5G Advanced to 6G: Exploring the Next Frontier in Wireless Technology

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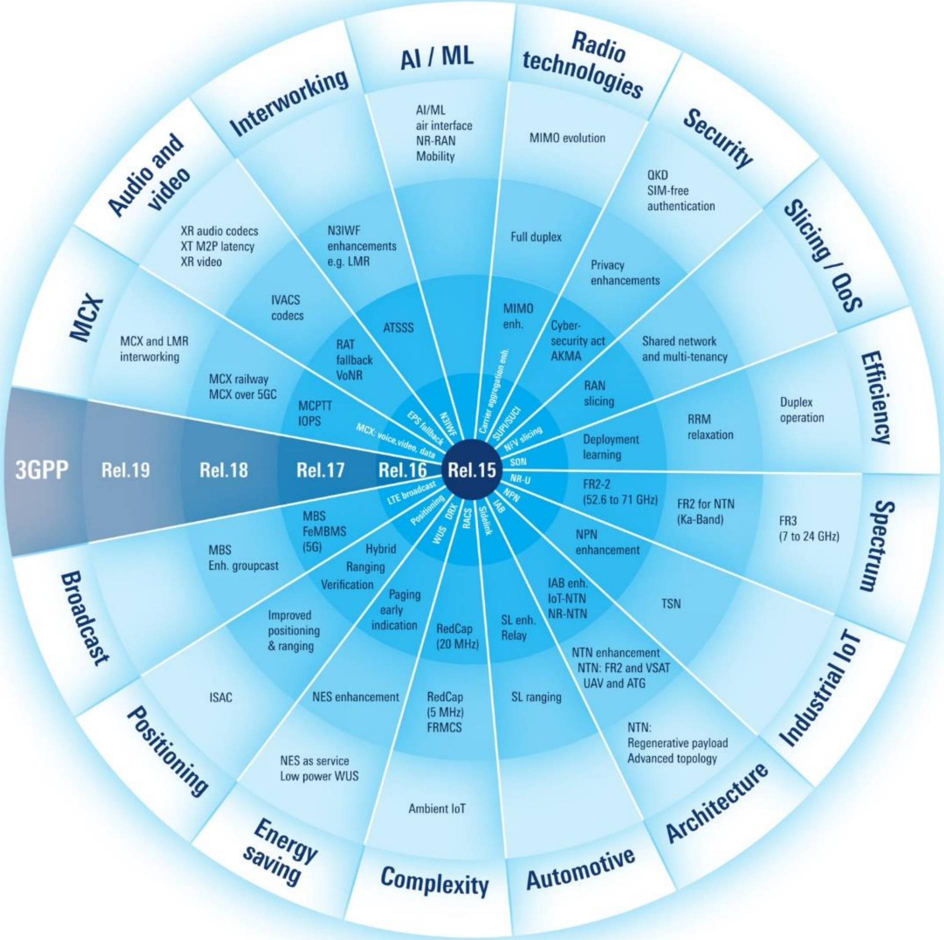
AGENDA

- **5G Advanced**
  - MIMO and Beamforming
  - Fixed Wireless Access
  - RedCap and NB-IoT
  - XR
  - MCX
  - AI/ML
  - 5G Interworking
  - Non-terrestrial networks (NTN)
  - Network Energy Savings
- **6G Key Research areas**
  - Frequency aspects, unified 3D architecture, AI, ISAC, RIS, THz and etc

THE “UNSTRUCTURED“ EVOLUTION OF 5G TOWARDS 6G



5G-Advanced & 6G major research topics

The ongoing evolution of 5G

5G EVOLUTION – MIMO AND BEAMFORMING

BEAM MANAGEMENT EVOLUTION IN 5G NR

Rel-15
- Basic beam management (BM) for each channel/signal
- PCell Beam Failure Recovery (BFR)

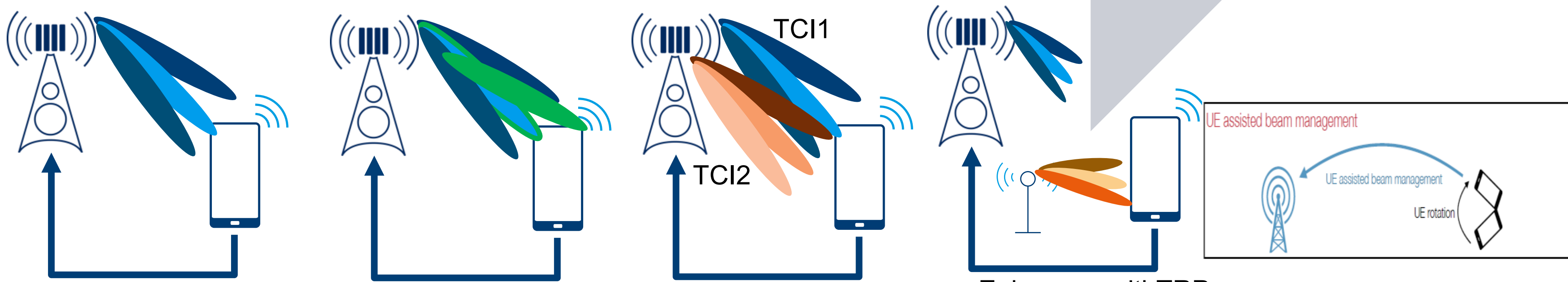
Rel-16
- Low latency/overhead BM:
  - default spatial relation mainly for beam correspondence case
  - Simultaneous UL/DL beam indication across multiple CC
- SCell BFR

Rel-17
- Unified TCI (uTCI) framework
- Per TRP BFR

Rel-18
- Extension of uTCI framework for multi TRP

Rel-19
- UE initiated/event-driven BM (targeting FR2 & sTRP intra- and inter-cell beam management)

Information source: RWS-230207



CSI-RS concept and UE sends CSI feedback

UL/DL beam correspondance

“combine“ beam characteristics (TCI)

Enhance multi-TRP

UE „event“ triggered CSI

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CHANNEL STATUS INFORMATION (CSI) EVOLUTION IN 5G NR

Rel-15
- Type I CSI (low resolution)
  - Single panel/multiple panel codebook
- Type II CSI (high resolution)
- L1-RSRP reporting

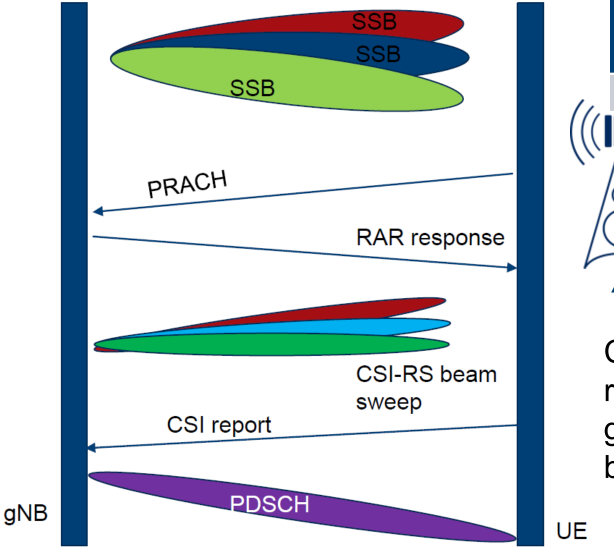
Rel-16
- eType II: Type-II with low overhead and rank 3 & 4
- L1-SINR reporting

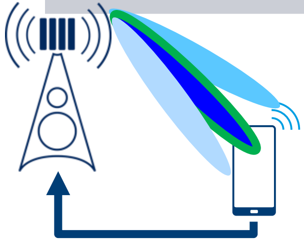
Rel-17
- NCJT CSI
- FeType II: type II with partial reciprocity by long term channel property in FDD band
- Group based beam reporting

Rel-18
- Type II CSI for CJT
- Type II for medium/high velocity
- Type II time domain channel property (TDCP) reporting

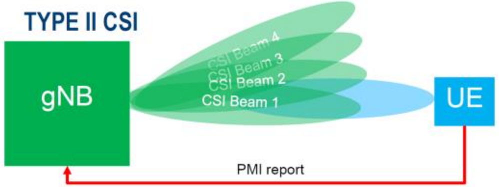
Rel-19 (targeting FR1)
- Type I codebook enhancements to support 128 CSI ports
- Type II enhancements to support 128 CSI ports (only changes needed to support 128)
- Extension of CRI-based CSI reporting for hybrid beamforming supporting 128 CSI-RS ports

Information source: RWS-230207

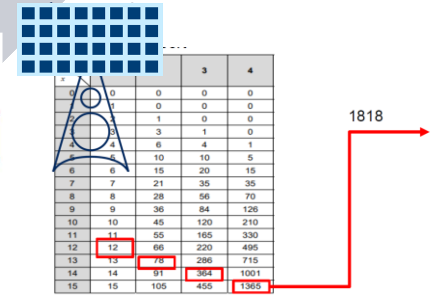




CSI type I, UE reports 1 beam, gNB TX along 1 beam



CSI type II, UE reports L beams, gNB TX = linear combination of multi-beams



gNB with #ports (e.g. 128 or higher)
⇒ CSI too large
⇒ compression

Multi-TX/RX point (mTRP) EVOLUTION IN 5G NR

Rel-15
- No spec support

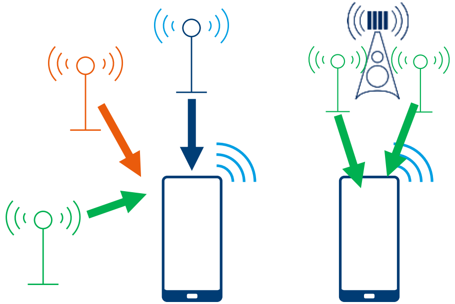
Rel-16
- mTRP SDM based PDSCH (for eMBB)
- mTRP PDSCH repetition (for URLLC)

Rel-17
- mTRP PDCCH/PUCCH/PUSCH repetition
- Inter-cell, HST scenario support

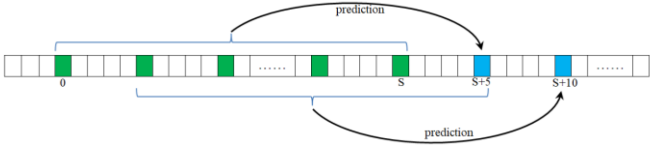
Rel-18
- 2 TAs for mDCI mTRP
- CJT based PDSCH

Rel-19
- CJT enhancements for UE to report Inter TRP time misalignment and frequency/phase offset
- Asymmetric DL sTRP / UL mTRP deployment scenario enhancements (for FR1 and FR2)

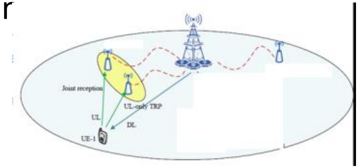
Information source: RWS-230207

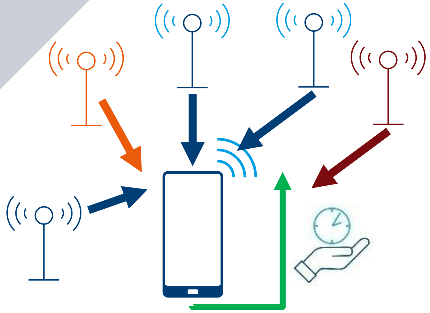


Inter-site or intra-site mTRP with single or multiple DCI



CSI problem: estimation done in the past, predicting the future! What if UE is at high speed? => UE reports time domain correlation properties (TDCP)





Coherent joint TX (CJT), UE reports TRP group & delay differences between TRPs
Heterogenous deployments

UL MIMO EVOLUTION IN 5G NR

Rel-15
- Codebook based (CB) PUSCH
- Non-Codebook based PUSCH
- SRS (≤4 ports, ≤4T4R for antenna switching)

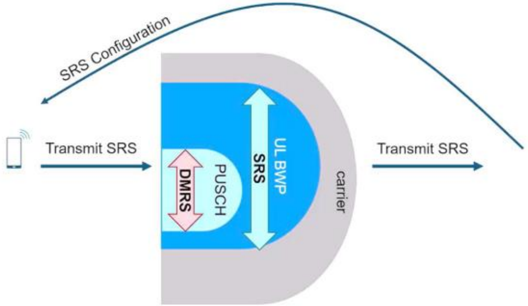
Rel-16
- Low PAPR RS
- UL full power TX

Rel-17: SRS
- Flexible AP triggering
- ≤4T8R for antenna switching
- Capacity / coverage enhancements

Rel-18
- Simultaneous Transmission by 2 panels
- DMRS, SRS, TPMI for UL 8 TX

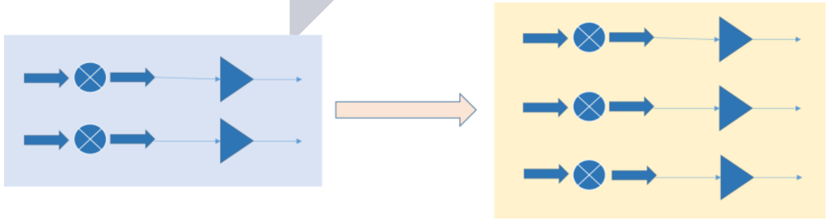
Rel-19
- 3 antenna port CB based TX

Information source: RWS-230207



Introduce SRS for better channel visibility

SRS TX switching for better antenna selection



Uplink with 3TX MIMO

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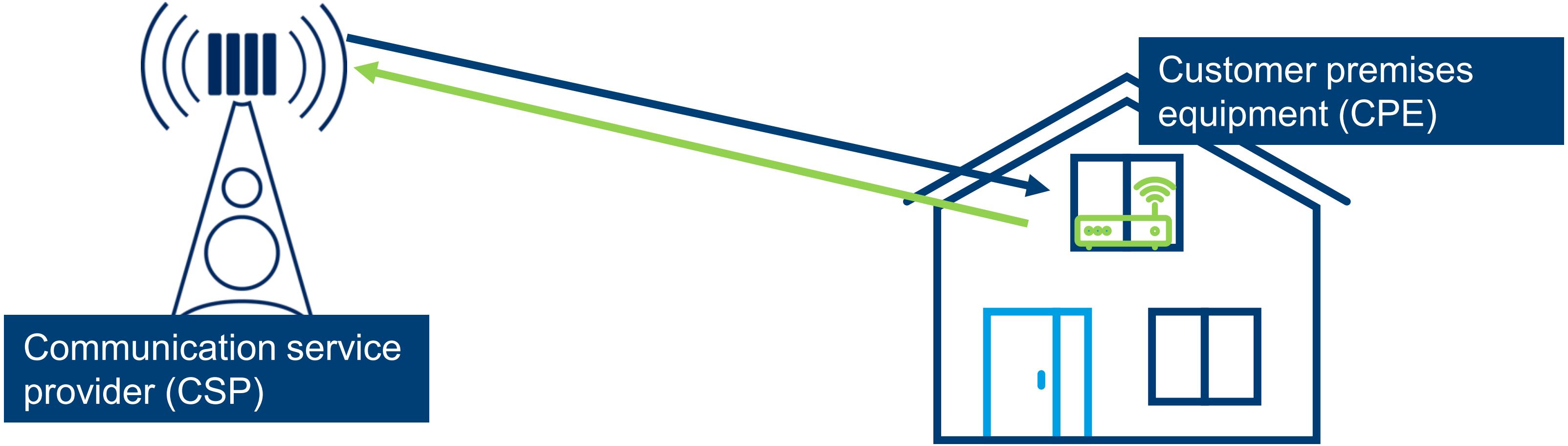
5G-Advanced & 6G major research topics

The ongoing evolution of 5G

FIXED WIRELESS ACCESS

FIXED WIRELESS ACCESS (FWA)



Fixed Wireless Access (FWA) is a wireless connection that provides broadband access to a specific location such as a home or enterprise premises. It enables consumers to connect to the network and access high-speed internet via radio signal, without the need for physical cables. It supports both 4G LTE and 5G technologies, but it's the speed and flexibility of 5G that really realizes the full value of FWA [Ericsson].

FIXED WIRELESS ACCESS (FWA)

Key benefits of telecom FWA

High bandwidth, low latency

Comparable speeds to fiber when supported by 5G.

Wireless freedom

No physical cabling infrastructure to manage or maintain.

Financial attractiveness

Affordable solutions with a light investment profile and lower risk.

Short time to market and revenue

Fast installation, deployed in 1-7 days, with quick revenue potential.

Easy to install

CPE can be self-installed and has a low footprint for simple relocation.

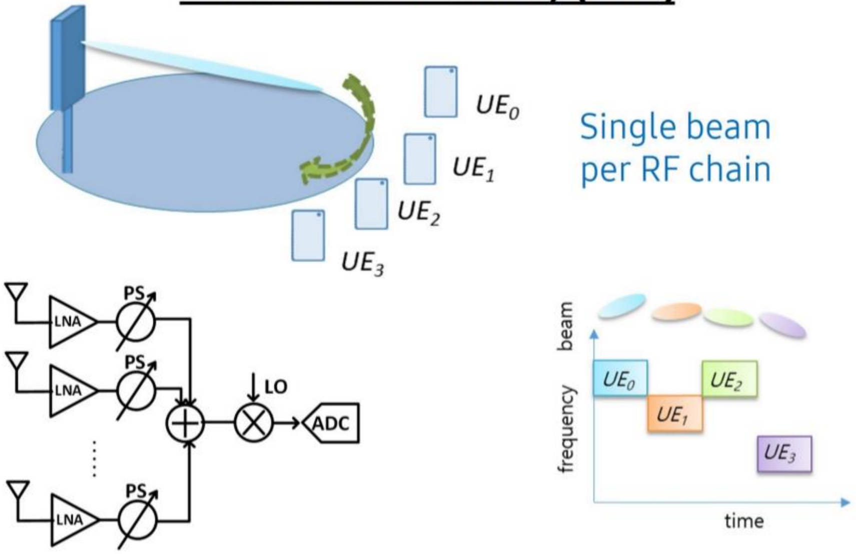
Simpler and more sustainable

Utilizes existing site infrastructure, unlike resource-intensive fiber or cables.

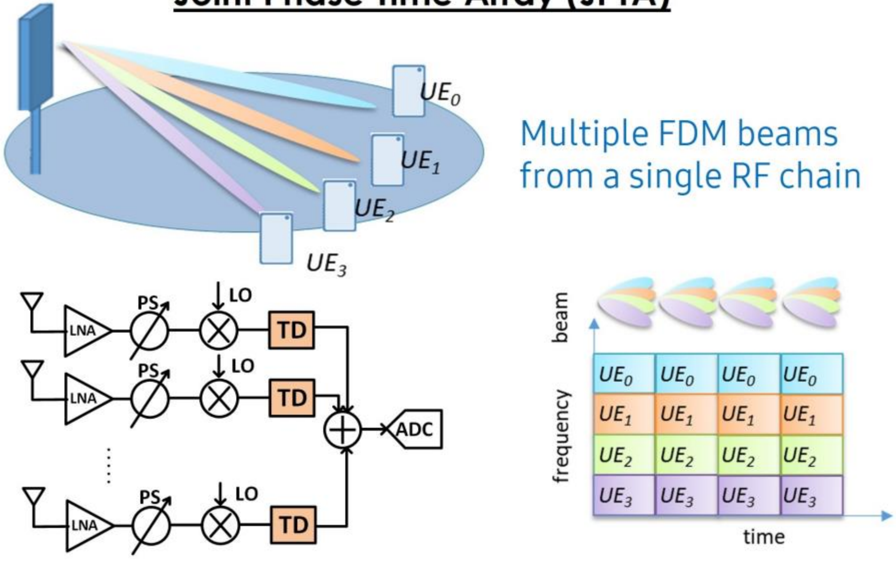
Source: Ericsson

FIXED WIRELESS ACCESS (FWA) – BEAMFORMING

Phased Antenna Array (PAA)



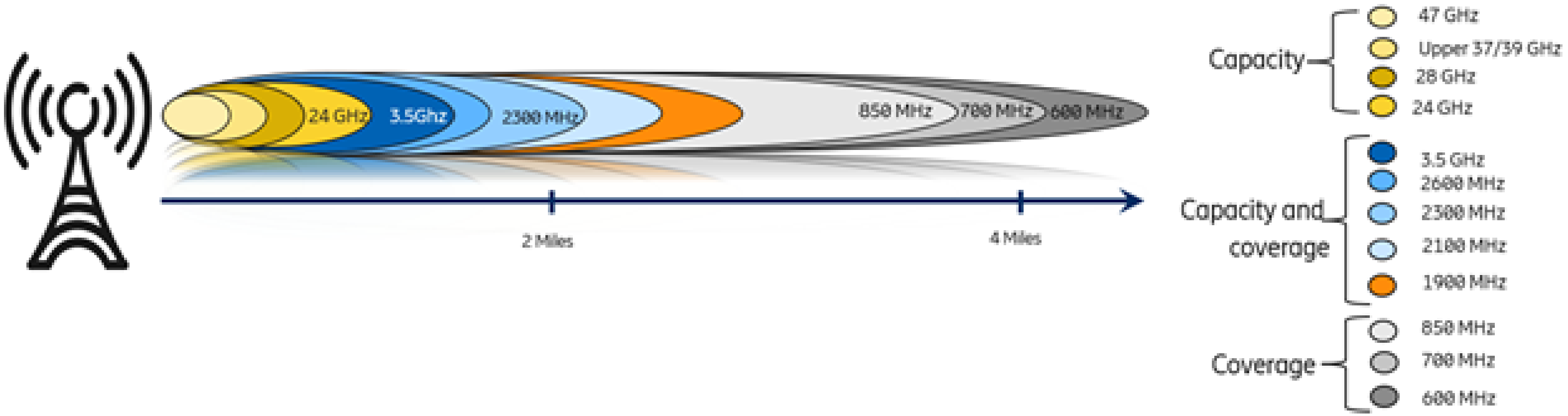
Joint Phase Time Array (JPTA)



Joint phase and time array antennas allow multiple beams simultaneously

Source: Samsung

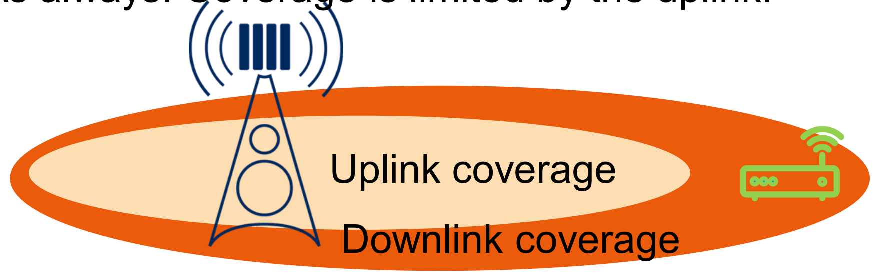
FIXED WIRELESS ACCESS AND SPECTRUM ASPECTS



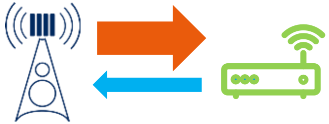
FWA was originally designed for WiMAX @ 66GHz
LTE TDD band 43 (~3.5GHz) was one of the first commercial deployment
With 5G FWA, both FR1 and FR2 frequency bands are possible, up to 47GHz deployments

FIXED WIRELESS ACCESS – UL IMPROVEMENTS

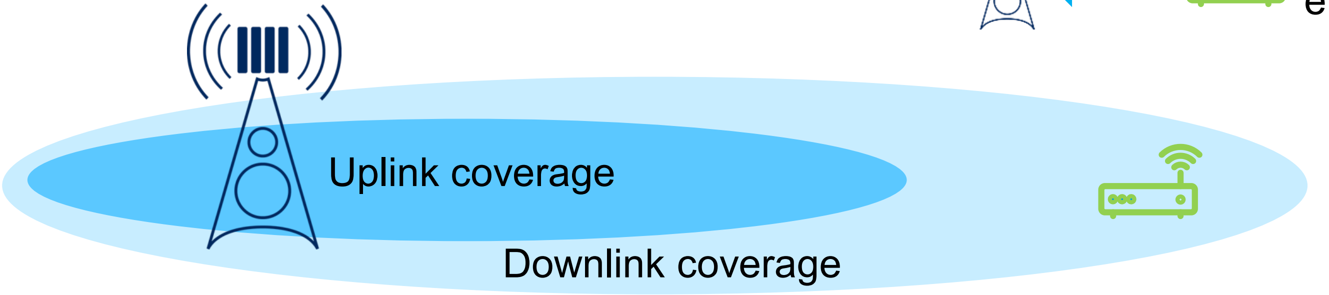
As always: Coverage is limited by the uplink!



Coverage situation at higher frequency bands



UL frequency switching enables larger coverage

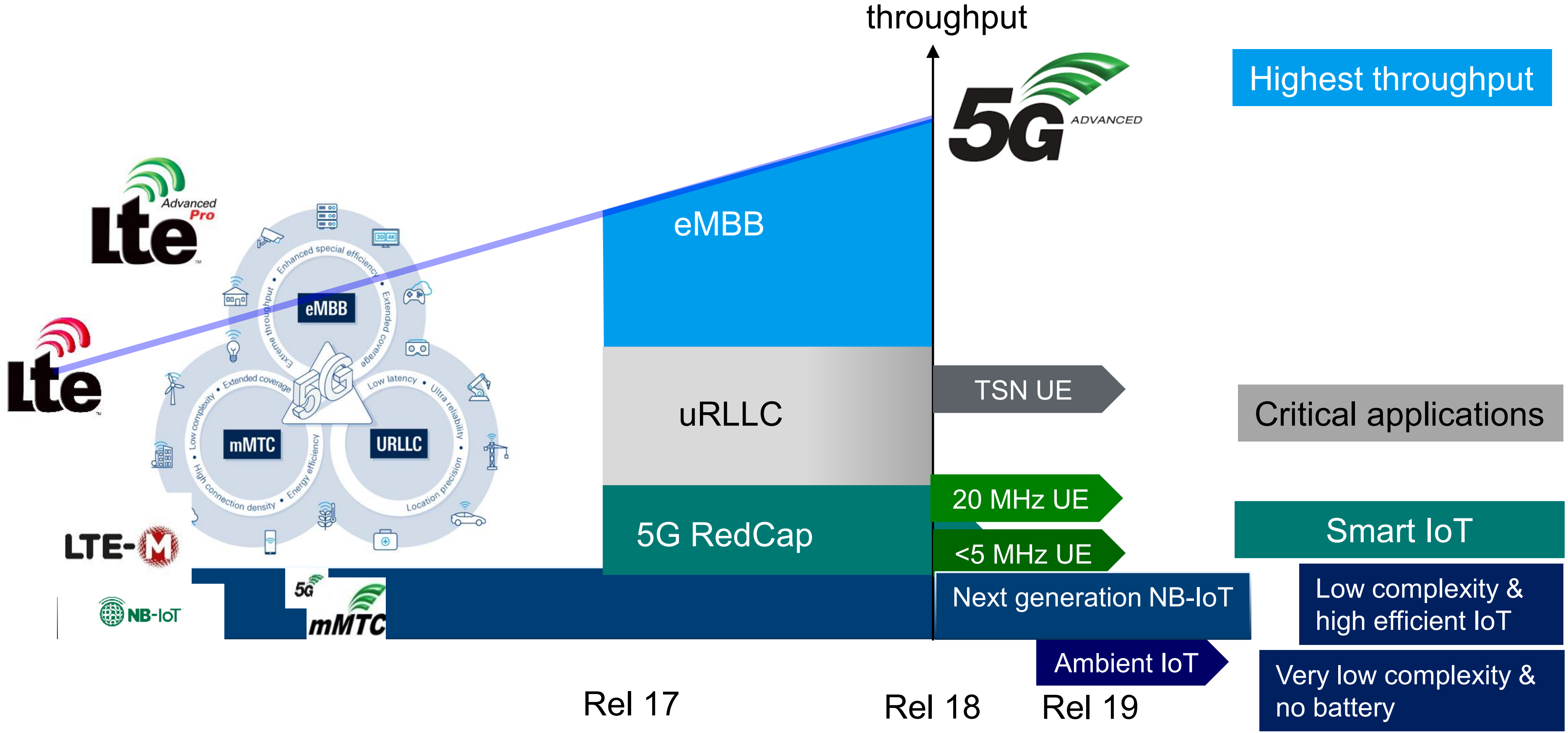


Coverage situation at lower frequency bands

The ongoing evolution of 5G

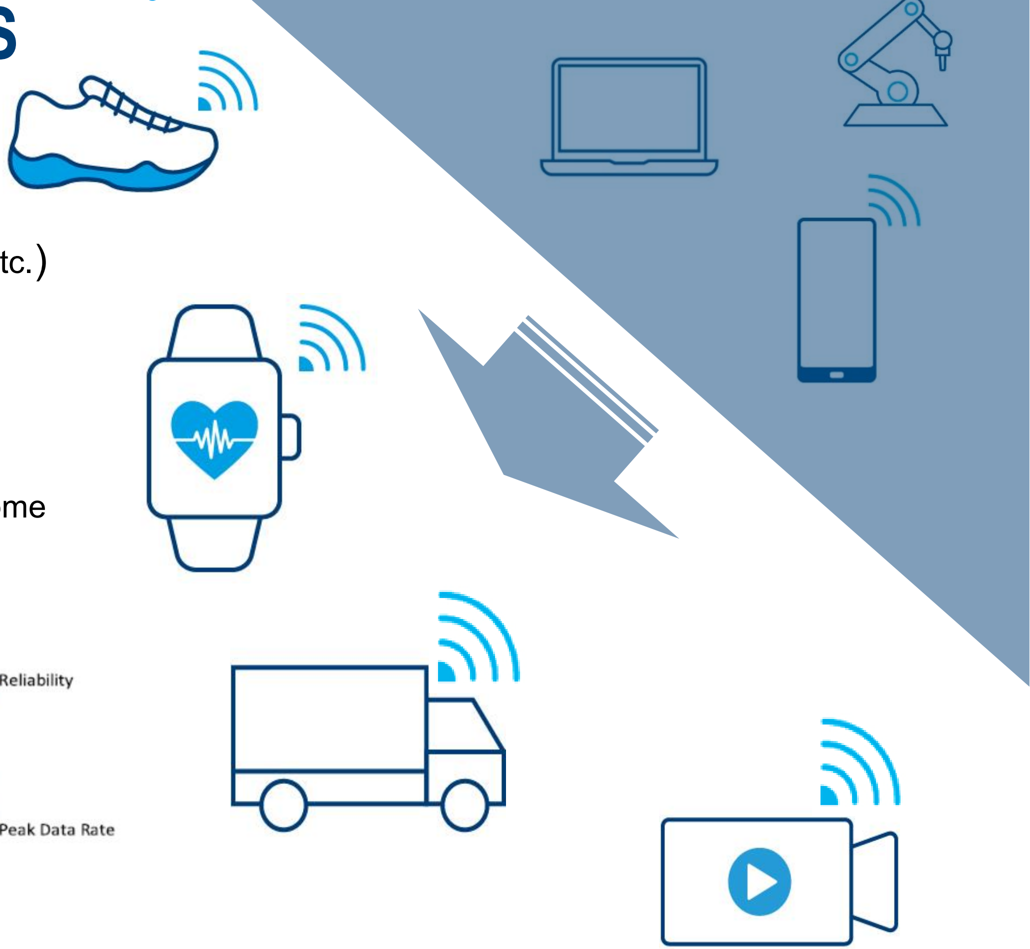
REDUCED CAPABILITY (RedCap) + AMBIENT IOT

5G NR: REDUCED CAPABILITIES (RedCap)

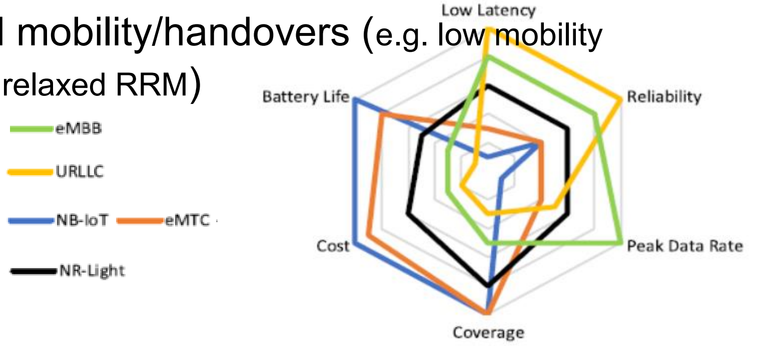


NR evolution – Reduced capabilities (RedCap) + Power saving

DEVICE OPTIMIZATION TOPICS



- ► Reduced capability (RedCap)
  - 20 MHz (FR1), 100MHz (FR2)
  - 1 or 2 Rx (more complex in reality: MIMO, FR1/2 etc.)
  - 1 TX antenna
  - 256QAM optional (FR1)
  - Half duplex FDD (but full-duplex is optional)
  - Lower transmit power (e.g. power class 7 for some bands in FR2)
  - Limited mobility/handovers (e.g. low mobility devices, relaxed RRM)

