6G from early research towards commercialization

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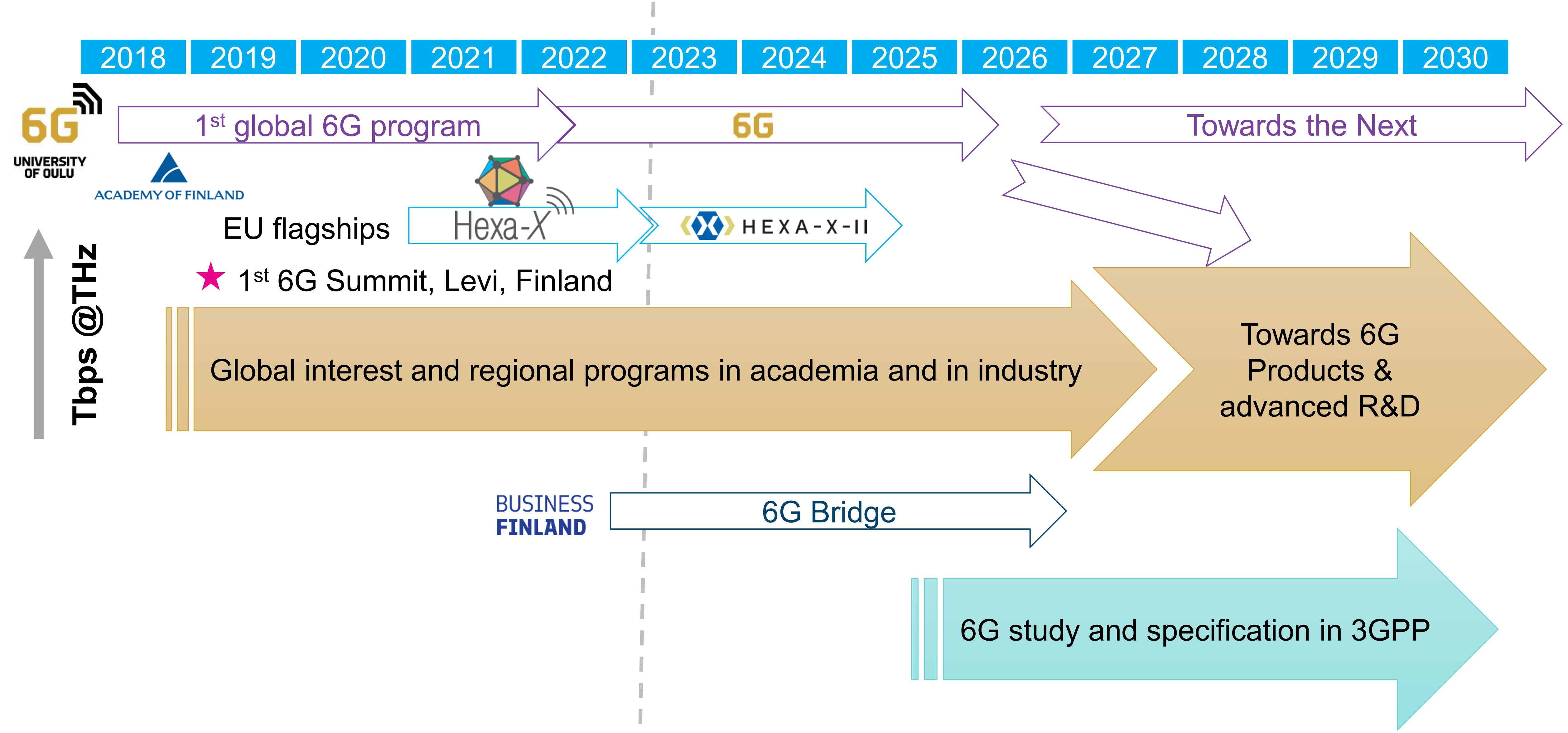
Evolution of 6G



Facts sheet

- National research flagship for 2018 – 2026 with a total volume of 250M€.
- 2nd phase started May 2022 – plan to continue until the end of 2028.
- Operated by University of Oulu.
- Currently involves 599 researchers from 52 nationalities.
- Steered the first 6G visions work via 15 6G White Papers (downloaded over 1M times).
- Published 4,266 per-reviewed papers and 173 doctoral theses.
- 457 company collaborators and 552 research projects so far.

* Numbers reported in October 2025.

6G FLAGSHIP
UNIVERSITY OF OULU

Overview

6G Flagship Vision for 2030

Data-driven sustainable future society enabled by near-instant, unlimited wireless connectivity

Strategic Research Areas (SRAs)

- Wireless connectivity solutions
- Device and circuit technologies
- Distributed intelligent wireless computing
- Sustainable human-centric services and applications

Flagship Goals

1. 6G technology enablers
2. 6GTN development
3. 6G vertical applications
4. 6G vision leadership

Impact Actions

A 6G-enabled Sustainable Society

B Strategic Vertical Areas (SVAs)
- Health
- Industry
- Vehicular
- Energy
- Security & Defence

C Global 6G Collaboration

D Research infra-structures – 6G Test Network (6GTN)

5G LTE 6G

Beyond 6G Flagship

6GTN as the core of 6G Radio Park

Training 6G experts for industry

Influence on 6G standard

Expertise building beyond 6G

2027 2028 2029 2030

From Human Centricity To Holistic Digitalization of Society

ABC (Always Best Connected)

Vision for future made in 2003

Next 50 billion connected things

2013 vision

6G metaverse and digital twins 2023

Critical Drivers For 6G Flagship Research

#1
Society

Digital inclusion via global coverage

- Connectivity is key to satisfy UN SDGs and needs of digital societies; current terrestrial technologies with evolutionary features need to be complemented by specific remote areas solutions including satellite.

#2
Business

New ecosystems and disruptive business models

- Digital societies and emergence of new verticals create new ecosystems and disrupts current business models requiring field specific regulation changes; ownership of customers and networks changes.

#3
Standards

Global collaboration and standards

- 6G coalitions forming in a new geopolitical landscape; a new standard is introduced after every 10-years – business reshaped in 20-year cycles; spectrum regulation principles changing ~25++ year cycles.

#4
Technology

- Security
- Network
- Radio
- AI

Data privacy and security

- Expansion of verticals with new stake holders and emergence of large number of new players providing different network elements, critical applications and operating different parts of networks sets new privacy & security requirements.

Service driven network architecture

- Networks are ubiquitous, local specialized services with various connectivity mechanisms are becoming more and more popular. Service driven architectures are becoming dominant after the network ownership driven era.

Super efficient local connectivity

- Extreme speeds, reliability, low latency and localization/sensing accuracy can be achieved only locally in rather short-range networks utilizing the higher frequency bands even above 100GHz.

Smart AI enabled networks and applications

- Networks and applications become intelligent, self-learning and context dependent; edge intelligence is the key technical enabler and challenges/complements centralized cloud solutions.

6G – How should we understand it?

- Something that is totally new?
- Everything that we couldn’t make in 5G with its 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?

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

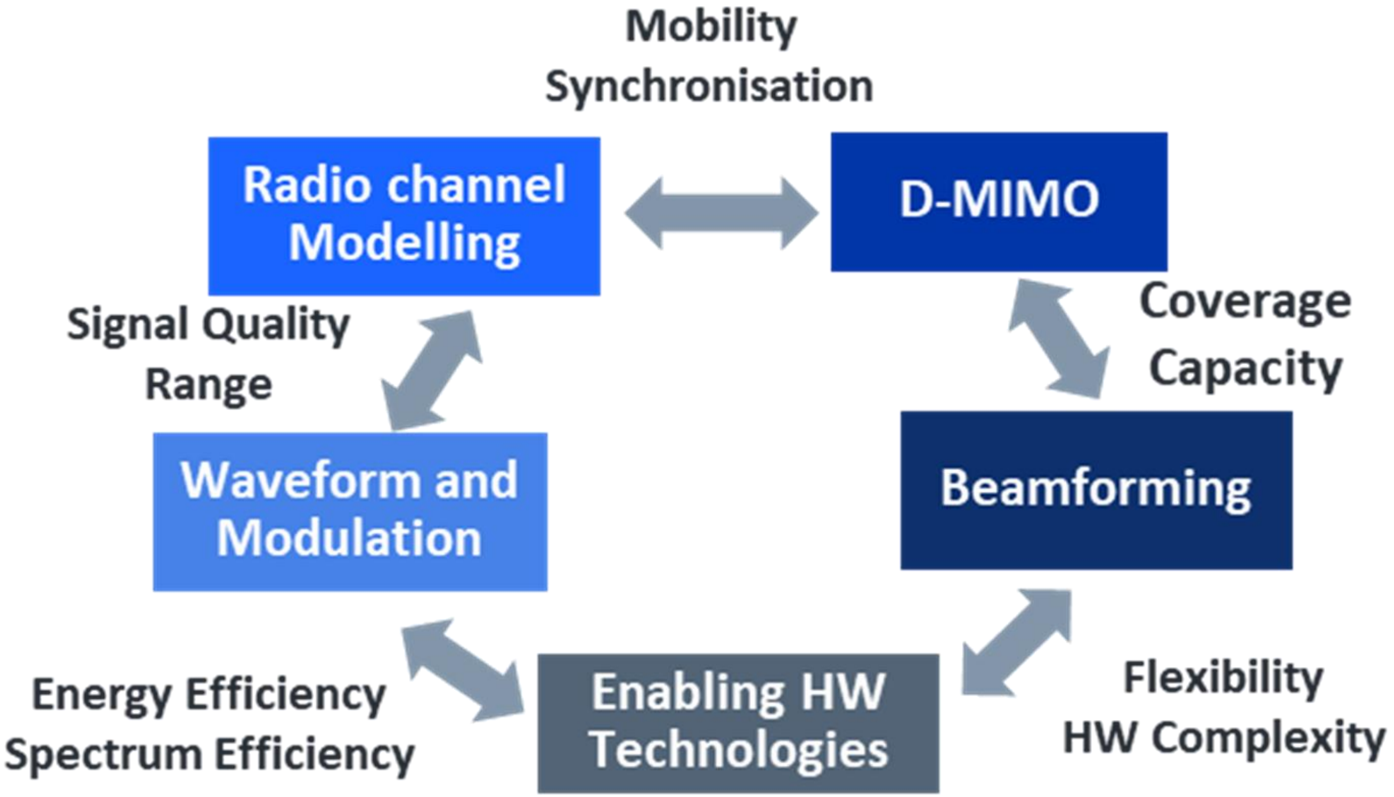
"6G must be designed to provide, at minimum, 20 times more wide-area capacity than 5G."

