6G FLAGSHIP
UNIVERSITY OF OULU

RF Towards 6G

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ACADEMY OF FINLAND

FLAGSHIP PROGRAMME

6G – How we should understand it?

- Something that is totally new?
- Everything that we couldn't make in 5G with it's evolution?
- Next scheduled major milestone in 3GPP roadmap?
- Revolution in communications?
- Natural evolution of technologies towards the next generation of communications (and sensing)?
- Radio or System?

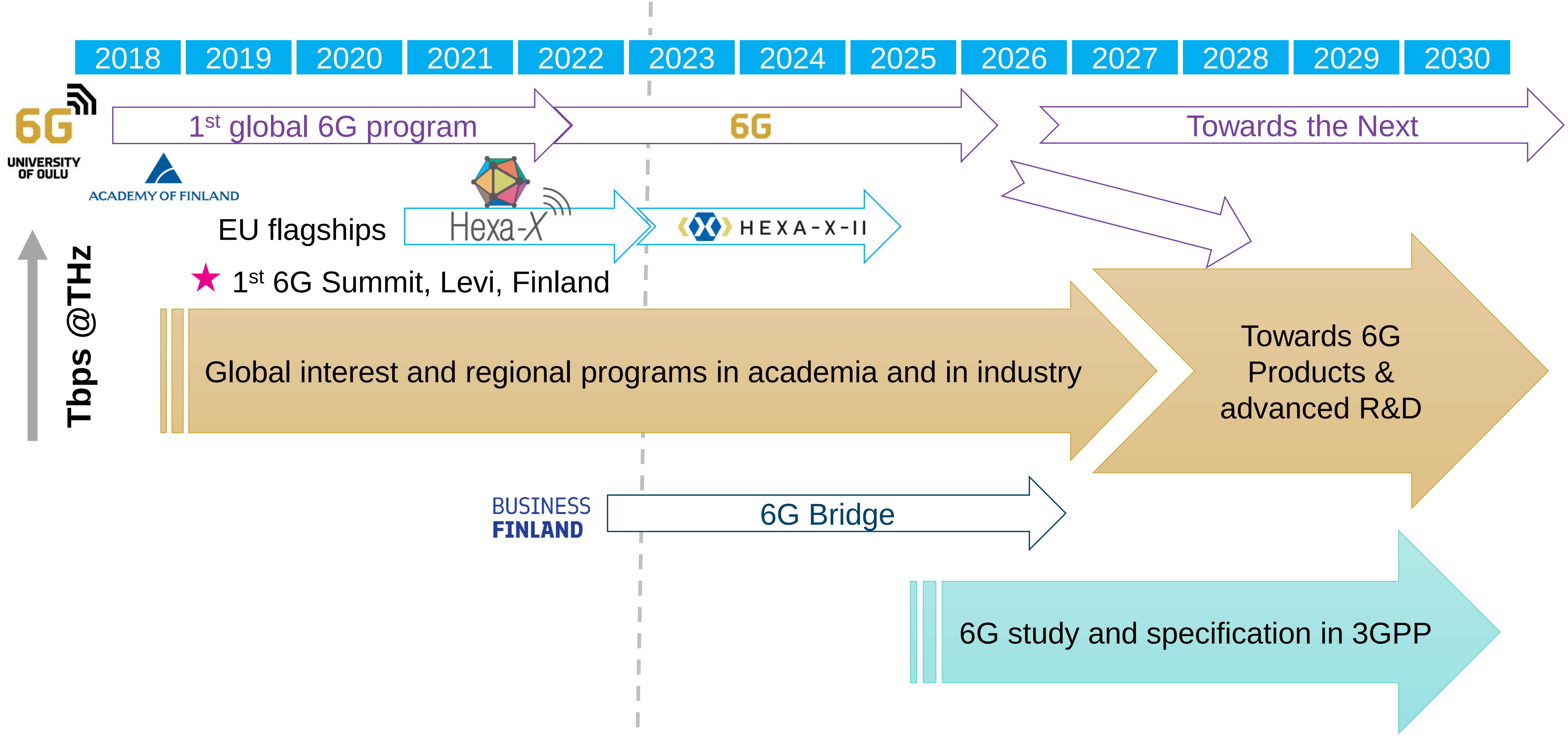
Vision

Vision for 2030

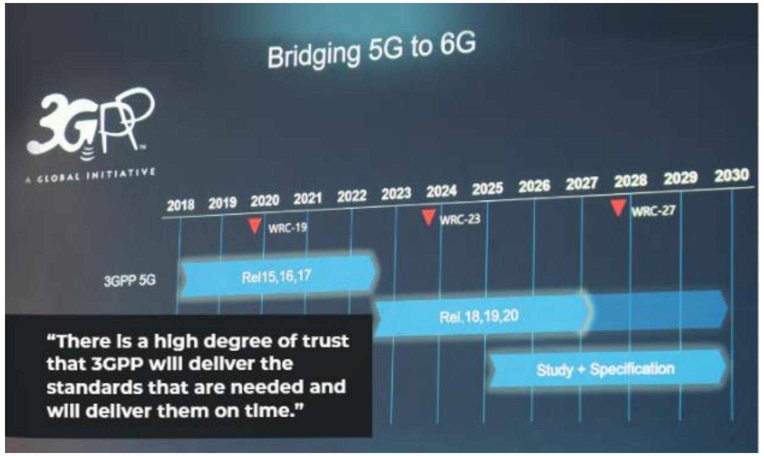
Our society is data-driven, enabled by near-instant, unlimited wireless connectivity.

6G will emerge around 2030 to satisfy the expectations not met with 5G, as well as, the new ones fusing AI inspired applications in every field of society with ubiquitous wireless connectivity.

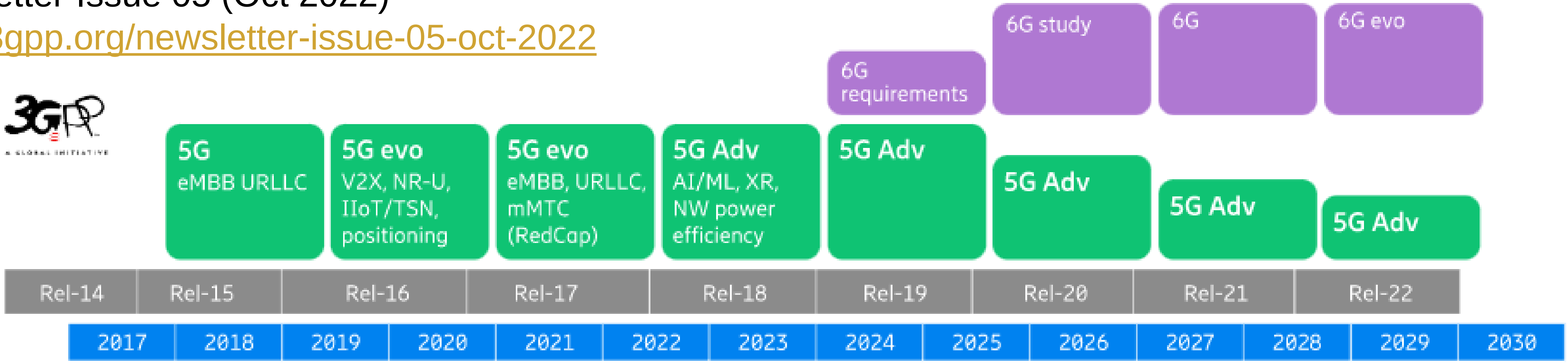
Evolution of 6G



Towards standardization



3GPP Newsletter Issue 05 (Oct 2022)
https://www.3gpp.org/newsletter-issue-05-oct-2022



Ericsson's view of the 5G Advanced and 6G timeline of 3GPP (dates beyond 2023 are indicative)
https://www.ericsson.com/en/reports-and-papers/white-papers/5g-advanced-evolution-towards-6g

Chicken or the egg?

- Technology or use case driven market?

	target	Killer app?	RF Technology
2G	Voice call	Voice, sms	BiCMOS
3G	Internet	Office in pocket	BiCMOS/CMOS
4G	Improved internet	Personal video distribution	CMOS
5G	Capacity & scalability	Verticals?	CMOS/BiCMOS
6G	Improved capacity and scalability ?	Wireless sensing, metaverse, holographic imaging, … ?	Exist but what and how ?

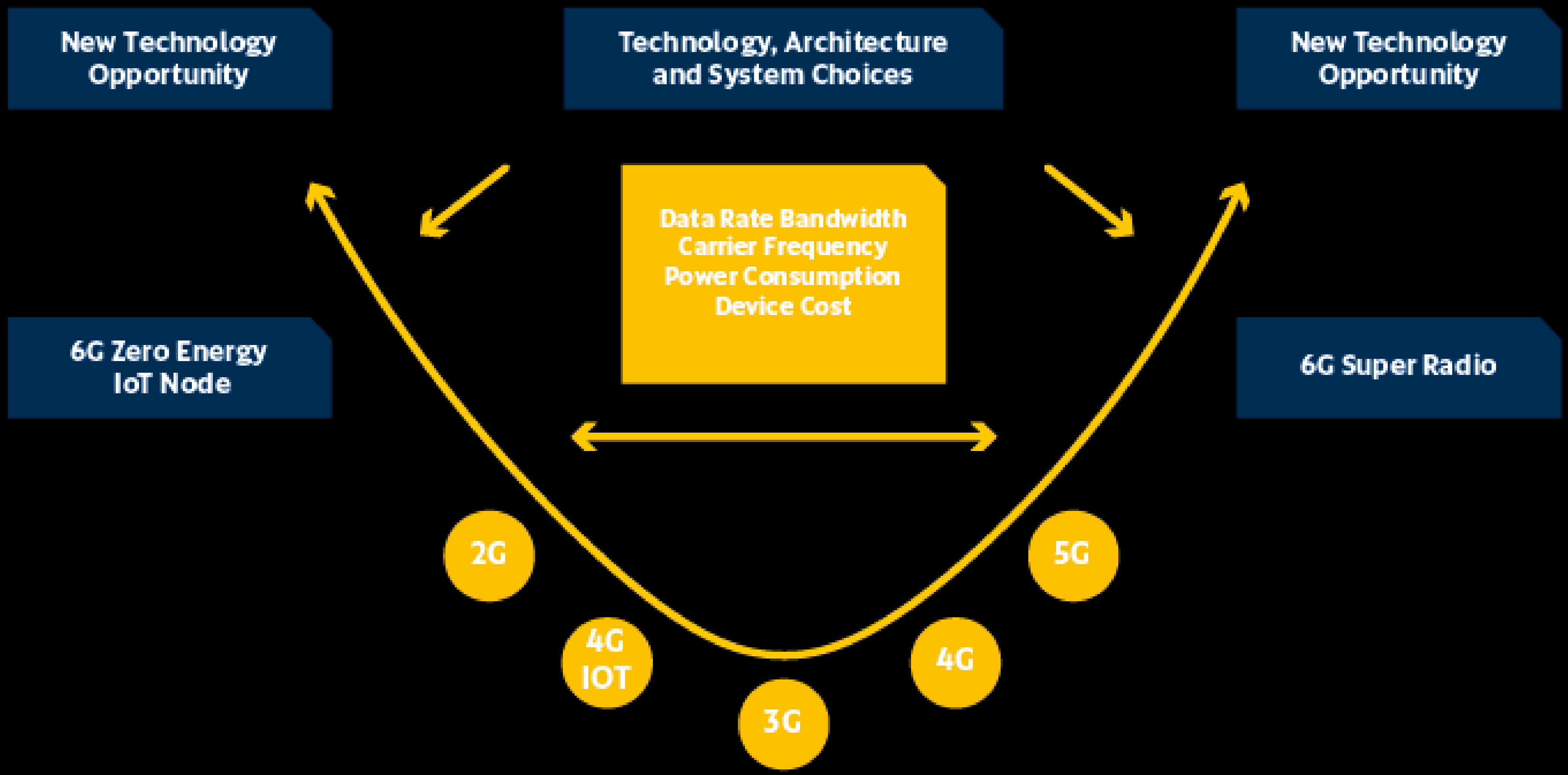
Industrial visions and targets

- 6G key technologies by Nokia

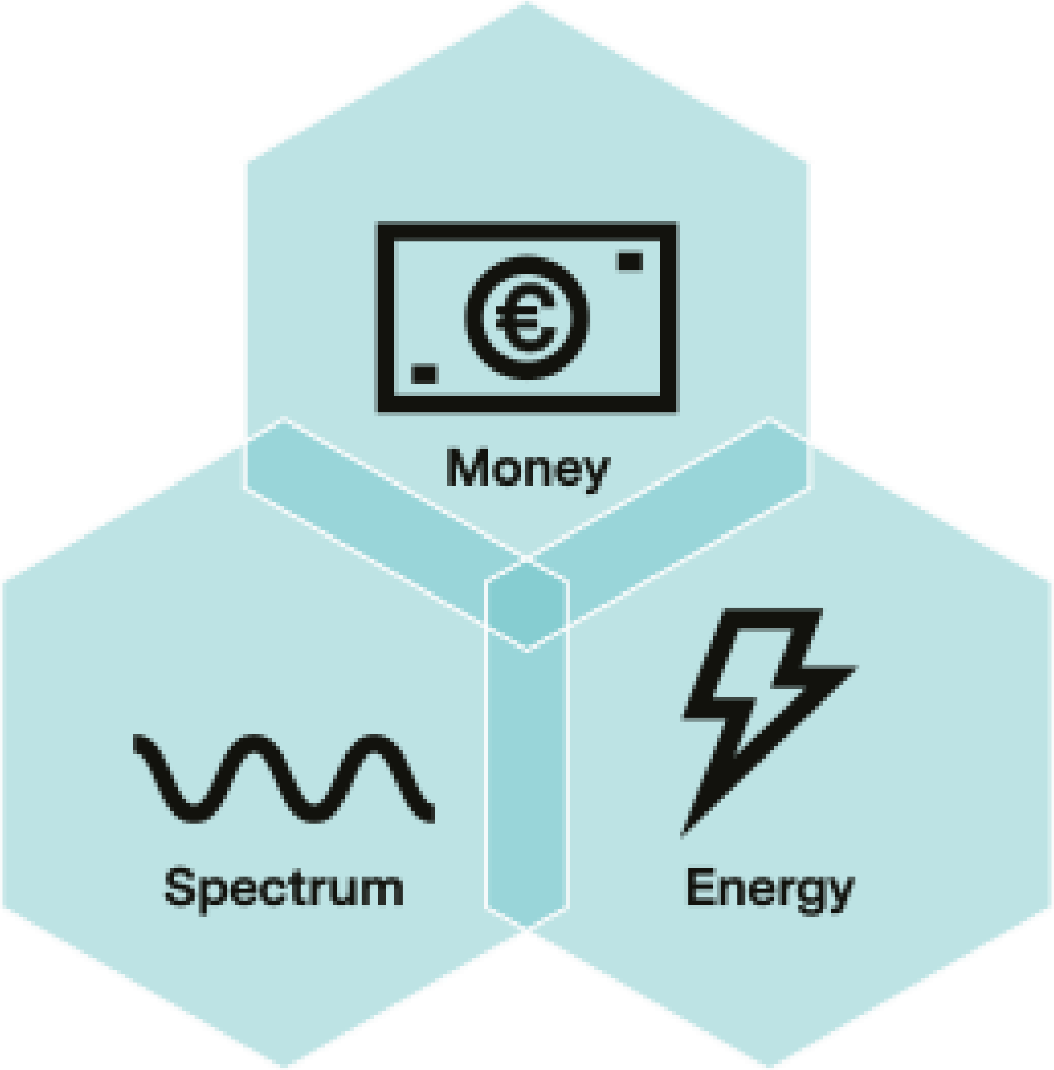
“6G must be designed to provide, at minimum, 20 times more wide-area capacity than 5G.”
Nokia Bell Labs, “Envisioning a 6G future”

https://d1p0gxnqcu0lvz.cloudfront.net/documents/Nokia_Bell_Labs_Envisioning_a_6G_future_eBook_EN.pdf

What is challenging?



Constraints of wireless communications



Exponential growth?

- Economics
- Moore's law
- Edholm's law
- User needs

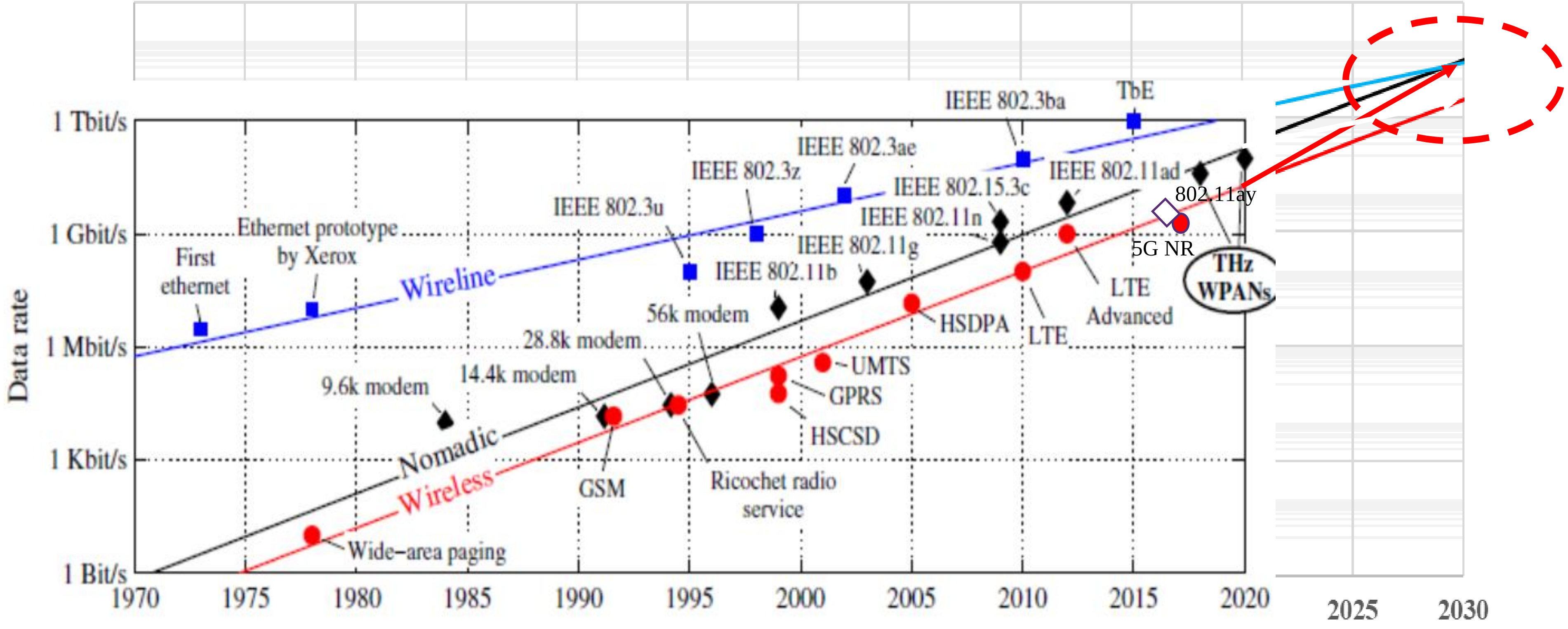


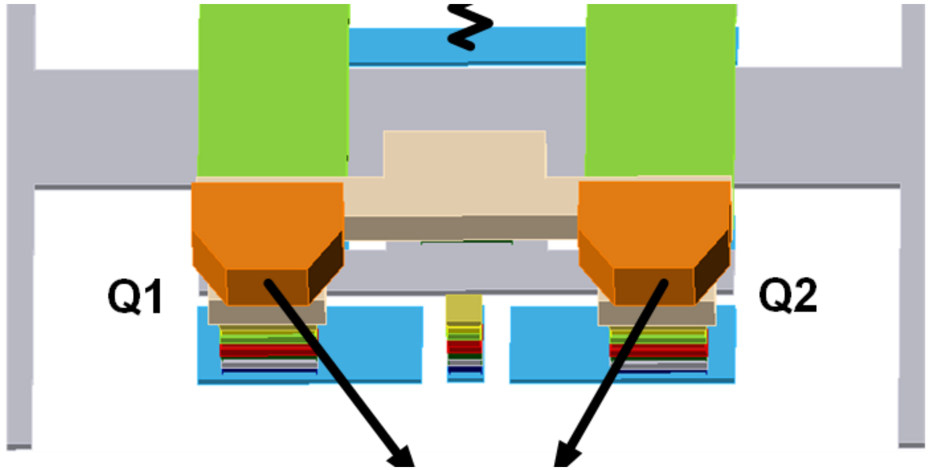
Figure 1 Development of data rates in wireline, nomadic and wireless systems (from [3])

