6G SPECTRUM AND WAVEFORMS: ENABLING THE NEXT GENERATION OF WIRELESS

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Application Engineer

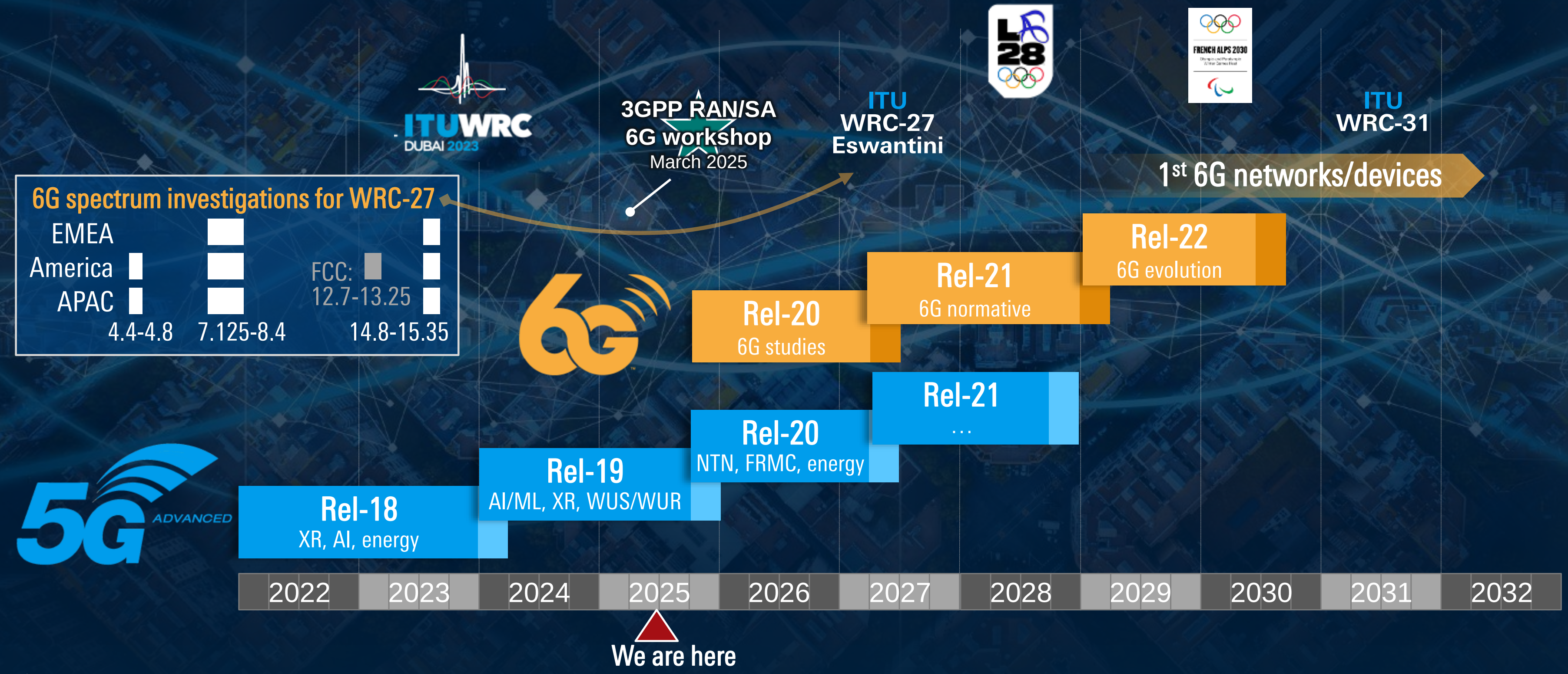
ROHDE&SCHWARZ

Make ideas real

Agenda

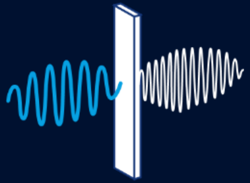
- Introduction
- 6G Roadmap
- 6G Technology & Application
- 6G Spectrum Resource
- 6G Modulation and Waveforms
- Conclusions

3GPP standardization and regulation
On the way towards planned 6G launch in 2030



6G Technology and Application

THz communication,
and **“FR3”**

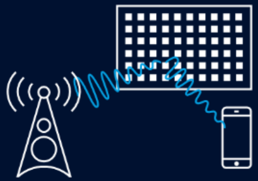


Integrated sensing
& communication

Satellite
Non-Terrestrial Network

Ultra-massive
MIMO

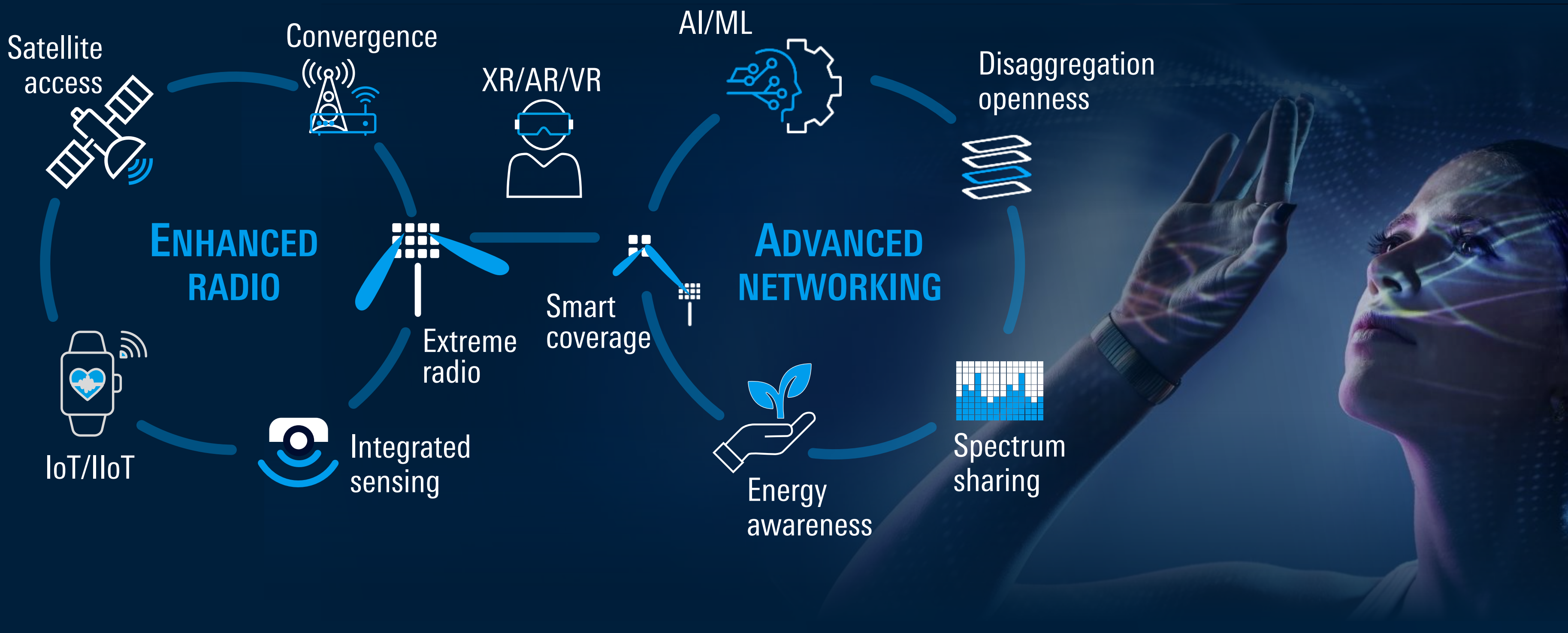
Artificial Intelligence
and Machine Learning



