise figure (NF)	9 dB
Antenna spacing	$d = (1/2)\lambda$
Number of pilots	$\tau_p = 8$
Coherence block length	$\tau_c = 2000$
BS height	5 m
S-AP height	5 m
Threshold for DCC	-40 dB
$P_{\max}$	30 dBm

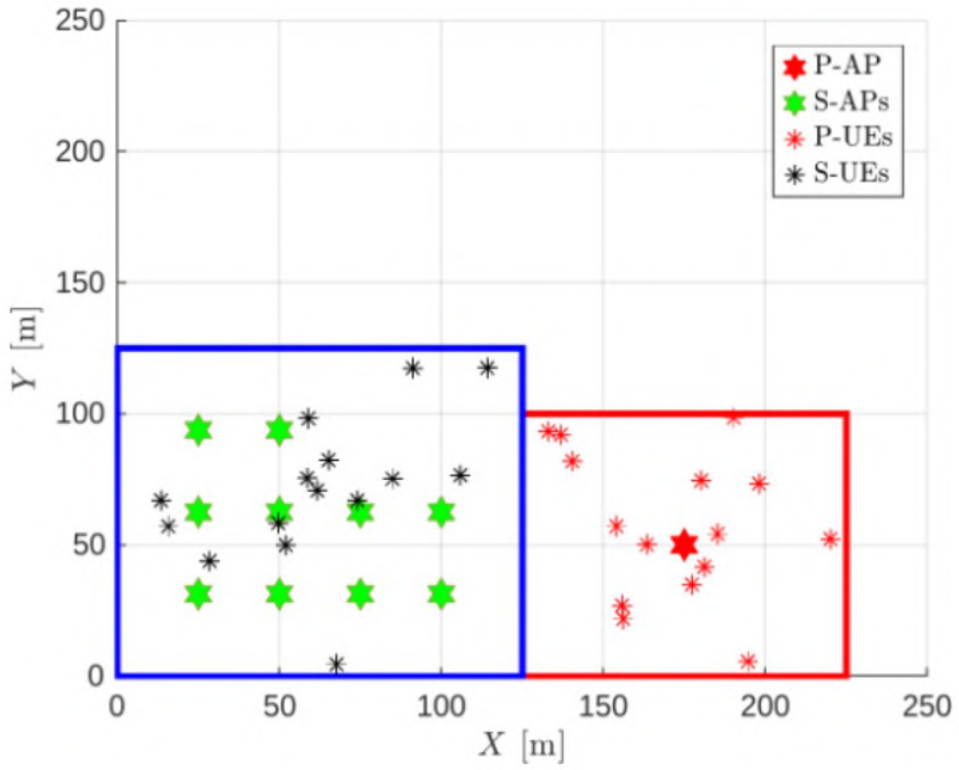


Figure – Network layout

S. S. Paula Filho et. al.; *"Precoding Strategies for Network Coexistence and Interference Mitigation on Licensed Spectrum"*, IEEE 2025 VCC Conference.

Performance evaluation

- MMSE precoder consistently outperforms MR in all scenarios (hence Fig. 3 focuses on MMSE performance).
- Increasing the number of unscheduled S-APs reduces interference, improving PN performance toward the ideal isolated case, at the cost of a decrease in SN performance.