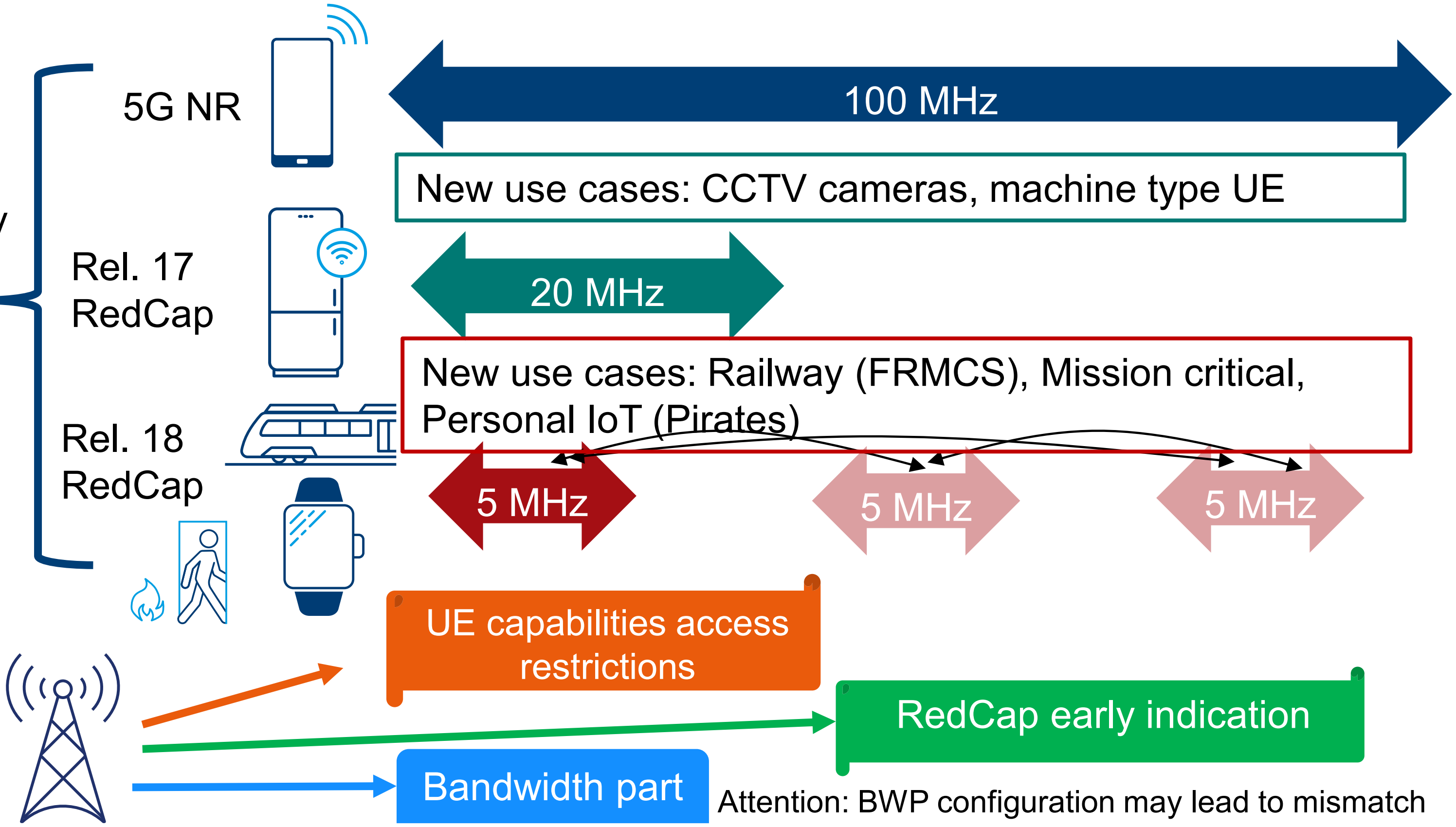


Source: Nokia

REDUCED CAPABILITIES ASPECTS & EVOLUTION

- 20MHz bandwidth
- Half-duplex
- 1 antenna
- 256QAM optional
- No dual connectivity

Coexistence

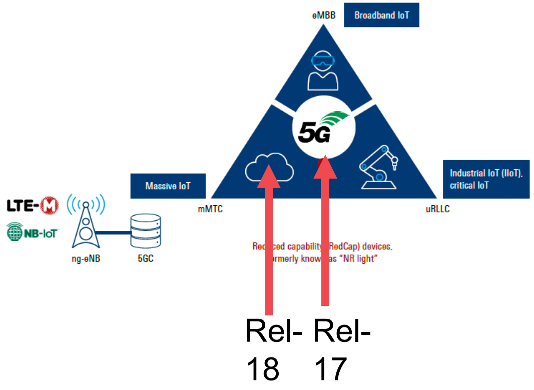


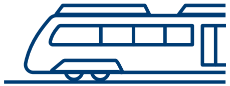
Network must operate in standalone 5G (SA)

Attention: BWP configuration may lead to mismatch

REDCAP DEVICES IN 3GPP REL17/18

RedCap evo	5G eMBB	Rel. 17	Rel. 18
Bandwidth	100 MHz	20 MHz	5 MHz
Peak rate	2 Gbps	100 Mbps	10 Mbps
Cost assessment	100%	-60%	-71%

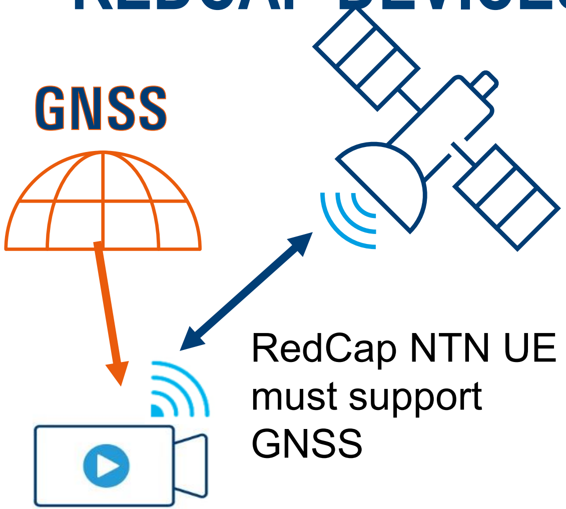




Future railway mobile communications system (FRMCS)
- 2*5.6 MHz FDD (874.4 – 880 MHz / 919.4 – 925 MHz)
- Parallel operation: GSM-R and NR
- ~3.6 MHz available for NR

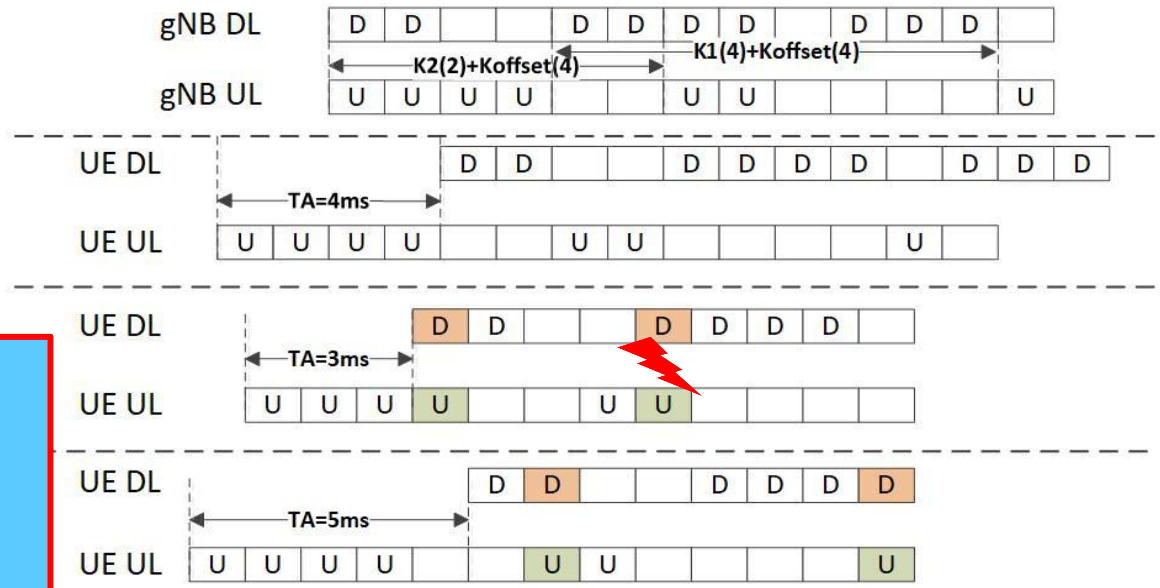
Public protection and disaster relief (PPDR)
- 2*3 MHz FDD in band n28

REDCAP DEVICES IN 3GPP REL19 AND BEYOND



RedCap NTN UE must support GNSS

Outlook: RedCap UE will also use NTN. => adaptations of protocol stack needed to adjust to Doppler, timing delay, etc.



Challenge: RedCap UE with half-duplex, collision between TX and RX due to long delay (timing advance) => discussion to solve by scheduling, i.e. no real half-duplex but more „bursted“ TX and RX

AMBIENT-IOT WIRELESS POWER TRANSFER : USE CASES

Supply Chain

Retail

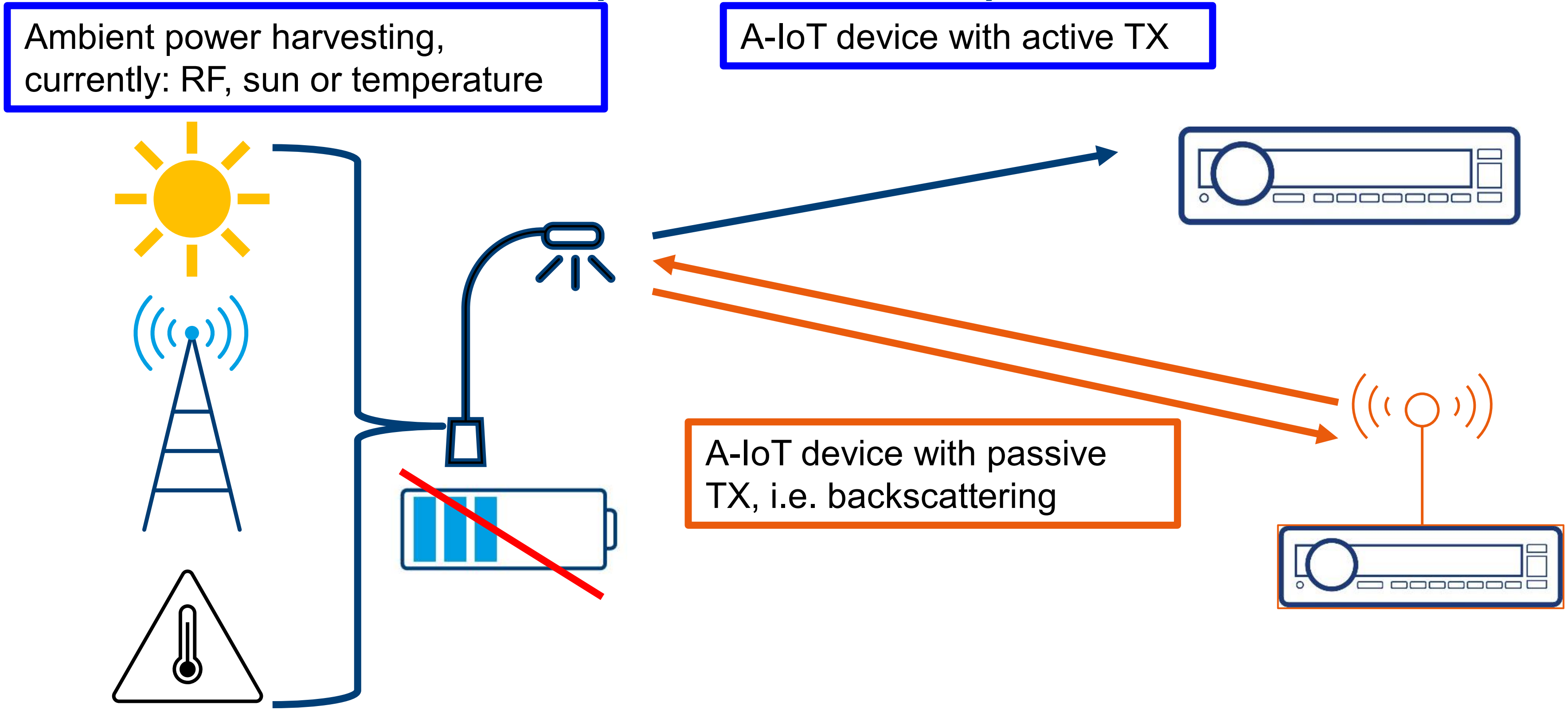
Patient care

Automotive

Smart home

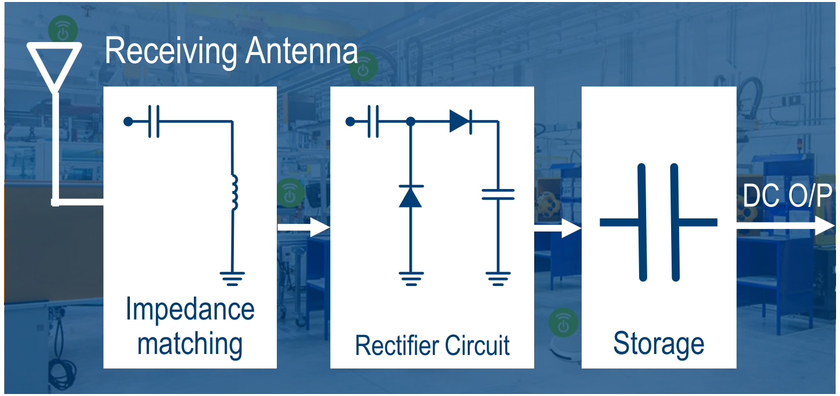
Consumer

ZERO POWER-IOT (AMBIENT IOT)



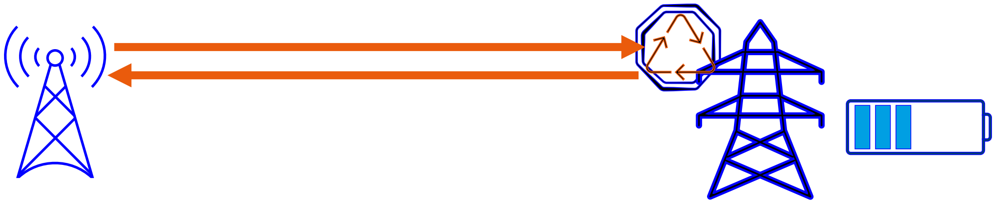
PRINCIPLES OF WIRELESS POWER TRANSFER (WPT)

$$d = \frac{2\,D^2}{\lambda} \quad d_{f=900\,MHz} \approx 16\ cm$$



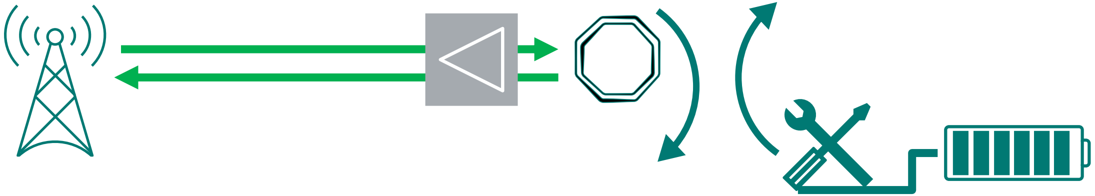
- ✓ Motion and device use while charging
- ✓ Scheduled Charging without down time

3GPP STUDY ON AMBIENT-IOT TR38.769

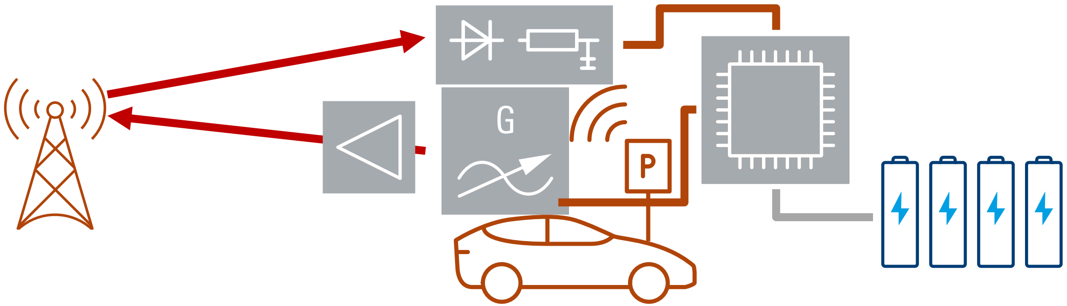


Device 1:
- Small energy storage
- Only backscattering, no amplification
- Energy consumption: ~1µW

Device 1 complexity < Device 2a complexity < Device 2c complexity



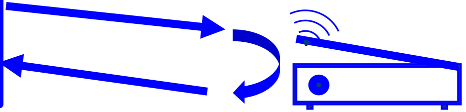
Device 2a:
- With energy storage
- Only backscattering
- With amplifier
- Energy consumption: ~100µW



Device 2b:
- With energy storage
- Active RF components for independent TRX
- Energy consumption: ~few 100µW

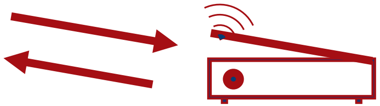
3GPP STUDY ON AMBIENT-IOT, REL. 19

Communication via backscattering! No independent TX possible. Amplification on backscattering possible



Communication scenarios

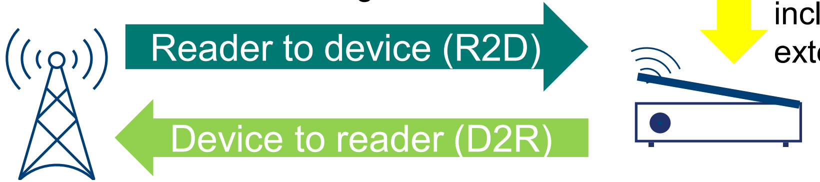
Communication via TRX within UE



A-IoT link scenarios

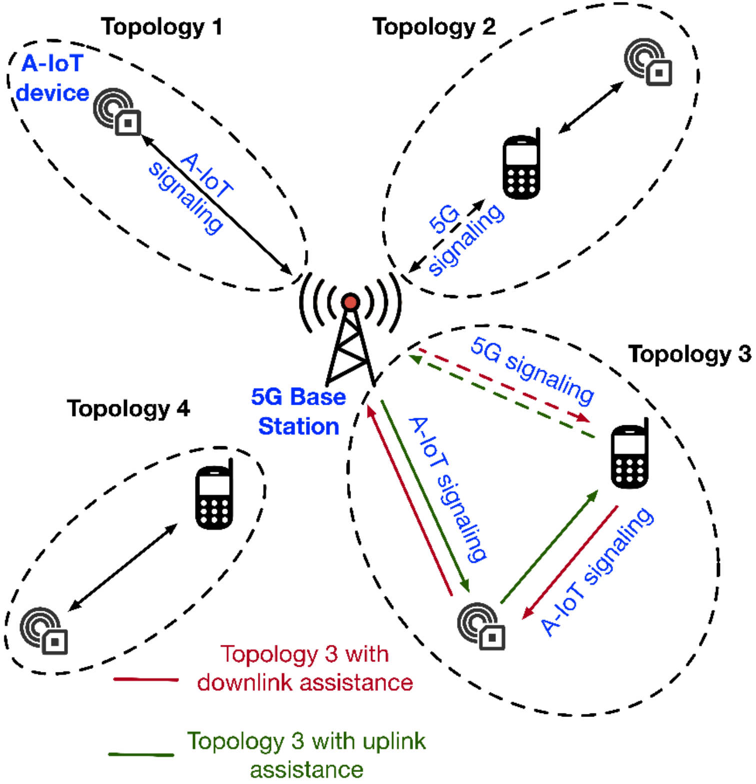
R2D = similar to 5G NR downlink, contains PHY signals & channels

CW-signal for energy harvesting possible, either included or via external



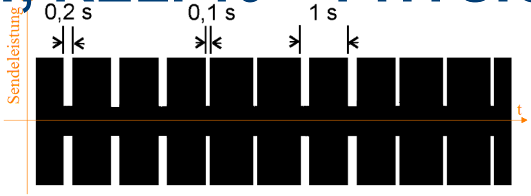
D2R = similar to 5G NR uplink, contains PHY signals & channels

AIoT topologies



3GPP STUDY ON AMBIENT-IOT, REL. 19 – PHYSICAL LAYER

A-IoT data is based on On-off-keying (OOK) waveform. E.g. DCF-77 time synchronization signal in Europe



OOK-1 or OOK-4 for higher chip rates
Manchester coding:
Bit 0 = {10}, Bit 1 = {01}

D-TAS	PDRCH	Midamble	PDRCH	Postamble

Option 1 with small TB

D-TAS	PDRCH	Midamble	PDRCH	Midamble	Postamble

Option 1 with longer TB

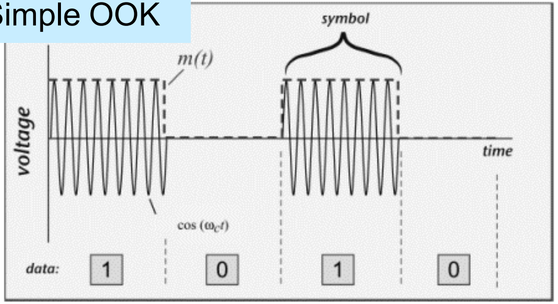
D-TAS	PDRCH	Midamble	(TBS is included)

Option 2 with small TB

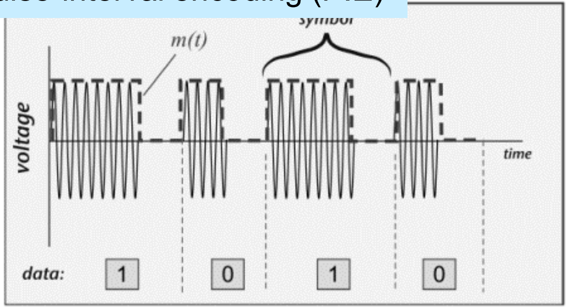
D-TAS	PDRCH	Midamble	PDRCH	Midamble	(TBS is included)

Option 2 with longer TB

Simple OOK



Pulse-interval encoding (PIE)



Discussion on structure. W/o midample (PIE), long or short TB size

The ongoing evolution of 5G

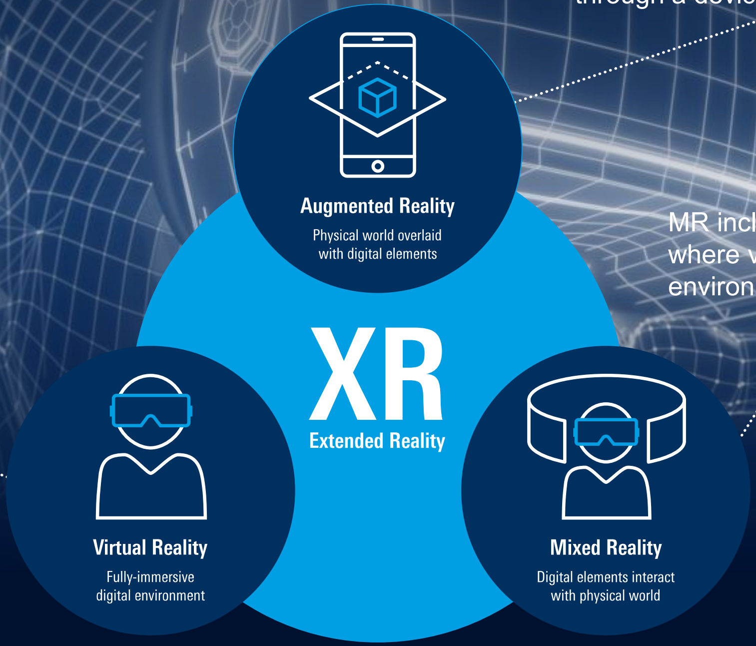
EXTENDED REALITY XR

XR DEFINITION AND STATE OF THE INDUSTRY
EXTENDED REALITY – AN UMBRELLA TERM

AR is one such variant, where digital information is overlaid on images of reality viewed through a device.

MR includes all variants where virtual and real environments are mixed.

Users are totally immersed in a simulated digital environment or a digital replica of reality.



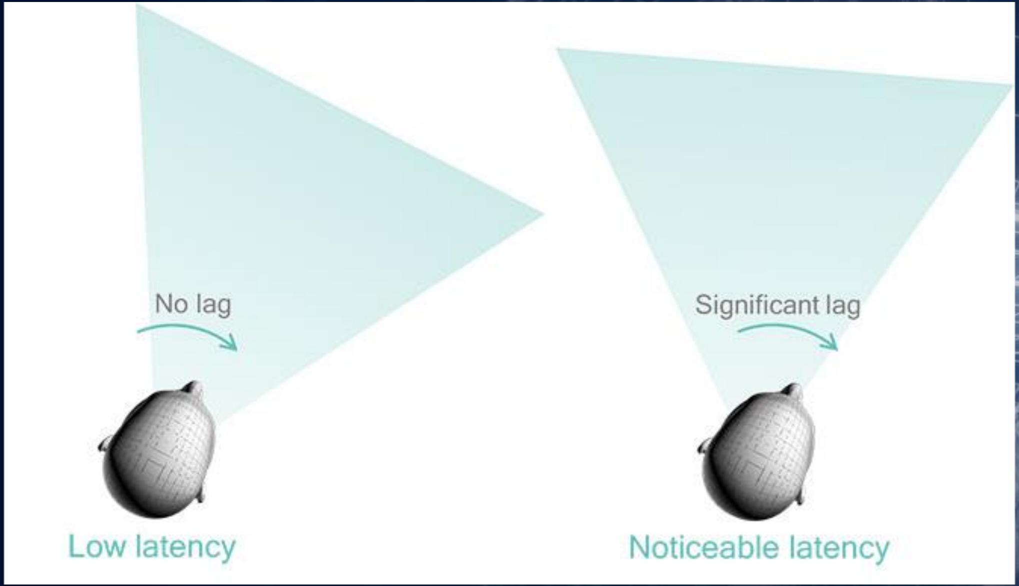
XR DEFINITION AND STATE OF THE INDUSTRY
GOAL: “EVERYDAY AR GLASSES”*

Source: *Meta*

- Comfortable form factor will require balancing hardware capabilities in four areas
  - Display
  - Compute
  - Power
  - Connectivity
- Network enabled compute offload
  - Will enable scaled mobile metaverse experiences

* Dr. Henry Fuchs, March 2024, NVIDIA GTC Presentation: *Everyday Augmented Reality Glasses: Past Predictions, Present Problems, Future Possibilities*

XR DEFINITION AND STATE OF THE INDUSTRY
CORE CONCEPT: MOTION TO PHOTON (M2P) LATENCY



Source: https://www.qualcomm.com/news/onq/2016/06/keeping-virtual-world-stable-vr

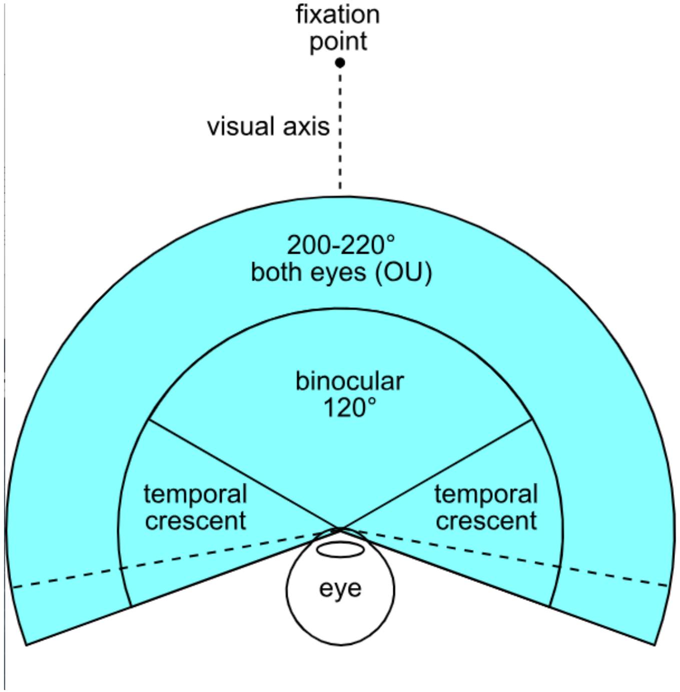
Component	Latency	Location
SLAM[1)]	50…70 ms	AR device
Object tracker	2…5 ms	AR device
Game simulation	2…5 ms	Remote server
Rendering	2…16 ms	AR device
AR device	7…8 ms	AR device
Video decoding	12 ms	Remote server
Object detection (OD)	250 ms	Remote server

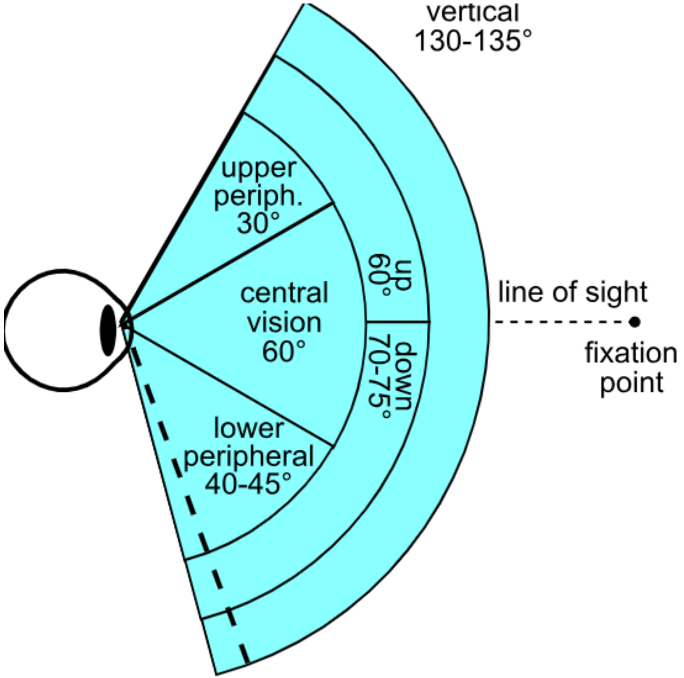
[1)] Simultaneous Localization And Mapping

Source: https://www.ericsson.com/en/blog/2022/11/network-performance-metaverse-5g

20 ms: Total E2E M2P latency budget for user comfort (no visual-vestibular conflict)

XR DEFINITION AND STATE OF THE INDUSTRY
CORE CONCEPT: FIELD OF VIEW (FOV)

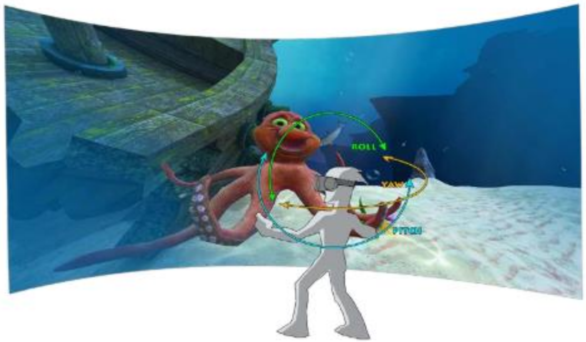




Source: Wikipedia

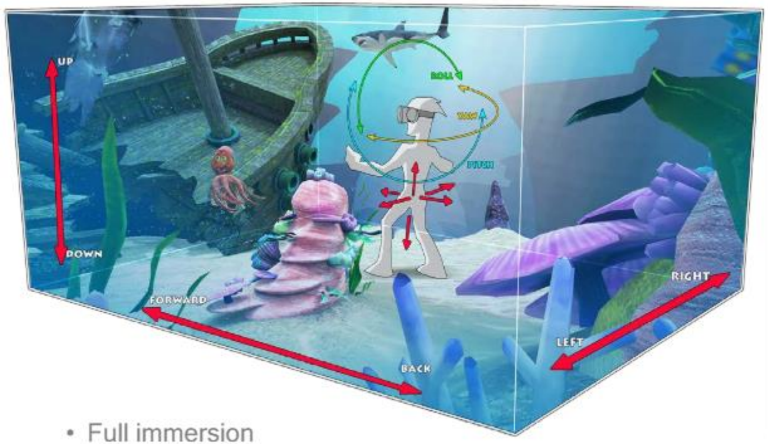
XR DEFINITION AND STATE OF THE INDUSTRY
DEGREES OF FREEDOM (DOF)

3 degrees of freedom (3-DoF)



- Can only watch

6 degrees of freedom (6-DoF)