Reconfigurable
Intelligent Surfaces

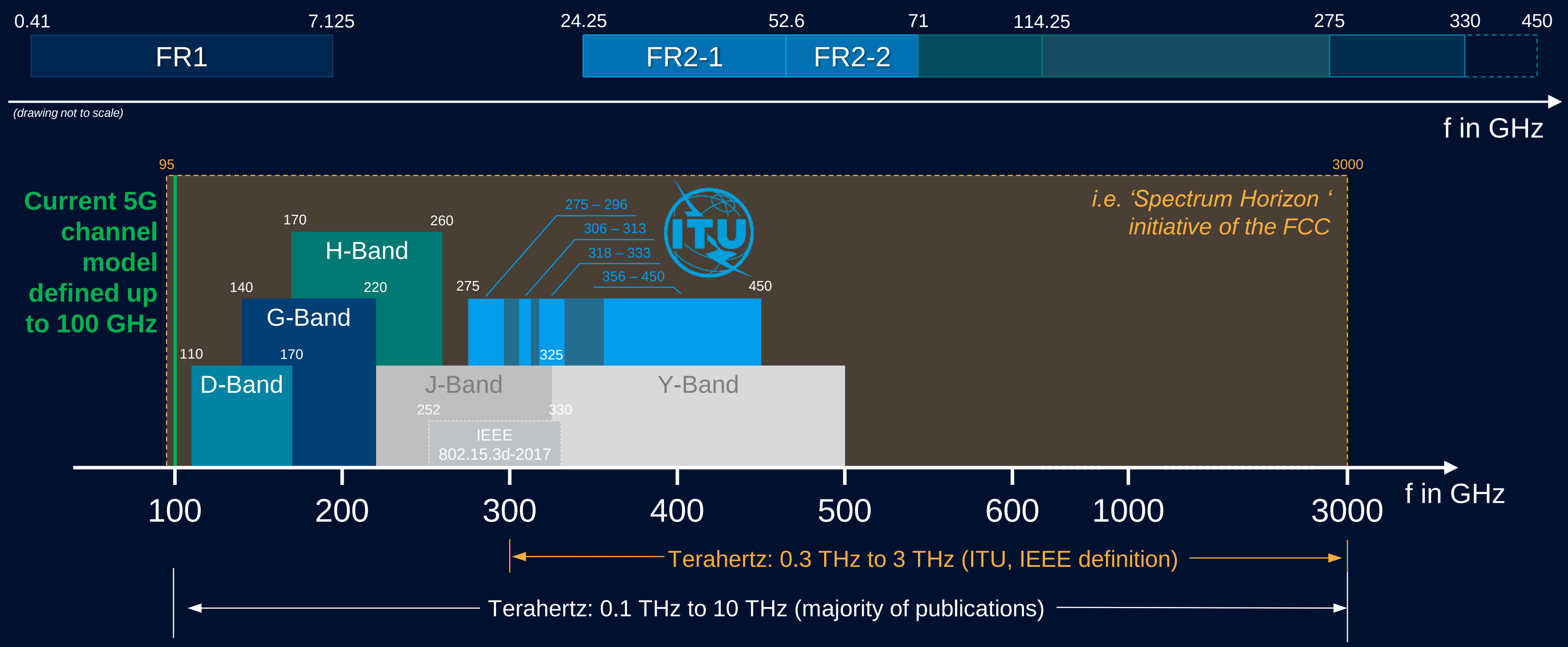
A high-level overview of all these research areas is provided in one of our #THINKSIX videos

Heading towards the future of wireless communication
Technology cornerstones



SPECTRUM RESOURCE

6G will deliver ultra-fast data connections
(sub)-THz was initially of interest and is still researched …



Hexa-X project
Use cases for upper & lower mmWave frequencies

6G mmWave technology
Lower (30 to 100 GHz) and upper (100 to 300 GHz) mmWave frequencies

Short-range wireless links
Small cell & access points (< 100 m)

- **Wireless access** (Device-to-Infrastructure)
- **Wireless access** (Device-to-Device)

