Hexa-X | WP2 | D2.3

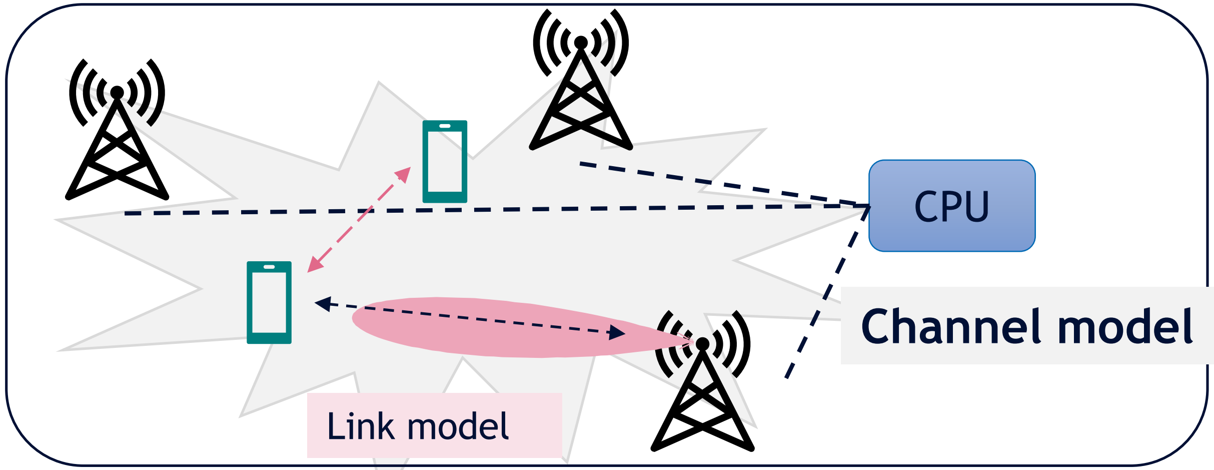
Radio models and enabling techniques towards ultra-high data rate links and capacity in 6G

31.03.2023

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



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

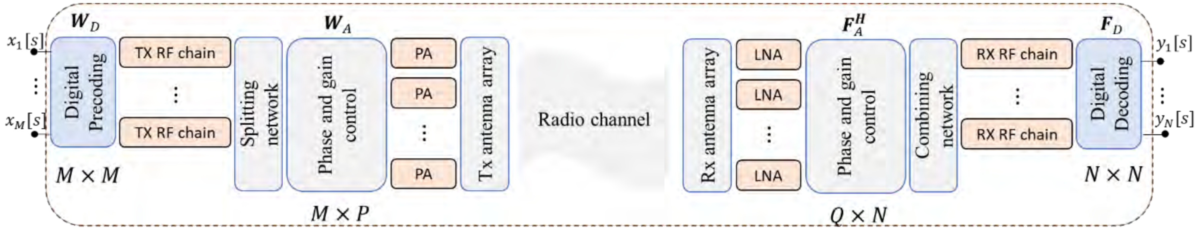
Impact of deployment scenarios on the power consumption, insights on the influence of radio channel on link and system performance

Scenarios and technical requirements

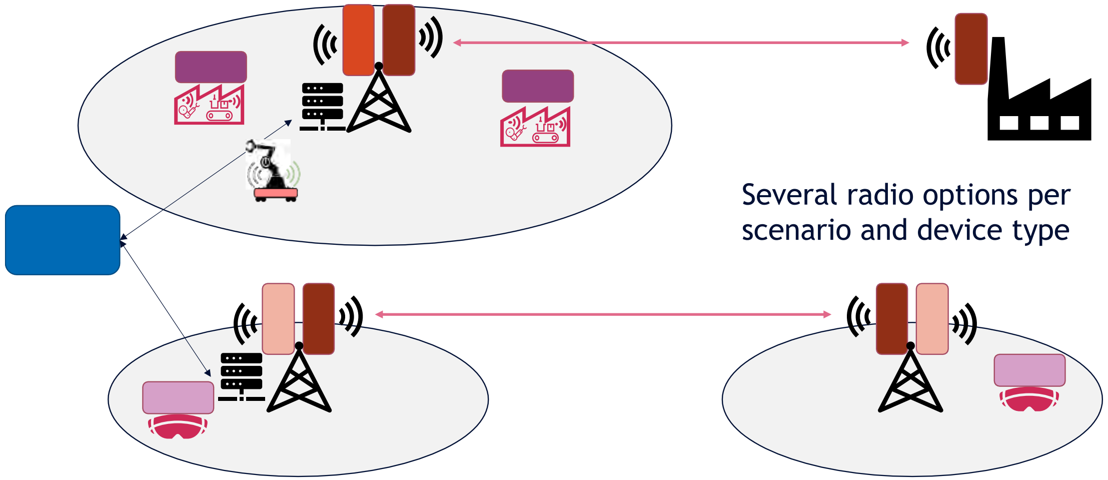
Sub-THz (100-300 GHz) communication scenarios requirements

	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 (Radio design aims at defining concrete parameters)



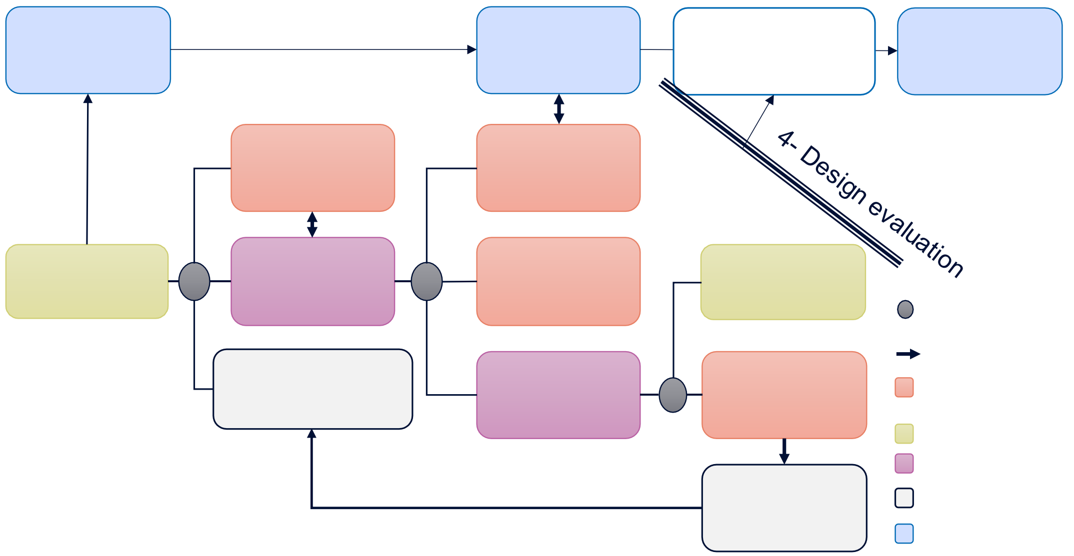
Deployment scenarios of different radio hardware options