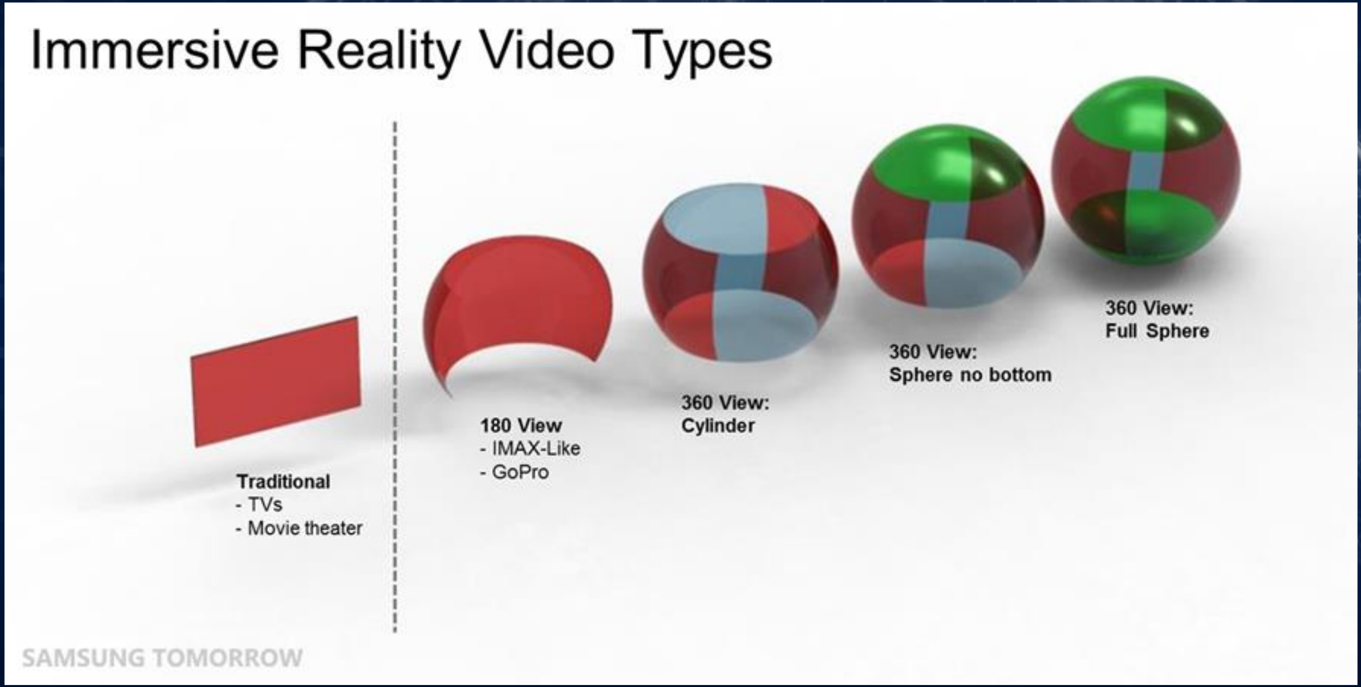


- Full immersion
- Can become part of the story
- Can now interact and change the story

8

Source: Qualcomm

IMMERSIVE VIDEO
3-DOF MEDIA: 180 – 360 DEGREE VIDEO FORMATS



Source: Samsung

XR/AR/VR ASPECTS AND ASSOCIATED CHALLENGES

New device categories

New QoS requirements

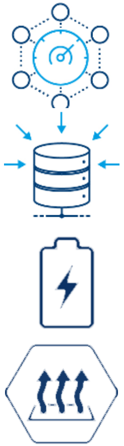
5QI Value	Resource Type	Default Priority Level	Packet Delay Budget (NOTE 3)	Packet Error Rate	Default Maximum Data Burst Volume (NOTE 2)	Default Averaging Window	Example Services
..	...	...	...	...	...	...	...
87		25	5 ms (NOTE 4)	10^{-3}	500 bytes	2000 ms	Interactive Service - Motion tracking data, (see TS 22.261 [2])
88		25	10 ms (NOTE 4)	10^{-3}	1125 bytes	2000 ms	Interactive Service - Motion tracking data, (see TS 22.261 [2])
89		25	15 ms (NOTE 4)	10^{-4}	17000 bytes	2000 ms	Visual content for cloud/edge/split rendering (see TS 22.261 [2])
90		25	20 ms (NOTE 4)	10^{-4}	63000 bytes	2000 ms	Visual content for cloud/edge/split rendering (see TS 22.261 [2])

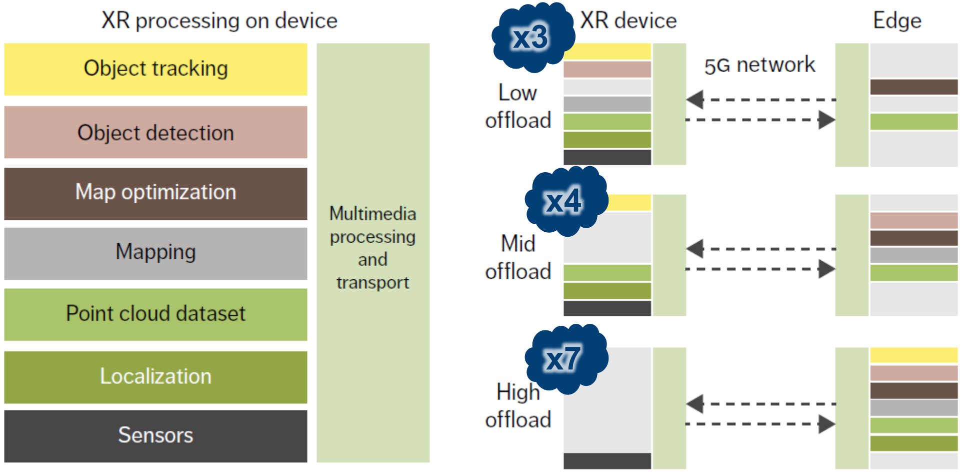
NOTE 1: A packet which is delayed more than PDB is not counted as lost, thus not included in the PER.
NOTE 2: It is required that default MDBV is supported by a PLMN supporting the related 5QIs.
NOTE 3: The Maximum Transfer Unit (MTU) size considerations in clause 9.3 and Annex C of TS 23.060 [56] are also applicable. IP fragmentation may have impacts to CN PDB, and details are provided in clause 5.6.10.
NOTE 4: A static value for the CN PDB of 1 ms for the delay between a UPF terminating N6 and a 5G-AN should be subtracted from a given PDB to derive the packet delay budget that applies to the radio interface. When a dynamic CN PDB is used, see clause 5.7.3.4.

- VR applications are generally speaking processing intensive and require connectivity to high-end computational devices, e.g. PCs, game consoles, GPU

Reduces power consumption by…

- Processing power
- Memory, storage
- Battery life
- Heat dissipation

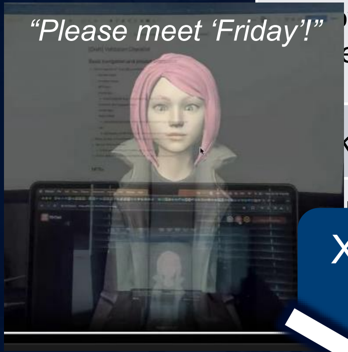




Extended reality XR

TESTING THE METAVERSE

Release 15	Release 16	Release 17	Release 18	Release 19
BWP switching	SCell dormancy	PDCCH skipping	enhanced cDRX	Enhanced multi-modal flows
wnlink emption	Cross-slot scheduling		Retransmission-less configured grant	RxTX in RRM, meas. gaps
	PDCCH Wake-up signal			
k skipping	Uplink configured grant		Low latency mobility	Spatial data capture/sharing
ni			QoS-based on multimedia payload	“XR UE”
			XR awareness	



XR Client App

USB-C connection

R&S®CMX500
5G One Box Signaling Tester

5G connection to AR/VR Edge+ 5G smartphone

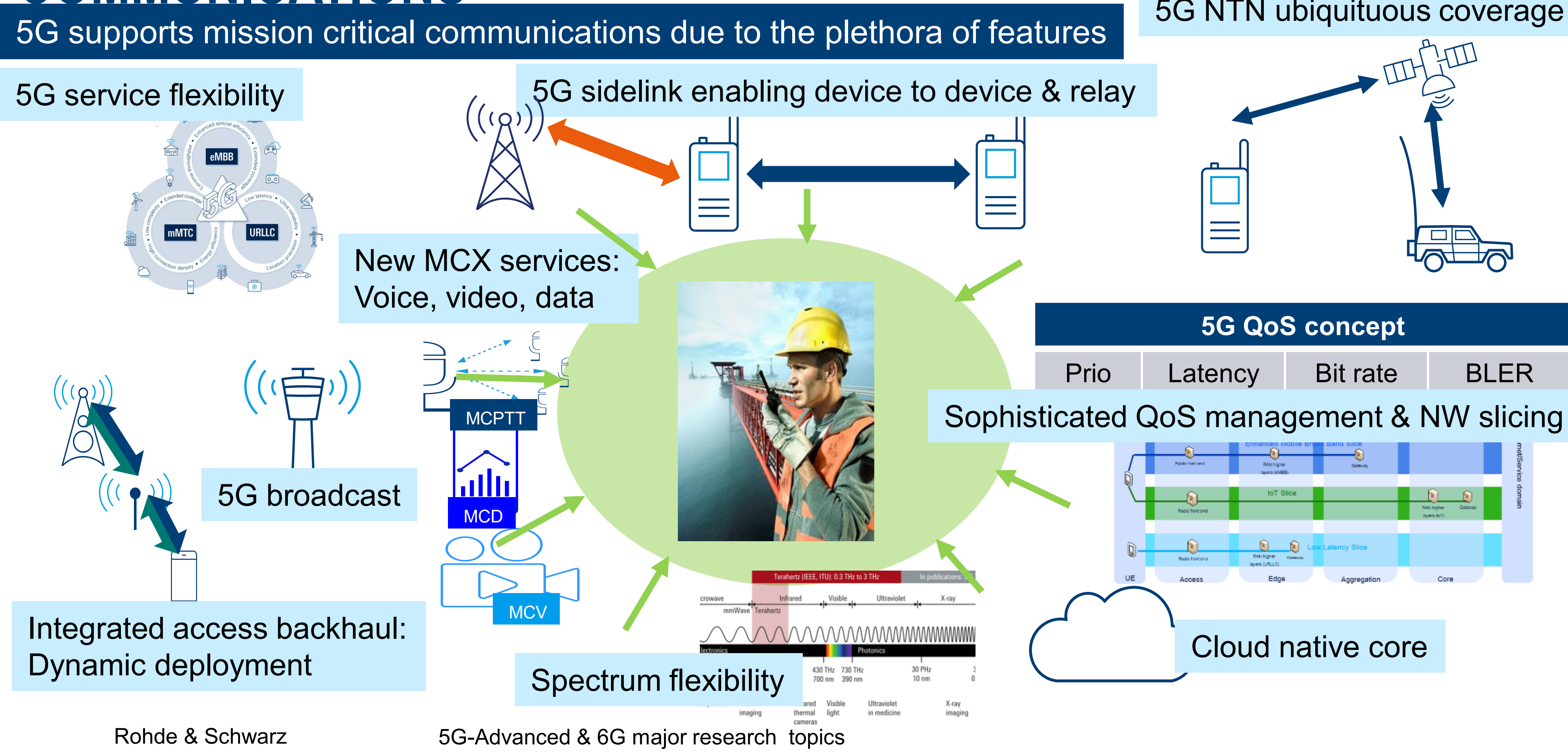
R&S®ATS1800C
RF shield box

5Gis a large toolbox, but we need to find the right “tools“ to optimize XR applications

5G radio technoloy aspects

MISSION CRITICAL COMMUNICATIONS

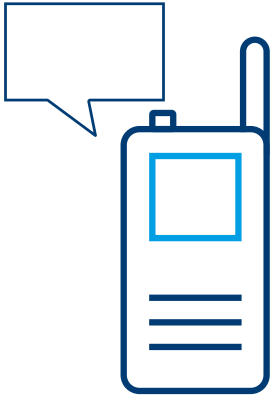
5G TECHNOLOGY ASPECTS SUPPORTING MISSION CRITICAL COMMUNICATIONS



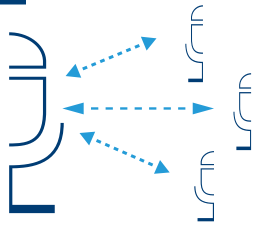
5G MISSION CRITICAL COMMUNICATIONS (MCX)

Narrowband land mobile radio (LMR), e.g. P.25, TETRA, etc.

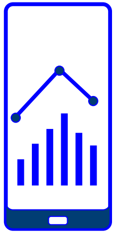
3GPP focusses on three major mission critical categories



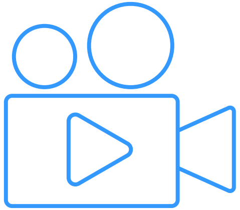
Mission critical push to talk (MCPTT)
Voice rate ~10..70 kbps



Mission critical data (MCD)
Data rate ~10kbps .. 1 Mbps



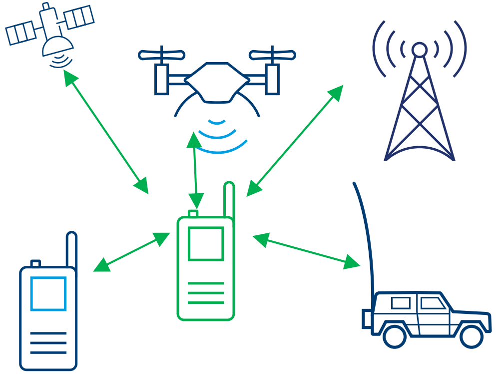
Mission critical video (MCV)
Datarate ~ 150kbps .. 5Mbps



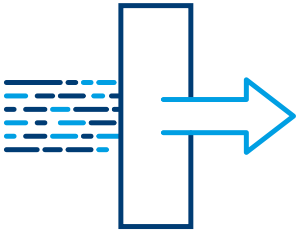
- Voice centric
- Limited data capability
- Difficult „inter-agency“ communications

5G MCX REQUIREMENTS AND CHALLENGES

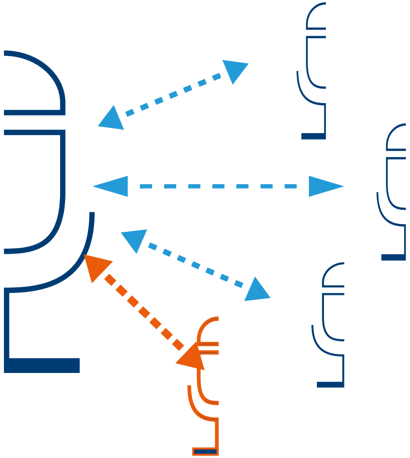
Limitless connectivity



Prioritization of MCX traffic



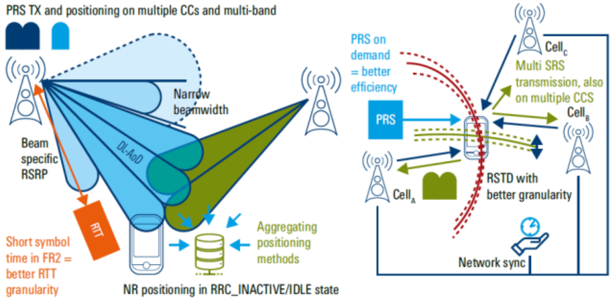
Efficient group communication, e.g. inter-organization MCPTT possible



MCX uses other 5G technologies:

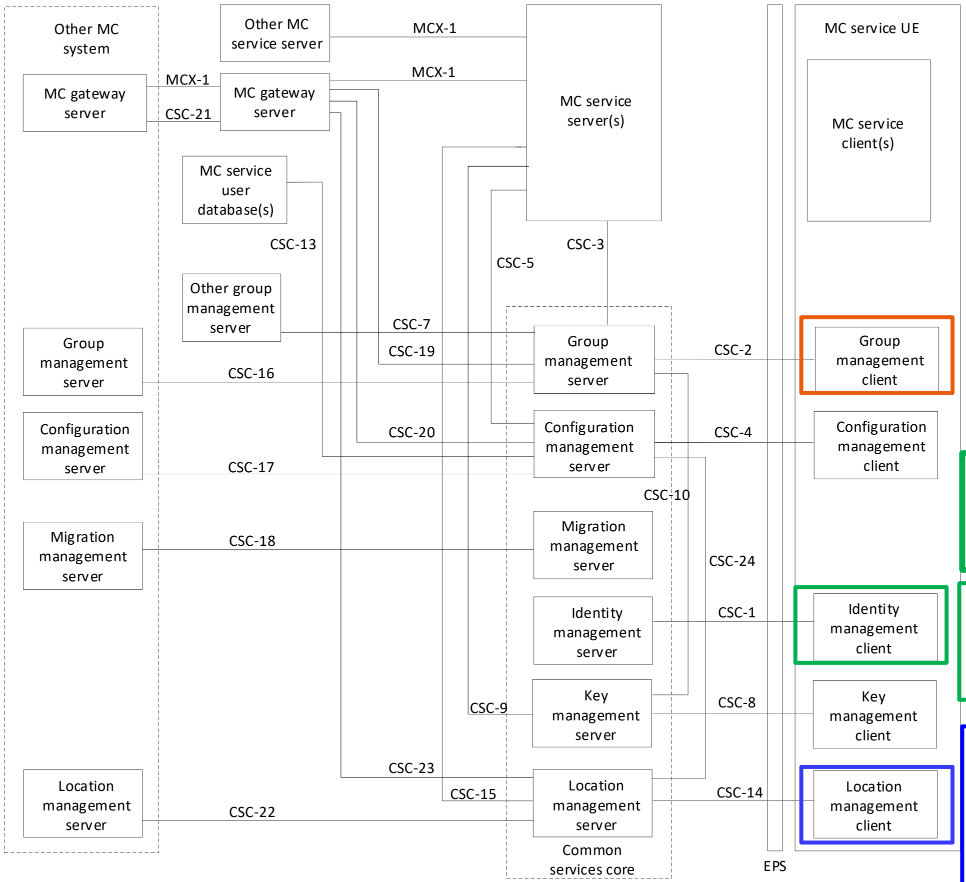
- IAB
- NTN
- Sidelink
- Sidelink relay
- 5G positioning

Accurate positioning (challenge: first responders, indoor, no visibility)



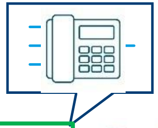
5G MISSION CRITICAL COMMUNICATIONS (MCX)

MCX introduces a „complex“ functional model. Just some aspects of reaching out to a MCX-UE



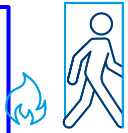
A MCX-UE is called because it belongs to a group

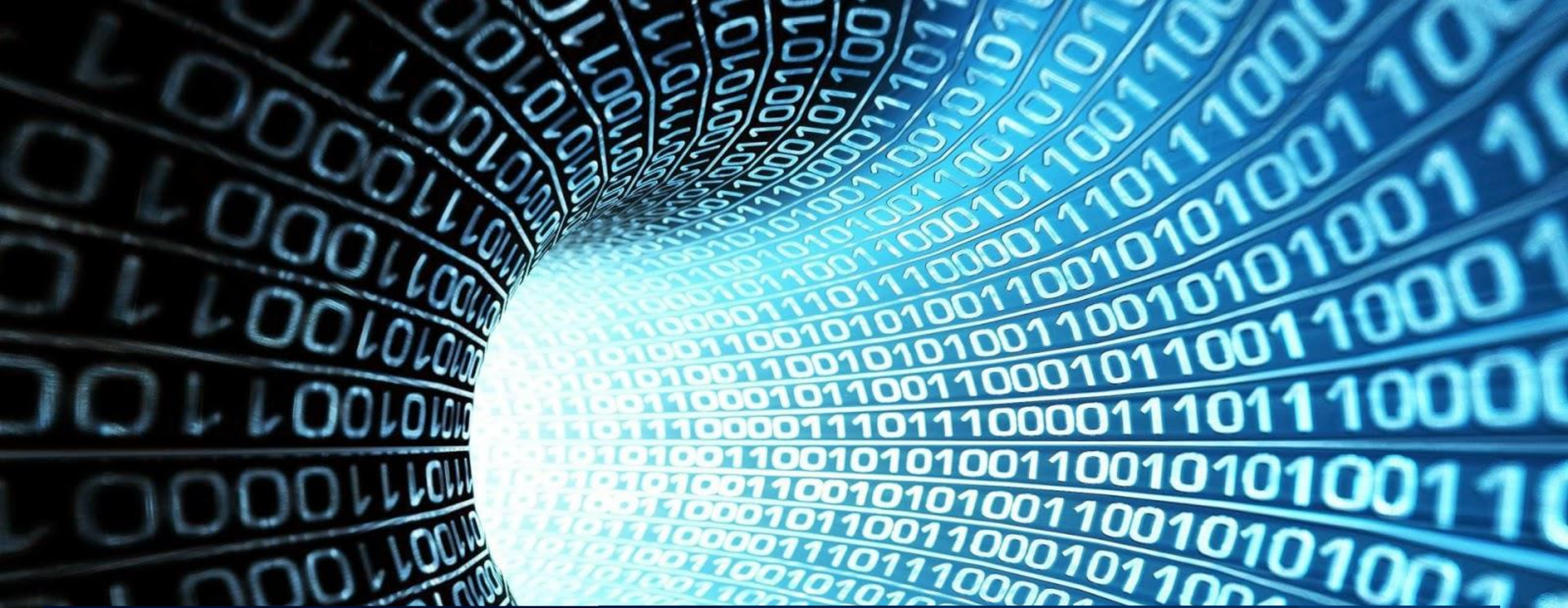
A MCX-UE is addressed by its name (e.g. phone number)



A MCX-UE is addressed by its function (e.g. education, profession)

A MCX-UE is addressed based on its location





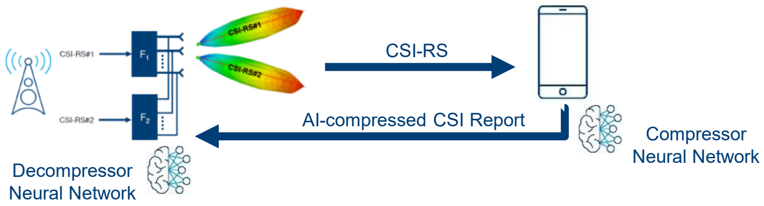
The ongoing evolution of 5G

ARTIFICIAL INTELLIGENCE (AI) IN 5G

3GPP REL-18/19: AI-NATIVE AIR INTERFACE

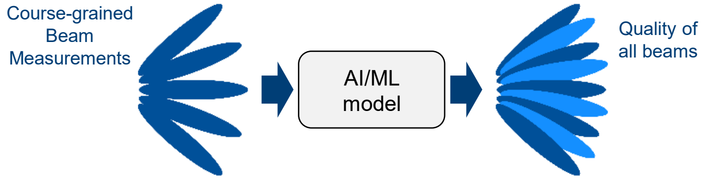
1. CSI Feedback Enhancements

- *Compression:* Autoencoder-based compression of channel state information transmitted from user device to base station
- *Prediction:* Prediction of channel state information to reduce frequency of transmission



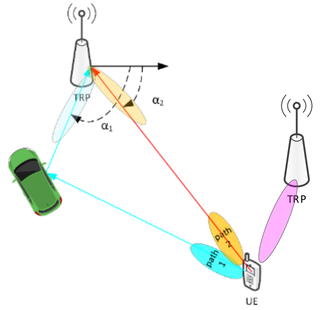
2. Beam Management

- *Spatial Prediction:* Infer best overall beams from measurements performed on only subset of beams
- *Time Prediction:* Which will be the best beams in the future?



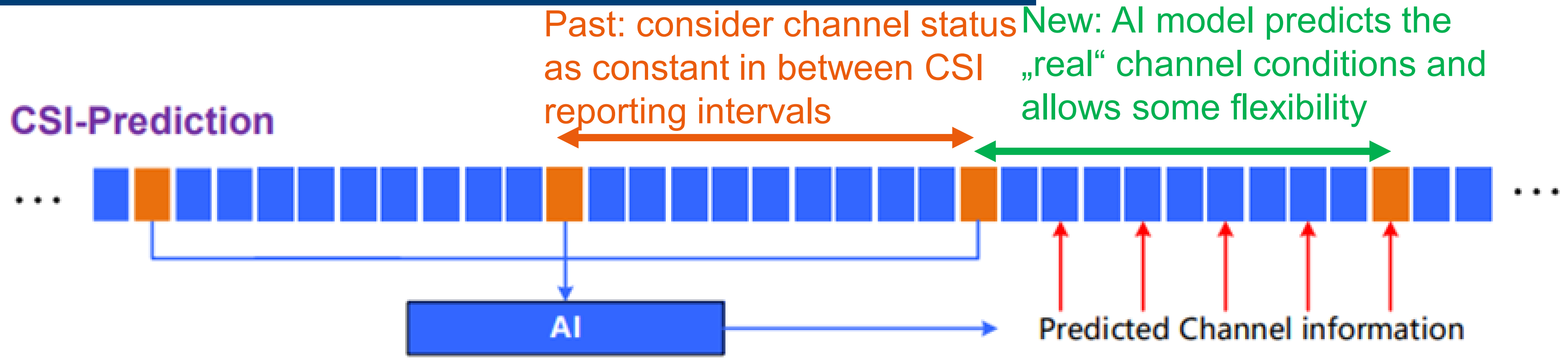
3. Position Accuracy Enhancements

- AI/ML-based inference of user device location based on channel estimates

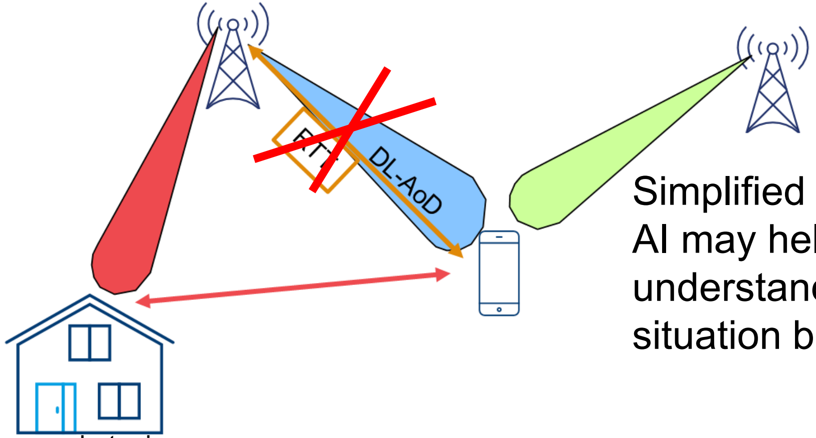


5G – AI FIRST USE CASES

AI to learn channel, predict and reduce #CSI signals needed

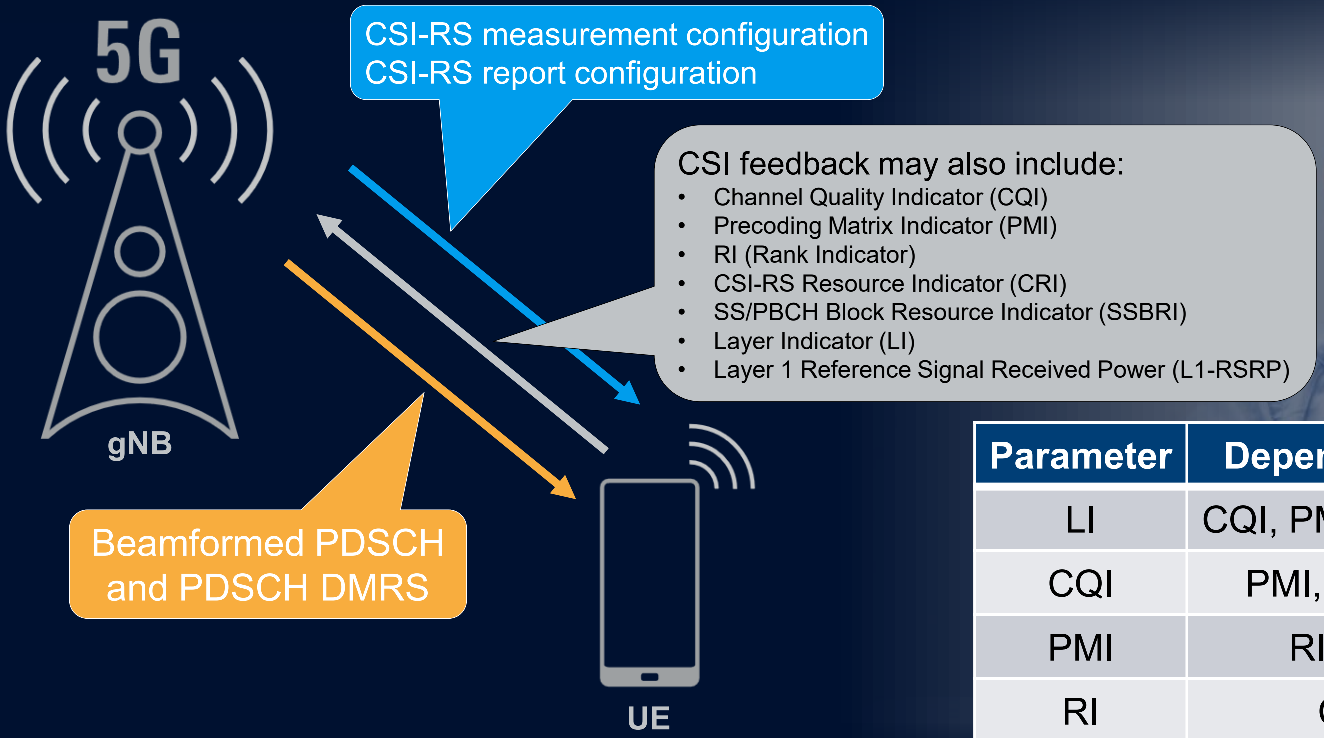


AI to enhance the position estimates + verify position determination



Simplified example: AI may help to understand the real situation better

MEASURING AND REPORTING CHANNEL QUALITY



Parameter	Dependencies
LI	CQI, PMI, CRI, RI
CQI	PMI, RI, CRI
PMI	RI, CRI
RI	CRI

WHY AI/ML FOR CSI-FEEDBACK ENHANCEMENT?