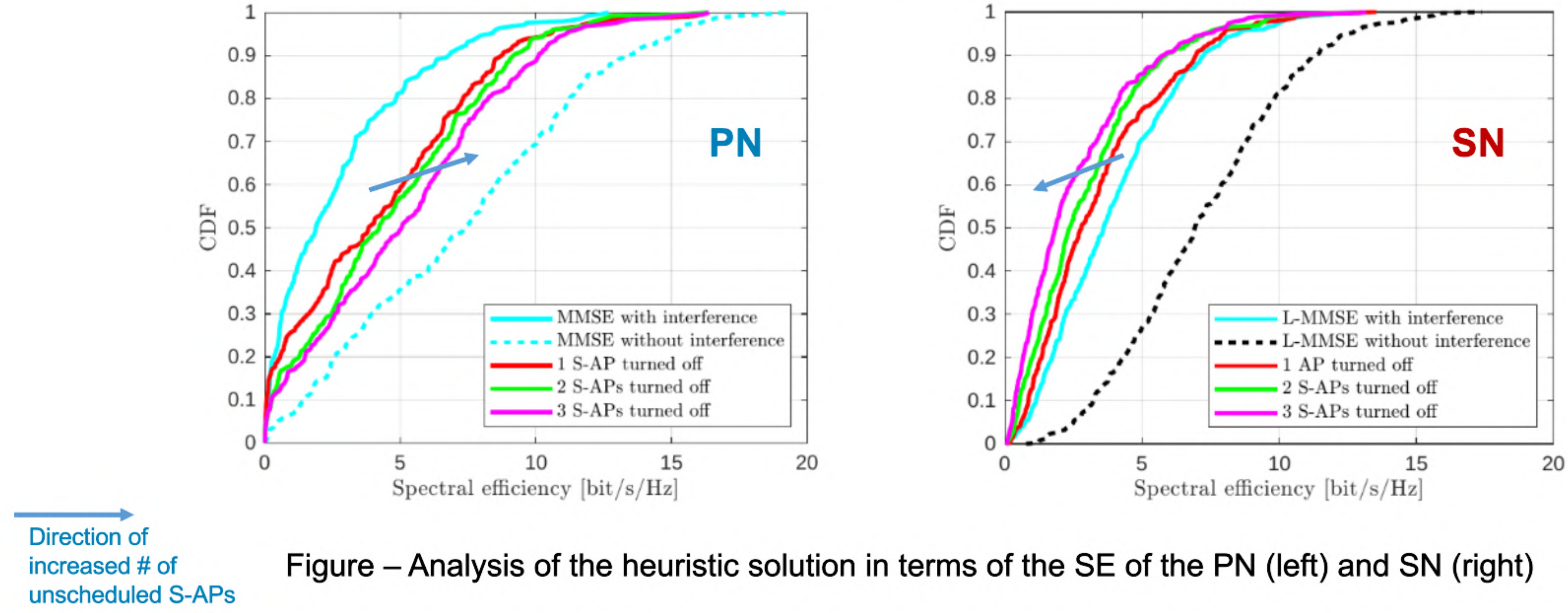
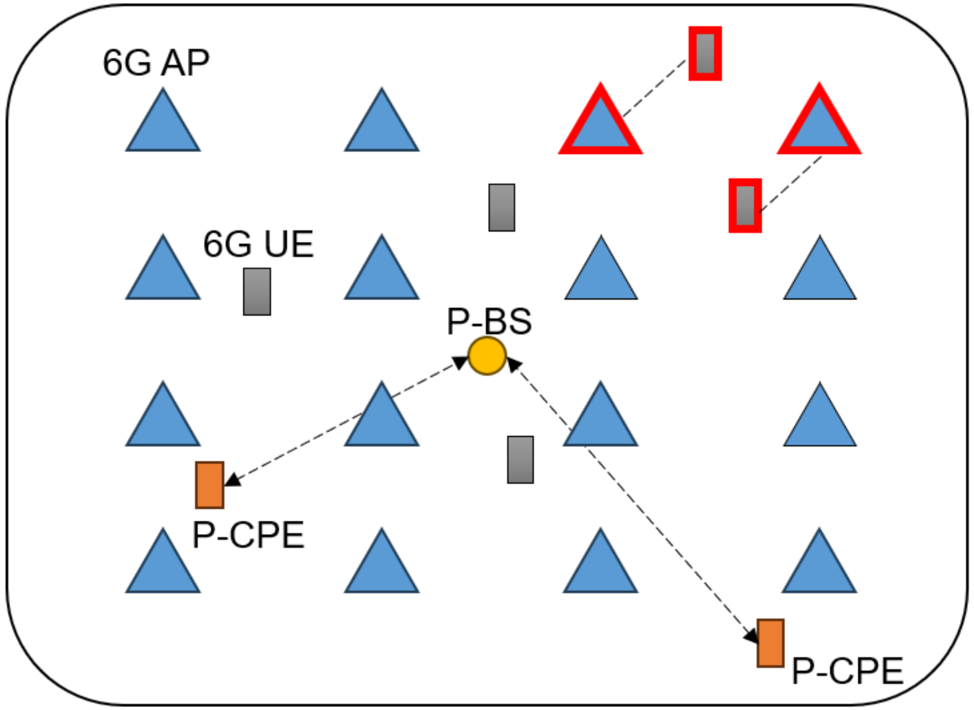


Figure – Analysis of the heuristic solution in terms of the SE of the PN (left) and SN (right)

6G Spectrum Sharing with Fixed Point-to-Point Radio in FR3

- Operator owns **exclusive spectrum in FR1** and shares **secondary spectrum in FR3**
- **UE automatically scheduled either in FR1 or FR3** (band scheduling);
- **Signaling and interference measurements** for automatic band scheduling.
- 6G system must respect **outage probability threshold** on primary network in FR3.



Automatic TDD Pattern Adjustment for Spectrum Sharing

- Dynamic TDD pattern adjustment for the coexistence between 6G D-MIMO and legacy massive MIMO networks.
- Address TDD pattern mismatch between Primary and Secondary Network (PN, SN) and guarantee coexistence constraints by using TDD pattern restrictions.
- Pattern adjustment via exchange of information or automatic measurements based on interference level and traffic load.

PN (DL heavy)	DL	DL	DL	DL	DL	DL	DL	UL	UL	UL
SN (Equal – DL first)	DL	DL	DL	DL	DL	UL	UL	UL	UL	UL

PN (DL heavy)	DL	DL	DL	DL	DL	DL	DL	UL	UL	UL
SN (Equal – UL first)	UL	UL	UL	UL	UL	DL	DL	DL	DL	DL