Modified from [T. Kürner and S. Priebe, JIMTW 2013]

Stack of Wireless Systems

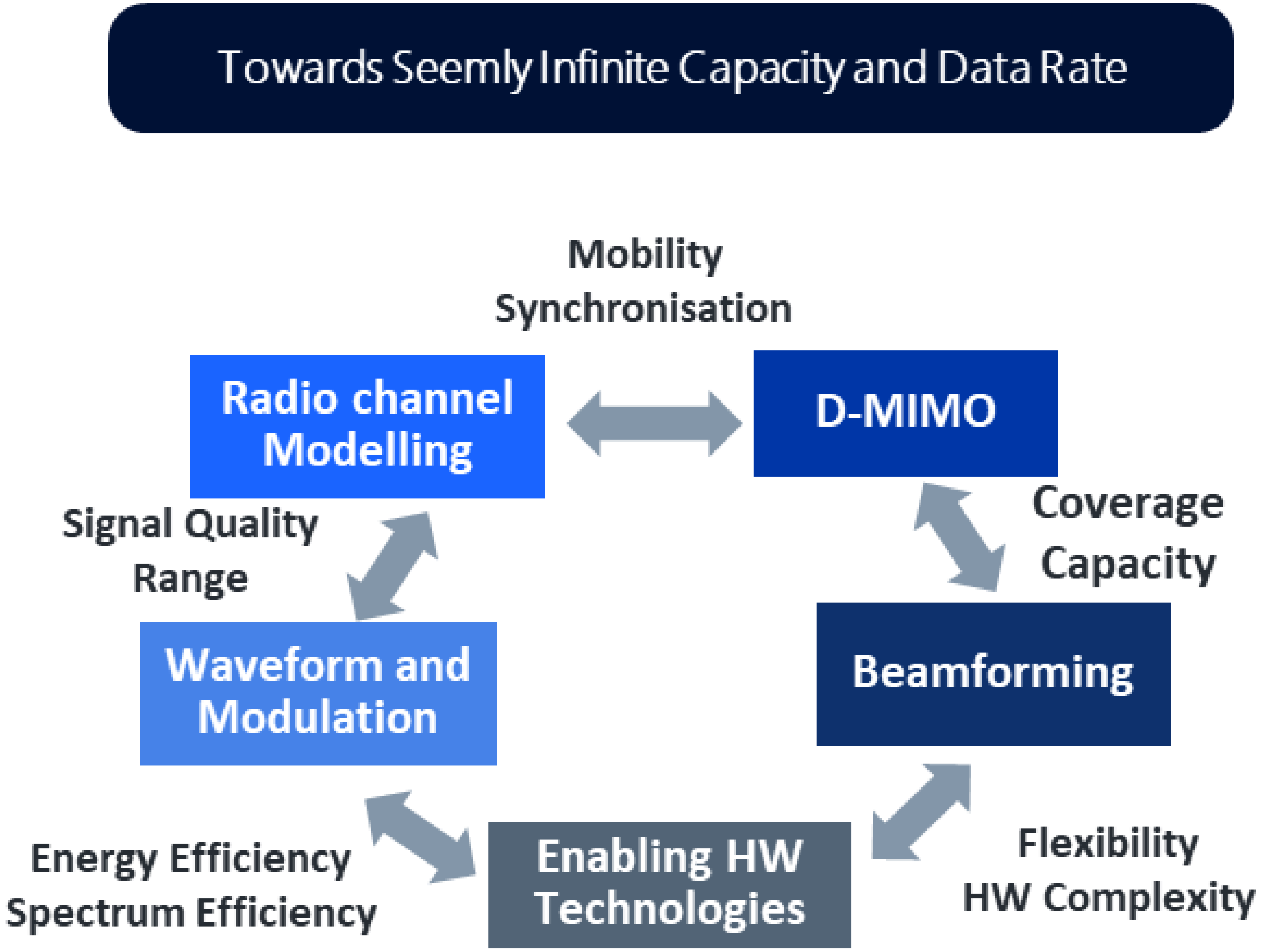
Users and Applications
Internet
Wireless Systems and Spectrum
Wireless Protocols (OSI)
Transceivers & Modems (HW & SW)
RF/Analog/Mixed-mode/Digital Circuits
Semiconductor Technologies
Materials

From devices to wireless systems



vs.

Hexa-x   Radio performance towards 6G



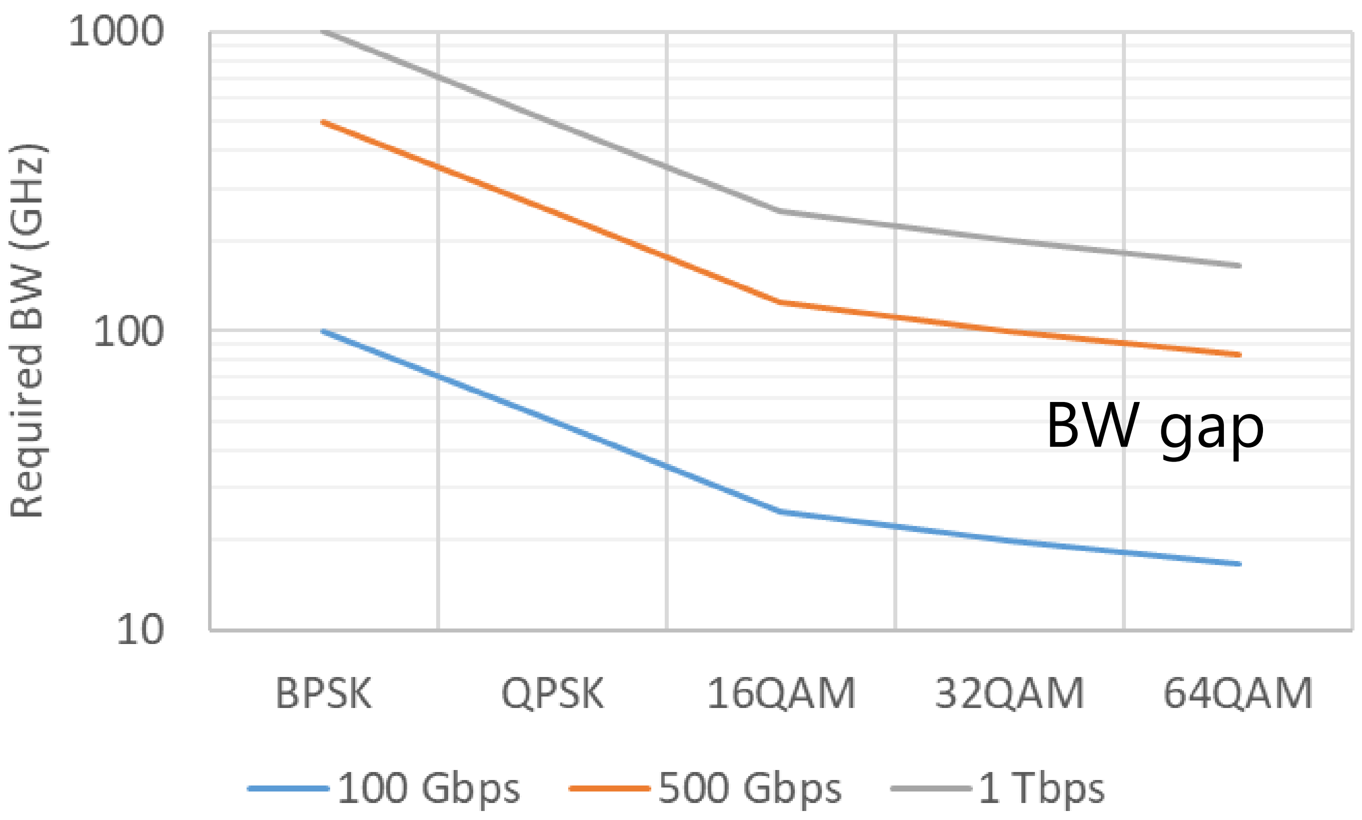
Initial Requirements for 6G Radio

Parameter	First wave 6G radio requirement	Long-term vision for 6G radio
Data rate (R)	100 Gbps	1 Tbps
Operational/carrier frequency (f_c)	100 – 200 GHz range	Up to 300 GHz range
Radio link range (d)	100 - 200 meters	10 – 100 meters
Duplex method	Time Division Duplexing (TDD)	TDD
Initial device class targets	Device to infrastructure, mobile backhaul/fronthaul	Infrastructure backhaul/front haul, local fixed links, and interfaces (data centres, robots, sensors, etc.)

Source: EU H2020 Hexa-X project

Bandwidth for 1Tbps

- Targets for 6G communications range from 0.1 to 1Tbps



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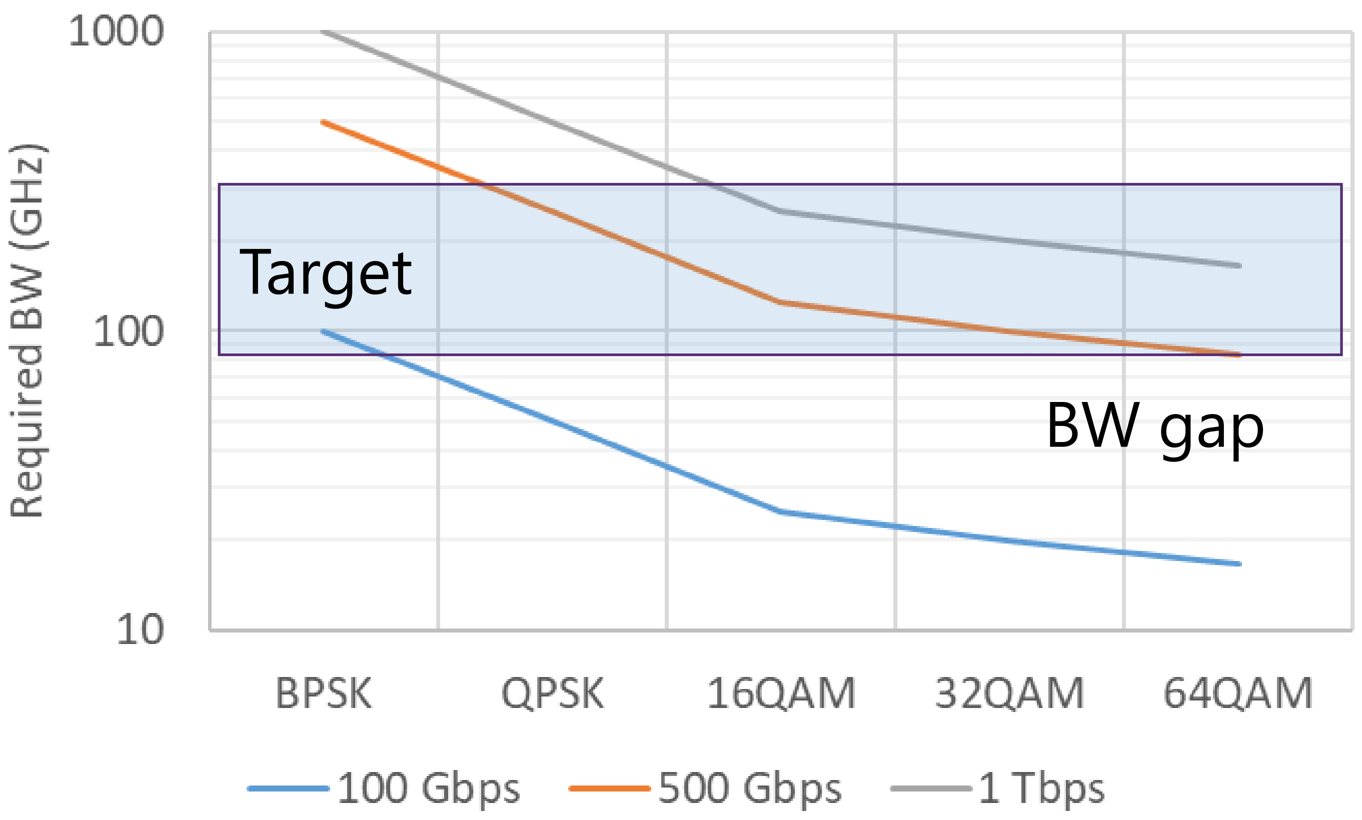

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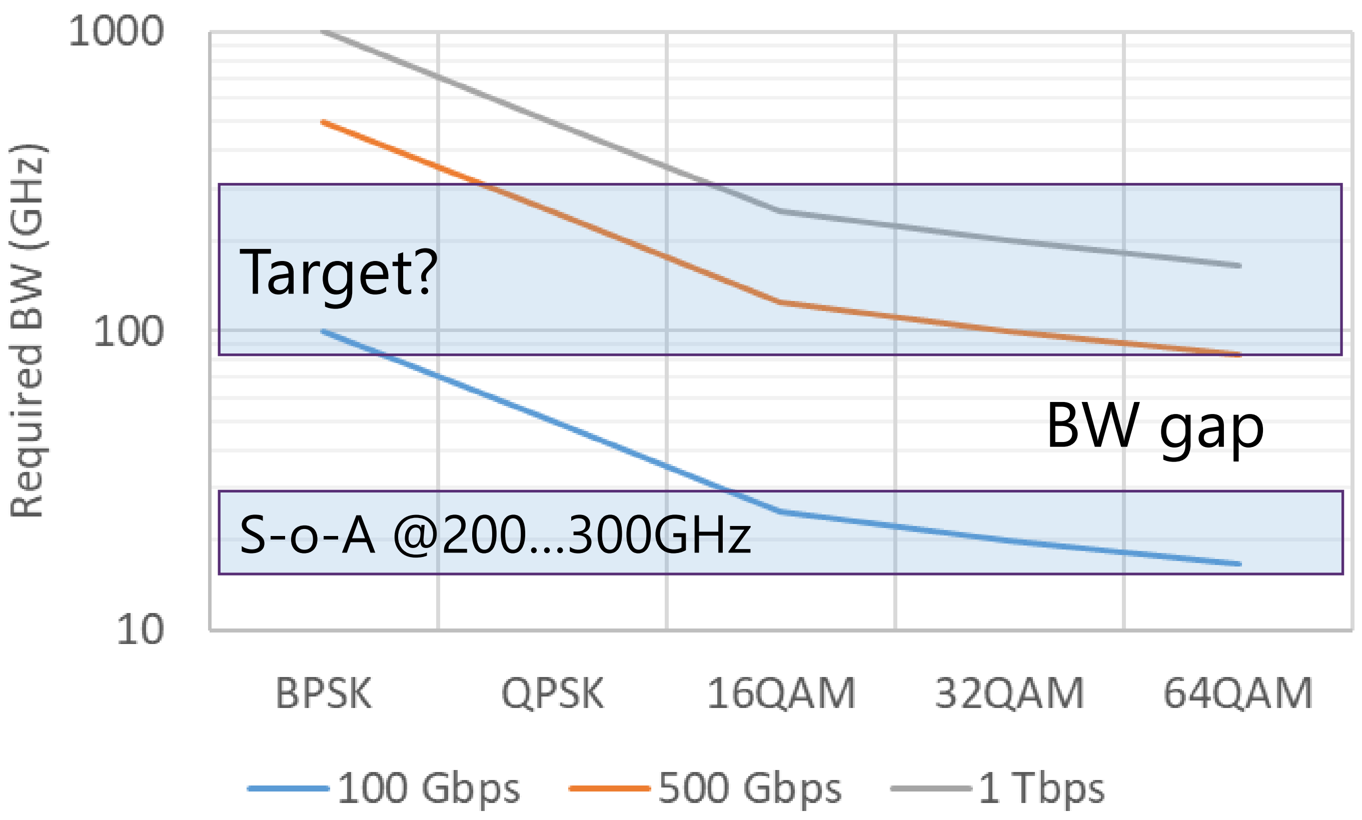
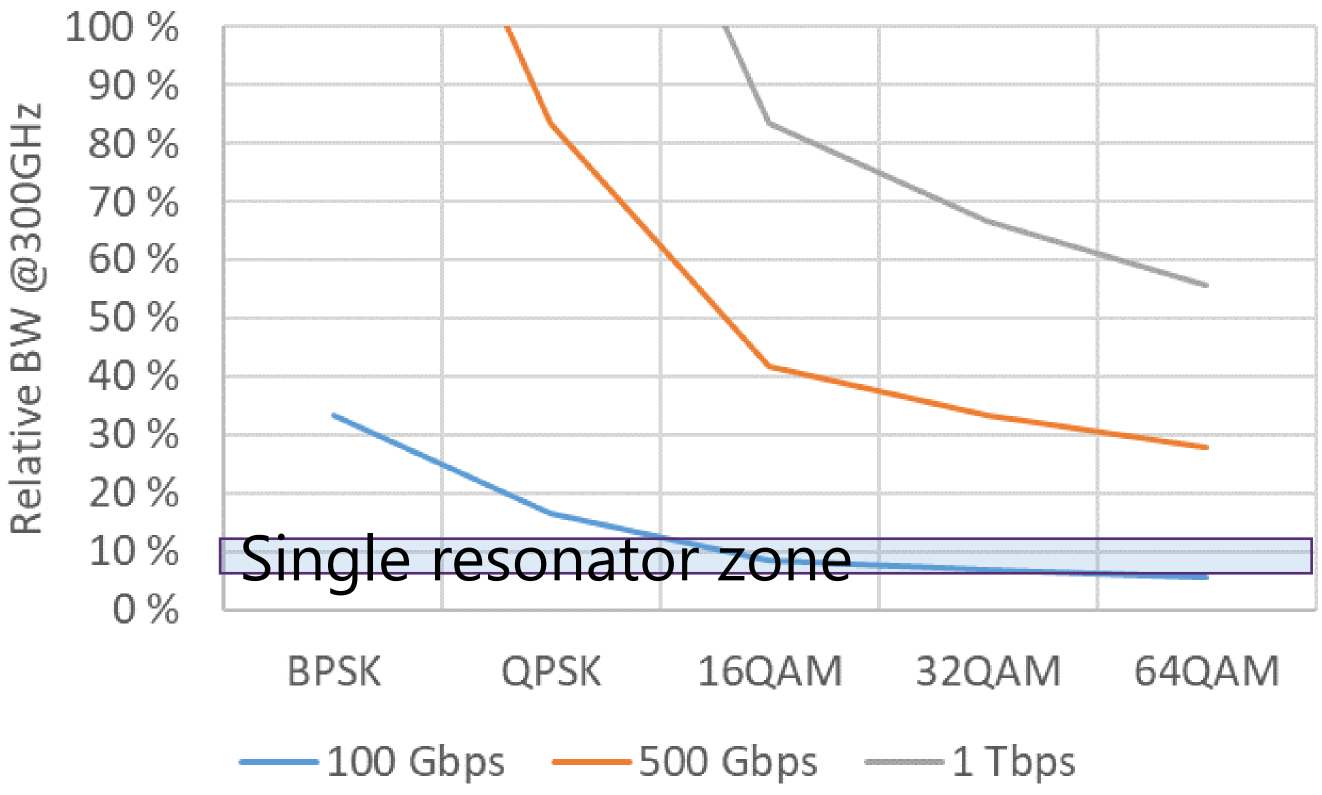


Relative Bandwidth for RF Design

- Matters in RF design equally as absolute BW/carrier frequency
- Integrated resonators with Q~10