	Information fields X_1					
	$i_{1,1}$	$i_{1,2}$	$i_{1,8,1}$	$i_{1,8,2}$	$i_{1,8,3}$	$i_{1,8,4}$
Rank=1 $N_3 \leq 19$	$\lceil \log_2(O_1 O_2) \rceil$	$\left\lceil \log_2 \binom{N_1 N_2}{L} \right\rceil$	$\lceil \log_2 K^{NZ} \rceil$	N/A	N/A	N/A

	Information fields X_2											
	$i_{2,3,1}$	$i_{2,3,2}$	$i_{2,3,3}$	$i_{2,3,4}$	$i_{1,5}$	$i_{1,6,1}$	$i_{1,6,2}$	$i_{1,6,3}$	$i_{1,6,4}$	$\{i_{2,4,l}\}_{l=1,\dots,\upsilon}$	$\{i_{2,5,l}\}_{l=1,\dots,\upsilon}$	$\{i_{1,7,l}\}_{l=1,\dots,\upsilon}$
Rank= 1 $N_3 \leq 19$	4	N/A	N/A	N/A	N/A	$\left\lceil \log_2 \binom{N_3 - 1}{M_1 - 1} \right\rceil$	N/A	N/A	N/A	$3(K^{NZ} - 1)$	$4(K^{NZ} - 1)$	$2LM_1$

Number of CSI-RS antenna ports, $P_{CSI\text{-}RS}$	(N_1, N_2)	(O_1, O_2)
4	(2,1)	(4,1)
8	(2,2)	(4,4)
	(4,1)	(4,1)
12	(3,2)	(4,4)
	(6,1)	(4,1)
16	(4,2)	(4,4)
	(8,1)	(4,1)
24	(4,3)	(4,4)
	(6,2)	(4,4)
	(12,1)	(4,1)
32	(4,4)	(4,4)
	(8,2)	(4,4)
	(16,1)	(4,1)

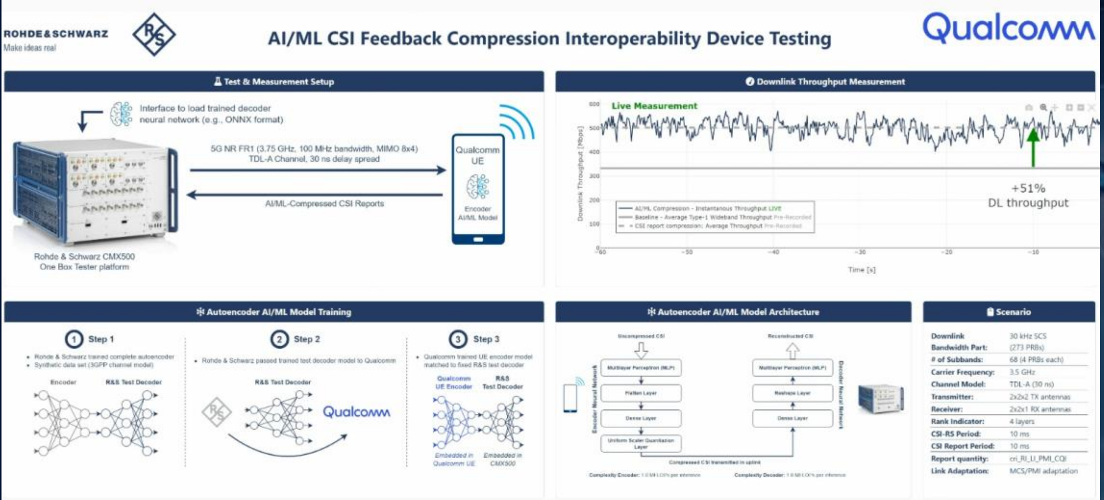
paramCombination-r16	L	p_υ		β
		$\upsilon \in \{1,2\}$	$\upsilon \in \{3,4\}$	
1	2	¼	1/8	¼
2	2	¼	1/8	½
3	4	¼	1/8	¼
4	4	¼	1/8	½
5	4	¼	¼	¾
6	4	½	¼	½
7	6	¼	-	½
8	6	¼	-	¾

- Example 1: 32 AP, Rank 1, 18 subbands, L = 6 beams: 287 bits
  - Example 2: 32 AP, Rank 2, 18 subbands, L=6 479 bits
  - Example 3: 32 AP, Rank 2, 18 subbands, L=4 307 bits
- AI/ML offers promising solutions by optimizing CSI feedback through predictive modeling and data-driven compression, aiming to reduce the feedback overhead significantly

MOBILE WORLD CONGRESS 2025
DEMO IMPRESSIONS

Demoed @

MWC GSMA | BARCELONA 3 – 6 MARCH 2025



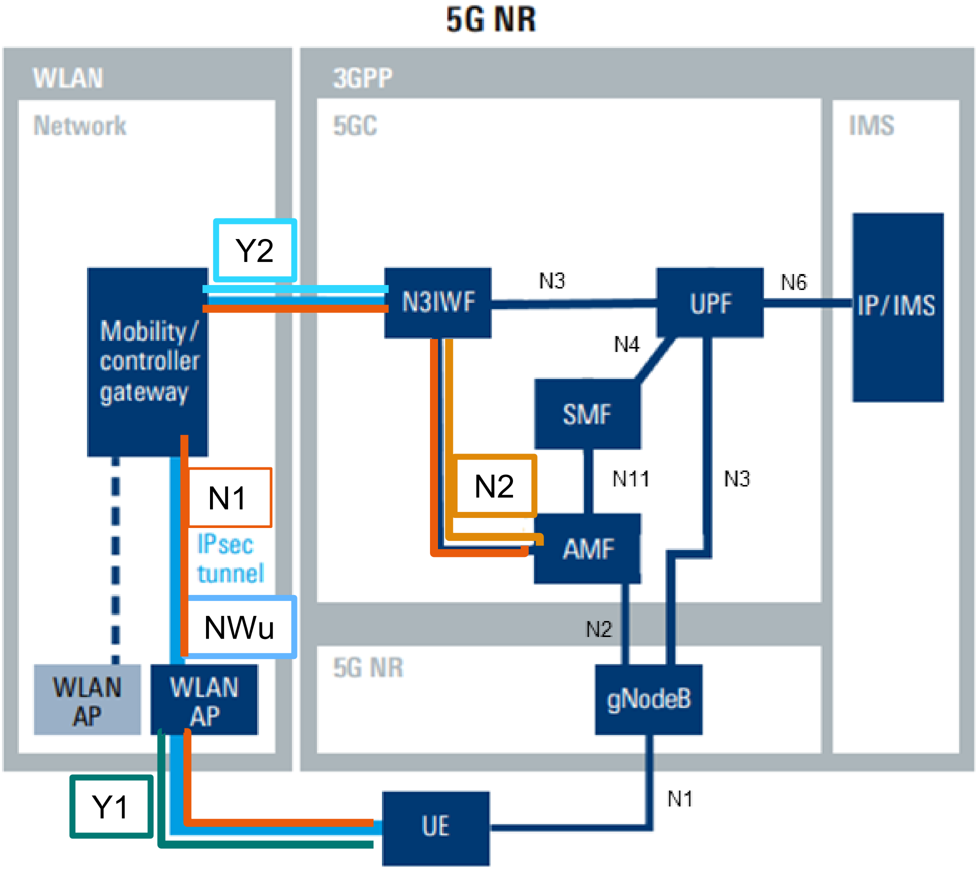
► Interoperability testing of 3GPP Rel-18/19 CSI Feedback Compression based on R&S CMX500

► Import and inference of ONNX-formatted decoder AI/ML models

The ongoing evolution of 5G

5G INTERWORKING - 5G AND WLAN CONVERGENCE

UNTRUSTED NON-3GPP ACCESS INTERWORKING (5G NR)

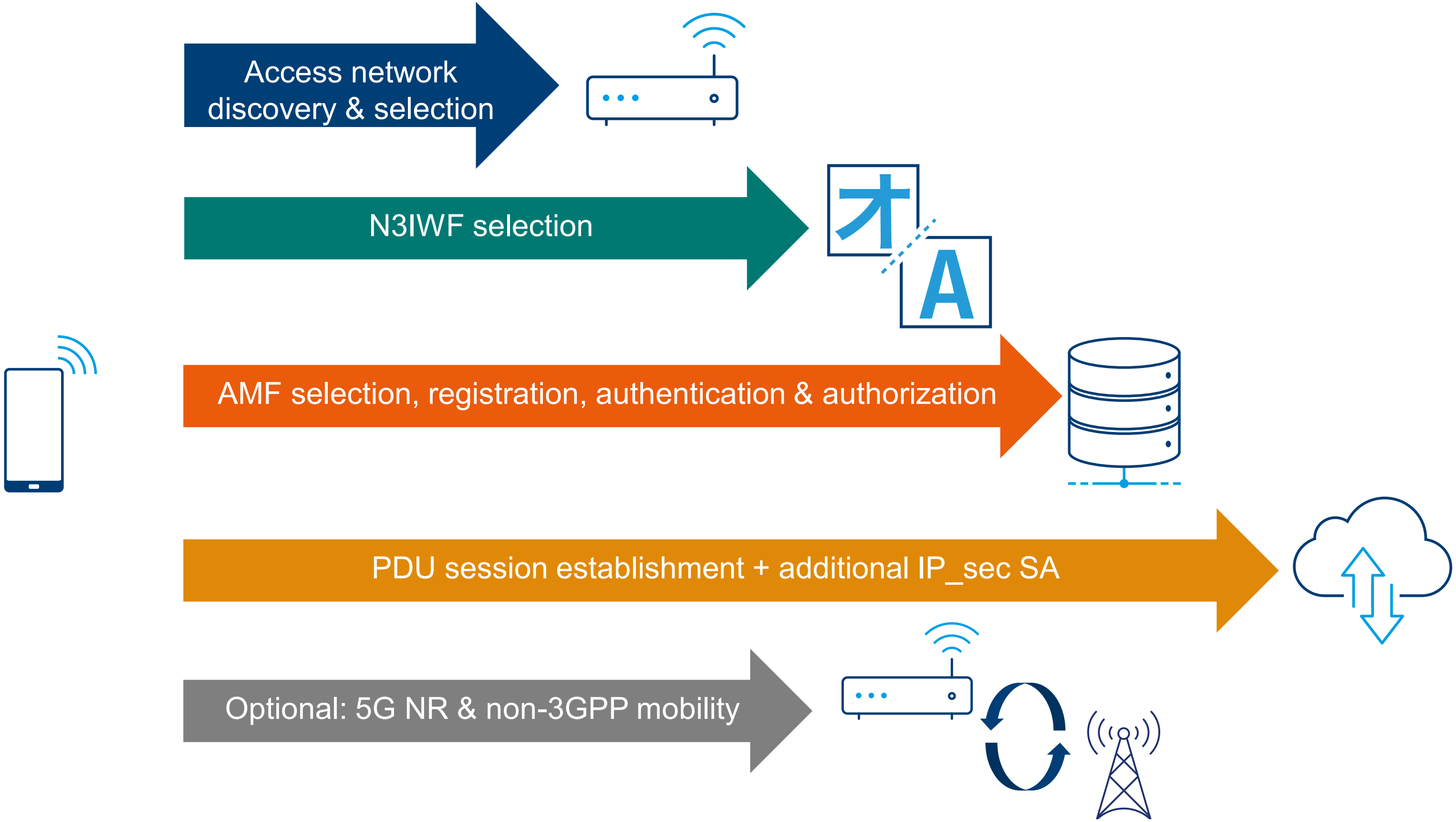


Reference points:

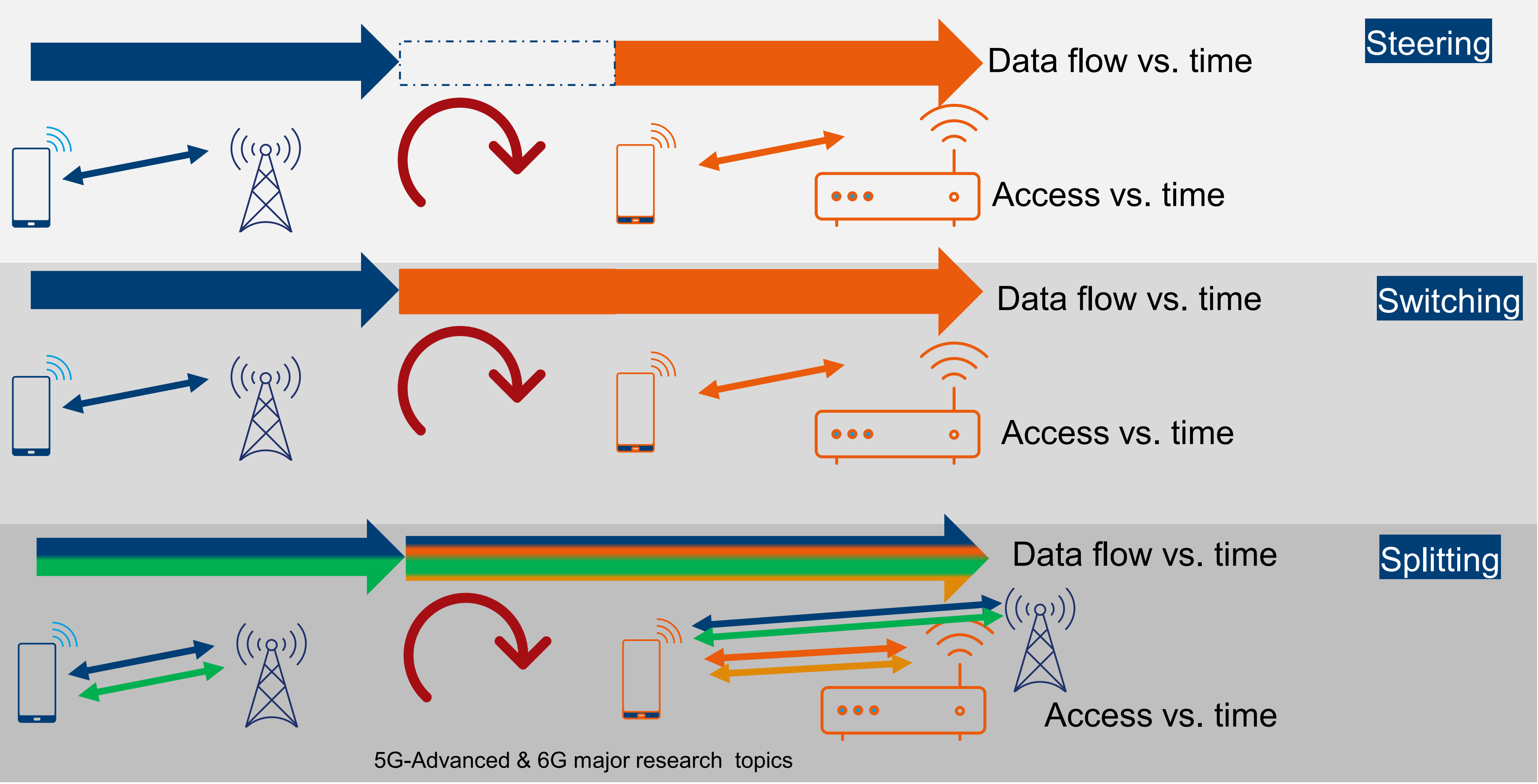
- N1 = reference point between UE and AMF (possible, one N1 for non-3GPP and one N1 for 3GPP access)
- N2 = reference point between RAN/N3IWF and AMF
- Y1 = reference point between UE and non-3GPP access, e.g. WiFi AP
- Y2 = reference point between non-3GPP access and N3IWF
- NWu = reference point between UE and N3IWF

- Main component: Non-3GPP interworking function (N3IWF)

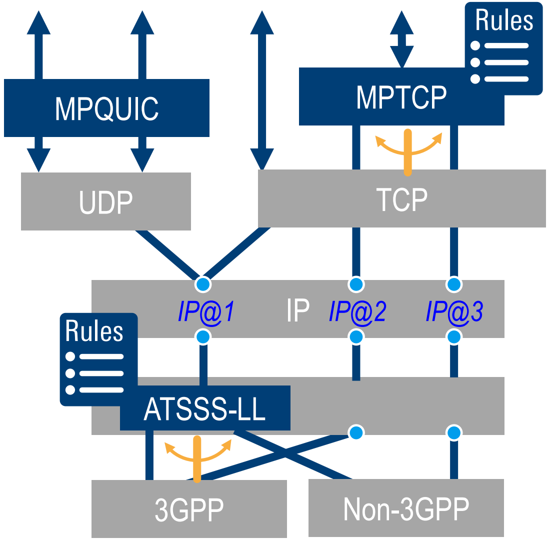
5G INTERWORKING PROCEDURES - OVERVIEW



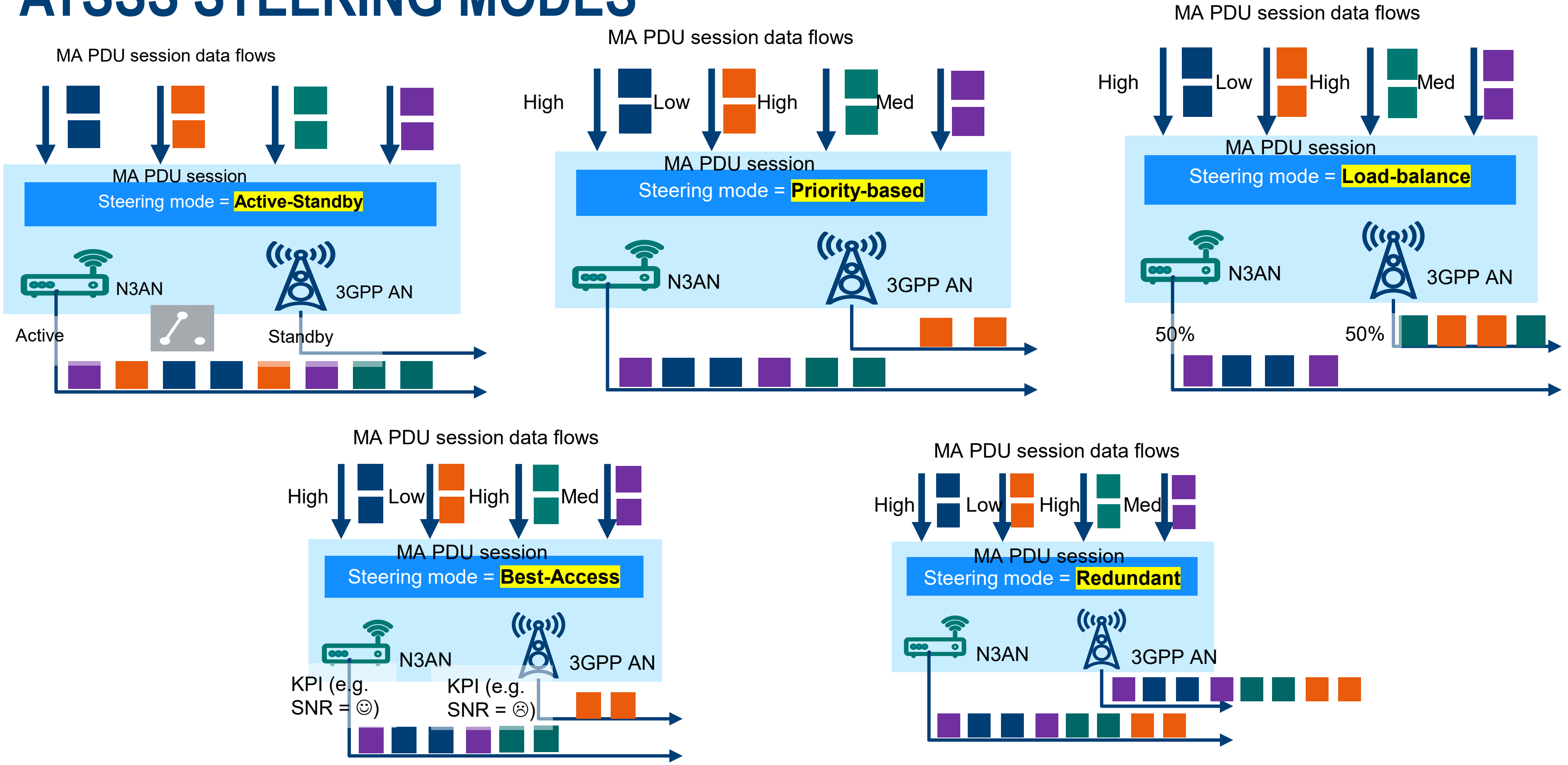
ATSSS: STEERING, SWITCHING, SPLITTING



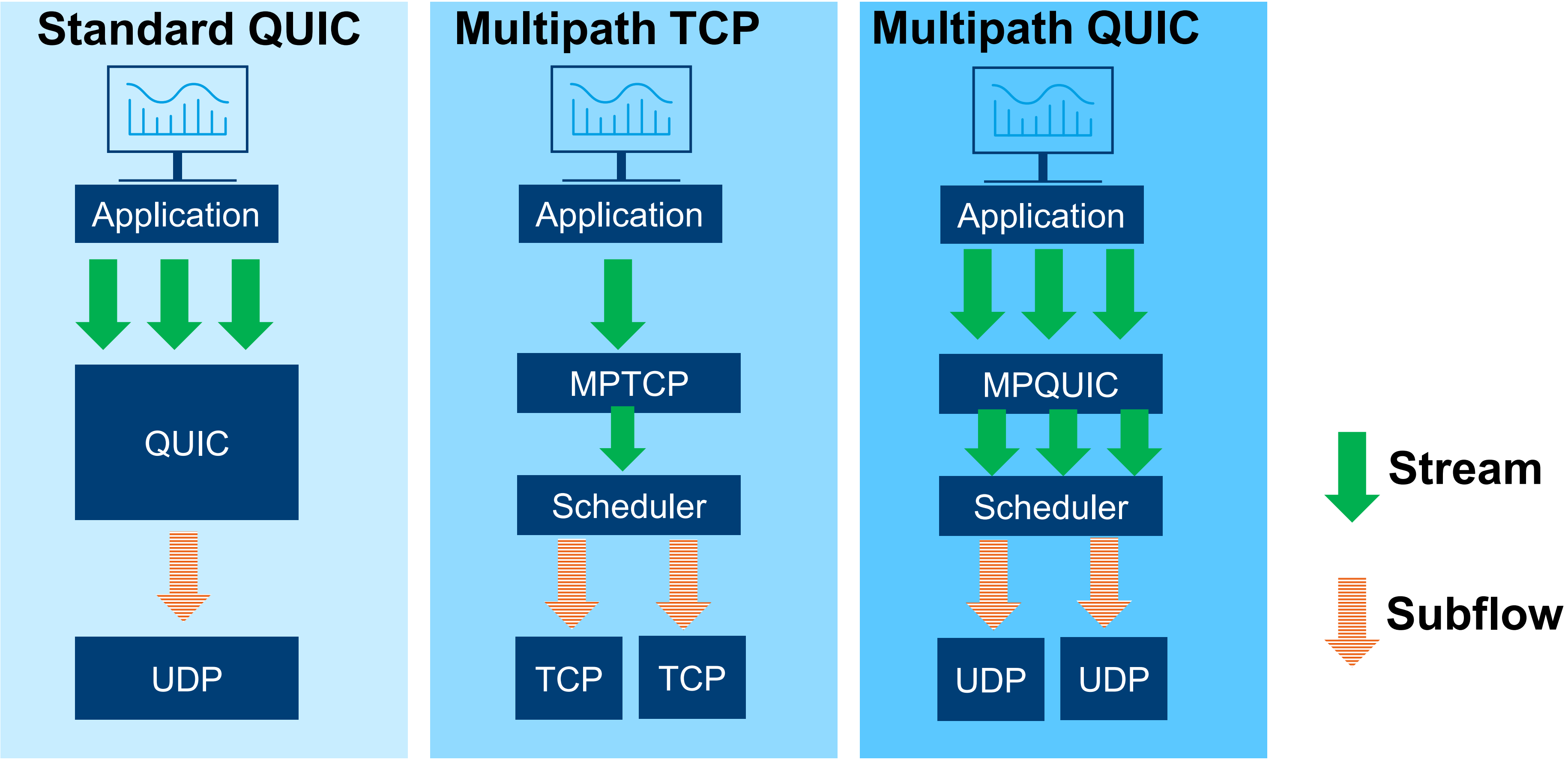
ACCESS TRAFFIC STEERING, SWITCHING AND SPLITTING (ATSSS)



ATSSS STEERING MODES



QUIC, MPTCP AND MPQUIC

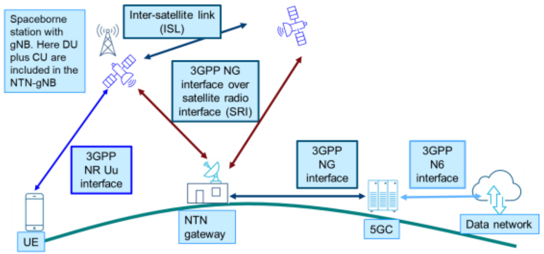


Non-terrestrial networks (NTN)

5G NTN EVOLUTION

NON-TERRESTRIAL NETWORKS - EVOLUTION

Rel. 17 baseline	Rel. 18 enhance	Rel. 19 phase 3
Transparent payload	Mobility enh. (TN - NTN)	Regenerative payload
FR1 – FDD/TDD	FR1 + FR2 (Ku & Ka-band)	Uplink enh. (high power UE)
IoT-NTN NR-NTN	Coverage enhancements	Satellite PDSCH power sharing
GNSS support	Network based UE location ver.	RedCap & NTN capable UE
Updated protocol stack	IoT-NTN voice call	Inter-RAT HO (EUTRA TN – NR NTN)



5G NTN SPECTRUM & UE ASPECTS

FR1: NTN bands (R17)

Band	Region	Related bands	Band type	UL low MHz	UL high MHz	DL low MHz	DL high MHz
n253	EU	L-ext	FDD	1668.0	1675.0	1518.0	1525.0
n254	EU	L+53	FDD	1610.0	1626.5	2483.5	2500.0
n255	EU	n65	FDD	1626.5	1660.5	1525.0	1559.0
n256	NA	n24	FDD	1980.0	2010.0	2170.0	2200.0

FR2-1N: new NTN bands (R18). FR2-1N range 17.3 – 52.6GHz

Band	Region	Band type	UL low MHz	UL high MHz	DL low MHz	DL high MHz
n510	US	FDD	27500	28350	17300	20200
n511	US	FDD	28350	30000	17300	20200
n512	EU	FDD	27500	30000	17300	20200

„FR3" bands Ku: requested in R19

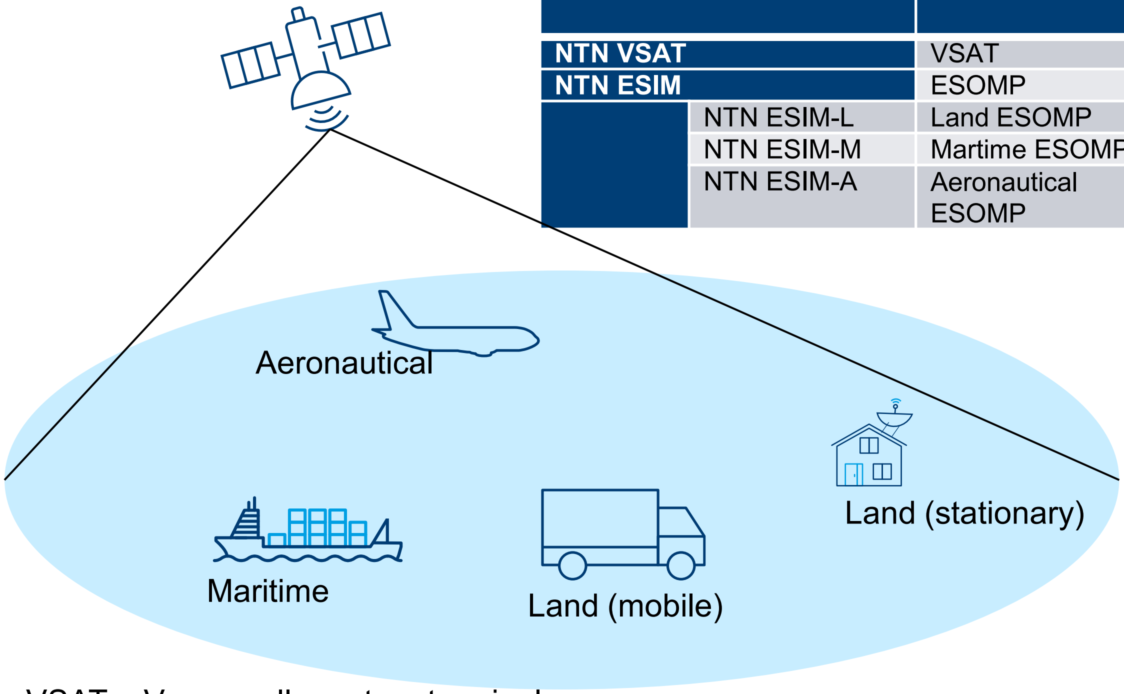
Band	Region	Band type	UL (Earth to space) GHz	DL (Space to Earth) MHz
Ku	Region 1	FDD	12.75 – 13.25 & 13.75 – 14.5	10.7 – 12.75
Ku	Region 2	FDD	12.75 – 13.25 & 13.75 – 14.5	10.7 – 12.7

UE aspects for NTN

Link level assumptions	FR1 NTN-UE or IoT-UE	FR2-1N VSAT UE
TX power	23dBm ± 2dB (200mW) (note: more likely 23 dBm + 2dB)	33 dBm (2W)
Antenna type	Omnidirectional	60cm aperture diameter
Antenna gain	TX/RX 0dBi	TX: 43.2 dBi / RX: 39.7 dBi
Noise figure	9 dB	1.2 dB
Polarization	Linear (dual polarized possible)	Circular polarized phased array antenna

NTN REL. 18 UE CATEGORY DISCUSSION (>10 GHZ)

Proposed naming in RAN4		CEPT	FCC	ACMA	Mobility	Satellite tracking feature
NTN VSAT		VSAT	Earth station	VSAT	No, fixed	No
NTN ESIM		ESOMP	ESIM	ESIM	Yes	Yes
	NTN ESIM-L	Land ESOMP	ESIM / VMES	ESIM-L		
	NTN ESIM-M	Martime ESOMP	ESIM / ESAA	ESIM-M		
	NTN ESIM-A	Aeronautical ESOMP	ESIM / ESV	ESIM-A		

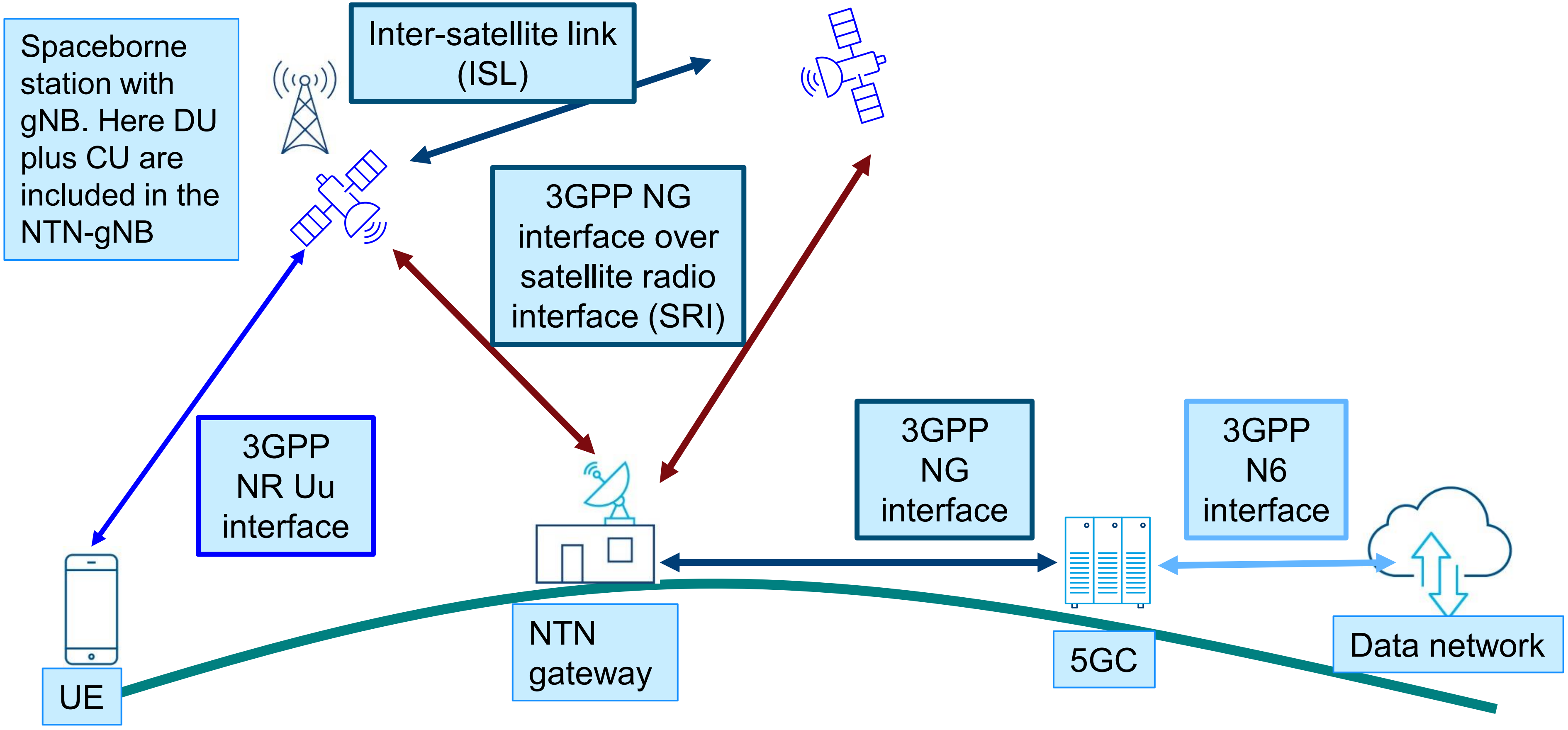


RRM discussions:
Case-1: Stationary UE for GSO
Case-2: Stationary UE for LEO
Case-3: Mobile UE for GSO

UE architectures:
Fully electronically-steered beam UEs (Type 1)
Fully mechanically-steered beam UEs (Type 2)

VSAT = Very small aperture terminal
ESIM = Earth station in motion
ESOMP = Earth station on mobile platform

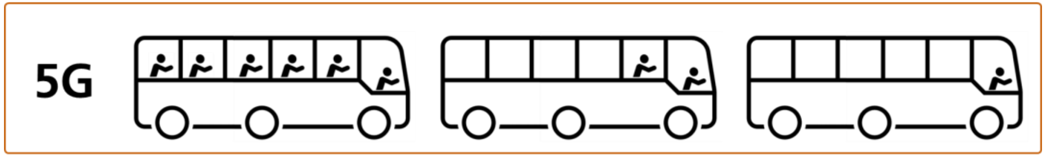
NTN: REGENERATIVE PAYLOAD ARCHITECTURE



The ongoing evolution of 5G

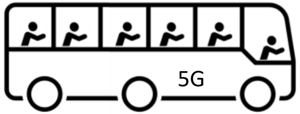
SUSTAINABILITY & NETWORK ENERGY SAVING

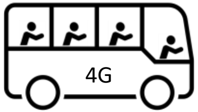
NETWORK DESIGN EVOLUTION



5G: "We designed a "bus"! Very efficient! But what if there is only one passenger?" Cicek Cavdar, KTH

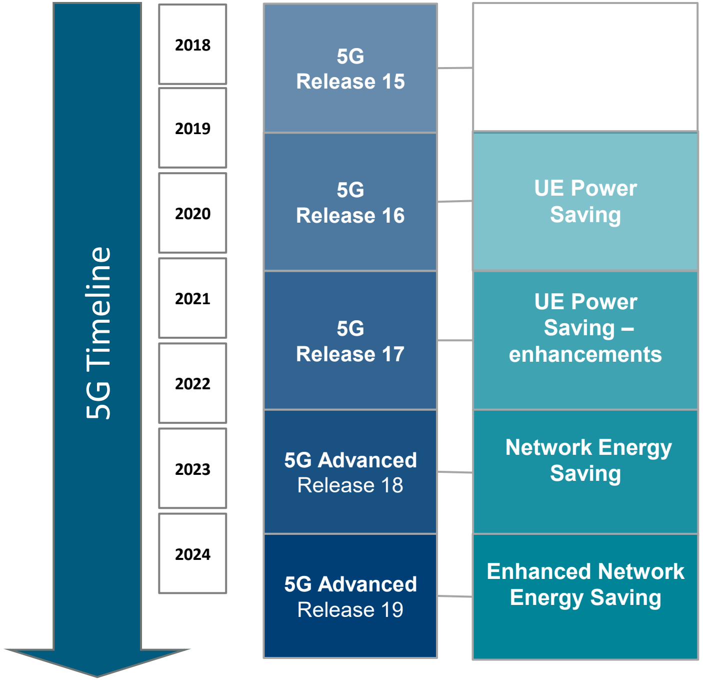
5G can carry much more data than 4G





5G is **more energy efficient** than **4G** but **consumes more energy**

What should 6G be?

