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Hexa-X overview of 6G radio enablers

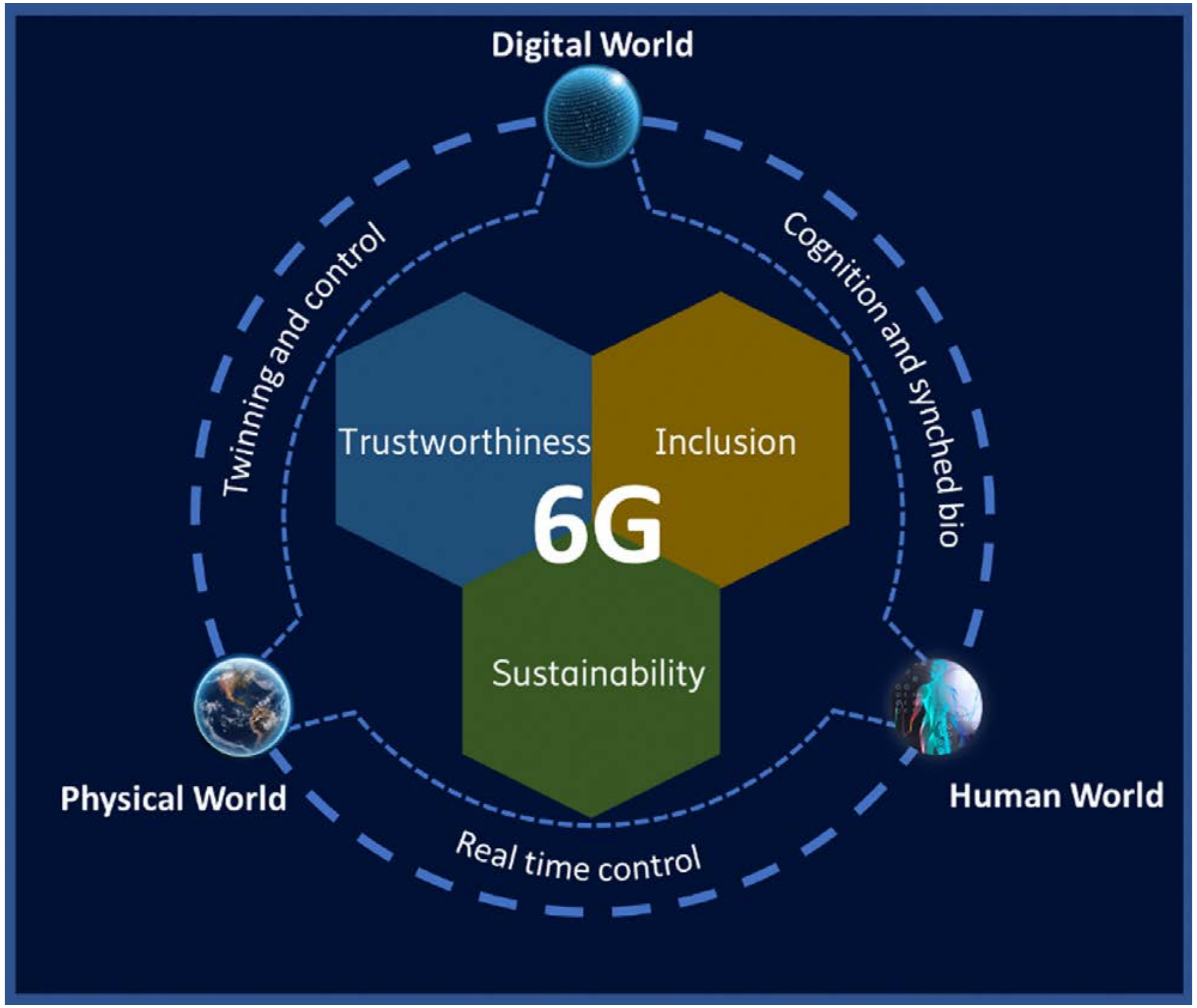
hamed.farhadi@ericsson.com

Hexa-X Technical Manager

hexa-x.eu

Hexa-X vision on 6G

- Connecting the physical, digital and human world
- Key values:
    - Sustainability
    - Inclusion
    - Trustworthiness
- Research challenges:
    - Connecting intelligence
    - Network of networks
    - Sustainability
    - Global service coverage
    - Extreme experience
    - Trustworthiness



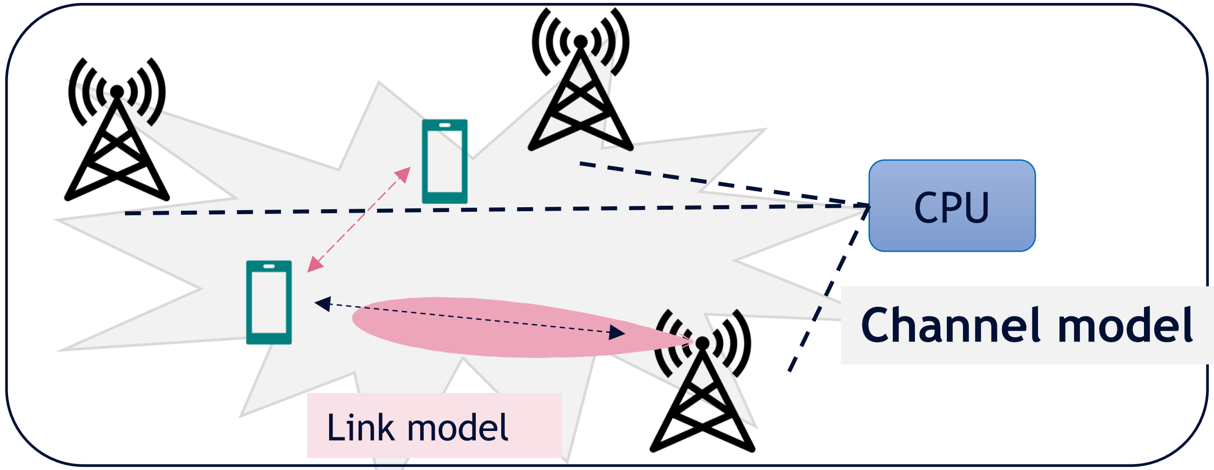
Outline

- Radio models and enablers for extreme performance
- AI-driven air interface design
- Radio enablers for services beoynd communication: localization and sensing

Scope and outline

Scenarios and technical requirements

Sub-THz (100 – 300 GHz) relevant use cases and communication scenarios, technical requirements, radio design methodology, and performance metrics



Channel model

Material parameters for 2-260 GHz, and stored channel model at 140 GHz based on measurement

Radio architecture and models

- RF transceiver architecture
- Hardware models
- D-MIMO architecture

RF transceiver for the frequency range (100 – 300 GHz), description and evaluation of the hardware models, and D-MIMO architectures

Signal processing techniques

- HW-aware waveform
- Beam management
- D-MIMO schemes

Guidelines for waveform and digital transceiver design, guidelines for beam management techniques in sub-THz system, studies of D-MIMO and integrated access and backhaul

Radio link and system performance analysis

Impact of deployment scenarios on the power consumption, insights on the influence of radio channel on link and system performance

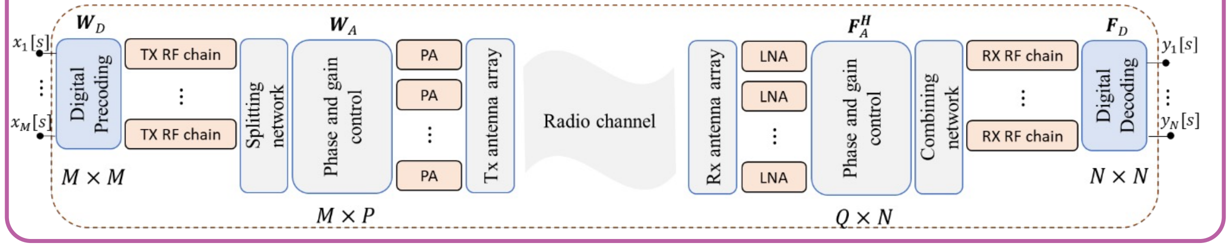
Scenarios, technical requirements, radio design methodology