Example @300GHz

Relative Bandwidth for RF Design

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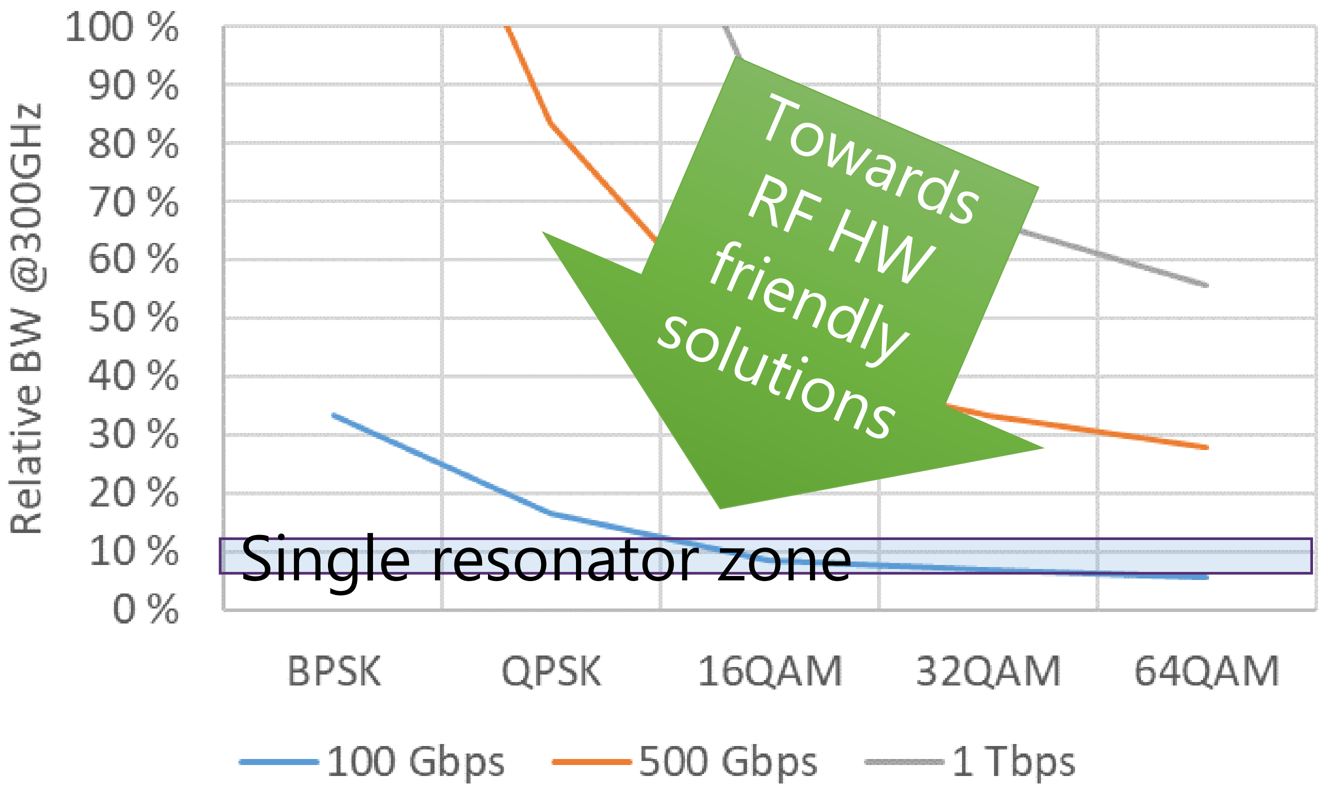


Number of orthogonal radio channels?

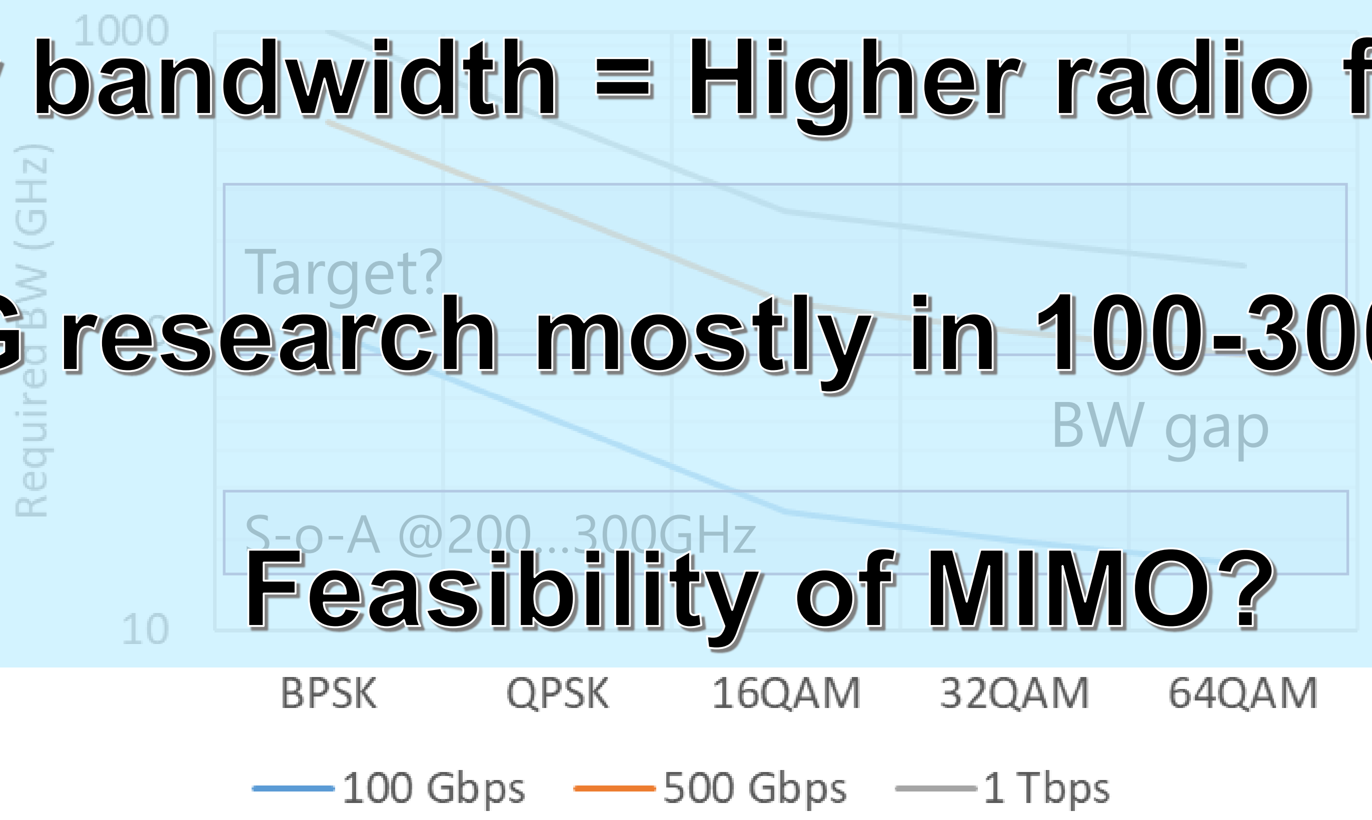
Bandwidth for 1Tbps

- Targets for 6G communications range from 0.1 to 1Tbps

Larger bandwidth = Higher radio frequency

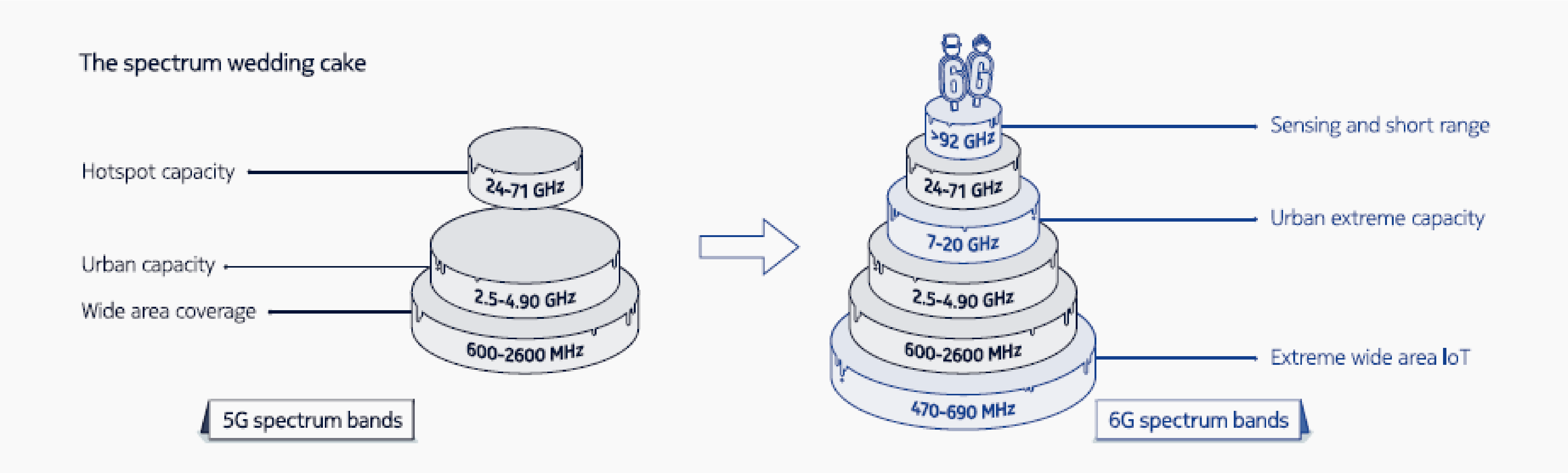
6G research mostly in 100-300GHz

Feasibility of MIMO?



What about realism?

- Most of the challenging use cases in ~100 Mbps…10 Gbps range
- Multiple users within the same cell
- Spectrum?



Nokia Bell Labs, "Envisioning a 6G future"

https://d1p0gxnqcu0lvz.cloudfront.net/documents/Nokia_Bell_Labs_Envisioning_a_6G_future_eBook_EN.pdf

What about realism?

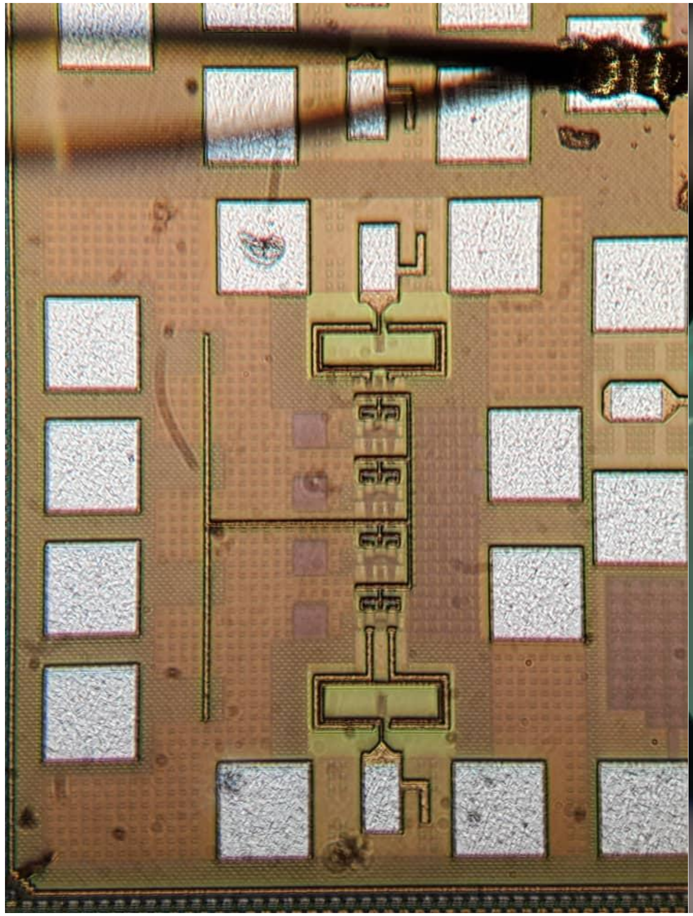
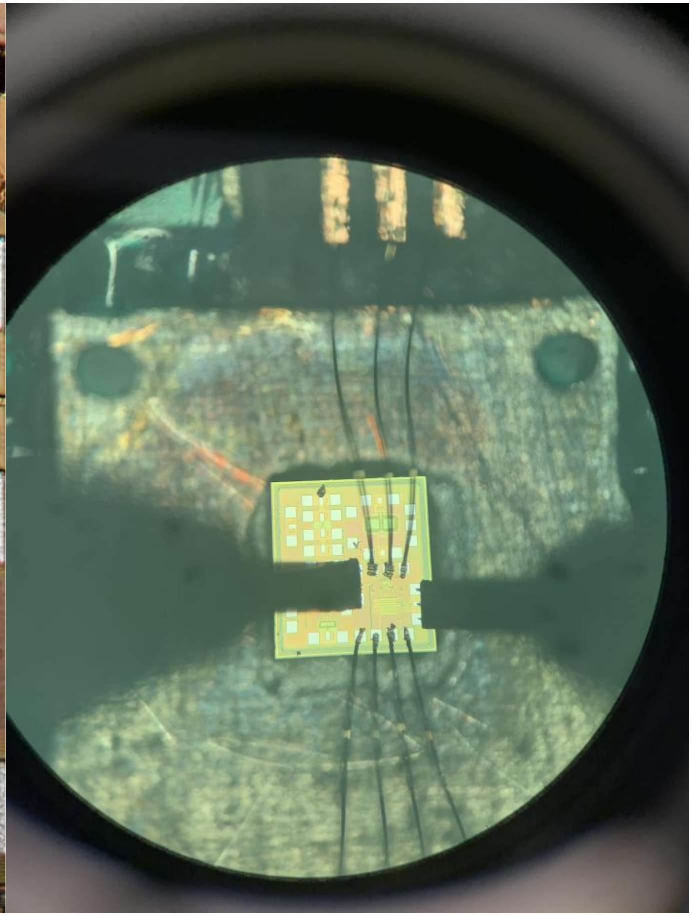
- Extreme speed and capacity?
- Minimalism?
- Ultimate scalability?

ALL OF THAT, THANK YOU!

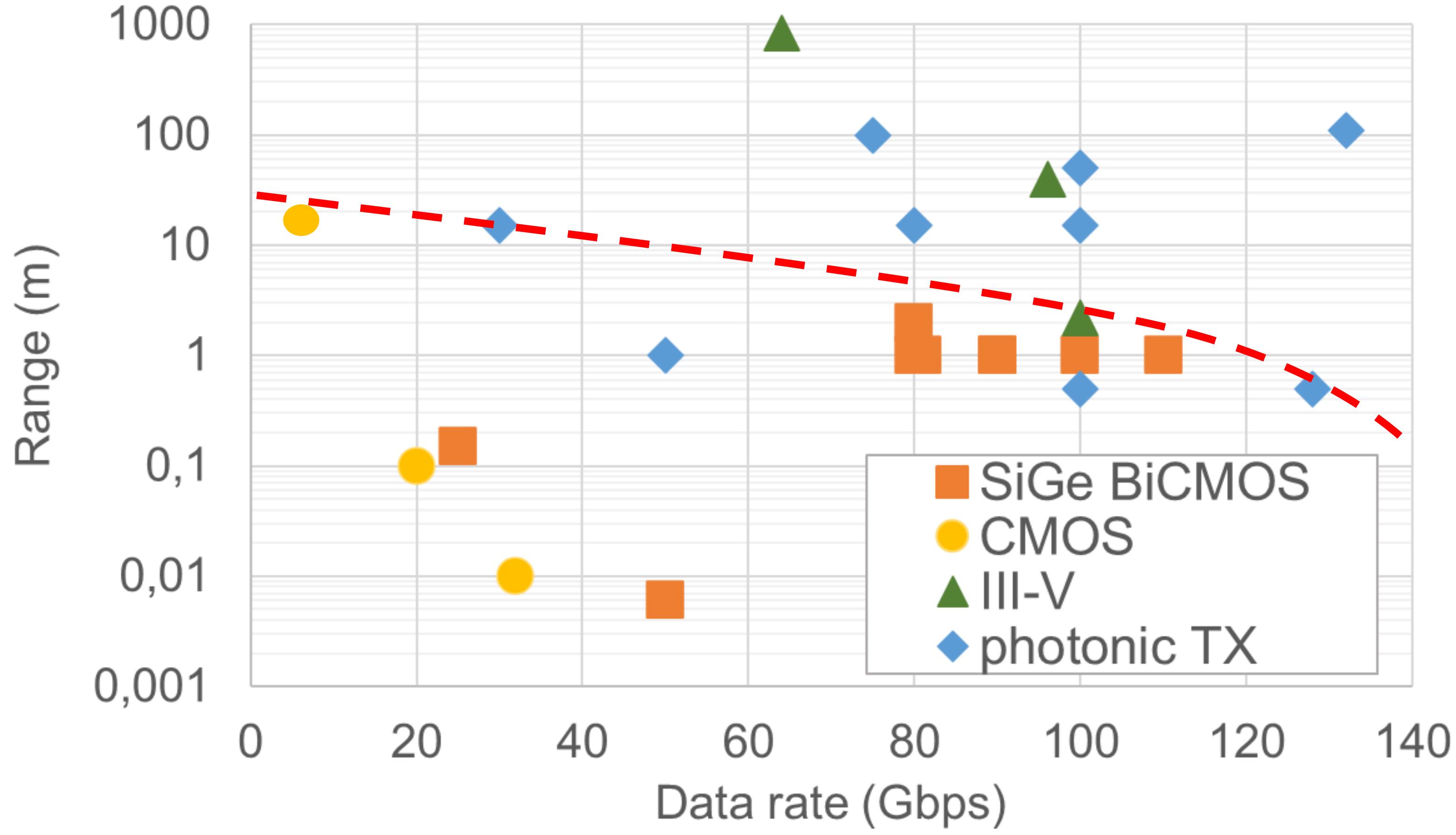
- With minimal complexity, power consumption and price?