Nokia Bell Labs, "Envisioning a 6G future"

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

- Seemingly infinite capacity and data rate

Hexa-X



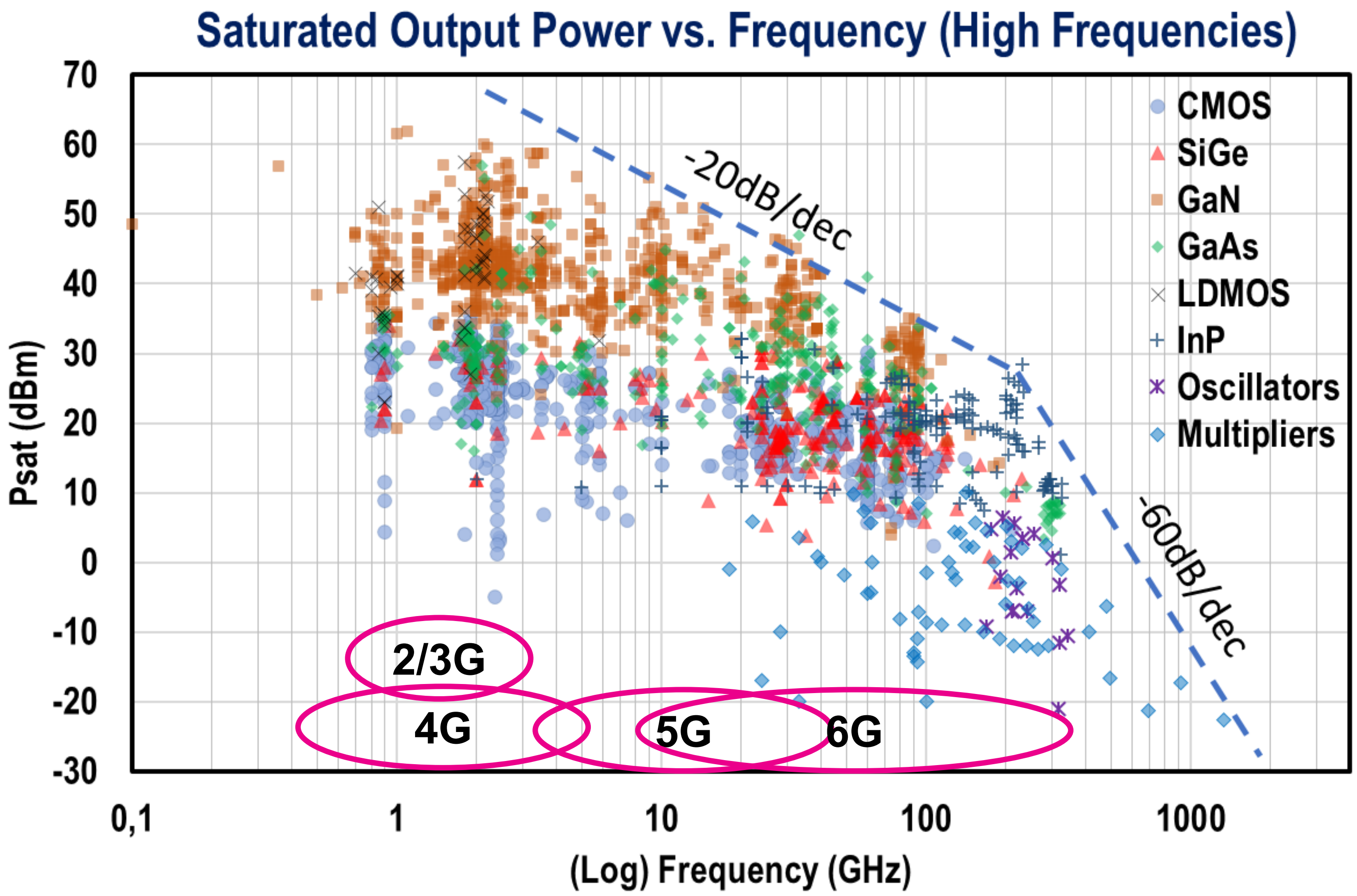
https://hexa-x.eu/ https://hexa-x-ii.eu/

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

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

Simple (?) solution – increase antenna gain

MIMO
- Full Flexibility
- RF & d… paral… n

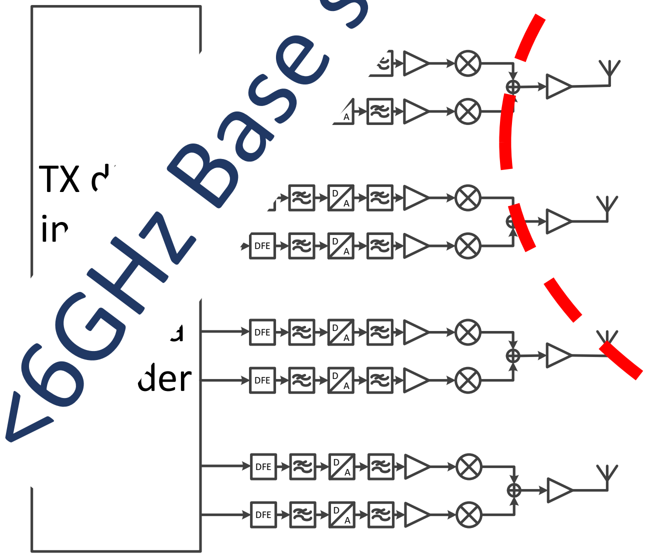
Phased array
- Steerability
- RF parallelism per data stream

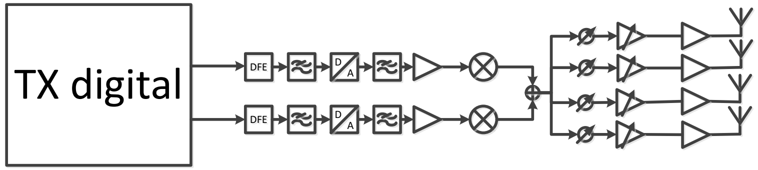
Directive antenna
- Large gain
- No parallelism
- Limited or r… steering

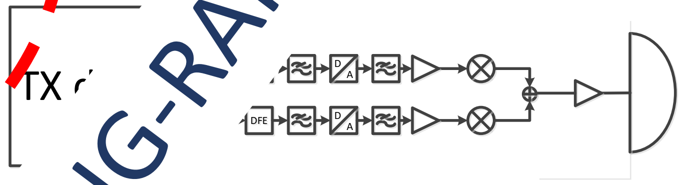
<6GHz Base station

compromizes needed

LONG-RANGE RADIO LINKS

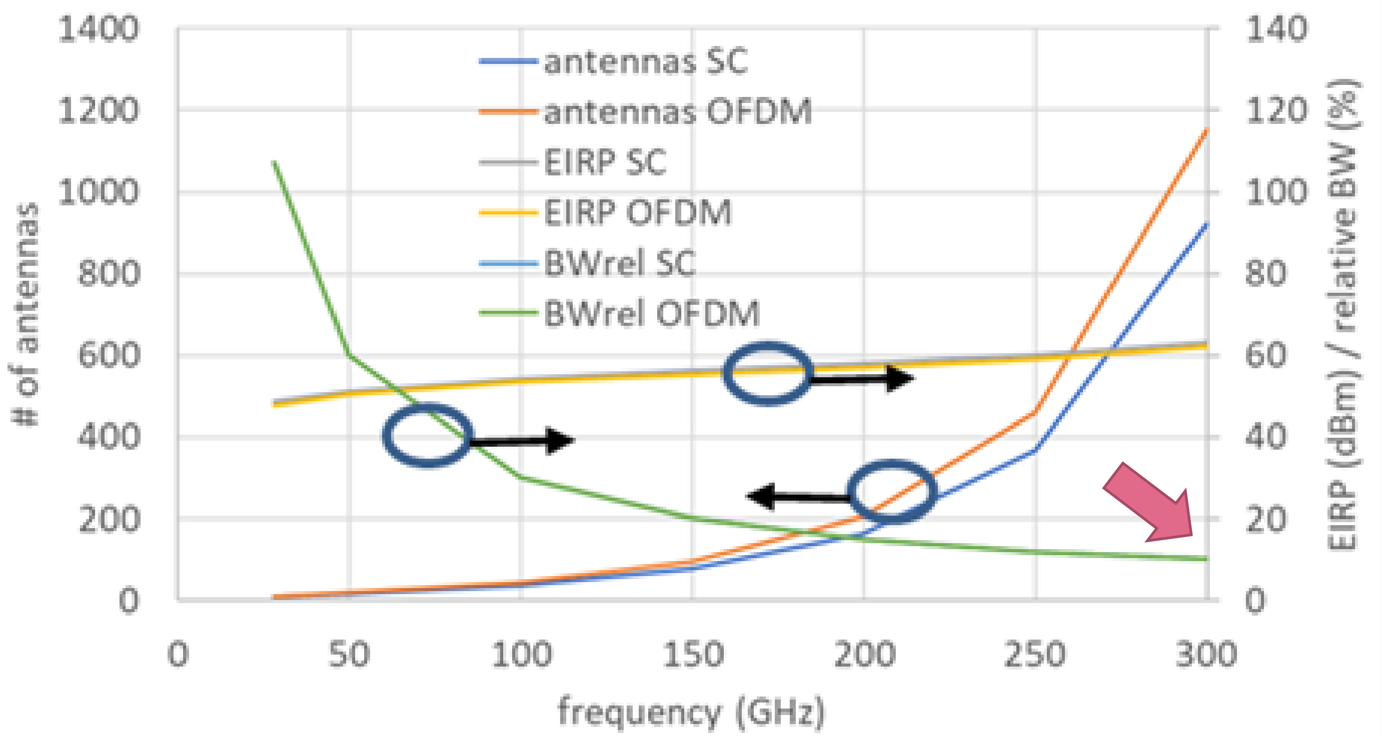






Impact of carrier frequency to radio performance with technology constraints

100 Gbps, 16QAM, 300 m distance, S-o-A SiGe

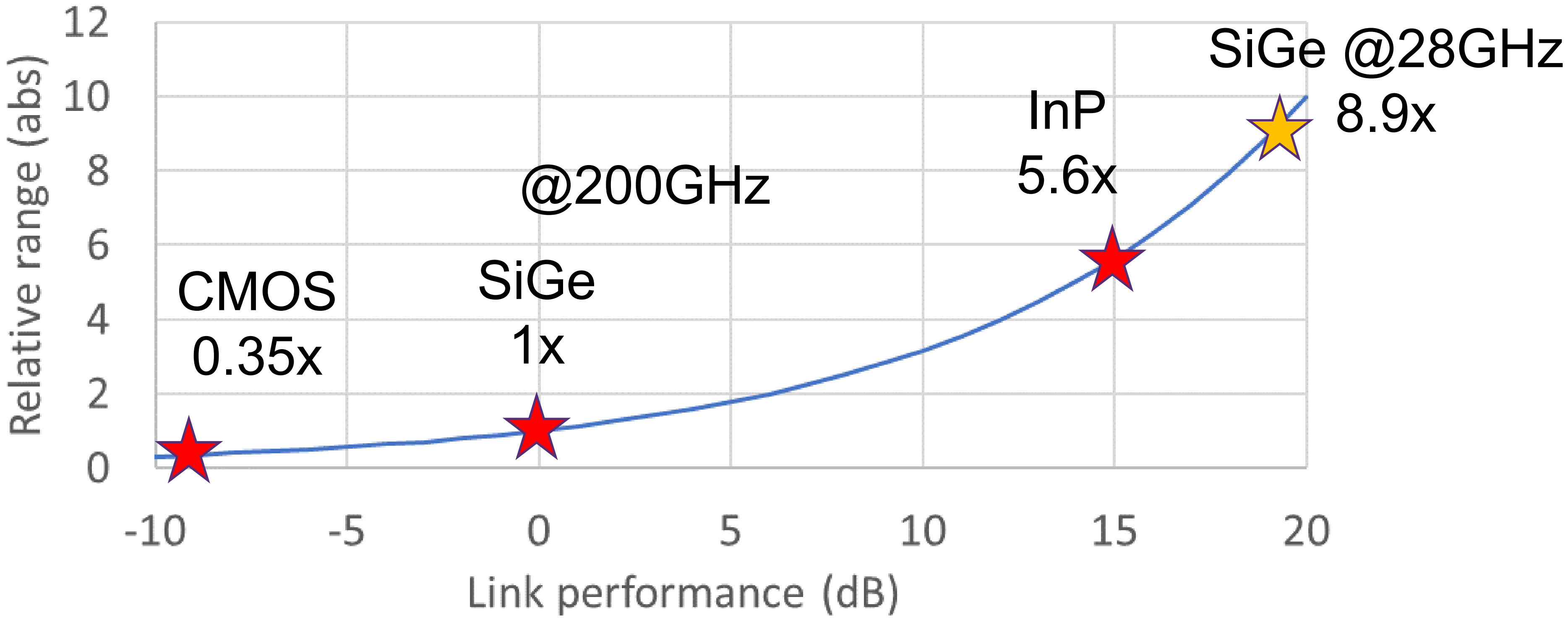


Number of antennas, EIRP and relative bandwidth as a function of frequency for 100 Gbps target data rate using single carrier or OFDM

Hexa-X D2.3 Radio models and enabling techniques towards ultra-high data rate links and capacity in 6G

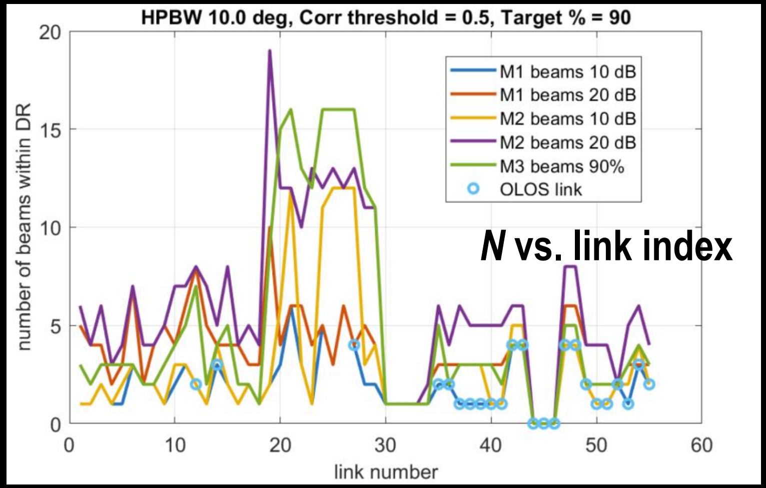
Choice of semiconductor technology?

