From 5G-Advanced to 6G ISAC

Channel Modeling, Evaluation Scenarios, and Proof-of-Concept Results from an Industry Perspective

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Railway control equipment from Ericsson installed at railway. Taiwan. 1982.

Key take-aways

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- ISAC is transitioning from 5G-Advanced evaluations to a core topic in 6G.
- Multi-TRP sensing enables high-accuracy detection and tracking of UAVs.
- 6G ISAC introduces fundamentally new capabilities:
  - UE participation,
  - NLOS sensing,
  - environmental reconstruction, and
  - large-scale coverage.

Why ISAC matters to industry

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- Enables new beyond-communication capabilities
  - industrial automation: track assets (robots, humans) in factories and warehouses
  - vehicular safety: protect vulnerable road users
  - smart-city monitoring: dynamic planning of traffic flow, crowd dynamics
  - mission critical: complement cameras to protect critical infrastructure.
  - drone monitoring: intrusion warning
  - situational awareness: real-time spatial data for XR

Business case:

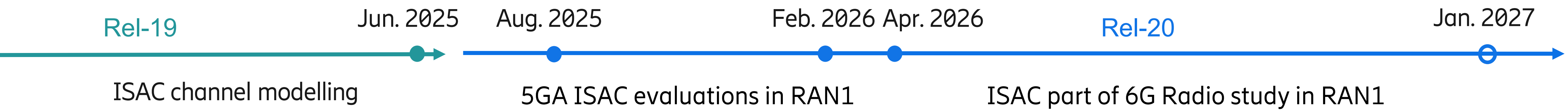
- Building on existing infrastructure brings down deployment costs.
  - Better performance than cheap off-the-shelf systems
  - Cheaper than dedicated radar systems
- Preserves privacy better than cameras

Remaining hurdles:

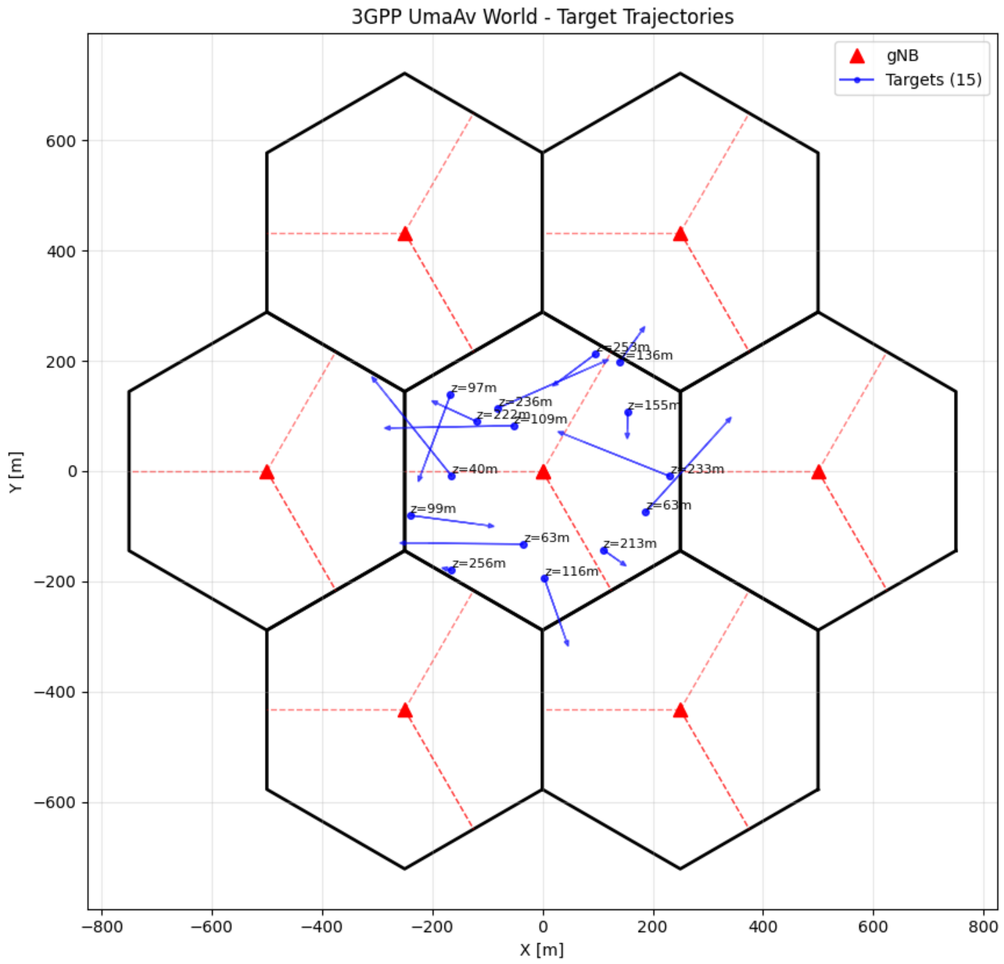
- Limited LOS probability, interference.
- How operators can monetize on sensing
- Transceiver architectures for monostatic links

3GPP ISAC standardization status

- Use cases in RAN1:
  - Object detection & tracking (UAV, human, vehicle, AGV)
  - Discuss evaluations of communication assistance
- RAN1 will evaluate all 6 modes (TRP mono/bistatic, TRP—UE, UE—TRP, UE mono/bistatic)
  - Not necessarily include specifications for all.
- CP-OFDM waveform and frame structure as for 6GR are used as starting point for ISAC.



UAV sensing scenario was evaluated in RAN1:
Position passive UAVs from single snapshot.

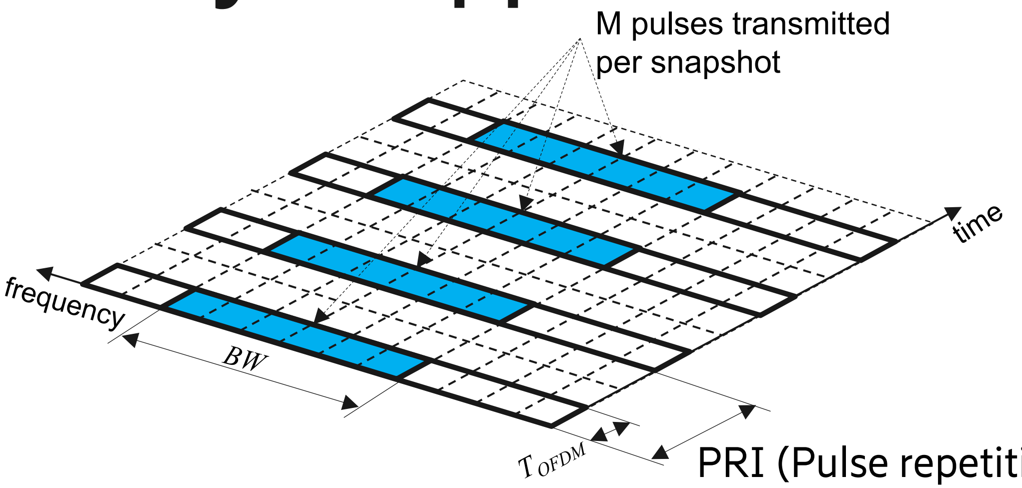


- 3GPP UMa-AV scenario
- 15 UAV targets in center hex (5 per sector)
- UAV height: 25m—300m
- UAV velocity:
  0—50 m/s horizontal, 0 m/s vertical

- 3-sector hexagonal deployment, 21 TRPs
- 500 m intersite distance
- Monostatic sensing

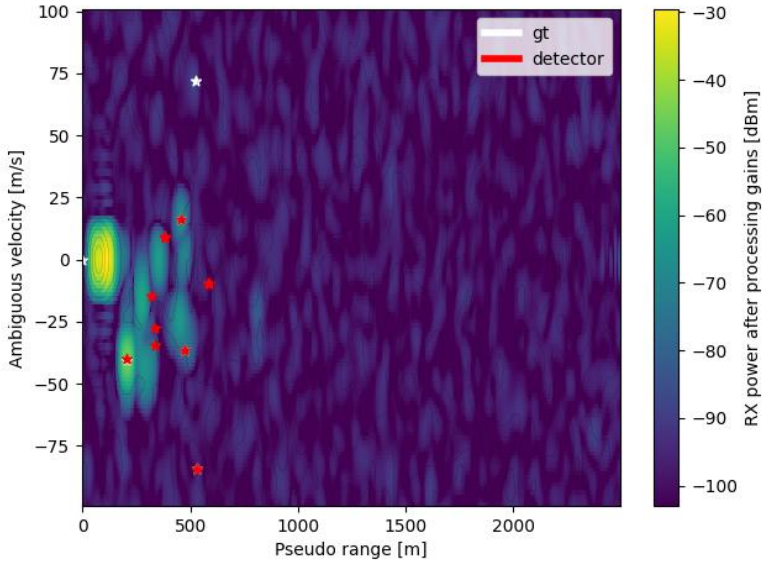
- 4GHz carrier frequency, 30kHz subcarrier spacing.
- 100 MHz bandwidth.