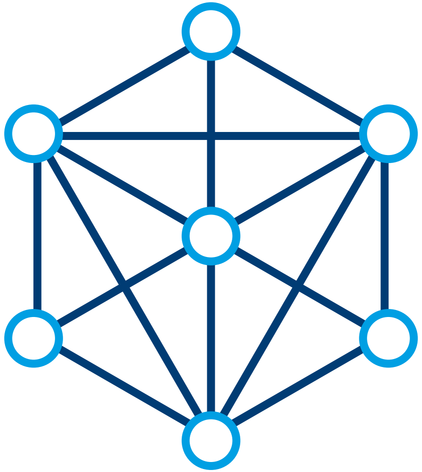


Source: Fraunhofer IIS

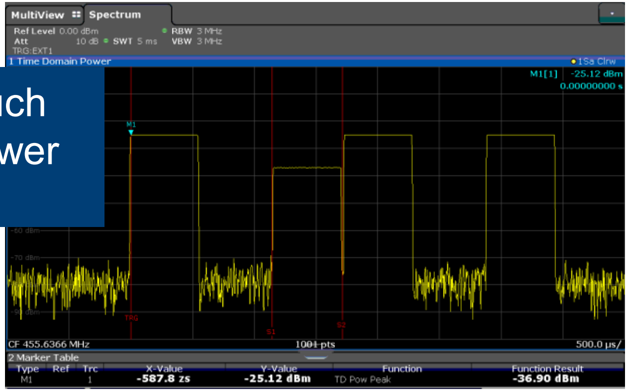
NETWORK ENERGY SAVING (NES)

ES = Energy saving
EE = Energy efficiency
EC = Energy consumption

1. NES affects the entire network



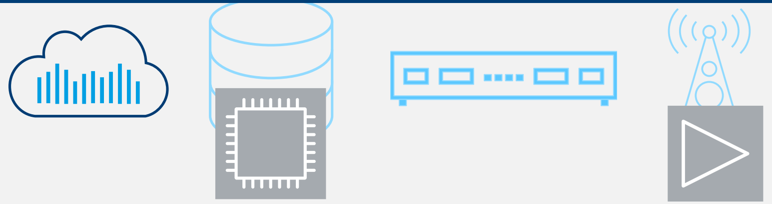
2. NES is much more than power ON/OFF



3. NES requires cooperation between RAN and UE

NETWORK ENERGY EFFICIENCY

Holistic approach: From cloud to component, energy saving methods in the entire 5G system



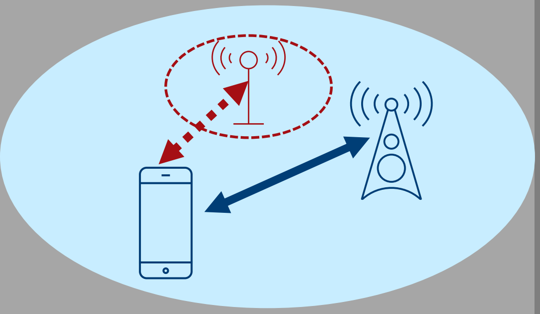
ETSI & 3GPP definition: Energy efficiency

$$EE_{MN,DV} = \frac{DV_{MN}}{EC_{MN}}$$

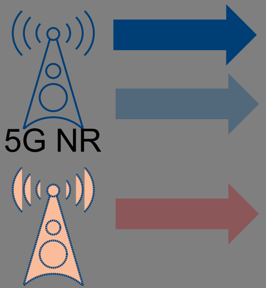
Data volume / energy consumption

$$EE_{MN,CoA} = \frac{CoA_{des.MN}}{EC_{MN}}$$

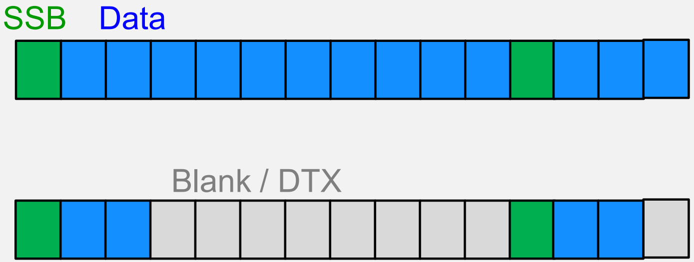
Designated coverage area / energy consumption



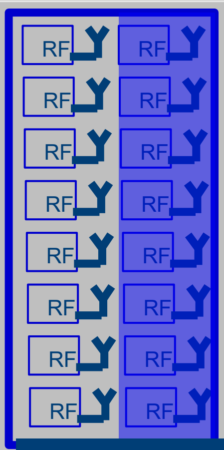
Turn on/off cells



Activate / de-activate carriers / RAT



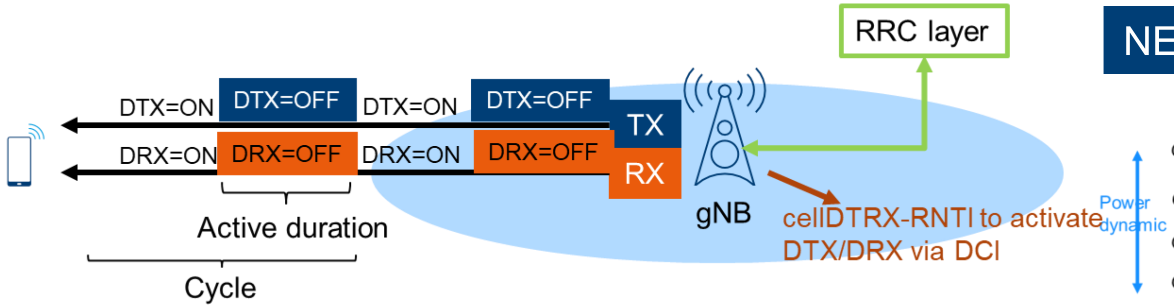
Advanced sleep mode (ASM)



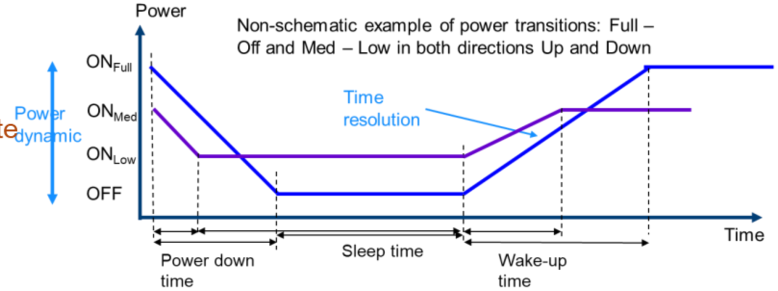
Turn on/off RF

NES: SUCCESSFUL COOPERATION BETWEEN UE AND RAN

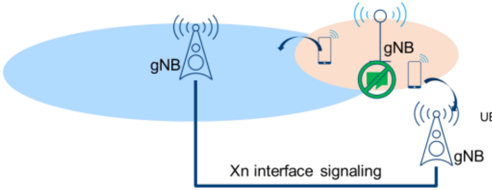
To facilitate gNB downlink RX and TX, UE can be configured with a periodic cell DTX/DRX pattern



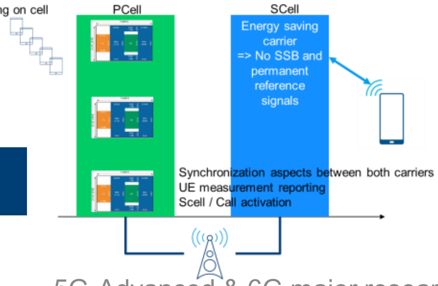
NES: Testing aspects, e.g. power on/off

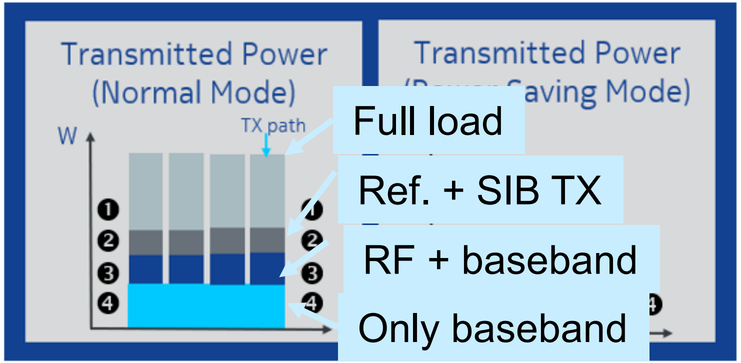


Intra/inter-system cell on/off



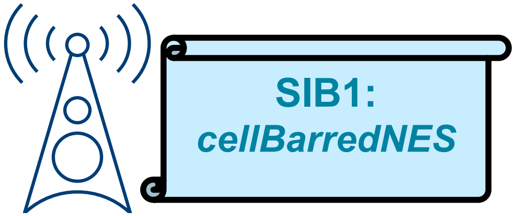
SCell energy saving carrier

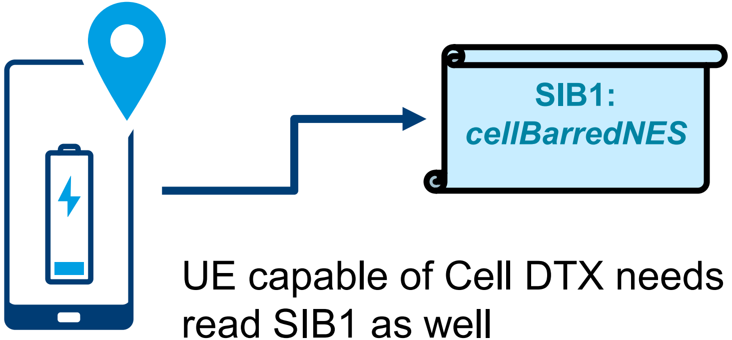




NES REL. 18 – CELL SELECTION/RE-SELECTION ASPECTS

Update of SIB1 with additional cell barring flag for NES



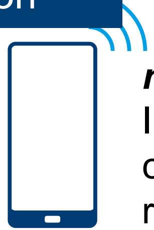


UE capable of Cell DTX needs to read SIB1 as well

The presence of this field indicates that the cell is allowed for UEs supporting NES cell DTX/DRX

UE not capable of Cell DTX follows MIB = barring indication

Update of UE capability indication



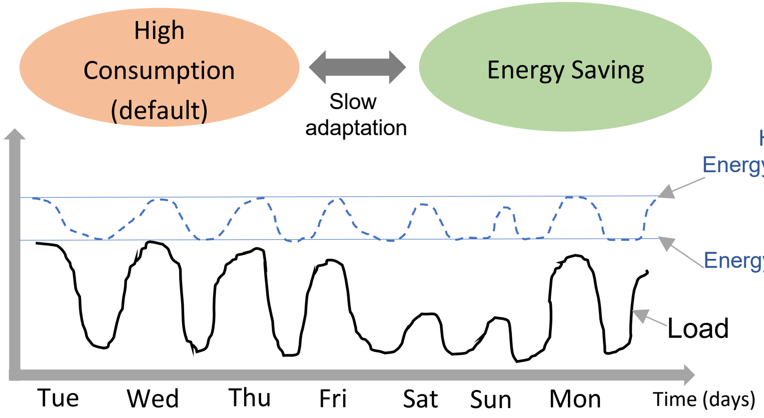
nes-CellDTX-DRX-r18

Indicates whether the UE supports cell DTX and/or DRX operation by RRC configuration. The supported number of cell DTX/DRX patterns per cell group is 2, regardless of each pattern is for cell DTX only, cell DRX only, or both.

6G VISION FOR ENHANCED NETWORK ENERGY SAVINGS

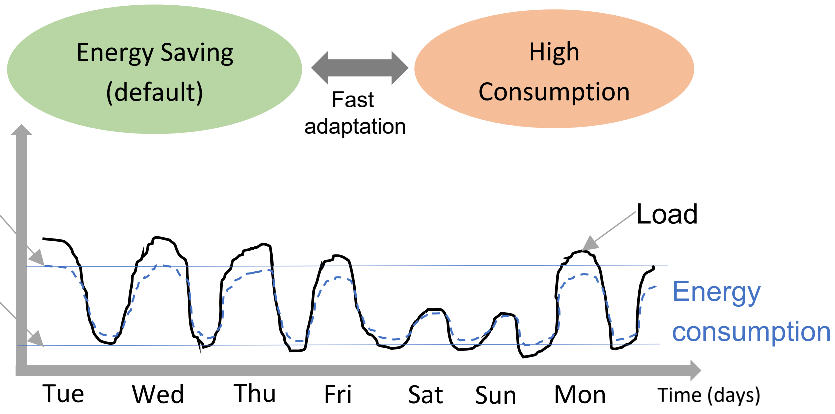
Today

- Network designed for high capacity
- Energy consumption: inelastic to load
- Basic NES techniques to opportunistically reduce energy consumption



Future

- Adaptive adjustment of energy consumption according to load
- Longer periods in energy saving states
- **AI-native design: Predict traffic load of networks and anticipate NES techniques**



THE “UNSTRUCTURED“ EVOLUTION OF 5G TOWARDS 6G

5G™

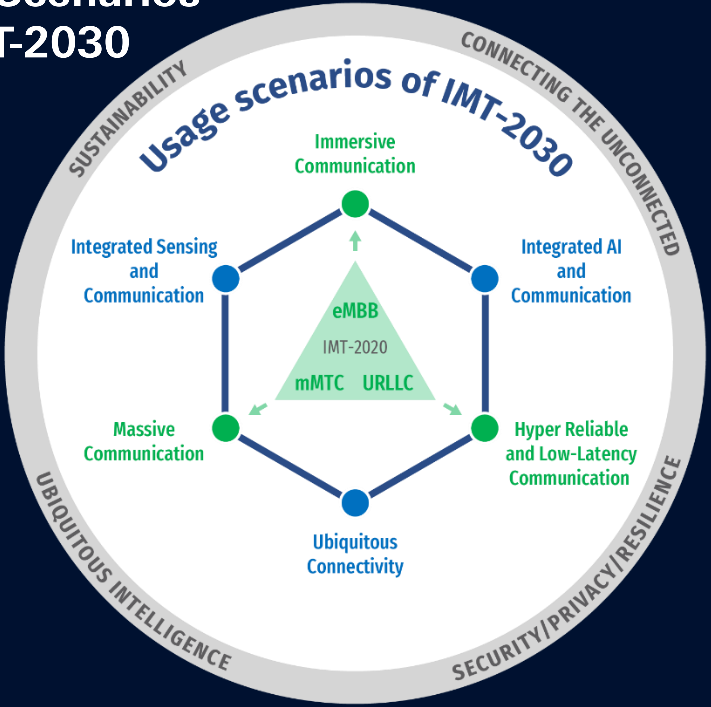
5G ADVANCED

6G™

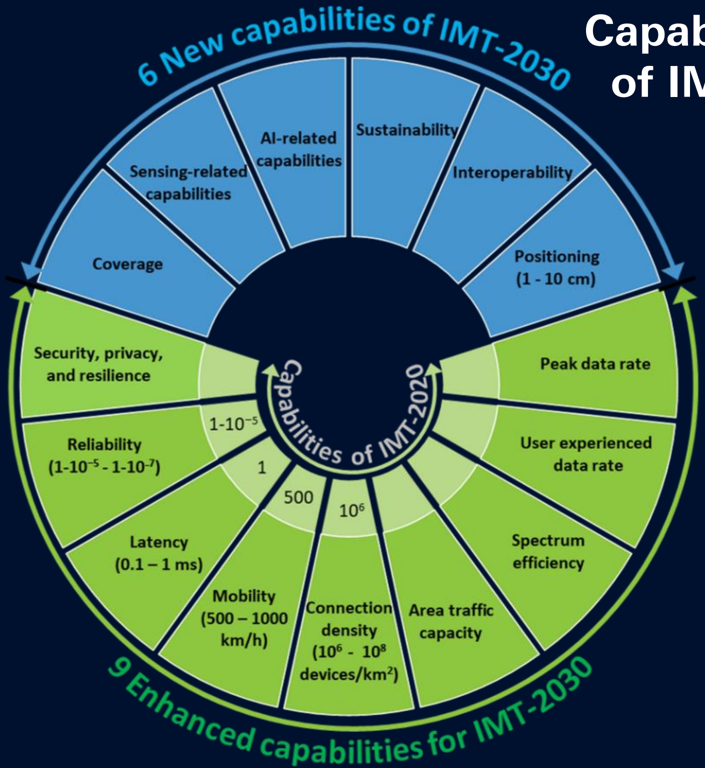
Evolution and not a revolution

IMT-2030 capabilities and usage scenarios

Usage Scenarios of IMT-2030



Capabilities of IMT-2030



RESEARCH AREAS FROM A T&M PERSPECTIVE

Spectrum for 6G: "FR3" and THz

Integrated sensing & communication

Artificial Intelligence and Machine Learning

Reconfigurable Intelligent Surfaces

Photonics, Visible Light Communication

New network topologies, distributed computing

Multiple access, new waveforms, channel coding

Ultra-massive MIMO

The Metaverse and eXtended Reality (XR)

Full-duplex communication

Security & Trustworthiness

A high-level overview of all these research areas is provided in one of our #THINKSIX videos

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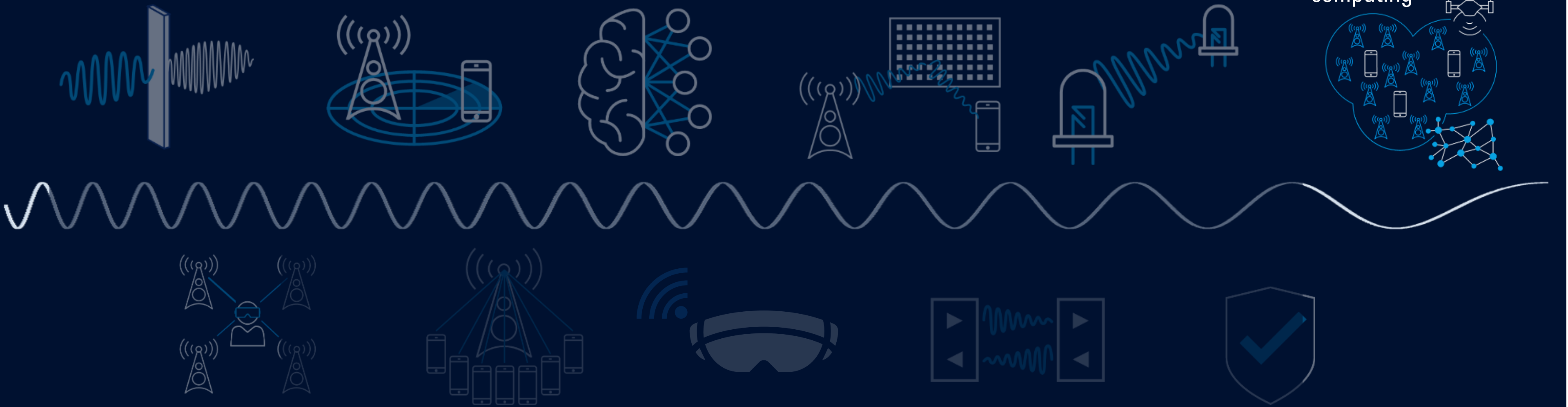

Multiple access, new waveforms, channel coding

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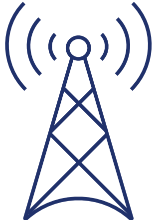
6G SYSTEM ARCHITECTURE – „PERSONAL“ NETWORKS

One example: The car of today
(Example: Reiners car, purchased Aug. 24)

Private

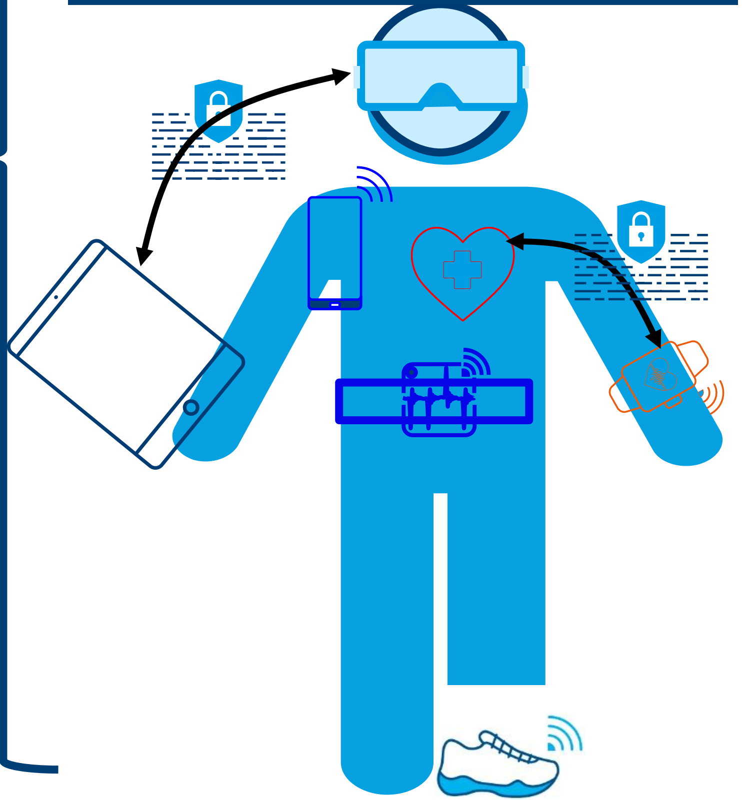
Company

Music

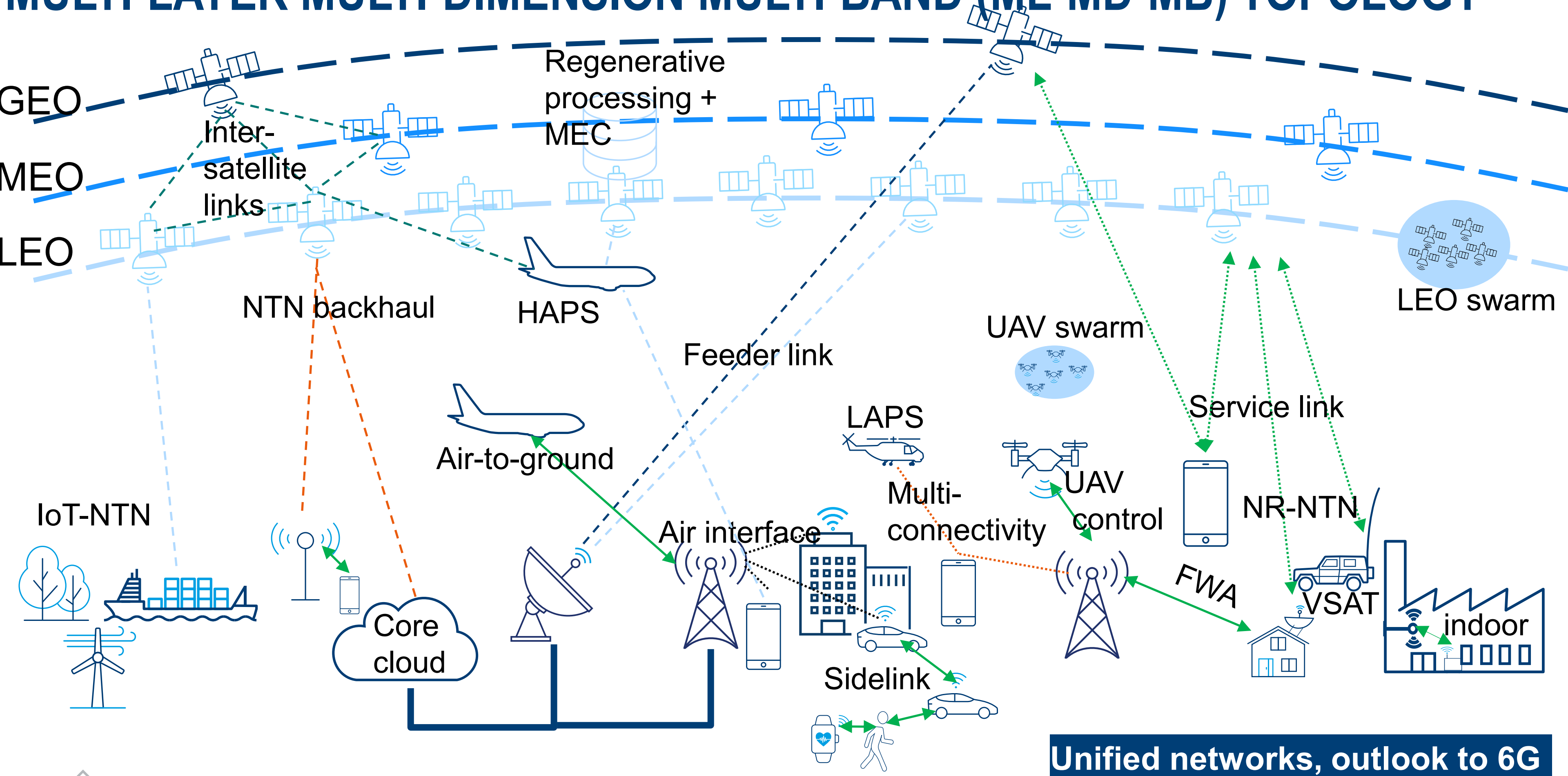


6G = “network of the networks“

One example: The future subscriber (personal IoT network)



MULTI-LAYER MULTI-DIMENSION MULTI-BAND (ML-MD-MB) TOPOLOGY



Unified networks, outlook to 6G

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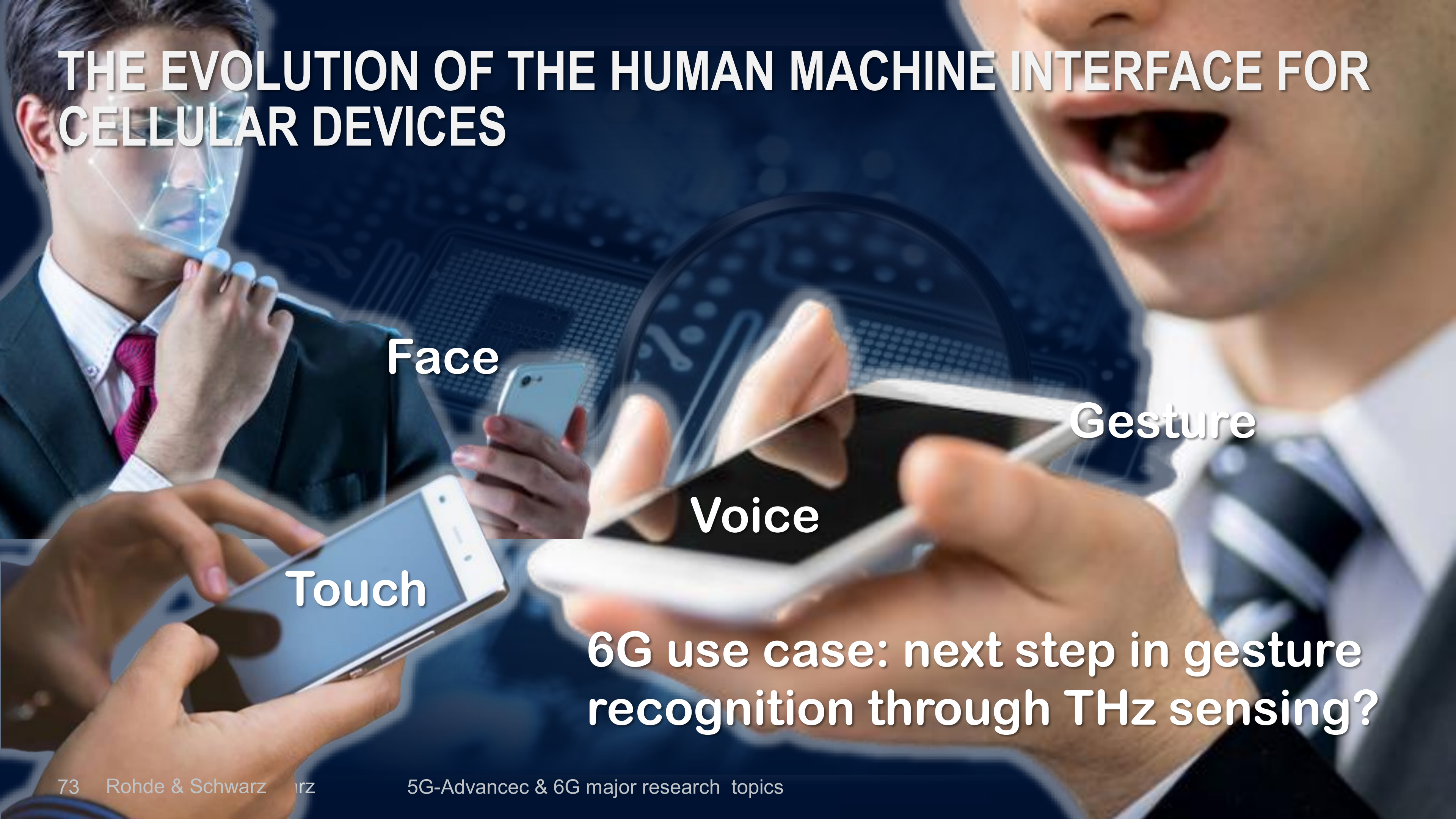
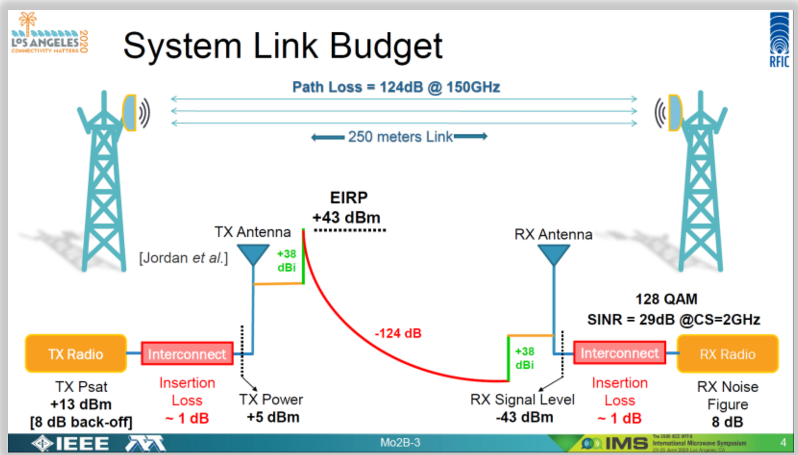
THE EVOLUTION OF THE HUMAN MACHINE INTERFACE FOR CELLULAR DEVICES

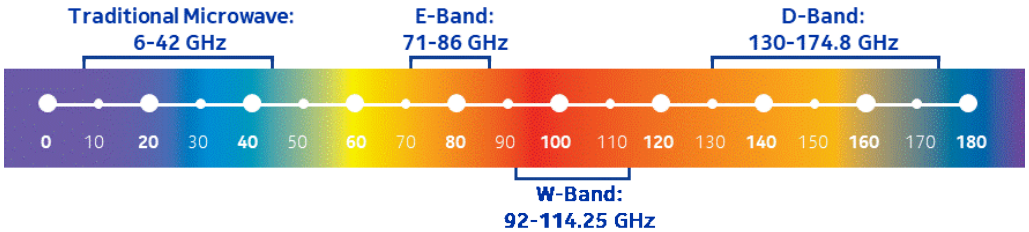


6G use case: next step in gesture recognition through THz sensing?