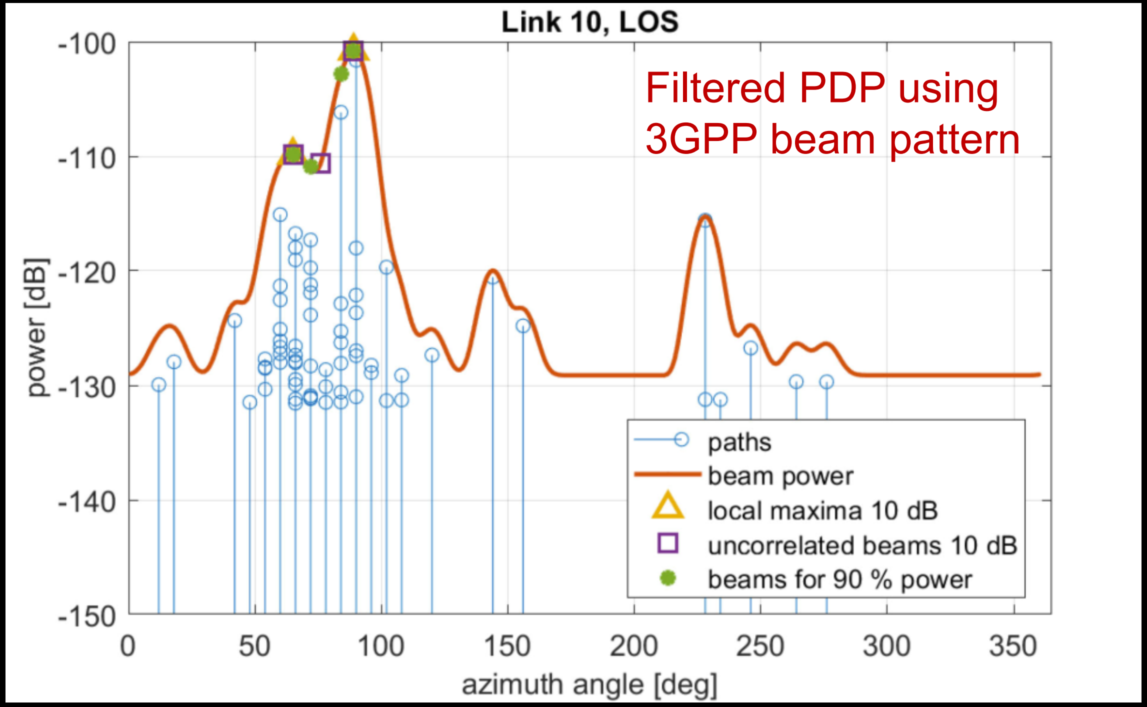
- We know the technology baseline of semiconductors towards 2030
- Being even close to anticipated 6G data rates requires
  - understanding of the semiconductors from transistors to complete wireless systems

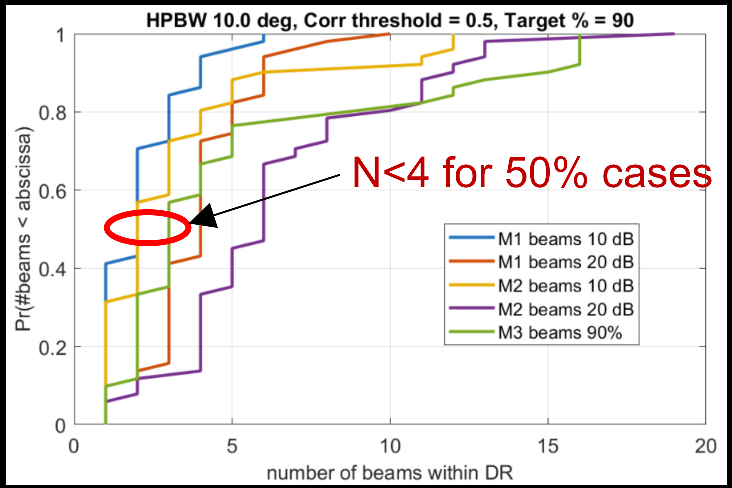


How Many Beams Does Sub-THz Channel Support?

- **Highly limited number of paths with <20dB attenuation compared to LOS**



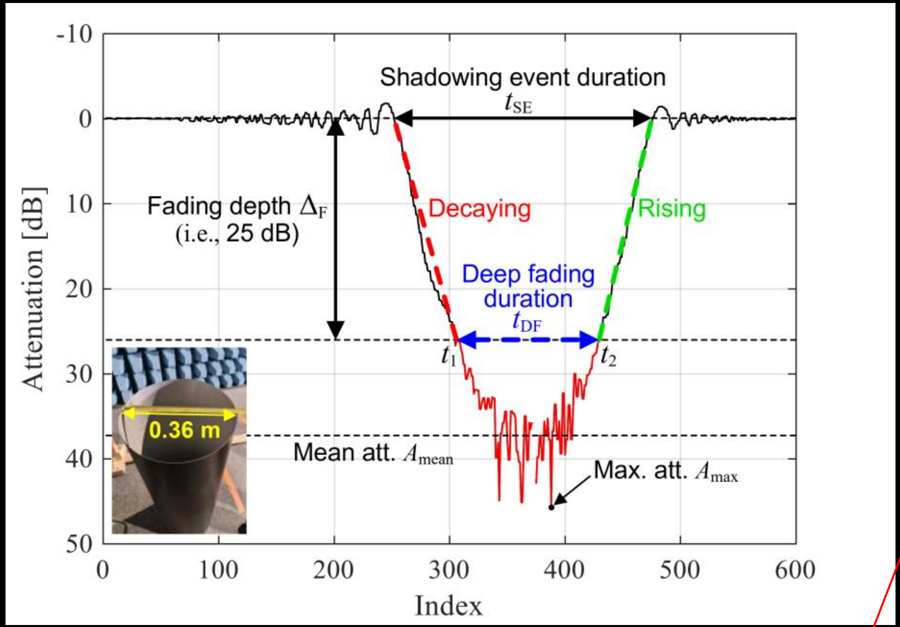




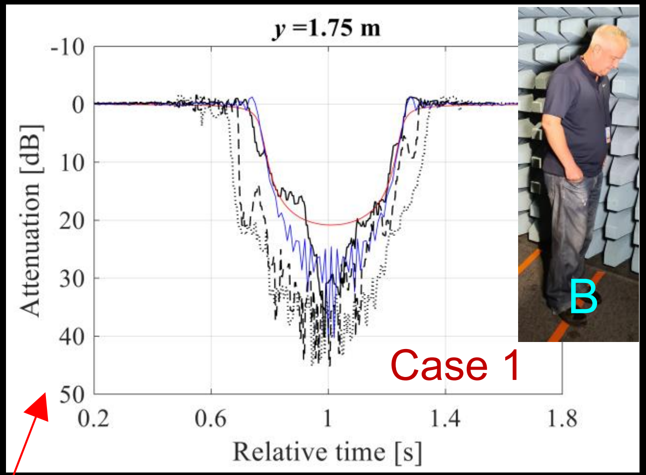
Pekka Kyösti, M. F. De Guzman, K. Haneda, N. Tervo and A. Pärssinen, “How Many Beams Does Sub-THz Channel Support?” ***IEEE Antennas Wireless Propag. Lett.***, vol. 21, no. 1, pp. 74-78, Jan. 2022