Pulse-train reference signals enable delay—Doppler channel estimation.



PRI (Pulse repetition interval)

Coherent processing interval: CPI = M PRI



Range resolution

- $R_r = \frac{c}{2BW}$

Unambiguous velocity

- $v_u = \frac{c}{4 f_c \mathrm{PRI}}$

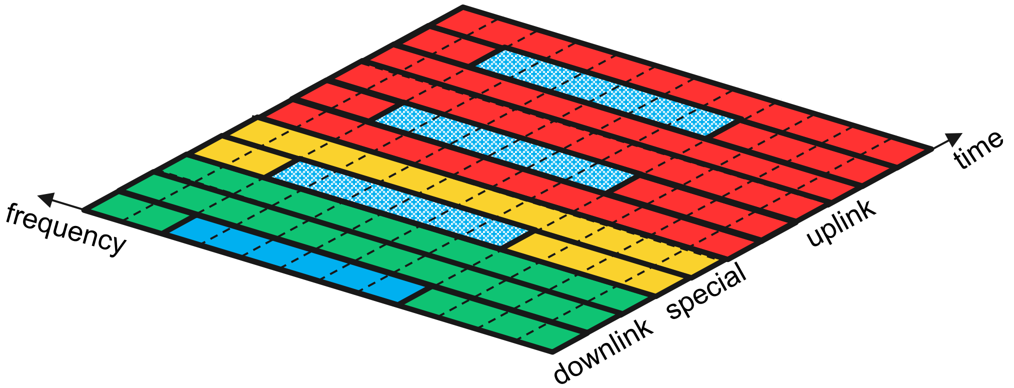
Velocity resolution

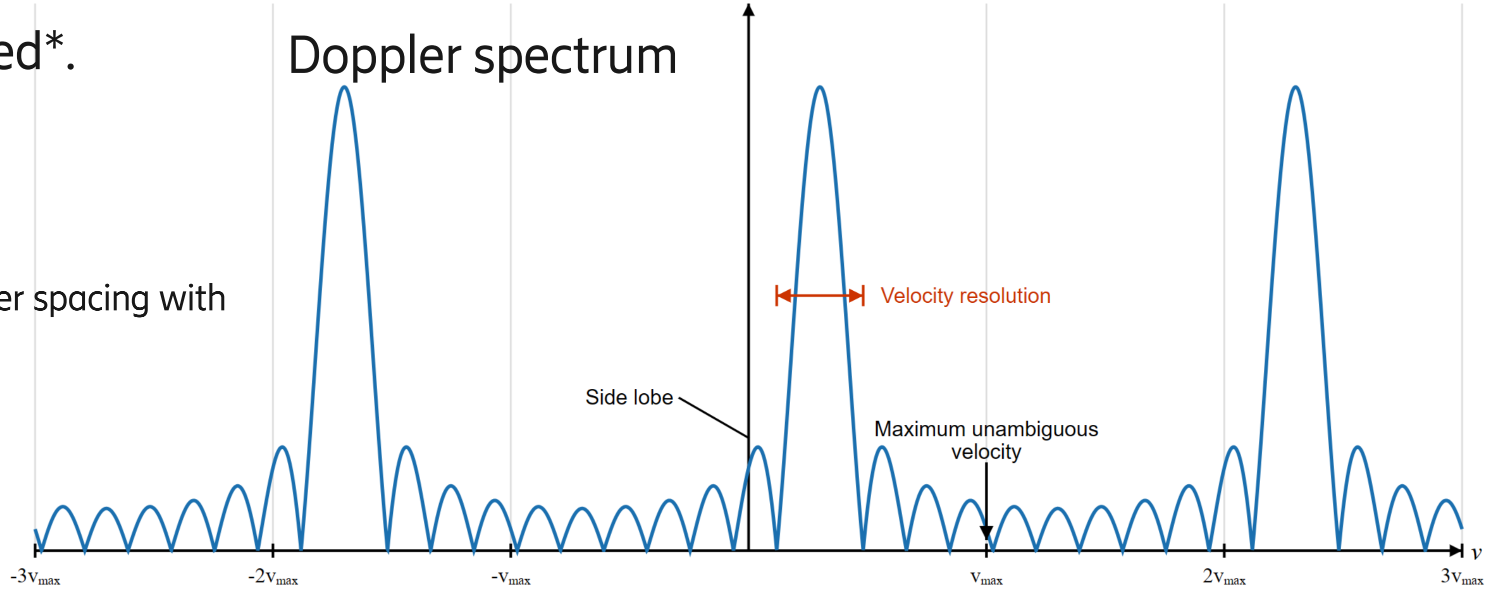
- $v_r = \frac{c}{2 f_c \mathrm{CPI}}$

2D Fourier transform of channel estimate reveals peaks in the delay—Doppler domain

TDD patterns constrain velocity sensing, since pulses must fall in downlink slots.

- TRP sensing uses downlink slots to avoid interfering with MBB transmission.
- Pulse trains must fit TDD patterns.
- PRI and CPI are dictated by DL availability, not sensing needs
- ⇒ *velocity resolution* and *maximum unambiguous velocity* are constrained*.





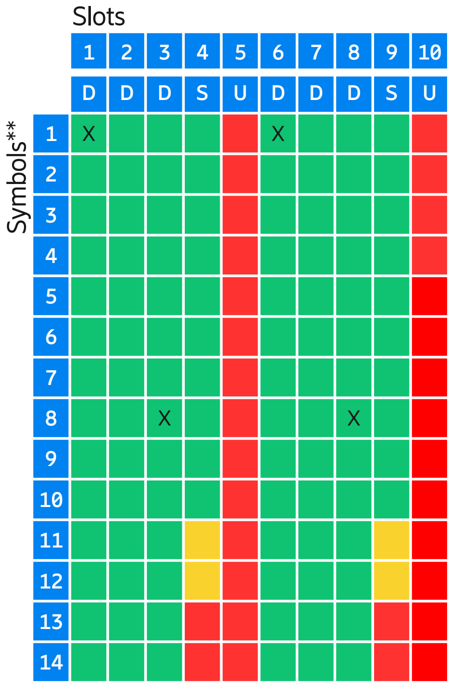
* Other factors might put other constraints, e.g., subcarrier spacing with per-pulse processing.

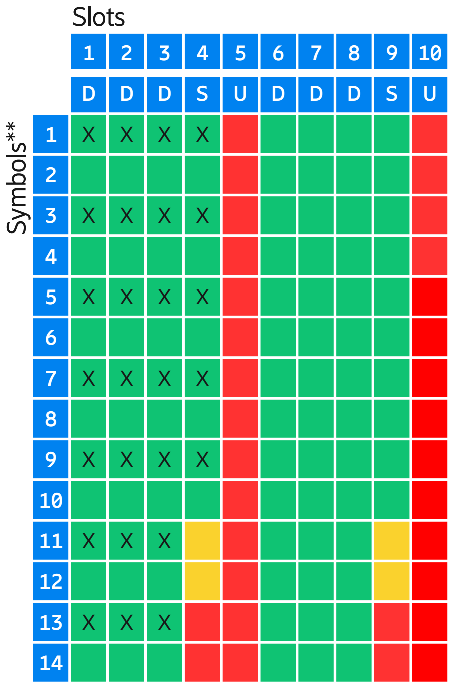
DDDSU (S=10:2:2) limits maximum unambiguous velocity.