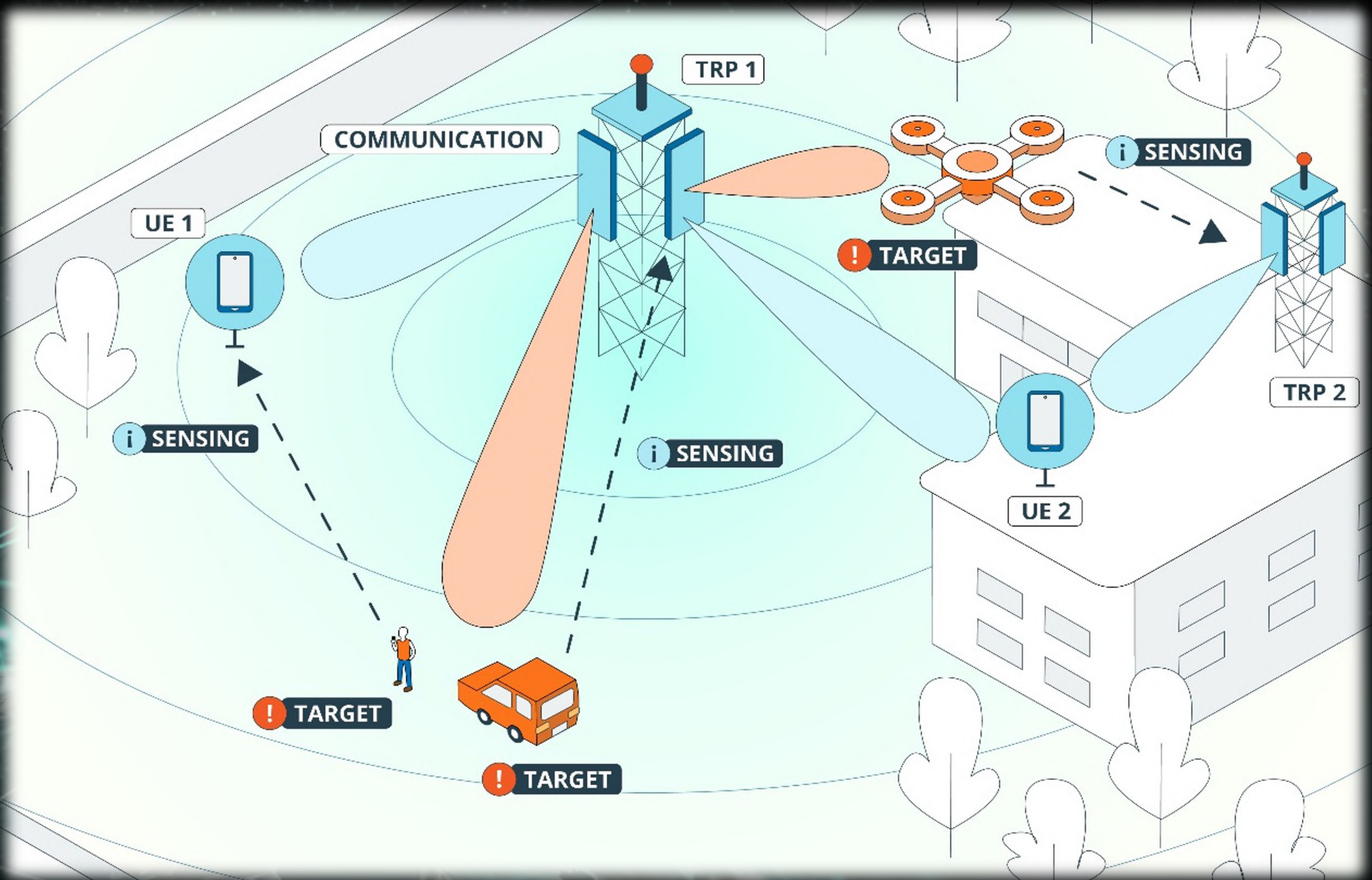
Integrated Sensing and Communications

3D Imaging for Situational Awareness in 6G

Organized by:

xGMobile Inatel FAPEMIG EMBRAPII GOVERNO DE MINAS AQUI O TREM PROSPERA. MINISTÉRIO DA CIÊNCIA, TECNOLOGIA E INOVAÇÃO GOVERNO DO BRASIL DO LADO DO POVO BRASILEIRO

Integrated Sensing and Communications (ISAC)



Situational Awareness

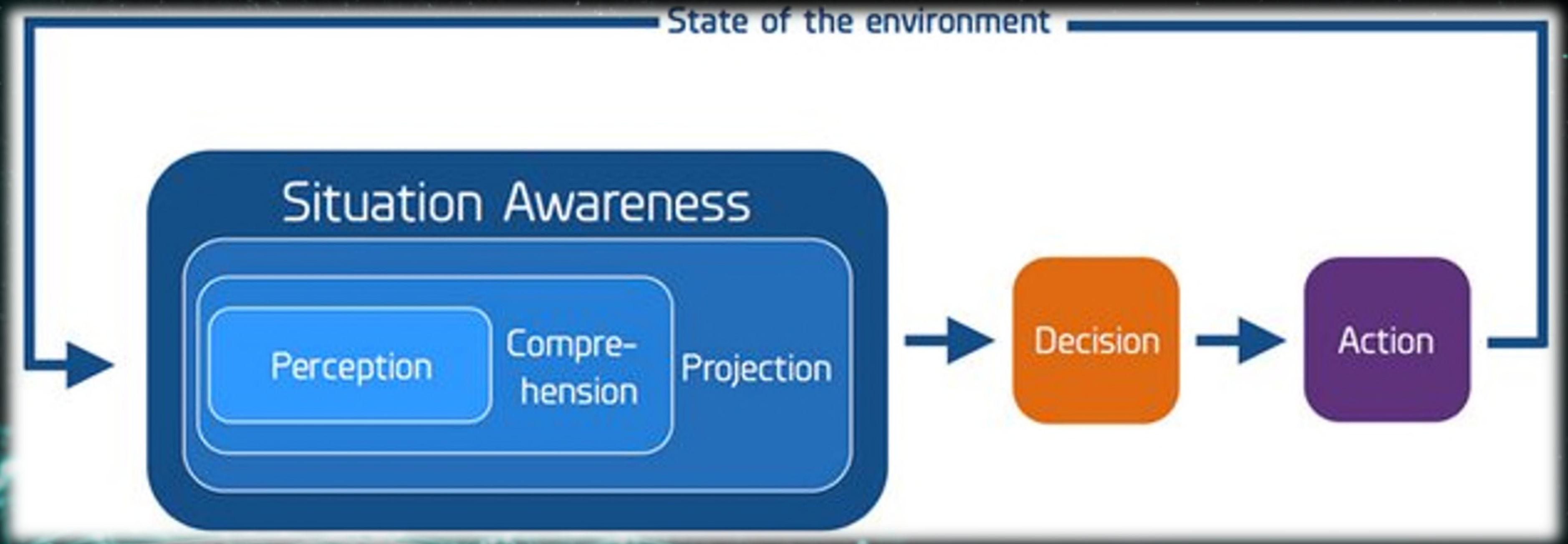


Figure Source:
"CRUSOE: A Toolset for Cyber Situational Awareness and Decision Support in Incident Handling"
Martin Husak et. al.; Computers & Security, January 2022.