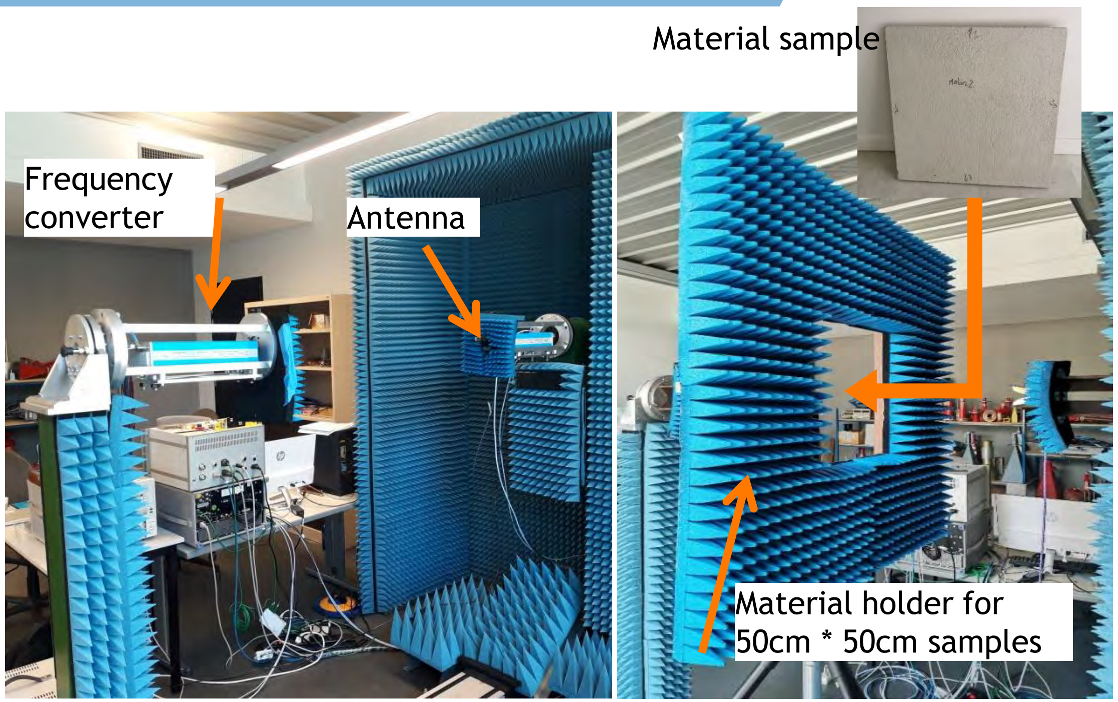
Several radio options per scenario and device type

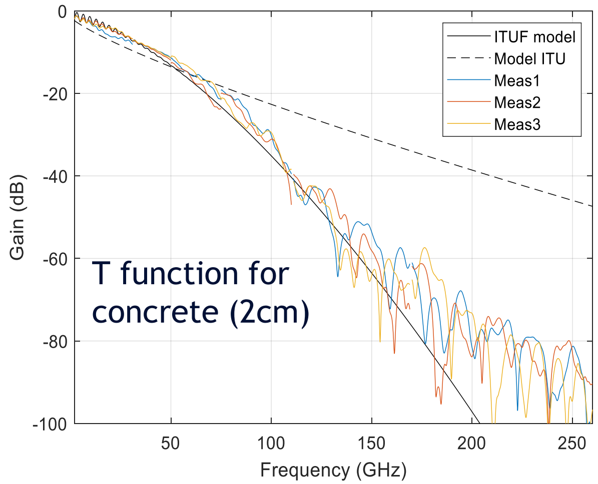
Radio design methodology

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

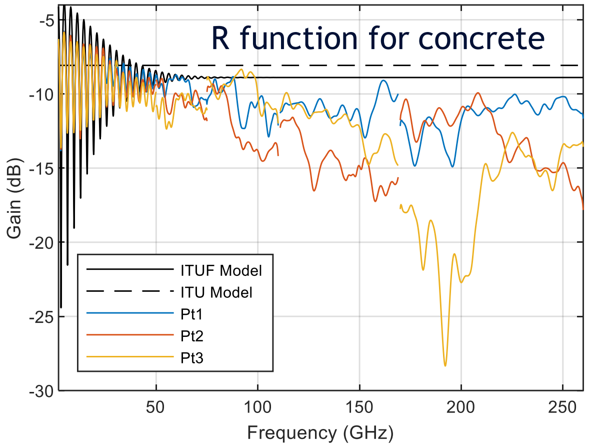


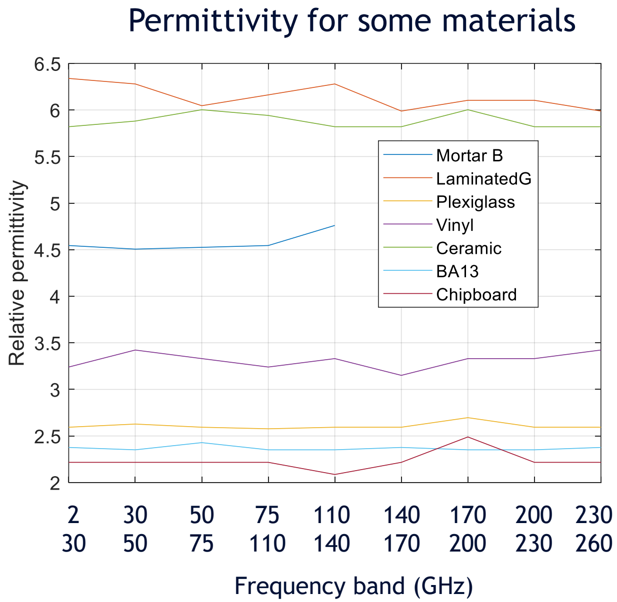
Channel model: Material permittivity and conductivity estimation from 2 to 260 GHz





ITUF= ITU model fitted by measurement





- **Context:** ITU-R P2040 model defines for frequencies up to 100 GHz constant permittivity ε_r and frequency-dependent conductivity σ with $\sigma = cf^d$
- **Objectives:** Validation of ITU model above 100 GHz and model parameter estimation (ε_r, c and d) for various materials
- **Measurement:** VNA-based measurement on 9 frequency bands (2-30 GHz, 30-50 GHz, 50-75 GHz, 75-110 GHz, 110-140 GHz, 140-170 GHz, 170-200 GHz, 200-230 GHz, 230-260 GHz) and various building materials (concrete, glass, wood, etc.)
- **Processing:** Reflection (R) and transmission (T) functions processing based on raw measurement time-gating and normalization by free space measurement. Permittivity and conductivity estimated from R and T functions.

Conclusions

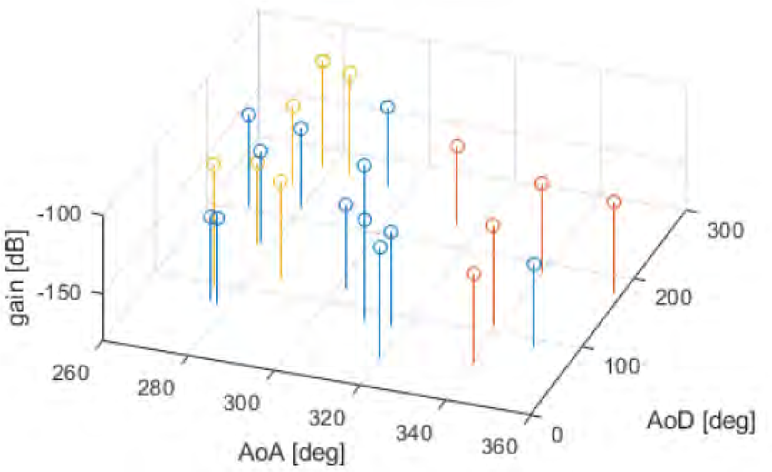
- The permittivity is independent of the frequency even at frequency above 100 GHz, and the measurements agree with ITU values for available materials
- Differences between model and measurement are observed for T and R functions due to internal or surface scattering. The ITU model should be improved by integrating an option considering rough surfaces
- The ITU conductivity parameters for some materials such as concrete or plasterboard need to be improved for a better accuracy at frequencies above 100 GHz