- For equidistant pulses, $PRI = 35\ sym$ or 70 sym.
- Using 35 sym, gives PRI=1.25ms, CPI arbitrary*
  - Maximum unambiguous velocity: 15m/s
  - Velocity resolution: arbitrary

- Alternatively, fit CPI in 52 symbols
- Using 2 sym, gives PRI=71.36µs, CPI=1.855ms
  - Maximum unambiguous velocity: 262.6m/s,
  - Velocity resolution: 20.2m/s

- Bad for fast UAVs.





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* but in practice limited by range migration.

** DL S UL

DDDDDDDSUU (S=6:4:4) limits velocity resolution.

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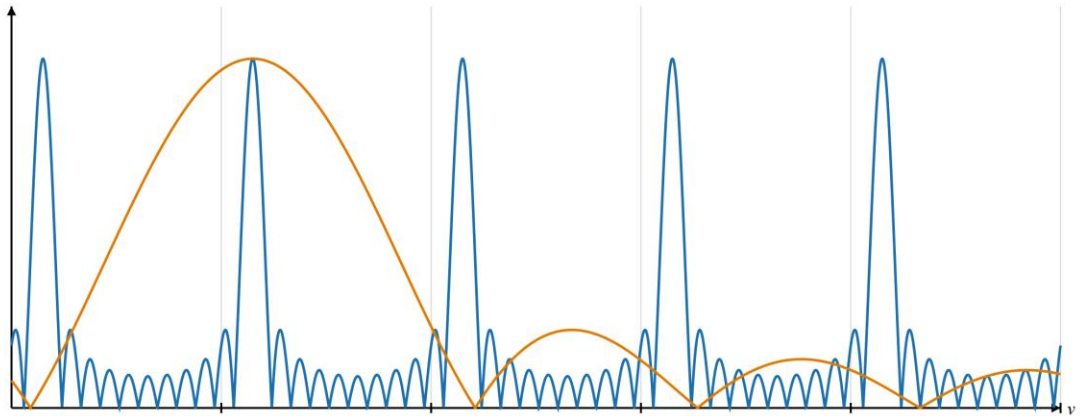
- CPI is practically constrained to one downlink.
- Every 3rd symbol, 34 pulses (PRI=107.04µs, CPI=3.64ms)
  - Maximum unambiguous velocity: 175m/s
  - Velocity resolution: 10.3m/s
- Good unambiguous velocity, poor resolution.

Symbols** \ Slots	1	2	3	4	5	6	7	8	9	10
	D	D	D	D	D	D	D	S	U	U
1	X			X			X			
2		X			X			X		
3			X			X				
4	X			X			X			
5		X			X			X		
6			X			X				
7	X			X			X			
8		X			X					
9			X			X				
10	X			X			X			
11		X			X					
12			X			X				
13	X			X			X			
14		X			X					

** DL S UL

A staggered pulse-train resolves velocity ambiguity while preserving resolution.

- Two slightly offset pulse trains provide two complimentary Doppler observations
- that allow us to resolve velocity ambiguity up to 175m/s.



Doppler spectrum

Slots

Symbols**	1	2	3	4	5	6	7	8	9	10
	D	D	D	S	U	D	D	D	S	U
1										
2										
3	X					X				
4										
5										
6	O					O				
7										
8										
9										
10			X					X		
11										
12										
13			O					O		
14										

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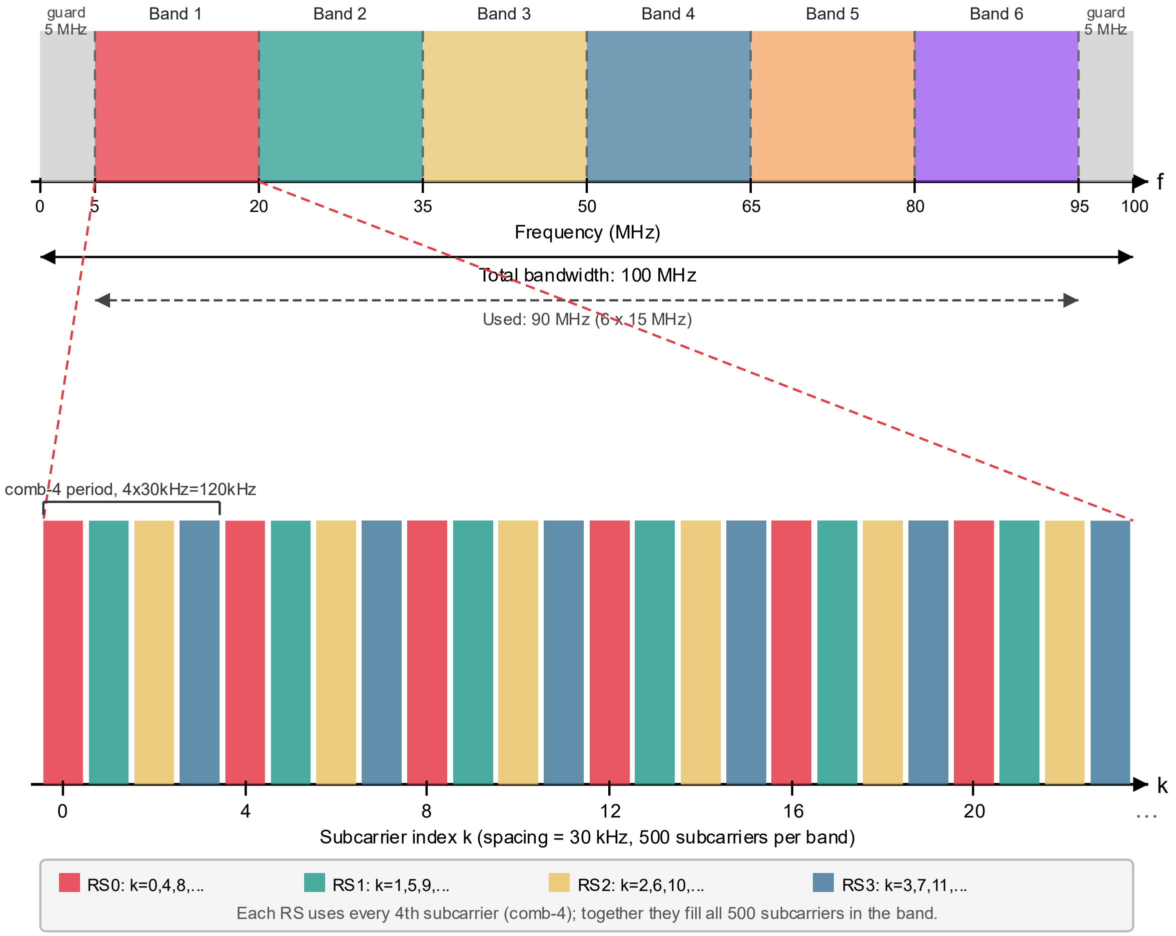
X: Pulse train 1

O: Pulse train 2

** DL S UL

Multiplex all TRPs in 15MHz sub-bands, each with 4 interleaved reference signals.