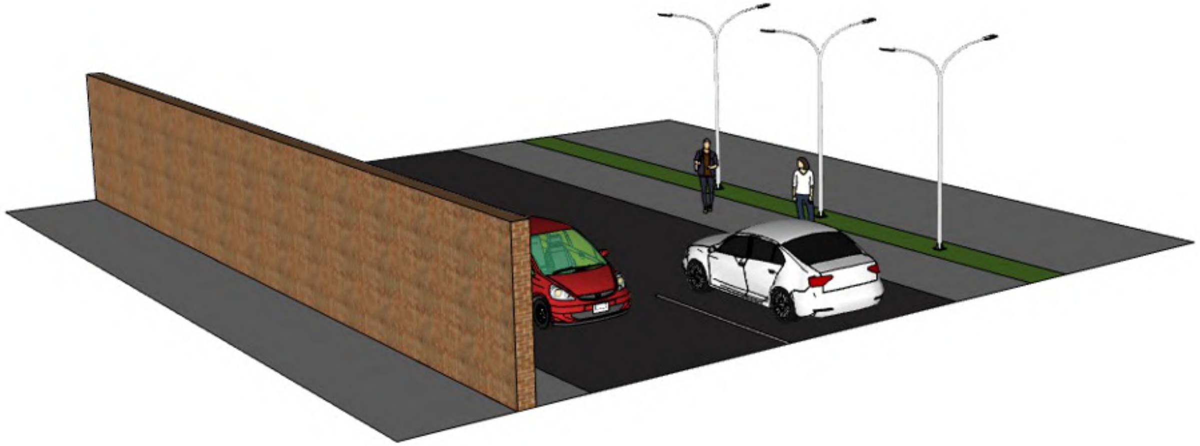
ISAC Imaging Case Study

Based on paper accepted at 2026 IEEE 6th International Symposium on Joint Communications and Sensing, *"On the Impact of Geometry, Radar Cross Section and Path Loss on ISAC Imaging Fidelity"*; C. Schwartz, W. C. Freitas Jr and G. Fodor.

Organized by:

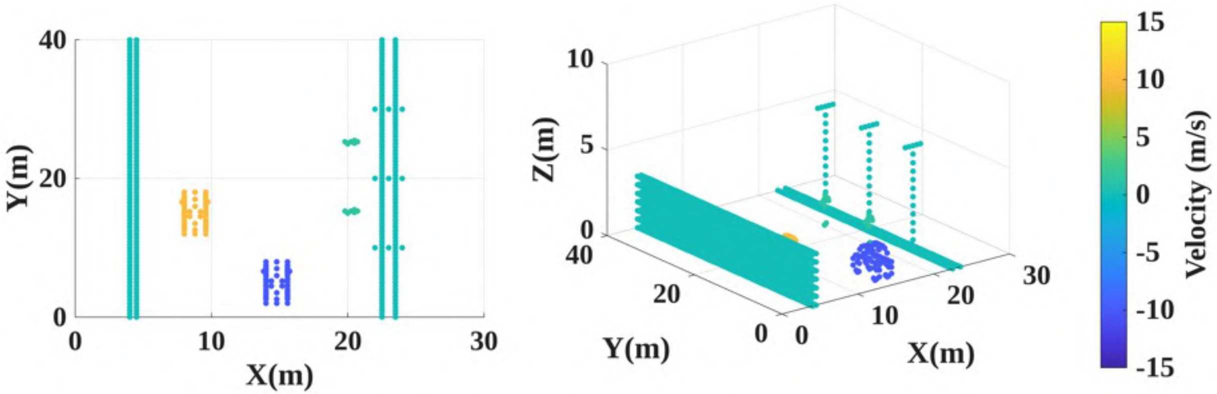
ISAC Imaging: the ground truth scenario

- **Scenario Composition:**
  - A complex urban environment was simulated, featuring a mix of dynamic and static objects:
    - **Moving Targets:**
      - Two cars with opposing velocities (∓10 m/s),
      - Two moving pedestrians (2 m/s);
    - **Static Targets:**
      - One static wall
      - One median strip containing poles.
  - The entire scene is represented by a point cloud of 1518 individual scatterers, where the total echo is the coherent sum of their reflections.



3D scenario representation.

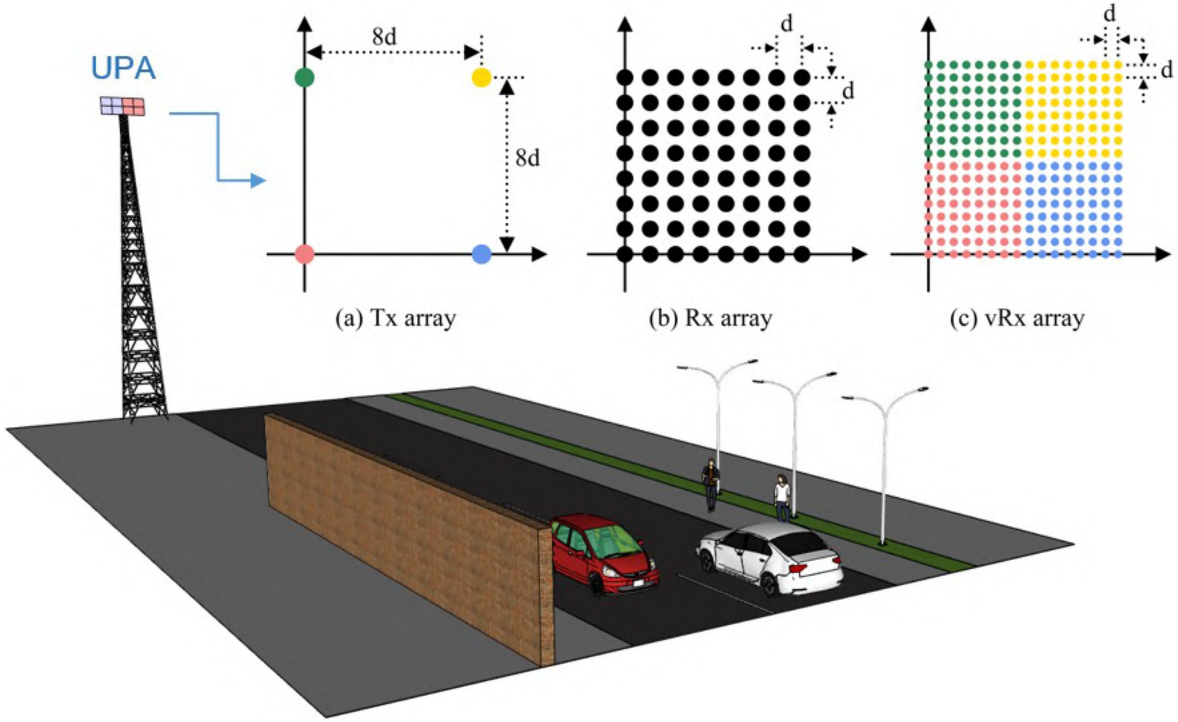
- **Simulation Space:**
  - All scatterers are located within a rectangular volume of approximately: 30m (X-axis) by 40m (Y-axis) by 6m (Z-axis).
  - Distinct base station (BS) positions were defined to study the impact of viewing geometry on reconstruction fidelity.
    - E.g., BS = [10, 100, 20] m.
  - Scatterer spacing is designed to be closer than the system's 30.5 cm resolution to model targets as continuous surfaces, not as individual points.