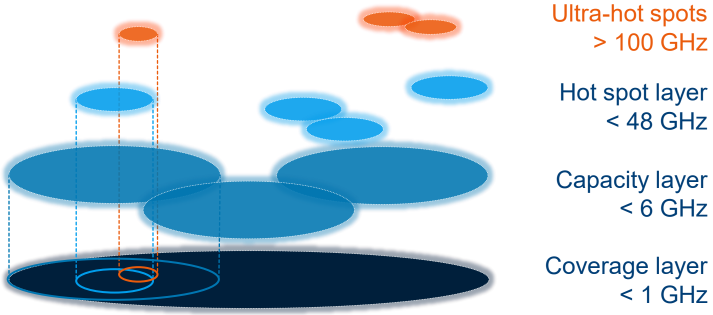
MORE LIKELY THE INITIAL USE CASE FOR SUB-THz

WIRELESS FRONT- AND BACKHAULING



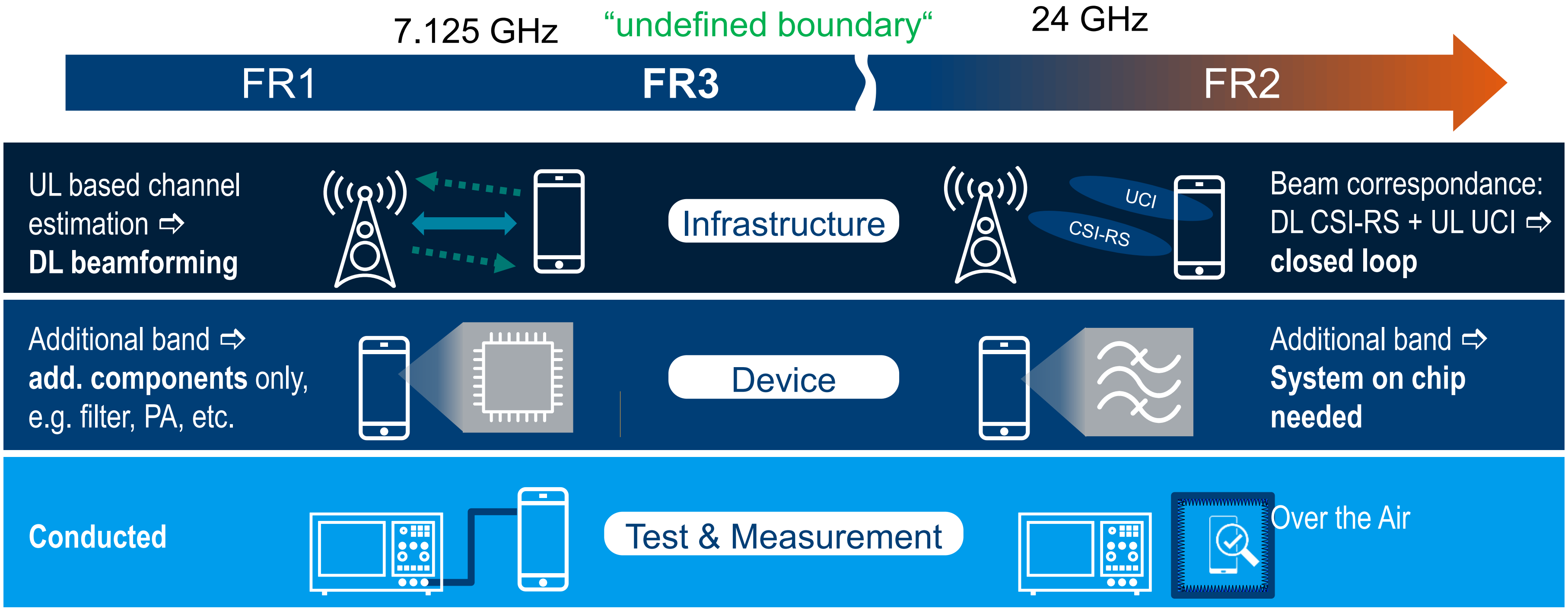


- ► Initial use case for D-Band is wireless backhaul and fronthaul applications
  - – Cellular: ultra-hot spots in combination with FR2?



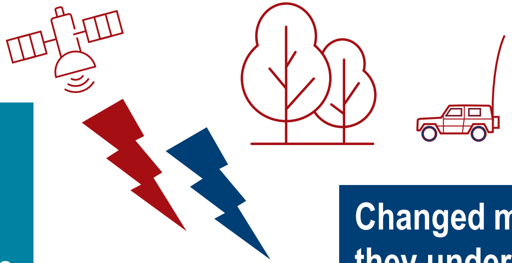
FREQUENCY RANGE 3 „“FR3“- 7-24GHz?

“FR3“ extends the known RF behaviour of FR1 (e.g. wave propagation + RF chain) but offers much wider bandwidth!



FR3, why is it different from legacy spectrum FR1 and FR2

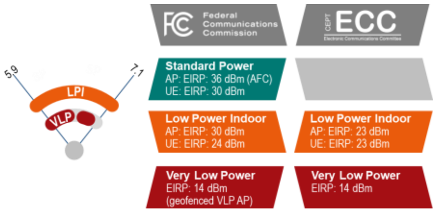
Challenge: "FR3" is already occupied by incumbent owners. Wireless needs to incorporate some spectrum coexistence methods and we need to improve spectrum efficiency!



Incorporate interference cancellation methodologies
6G = victim

Incorporate interference reduction methodologies
6G = aggressor

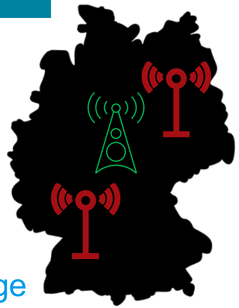
Example
WiFi7 with power reduction



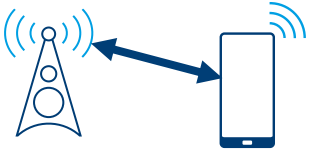
Changed mindset within regulatory bodies, they understand spectrum crunch

Past: Focus on TX side only: e.g. spectrum emission, ACLR limits, max. TX power

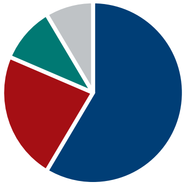
Future: Consider RX side as well: e.g. RX resistence & interference mitigation stragies



Example:
geolocation controlled spectrum usage

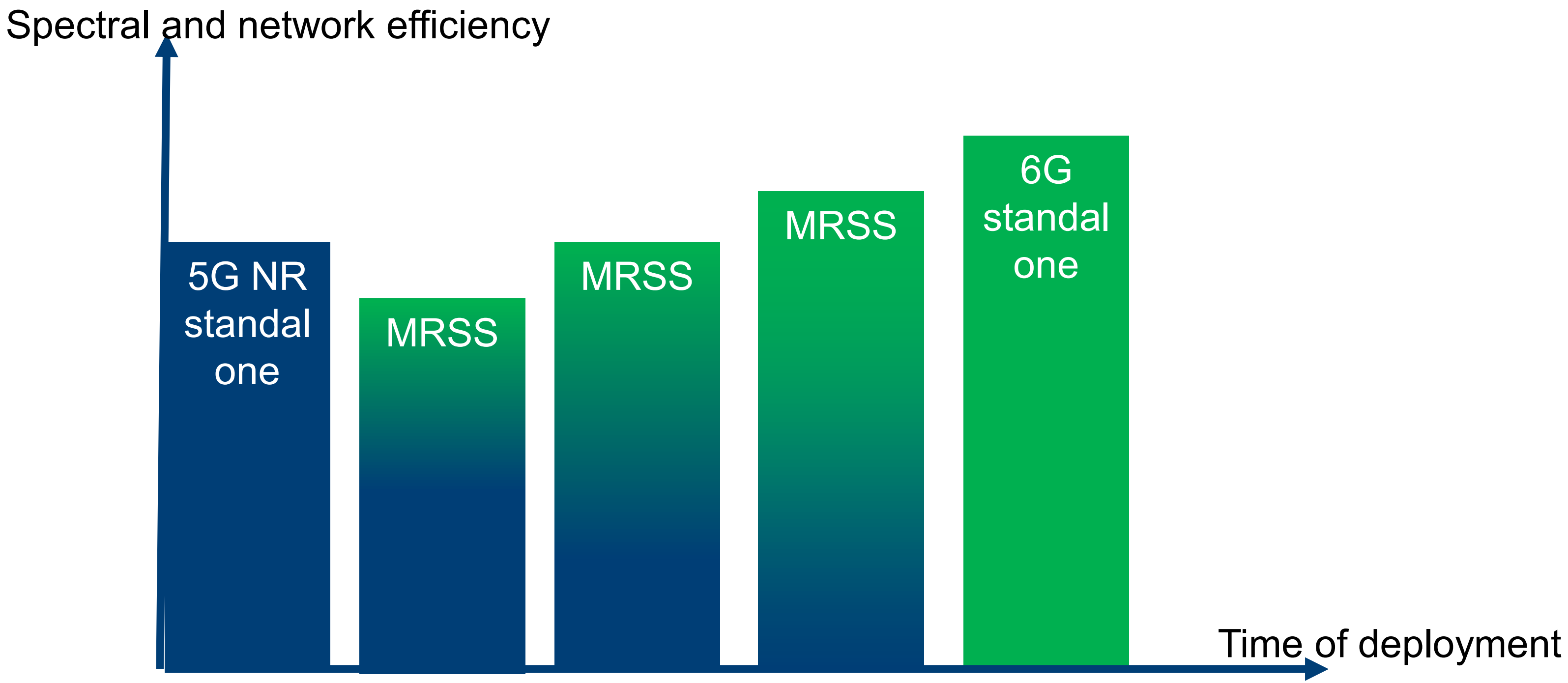


Example:
new methods for dynamic spectrum sharing



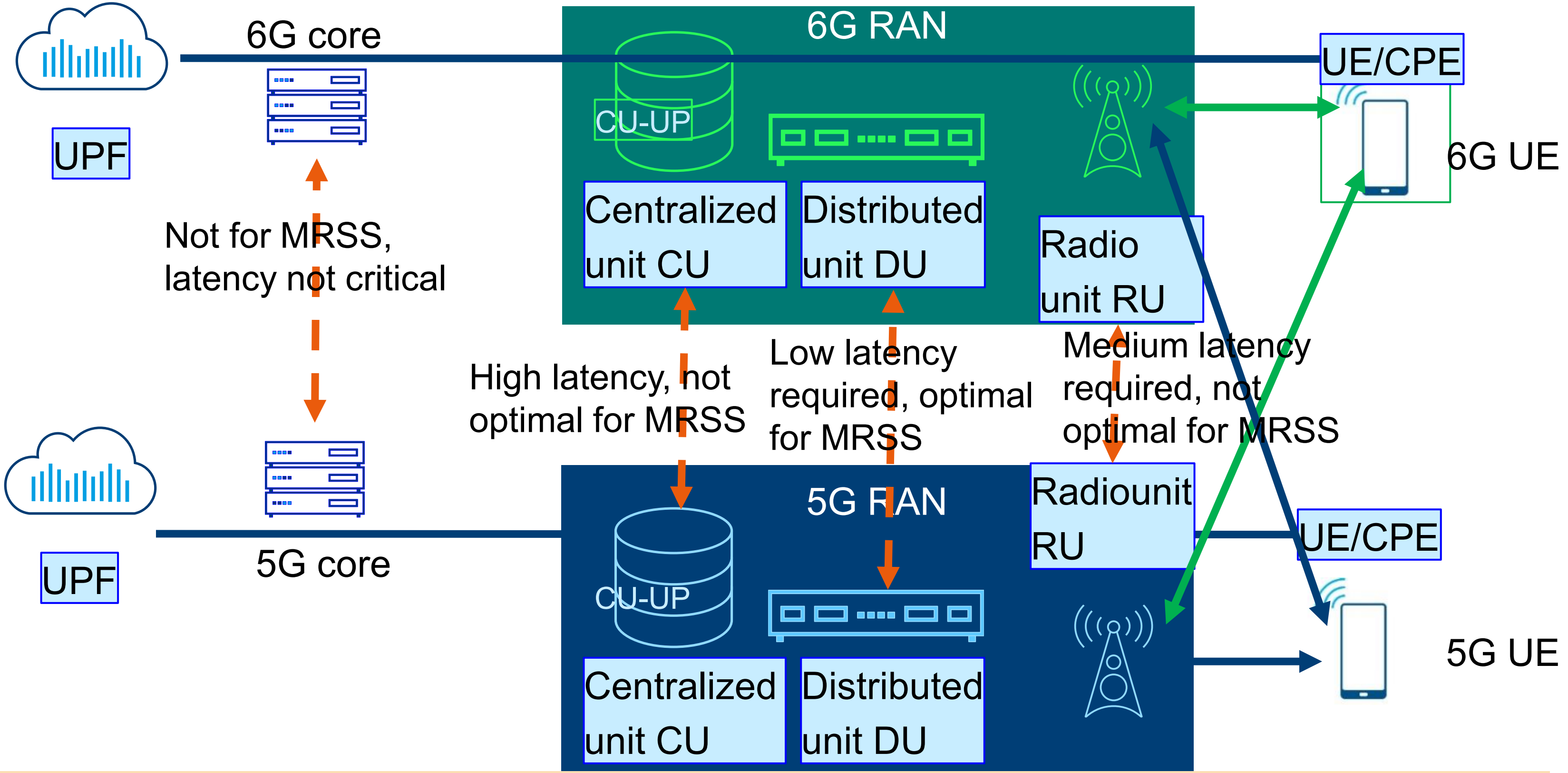
Example:
time of day controlled spectrum usage

FR3 MULTI-RAT SPECTRUM SHARING (MRSS)



MRSS allows a flexible introduction and spectrum sharing between 5G NR and 6G

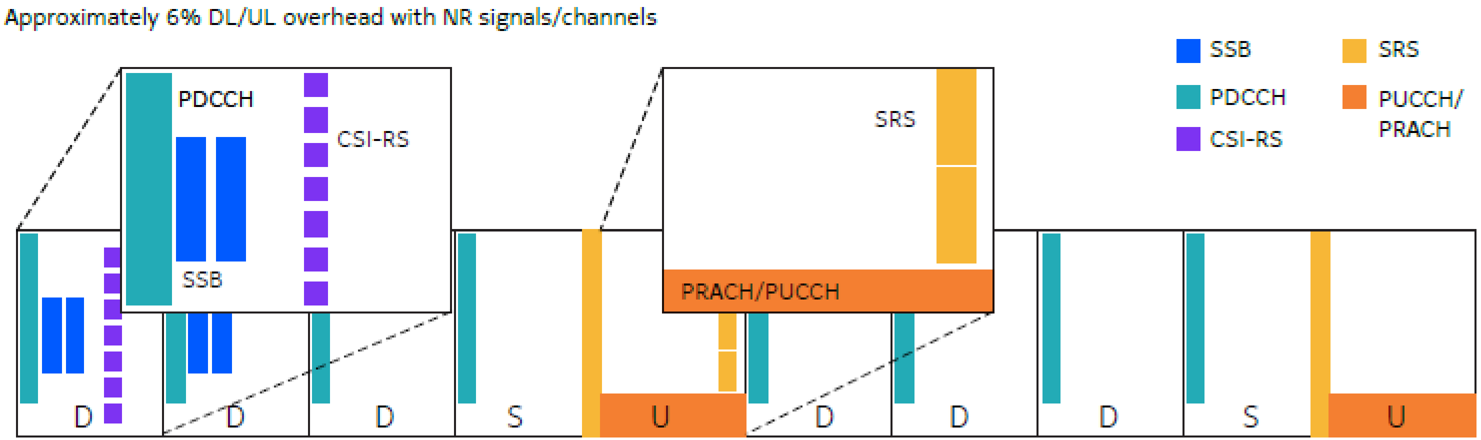
MRSS – ARCHITECTURE CONSIDERATIONS



Assumption: to coordinate MRSS, it would be efficient, to have joint DU or a low latency interface between DU to coordinate high PHY scheduling decisions

MRSS – ARCHITECTURE CONSIDERATIONS

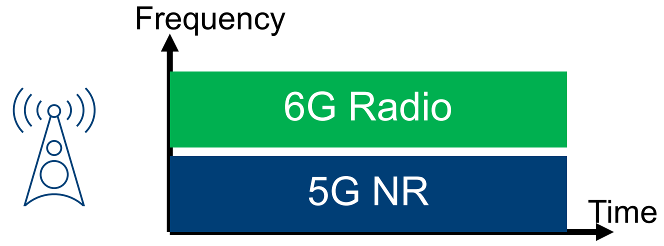
Assumption: MRSS needs to consider static reference signal architecture. In 5G, it is about 6% overhead

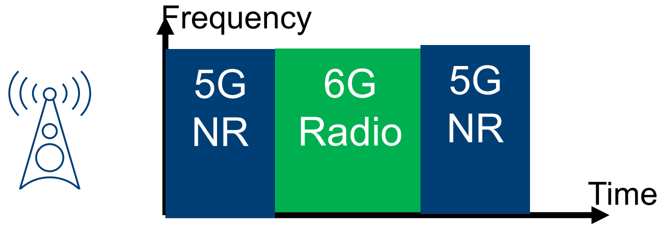


Source: Nokia

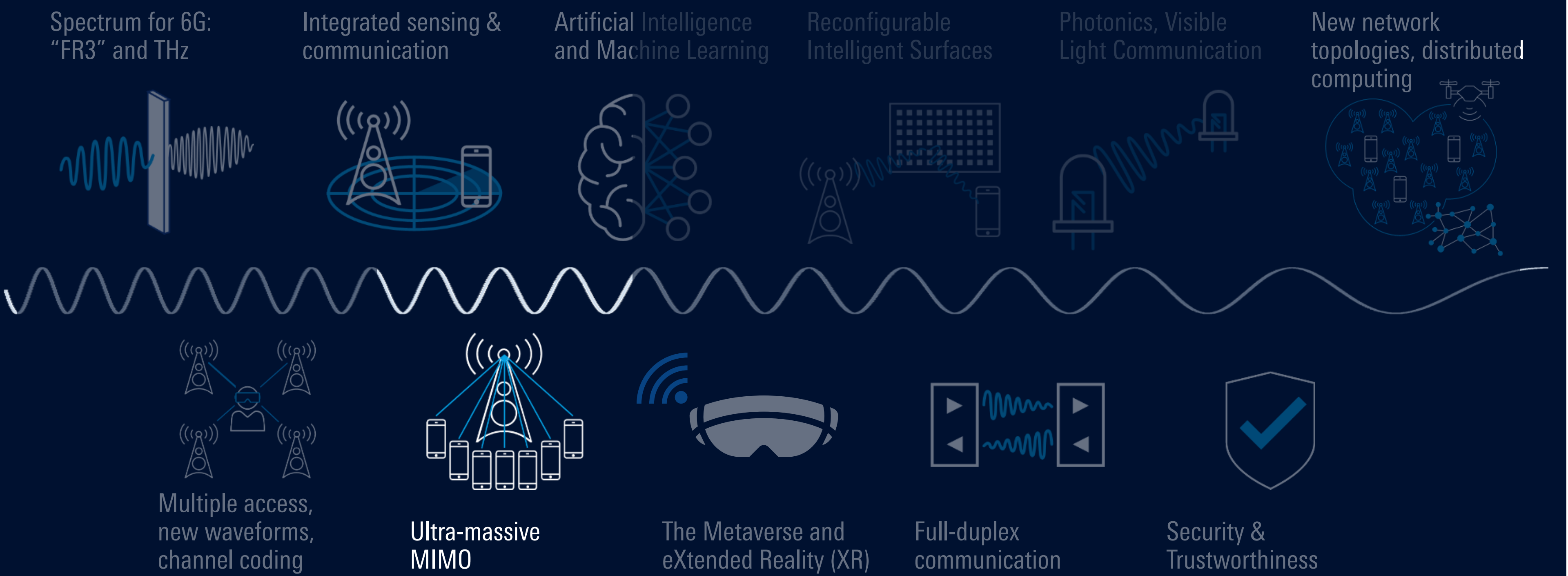
Compared to 5G/4G DSS, 5G NR offers a lean channel concept with flexible reference signal mapping => better efficiency for MRSS

MRSS – SOME GENERAL CONSIDERATIONS





RESEARCH AREAS FROM A T&M PERSPECTIVE



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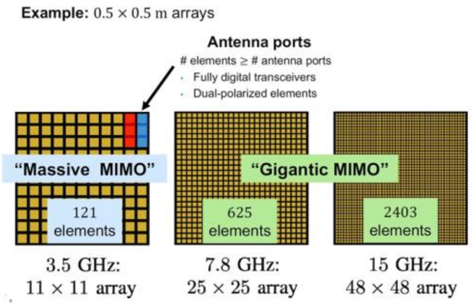
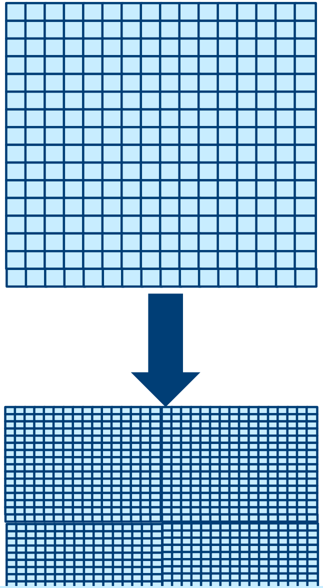
Giga MIMO or Gigantic MIMO - definition

giga MIMO or gigantic MIMO (gMIMO):
While mMIMO was designed with mid-band and high-band (mmWave) in mind and umMIMO was conceptualised with mmWave and sub-THz in mind, gMIMO has been visualised for cmWave bands.





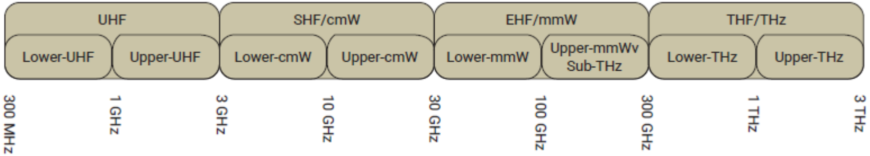


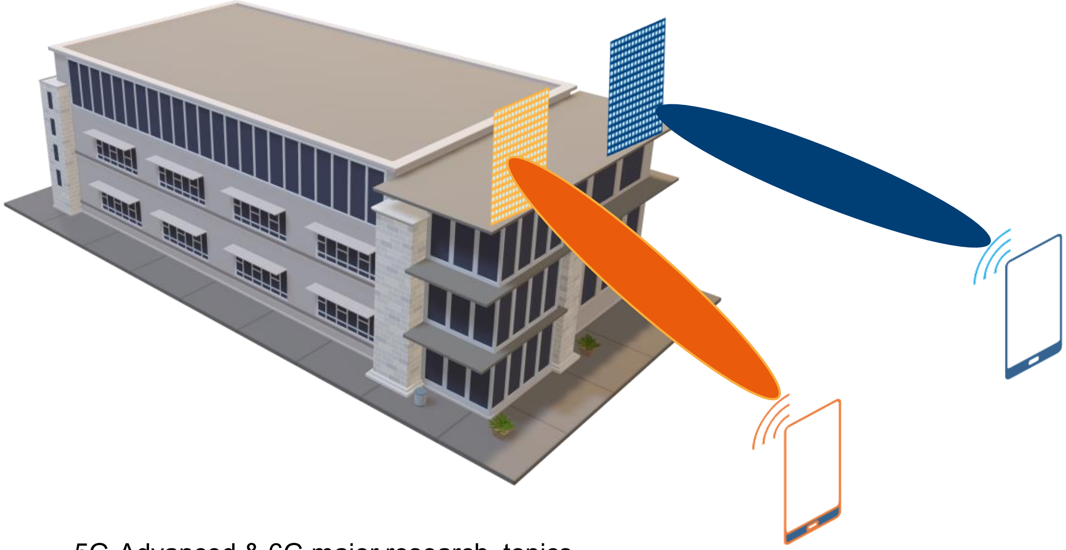
Figure 1 – Acceptable common terminology in NGA documentation

Definition from ATIS

Extension in frequency from FR1 to FR3: keep aperture size but increase #antenna elements

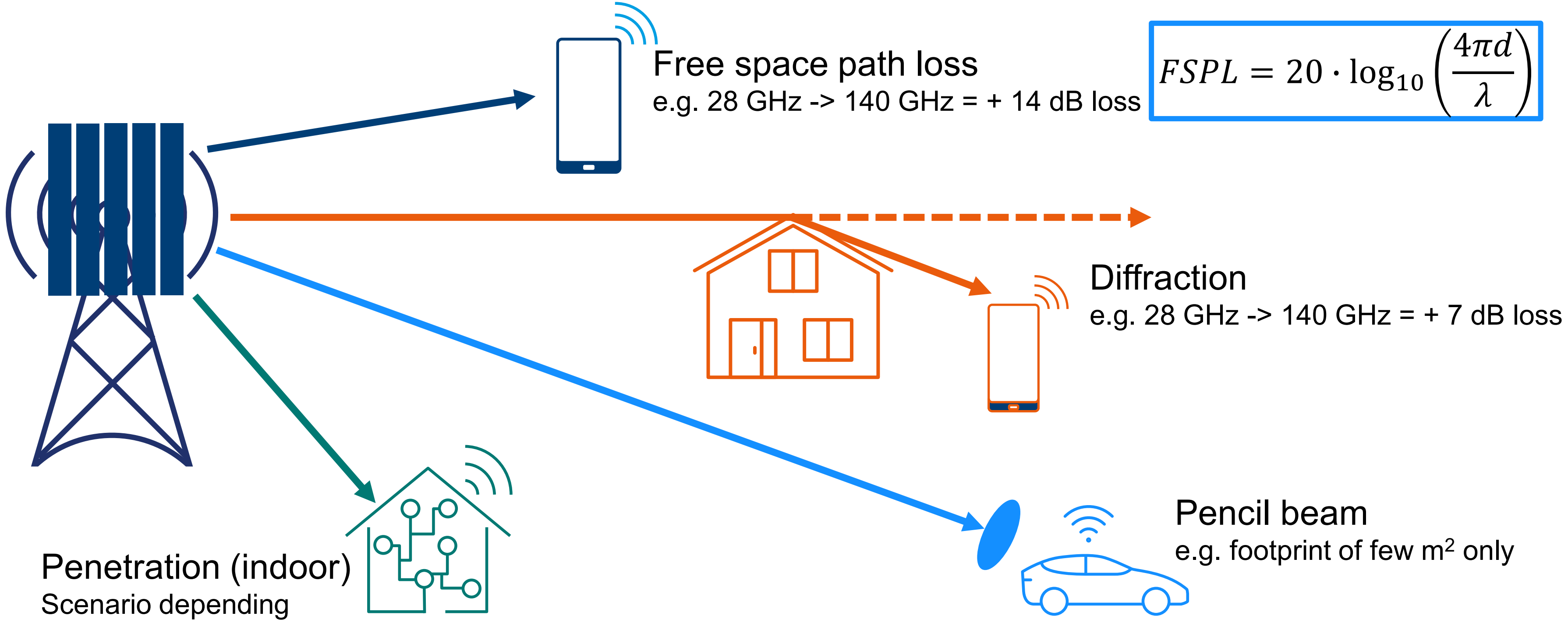
Giga MIMO or Gigantic MIMO - challenges

- Frequency band, upper mid-band or cmWave (7-24 GHz)
- More antenna elements (~512 – 2048 array)
- Distributed subarray deployment as option
- Precise beamforming required
- 3D localization and sensing as future options



ULTRA-MASSIVE MIMO – ONLY ONE SLIDE ON CHALLENGES

6G is the continuation of beamforming, and MIMO, but few things to consider ☹



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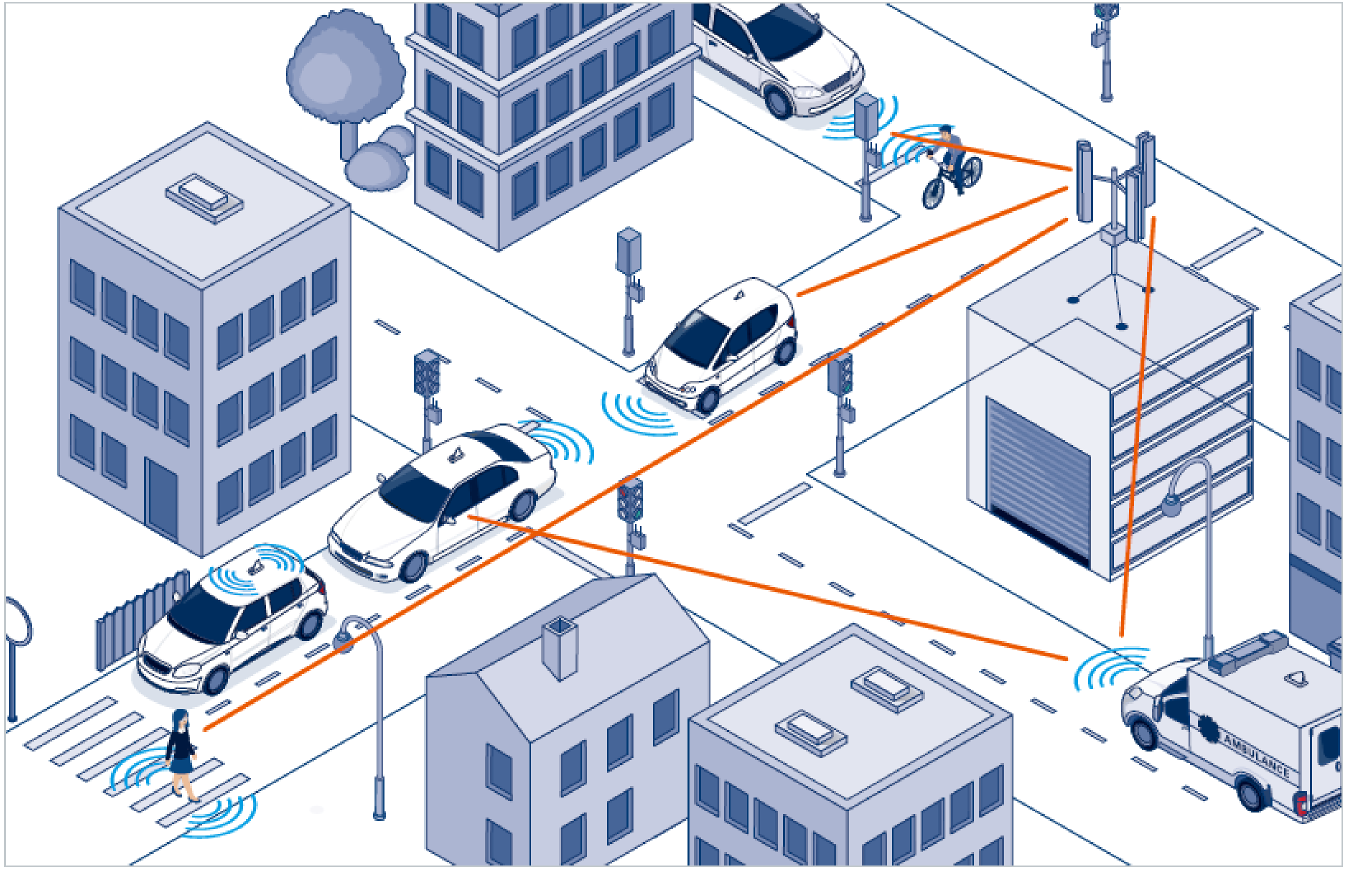
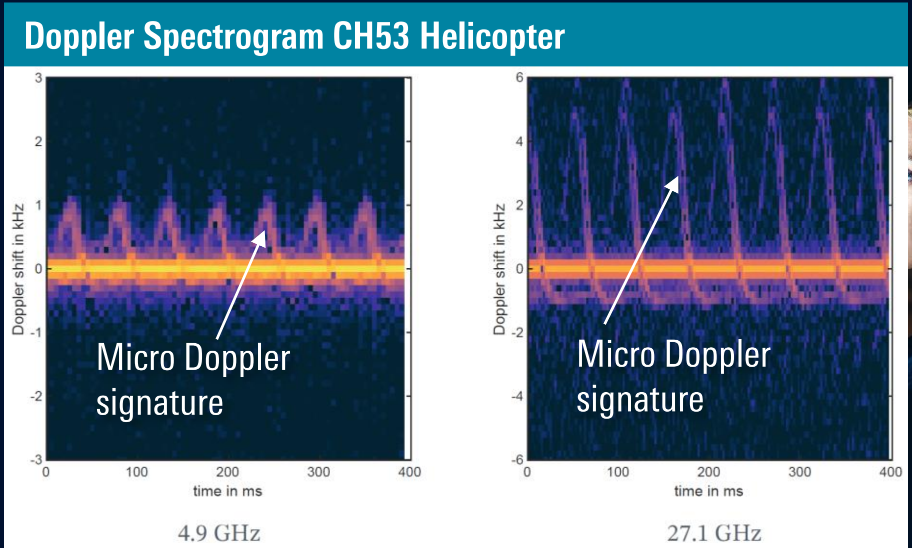
JOINT COMMUNICATION AND SENSING (JCAS)