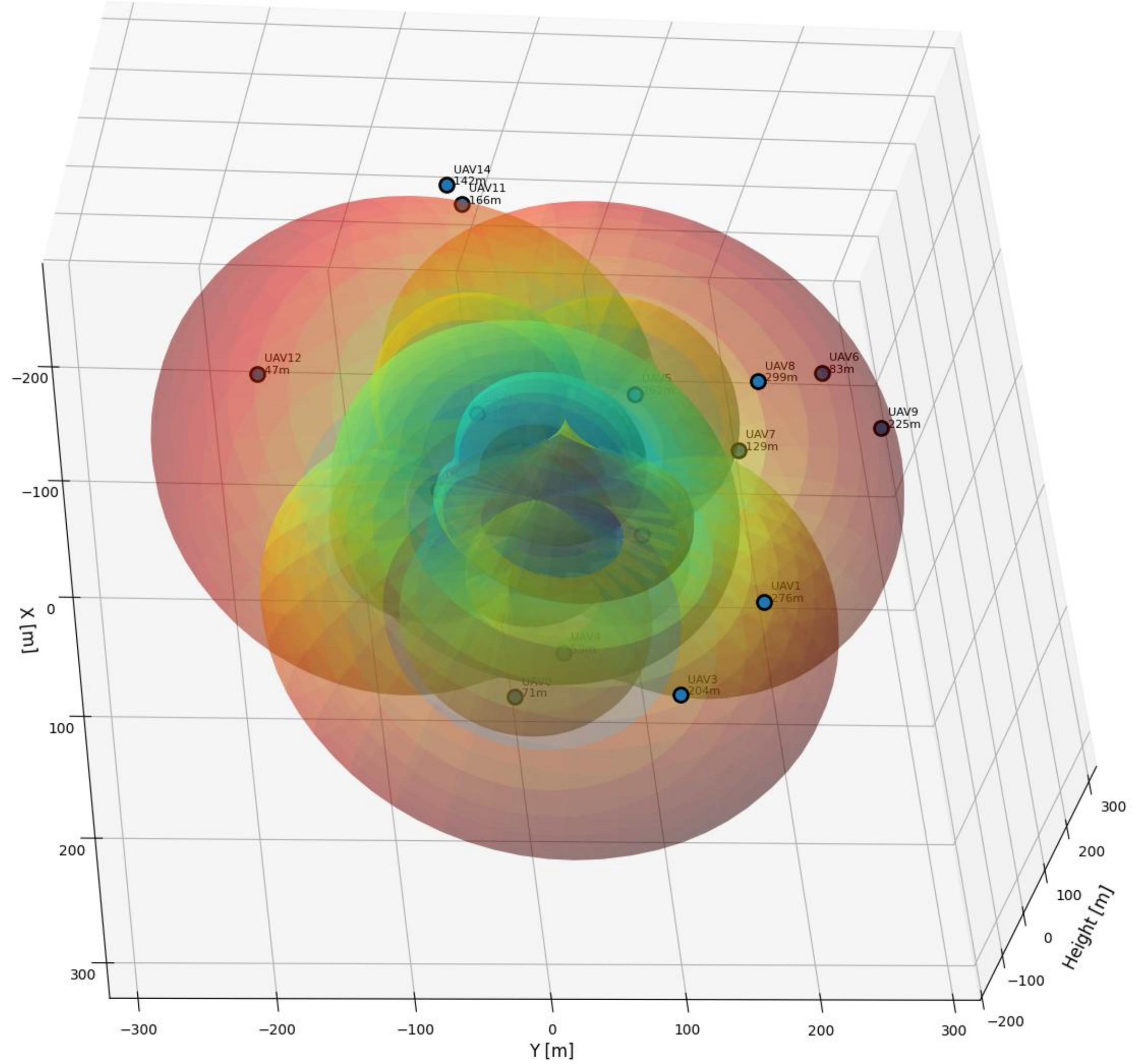
- OFDM symbol covers 100 MHz (subcarrier spacing is 30 kHz)
- Divide in 6 bands, each 15 MHz wide.
- Interleave 4 reference signals using a comb-4 pattern.
- This enables 24 orthogonal TRPs per OFDM symbol
- Range resolution: $\frac{c}{2\,BW}$ =10m
- Max unambiguous range: $\frac{c}{2\,\Delta f * 4} = 1250$m
- Note that sensing only uses 4 out of 42 downlink symbols, which gives room for MBB traffic.



Reference signals are beamformed with a wide beam.

- Single wide Tx beam.
- Beampattern of antenna element sets the beam width.
- The 3GPP 65 x 65 degrees HPBW antenna model is used (TR38.901).

- Subarray spacing: (1.6 λ, 0.5 λ)
- Gives rise to ambiguous vertical angle observations.



Summary of network parameters (for reference)

Link Settings

- Carrier Frequency: 4 GHz
- Subcarrier Spacing: 30 kHz
- Comb Size: 4
- Number of used subcarriers: 125
- Number of Pulses: 128
- PRI (Pulse Repetition Interval): 1.25 ms
- Reference Signal TX Power: 37 dBm (configurable: 37/52 dBm)

Antenna Array (per TRP):

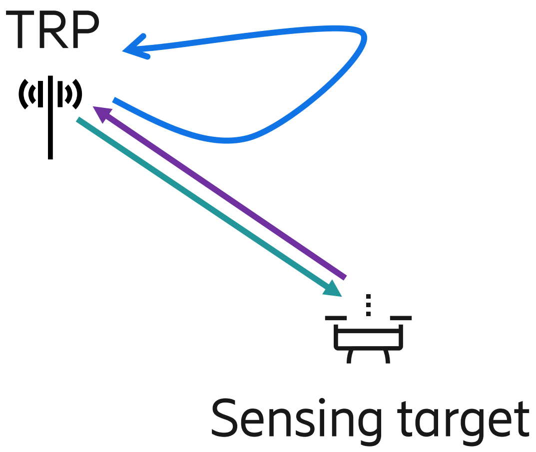
- Array Size: 4 (vertical) × 8 (horizontal) elements
- Subarray Size: 2 × 1
- Element Spacing: 0.06m (vertical), 0.0375m (horizontal)
- Dual Polarized: Yes
- Electrical Tilt: 0°
- Noise Figure: 5 dB

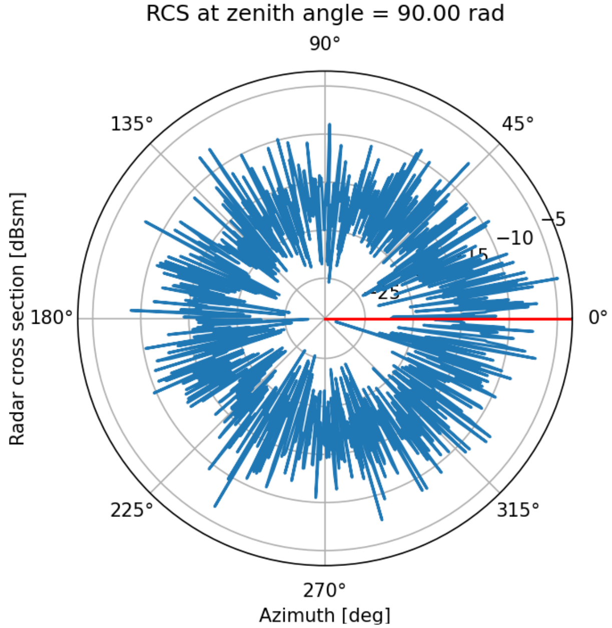
Other properties:

- TDD pattern: DDDSU
  (4 OFDM symbols per 5 slots used for sensing)
- CPI: 128×1.25 = 160ms
- Bandwidth: 30kHz×4×125 = 15 MHz
- Range resolution: c/(2×BW)=10m
- Max unambiguous range: c/(2*comb_size*scs)=1250m
- Velocity resolution: λ/(2×CPI)=0.234 m/s
- Max unambiguous velocity: λ/(4×PRI) = 15m/s
- Max unambiguous velocity with staggered pulses: 175m/s