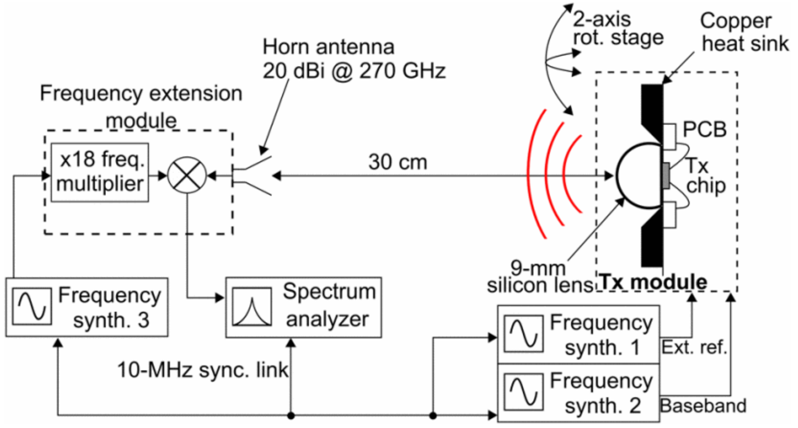
Enablers for wireless era

- CMOS and other semiconductors
- Laser based optics
- Information theory

Test beds towards Tbps - technology comparison

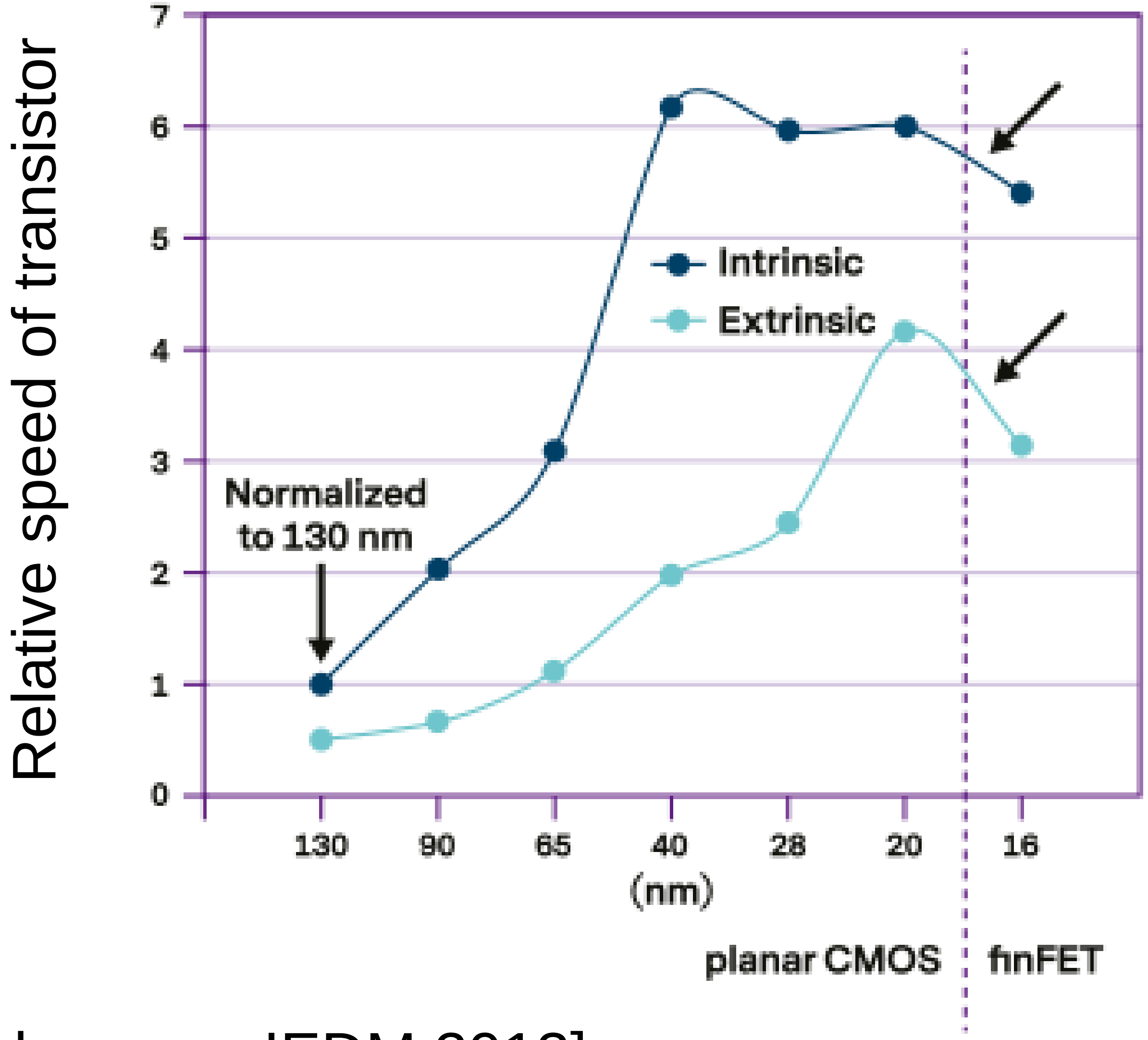




[Rodríguez-Vázquez, et al., 6G SUMMIT 2020]

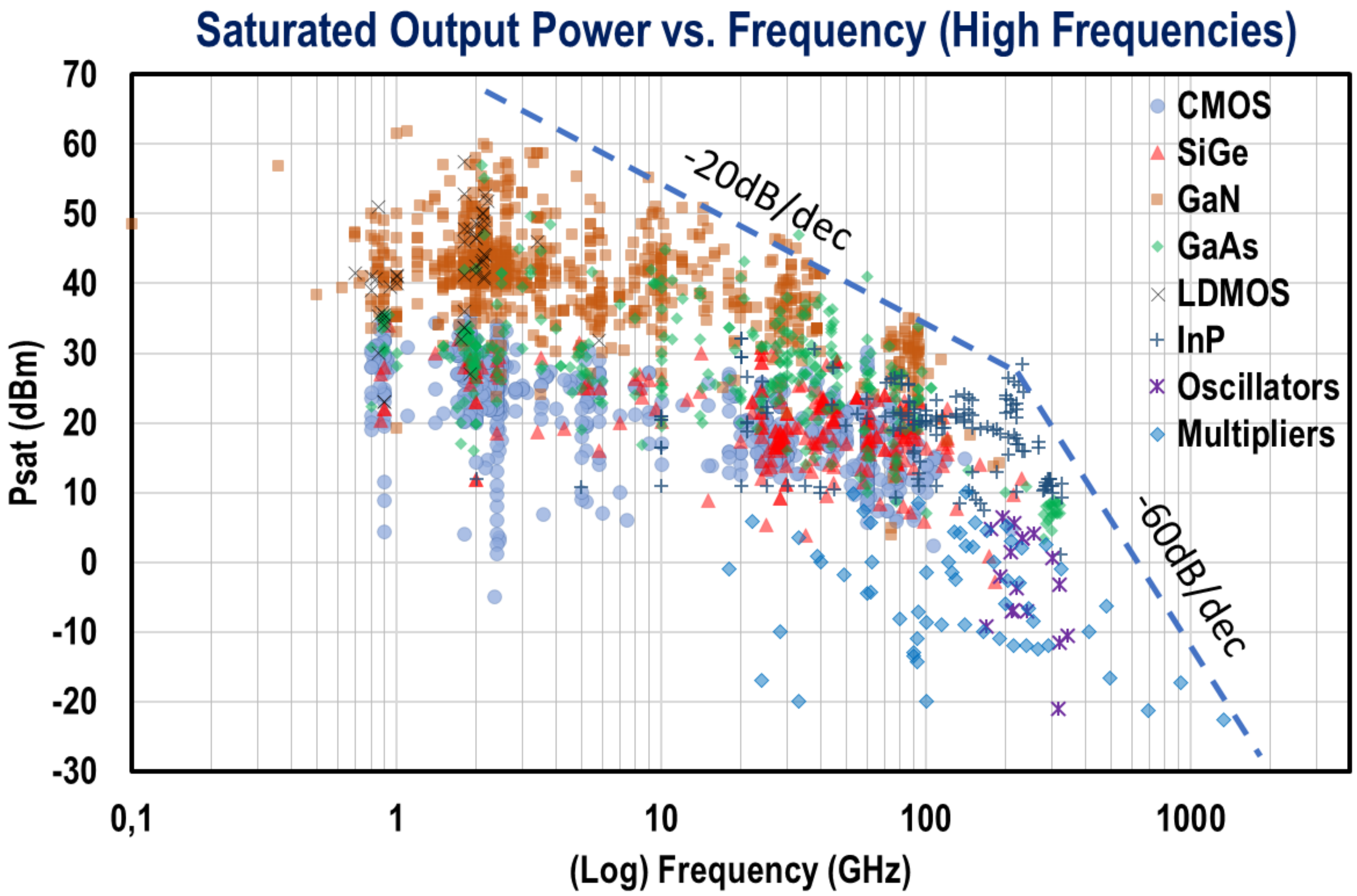
Tbps

Semiconductor scaling not anymore generally granted



[Wakayama, IEDM 2013]

More data – higher frequency – less power – shorter range



[H. Wang, et al., "Power Amplifiers Performance Survey 2000-Present," online] Available: https://gems.ece.gatech.edu/PA_survey.html

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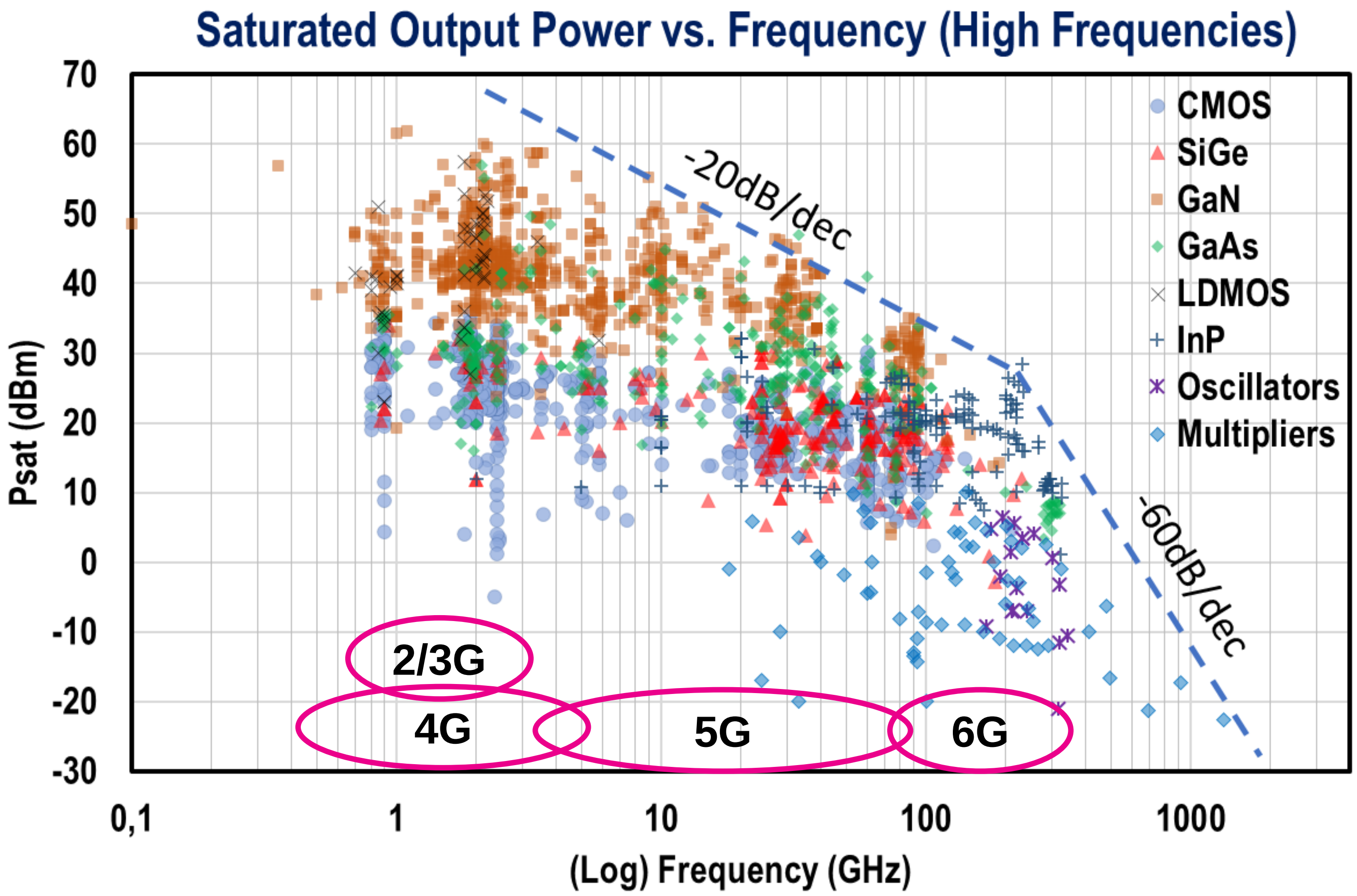

[H. Wang, et al., "Power Amplifiers Performance Survey 2000-Present," online]
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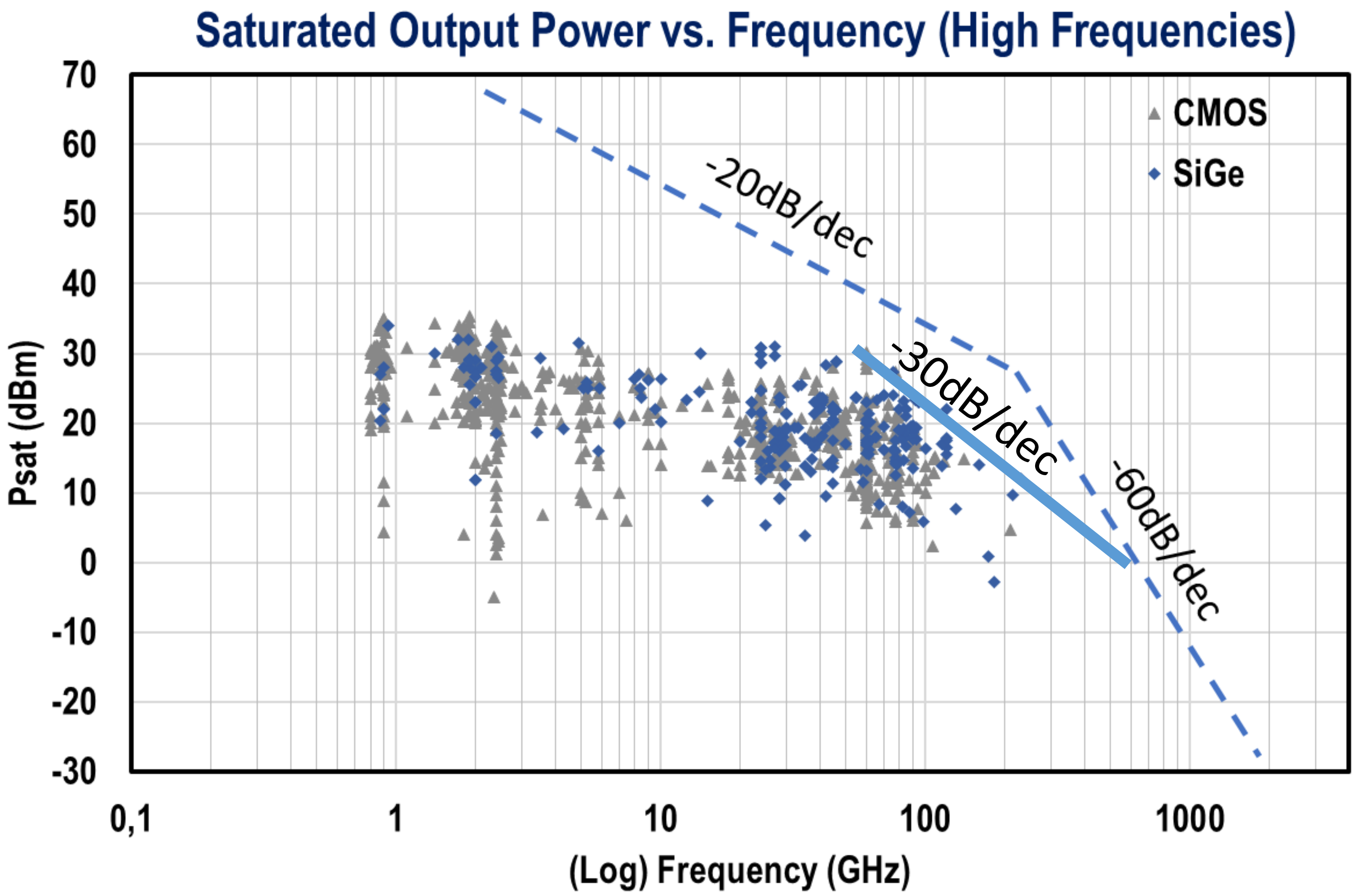
Output power – silicon



[H. Wang, et al., "Power Amplifiers Performance Survey 2000-Present," online]
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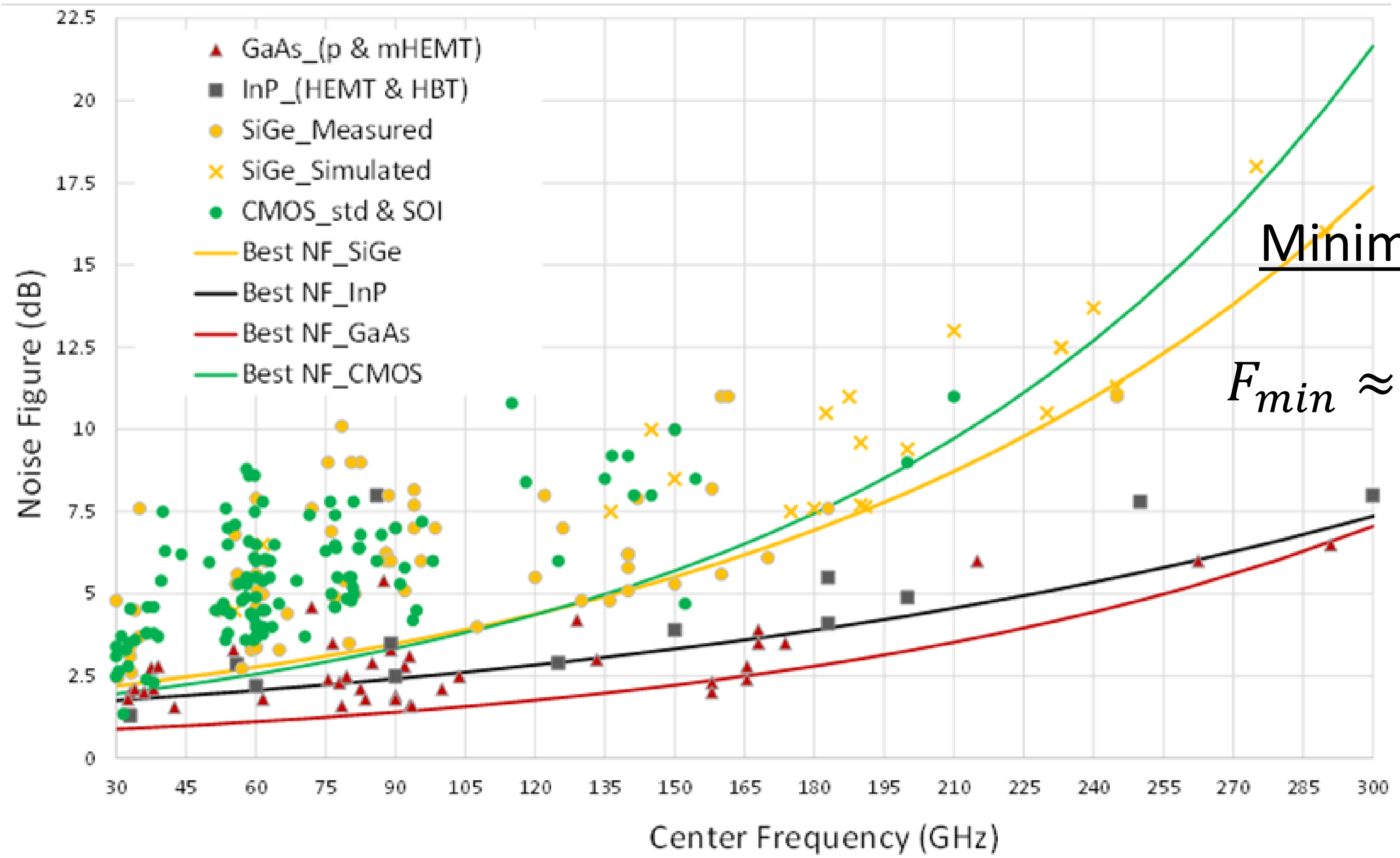
Performance Limits of LNAs