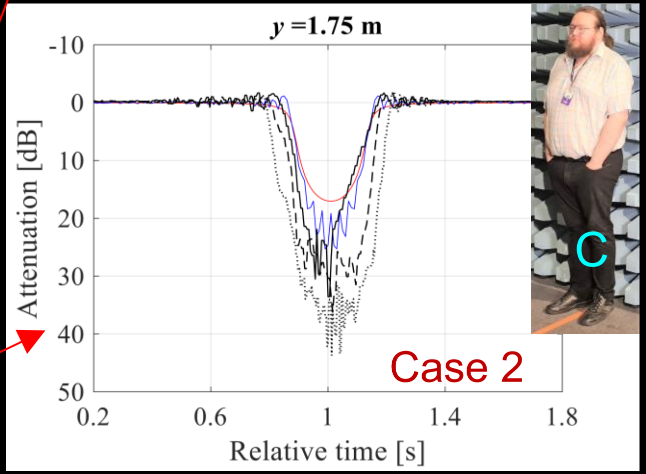
D-Band (140GHz) Human Body Shadowing

Single-Person Human Blockage Effect

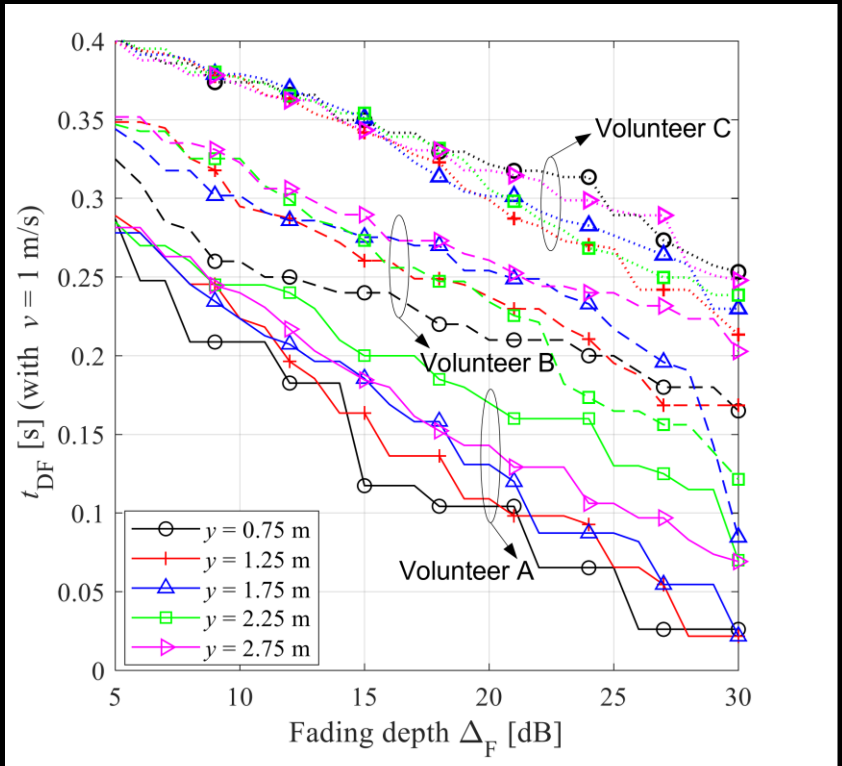


Reference measurement with metallic cylinder





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,” **EuCAP 2023.**

Impact of NLOS to HW complexity

- Compensating multipath, blockage or any other fading when PAs on their limit

$$G_{array} = 20\log_{10}(n_{ANT,TX}) + 10\log_{10}(n_{ANT,RX})$$

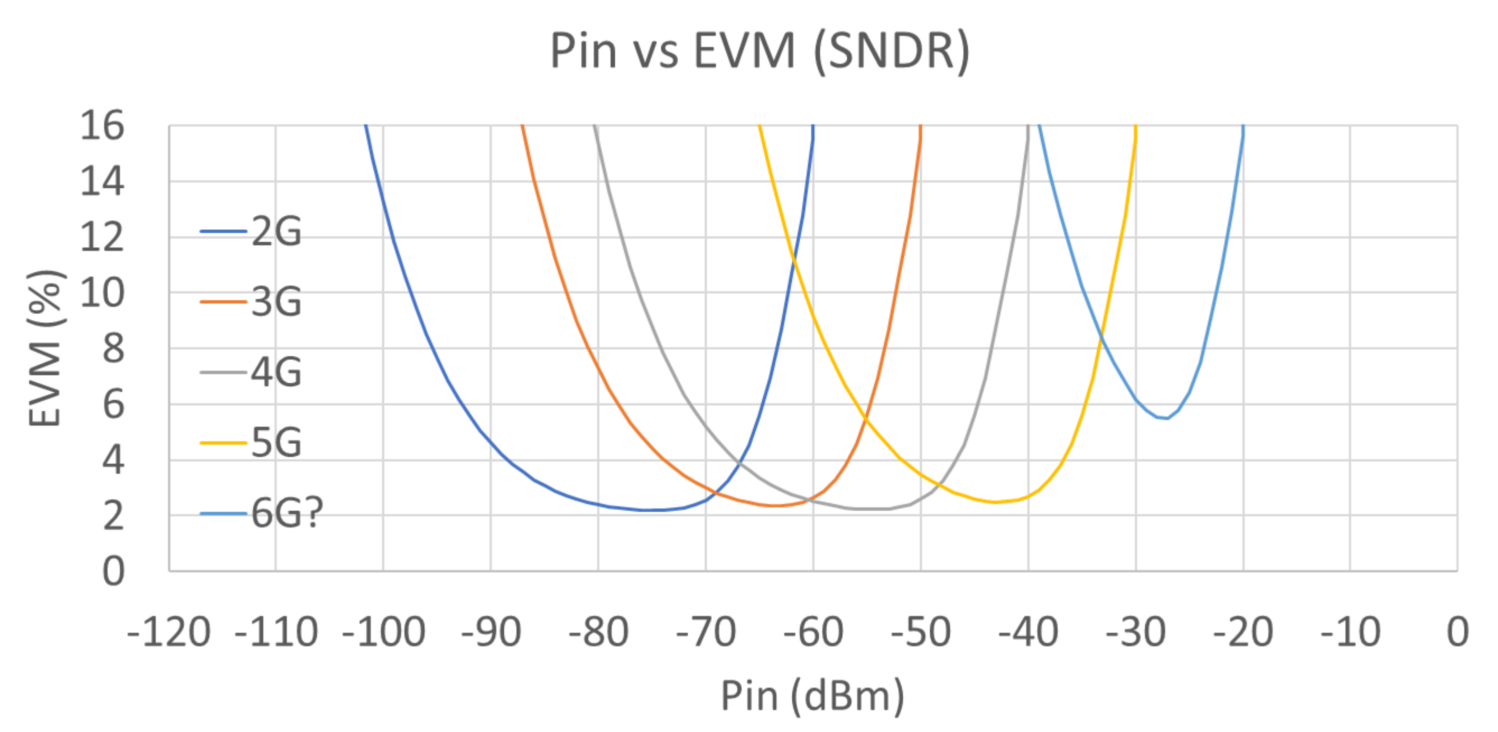
Additional path loss [dB]	Antenna increase (equal in TX&RX)	# of antennas with LOS (ref # 1000)
5	1,47x	1470
10	2,15x	2150
20	4,64x	4640
30	10x	10000
40	21,5x	21500

Increase in antenna area and ~power consumption & near field limit gets farther

Dynamic range evolution

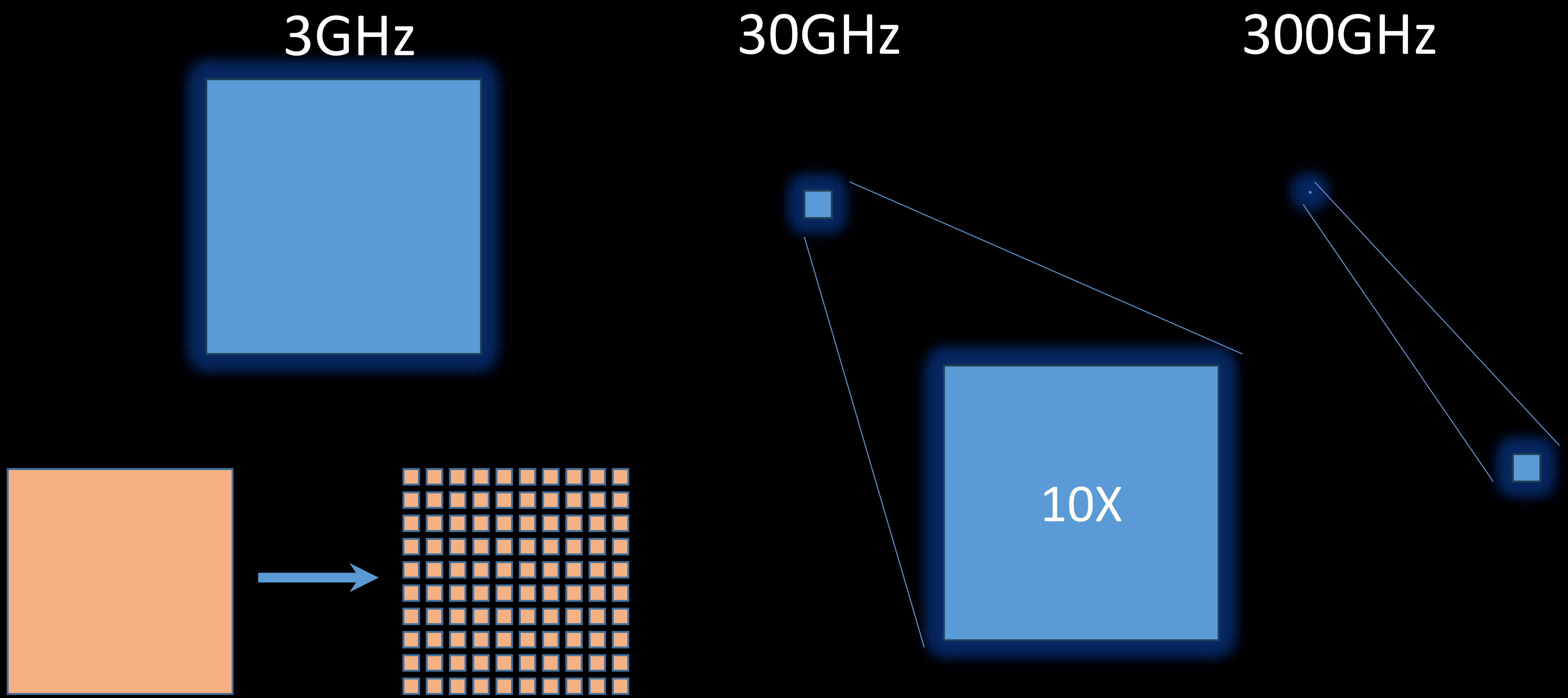
	2G	3G	4G	5G	6G?
ICP1 (dBm)	-60	-50	-40	-30	-20
EVM, flat (%)	2	2	2	2	2
NF (dB)	5	5	5	7	16
BW (MHz)	0,135	3,84	18,1	400	20000

Linearity will be a bottleneck with large antenna gains!



Form factor

- Area for antenna at λ/2 distance



Case study: Optimum carrier frequency vs. data rate

- Research question: What is the optimum carrier frequency send X bits/s over Y meters distance with minimum RF power consumtion using technology Z?

1. Link budget (LOS in this case)
2. Frequency scalable HW models (22nm FD-SOI)
3. Scalable phased array (# of antennas)
4. Multi-variable sweeps

M. Hietanen, et al.,, ”Technology Dependent Capacity Analysis for 6G RF Front-ends with D-band Implementation using 22 nm CMOS SOI,” Trans. on Microwave Theory and Tech., Aug. 2025

Case study: Optimum carrier frequency vs. data rate

Define models

- BW (%) **10%**
- f_{max} **360GHz**
- SW loss **(f)**
- LNA gain per stage **(f)**
- LNA NF **(f)**
- LNA ICP **-25dBm**
- Combiner loss per stage **1dB**
- Receiver BO **10dB**
- LNA Pdiss per stage **5mW**
- PA Psat **(f)**
- PA Gain **15dB**
- PA PAE **(f)**
- PA BO **10dB**
- Antenna loss (TX & RX) **0dB**
  directivity (TX & RX) **0dBi**

Example value

Define sweeps

- Frequency range **1..f_{max}**
- Link range **1..1000m**
- Data rate **10..140Gbps**
- Mrx **1..1000 000**
- Mtx **1..1000 000**

Perform calculations

1. Sweep Link range

2. Sweep data rate target

3. Sweep M_{rx}

4. Sweep M_{tx}

5. Sweep Frequency

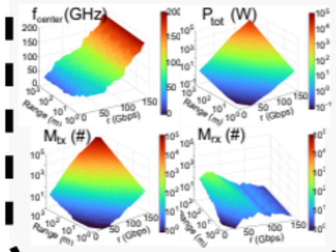
LNA P_{diss}
PA P_{diss}
Total P_{diss}
TX EIRP
Channel loss
Receiver ICP
Receiver NF
Receiver P_{rx}
Thermal noise
SNR
Data rate

➡ *Frequency fulfilling data rate target with minimum P_{diss}*

➡ *M_{tx}, M_{rx} & frequency fulfilling data rate target with minimum P_{diss}*

Analyze results

Carrier frequency
M_{tx}
M_{rx}
P_{diss}

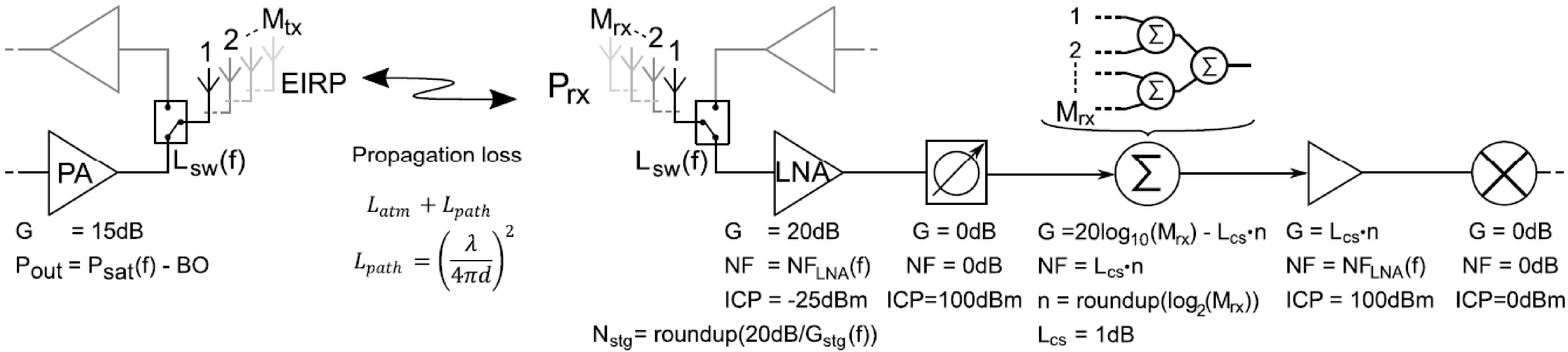


M. Hietanen, et al., TMTT, Aug. 2025

Case study: Optimum carrier frequency vs. data rate

Link model

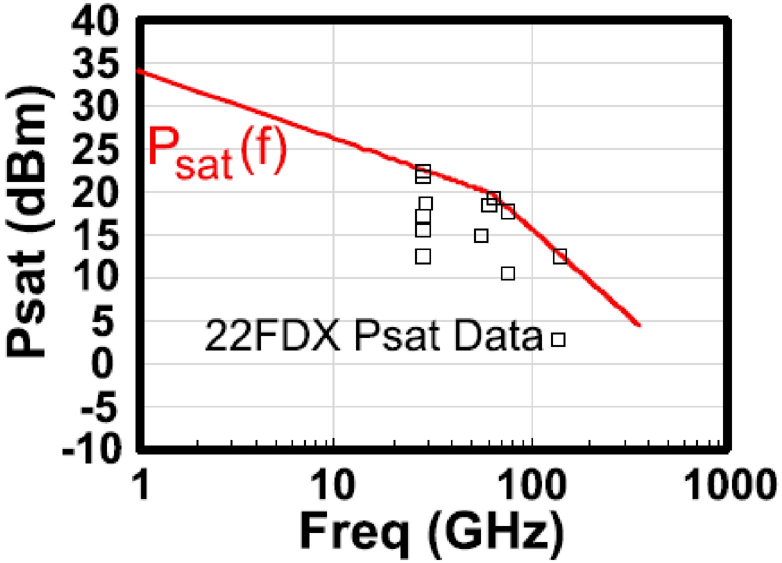
- Highly simplified behavioral model on the link and HW