Scenario represented by scatterers

ISAC Imaging (monostatic): system parameters

- **Antenna array configuration**
  - Transmit (Tx) Array: 2x2 Uniform Planar Array (UPA).
  - Eight-times standard element spacing (8d).
  - Receive (Rx) Array: 8x8 UPA with a standard half-wavelength element spacing ($\mathrm{d} = \lambda/2$).
  - Synthesized Virtual Array: 16x16 virtual receive array using a MIMO virtual aperture technique.



- **Received signal model ($S_{\mathbf{Rx}}$)**
  - Modelled as the coherent sum of echoes from all K scatterers.
  - The signal for each OFDM symbol m and subcarrier n is given by

$$s_{Rx}(m,n) = \sum_{k=1}^{K} \alpha_k \, s_{Tx}(m,n) e^{-j2\pi f_n \frac{(2R_k)}{c}} e^{j2\pi \, f_d(k) m T_s} \tag{1}$$

where:

α_k is the attenuation factor,

R_k is the range,

$f_d(k)$ is the Doppler shift,

T_s is the symbol duration,

f_n is the subcarrier frequency,

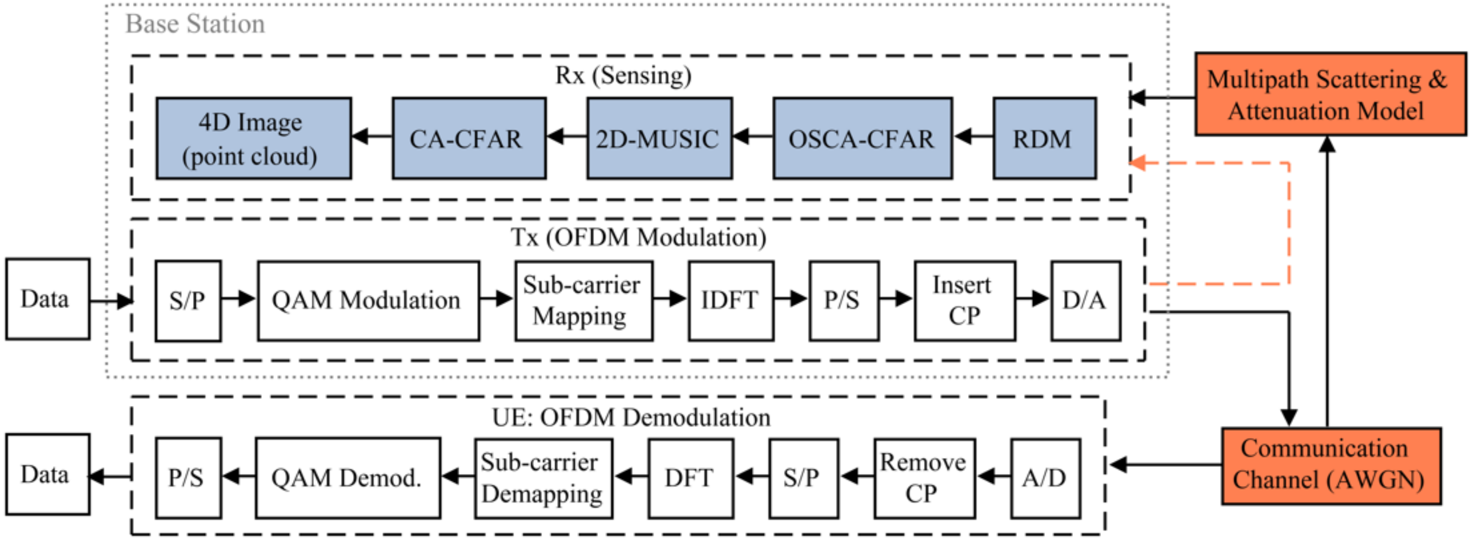
$s_{Tx}(m,n)$ are the modulated 4-QAM symbols, of the transmitted signal $\mathbf{S_{Tx}}$.

- **Channel state information at receiver (CSIR)**
  - The channel response $(\mathbf{H})$ for the antenna element $(\boldsymbol{p},\boldsymbol{q})$ is extracted via an element-wise division of the received $(\mathbf{S_{Rx}})$ by the known transmitted signal $(\mathbf{S_{Tx}})$:

$$\mathbf{H}^{(\boldsymbol{p},\boldsymbol{q})} = \mathbf{S}_{\mathbf{Rx}}^{(p,q)} \oslash \mathbf{S_{Tx}} = \sum_{k=1}^{K} \alpha_k (\mathbf{d}_k \circ \mathbf{r}_k) \tag{2}$$

where $\mathbf{d}_k$ and $\mathbf{r}_k$ are the Doppler and range steering vectors, $\oslash$ is the element-wise division, and $\circ$ is de outer product.