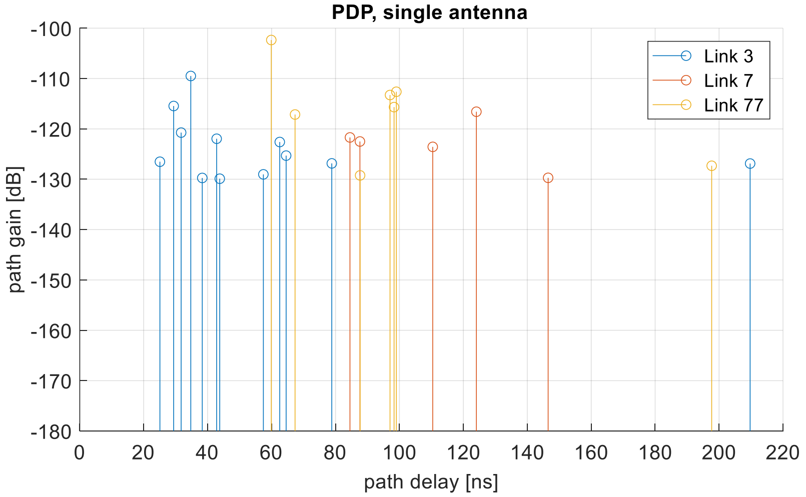
Channel model: Stored channel model at 140 GHz

1. The channel model is based on measurements in four sites

	Entrance Hall	Suburban	Residential	City Centre
Number of LOS Links	5	5	5	5
Number of NLOS Links	12	32	13	19
Link Distance Range (m)	3-66	2-172	20-175	10-178

2. Double-directional multipath data are available for the four sites



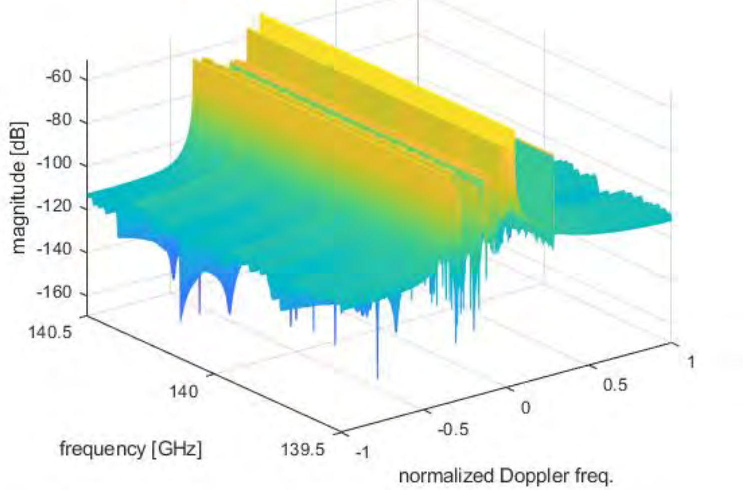


3. Time-varying MIMO channels are reproduced based on the multipath data

$$\mathbf{H}_q(t,f) = \sum_{l=1}^{L_q} \mathbf{g}_{\mathrm{rx}}\left(\Omega_{q,l}^{\mathrm{rx}}\right) \sqrt{P_{q,l}}\, e^{j(\varphi_{q,l}+2\pi\nu_{q,l}t)}\, e^{-j2\pi f\tau_{q,l}}\, \mathbf{g}_{\mathrm{tx}}\left(\Omega_{q,l}^{\mathrm{tx}}\right)^T \in \mathbb{C}^{M\times N}$$

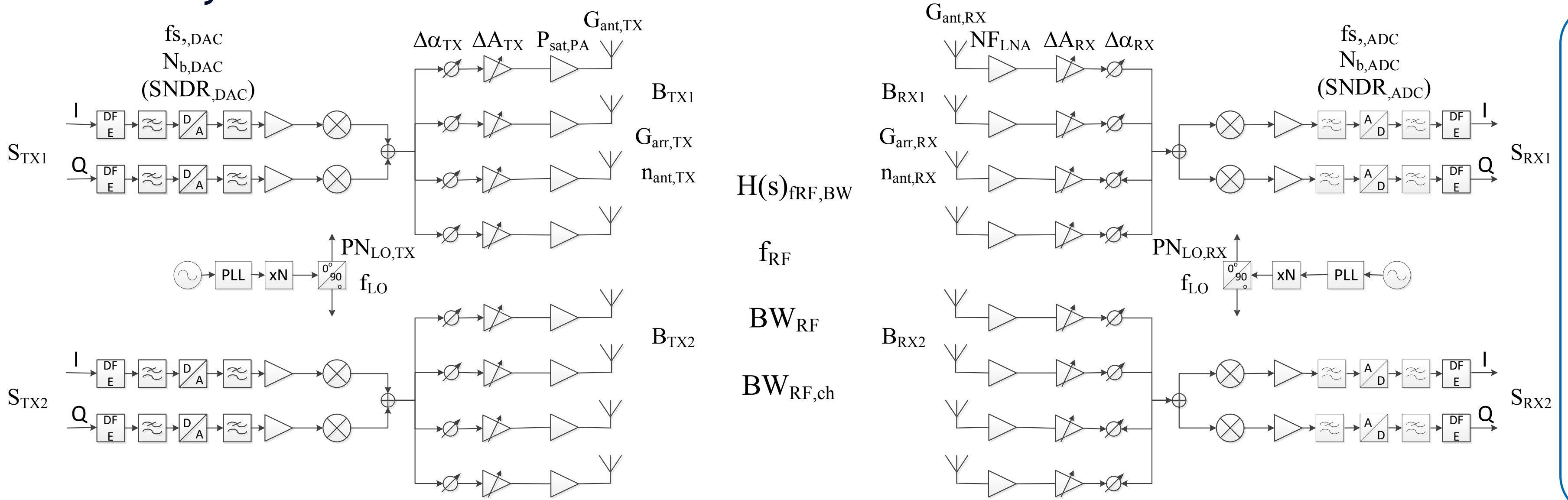
Channel model codes are available at https://doi.org/10.5281/zenodo.7640352