<u>Minimum noise of a single transistor</u>

$$F_{min} \approx 1 + K \cdot \frac{\omega_0}{\omega_T}\sqrt{g_m\left(R_g + R_i + R_s\right)}$$

$$\approx 1 + 2.3\left(\frac{\omega_0}{\omega_T}\right)$$

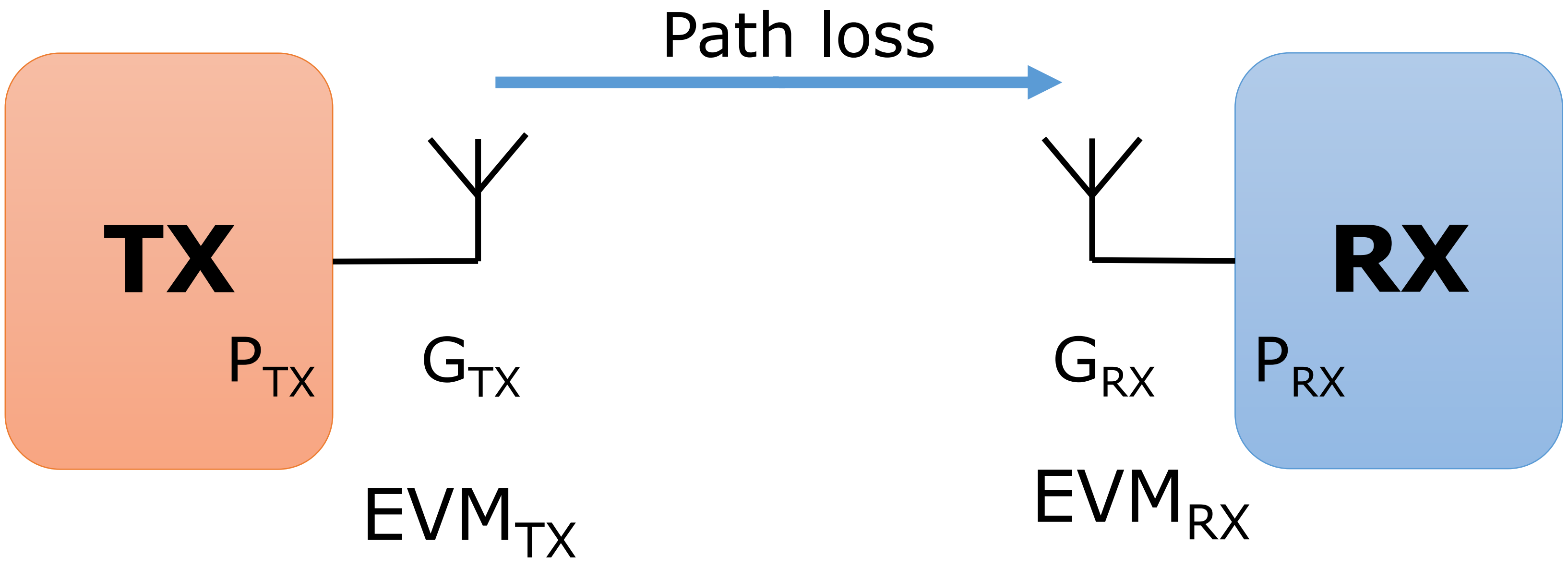
[EU H2020 Hexa-x project, devirable D2.2, "Initial radio models and analysis towards ultra-high data rate links in 6G," online], available: https://hexa-x.eu

Link Budget

Received signal, TX power, antenna gains

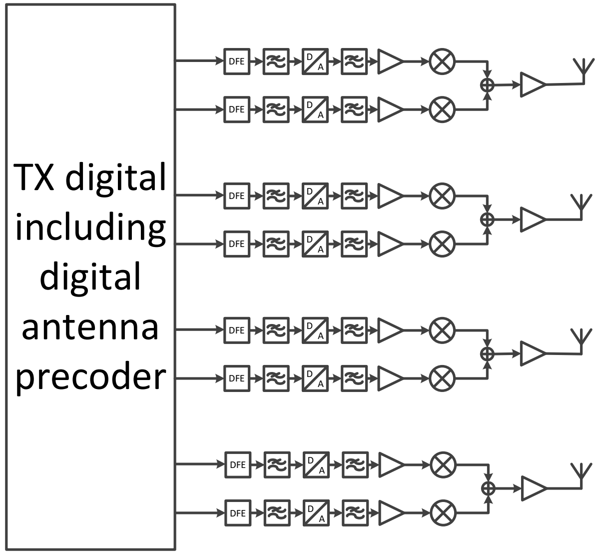
$$P_{RX} = P_{TX} - L_{path} - L_{fade} + G_{TX} + G_{RX}$$

Path loss, Fading margin

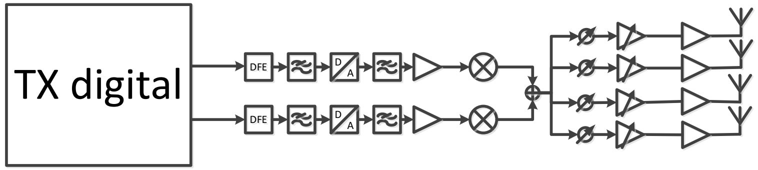


Simple (?) solution – increase antenna gain

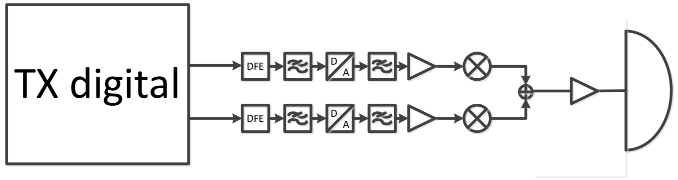
MIMO
- Full Flexibility
- RF & digital parallelism



Phased array
- Steerability
- RF parallelism per data stream



Directive antenna
- Large gain
- No parallelism
- Limited or no steering



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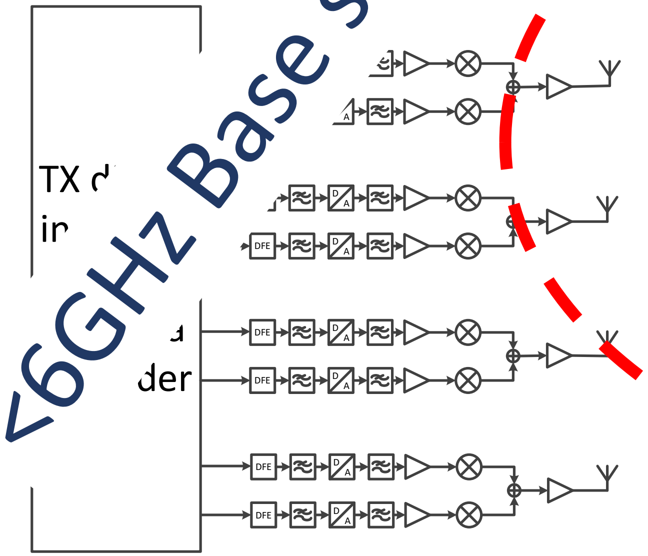

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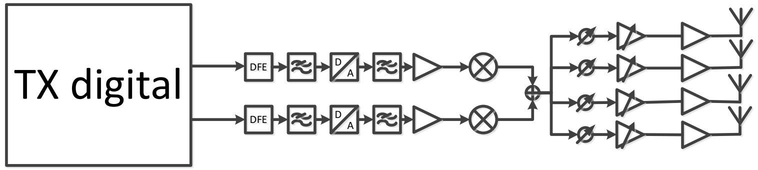

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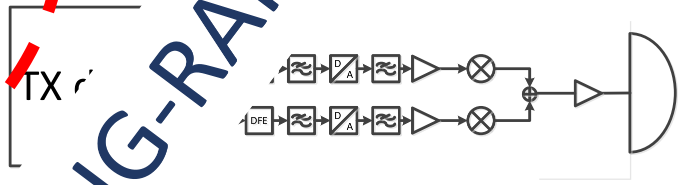


<6GHz Base station

compromizes needed

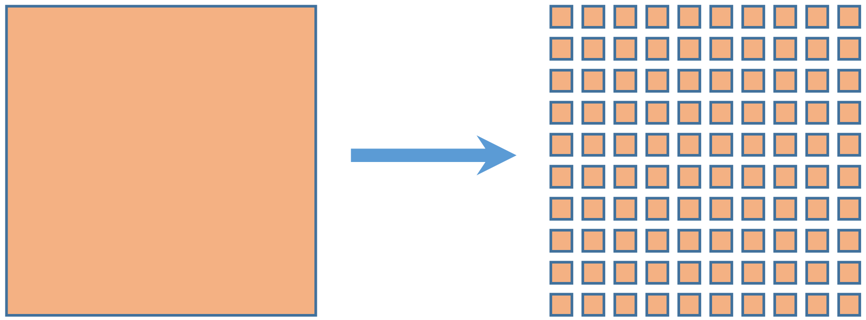
LONG-RANGE RADIO LINKS

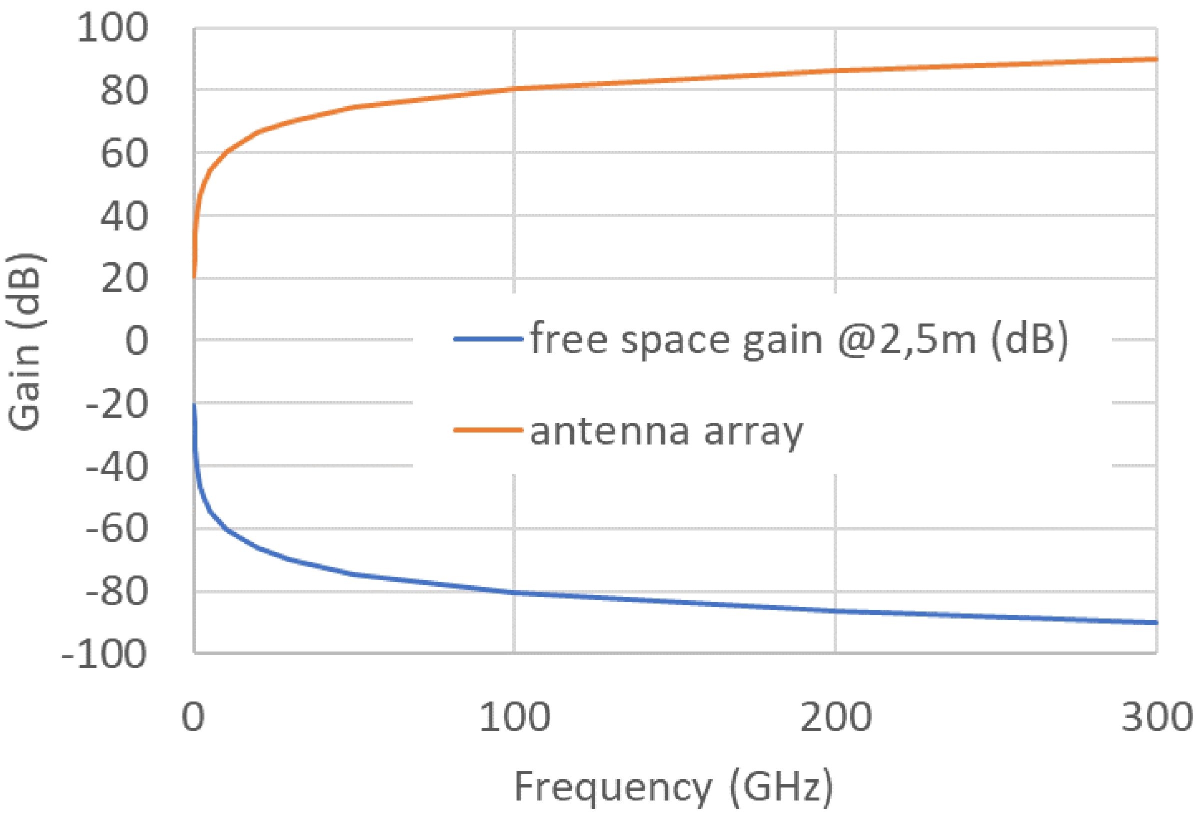
Link budget for phased arrays

- Constant antenna aperture removes frequency dependency

$$L = 20\log_{10}\left(\frac{4\pi d}{\lambda}\right)$$

$$G_{array} = 10\log_{10}(n_{ANT})$$
$$= 10\log_{10}\left(\frac{A}{(\lambda/2)^2}\right)$$





Elements of sub-THz link

Case examples

How Many Beams Does Sub-THz Channel Support?

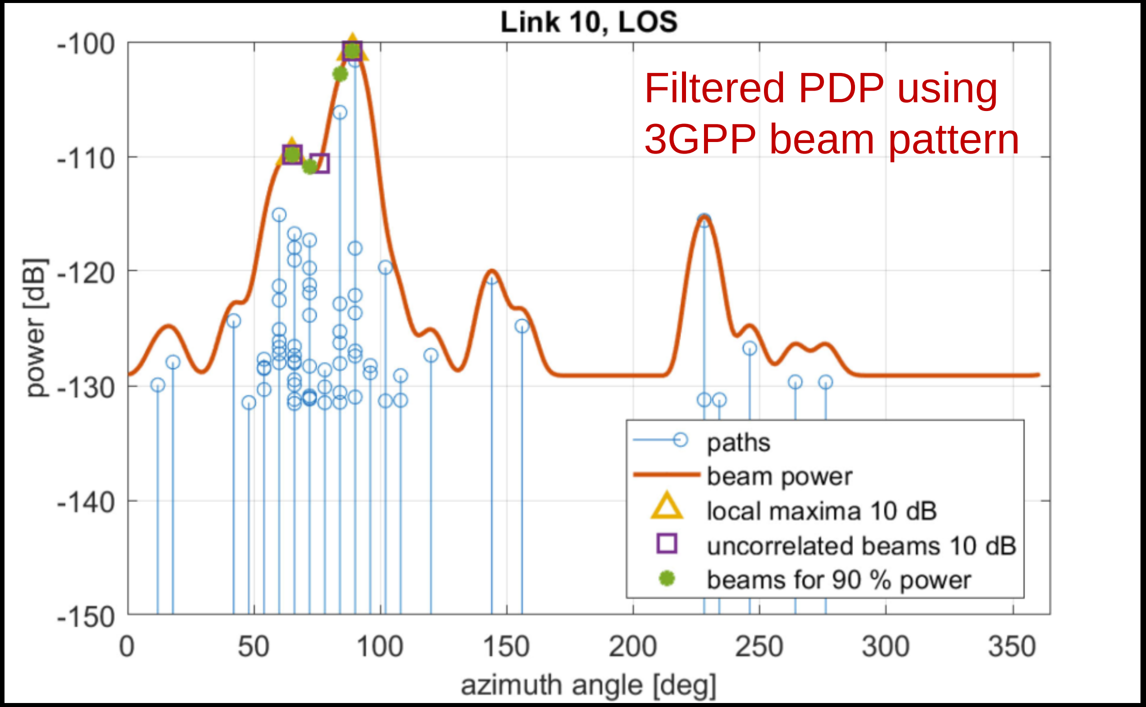
- **Three Methods to Evaluate the Number of Beams**

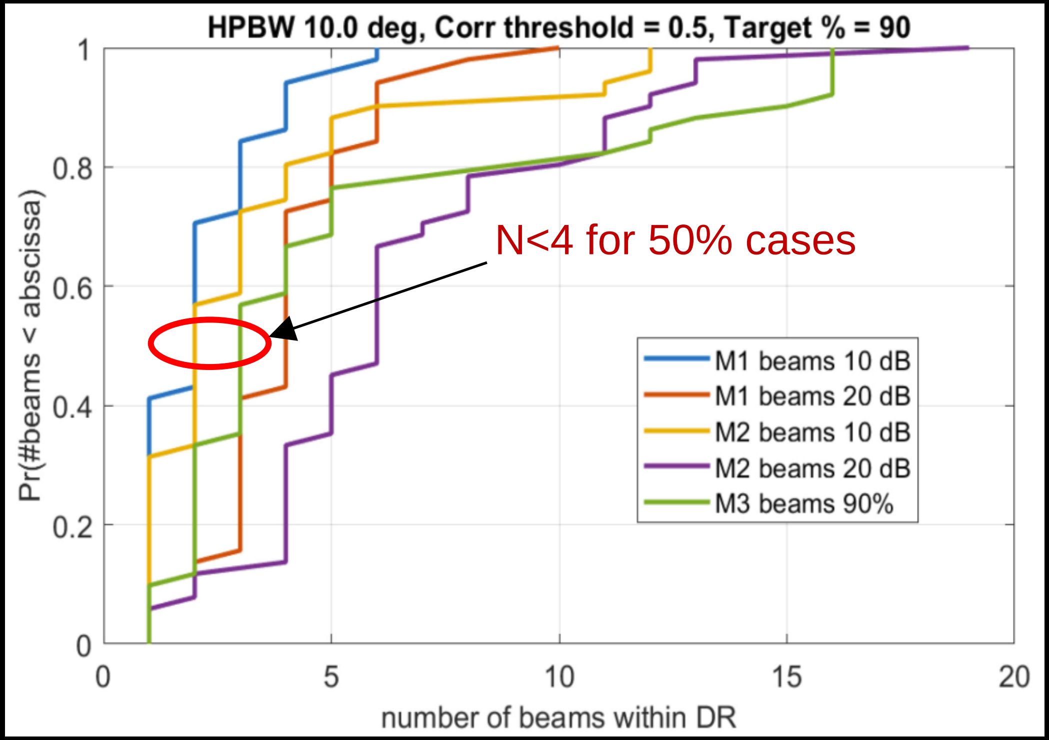
✓ Using ray-tracing assisted measurement data from Aalto Univ.

✓ Method 1: Number of local maxima

✓ Method 2: Number of uncorrelated beams

✓ Method 3: Minimum number of beams for X% power





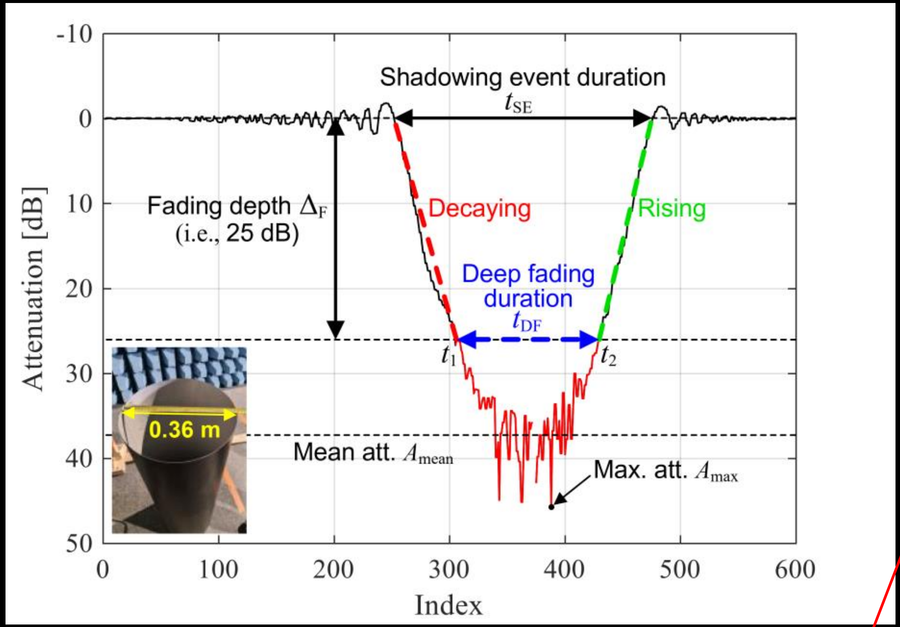
Pekka Kyösti, M. F. De Guzman, K. Haneda, N. Tervo and A. Pärssinen, "How Many Beams Does Sub-THz Channel Support?" ***IEEE Antennas Wireless Propag. Lett.***, vol. 21, no. 1, pp. 74-78, Jan. 2022

Aalto University

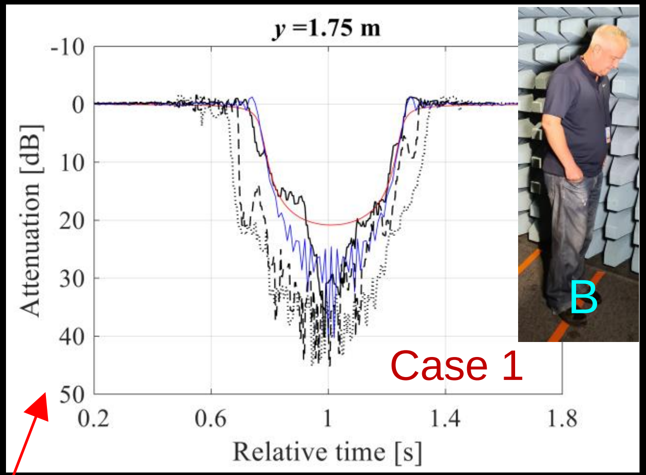
D-Band (140GHz) Human Body Shadowing

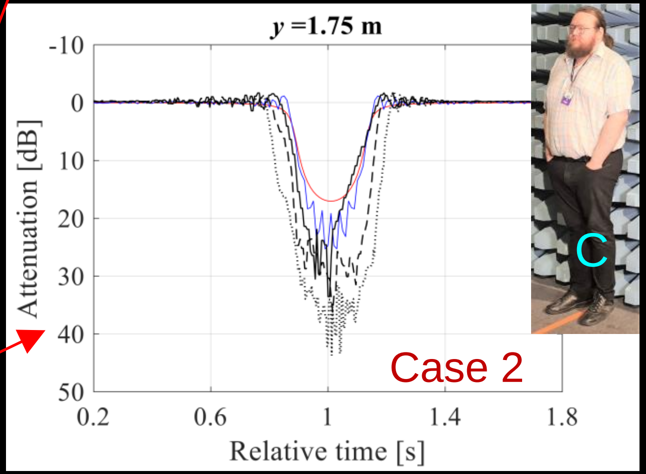
Initial Results of Single-Person Human Blockage Effect