ISAC Imaging (monostatic): system parameters



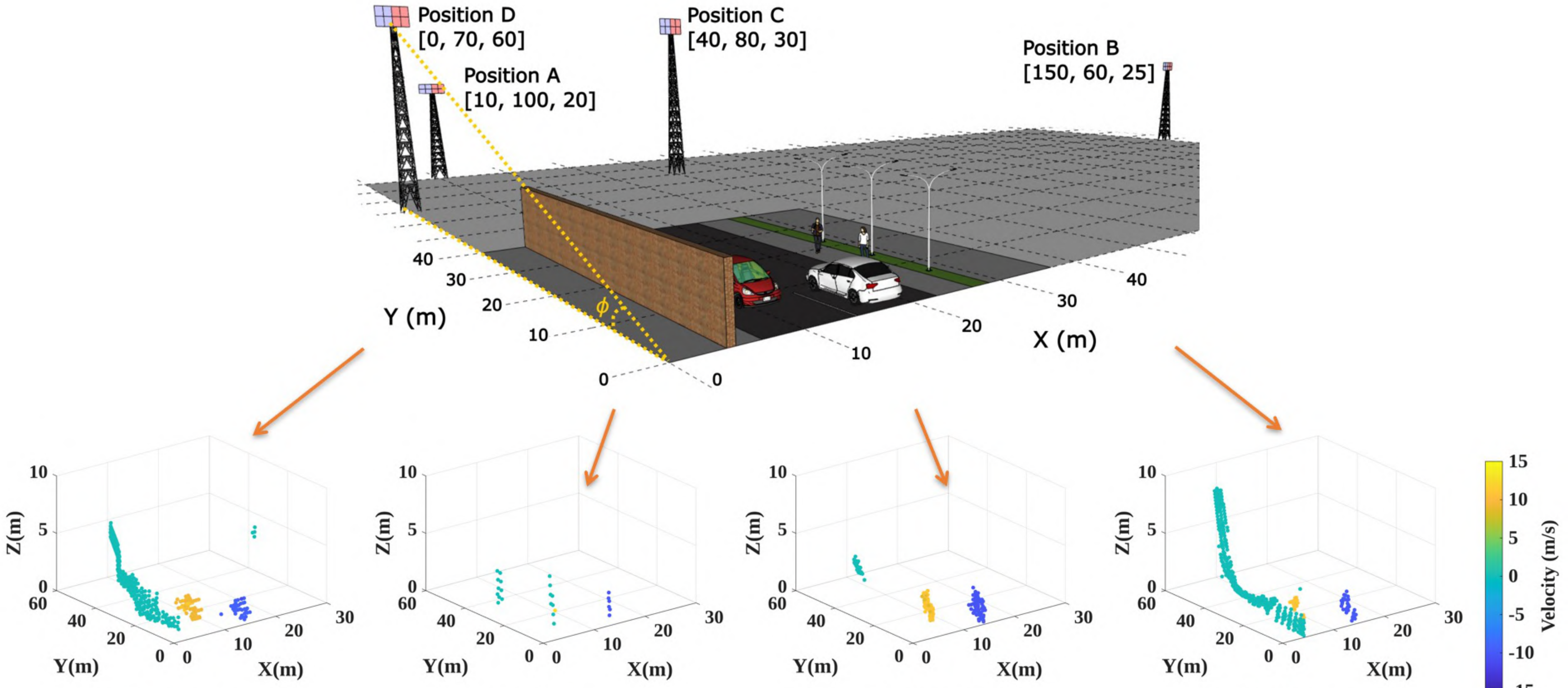
Communication link:

- Carrier frequency: 70GHz
- Bandwidth: 491.52MHz
- Subcarrier spacing: 240kHz
- Subcarrier count: 2048
- OFDM symbol: 224
- Slot count: 16
- Cyclic prefix ratio: 1/4
- Cyclic suffix ratio: 1/32
- **SNR: 20 dB**
- Modulation: 4-QAM

- **Distance and velocity estimation**:
  - Generated from Range-Doppler Map (RDM).
    - Range: IDFT across subcarriers.
    - Velocity: DFT across OFDM symbols.
  - Detection: OSCA-CFAR algorithm on RDM peaks.
- **Direction estimation:**
  - Performed for each peak detected in the RDM.
  - MUSIC algorithm used for direction of arrival (DoA), using spatial smoothing for coherent signals.
  - Detection: CA-CFAR algorithm.