4. Exemplary plot of reproduced channel



Radio architecture and models: RF transceiver architecture

Multi-array RF transceiver architecture

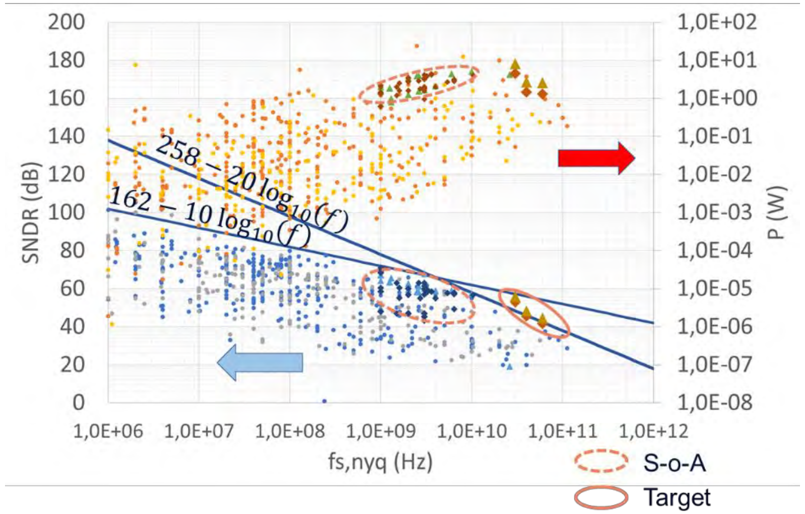


Data-rate
→EVM/SNDR & BW requirements

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

Partitioning for RF requirement analysis
→ Module & component requirements

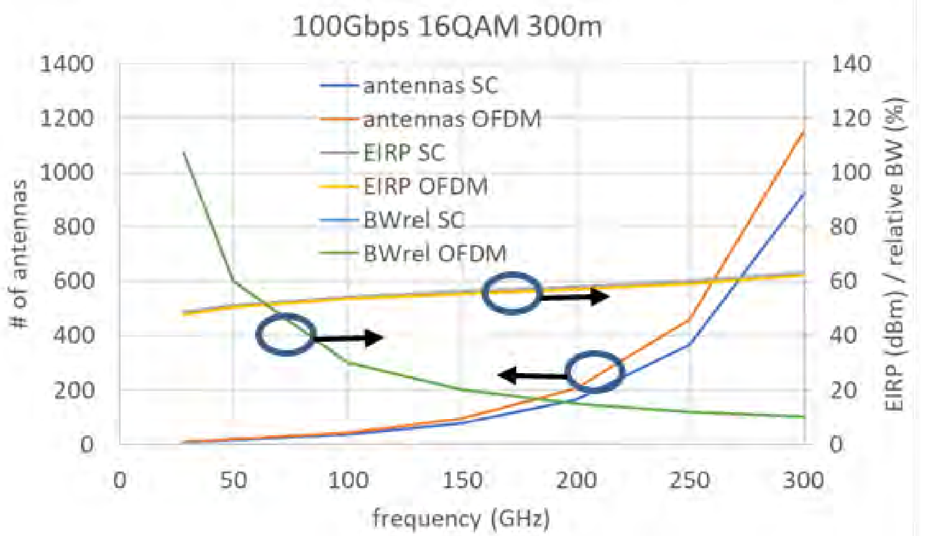
ADC requirement & performance analysis for 100 Gbps



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

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



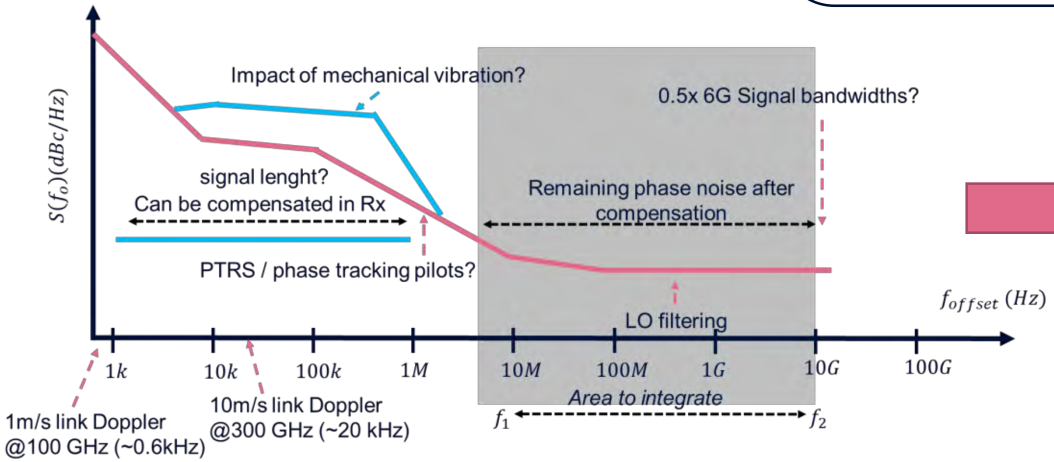
Radio architecture and models: hardware models

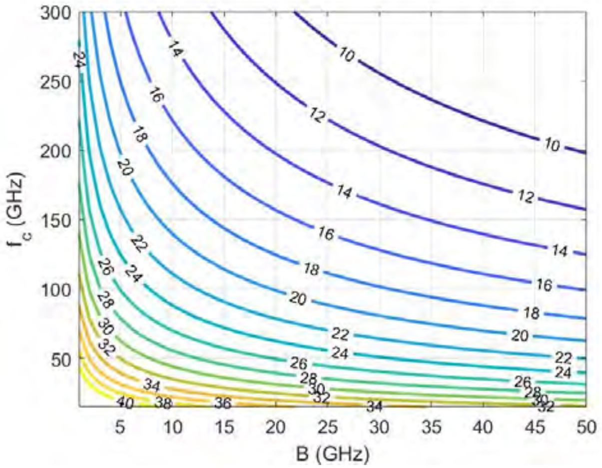
Phase noise

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

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

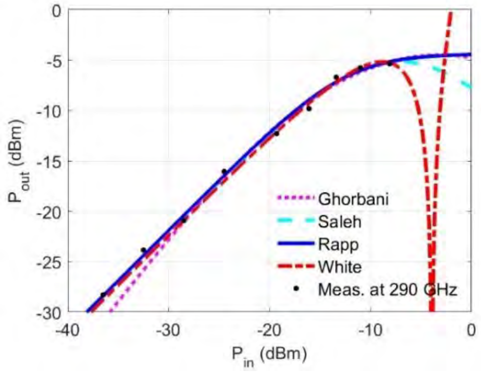
f_{vco}	15 GHz			
N_{ref}	−62 dB			
$N_{th,pll}$	−149.8 dB			
n, m	$f_{z,n}$	$\alpha_{z,n}$	$f_{p,m}$	$\alpha_{p,m}$
1	25 k	1.3	1	1.1
2	N/A	N/A	650 k	3

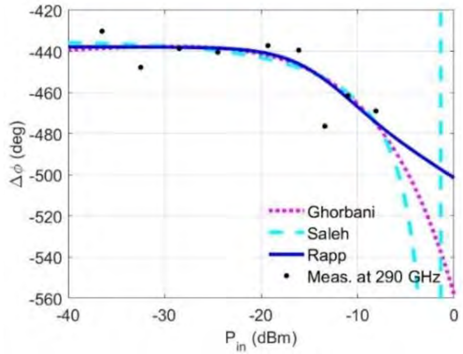




Power amplifiers

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





Radio architecture and models: D-MIMO radio architecture

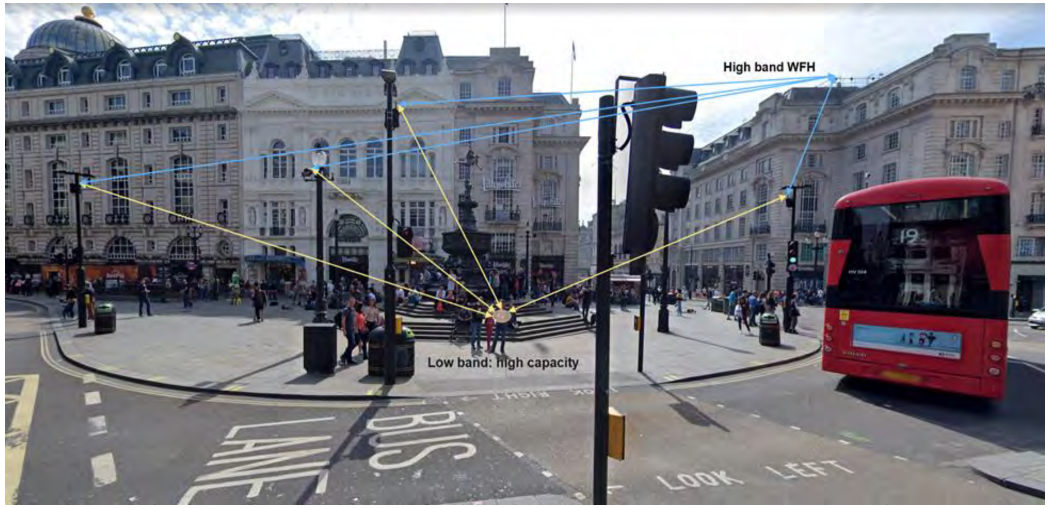
Architectural options for D-MIMO

Technology sub-components			
Fronthaul	Transmission	Processing	Deployment
Wireless / Wired	Coherent / Non-coherent	Centralized / Distributed	Star / Cascaded
Optical / Electrical	Narrowband / Wideband	Analog / Digital	
Analog / Digital			