- ✓ Reference measurement results using standard cylinder
- ✓ Characterization of human body shadowing with volunteer A/B/C

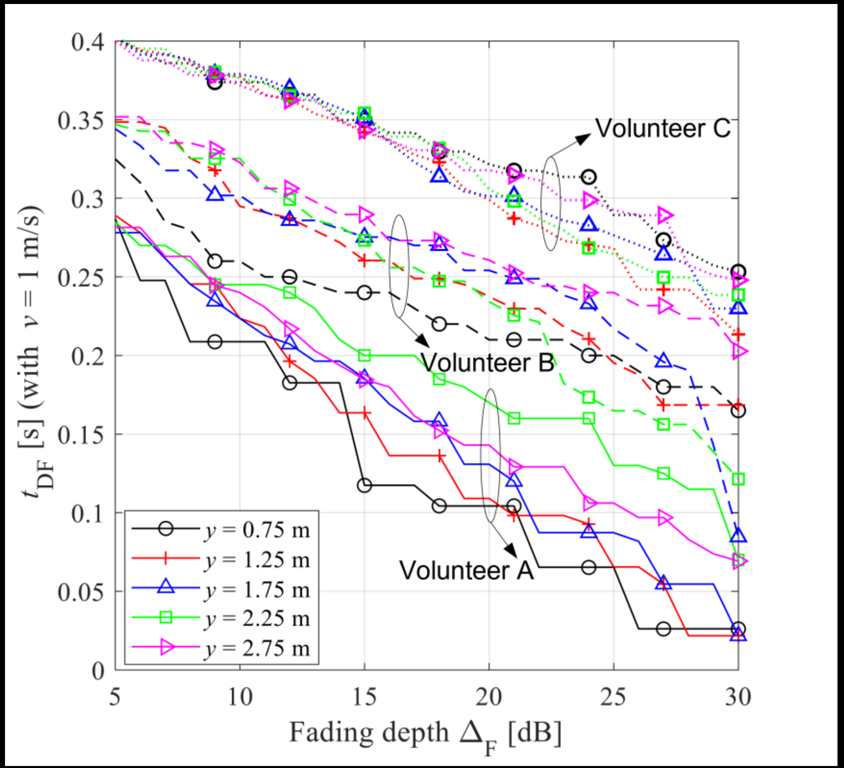


Reference measurement with metallic cylinder





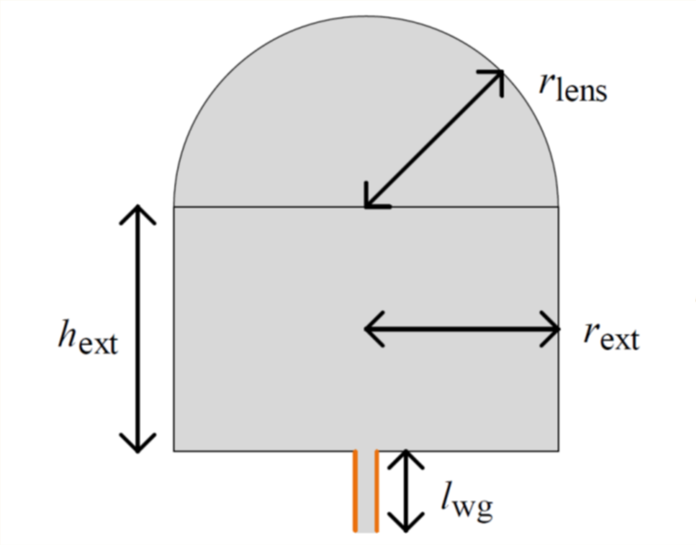
Comparison of D-band human blockage attenuation from measurement and theoretical models

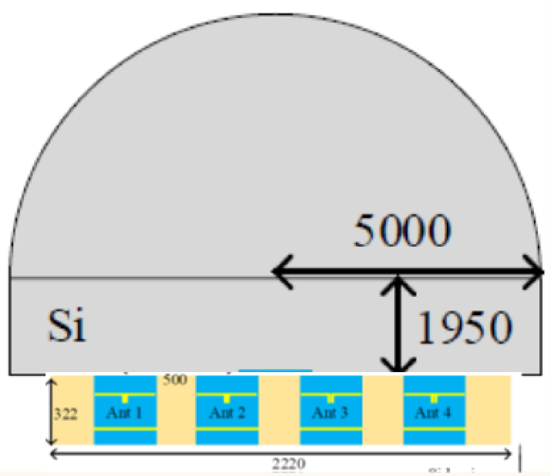


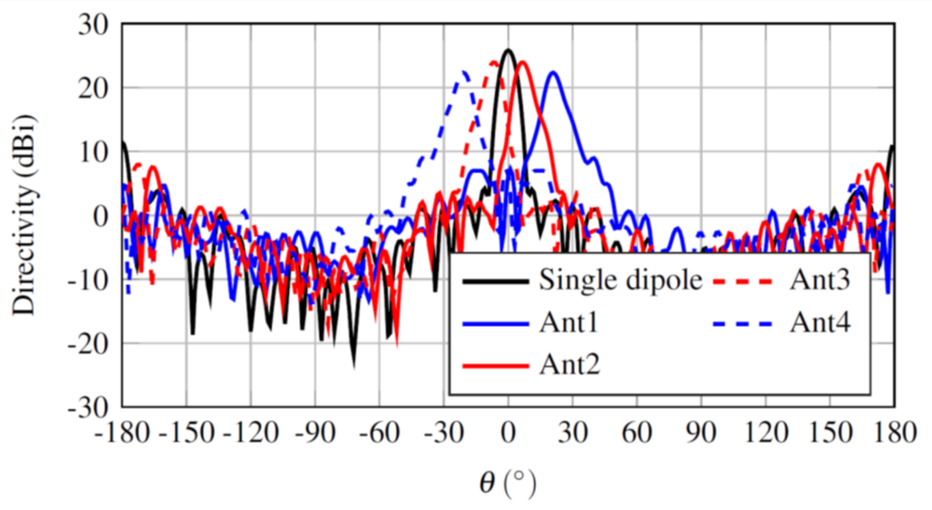
Peize Zhang, Pekka Kyösti, Mikkel Bengtson, Veikko Hovinen, Klaus Nevala, Joonas Kokkoniemi, and Aarno Pärssinen, "Experimental Characterization of D-Band Human Body Shadowing," accepted to **EuCAP 2023.**

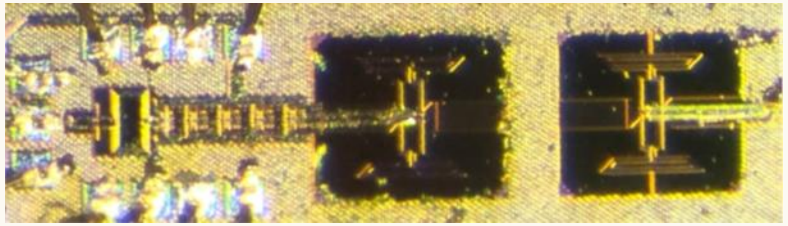
Dielectric Lens Antennas for 300-GHz Applications

- Parametric studies on lens antennas for 6G
- Linear 1x4 feed array with different feeding scenarios







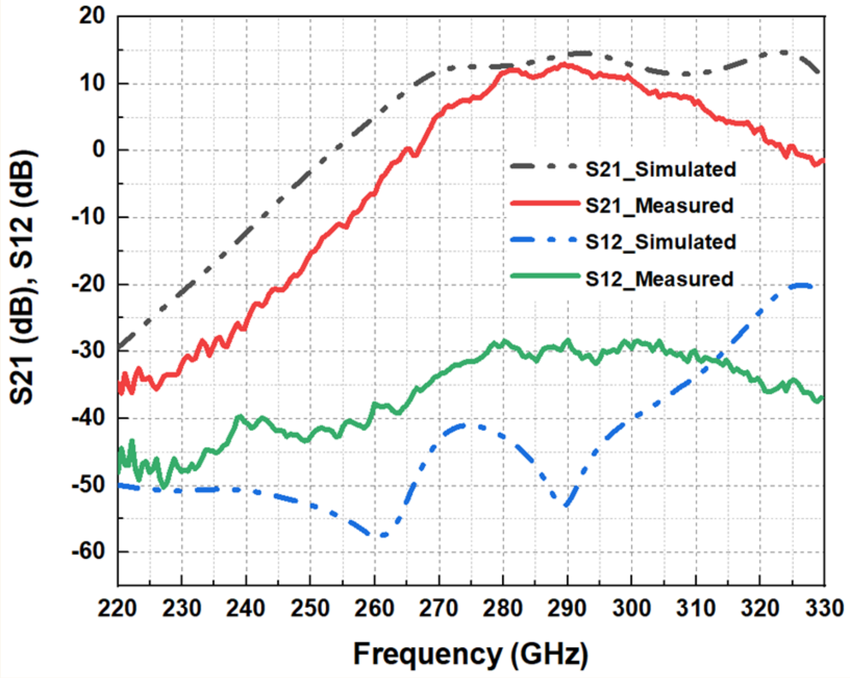


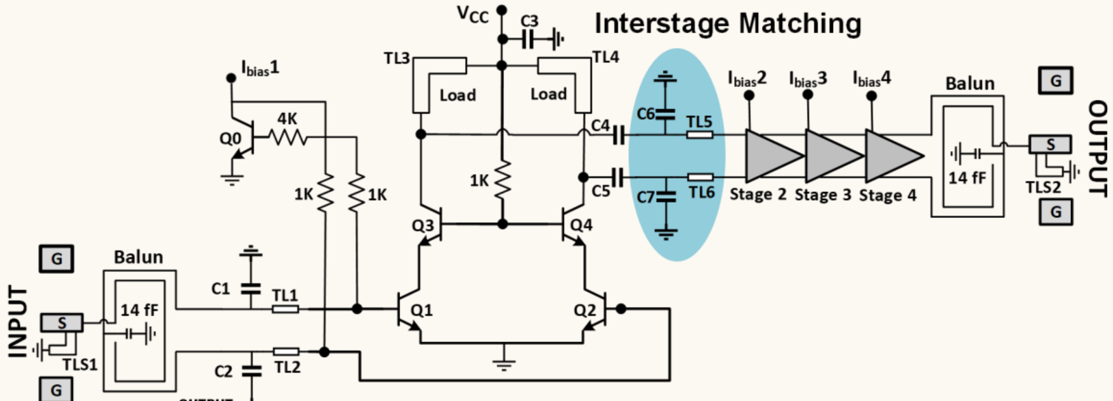
6GFLAGSHIP.COM, #6GFLAGSHIP

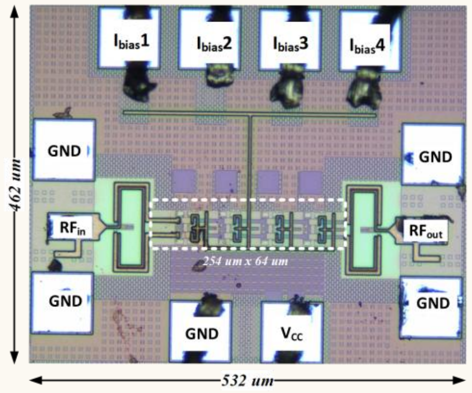
K. Rasilainen, J. Chen, M. Berg, A. Pärssinen, "Dielectric Lens Antennas for 300-GHz Applications," 15th European Conference on Antennas and Propagation (EuCAP), 22-26 March 2021, Düsseldorf, Germany.

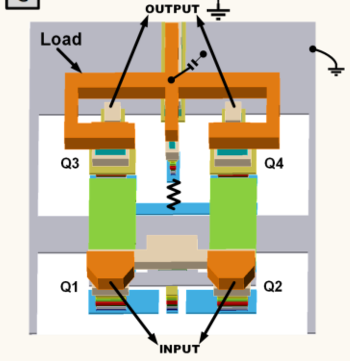
290GHz SiGe Low Noise Amplifier

- LNA at 2/3 of fmax is successfully implemented
- Achieves gains of 12.9dB @290GHz and 11 dB @300GHz
- BiCMOS having ft /fmax 300GHz/450GHz





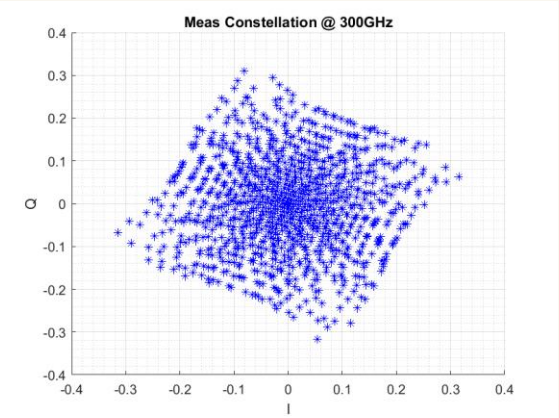


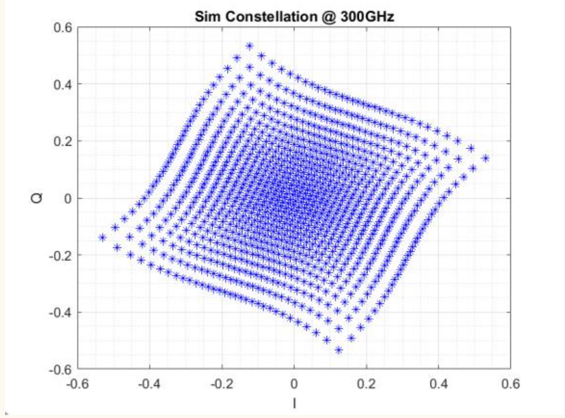


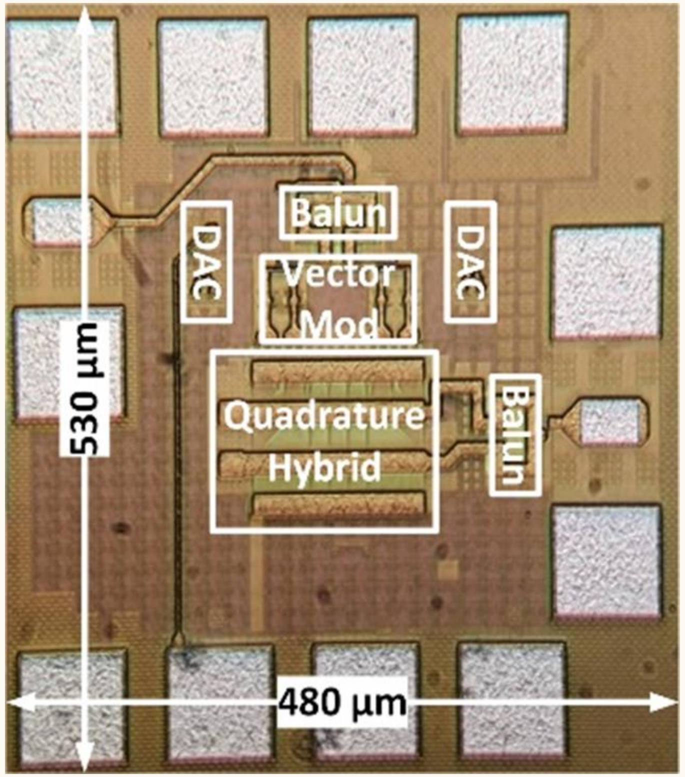
S. P. Singh, T. Rahkonen, M. E. Leinonen, A. Pärssinen, “A 290GHz Low Noise Amplifier Operating Above fmax/2 in 130nm SiGe Technology for Sub-THz/THz Receivers,” IEEE Radio Frequency Integrated Circuits Symposium, 7-9 June 2021, Atlanta, GA, United States & 20-25 June 2021

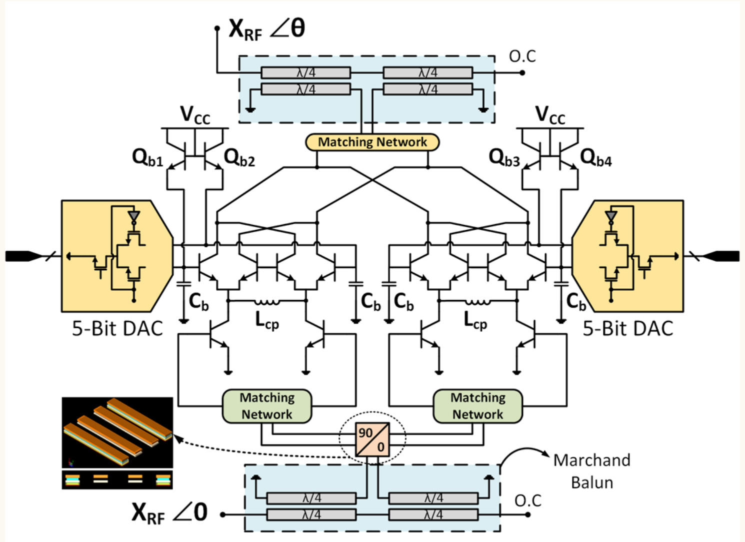
270-330GHz SiGe Phase Shifter

- Vector modulator with digital control
- Achieves <1° phase error
- BiCMOS having ft /fmax 300GHz/450GHz