Time-domain channel measurements for FCAS research

Characterization of Helicopter Rotor Blade Modulation in UHF and Microwave Bands

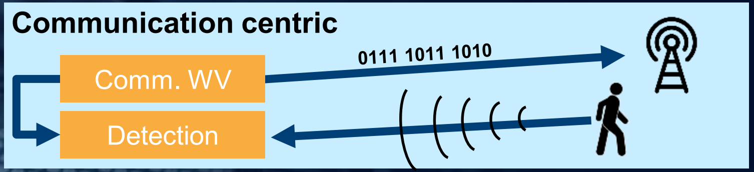


"Characterization of Helicopter Rotor Blade Modulation in UHF and Microwave Bands", submitted to MILCOM2024

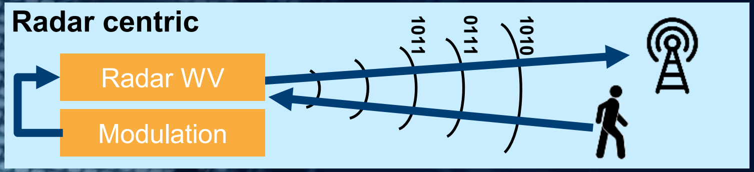
JOINT COMMUNICATION AND SENSING (JCAS)
MOTIVATION AND RESEARCH CHALLENGES

► Integrated JCAS system using single transmitted waveform and full-duplex operation:

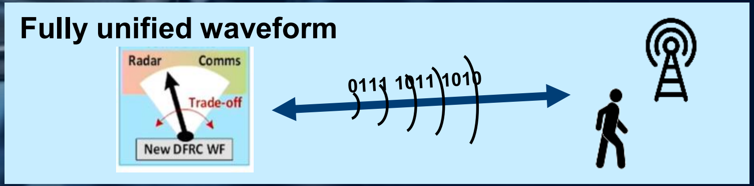
– Communication-centric design, with guaranteed communication performance (e.g. OFDM-based)



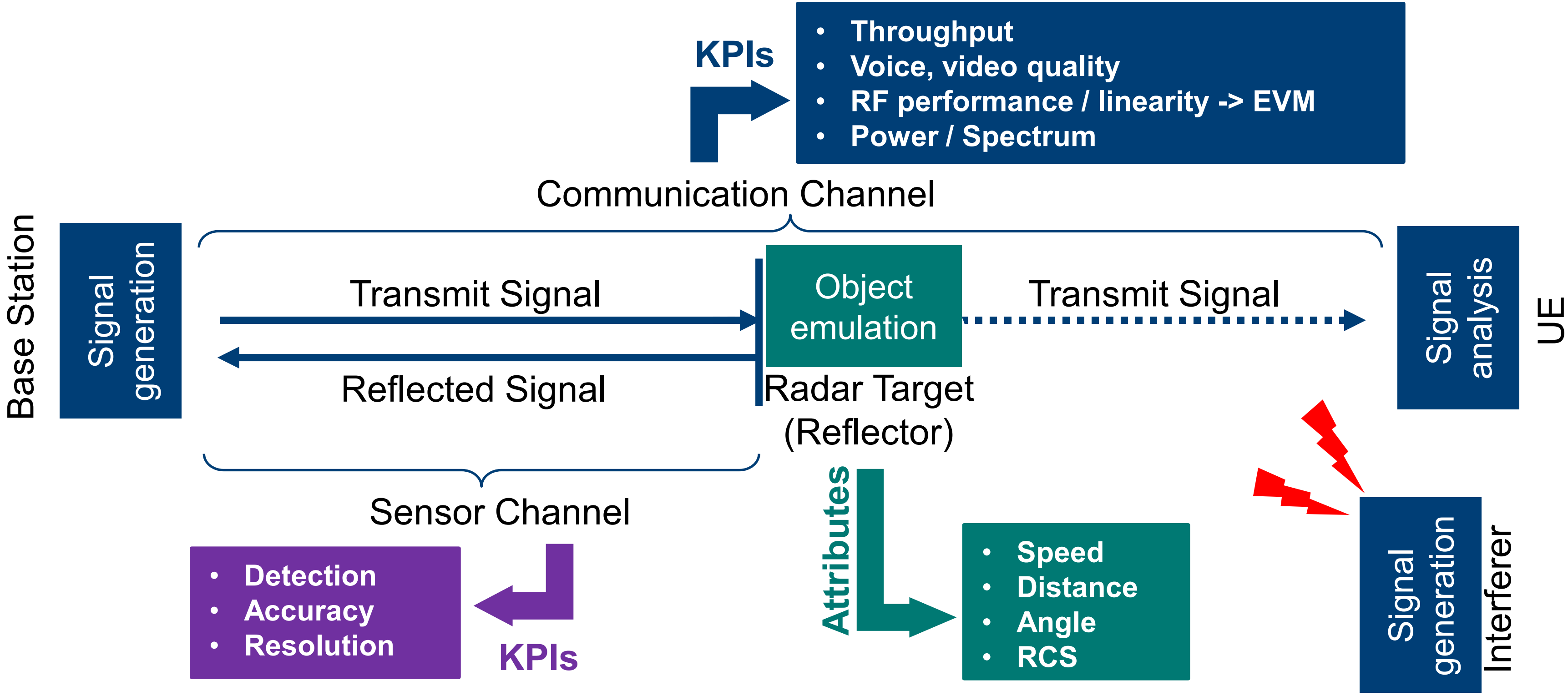
– Radar-centric design, optimized for sensing performance (e.g. using chirp signals as information carriers → PC-FMCW)



– Jointly optimized design, with freely scalable sensing and communication performance trade-off



JOINT COMMUNICATION AND SENSING
DIFFERENCES IN PERFORMANCE INDICATION



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- Spectrum for 6G: "FR3" and THz
- Integrated sensing & communication
- Artificial Intelligence and Machine Learning
- Reconfigurable Intelligent Surfaces
- Photonics, Visible Light Communication
- New network topologies, distributed computing
- Multiple access, new waveforms, channel coding
- Ultra-massive MIMO
- The Metaverse and eXtended Reality (XR)
- Full-duplex communication
- Security & Trustworthiness

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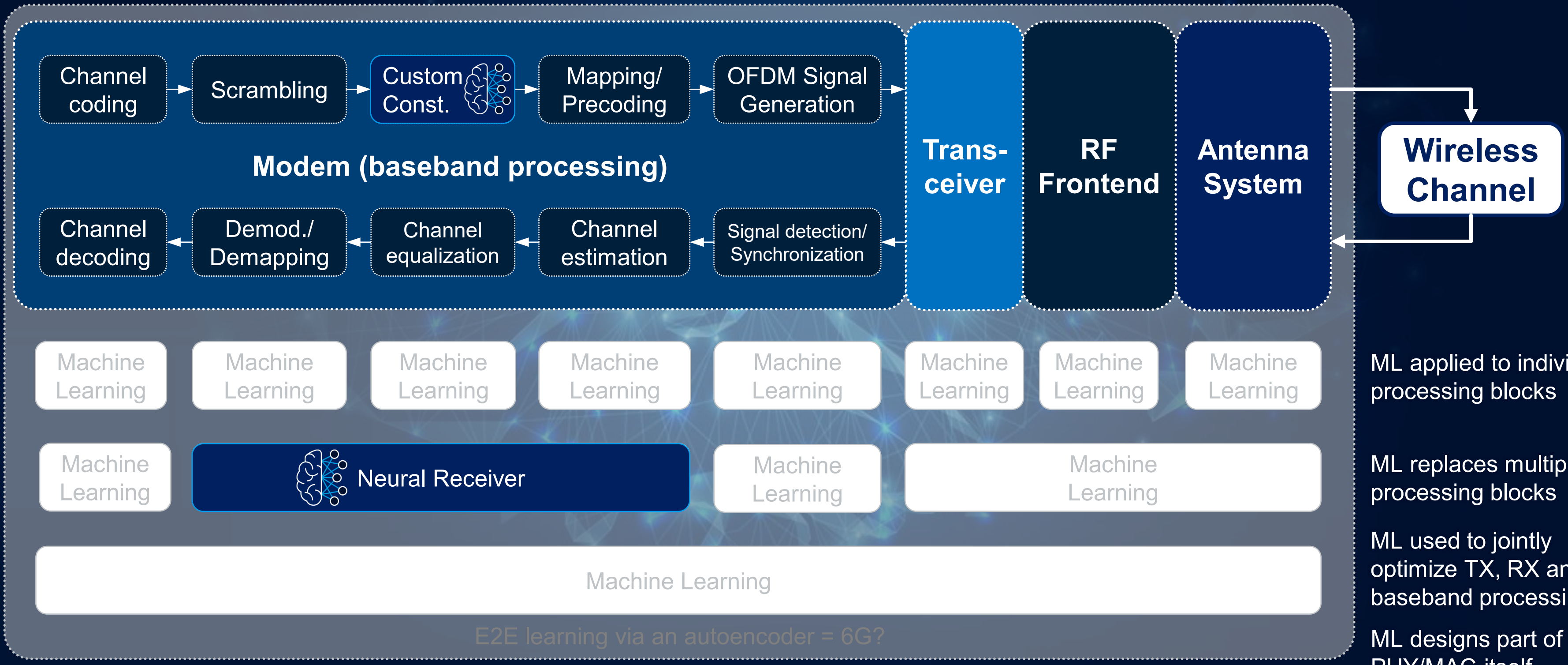
TOWARDS AN AI-NATIVE AIR INTERFACE FOR 6G
ADVANCING THE NEURAL RECEIVER WITH CUSTOM CONSTELLATION



ML applied to individual processing blocks

ML replaces multiple processing blocks

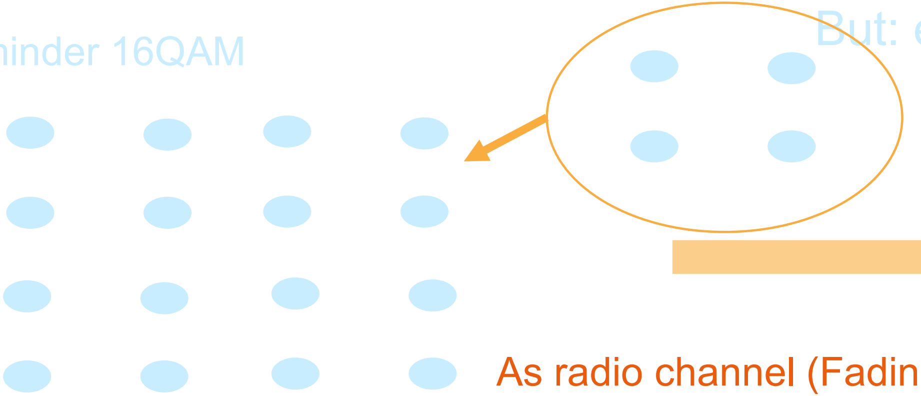
ML used to jointly optimize TX, RX and baseband processing;

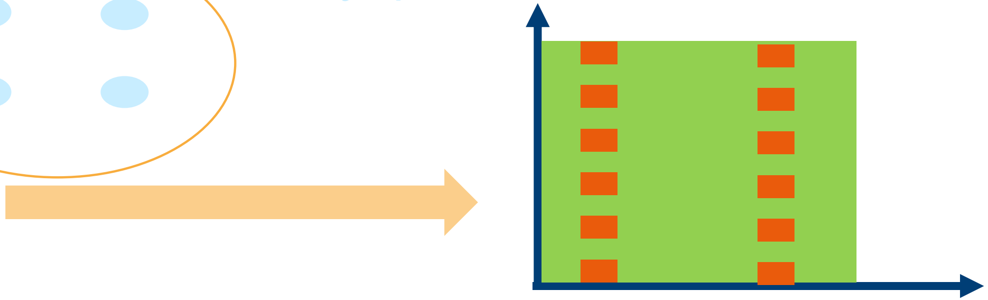
ML designs part of 6G PHY/MAC itself

MODULATION SCHEME CONSTELLATION ASPECTS

Reminder 16QAM

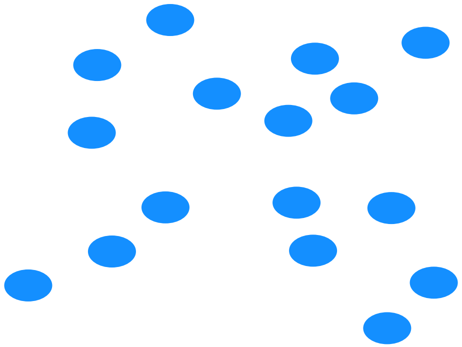
But: every quadrant is identical



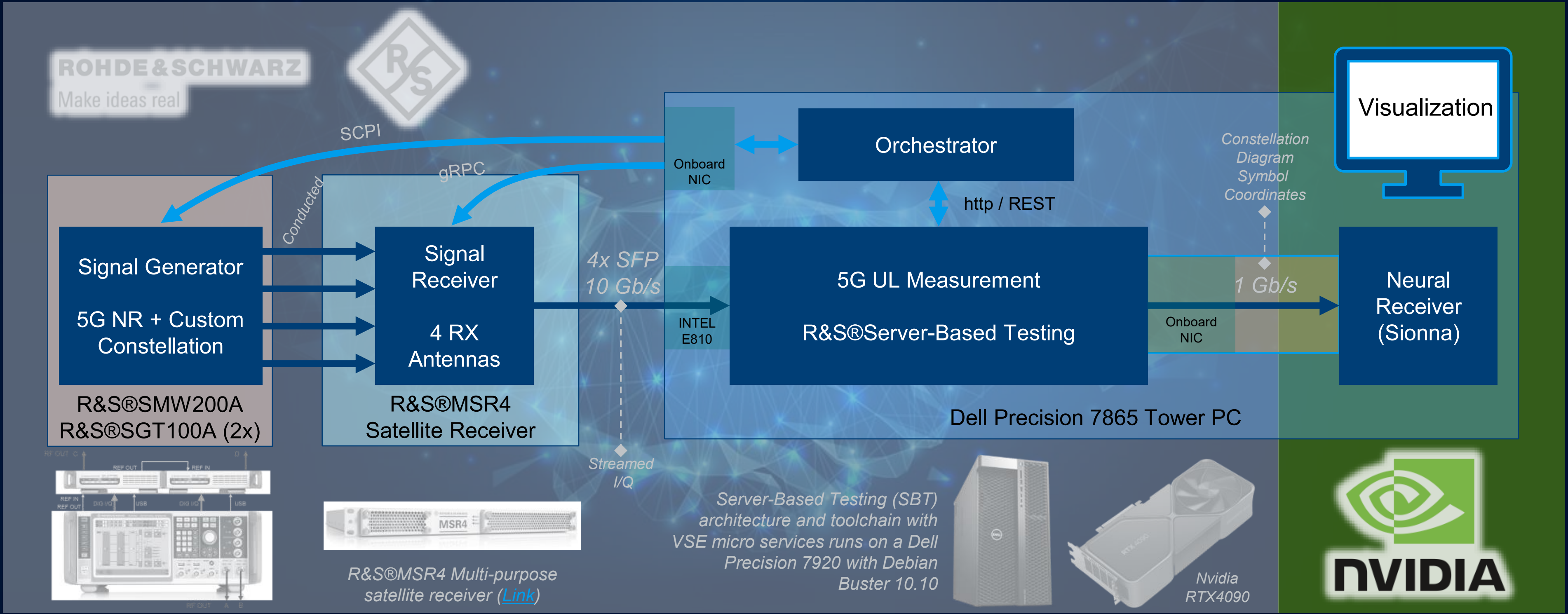


As radio channel (Fading) deteriorates the signal,
we need pilots, e.g. DMRS for channel estimation and equalization

Idea: If we apply a scenario specific, pseudo-random looking constellation diagram, we may understand the constellation position as kind of reference signals



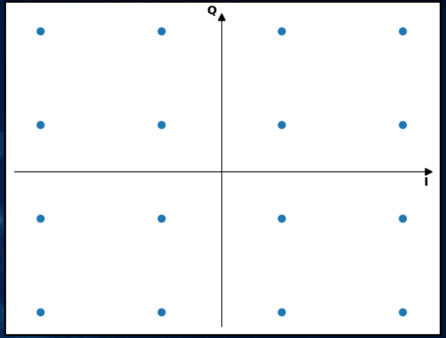
TESTBED SETUP



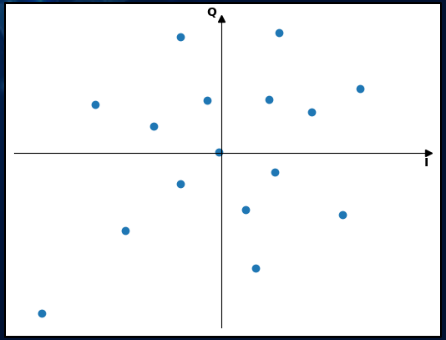
END-TO-END CONSTELLATION LEARNING

- Joint **End-to-End Learning** (TX, wireless channel, RX) of custom constellation points and neural receiver
- AI/ML models learn constellation with superimposed pilots; joint optimization of neural receiver performance
- **Pilotless Communication:** No need for 5G NR Demodulation Reference Signals (DMRS)
- Free resources can be used for data transmission → higher bandwidth efficiency/throughput
- **Additionally in this demo:** Neural RX trained with carrier frequency offsets in range 0 – 0.5 ppm

From QAM16…



… to an AI/ML-learned constellation



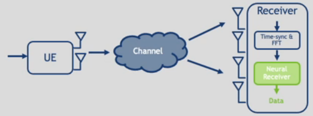
CAPTURE OF DEMO

AI/ML towards 6G: End-to-End Learning of Neural Receivers & Custom Constellations for Pilotless Communication

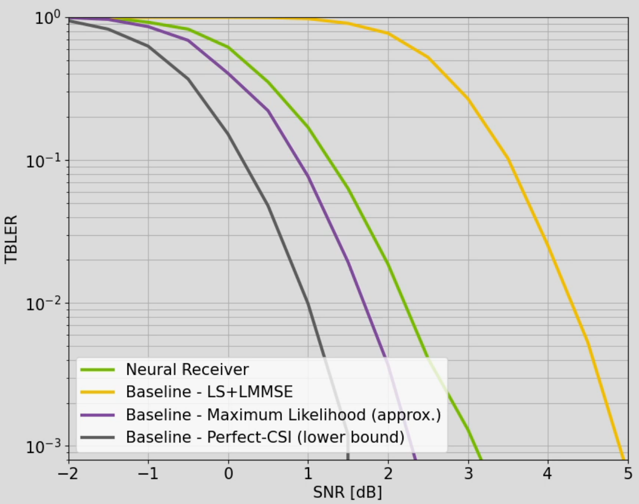
Reset Figure | Measurement stopped | Measure Performance | SNR [dB]: 0

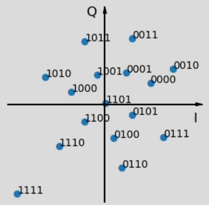
Evaluate LS-Baseline

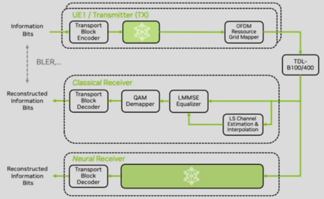
Show Goodput



Channel	TDL-B 100ns/400Hz
Number of PRBs	273 (100 MHz)
Modulation order	16
Target coderate	0.54
Transport block size	92200 bit
DMRS Overhead	3276 REs
Effective PUSCH throughput	57.8 slots/s
Occupied REs Baseline	45864
Occupied REs NRX	42588







ROHDE&SCHWARZ

Made with Sionna™ NVIDIA

Funded by the European Union

This work is funded by the European Union under Grant Agreement 101096379

CENTRIC

RESEARCH AREAS FROM A T&M PERSPECTIVE

Spectrum for 6G: “FR3” and THz

Integrated sensing & communication

Artificial Intelligence and Machine Learning

Reconfigurable Intelligent Surfaces

Photonics, Visible Light Communication

New network topologies, distributed computing

Multiple access, new waveforms, channel coding

Ultra-massive MIMO

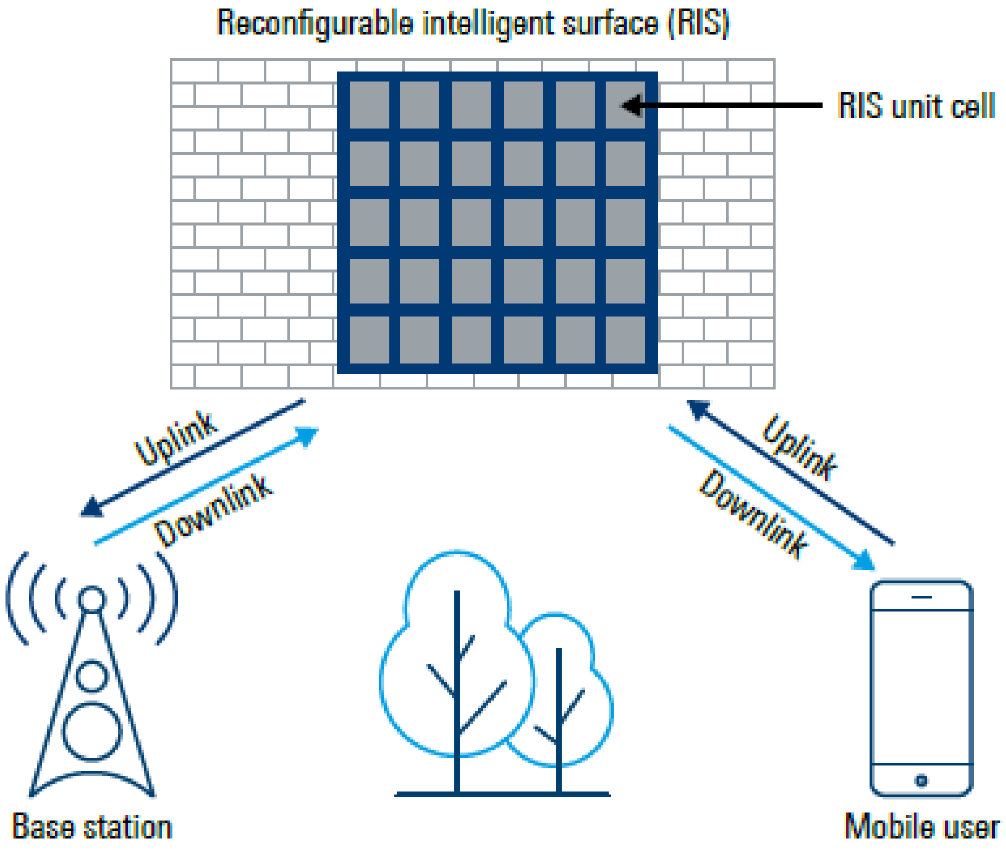
The Metaverse and eXtended Reality (XR)

Full-duplex communication

Security & Trustworthiness

A high-level overview of all these research areas is provided in one of our #THINKSIX videos

RECONFIGURABLE INTELLIGENT SURFACES (RIS)



ADJUST THE CHANNEL – ALONG WITH THE SIGNAL

$$r(t) = h(t)s(t) + n(t)$$

- The classical approach to maximize reception quality:
  - Adapt s(t) transmission scheme to target channel h(t), e.g., CP-OFDM for the multipath channel, carrier frequency, and bandwidth, pre-coding/equalization, modulation and coding schemes, etc.
- IRS offers an adaptation of channel h(t) to maximize reception quality.

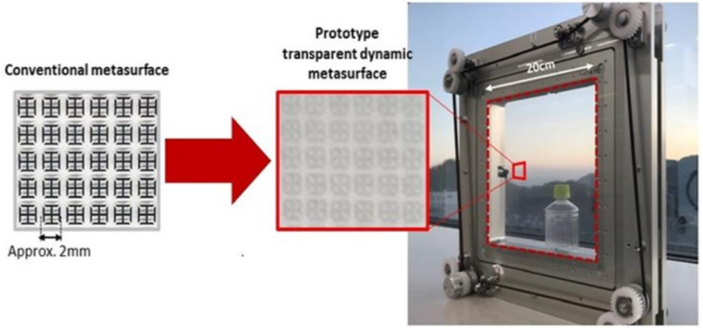
Press Release

https://www.nttdocomo.co.jp/english/info/media_center/pr/2020/0117_00.html

January 17, 2020

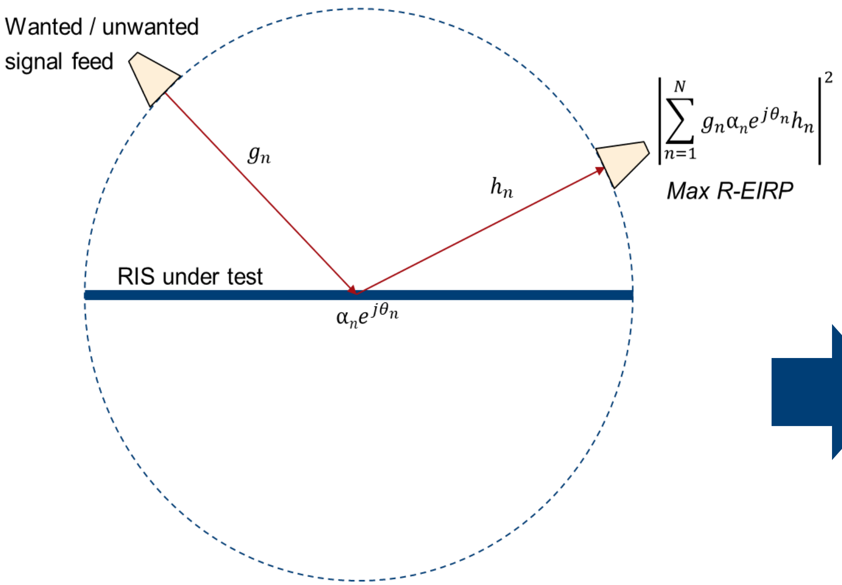
DOCOMO Conducts World's First Successful Trial of Transparent Dynamic Metasurface

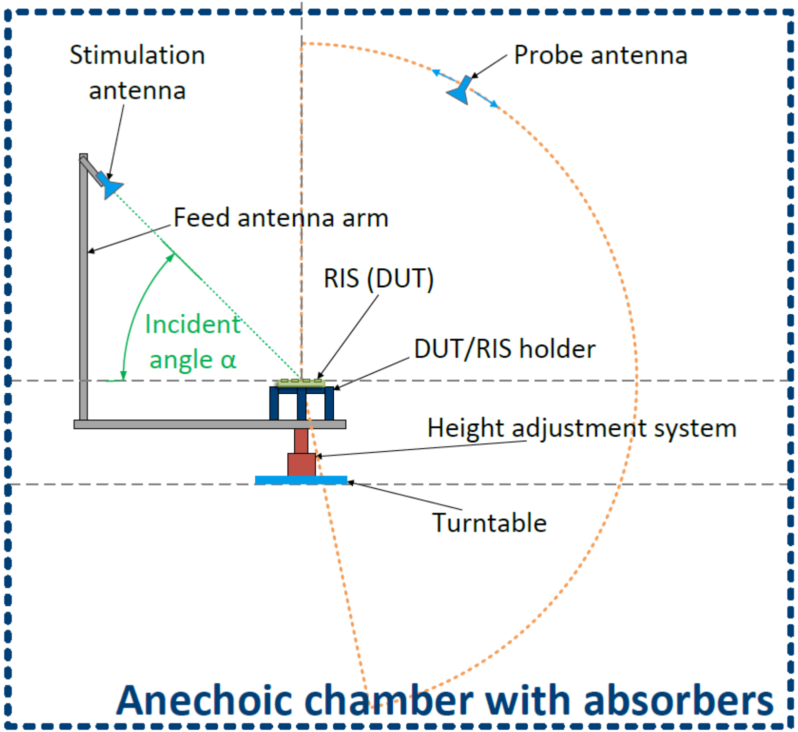
— Dynamic wave manipulation and high transparency expected to optimize 5G network construction —



Prototype of transparent dynamic metasurface

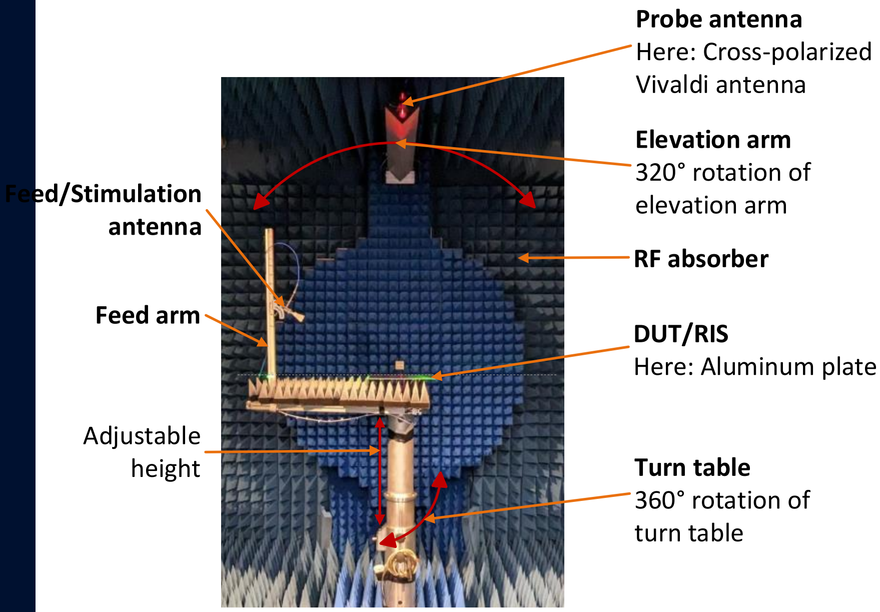
RADIATED RIS MEASUREMENT PRINCIPLE





Source: ETSI ISG RIS GR002

Spectrum for 6G:
Reconfigurable Intelligent Surfaces



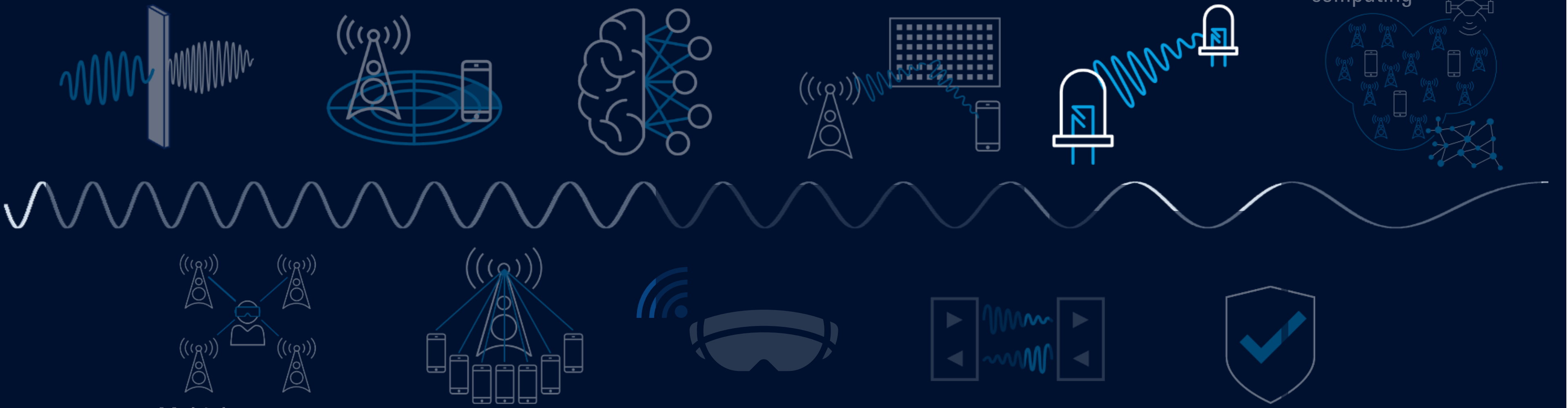
Munich / 05-Sep-2023

Rohde & Schwarz and Greenerwave collaborate to verify RIS modules and drive 6G research

Reconfigurable intelligent surfaces (RIS) are drawing attention in the wireless industry due to their potential for an efficient 5G mmWave rollout as well as future 6G applications. A measurement campaign by Rohde & Schwarz and Greenerwave recently characterized the configurable radio wave reflection properties of a novel FR2 RIS module developed by Greenerwave with an over-the-air (OTA) antenna test system from Rohde & Schwarz. It is one of the first real measurements confirming that a metamaterial-based RIS can improve the coverage and efficiency of wireless communications performance, especially for 5G FR2. The groundbreaking work will pave the way for further 6G developments.