Scenarios, technical requirements, radio design

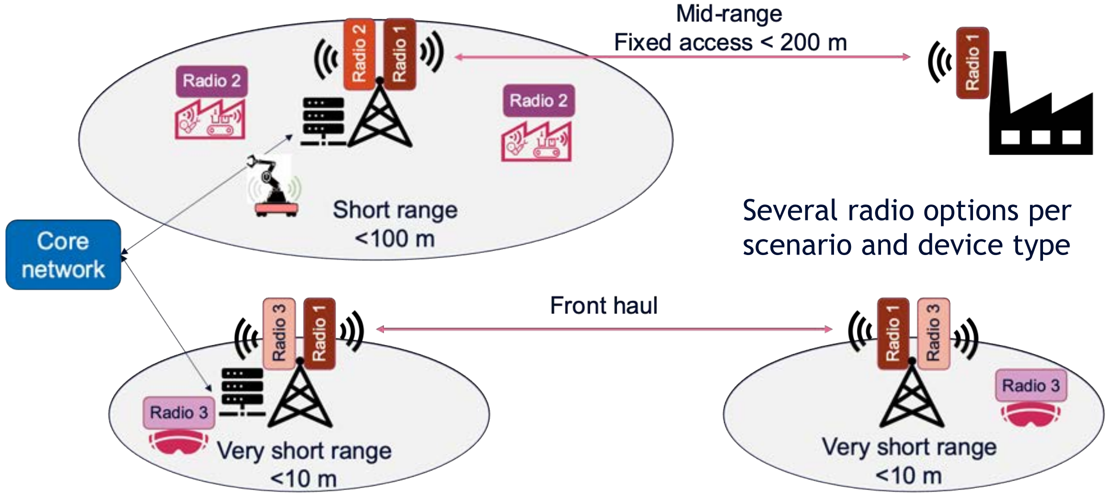
Sub-THz (100-300 GHz) communication scenarios requirements

	Mid-range wireless access	Short-range wireless access	Very short-range wireless access
Example use cases	Digital twins for manufacturing, fixed wireless access, Wireless fronthaul	Digital twins for manufacturing, fully-merged cyber-physical worlds	Fully-merged cyber-physical worlds, holographic communication
Targeted data rate	100 Gbps	10 Gbps	100 Gbps
Typical link range	200 m	10-100 m	10 m
E2E latency	0.1 – 100 ms	0.1 – 100 ms	< 20 ms
Mobility	Stationary (0 m/s)	Mid-speed vehicular (<15 m/s)	Walking speed (<3 m/s)
Radio channel	Outdoor	Indoor/outdoor	Indoor/outdoor
Device classes	AP	AP, mobile device	AP, mobile device
Radio design type	Symmetric	Asymmetric	Asymmetric
Duplex mode	TDD	TDD	TDD
Carrier frequency	140 GHz, 200 GHz, 300 GHz	140 GHz, 200 GHz, 300 GHz	140 GHz, 200 GHz, 300 GHz
Positioning / sensing accuracy	0.1-1 m	0.01 m	<0.01 m
Positioning / sensing latency (depends on mobility)	10 – 100 ms	100 ms	1-100 ms
Delay/distance resolution	0.5 m	0.1 m	0.1 m
Angle resolution	10 degrees	2-10 degrees	2 degrees

Generic radio architecture

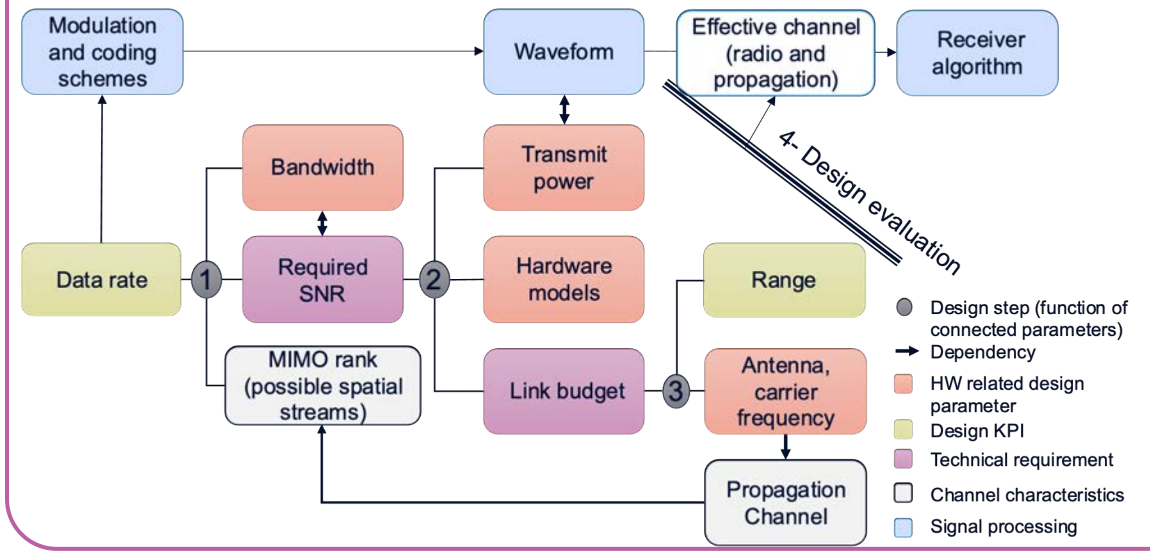


Deployment scenarios of different radio hardware options



Positioning/sensing requirements are needed for joint communication and sensing radio design