Long-range wireless links
Front-, mid- and backhaul

- **Fixed wireless links**
- **Mobile wireless links**

Sensing w/ radio waves

- **Locali-zation**
- **Mapping, tracking**
- **Spectros-copy**


Holographic communications

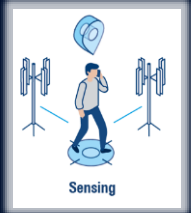

In-vehicle entertainment


Wireless link in data centers


Wireless fronthauling and backhauling


Digital twinning


Extended realities

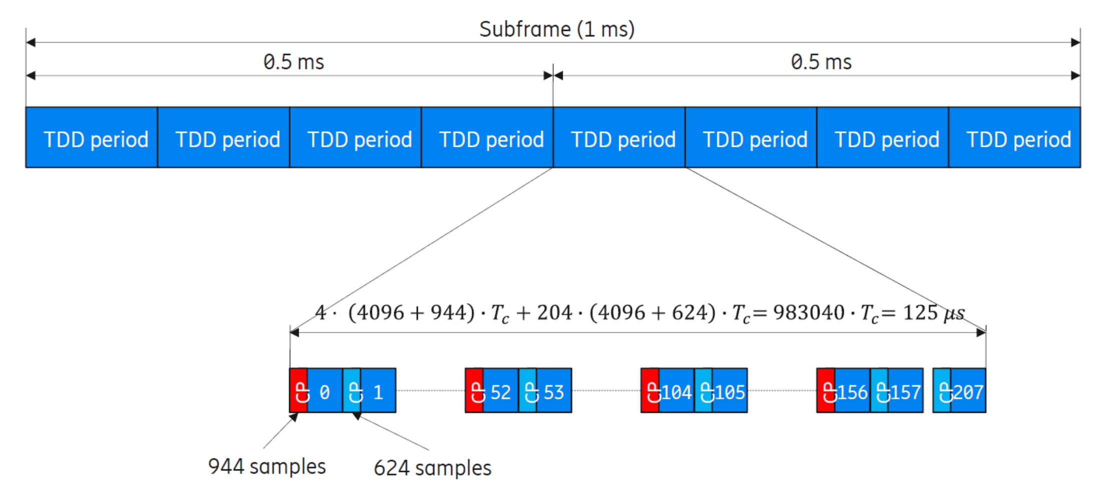

Sensing

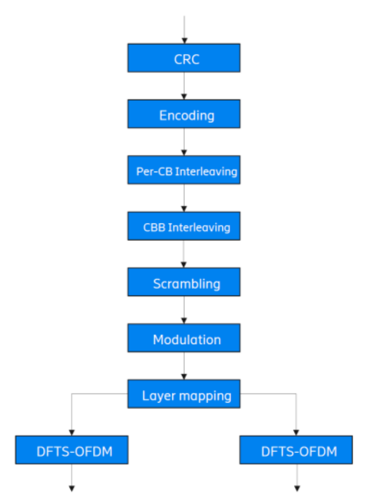
Source: https://hexa-x.eu/wp-content/uploads/2021/08/D2.1-summary-slides-short.pdf

One sub-THz waveform example
”A concept for evaluating sub-THz communication for future 6G”

- TDD / DFTs-OFDM low latency approach without real frame structure, rather TDD period based.
- High SCS (1920 kHz) to support large bandwidth and to handle phase noise.

Subcarrier spacing	Useful symbol time, T_u	Cyclic prefix, T_{CP}
1920 kHz	$4096T_{\bar{c}} \approx 521$ ns	$624T_{\bar{c}} \approx 79$ ns[1]





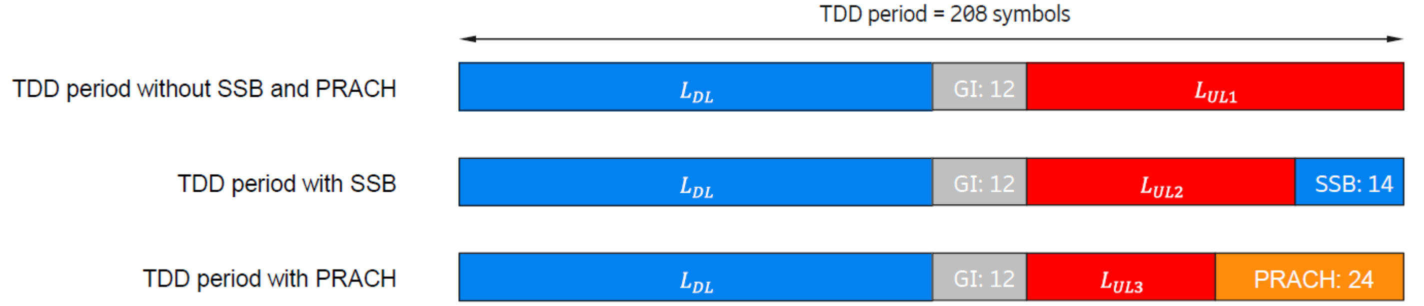
Transport-channel processing

One sub-THz waveform example

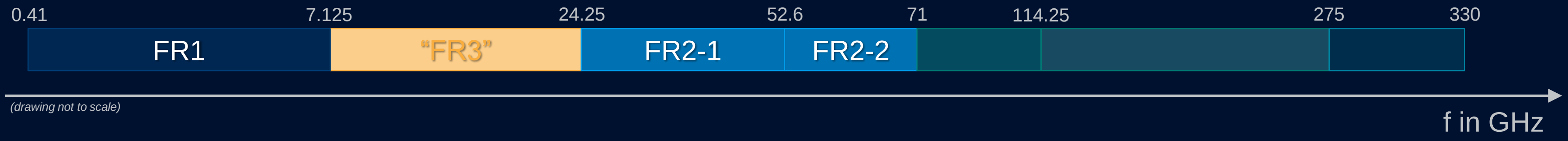
”A concept for evaluating sub-THz communication for future 6G”

- Three example configurations are described reflecting DL heavy, balanced and UL heavy traffic patterns.

Ratio	Downlink L_{DL}	Guard L_{GI}	Uplink $L_{UL,1}$ (no PRACH, no SSB)	$L_{UL,2}$ (SSB)	$L_{UL,3}$ (PRACH)
3:1	140	12	56	42	32
1:1	90	12	106	92	82
1:3	48	12	148	134	124



… but the commercial 6G spectrum interest is cm-wave
Focus is on upper mid-band ~ 6 GHz to 15 GHz



- 6.1.6 Potential Spectrum bands for study
  - 6.1.6.1 UHF Band
    - 6.1.6.1.1 1300-1350 MHz
    - 6.1.6.1.2 1780-1850 MHz
  - 6.1.6.2 Lower-cmW spectrum
    - 6.1.6.2.1 3100-3450 MHz
    - 6.1.6.2.2 3980-4180 MHz (TBD)
    - 6.1.6.2.3 4400-4940 MHz
    - 6.1.6.2.4 7125-8500 MHz
  - 6.1.6.3 Upper-cmW spectrum
    - 6.1.6.3.1 10-10.5 GHz
    - 6.1.6.3.2 10.7-12.2
    - 6.1.6.3.3 12.2 – 12.7 GHz
    - 6.1.6.3.4 12.7-13.75 GHz
    - 6.1.6.3.5 13.75-15 GHz
    - 6.1.6.3.6 25.25-27.5 (TBD)
  - 6.1.6.4 EHF Band
    - 6.1.6.4.1 37.0-37.6 GHz
    - 6.1.6.4.2 42-43.5 (TBD)
    - 6.1.6.4.3 92-114.25 GHz (W-band) and 122.25-174.8 GHz (D-band):

NEXT G ALLIANCE

Source:
Spectrum Working Group

6G cmWave performance

ERICSSON

This MWC demo used a highly accurate digital model of Dubai, the location for the recent World Radiocommunication Conference (WRC-23), to show how the coverage compares between 3.5GHz, 7GHz, and 14GHz. The basic conclusion is that 7-8GHz is very interesting spectrum that can come quite close to matching the DL coverage of 3.5GHz. This means that re-use of the existing grid becomes a more likely possibility and this needs to be further explored.