TR38.901 ISAC channel

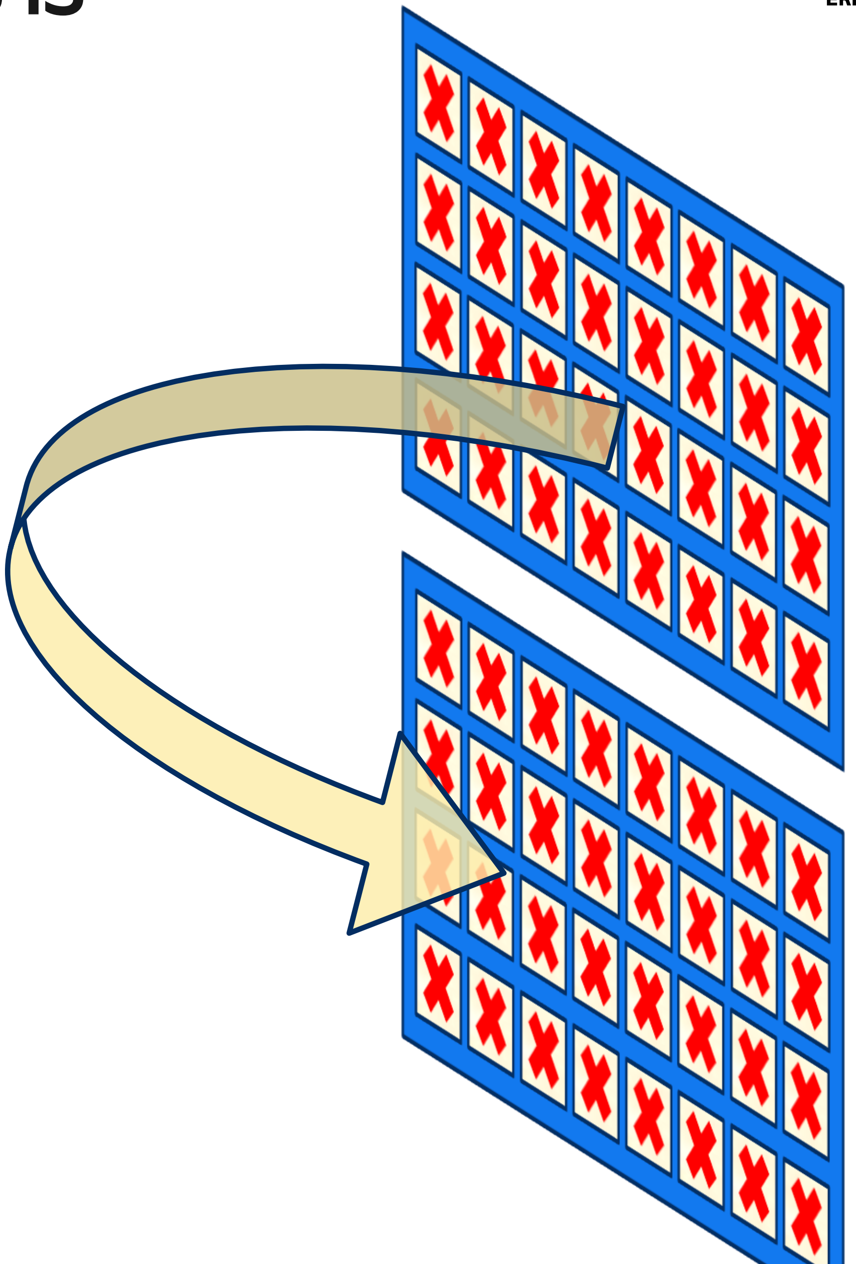
- Monostatic background channel + target channel.
- Background channel was added in Rel-19.
  - This is a modeling construct, not measured reality.
- Target channel is concatenation of Tx-ST link and ST-Rx link.
- Each link is modelled using classical 38.901 clusters and rays.
- Concatenation is done using a
  - target RCS, and
  - target cross-polarization matrix.
- RCS for UAVs, humans, vehicles and AGVs are defined.





Self-interference in monostatic links is severe.

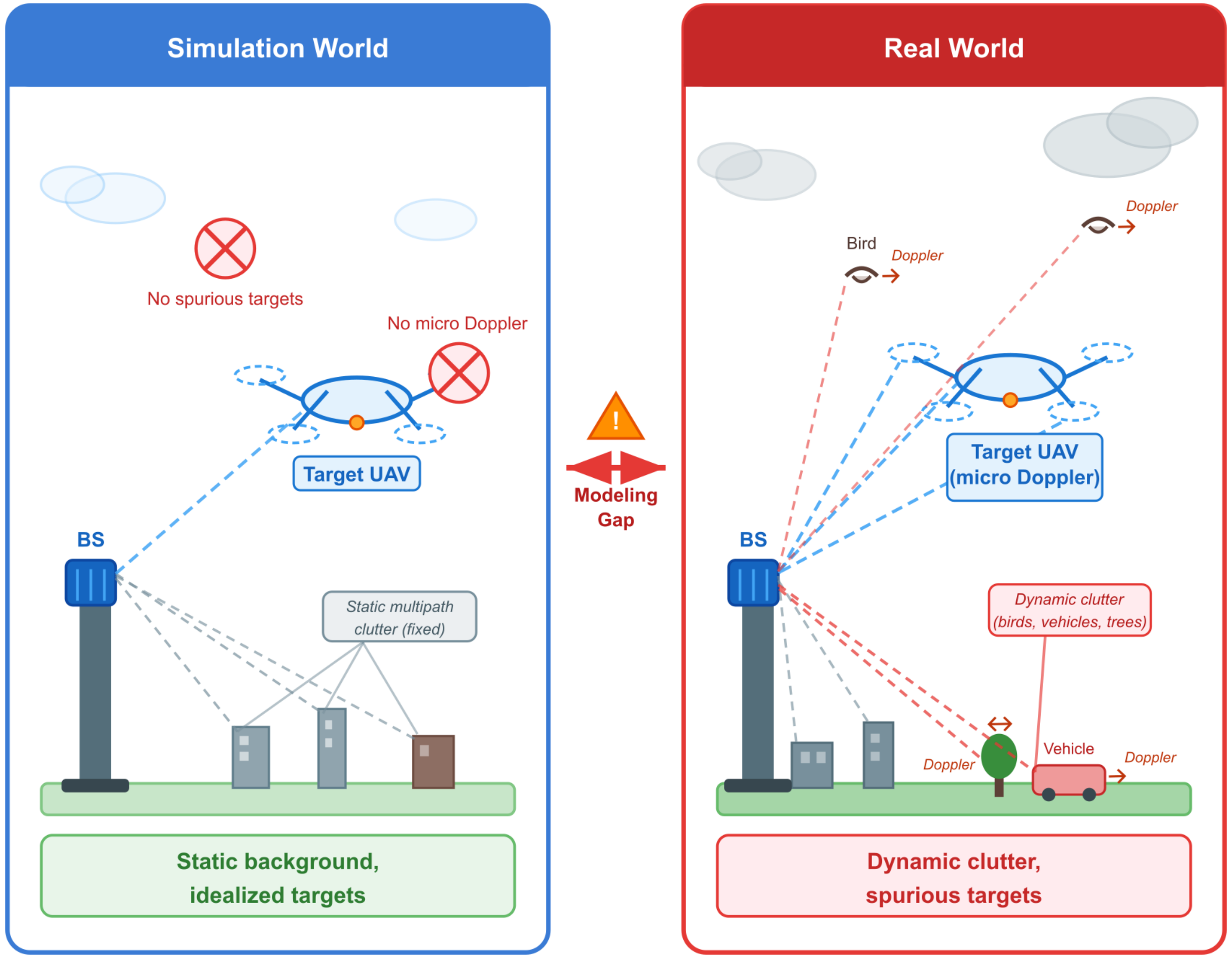
- Self-interference modelled statistically (c.f. Bussgang theorem):
  - Uncorrelated part modelled with AWGN
  - Correlated part modelled as 0-delay channel tap with -65dB gain.
- Self interference = $\sqrt{g}x + z$, (x is transmitted signal)



ISAC channel modeling limitations affect detection performance.

Channel model has...

- Limited target and scenario diversity
- Limited possibility to distinguish targets from spurious targets
- No micro-Doppler signatures
- Limited spatial consistency
- Static background
  (target is the only moving object)
  - **Detection performance can be over-estimated!**



Each UAV is seen from multiple TRPs — used to resolve ambiguities.