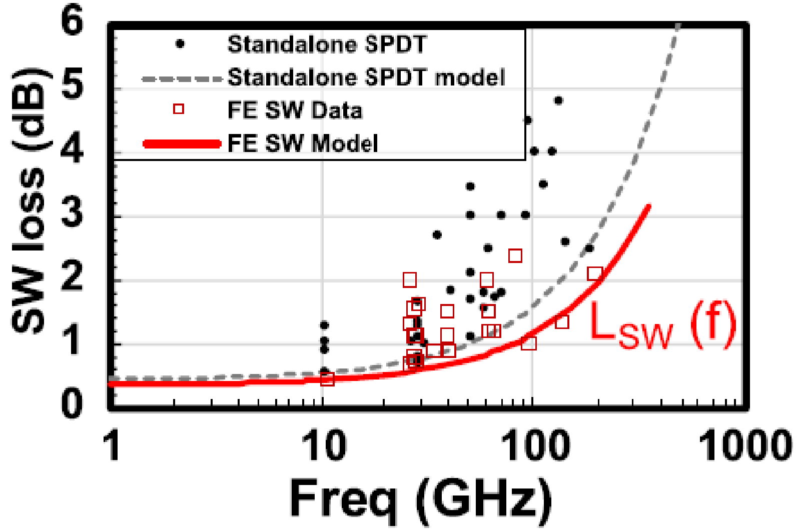


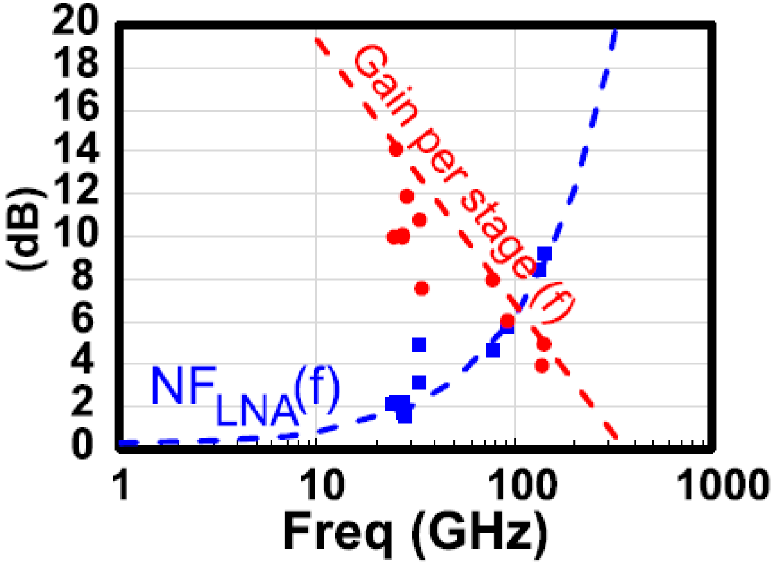
M. Hietanen, et al., TMTT, Aug. 2025

Case study: Optimum carrier frequency vs. data rate

- Frequency scalable HW models
- Here 22nm FD-SOI but can be any technology







$f < 64$ GHz

$$P_{sat}(f) = -8 \cdot \log_{10}(f[\mathrm{GHz}]) + 34.2 \ [\mathrm{dBm}]$$

and $f \geq 64$ GHz

$$P_{sat}(f) = -20.5 \cdot \log_{10}(f[\mathrm{GHz}]) + 56.7 \ [\mathrm{dBm}]$$

$$L_{sw}(f) = 0.008 \cdot f[\mathrm{GHz}] + 0.36 \ [\mathrm{dB}]$$

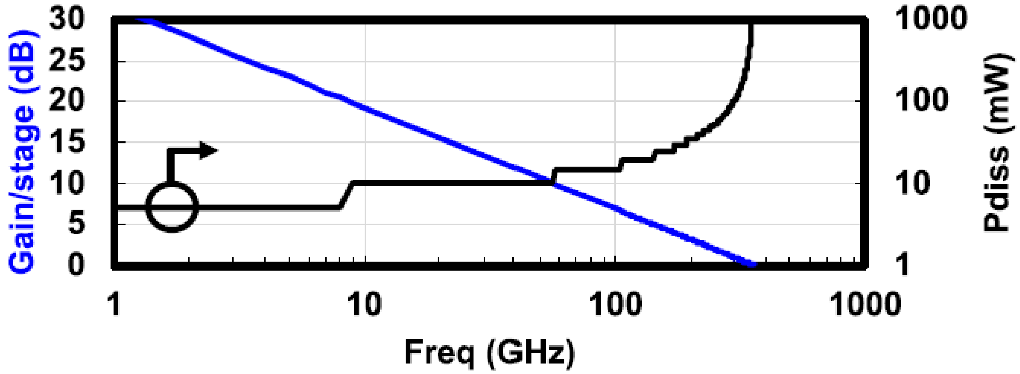
$$\mathrm{NF}_{\mathrm{LNA}}(f) = 0.06 \cdot f[\mathrm{GHz}] + 0.2 \ [\mathrm{dB}]$$

$$G_{stg}(f) = -12.4 \cdot \log_{10}(f[\mathrm{GHz}]) + 31.7 \ [\mathrm{dB}]$$

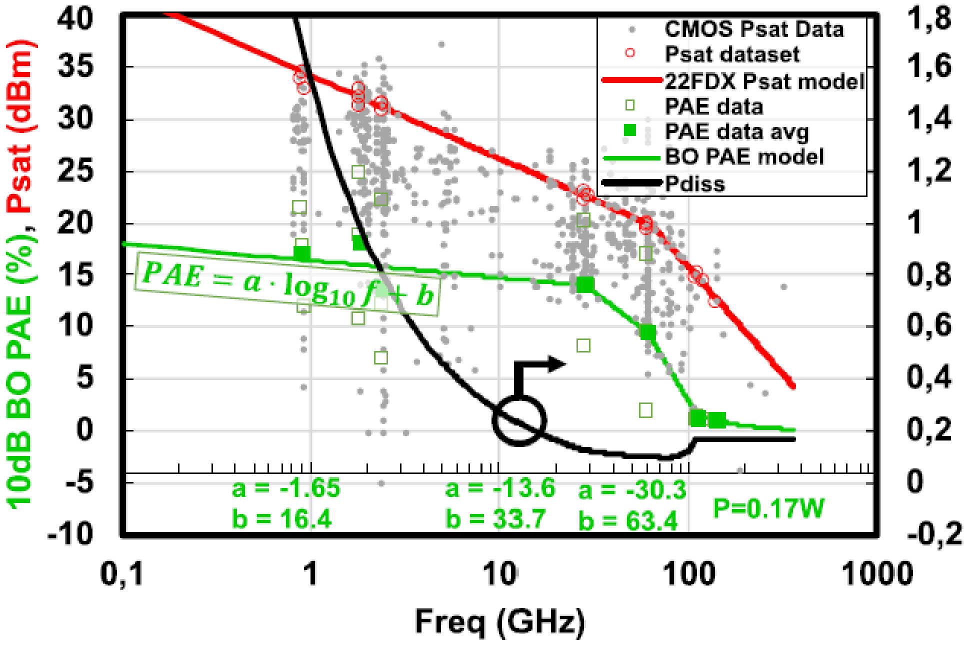
M. Hietanen, et al., TMTT, Aug. 2025

Case study: Optimum carrier frequency vs. data rate

- Power consumption models
  - (a) LNA
  - (b) PA



(a)



(b)

M. Hietanen, et al., TMTT, Aug. 2025

Case study: Optimum carrier frequency vs. data rate

- Finally some results

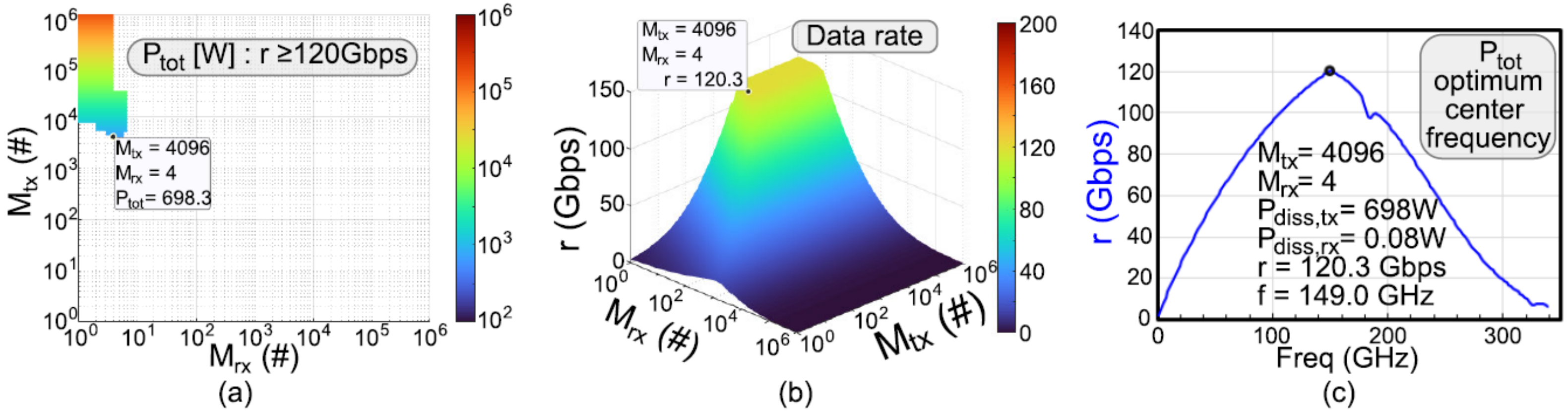


Fig. 6. Example array size optimization sweep for 120 Gb/s and 100 m. (a) Total power dissipation. (b) Data rates. (c) Frequency sweep of the minimum power solution.