Radio design methodology

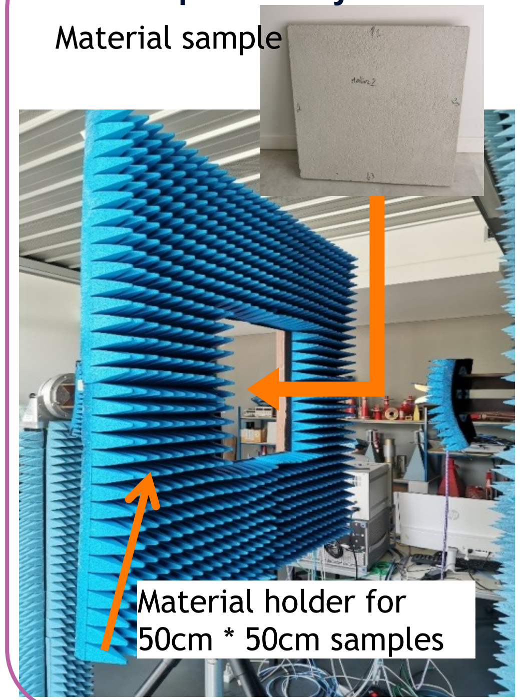


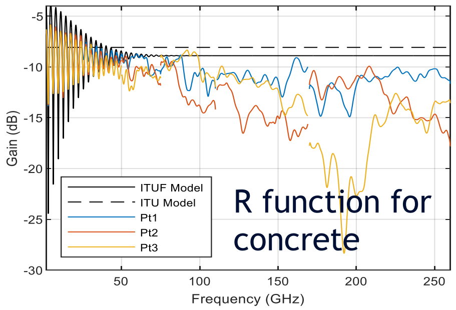
Channel & hardware modeling

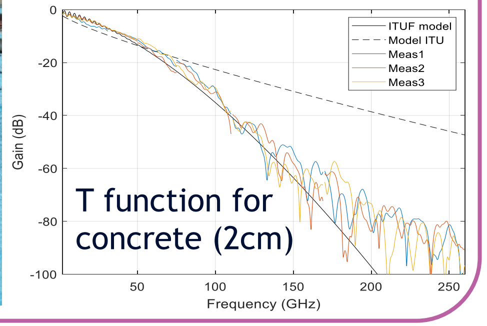
Channel and hardware modelling

Material permittivity & conductivity estimation: 2 to 260 GHz

Material sample

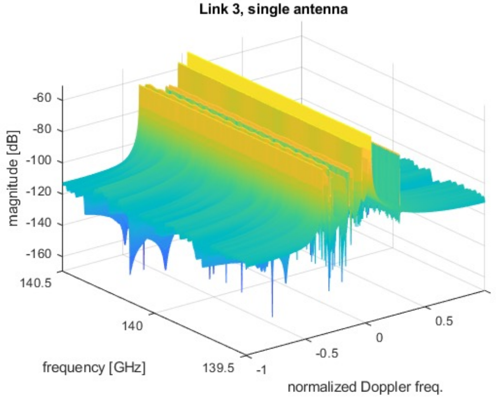






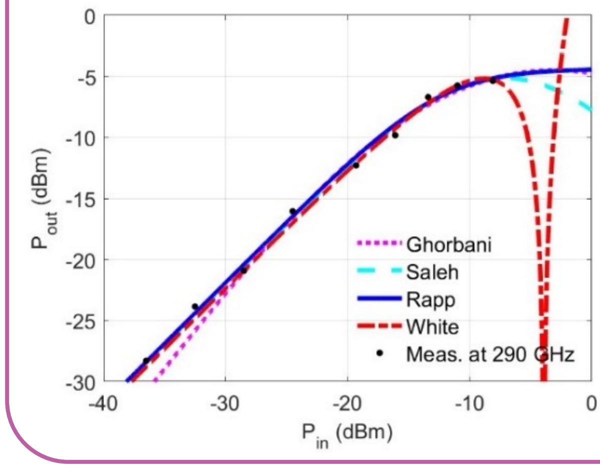
Channel model at 140 GHz

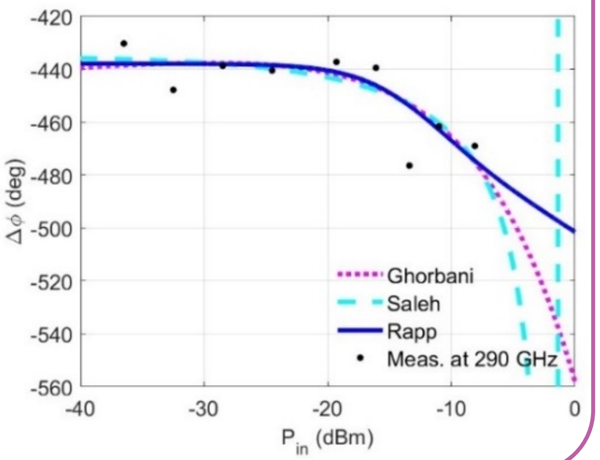
Measurements in four sites



Power amplifiers

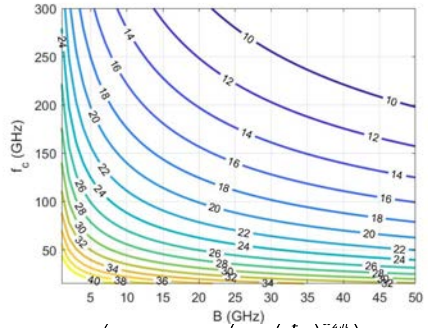
- Technology & centre frequency dependent modelling of saturated power
- Memoryless & memory-dependent nonlinearity
- Parametrized models using measurements at 300 GHz





Phase noise

- Multiplier-based LO architecture
- Frequency scalable model parametrization
- System view on radio link phase noise
- BW / f0 analysis: flat phase noise limits bandwidth

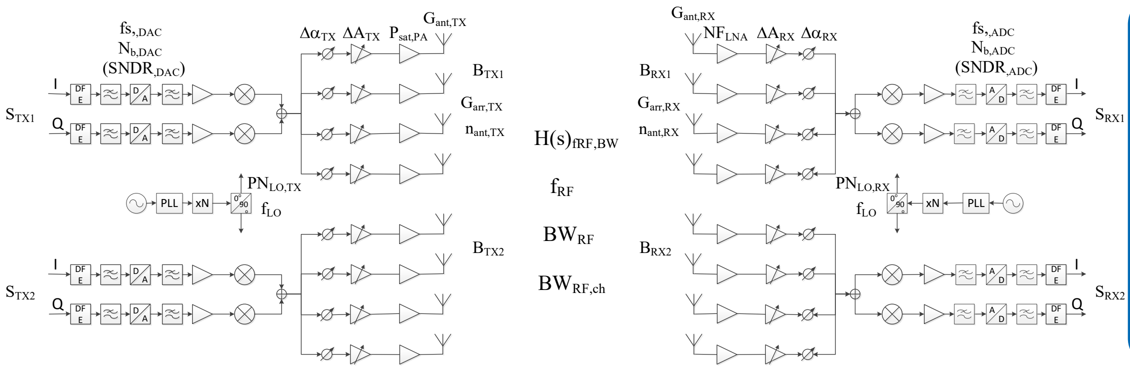


$$S(f_o) = \left(\frac{f_c}{f_{pll}}\right)^2 \left(10^{\frac{N_{ref}}{10}} \frac{\prod_{n=1}^{N}\left(1+\left(\frac{f_o}{f_{z,n}}\right)^{\alpha_{z,n}}\right)}{\prod_{m=1}^{M}\left(1+\left(\frac{f_o}{f_{p,m}}\right)^{\alpha_{p,m}}\right)} + 10^{\frac{N_{th,pll}}{10}}\right)$$