RESEARCH AREAS FROM A T&M PERSPECTIVE

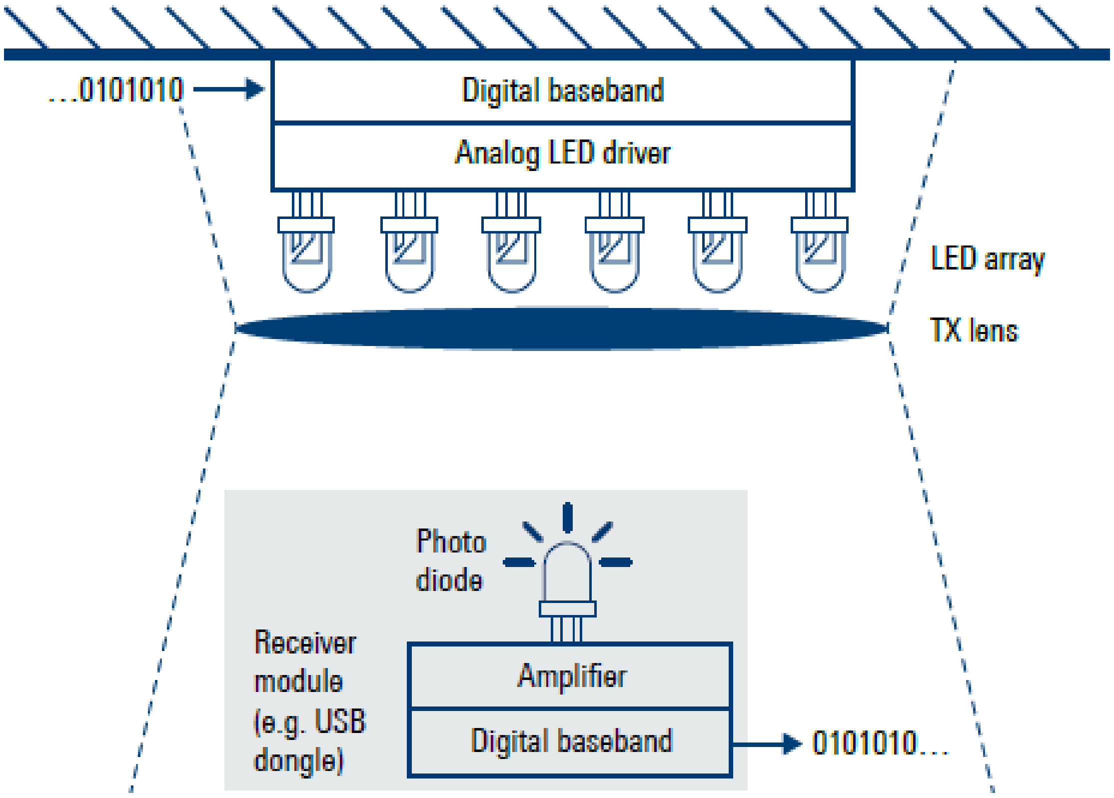
- Spectrum for 6G: “FR3” and THz
- Integrated sensing & communication
- Artificial Intelligence and Machine Learning
- Reconfigurable Intelligent Surfaces
- Photonics, Visible Light Communication
- New network topologies, distributed computing



- Multiple access, new waveforms, channel coding
- Ultra-massive MIMO
- The Metaverse and eXtended Reality (XR)
- Full-duplex communication
- Security & Trustworthiness

A high-level overview of all these research areas is provided in one of our #THINKSIX videos

VISIBLE LIGHT COMMUNICATIONS (VLC) USING LED

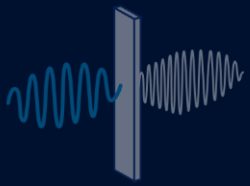


Pro:
~300 THz license-free bandwidth
Cost-efficient approach and easy integration
Robustness against interference
Security (MIM attacks difficult)

Con:
Requires kind of LOS connection
Complement to RAT only

RESEARCH AREAS FROM A T&M PERSPECTIVE

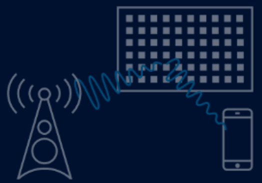
Spectrum for 6G: "FR3" and THz



Integrated sensing & communication

Artificial Intelligence and Machine Learning

Reconfigurable Intelligent Surfaces



Photonics, Visible Light Communication

New network topologies, distributed computing

Multiple access, new waveforms, channel coding

Ultra-massive MIMO

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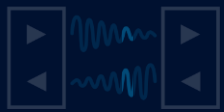

Full-duplex communication

Security & Trustworthiness

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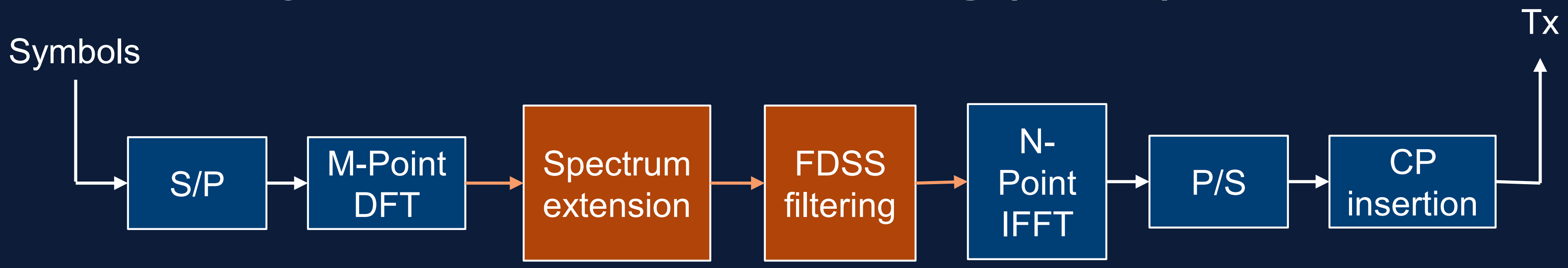
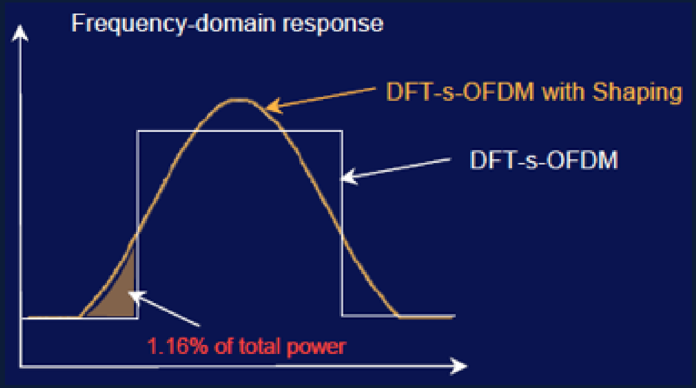
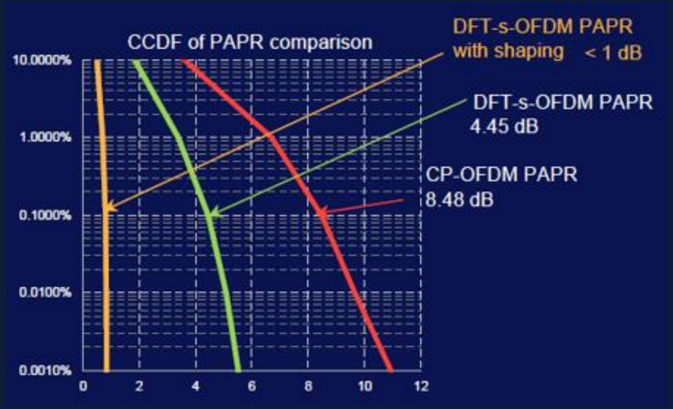
6G waveform proposals 6GWS-250036
Frequency-domain spectrum shaping (FDSS) in UL

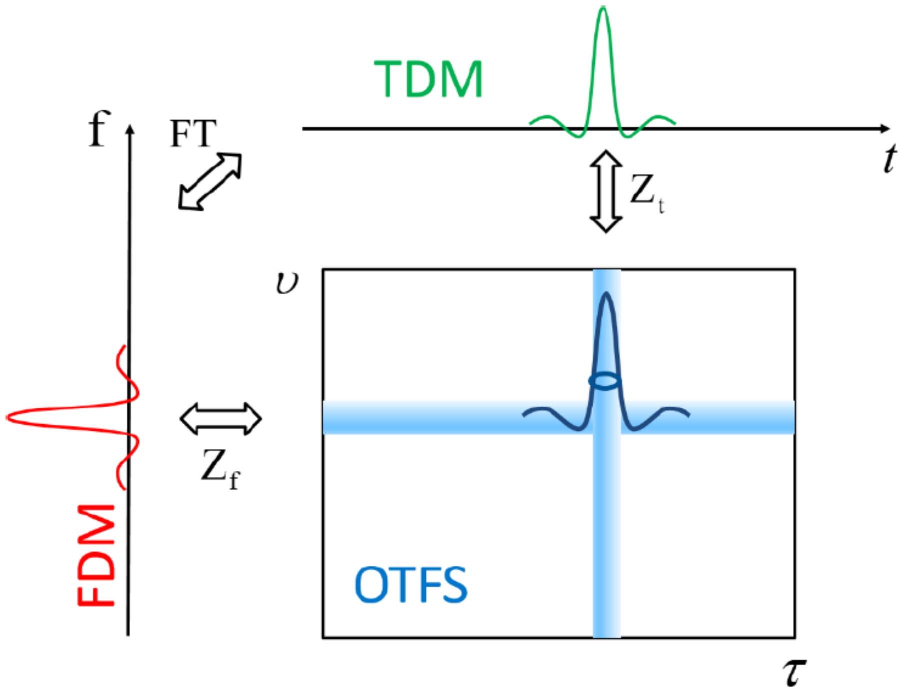






ORTHOGONAL TIME FREQUENCY & SPACE (OTFS)

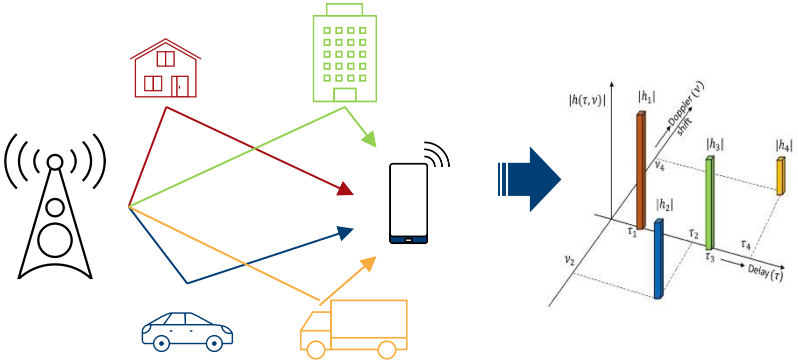
Delay-Doppler modulation scheme

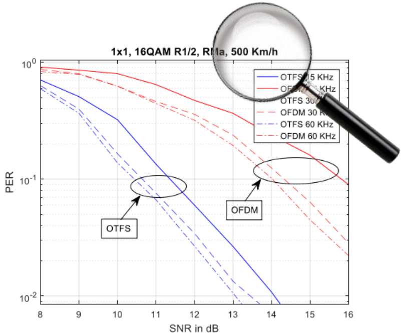


ANOTHER WAVEFORM OF INTEREST
OTFS - ORTHOGONAL TIME FREQUENCY SPACE MODULATION

- For TDM and FDM the signal is localized in time or in frequency → time selective or frequency selective fading
- **Idea: Go to the Delay-Doppler (DD) domain**

- Doppler Delay Modulation (DDM)
  - Information is carried over DD domain pulse
  - Delay period τ_p ; Doppler period $\nu_p = \frac{1}{\tau_p}$
  - Zac transform z_t, used to transform the DD signal to a TD signal $x(t)$





Ref: R1-1609825, 3GPP TSG RAN WG1 Meeting #86bis, 2016

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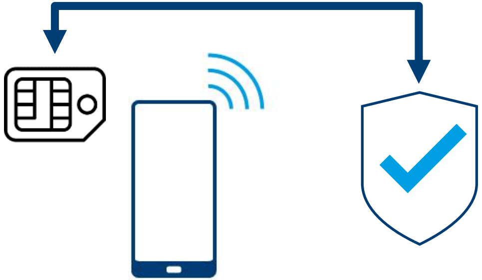
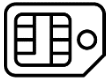
6G RESEARCH TOPICS RELATED TO SECURITY

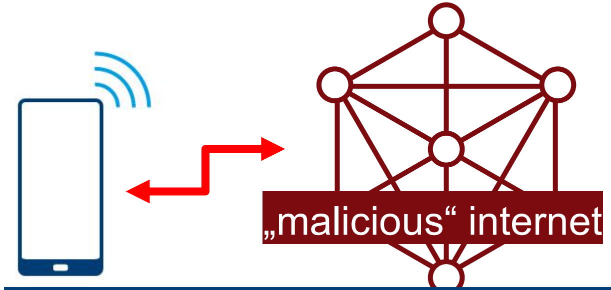
Symmetric key encryption/authentication = proven, scaled well up to billions of devices and will sustain in future networks! But there are some challenges we need to consider ☹ ….

Mutual authentication between UE and HSS.
But what if HSS is not available?



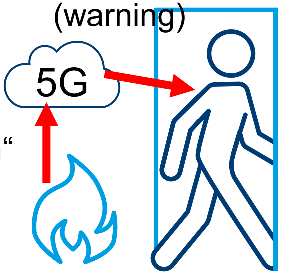
SIM = privacy





Authentication is always against the network.
Trust network? I.e. rogue BTS, faked networks, IMSI catcher…

„Fire alarm“
(warning)



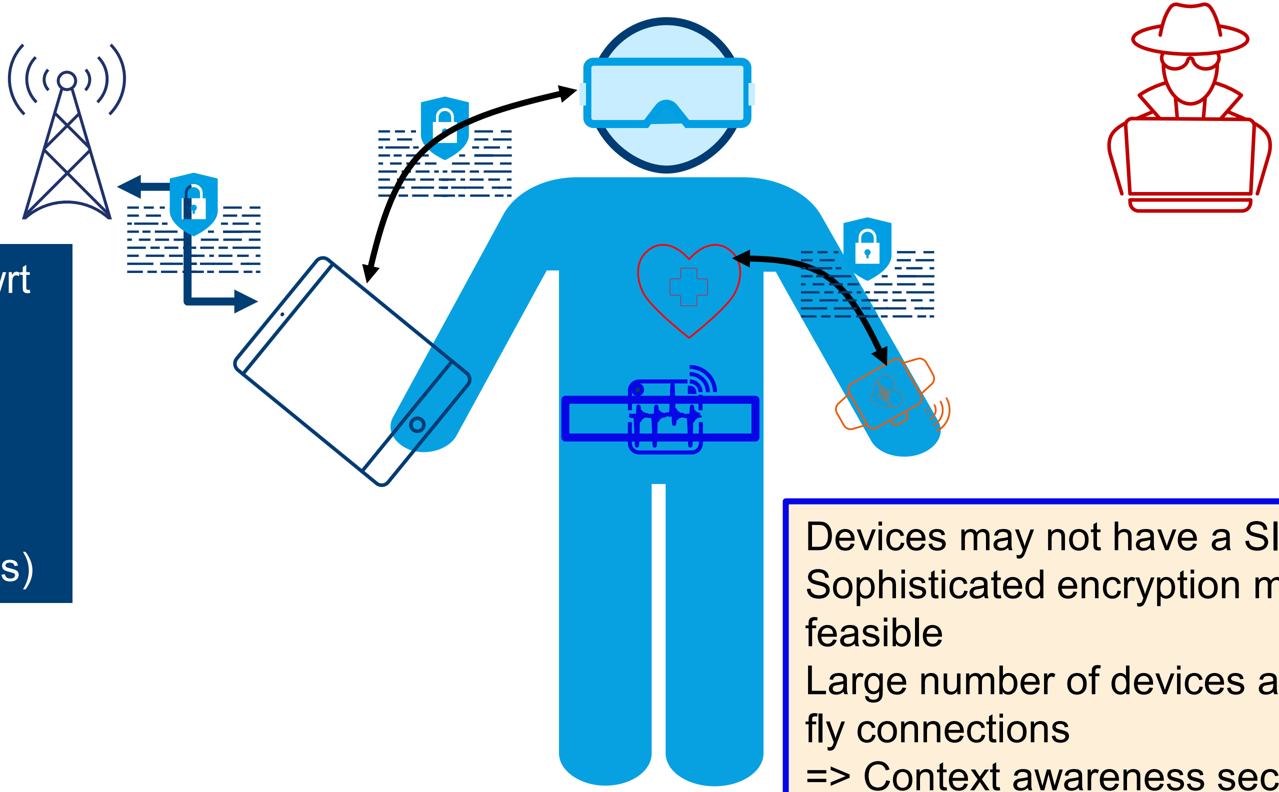
„Fire alarm“
(sensor)

SIM free, dynamic network access, on the fly authentication needed

IoT devices: SIM free network access needed

Ideas to extend via asymmetric public/private keys PKI infrastructure and distributed ledger models

6G NOVEL PHY LAYER ARCHITECTURE IDEAS - SECURITY

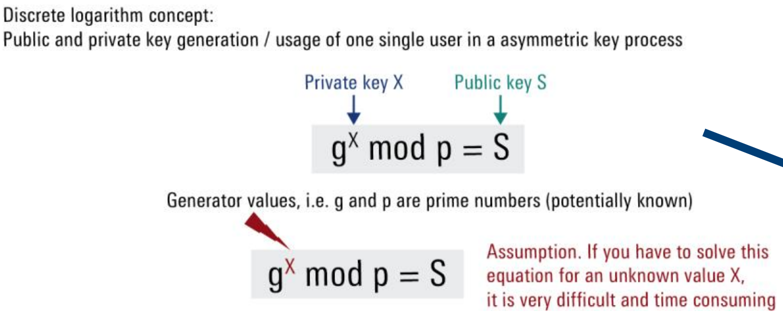


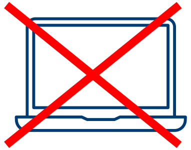
New constraints wrt device capability, form factor & use cases and new network topology, i.e. multi-layer (personal networks)

Devices may not have a SIM
Sophisticated encryption may not be feasible
Large number of devices and on-the-fly connections
=> Context awareness security model

6G RESEARCH TOPICS RELATED TO SECURITY

Post-quantum preparation needed …. But don‘t panic ☺ !





Today asymmetric key like the discrete logarithm rely on the fact, that contemporary computers can not solve the calculation efficiently. But Quantum computers may do

There won‘t be large-scale quantum computers available in the near future!

Grover‘s algorithm: double the size of asymmetric keys to resist quantum computer threat!

So, don‘t panic ☺.
There are public-key primitives like e.g. code-based encryption (McEliece) and lattice-based NTRU that outperform elliptic curve discrete logarithm problems (ECDLP), but they incur costs as efficiency is poor and key sizes are large. => research needed to satisfy envisioned performance & functionality

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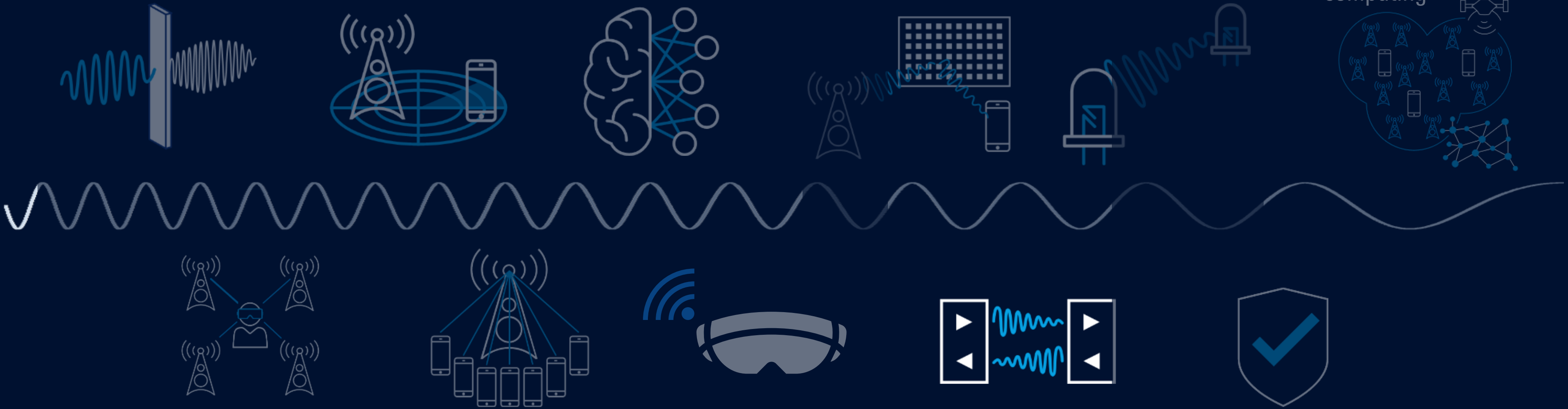

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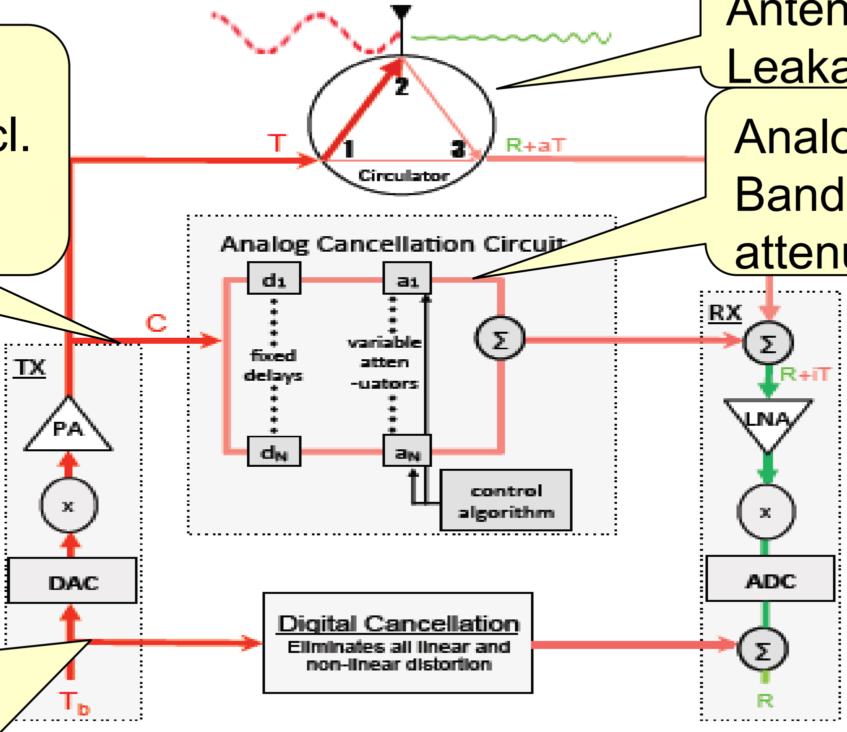
FULL DUPLEX RADIO - ARCHITECTURE

Tap signal to get a „copy“ of Tx signal (incl. Linear + non-linear distortions)

Antenna as 3 port. Leakage from Tx to Rx

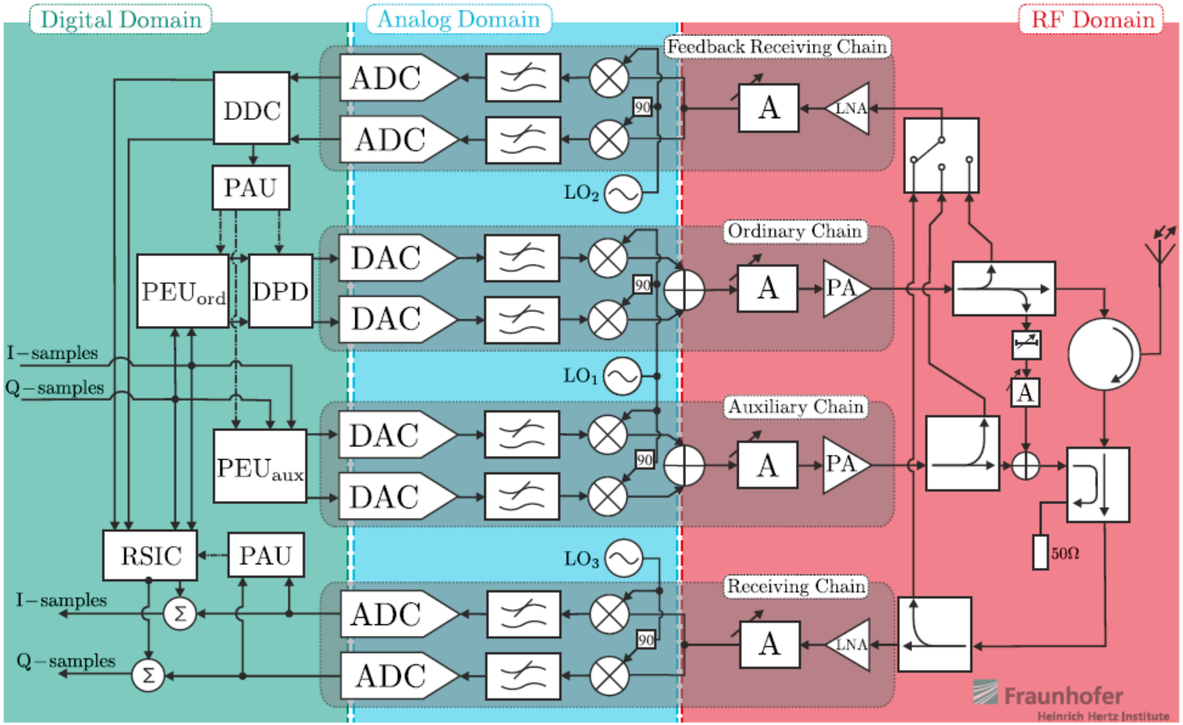
Analog circuit: Band of variable attenuators + delay

Digital circuit: Linear equalization strategies, maximum likelihood estimation based on samples



Source: Full duplex radios. Stanford university. Bharadia, McMillin, Katti

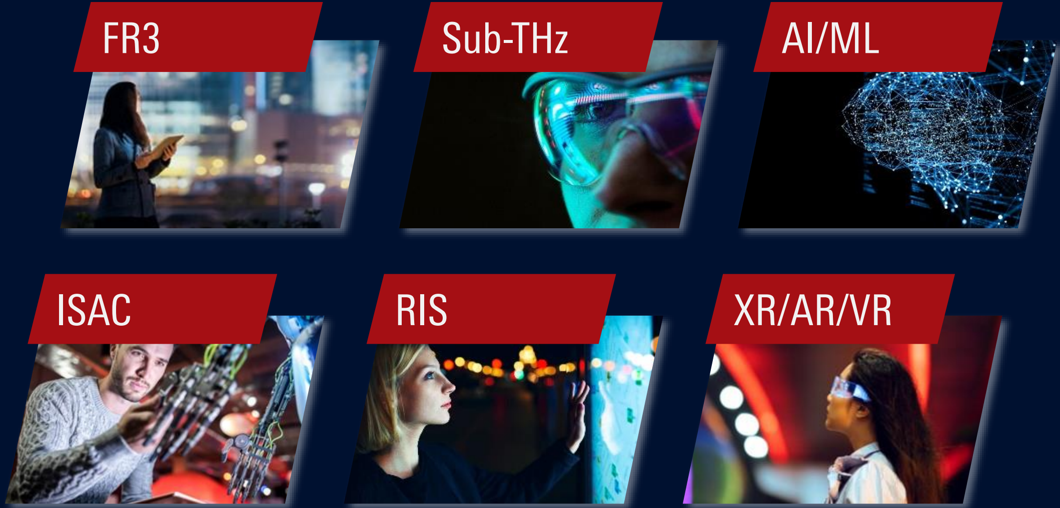
FULL DUPLEX RADIO – ARCHITECTURE COMPLEXITY



DPD : Digital Pre-Distorter
PAU : Parameter Acquisition Unit
RSIC: Residual Self-Interference Canceller
DDC: Digital Down Converter
PEU: Pre-Equalization Unit

Askar, Ramez & Schubert, Benjamin & Keusgen, Wilhelm & Haustein, Thomas. (2015). Full-Duplex: Wireless Communication Systems. 10.13140/RG.2.1.3500.1684.

Thought & solution leadership on the way to the next generation of mobile communication (6G)

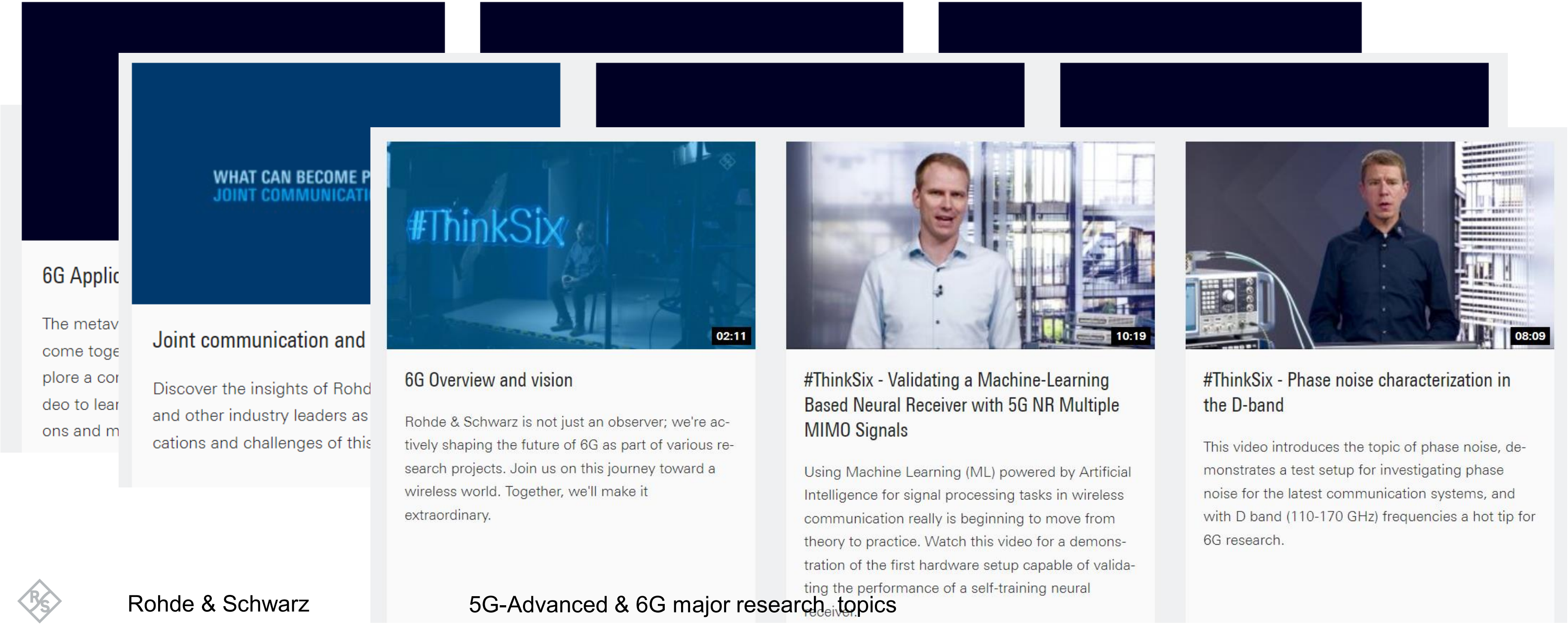


- Target simulation for Integrated Sensing and Communication (ISAC)
- Testing Reconfigurable Intelligent Surfaces (RIS)
- AI/ML training and performance test
- Sub-THz mesesurements

R&S®FSW/SMW | R&S®FE170ST/SR | R&S®NRP170 | R&S®AREG800A | R&S®RTP | R&S®CMX500 | R&S®ATS1800C

#THINKSIX – VIDEO SERIES

The #ThinkSix video series explores important topics relevant to the question of what is beyond 5G. We will follow the surrounding discussions and work with partners and customers to support this initial phase of research on the road to 6G



SUMMARY

- Deployment of 5G networks is in full swing! Clear evolution path provided by the industry’s standardization organization
- Academia and key industry players are exploring the boundaries and started looking into next generation of wireless communication aka 6G
- New, challenging technology components may complement the existing concept of cellular networks or even provide revolutionary aspects
- Rohde&Schwarz is actively engaged in this phase of fundamental research, providing our expertise in test and measurement to make ideas real