Laying the groundwork for new spectrum

Qualcomm

Securing spectrum for 6G is a decade-long journey that is already underway. Frequencies between 6 GHz and 15 GHz — known as the upper mid-band — have been identified as prime candidates for 6G use. The International Telecommunication Union (ITU)'s World Radiocommunication Conference 2023 (WRC-23) have initiated studies to identify bands within this range for 5G Advanced and 6G. For instance, one of the most impactful agenda items for WRC-27 involves the identification of several frequency bands, including 4.4-4.8 GHz, 7.125-8.4 GHz and 14.8-15.35 GHz, for potential International Mobile Telecommunications (IMT) use. In addition, many countries throughout the world are planning to deploy IMT services in the upper 6 GHz band (6.425-7.125 GHz).

Operators view on 6G spectrum

Some examples

410 - 7125

Supports all bands in FR1 from 410 – 7125 MHz

As 5G NR, 6G continues to support all FR1 bands

Pot. new FR1 spectrum only upper 6 GHz band

6425 - 7125

Clean exclusive IMT spectrum (without RLAN usage) needed for efficient 6G deployment

u6GHz: 6425 – 7125 MHz for IMT only

200 MHz CBW support (400 opt.)

> 24 GHz

"FR2" and (lower) THz

Lower priority for DT, but 6G assumed to work up to 71 GHz as NR does

We do not see lower THz (71-300 GHz) or even higher frequencies as candidate bands for 6G radio deployments

"FR3"

{7-24 GHz}

No potential for Europe currently seen

6GWS-250011

Operators view on 6G spectrum
Some examples

700 | 800 | 900 | 1500
1800 | 2100 | 2600 | 3500

Upper 6 GHz | 7 – 15 GHz | mmWave | Sub-THz

Legacy Bands (4G/5G)

- Spectrum Sharing, e.g.
  - ✓ 3500 MHz for capacity
  - ✓ 700 MHz for coverage
  - ✓ 2100 MHz & potentially any 5G band if Spectrum Sharing overhead / cost is low

6 GHz seen as prime 6G band

- Upper 6 GHz to be pushed for exclusive use for IMT
- Light indoor coverage

7 – 15 GHz as potential complement

- 7.125 – 7.25 GHz is a priority
- 7.75-8.4 GHz & 14.8-15.35 GHz more uncertain (NATO, fixed links)

mmWave (26 GHz)

- Still uncertain
- Business case not better in 6G vs 5G

Sub-THz

- Not foreseen in the 6G timeframe

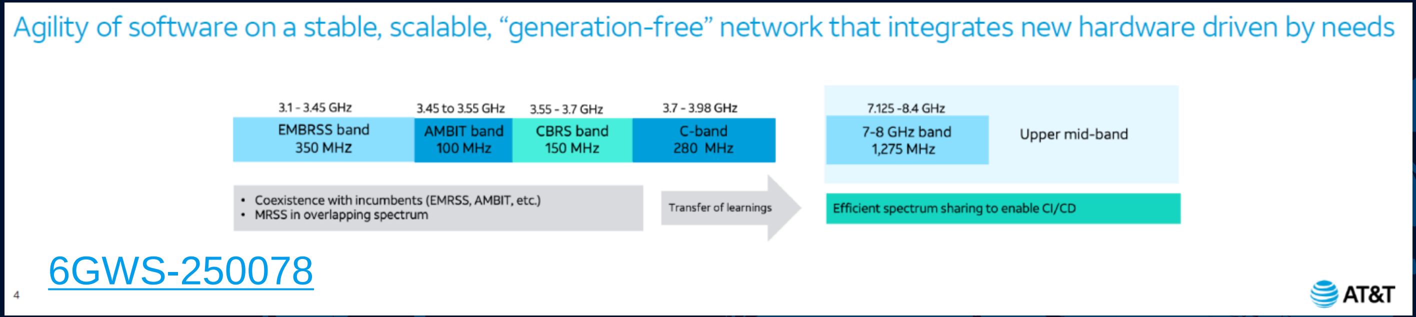
orange

6GWS-250130

Orange Position

- Ideal initial 6G spectrum = **6 GHz + several legacy 5G bands in spectrum sharing** (e.g. 3500 / 700 MHz at least)
- Need for **higher bandwidth (e.g. 200 MHz)** and **higher number of MIMO layers** in **6 GHz** at least