Radio architecture

RF transceiver architecture

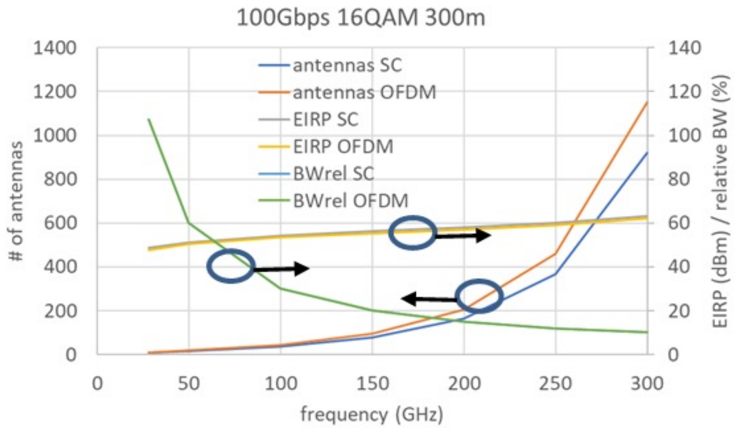
Multi-array RF transceiver architecture



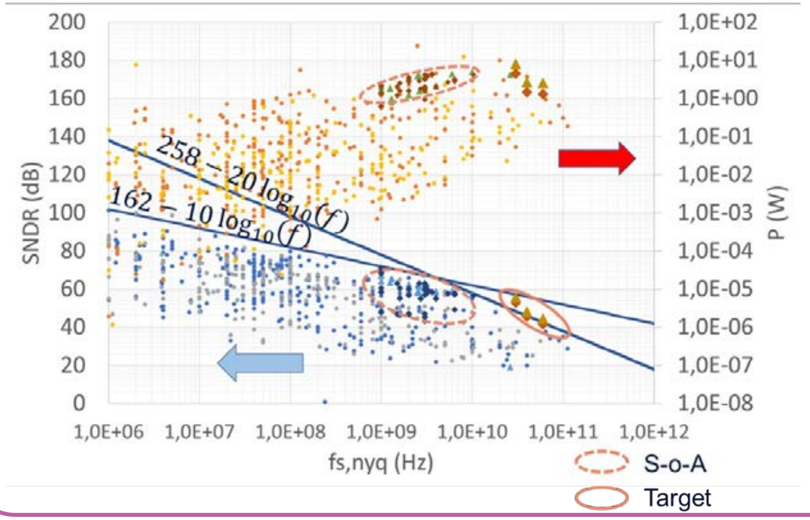
Data-rate
→EVM/SNDR & BW requirements

Link range
→ Beamforming, power, noise
& rest of the RF impairments

Partitioning for RF requirement analysis
→ Module & component requirements



ADC requirement & performance analysis for 100 Gbps



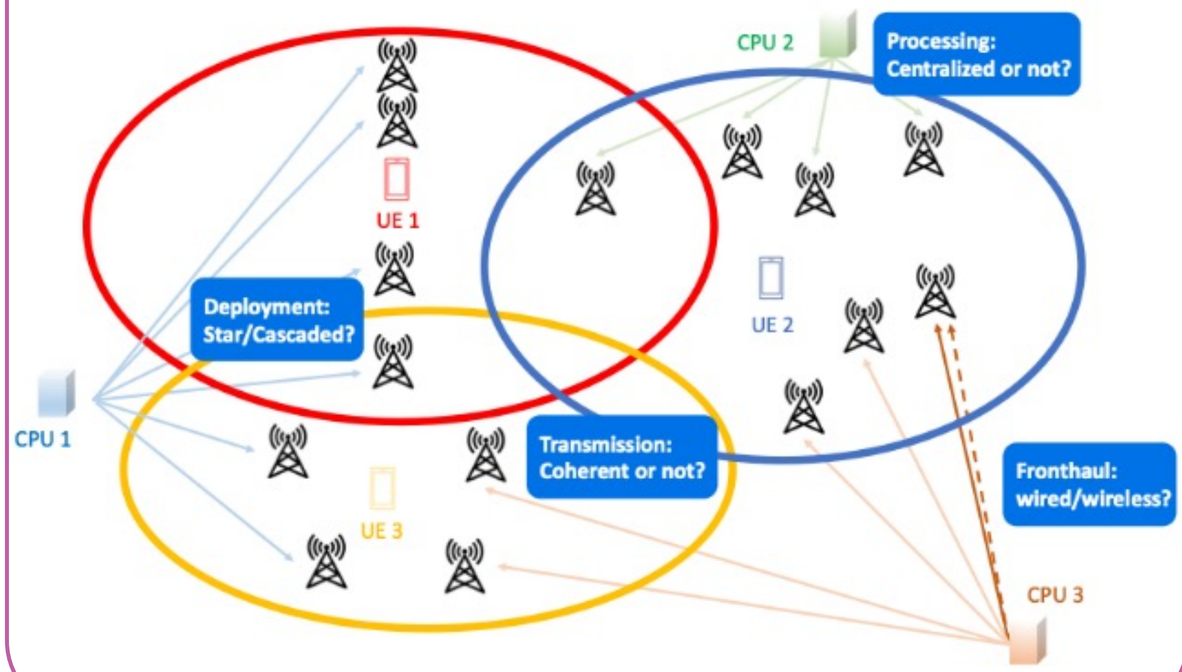
$$f_s = \frac{2}{R_c M} R_u$$

R_u data rate
R_c code rate
M modulation order

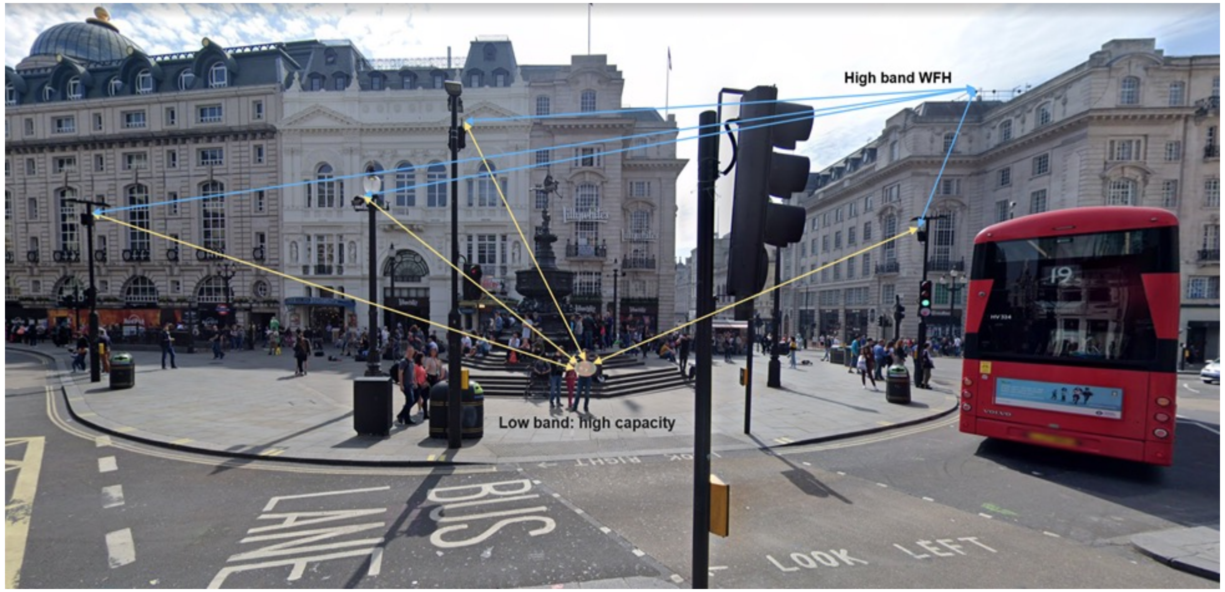
OFDM, R_u = 100 Gbps, R_c = 5/6				
	RF BW factor	BW GHz	fs GHz	SNDR ADC
16-QAM	0.33	33	60	44.6
64-QAM	0.22	22	40	48.4
256-QAM	0.17	16.5	30	55.7

D-MIMO radio architecture

Distributed MIMO with key architectural design options



D-MIMO with wireless **fronthaul operating at high bands** while **access links at low bands.**

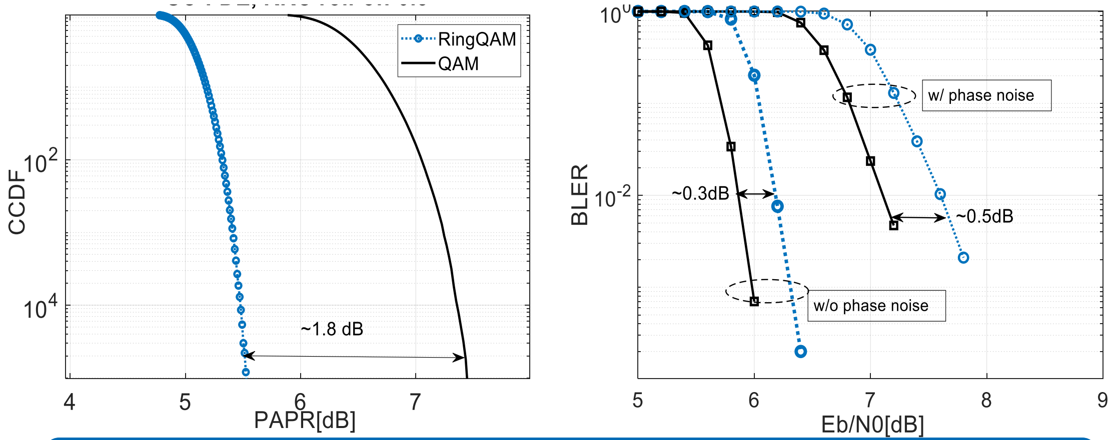


- **At sub-6GHz**, D-MIMO is mainly driven by the need for high-spectral efficiency.
- **At very high frequencies**, it is driven by the need to produce reliable communication links.
- Allowing serving antenna to be closer to a UE provides a more reliable link.