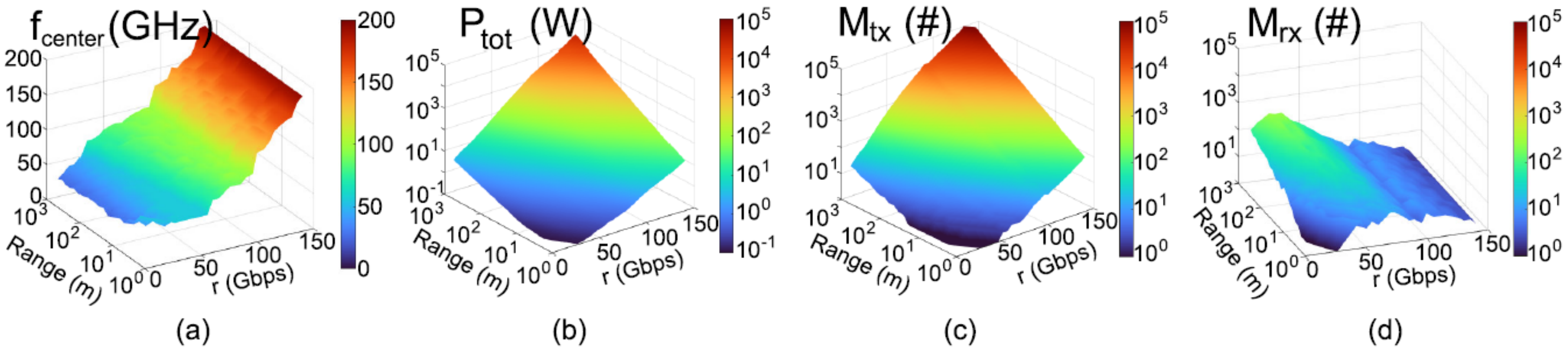
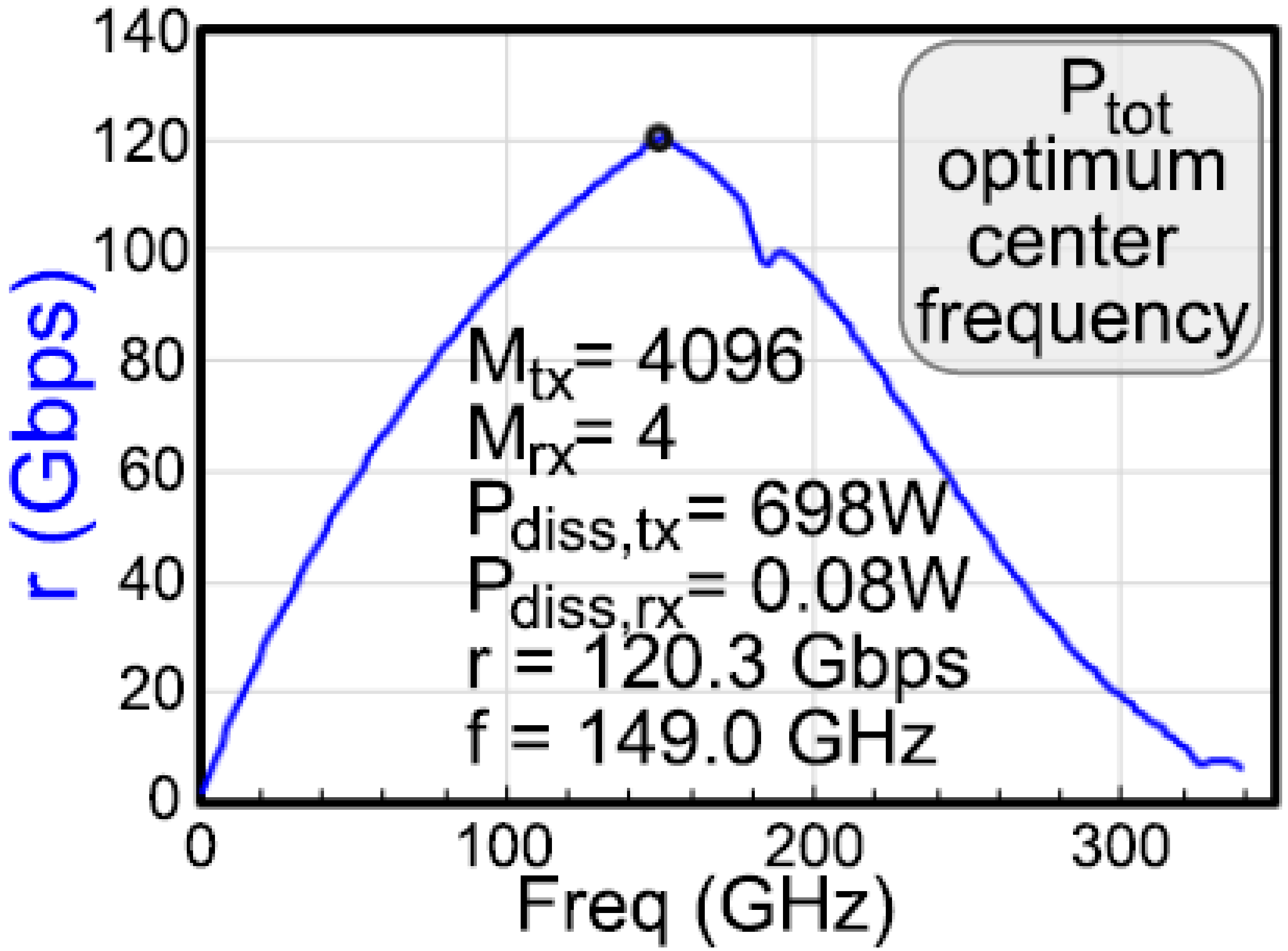


Fig. 7. Extensive sweep of range from 1 to 1000 m and data rate from 10 to 140 Gb/s. (a) Optimal center frequency. (b) Total power dissipation. (c) Number of transmitter elements. (d) Number of receiver elements.