Operators view on 6G spectrum
Some examples



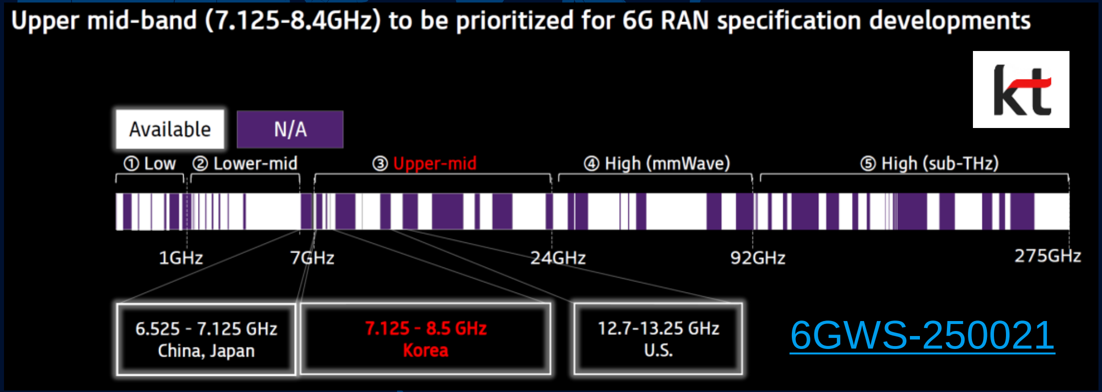
6GWS-250078

6GWS-250143

中国移动 China Mobile

Higher Frequency

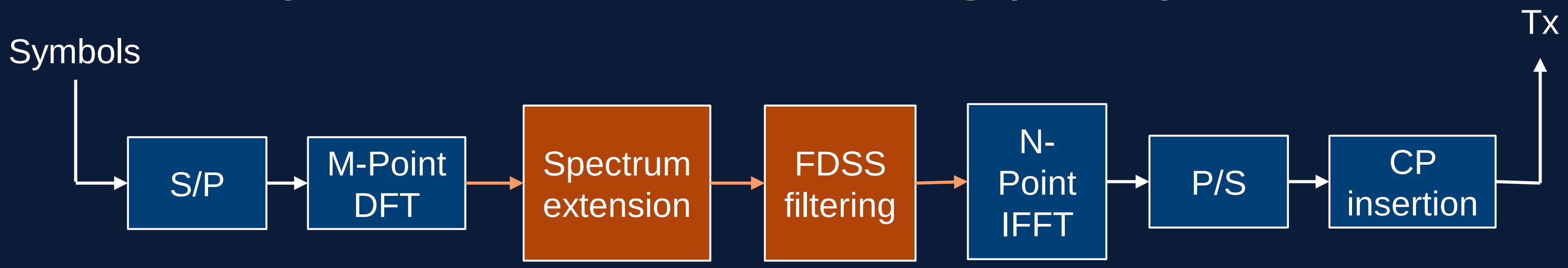
1 2.6/3.5GHz → 6-7GHz

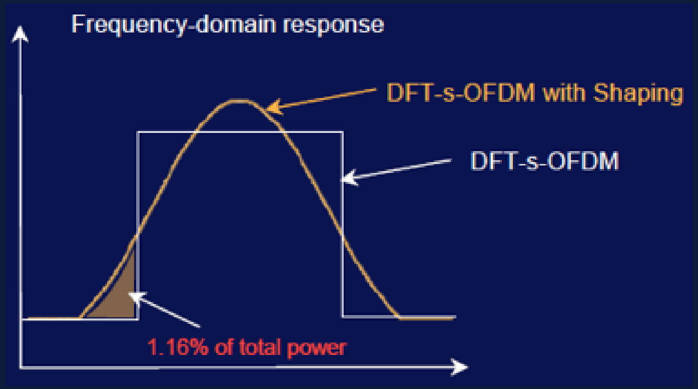


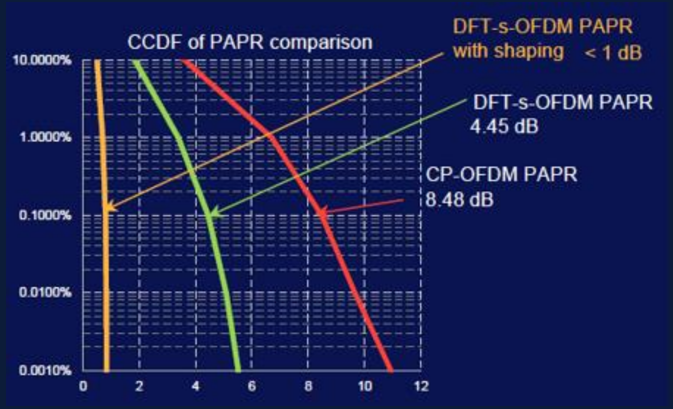
6GWS-250021

6G WAVEFORM

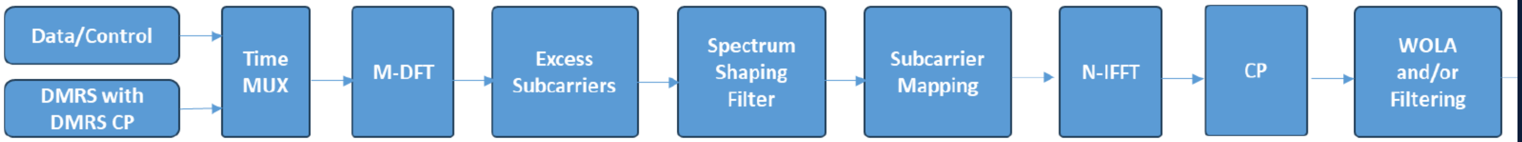
6G waveform proposals [6GWS-250036](6GWS-250036)
Frequency-domain spectrum shaping (FDSS) in UL







6G waveform proposals: 6GWS-250026
Orthogonal Time Frequency Division Multiplexing (OTFDM)



Time Division Multiplexing in one Symbol
- Time multiplexing of Data and Control & DMRS with DMRS CP
- Instantaneous Channel Estimation with low DMRS overhead
- Information transfer in one shot with the Least Possible Latency

DFT Excess BW Spectrum Shaping Filter
- Nyquist Criterion for Zero ISI
- Excess BW signal shaping Controls the ISI caused by the pulse, reduces the tails of the ISI channel power to a below-noise floor, Reduces Effective ISI channel length, Enables DMRS-based estimation of the effective ISI channel
- Excess BW reduces PAPR further

Standard OFDM Operations
- Subcarrier mapping enables the multiplexing of multiple users/signals
- CP to offer frequency domain receiver processing
- Same spectral properties as OFDM - WOLA/filter for spectral confinement

OTFDM achieves the targets: low PAPR, Hyper low-latency
Enables multi-user multiplexing in time/frequency
Applicable in UL/DL