Signal processing techniques

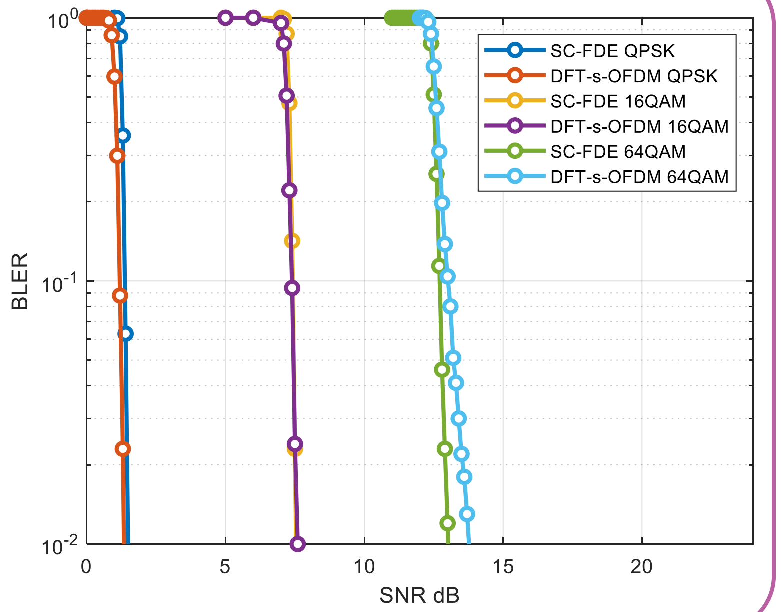
HW-aware waveform and baseband transceiver design

4-bits Modulation

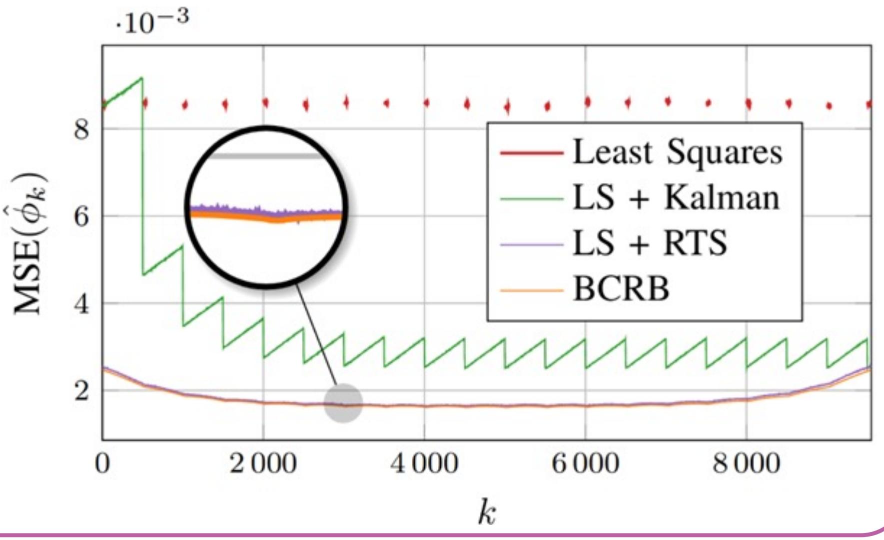


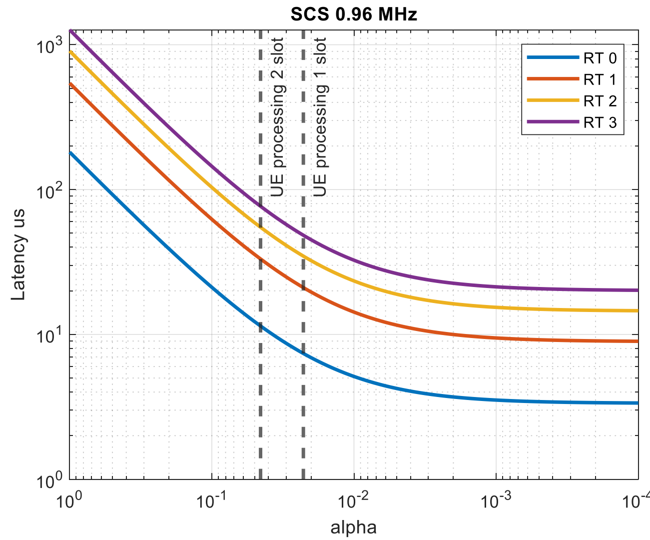
Constellation shaping in SC-FDE improves PAPR

DFTS-OFDM and SC-FDE perform similarly under phase noise and nonlinearity



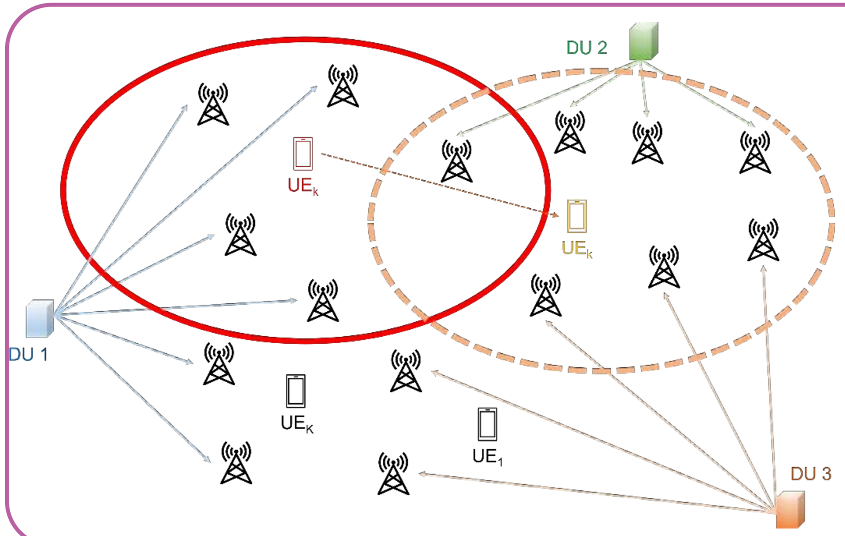
Forward-backward phase noise estimation in 1-bit systems achieves performance bound