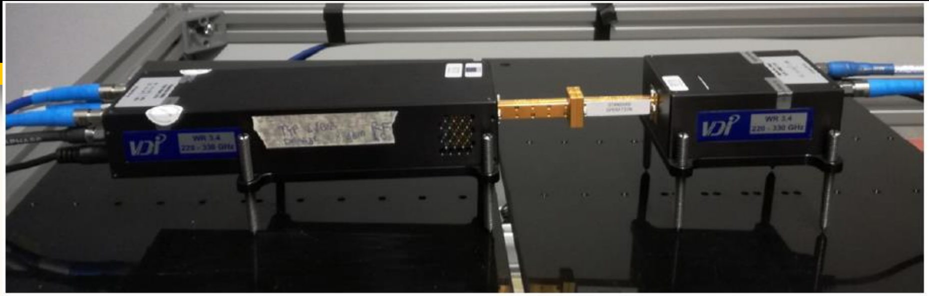


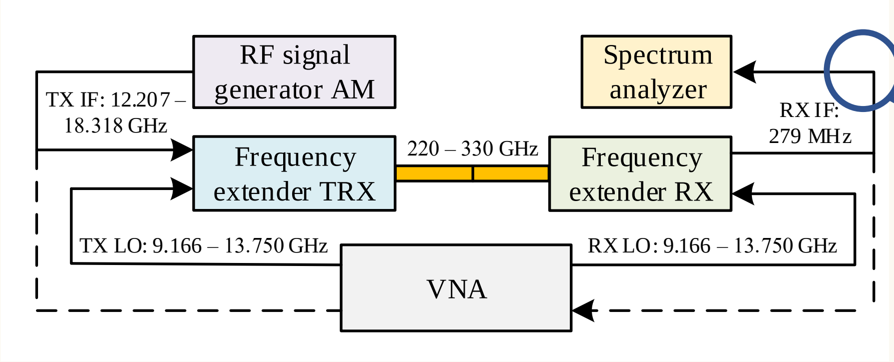


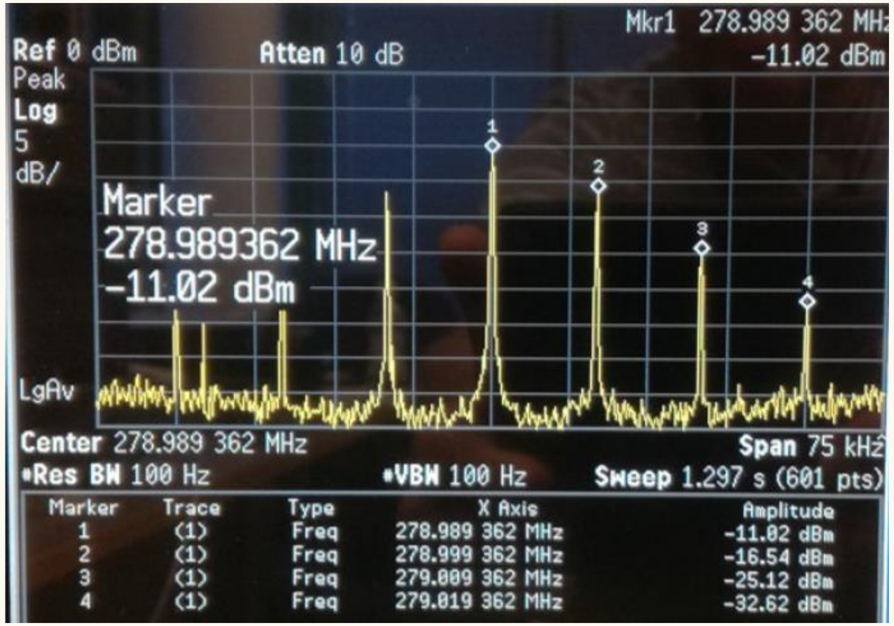


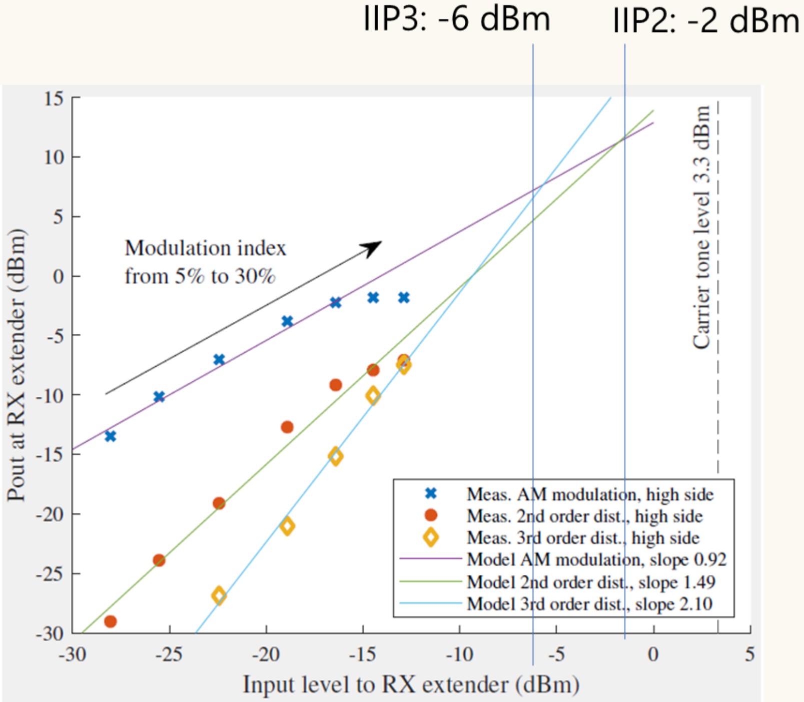
M. Montaseri, S. Singh, M. Jokinen,T. Rahkonen, M. Leinonen, A.Pärssinen, "A 270 – 330 GHz Vector Modulator Phase Shifter in 130nm SiGe BiCMOS," 16th European Microwave Integrated Circuits Conference (EuMIC), 2-7 April 2022, London, United Kingdom, pp. 309-312.

Linearity Measurements with Freq. Extenders @330 GHz





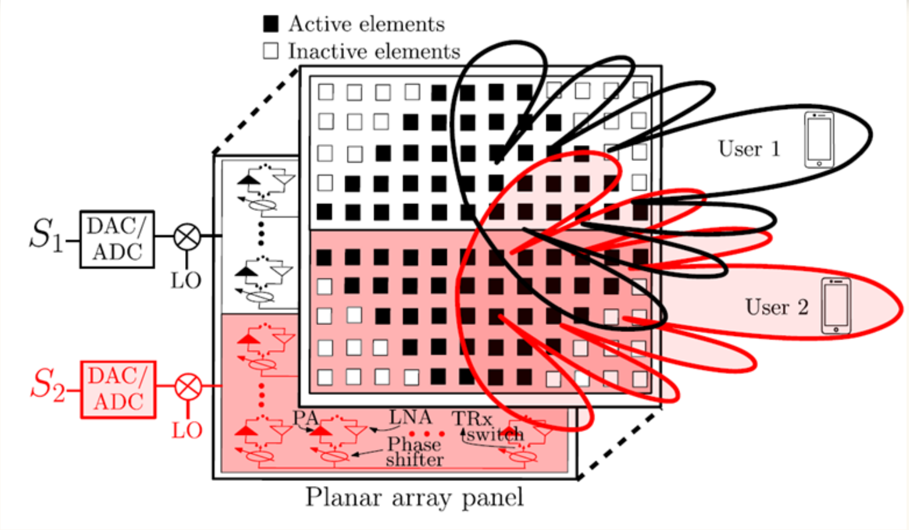


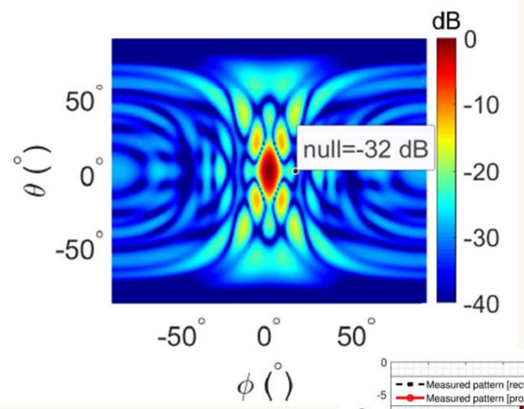


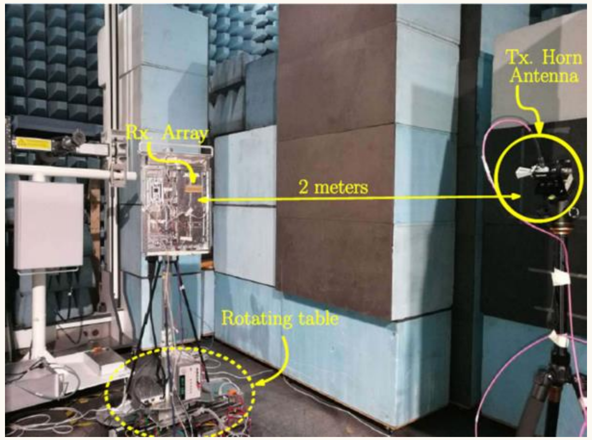
M. Leinonen, K. Nevala, N. Tervo, A. Pärssinen, ”Linearity Measurement of 6G Receiver with One Transmission Frequency Extender Operating at 330 GHz,” 96th ARFTG Microwave Measurement Conference, 17-20 January 2021, San Diego, USA.

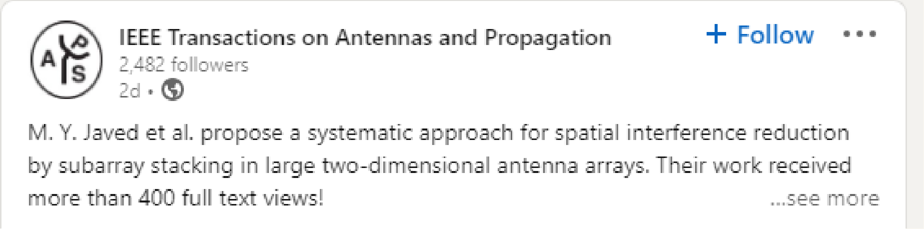
Spatial Interference Reduction

- Multi-beam transceivers and inter-beam interference (IBI)
- Interference reduction techniques for known and unknown interferers: amplitude tapering, thinning, spatial tapering, null forming
- Arbitrary directions

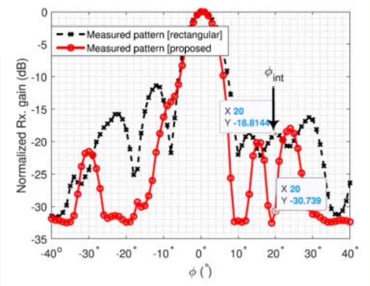


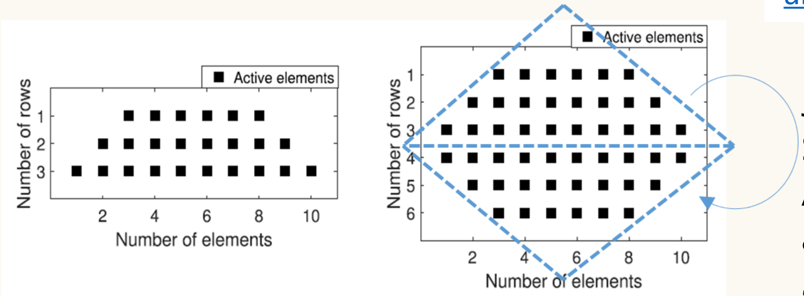






https://www.linkedin.com/posts/ieee-tap_ieeeaps-ieeetap-antenna-activity-6843420320896970752-nDTq

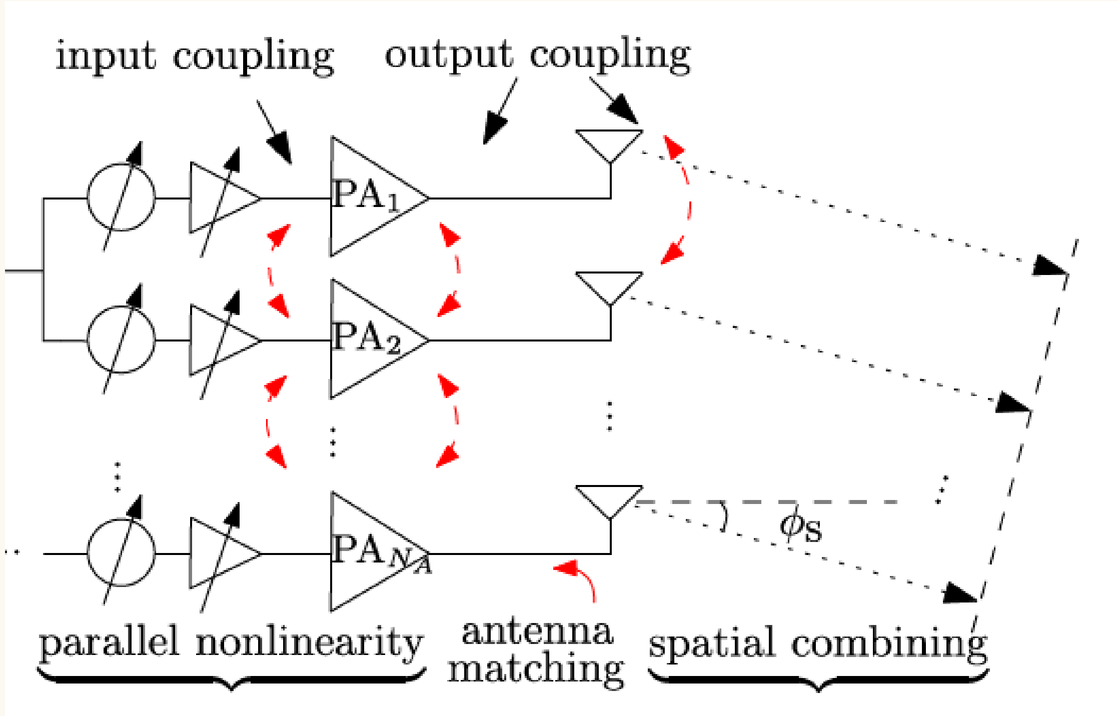




Javed et al., Spatial Interference Reduction by Subarray Stacking in Large Two-Dimensional Antenna Arrays," in IEEE Transactions on Antennas and Propagation, vol. 69, no. 7, pp. 3863-3874, July 2021.

Nonlinear distortion in phased arrays

- Why individual PAs have different nonlinear behavior
  - Beamforming
  - Process variations/manufacturing
  - Different loads (antennas)
  - Antenna/PA coupling
  - Thermal coupling
- How are the differences seen in the radiated signal?
  - Distortion may have different beam shape compared with the linear part of the signal
  - Where the distortion goes in space?



[N. Tervo et al. ISWCS2019]

From 36Mbps (4G) to 40Gbps (6G)

Parameter	Unit	LTE 20M	5G NR 200M	6G 20G?
Occupied BW	MHz	18.015	200	20000
Nth	dBm	-101	-91	-71
Modulation		64-QAM	64-QAM	64-QAM
Coding		1/3	1/3	1/3
Data Rate	Gbps	**0.036**	**0.4**	**40**
RX, SNRmin (with coding gain)	dB	**19.2**	**19.2**	**19.2**
Carrier Frequency (DL)	GHz	2.65	28	200
M_I (DSP margin) - assumption	dB	1.0	1.0	1.0
NF (RX) - assumption	dB	9.0	12	16
Sensitivity, 64-QAM (FDD)	dBm	**-73.2**	**-59.7**	**-35.7**
Link Distance (line-of-sight)	m	**411**	**3.3**	**0.013**

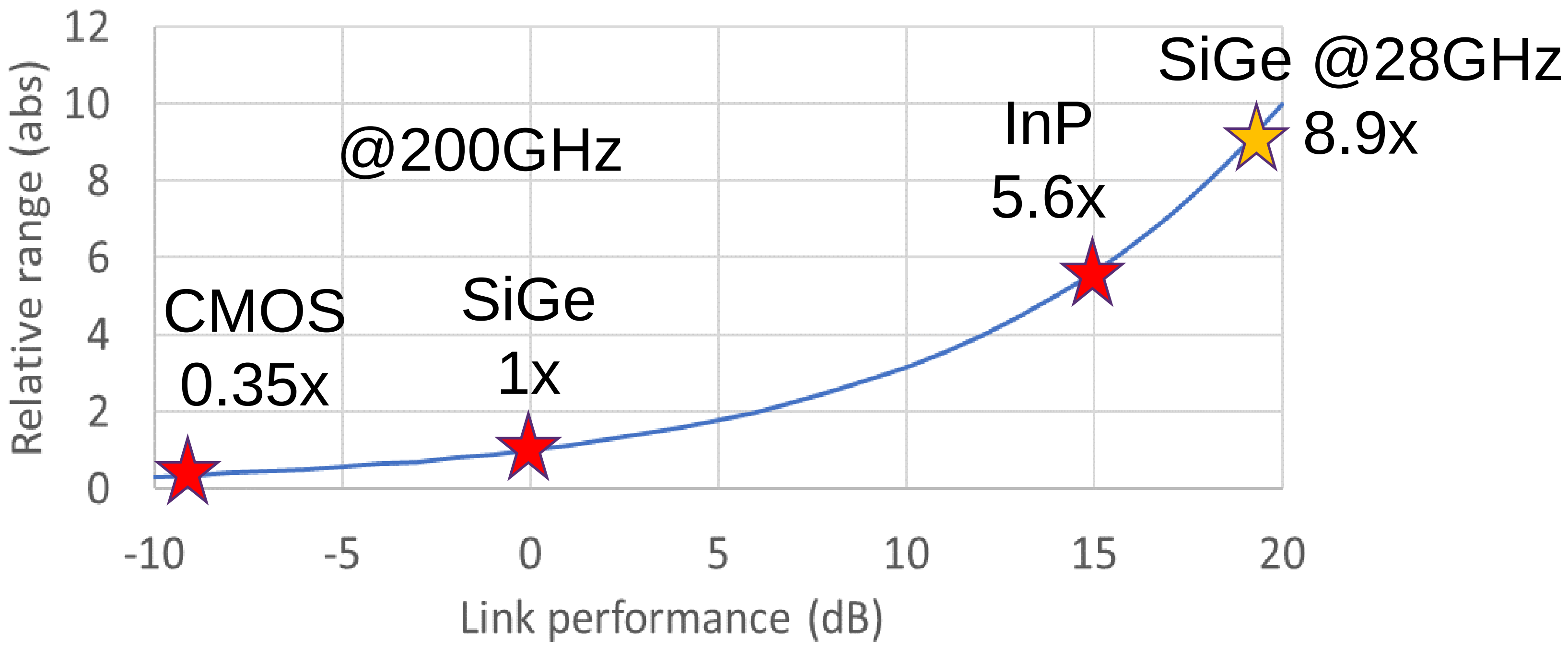
From 36Mbps to 40Gbps

Parameter	Unit	LTE 20M	5G NR 200M	6G 20G?
Link Distance (line-of-sight)	m	**411**	**3.3**	**0.013**
Equal link distance	m	**411**	**411**	**411**
Free space loss	dB	93.2	114	131
P_{out}, PA	dBm	20	12	5
Sensitivity, 64-QAM (FDD)	dBm	-73.2	-59.7	-35.7
Margin to compensate	dB	0	41.9	90.0
Number of RX and TX antennas	pcs	**1**	**25**	**1001**
Antenna (array) aperture	mm^2	**3198**	**716**	**562**
Antenna element area (*	mm^2	**3198**	**28.6**	**0.56**

*) Typical RF transceiver area at mmW range ~1mm^2 per antenna

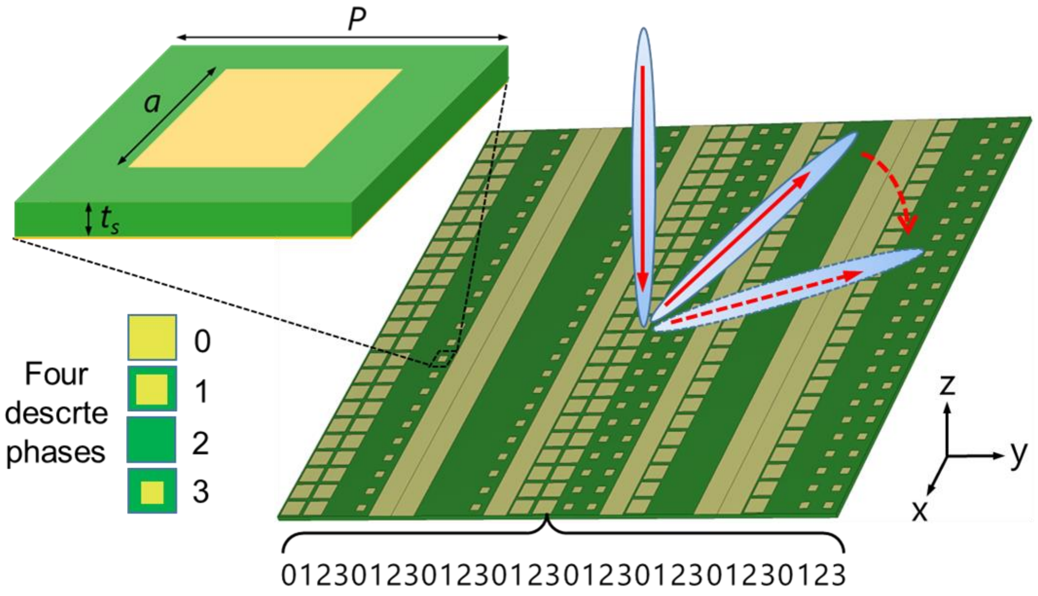
Choice of semiconductor technology?