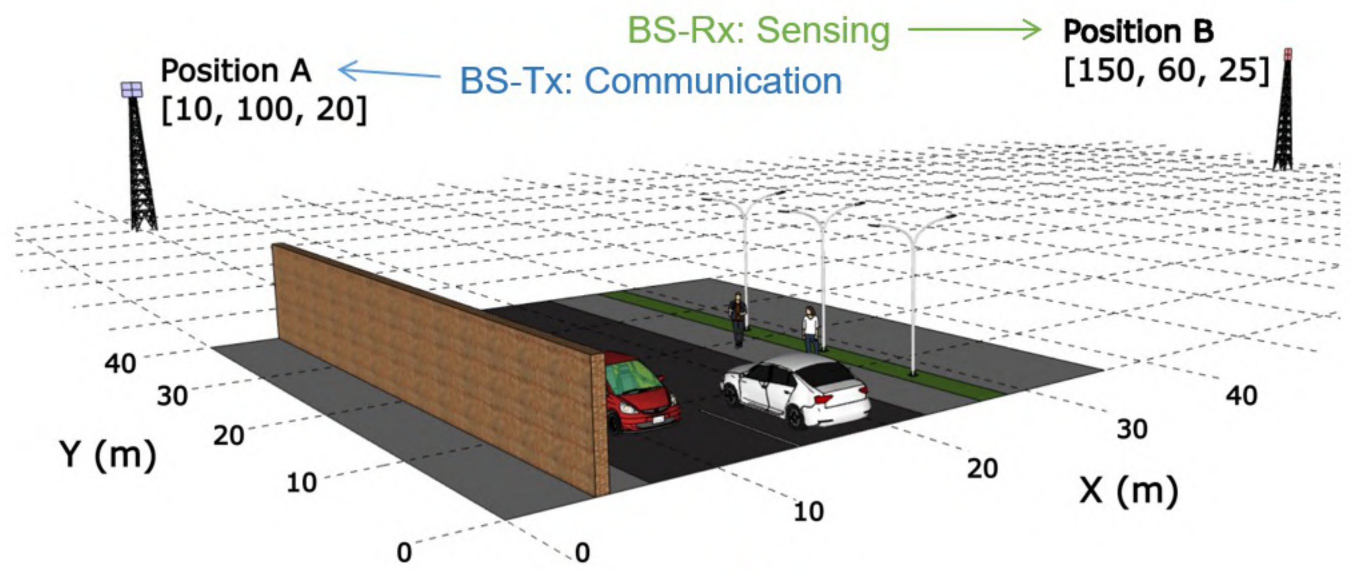
- **Channel attenuation model**
  - Derived from the mono-static radar range equation.
  - It is proportional to the square root of the target's radar cross section (σ_k) and inversely proportional to the square of its range (R_k): $\alpha_k \propto \frac{\sqrt{\sigma_k}}{R_k^2}$
  - Assigns distinct RCS values (σ_k) per object:
    - Vehicle (Metal): 80.0 m²
    - Wall (Metal/Concrete) 15.0 m²
    - Pole (Metal/Concrete): 5.0 m²
    - Pedestrian: 1.5 m²
    - Vegetation (Median Strip): 0.8 m²

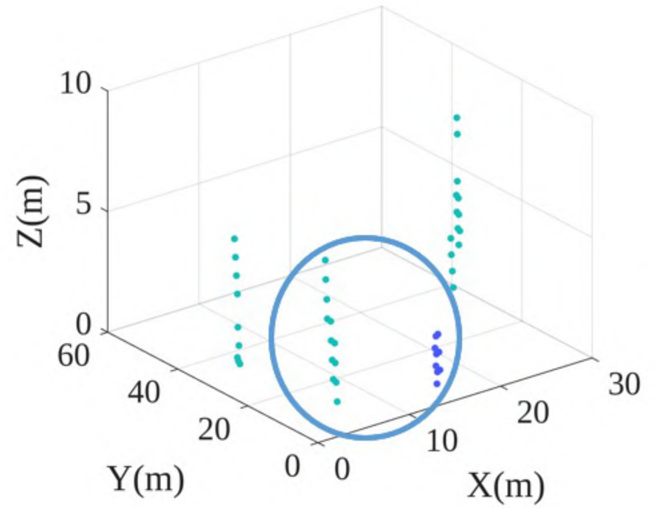
ISAC Imaging (monostatic): results for different BS positions



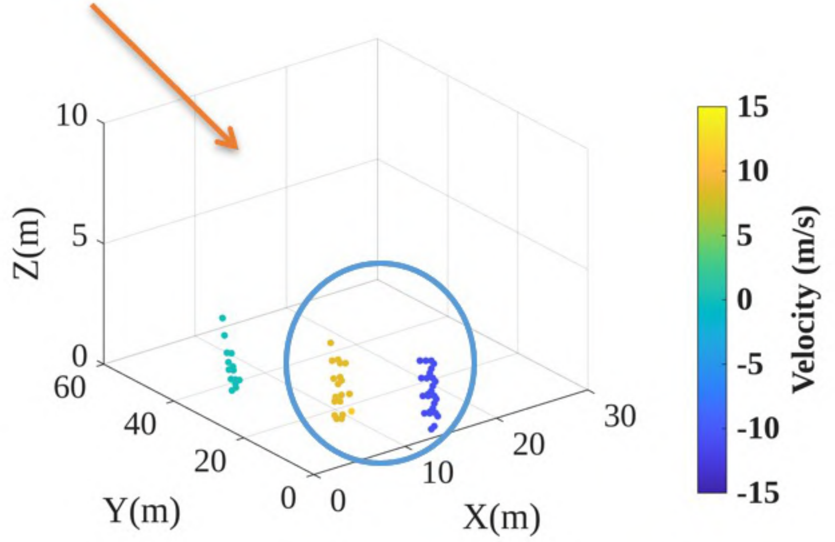
Position A Position B Position C Position D

ISAC Imaging (bistatic): improving poor geometries





Monostatic: BS at Position B.



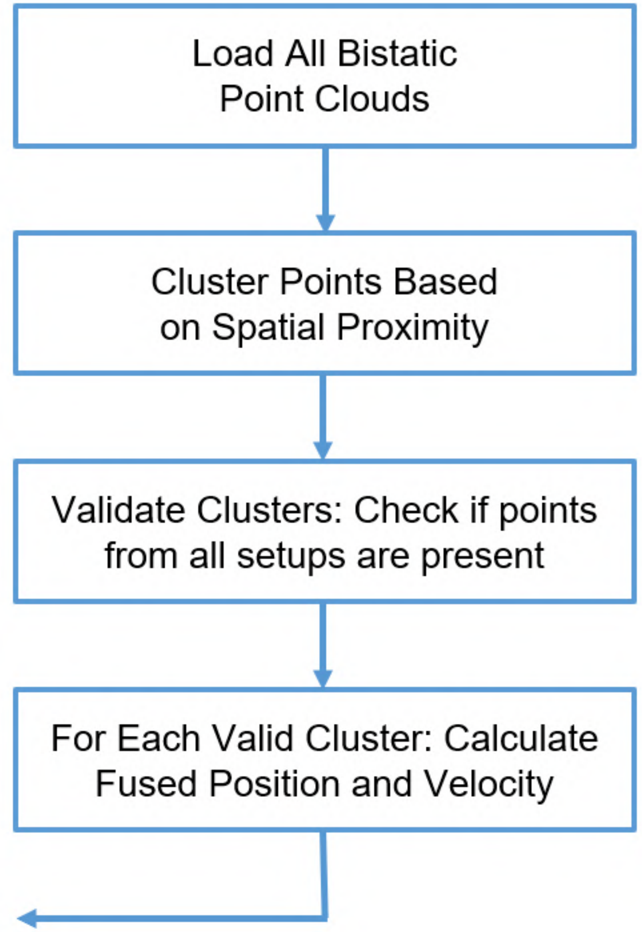
Bistatic: Tx at Position A; Rx at Position B.