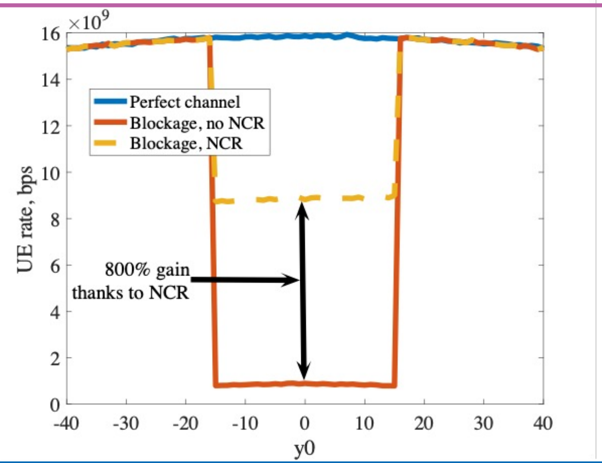


Layer-2 latency limited by baseband processing latency

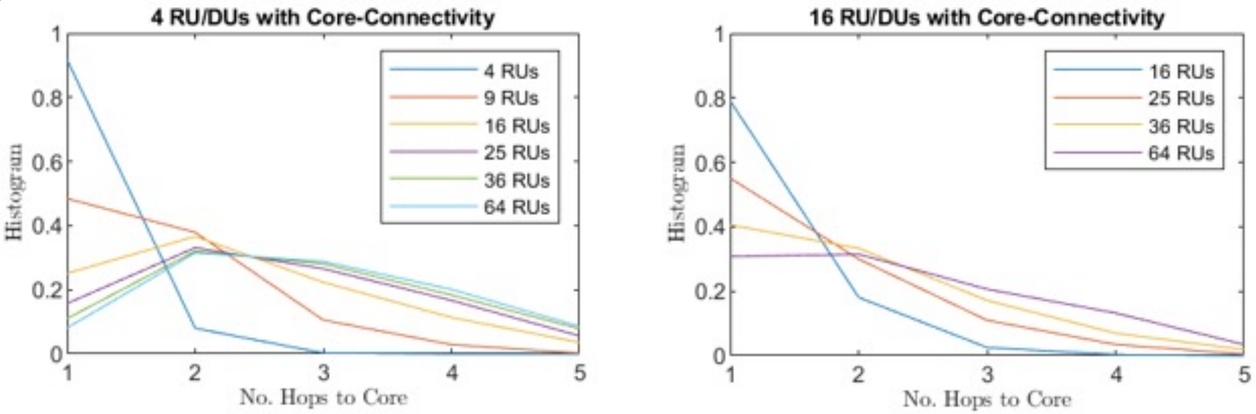
D-MIMO schemes



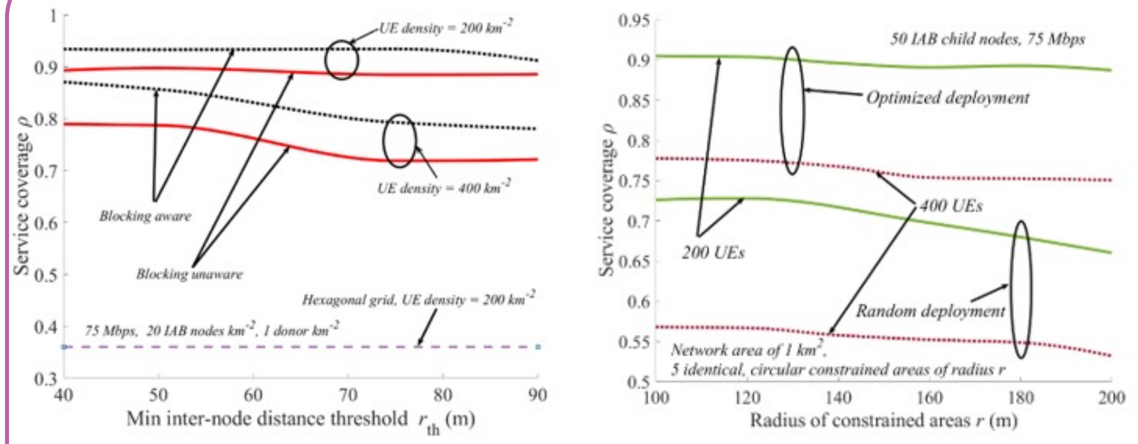
L1 mobility in D-MIMO with spatial repetition transmission



NCR helps the network in the presence of blockage



Distribution of number of hops for different number of core-DU/RUs and RUs. Iterative Dijkstra optimizing for link SINR for calculating routes through the mesh.

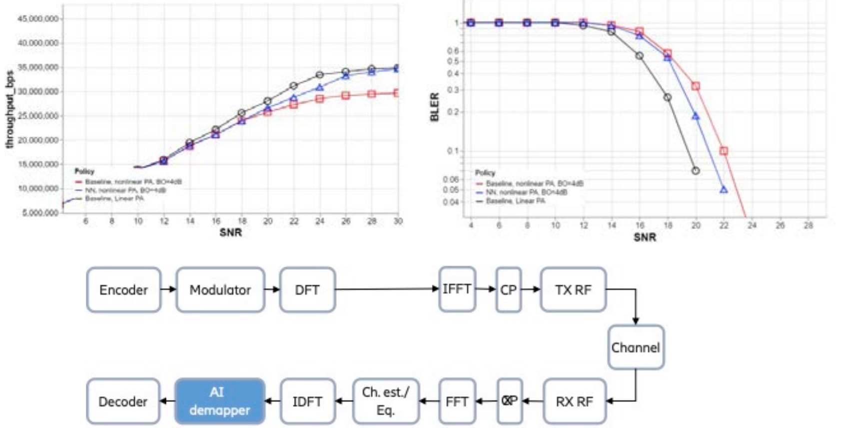


Service coverage with constrained IAB deployment optimization

AI-driven air interface design

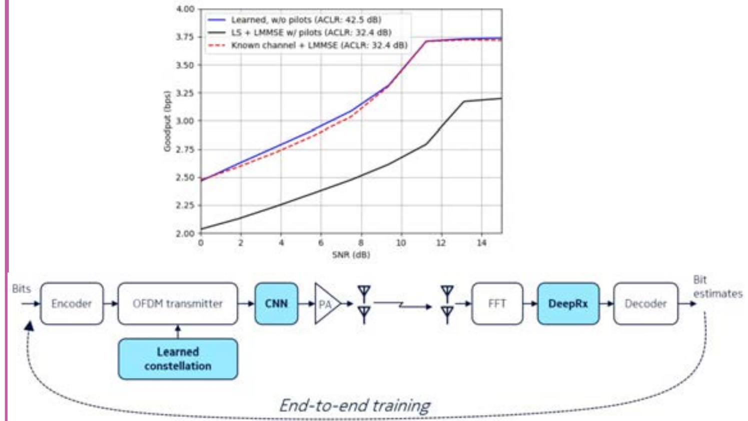
AI-driven air interface design

NN-based Rx demapper to reduce PA non-linearity distortions



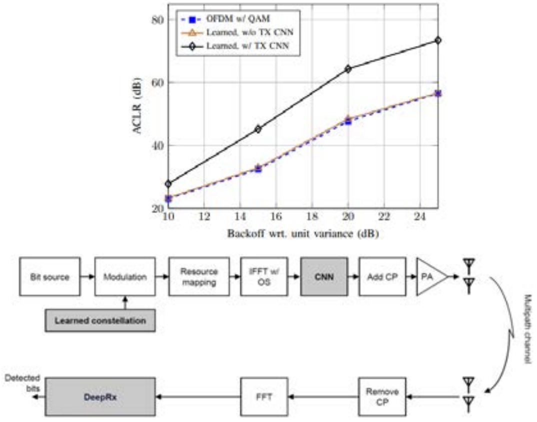
Using AI/ML to reduce BLER and improve throughput

AI-Based Enhancements for Sub-THz



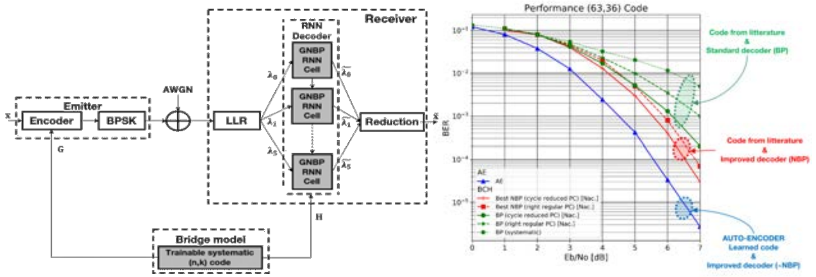
Reduce overhead with pilotless transmission
Learn a waveform and a receiver jointly