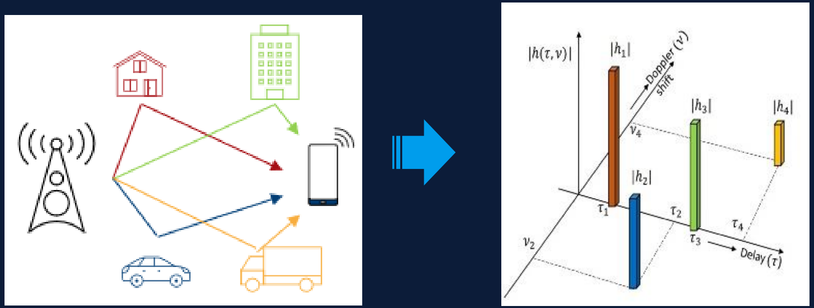
OTFDM publication pre-print

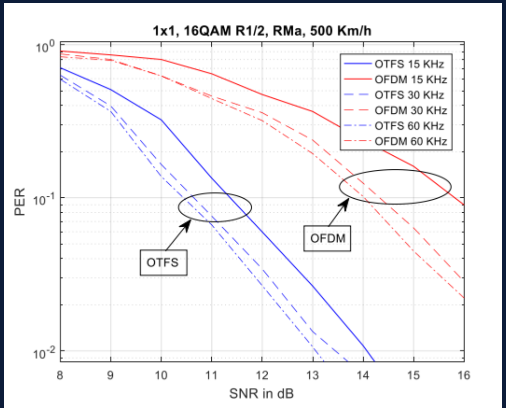
https://arxiv.org/abs/2409.01114

6G waveform proposals 6GWS-250233
Zak-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 $x(t)$

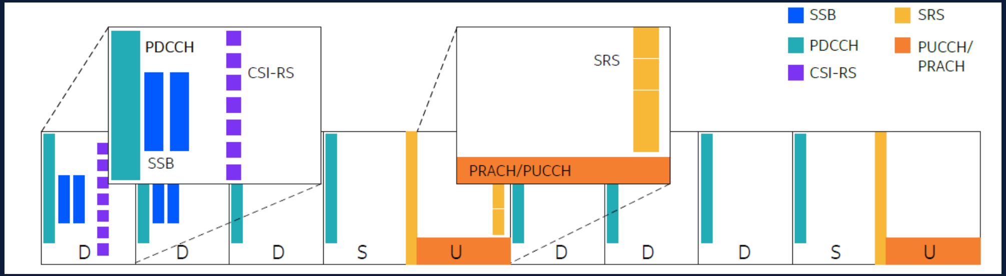




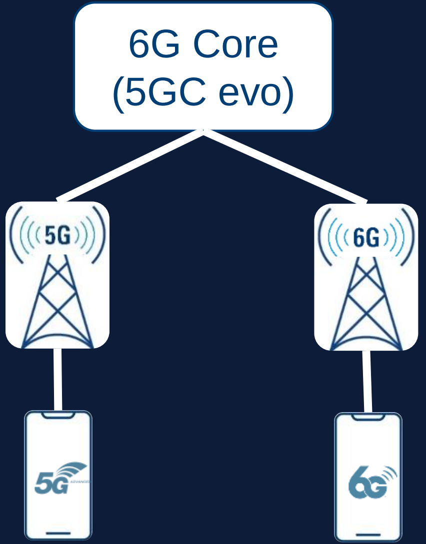
Ref: R1-1609825, 3GPP TSG RAN WG1 Meeting #86bis, 2016

6G waveform at cm-wave spectrum
MRSS motivates similarity with 5G NR

- Clear requirement to allow 6G SA operation in existing FR1 spectrum
- Potential solution: Multi-RAT Spectrum Sharing with focus on 5G/6G MRSS
- Based on similar principles than DSS in 5G/4G but leveraging 5G flexibility for always on signals



Source: Nokia white paper on „Simplifying spectrum migration from 5G to 6G "

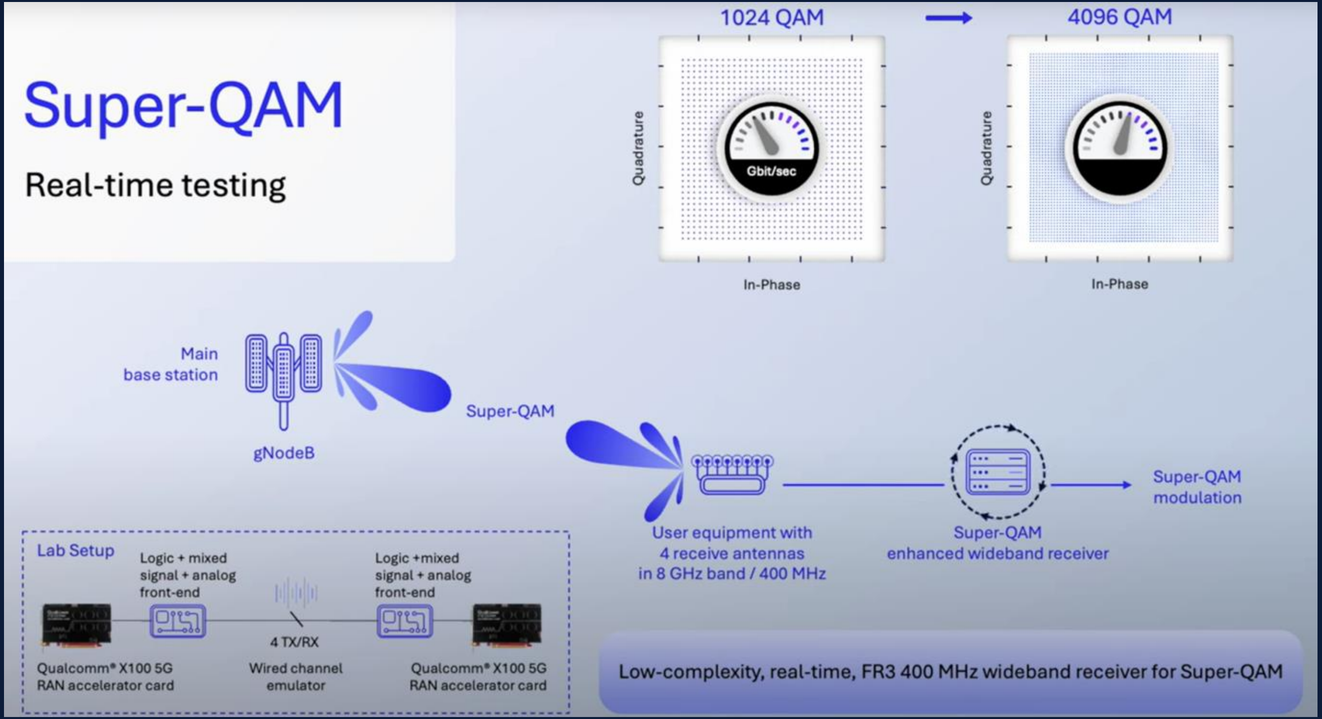


Chair's summary of the 3GPP WS on 6G radio interface (6GWS-250243):

"Non-backwards compatible (from a UE perspective) to exploit full potential, with certain characteristics (e.g. waveform, modulation and channel coding) based on 5G NR with possible enhancements."