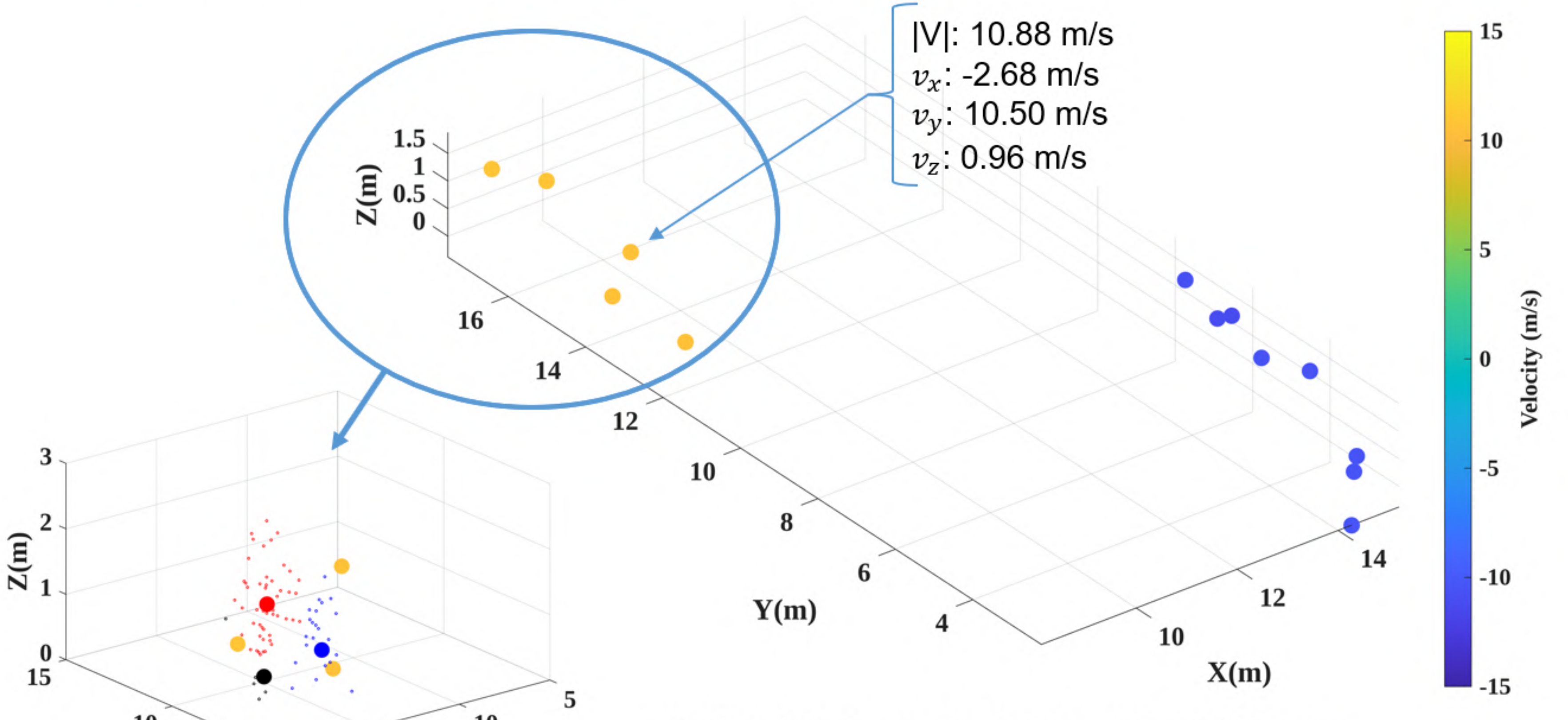
Monostatic to bistatic configuration:

- Update signal model geometry:
  - New path length for time delay: $R_{total} = R_{Tx} + R_{Rx}$
  - Use bistatic model for Doppler shift.
- Update Attenuation (α_k):
  - Signal attenuation proportional to:
    $$\alpha_k \propto \frac{\sqrt{\sigma_k}}{R_{Tx} \cdot R_{Rx}}$$
- Centre DoA on receiver:
  - All angle estimation must be relative to the Rx.
  - Adjust the formulas that converts the RDM range and Doppler bin to meters.
- Adjust coordinate reconstruction:
  - The time delay measurement now defines an **ellipsoid, not a sphere**.
  - The DoA measurement defines a line from the Rx.
  - The target's position is the intersection of this line and the ellipsoid.

ISAC Imaging (Multi-static): Data Fusion via Clustering

- Resolving the full 3D velocity vector, $\mathbf{v}_{target} = [v_x, v_y, v_z]^T$, by fusing measurements from three or more setups, instead of relying on single measurement radial velocity.
  - Setup 1: Tx at Position A [10,100,20]; Rx at Position C [40,80,30].
  - Setup 2: Tx at Position A [10,100,20]; Rx at Position D [0,70,60].
  - Setup 3: Tx at Position A [10,100,20]; Rx at Position B [150,60,20].





Multi-static fusion results: Estimated True 3D Velocity.

Thank you!

My Co-PIs and Project Teams:

Prof. Walter Freitas Jr.

Prof. Victor Monteiro

Prof. Yuri Silva

Prof. André de Almeida

www.gtel.ufc.br ↗