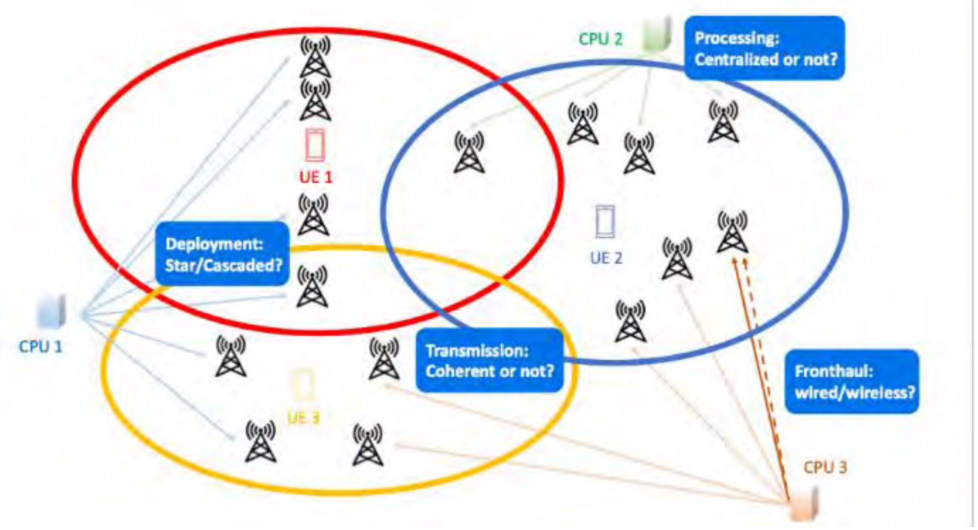
1. Transport media: The backhaul/fronthaul can either be wired or wireless.
2. Signalling: Digitally encoded or analogue signal modulated onto a carrier.
3. Processing: Can either be performed analogue/digital or centralized/distributed.
4. Transmission: Coherent or non-coherent

- 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.
- Allows serving antenna to be closer to a UE providing a more reliable link.

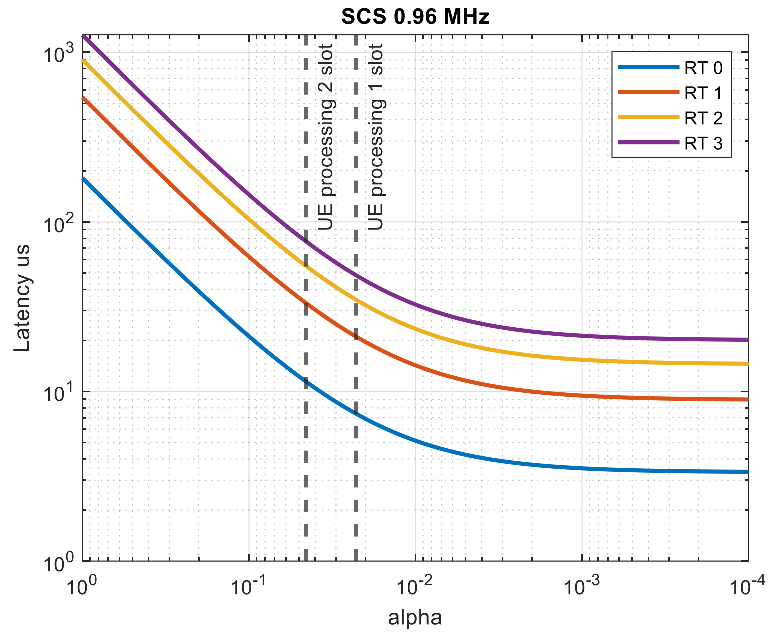
D-MIMO with wireless fronthaul operating at high bands while access links at low bands.



Distributed MIMO with key design options

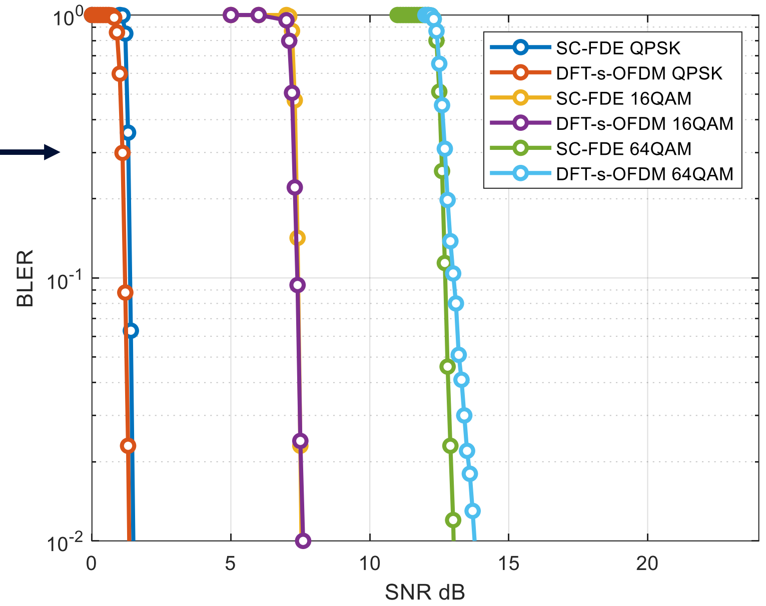


Signal processing techniques: HW-aware waveform and baseband transceiver design



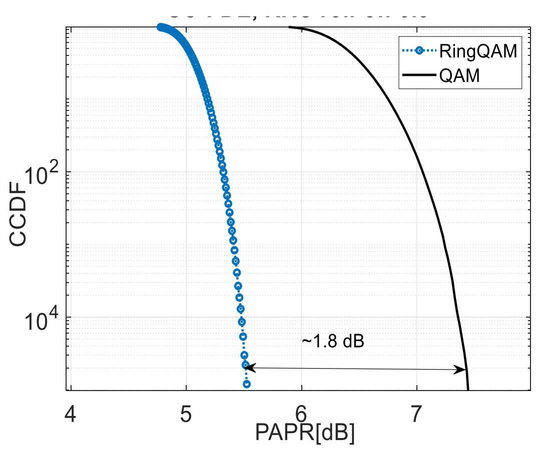
Layer-2 latency limited by baseband processing latency

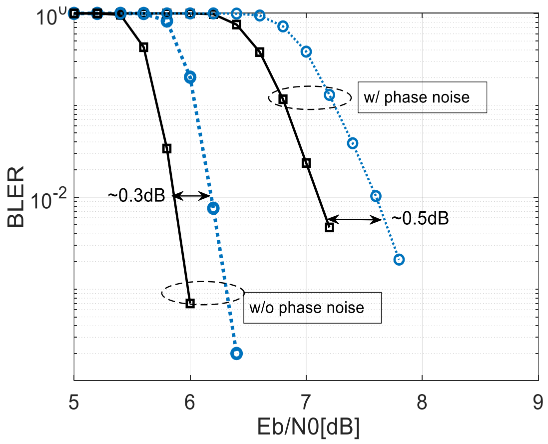
DFTS-OFDM and SC-FDE perform similarly under phase noise and nonlinearity