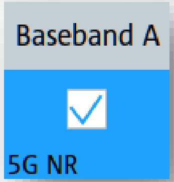
6G waveform at cm-wave spectrum
Evolution of modulation: Super-QAM

- Qualcomm video on „Super-QAM“ to „enable significant increase in speed and spectral efficiency“



DEMO SETUP

R&S®SMW200A Vector Signal Generator



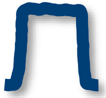
Signal Generation and Analysis

R&S®FSW Signal and Spectrum Analyzer

RF

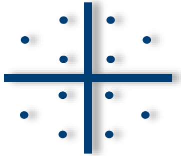
Non-Standard Channel BW

e.g. 500 MHz, 4 GHz, 8 GHz

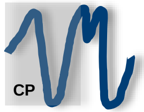


Non-Standard modulation format

e.g. 4kQAM, Custom, …

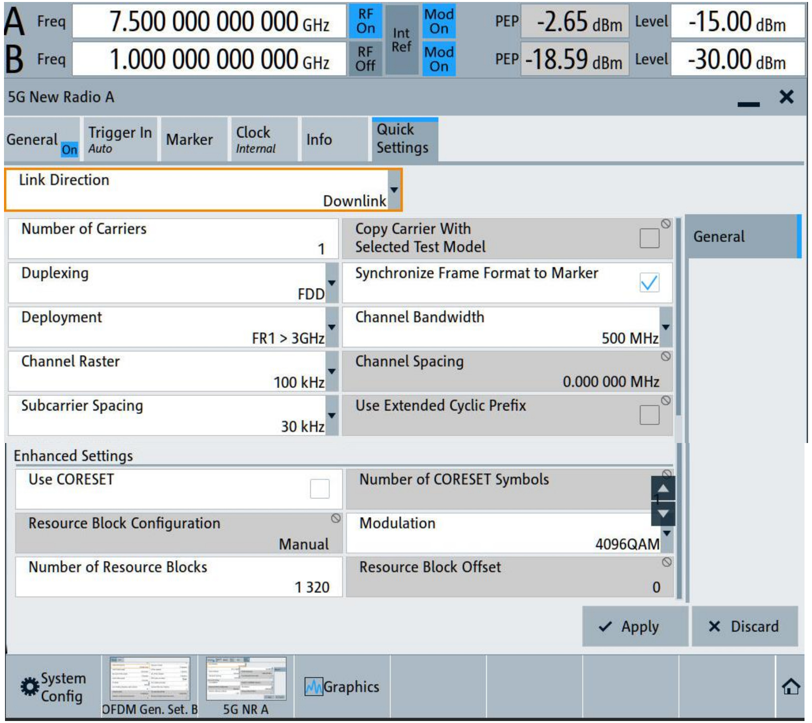


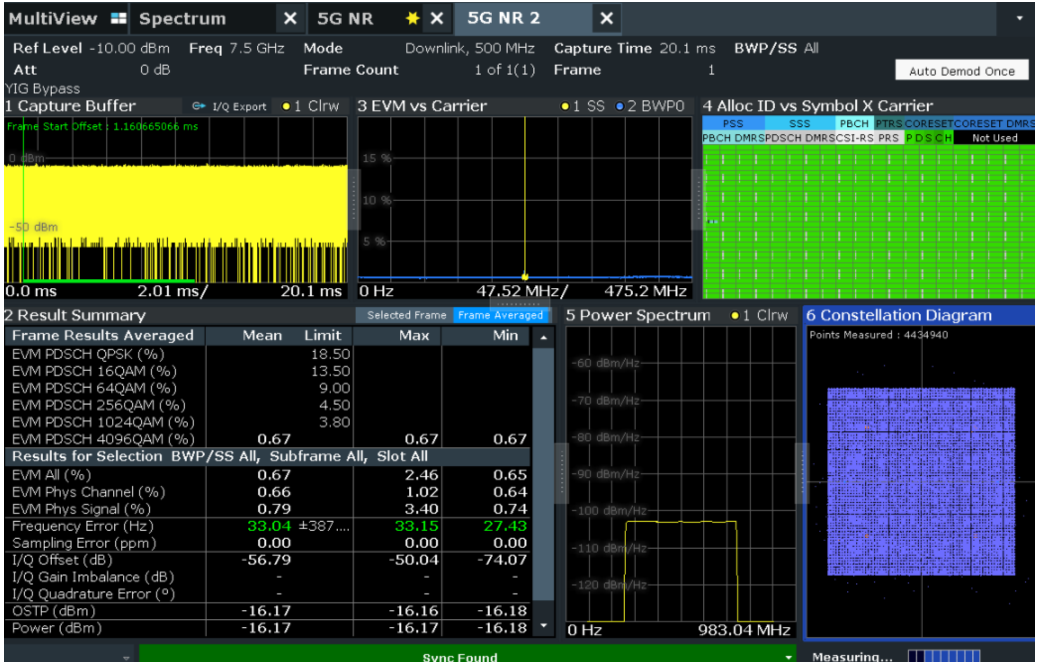
Non-Standard cyclic prefix



And more…

DEMO SETUP



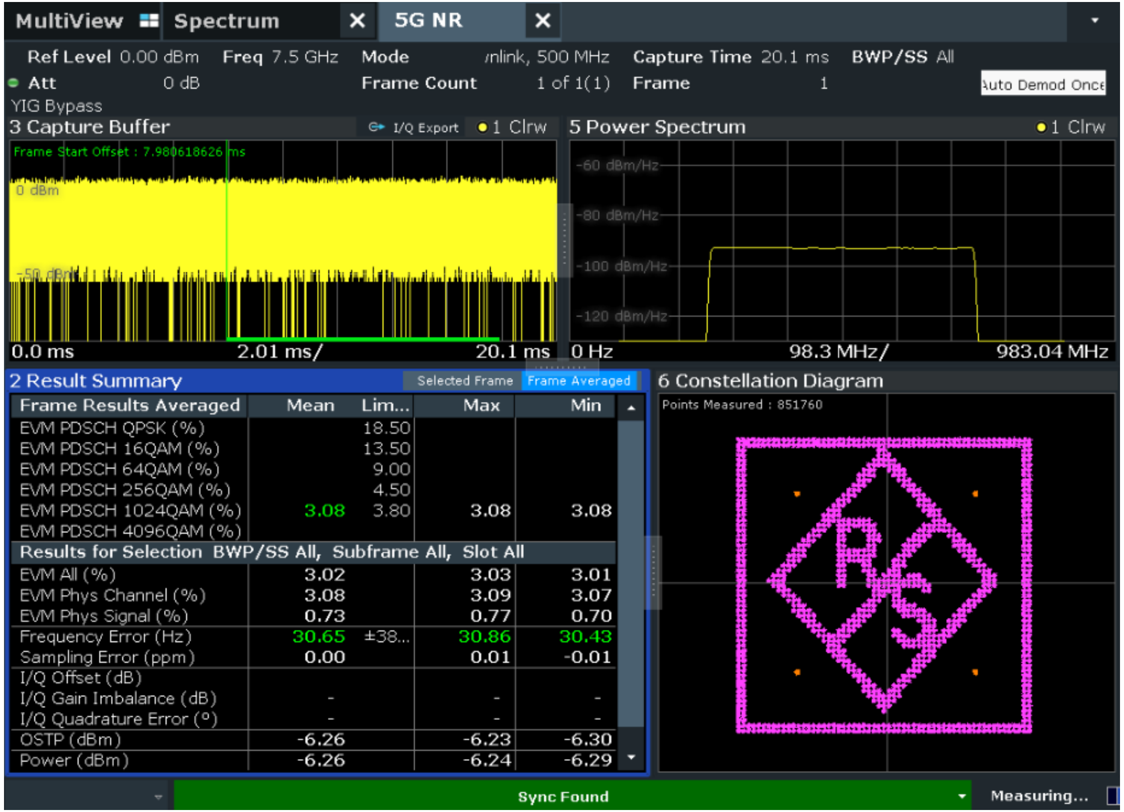


- Frequency : 7.5GHz
- Bandwidth : 500MHz
- Modulation : 4096 QAM

DEMO SETUP

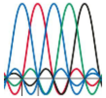
Customized Constellation!

- ▶ Frequency : 7.5GHz
- ▶ Bandwidth : 500MHz



OFDM DEMO SETUP

R&S®SMW200A Vector Signal Generator



OFDM

Signal Generation and Analysis

R&S®FE110ST Frontends R&S®FE110SR

IF

RF

IF

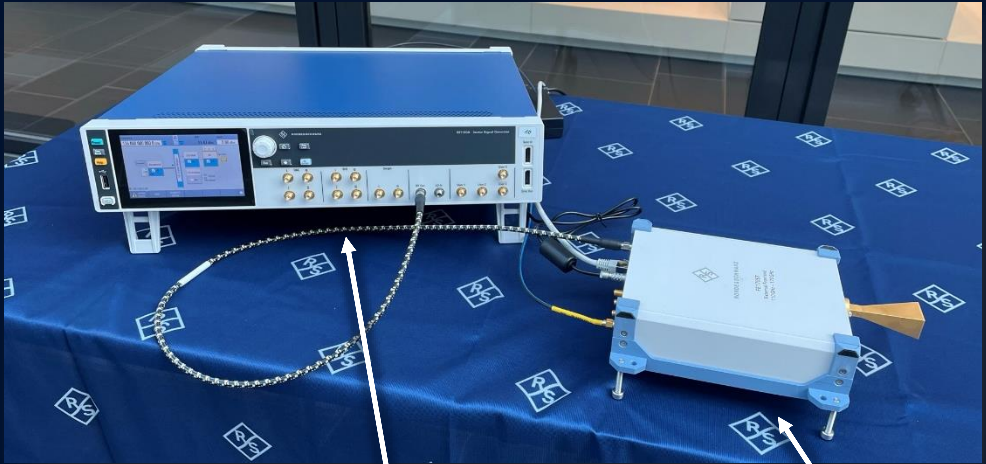