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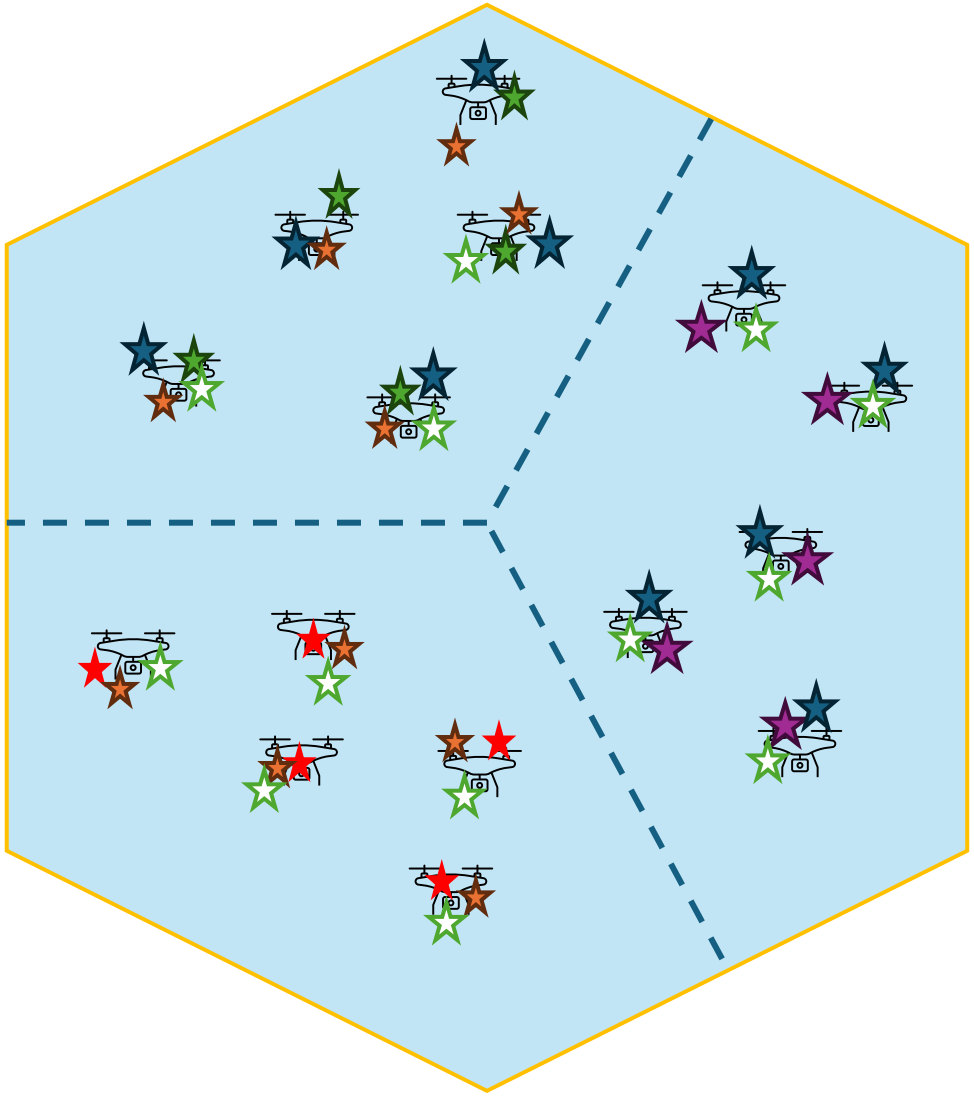
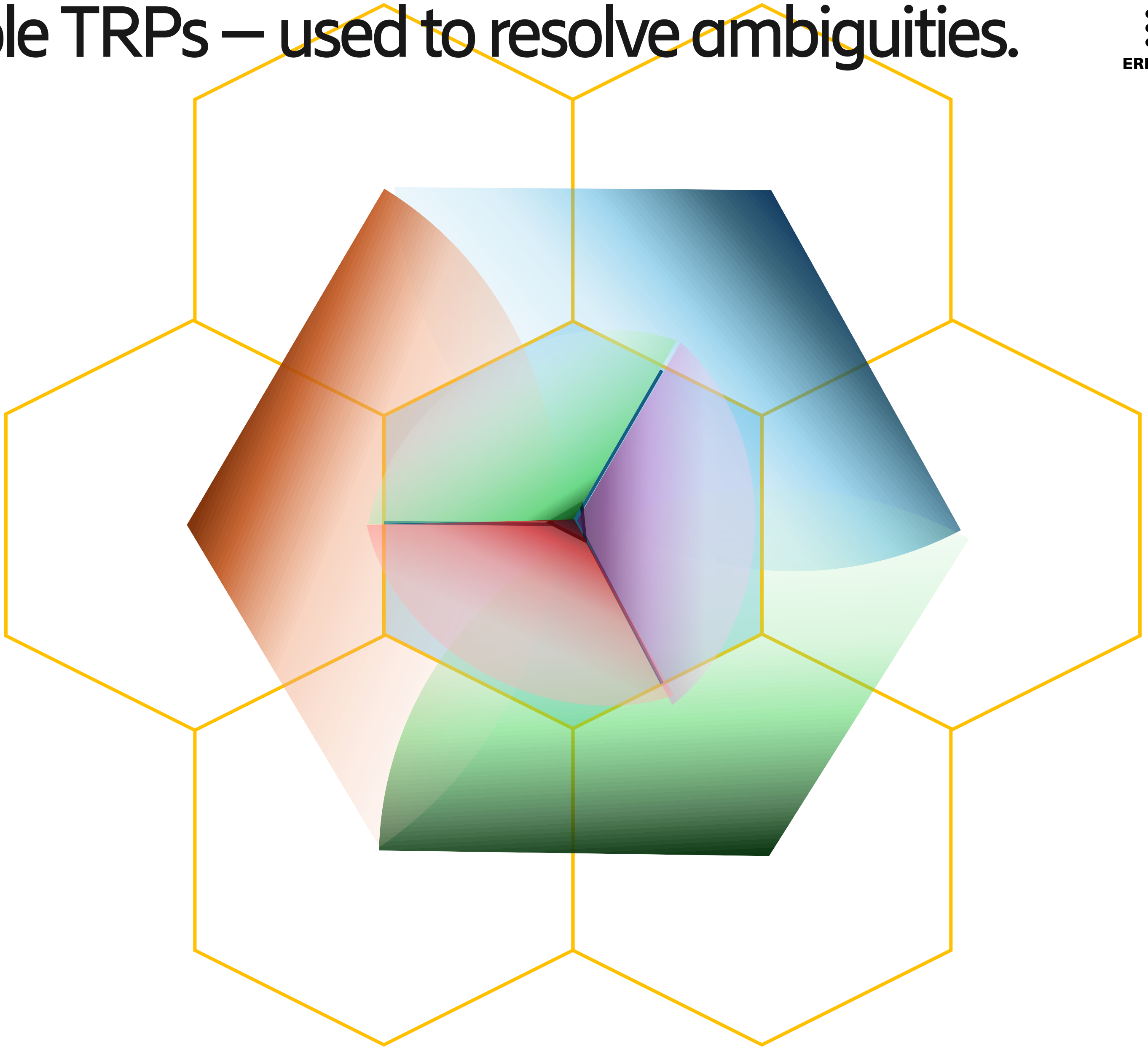


UAVs and field-of-view of the TRPs



One observation maps to multiple positions.