M. Hietanen, et al., TMTT, Aug. 2025

Case study: Optimum carrier frequency vs. data rate

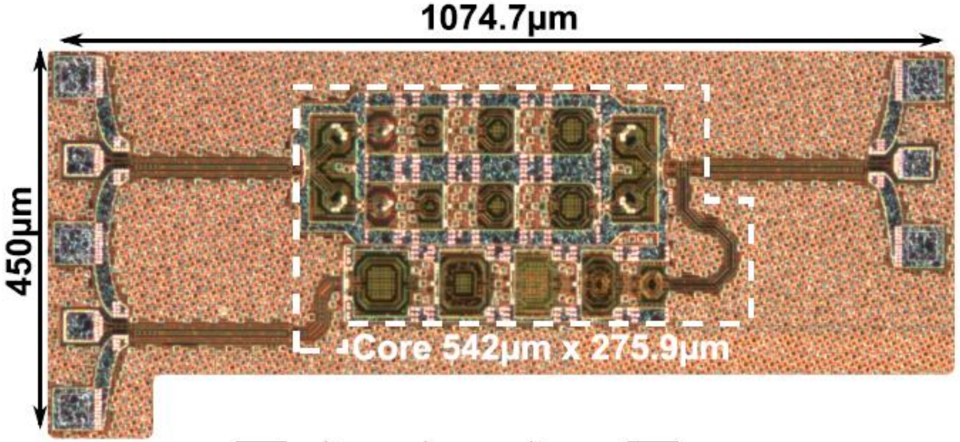
- Finally some results

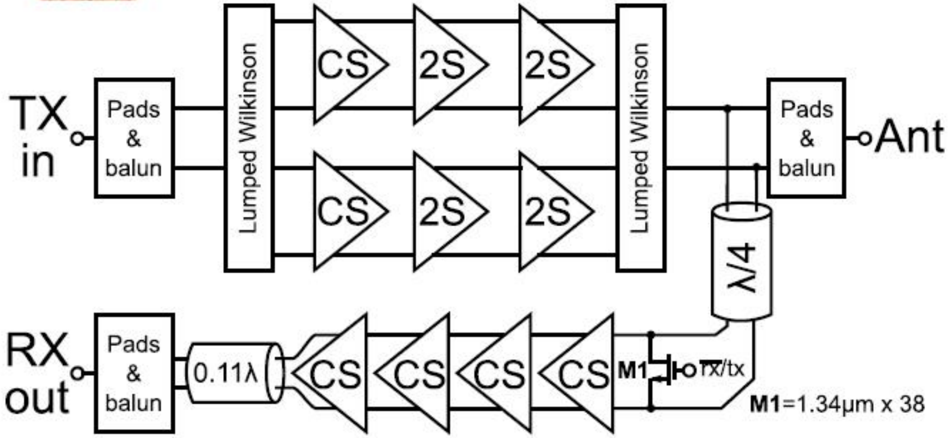


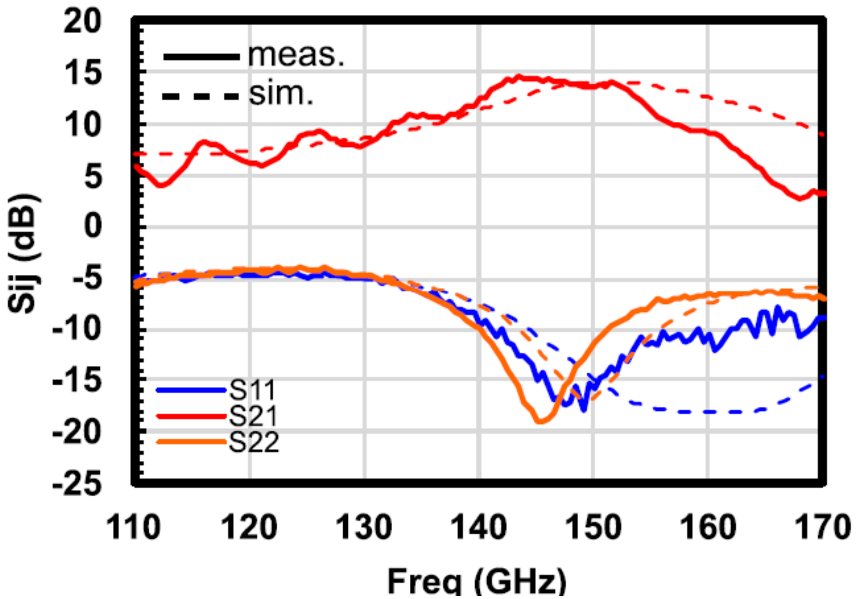
M. Hietanen, et al., TMTT, Aug. 2025

Case study: Optimum carrier frequency vs. data rate

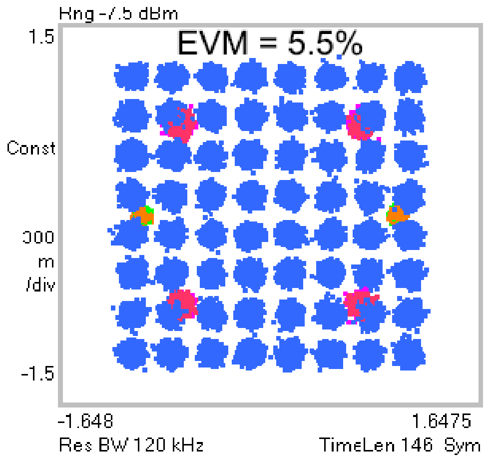
- Test chip



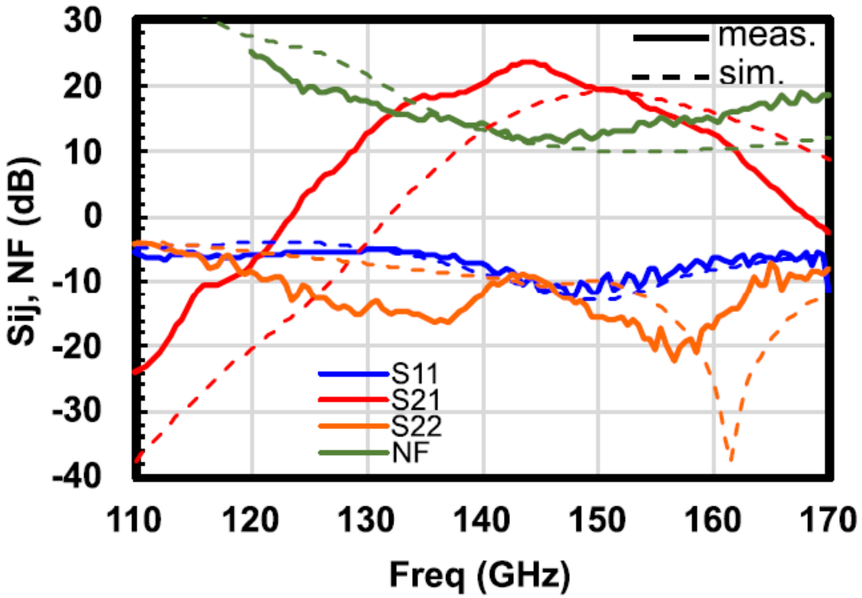




TX



RX

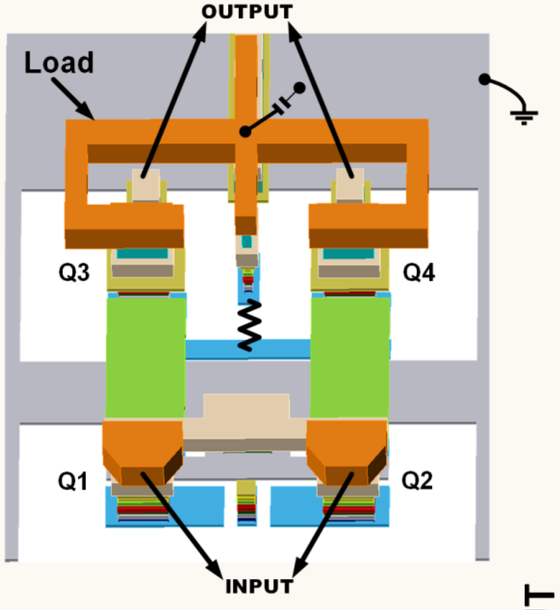


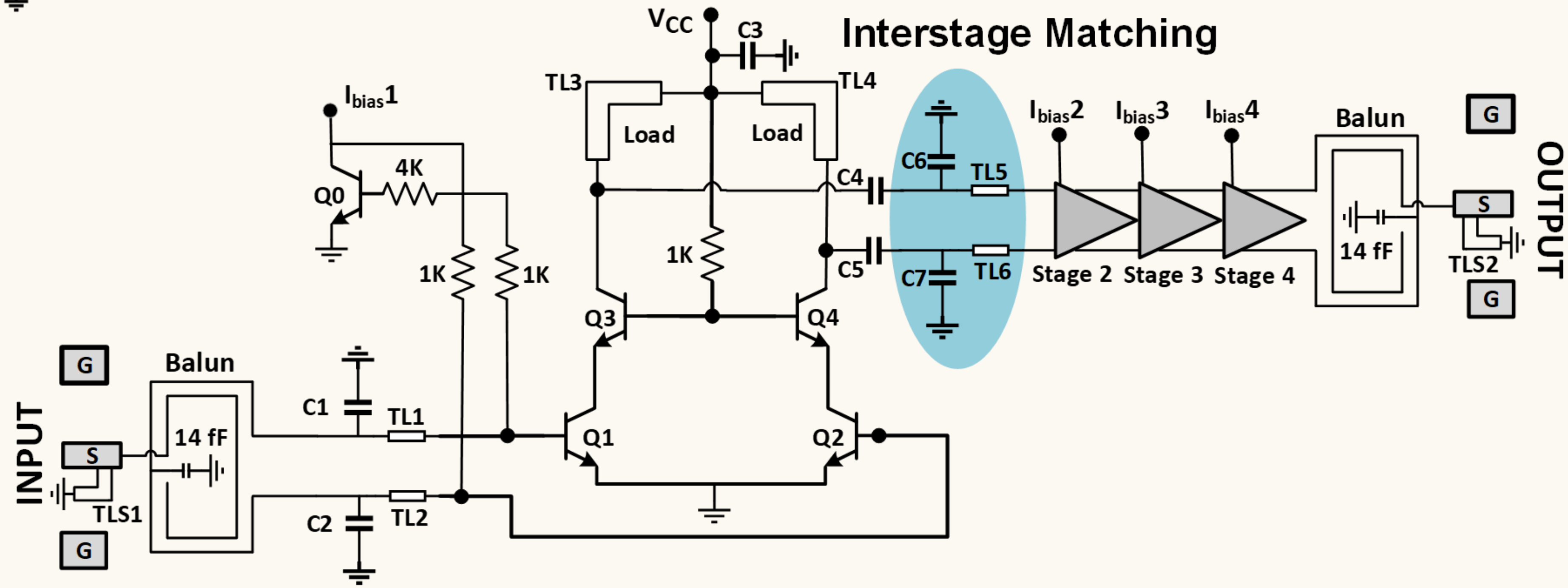
M. Hietanen, et al., TMTT, Aug. 2025

290GHz SiGe Low Noise Amplifier

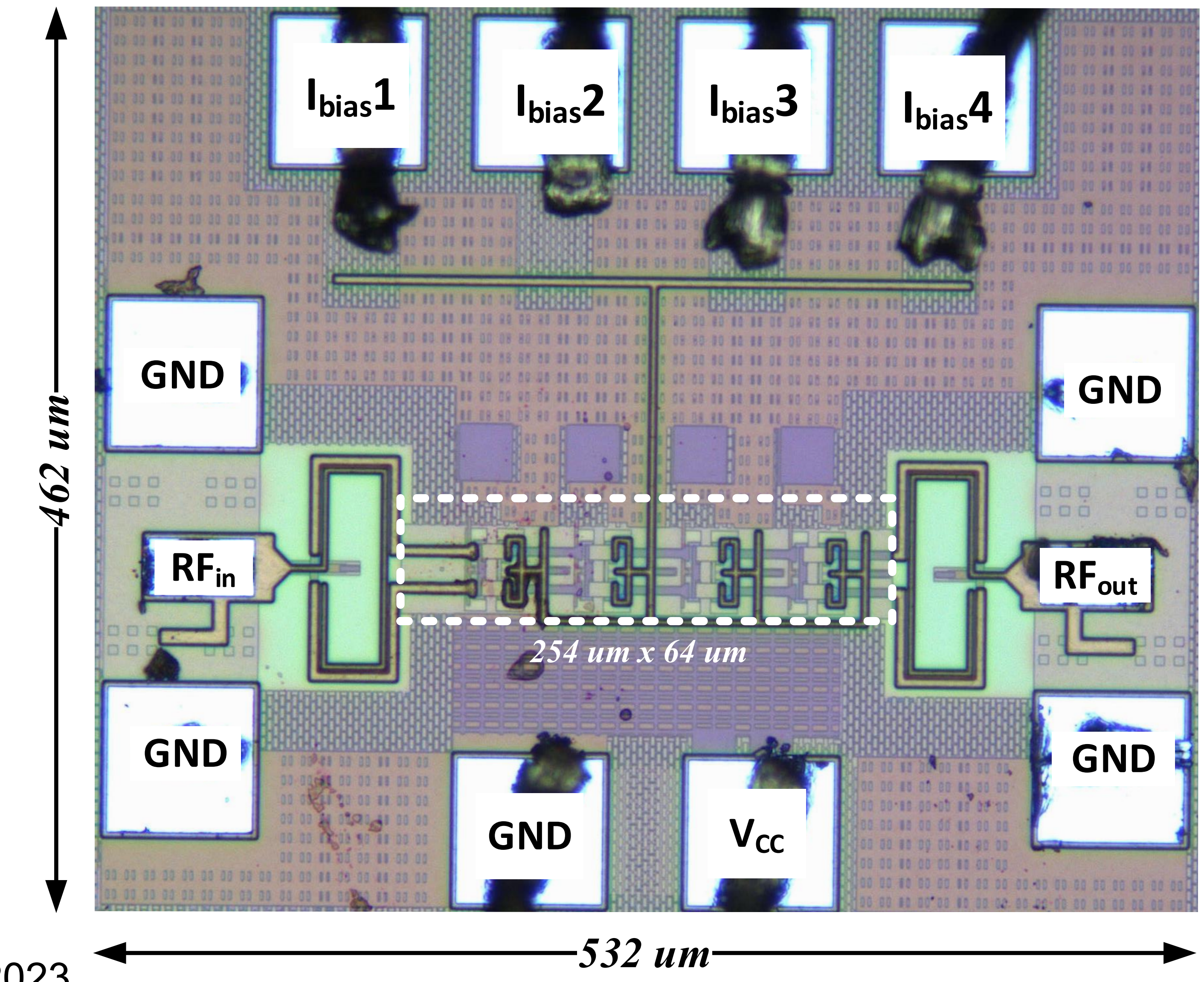
- LNA at 2/3 of fmax
- BiCMOS having ft /fmax 300GHz/450GHz

S. P. Singh, et al., "Design Aspects of Single-Ended and Differential SiGe Low Noise Amplifiers Operating above Fmax/2 in sub-THz/THz Frequencies," IEEE J. of Solid-State Circuits, 2023.