R&S®FSW Signal and Spectrum Analyzer

Other Frontends and Converters

R&S®FE170ST/FE170SR

R&S®FC330ST/FC330SR

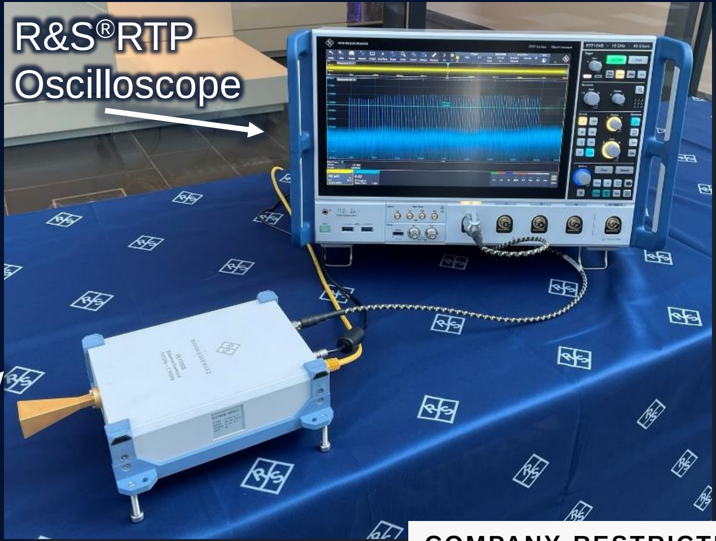
SUPPORT OF WIDER RF SIGNAL BANDWIDTH & PRECISE POWER MEASUREMENTS AT D-BAND



R&S®NRP170TWG
Power Sensor

R&S®SFI100A Wideband IF Generator
For modulation bandwidths up to 10 GHz

R&S®FE170ST/R
RF Frontend



R&S®RTP
Oscilloscope

OVER-THE-AIR (OTA) TESTING IN D-BAND

R&S®FE110/170 FRONTENDS INTEGRATED INTO OUR CHAMBERS

R&S®ATS1800C

Compact 3GPP-compliant OTA chamber for 5G NR mmWave signals

CONCLUSIONS

- Although 3GPP has laid out the schedule for specifying the next generation of cellular technology, namely 6G, details will only become available over years to come.

- Early testing of components and RF modules with new physical layer parameters requires flexible software options already today.

- Rohde & Schwarz is committed to support our customers 6G product development to make their ideas real.

THANK YOU!

No one can whistle a symphony.
It takes a whole orchestra to play it.

Halford E. Luccock (1885-1960)

www.rohde-schwarz.com/6G