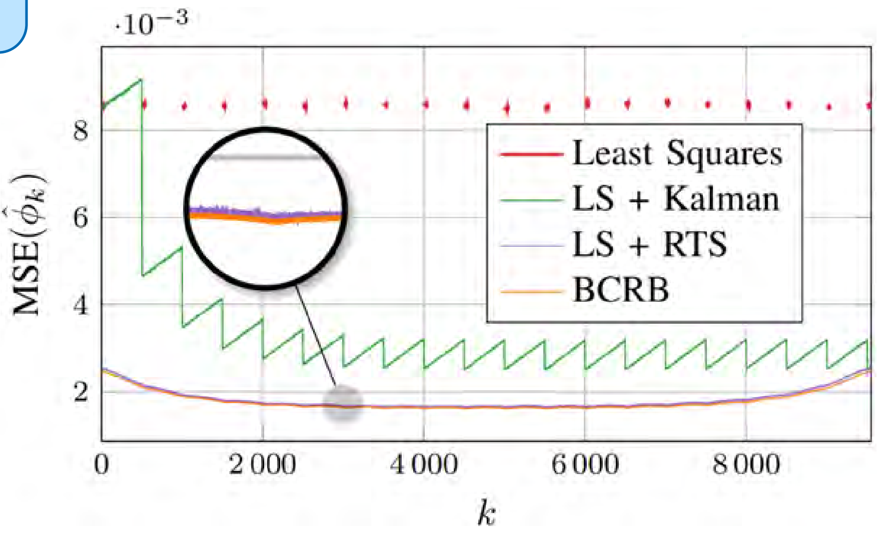
Constellation shaping in SC-FDE improves PAPR

4-bits Modulation

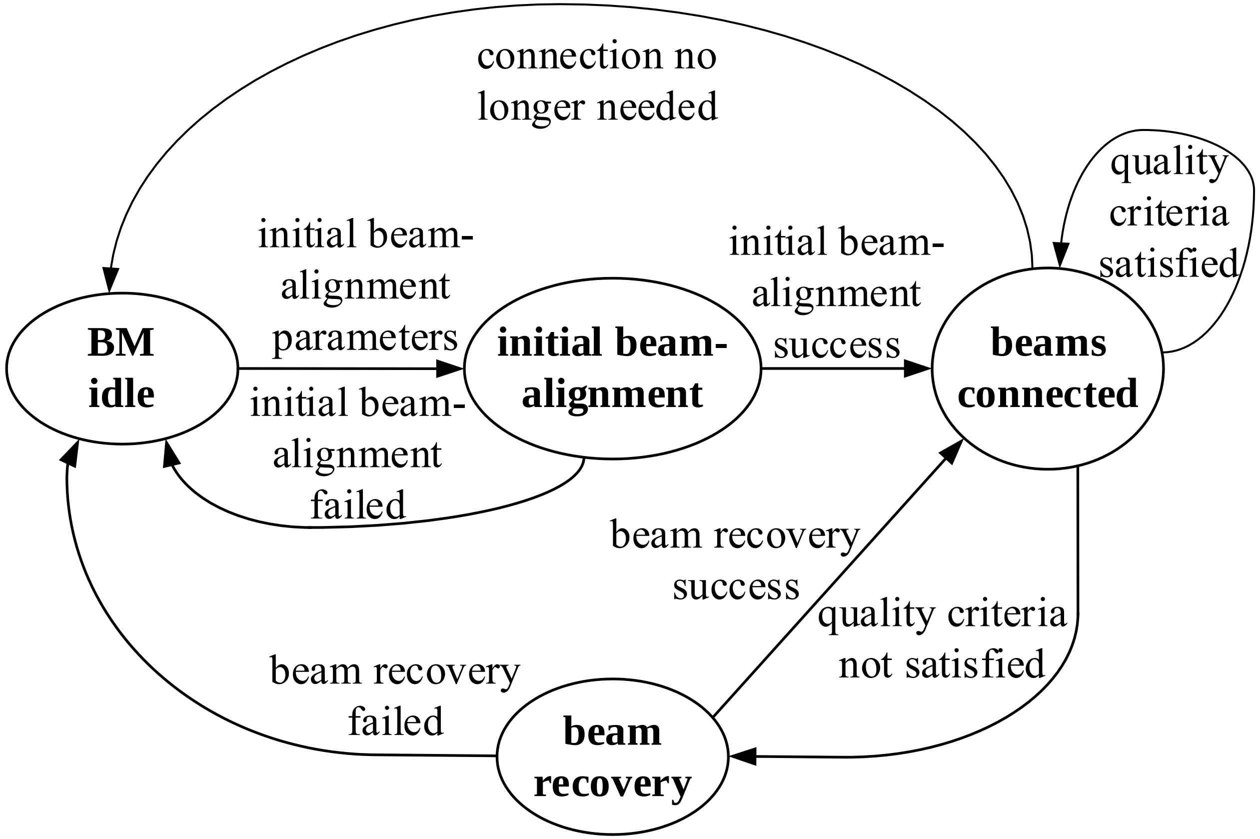




Forward-backward phase noise estimation in 1-bit systems achieves performance bound



Signal processing techniques: Beam management techniques

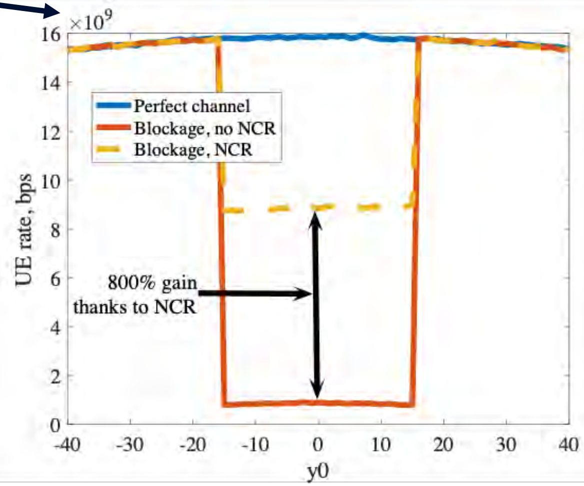


- This finite state machine represents all procedures involved in the establishment and maintenance of beams for communication

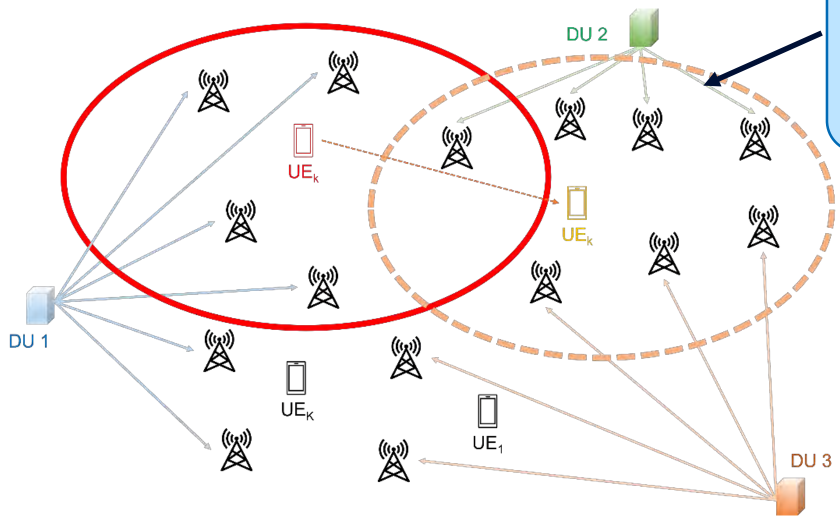
- Scaling current 5G solutions is not possible as the number of beams that need to be tested is too larger. Scaling the current approach to the frequency range of 100 to 300 GHz does lead to initial beam alignment requiring more than 4.5 s
- Side information like positioning information, stored beam alignment results, or channel observations at another frequency need to be utilized to reduce the number of beams to be tested