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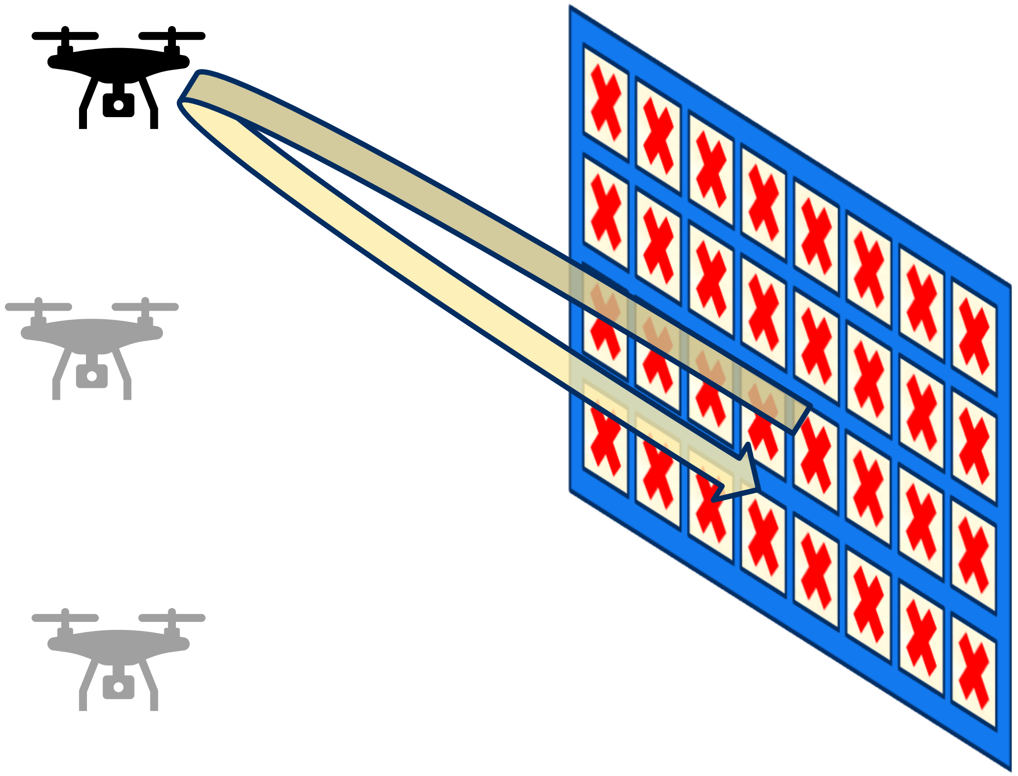
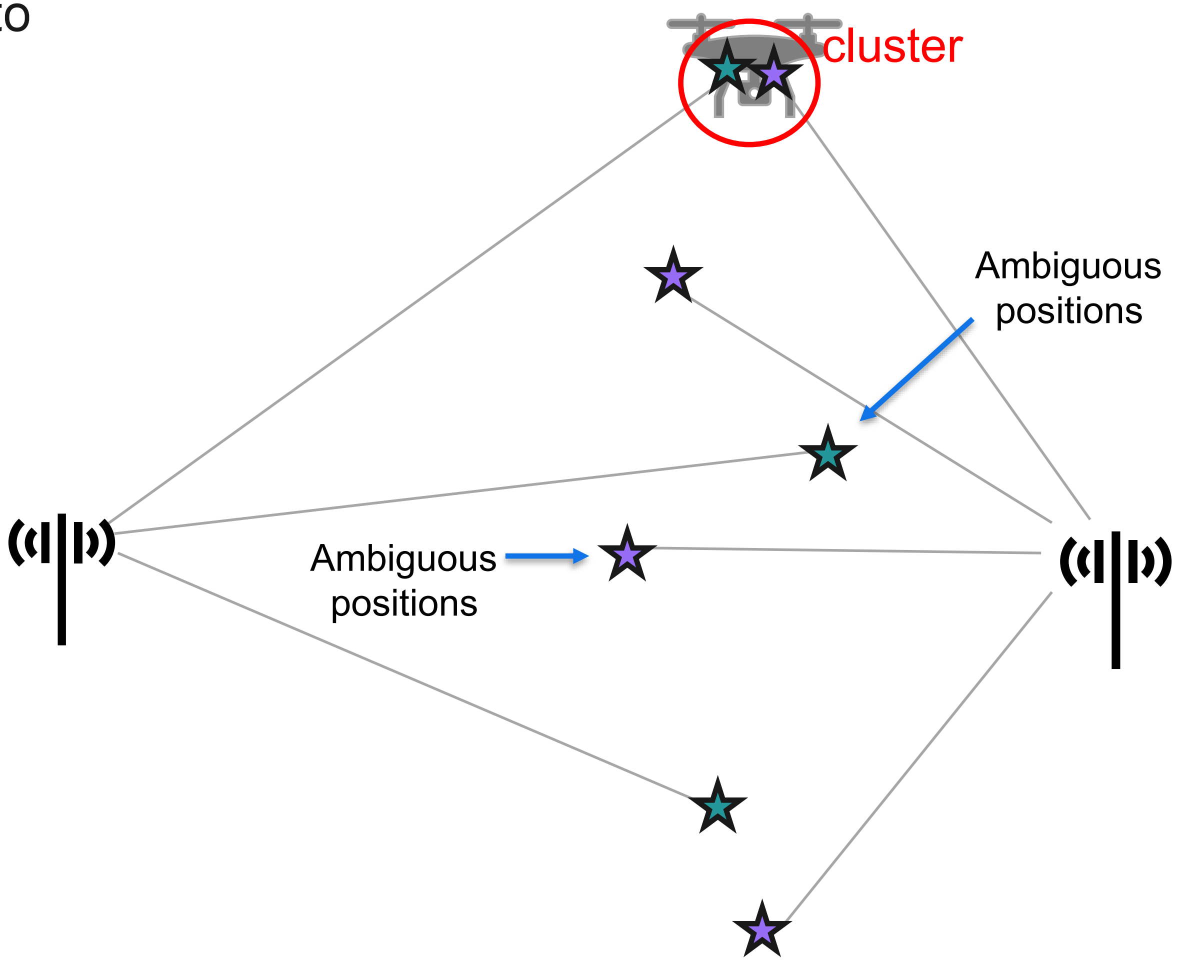
- Targets detected by peak detection on measured power profile in 4D, for each TRP we have:
    1. range,
    2. elongation rate (radial velocity component),
    3. vertical spatial frequency,
    4. horizontal spatial frequency.
- The observations from each TRP are converted to multiple positions
    - caused by 1.6λ vertical spacing.



Clustering removes spurious observations and associates observations into tracks.

- Vertical ambiguities cause one observation to map to multiple positions.
- The positions are clustered together using DBSCAN based on Mahalanobis distance.
- Minimum cluster points are 3.
- Filtering: In each cluster, positions must be reported from at least 3 different TRPs.
- This reduces false alarm rate but decreases detection rate.



Tracks are fused in a least-squares filter to obtain target position and velocity.

- The final estimate of the position p and velocity v is the solution that minimizes:

$$C(p,\, v) = \sum_{i \in \mathcal{T}} (z_i - p)^T P_i^{-1} (z_i - p) + \sum_{i \in \mathcal{T}} \left(\dot{r}_i - v^T \frac{(p - s_{m_i})}{\lVert p - s_{m_i} \rVert} \right)^2 + v^T C_v^{-1} v,$$

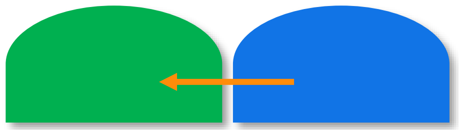
- where i is an observation index in the cluster index set $\mathcal{T}$,
  z_i the position observation,
  P_i covariance of position observation,
  $\dot{r}_i$ radial velocity observation,
  s_m position of TRP m
  σ_i^2 variance of radial velocity observation,
  C_v velocity prior covariance (3×3).
- This is a standard least-squares function and is solved using standard optimization tools.

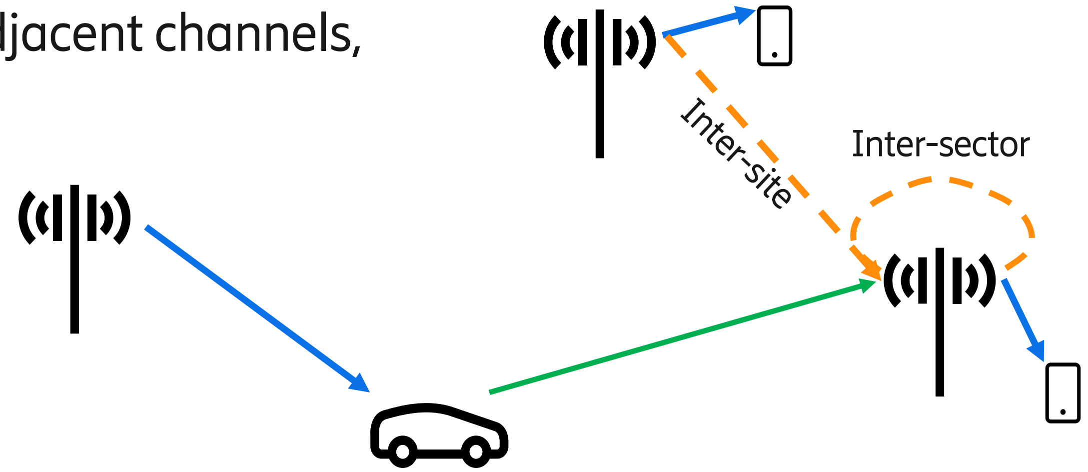
Setting results into perspective

Results seen as **upper bound, best-case scenario** due to simplifying assumptions:

- Optimistic self-interference isolation assumptions
- Neglected interference
  - Inter-site: interference from other sites
  - Co-site inter-sector: signal leakage from active communication users in adjacent sectors (due to imperfect antenna isolation and sidelobe coupling)
  - Inter-carrier: neighboring network interference from adjacent channels, which would raise the noise floor in practical systems
- Limitations/simplifications of the ISAC channel model