Reduced out-of-band emission with NN



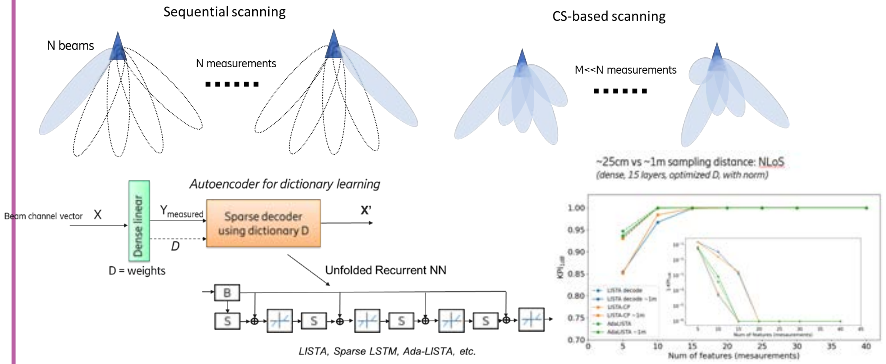
Train a lightweight Tx-side CNN jointly with an ML-based receiver to minimize OOB emissions

ML-aided channel (de)coding for constrained devices



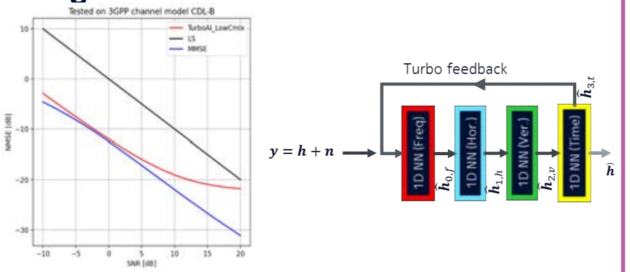
Improve the efficiency of Forward Error Correction (FEC) mechanisms for short packets in IoT use-cases

AI-based beam selection for D-MIMO



Reduce beam scanning overhead with *simultaneous beam testing*
AI/ML can provide ***joint dictionary and decoder design***

Low complexity channel estimation using NNs



To save computation complexity use **Turbo AI architecture** for different domains of the channel, i.e., Spatial, Frequency, time, separately.

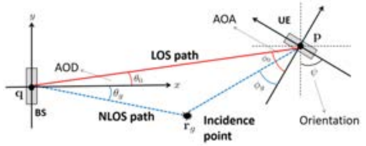
Joint communication and sensing

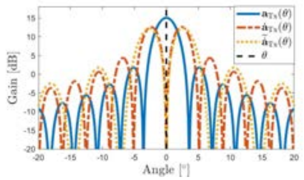
Methods, signals, and protocols for localisation and mapping

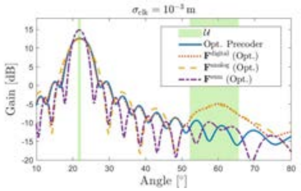
Methods, signals, and protocols for localisation and mapping

Signal design for localization & sensing

Spatial signal optimization for sensing
Best combination of LoS and NLoS beam



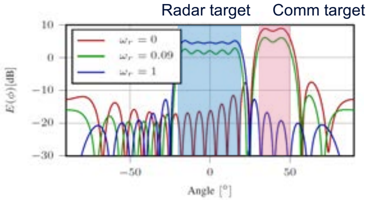


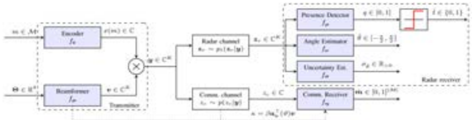


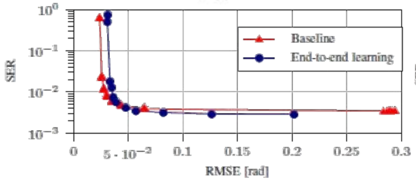
Improve accuracy by pre-coding with a-priori knowledge of direction

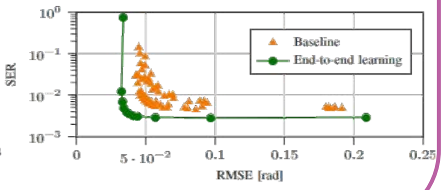
Joint communication and sensing
ML-based method to optimize beam pattern

Without HW impairments **With HW impairments**



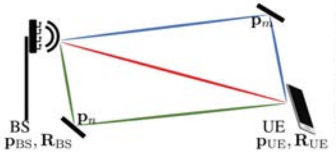


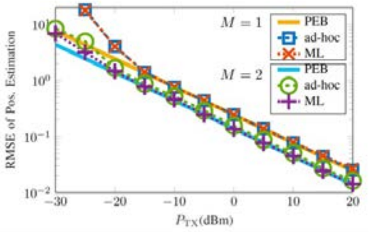




Localization methods

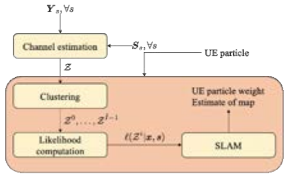
6D localization and synchronization

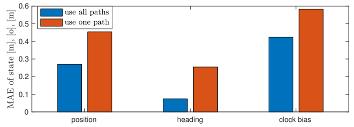




Single snap-shot of DL MIMO-OFDM to determine 6D orientation

Simultaneous localization and mapping

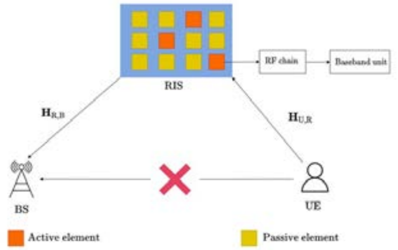


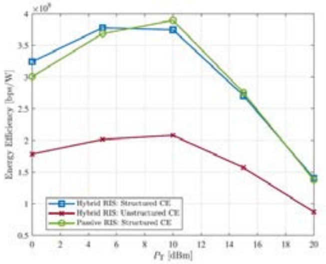


Estimate the UE location and orientation
Synchronize with the BS
Provide a radar-like map of the environment

Channel estimation

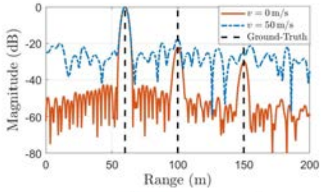
RIS-assisted CSI acquisition

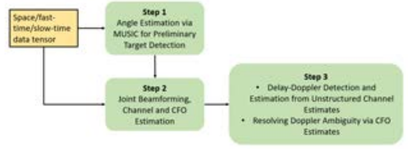


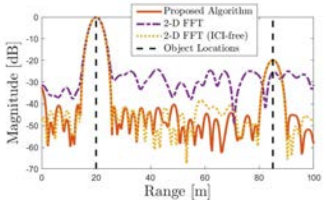


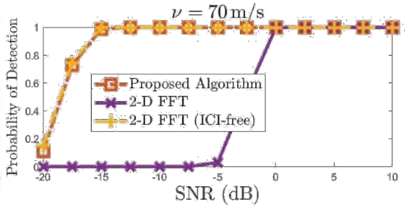
Energy efficiency performance with structured or unstructured channel estimation