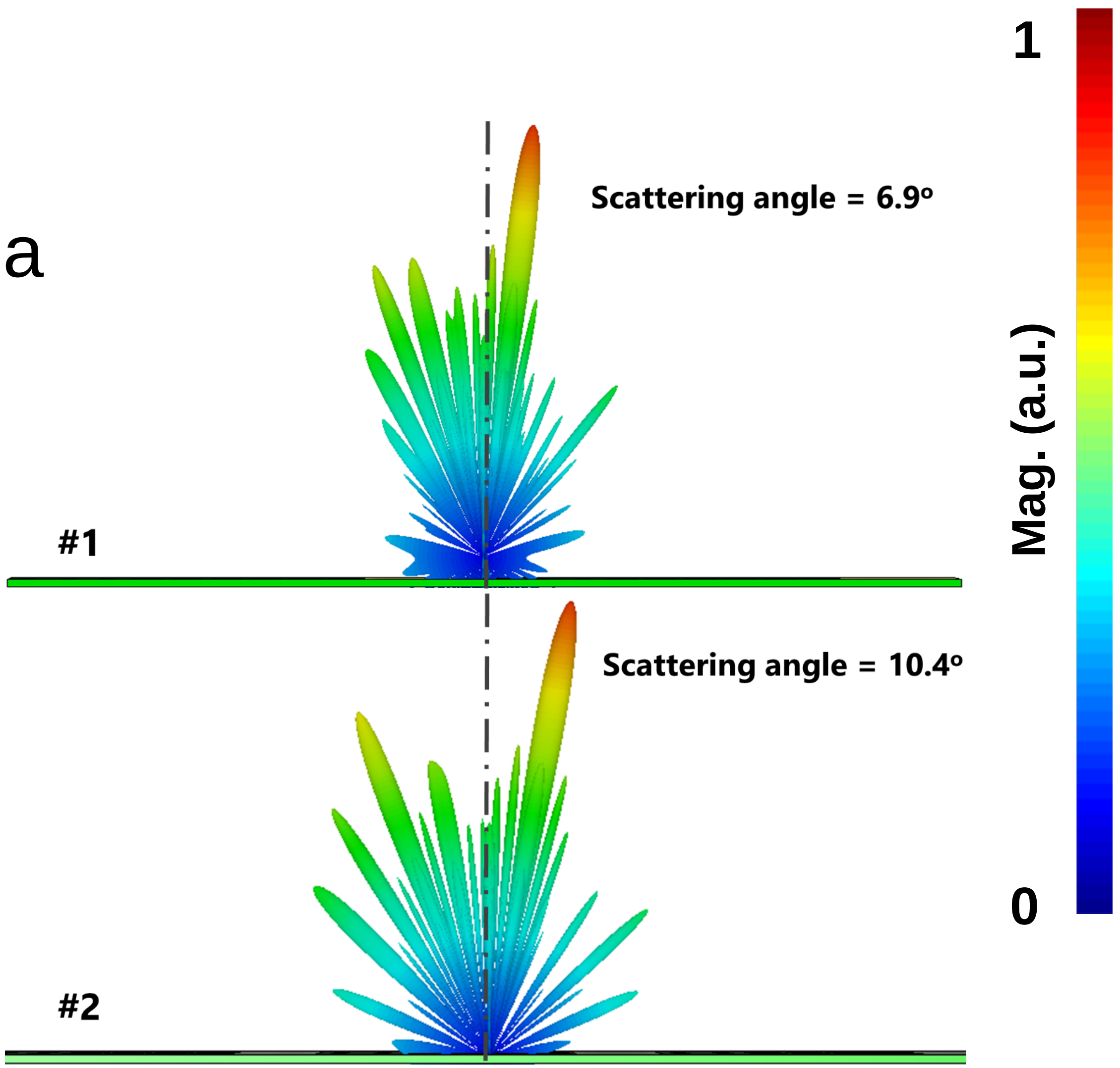
- We know the technology baseline of semiconductors towards 2030
- Being even close to 5G range in 6G data rates requires
  - radical changes in our thinking
  - understanding of the semiconductors from transistors to complete wireless systems



RIS – Reflective Intelligent Surfaces

- Solution for NLOS in mmW?
- Passive 'not so intelligent' surface
- Control by pointing to suitable sub-area
- Controllable reflective elements

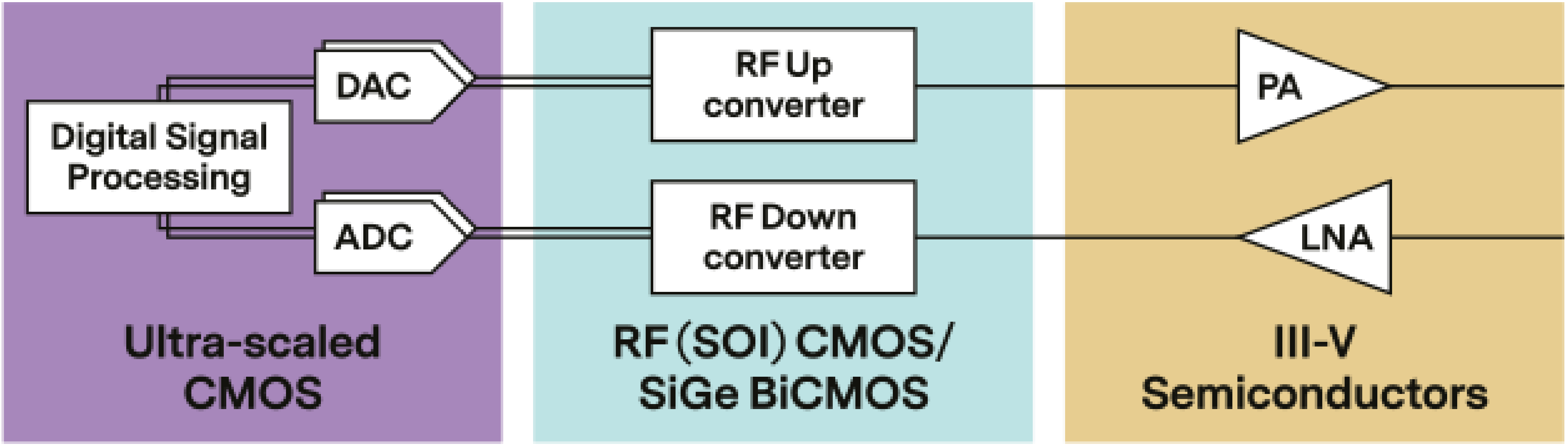




D. T. Phan, J. Chen, M. E. Leinonen, A. Pärssinen, and P. J. Soh, "Digitally Coded Reflector at 140 GHz Targeted for 6G Communications" EuCAP 2023

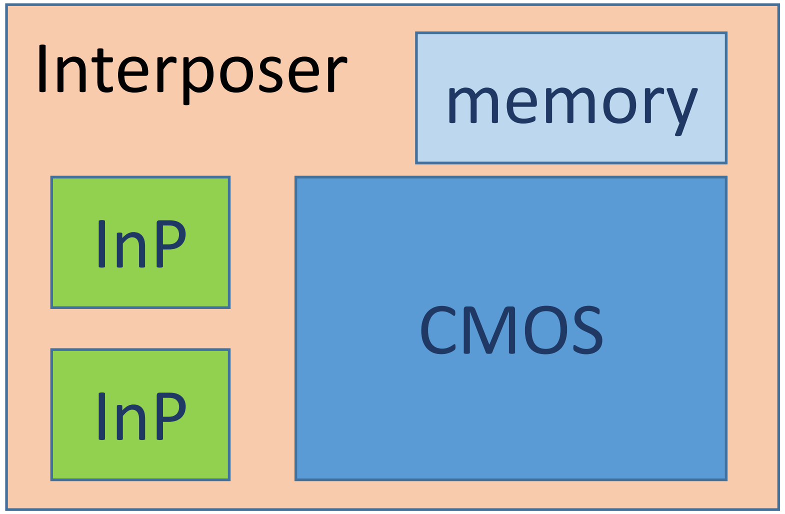
The Best Technology for Every Component?

- Heterogeneous integration / 3D packaging?

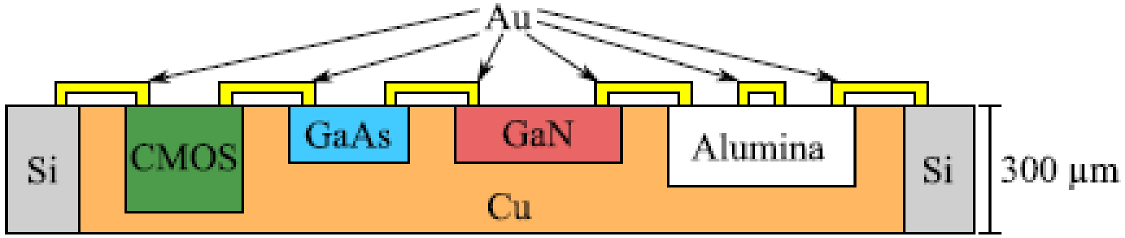


Chiplets and packaging

- Select **<u>the best technology</u>** for each function
  - Digital logic and memory
  - RF performance vs. integration level
  - Power control/management
- **<u>Reuse</u>** of chip level IPs for multiple platforms
- **<u>Interposer</u>** as interconnect, RF transmission lines, etc.
- **<u>Design flow</u>** with multiple technologies / design kits
- **<u>Connecting chips</u>**
  - Bond wires
  - Flip chip
  - **Post processing wires**
- **<u>Interconnect losses</u>**



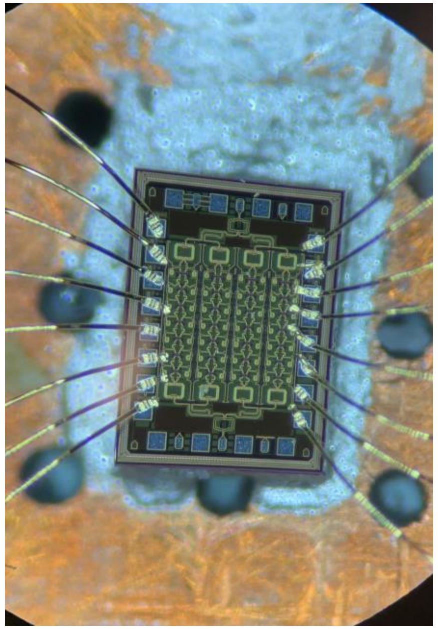
Photolithographically defined Au interconnects

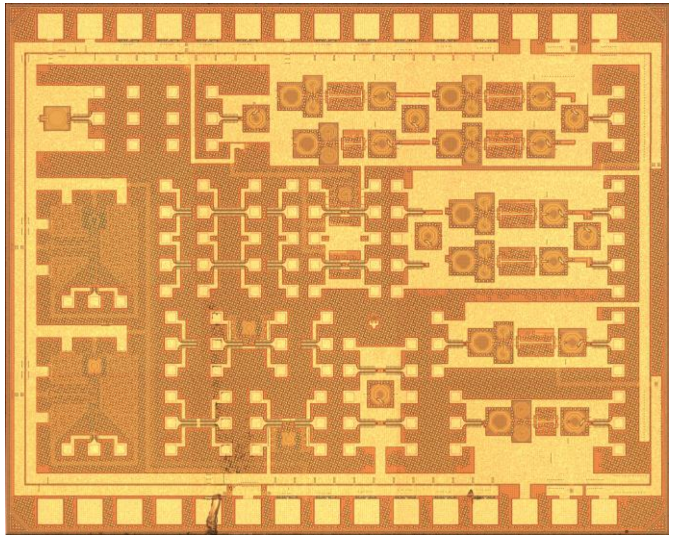


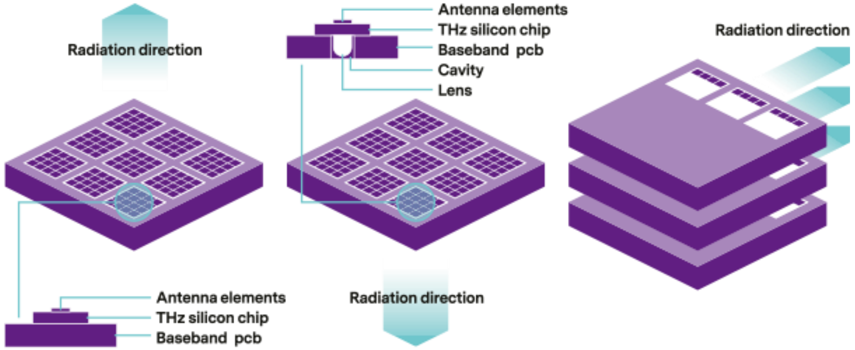
[Estrada et. al, IEEE TMTT Sep 2019]

What? When? How?

- Technology will not automatically take us forward
- Multi-disciplinary perspective and radio HW innovation
- **HW aware (or even friendly) protocol design for 6G**
- New use cases will come - after enablement
- Now research - next products

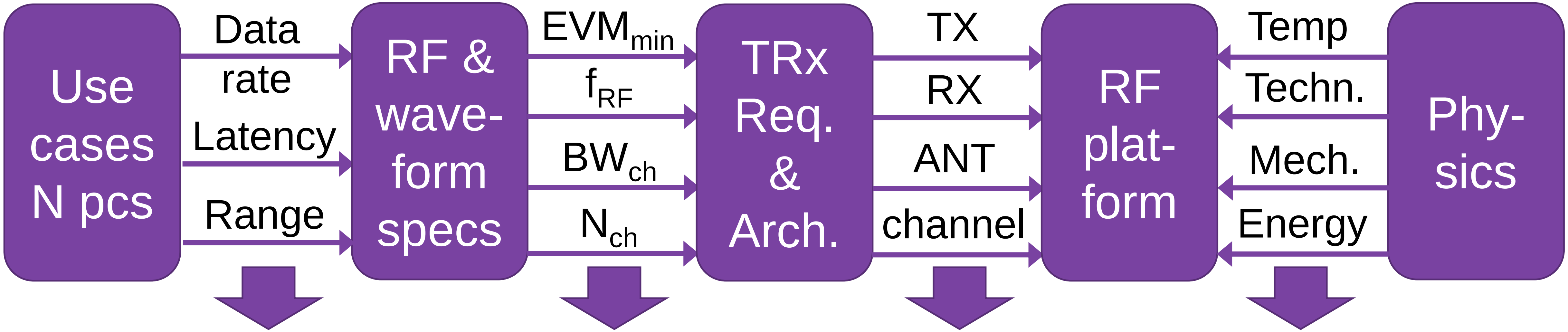


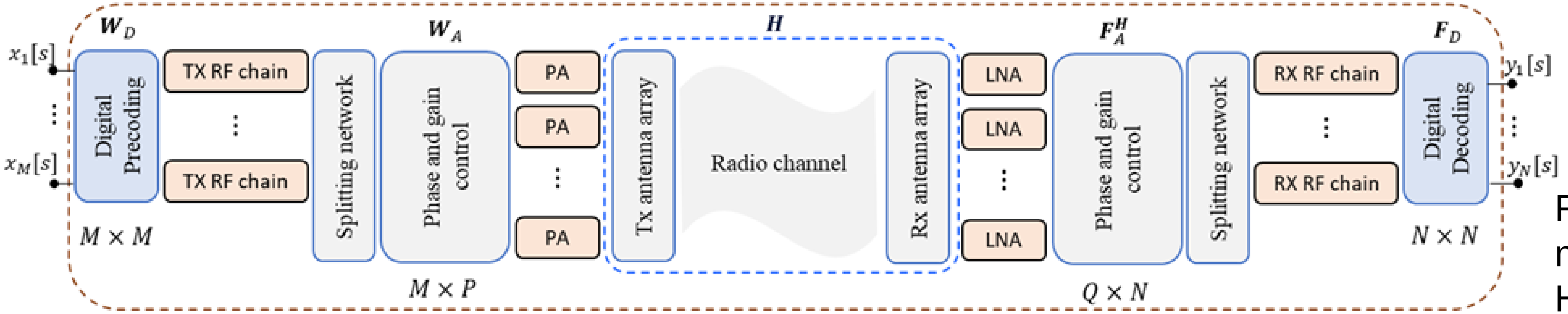




Simple when complex?

- MBSE: Layered and structured design and interaction





RF system model Hexa-x

Towards 6G

- Entropy tends to increase from business to technology
- Take all out from existing
- Make it better
- Create something that is not obvious

6G ?

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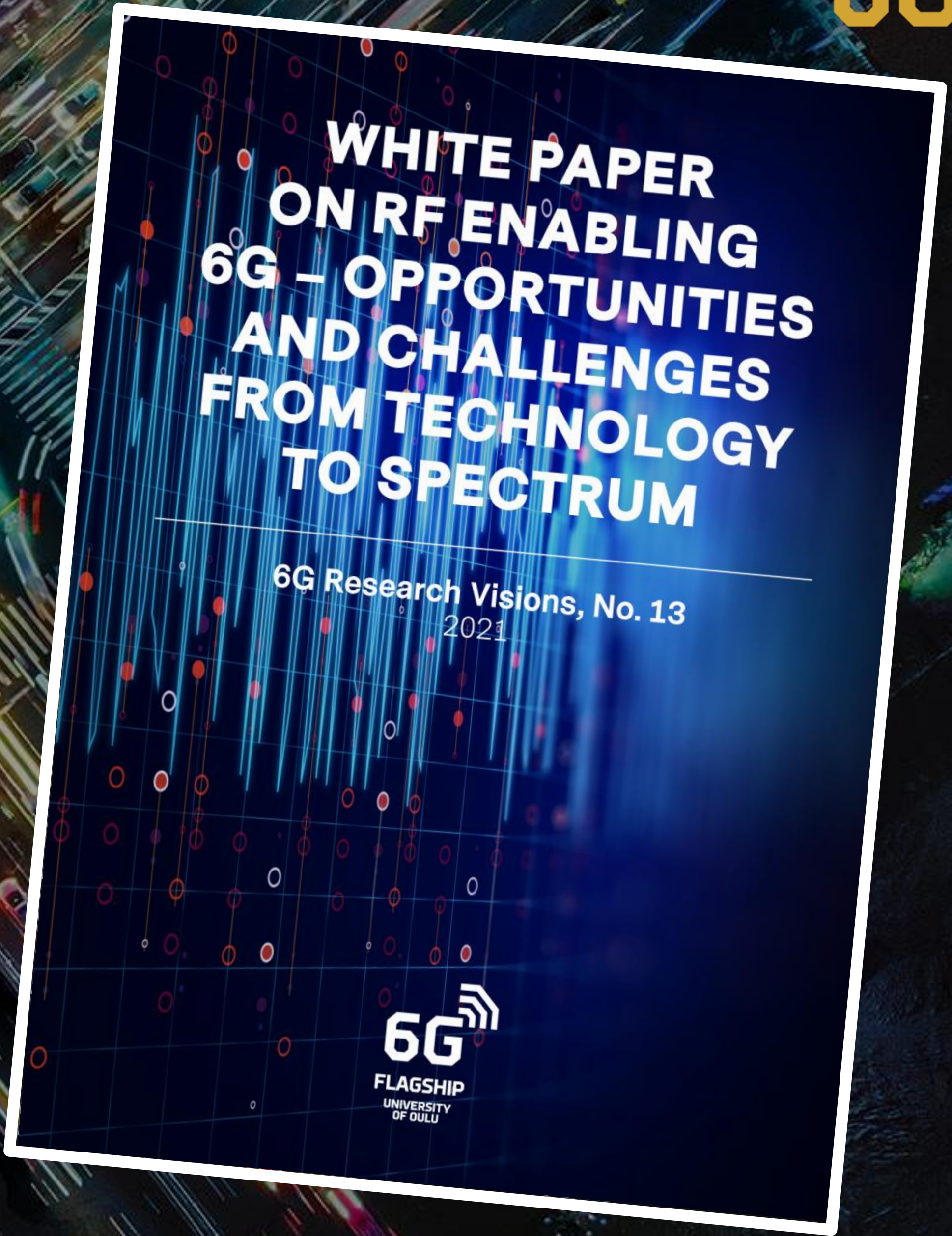

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Thank you!

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