Inter-carrier

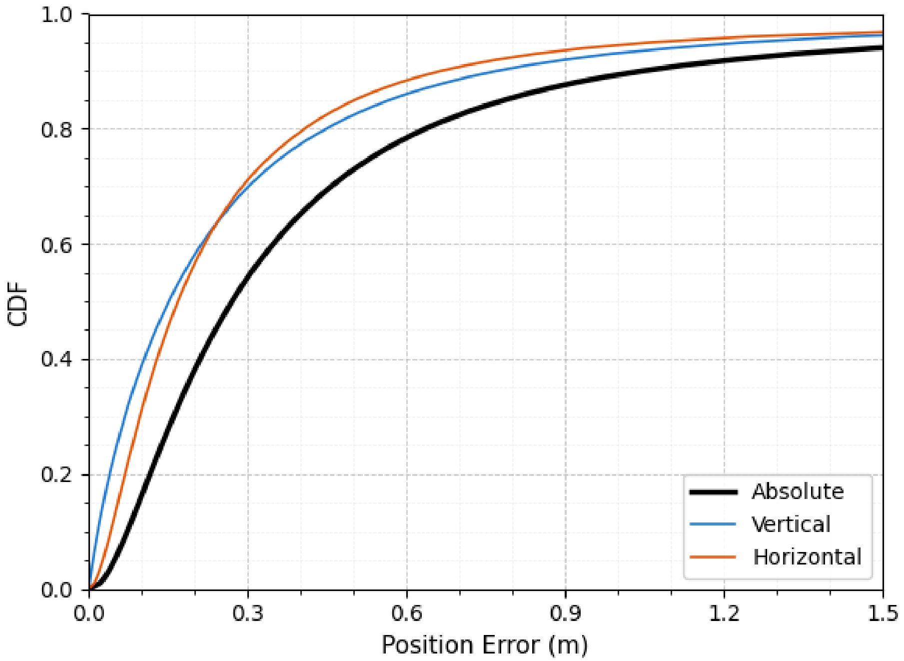


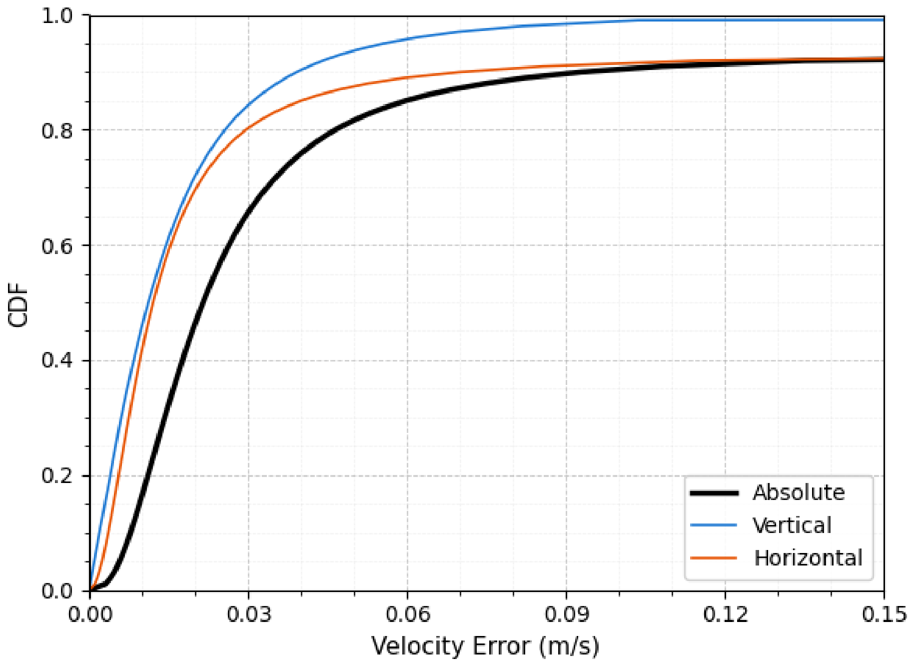


Multi-TRP sensing meets and exceeds the defined performance targets.

Metric	Target (Objective)	Achieved (All TRPs + Clustering)
90-percentile positioning accuracy	10 m	1.092 m
90-percentile velocity accuracy	5 m/s	0.1 m/s
Detection rate	95 %	96.08 %
False alarm rate	5 %	1.53 %

(Baseline 2, 37 dBm, with 160 ms CPI)





What makes 6G ISAC different from 5GA?

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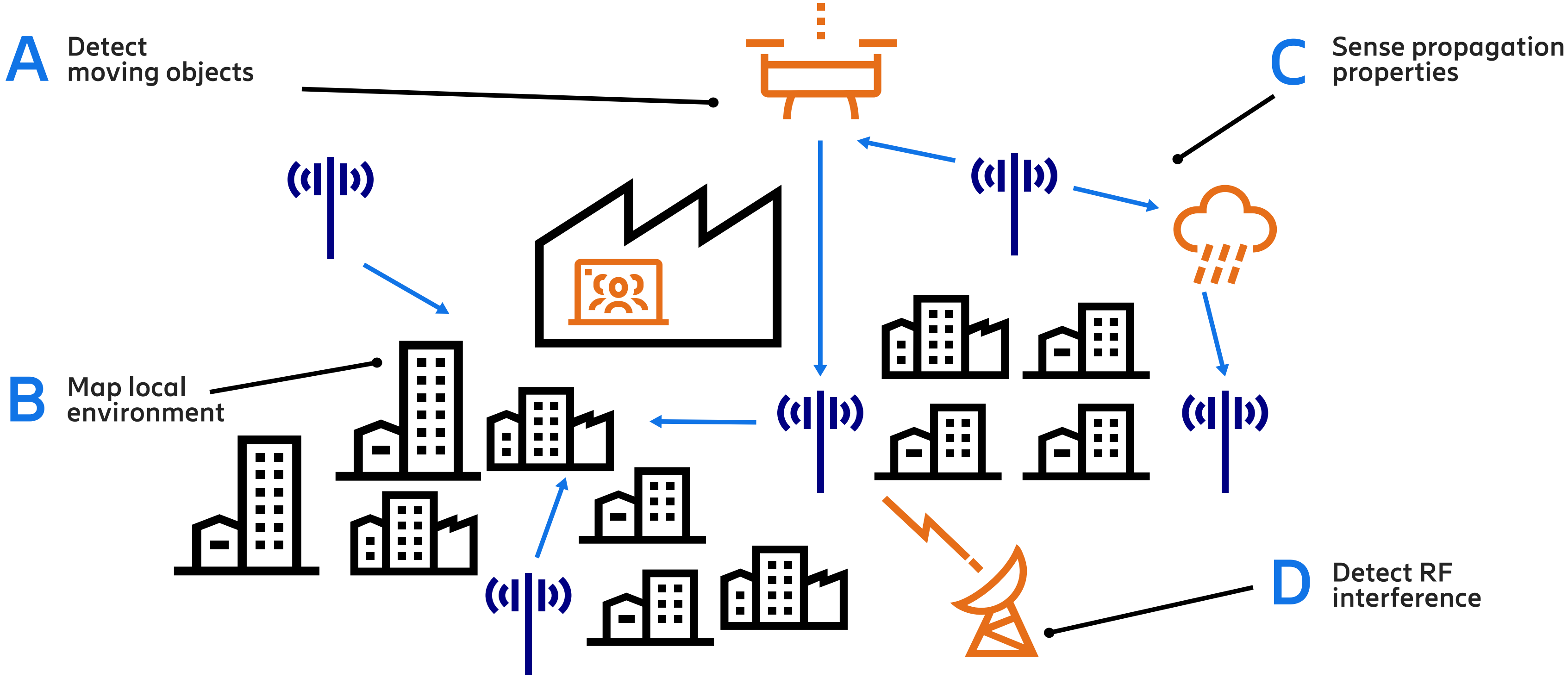
- Extend use cases (not only UAVs)
- UEs participation in sensing
  - Extend ground coverage
- NLOS sensing
  - Sensing through reflections
- Environmental reconstruction
  - 3D scene mapping
- Large-scale deployments
  - Scalable tracking and fusion
- Interference managements
  - Sensing—sensing, MBB—sensing interference.



https://www.ericsson.com/en/reports-and-papers/ericsson-technology-review/articles/sensing-in-6g-use-cases-and-architecture

Open questions to make 6G ISAC a success

- Interference (Inter-site, inter-operator):
  - Intra-sensing interference.
  - Sensing—MBB interference
- Limited line-of-sight coverage
  - How to overcome?
  - Non-line-of-sight sensing
- Full-duplex transceivers
  - Antenna design, self-interference suppression
- Realistic channel and clutter modeling
  - Dynamic clutter, micro-Doppler signature.
- Resource-allocation trade-offs
  - Sensing vs. MBB scheduling in time—frequency—space
- Scalability
  - How to scale to nationwide deployments?

Telephone station ARM in Hong Kong. 1979.