Signal processing techniques: D-MIMO schemes

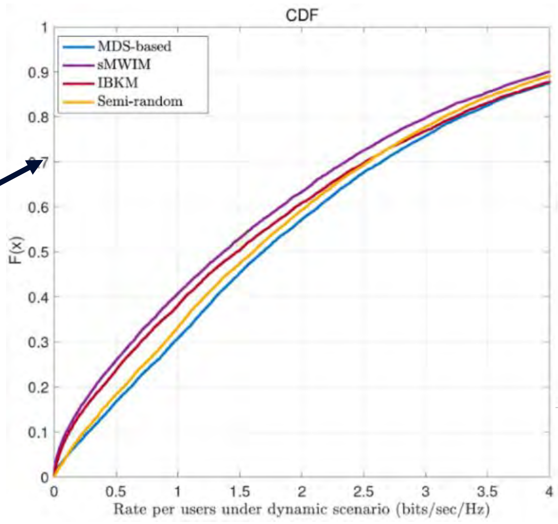
NCR helps the network in the presence of blockage



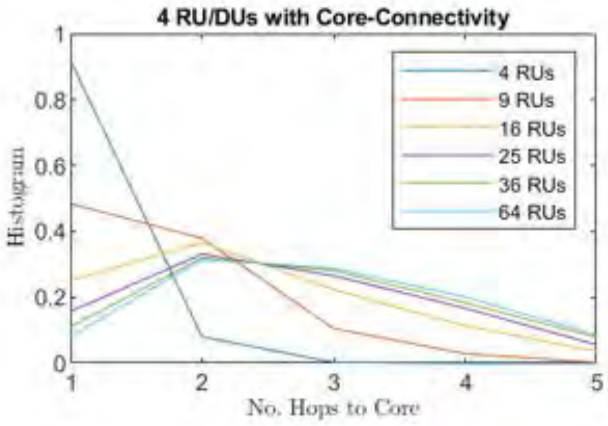
L1 mobility in D-MIMO with spatial repetition transmission

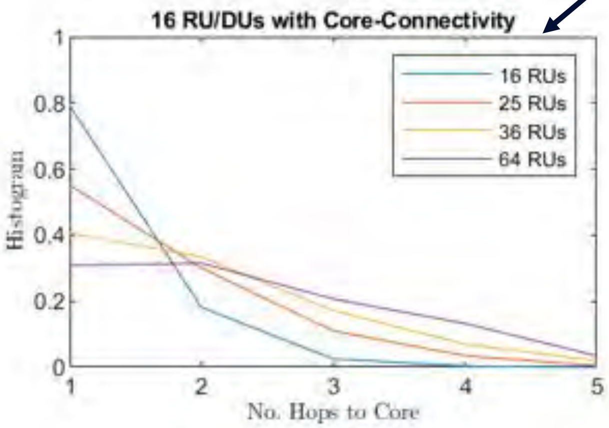


Downlink achievable rate per user under the dynamic scenario with MDS based channel estimation

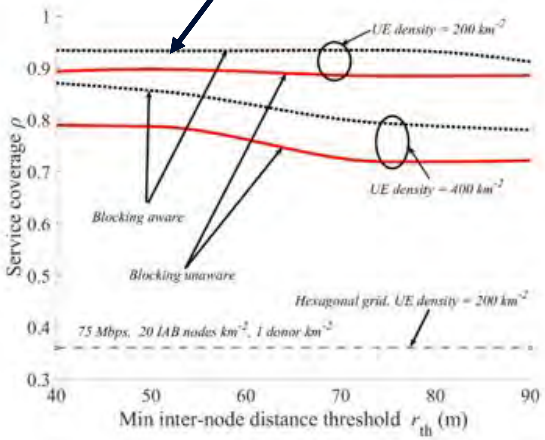


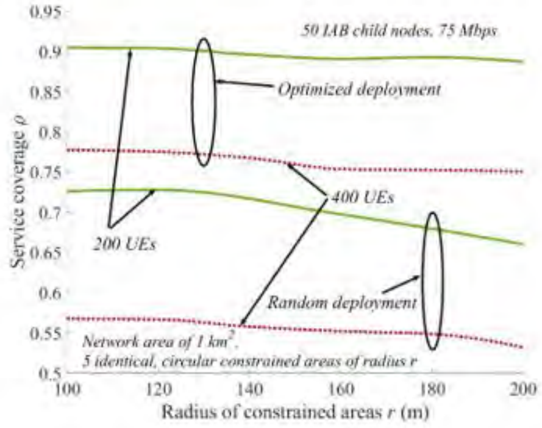
Distribution of number of hops for a different of core-DU/RUs and RUs. Iteratively applied Dijkstra optimizing for link SINR is used for calculating routes through the mesh.





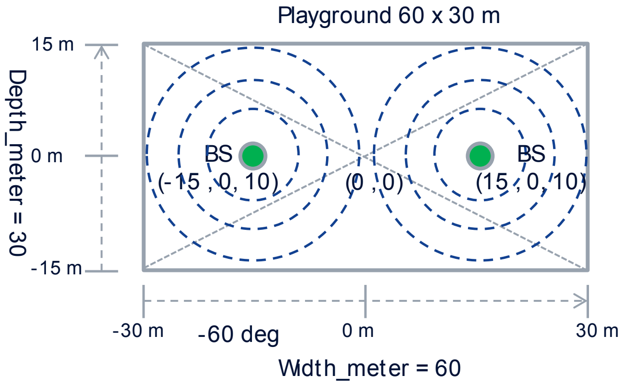
Service coverage with constrained IAB deployment optimization