Inter-carrier interference (ICI) mitigation for sensing of moving targets





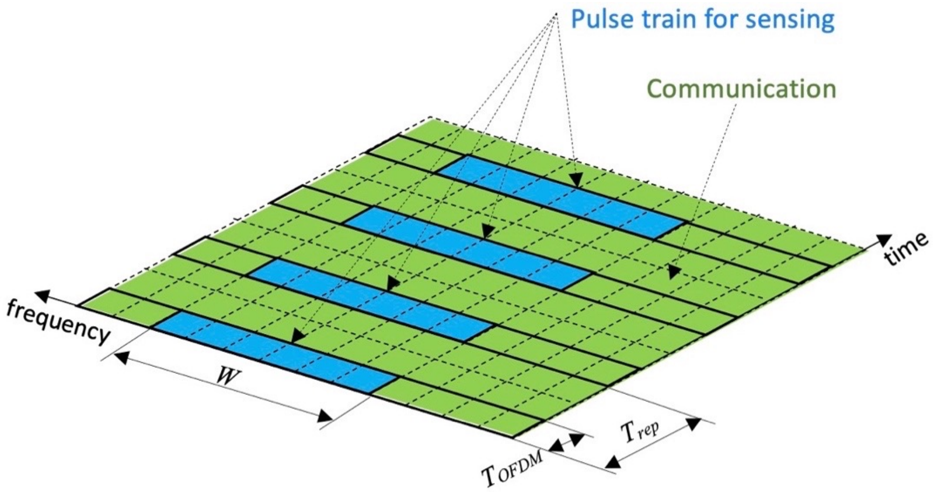


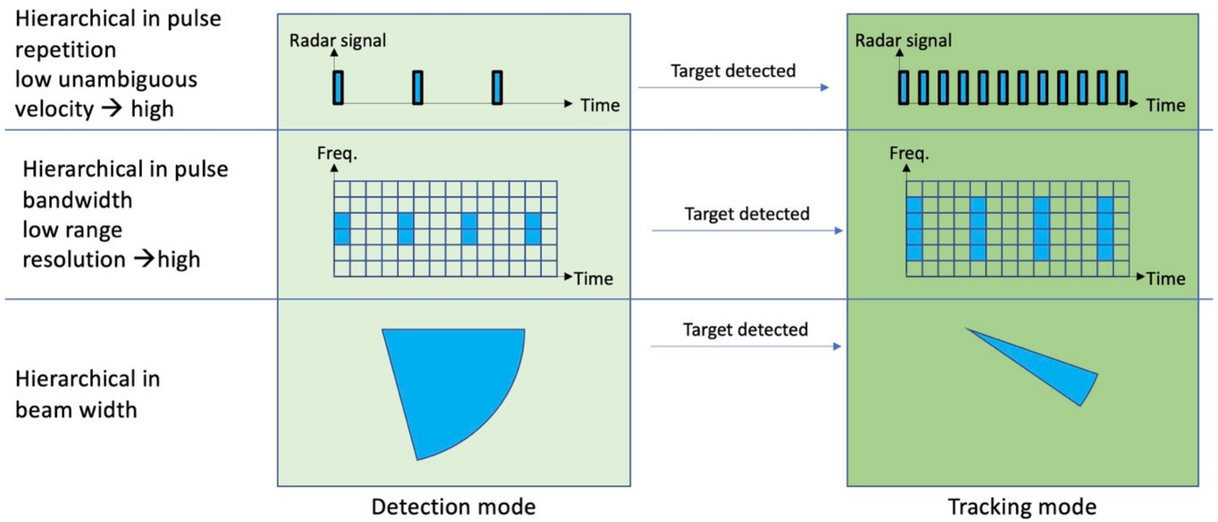


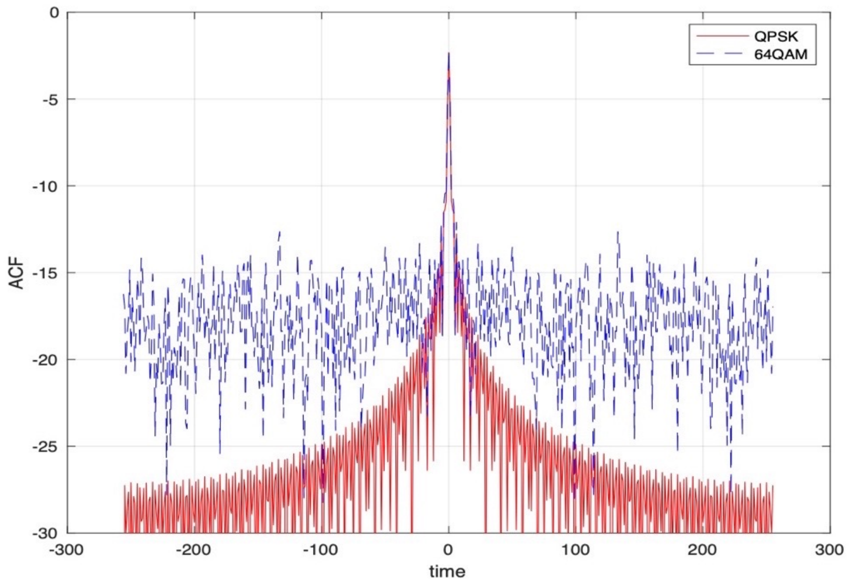
Localisation and sensing in the 6G ecosystem

Allocation of space, time, frequency resources

- Time-frequency perspective
  - Focus on OFDM-like waveforms
  - Dedicated pilots vs use of modulated data
  - Constant-modulus constellations preferred
- Space perspective





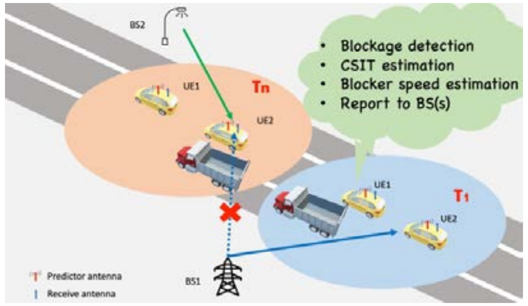


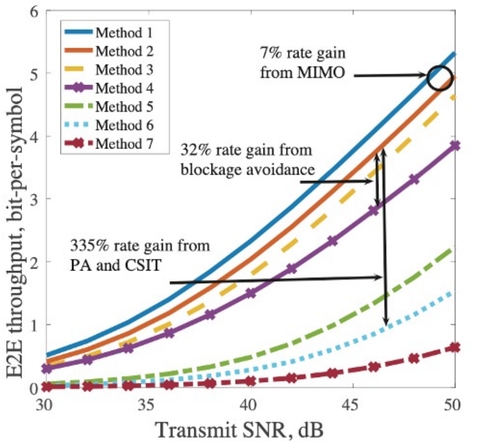
Ambiguity function for different modulation formats

Enhanced communication services with location and sensing information

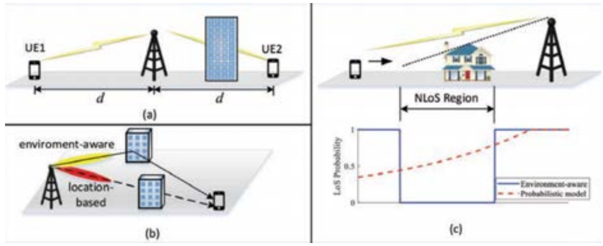
Enhanced communication services with location and sensing information

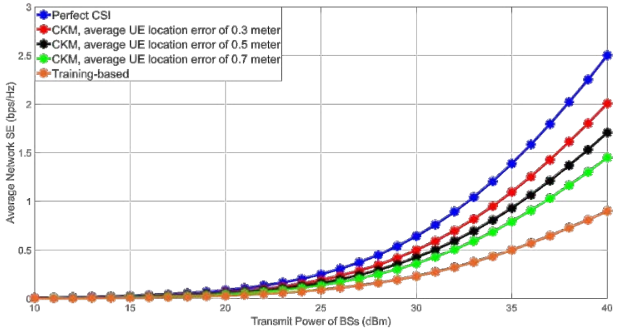
Dynamic blockage avoidance with context awareness





Environment-aware communication





Spectral efficiency with channel training or known UE location

Thank you!

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