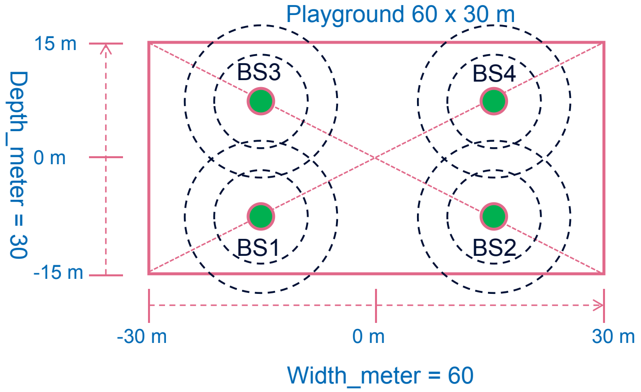




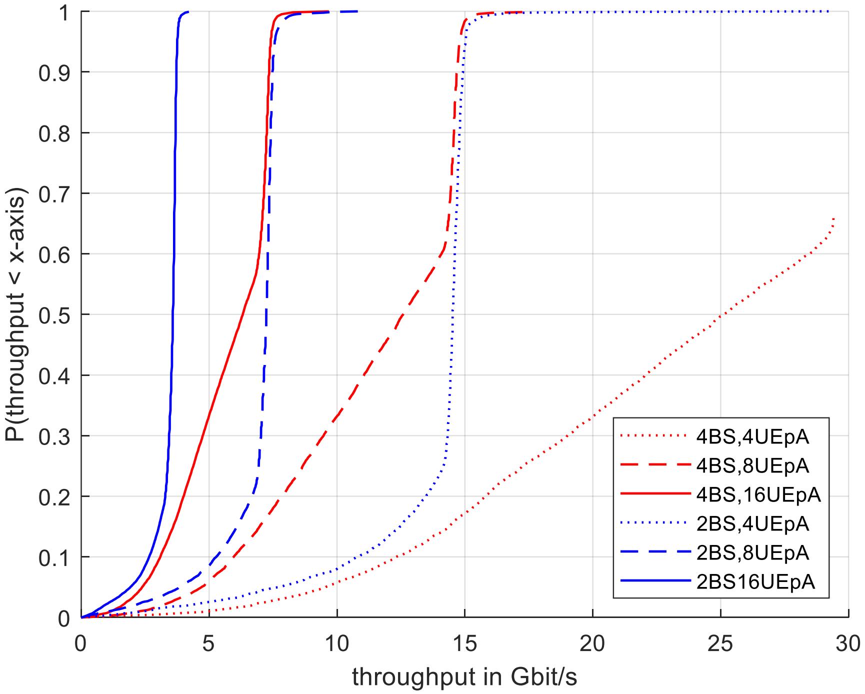
Radio link and system performance analysis: Impact of deployment scenarios on power consumption

- Area throughput and power consumption comparison
  (Tx and Rx RF frontend, exemplary simple scenario)
- BS with 1, 2 or 4 subpanels, analogue Gob

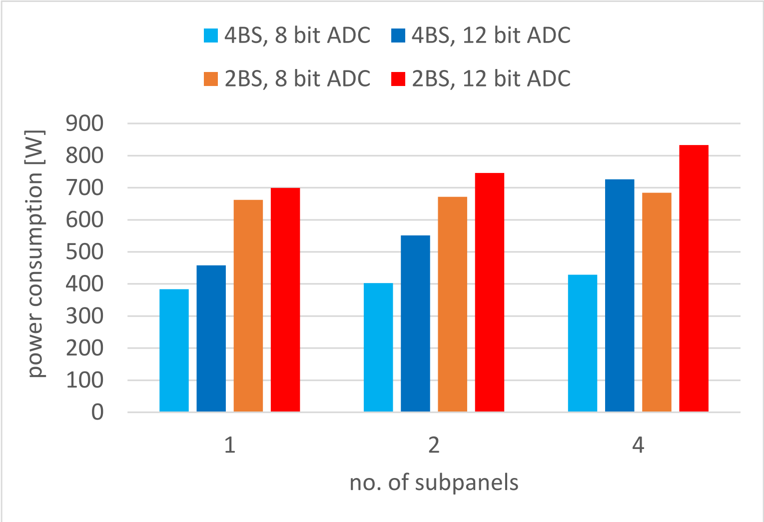




Deployment area:
2 BS 10 m height
4 BS 5 m height
pointing from the ceiling



UE throughput CDF for 4, 8 and 16 simultaneously served UEs within deployment area
=> 4 BS achieve higher throughput



Total power consumption of 2-BS scenario is higher than of 4-BS
Higher ADC resolution: power consumption increases with number of RF chains

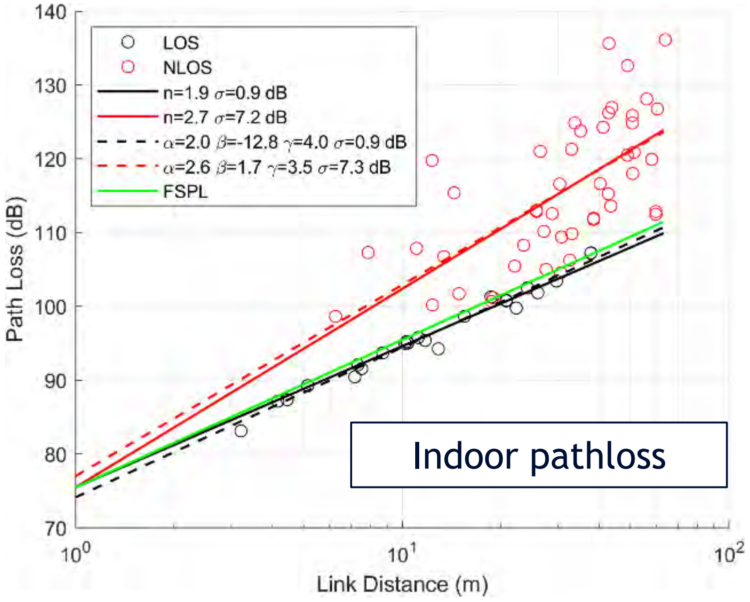
BS: base station
CDF: Cumulative Density Function
UE: User Equipment
GoB: Grid of Beams

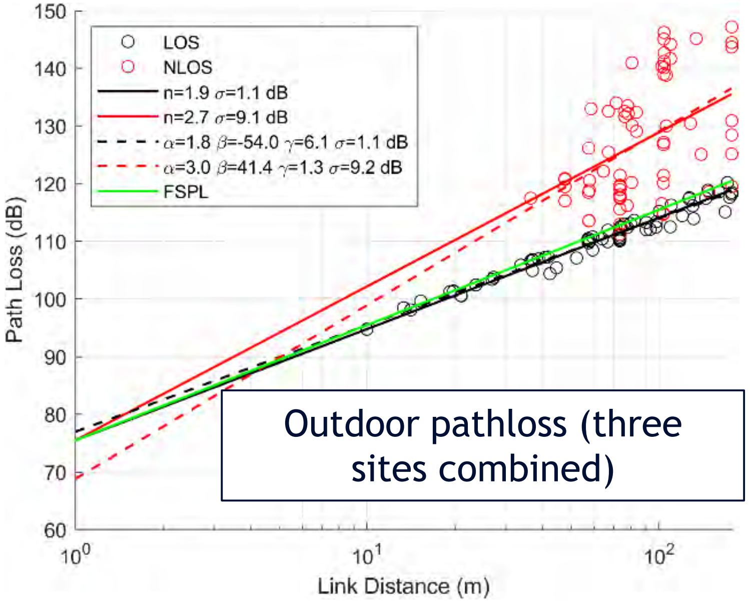
Radio link and system performance analysis: Radio channel properties influencing link and system performance

Pathloss and large-scale parameters at 142 GHz were derived from channel sounding at three outdoor and one indoor sites.

Residential site

City center site





Scenario		AoD [deg]		ZoD [deg]		AoA [deg]		ZoA [deg]		Delay Spread [ns]	
		μ	σ	μ	σ	μ	σ	μ	σ	μ	σ
Indoor	LOS	25	9	6	5	14	8	3	2	14.6	4.4
	NLOS	38	13	8	5	22	11	4	2	26.3	11.8
Suburban	LOS	10	7	2	1	9	10	1	1	25.7	24.2
	NLOS	9	11	3	3	5	4	1	2	15.1	14.8
Residential	LOS	13	9	2	2	11	10	1	1	24.9	19.4
	NLOS	20	18	3	3	6	6	1	2	26.9	37.9
City Center	LOS	18	9	4	6	13	4	2	1	21.3	9
	NLOS	24	17	4	3	14	9	2	2	25.4	19.9
Outdoor	LOS	12	9	2	3	10	9	1	1	24.7	20.6
	NLOS	21	18	3	3	9	8	2	2	25.6	31.0

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