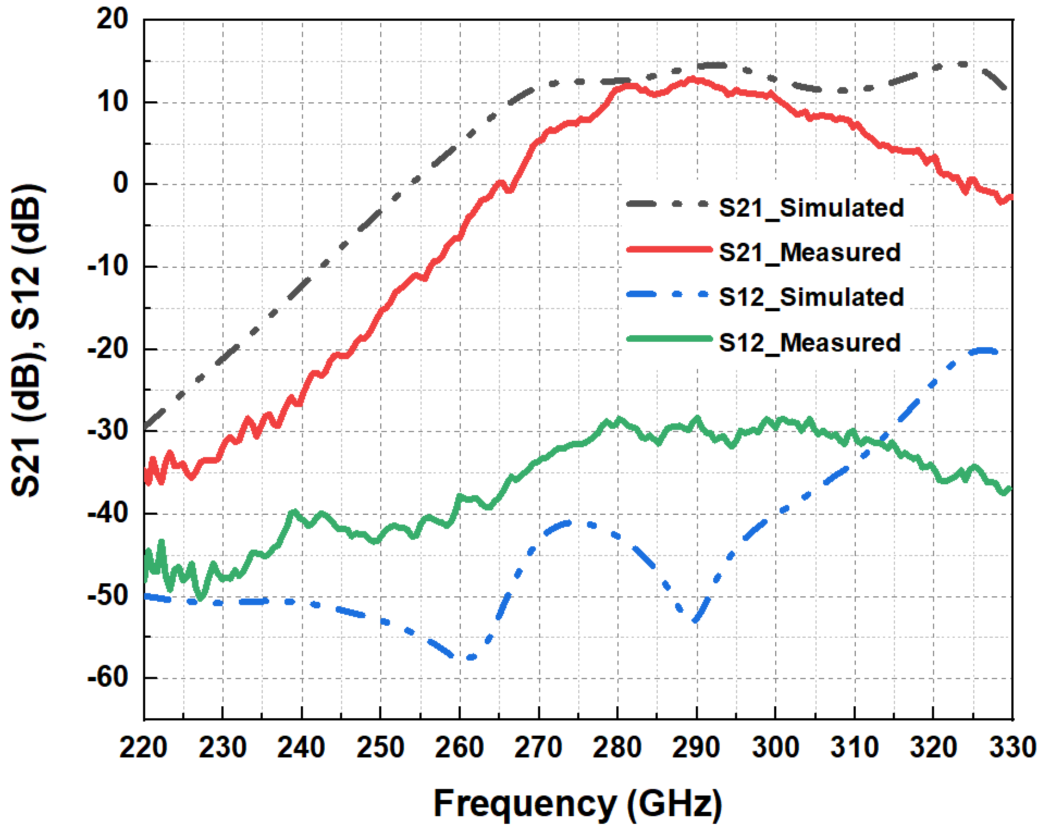


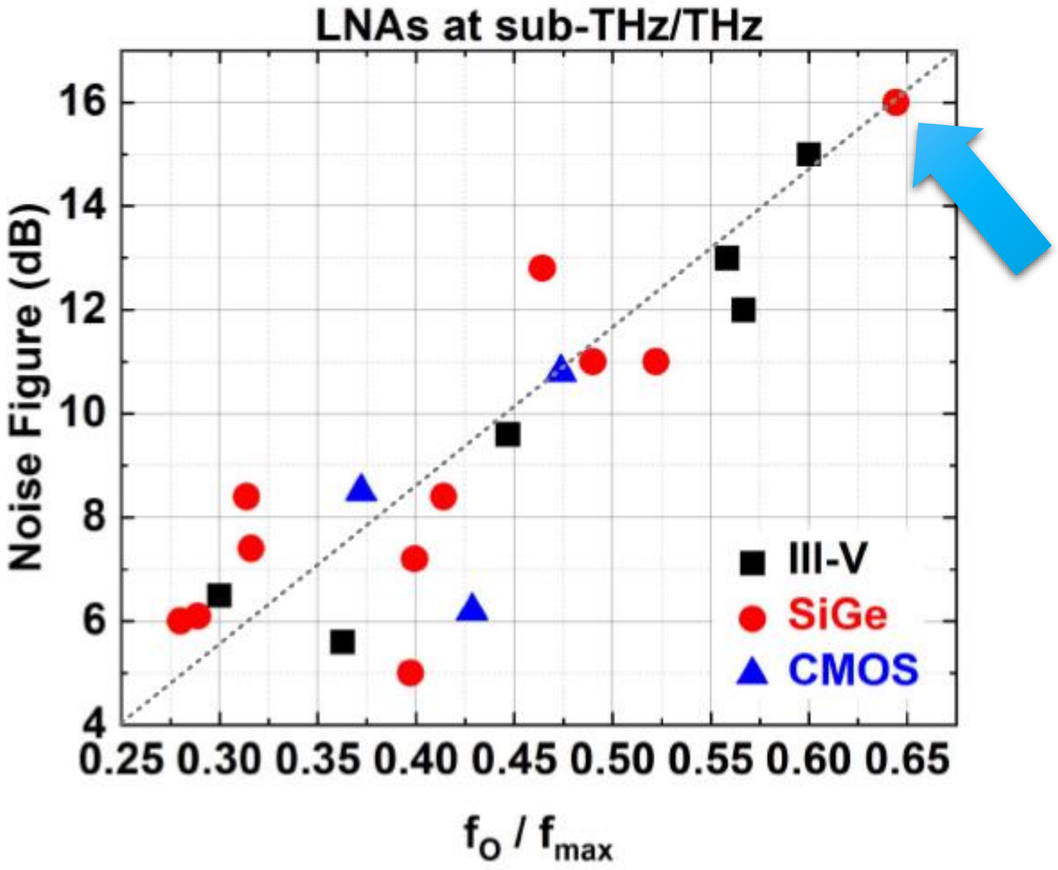
LNA - Microphotograph



S. P. Singh, et al., JSSC 2023

LNA performance

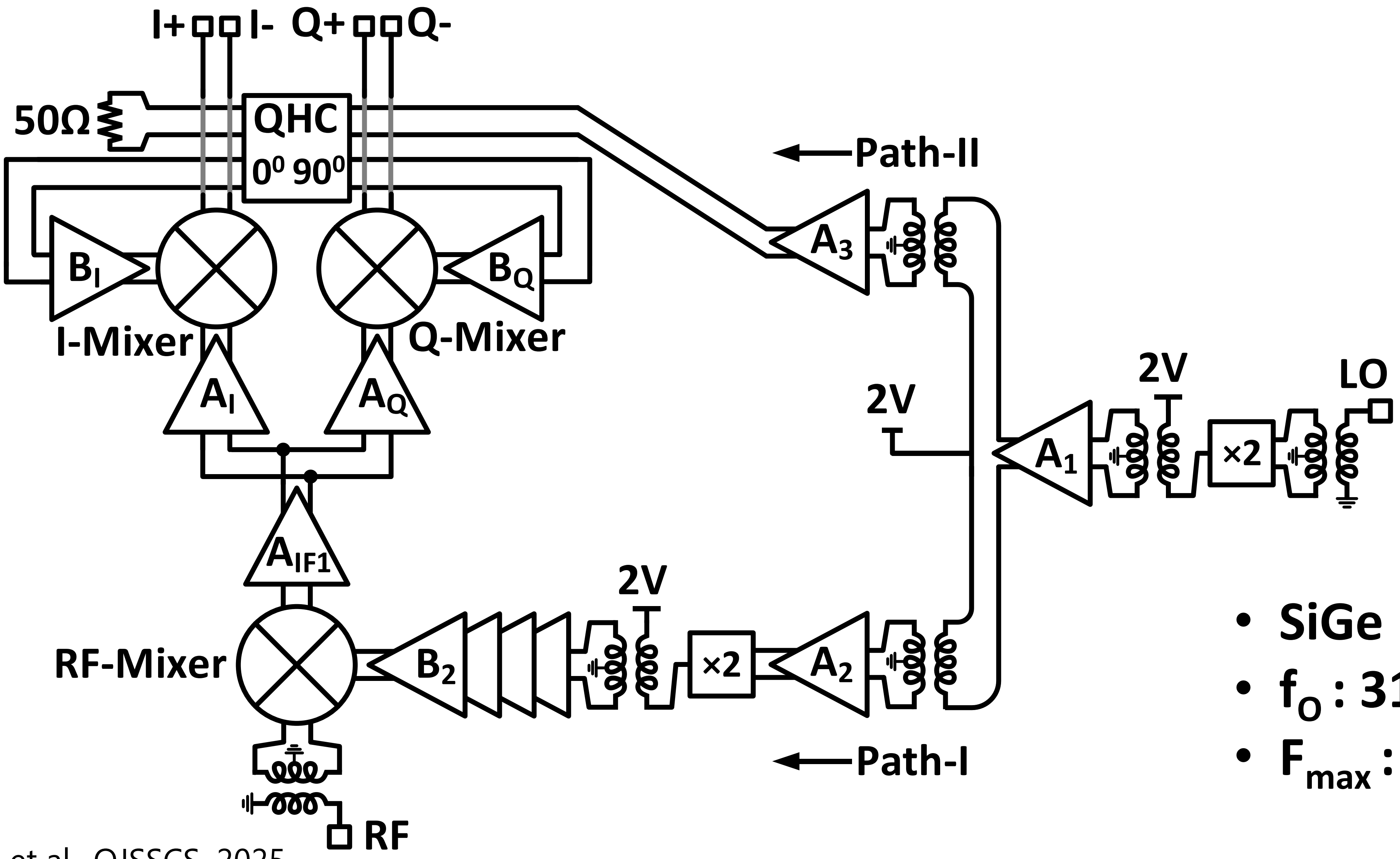




- ❑ S21 is 12.9 dB and 11.2 dB at 290 GHz and 300 GHz, respectively

S. P. Singh, et al., JSSC 2023 & OJSSCS 2025

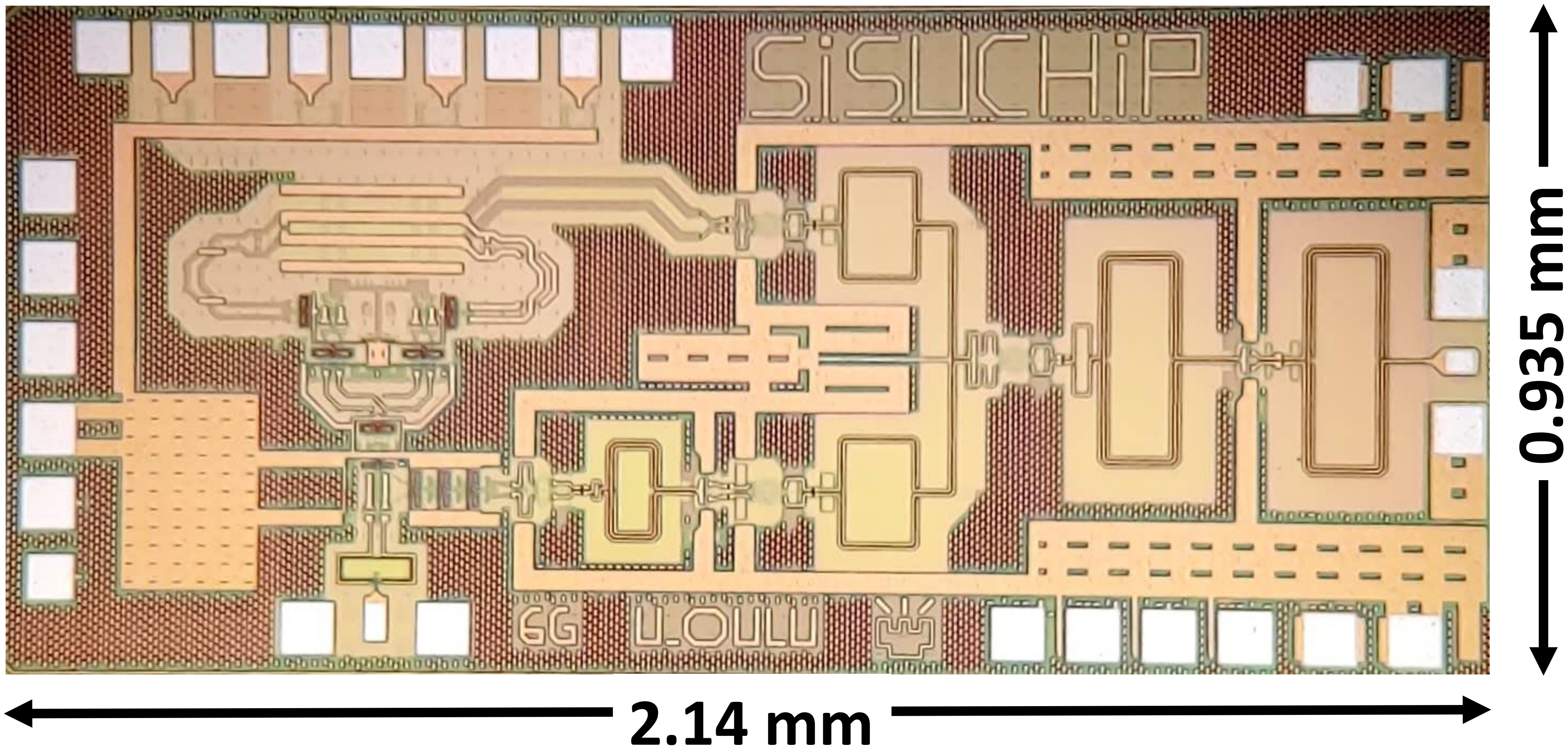
300 GHz sliding IF receiver FE



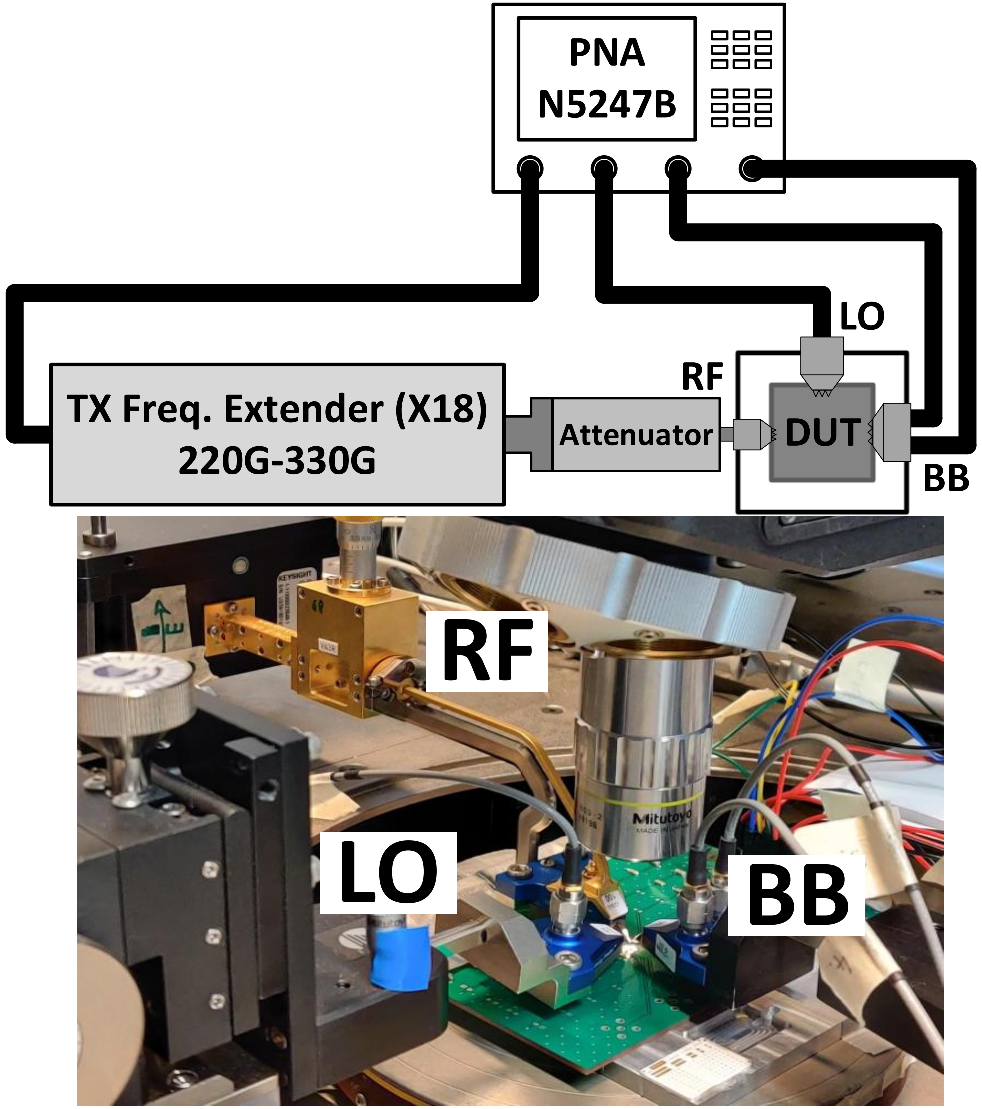
- SiGe BiCMOS
- f_O : 310 GHz
- F_{max} : 450 GHz

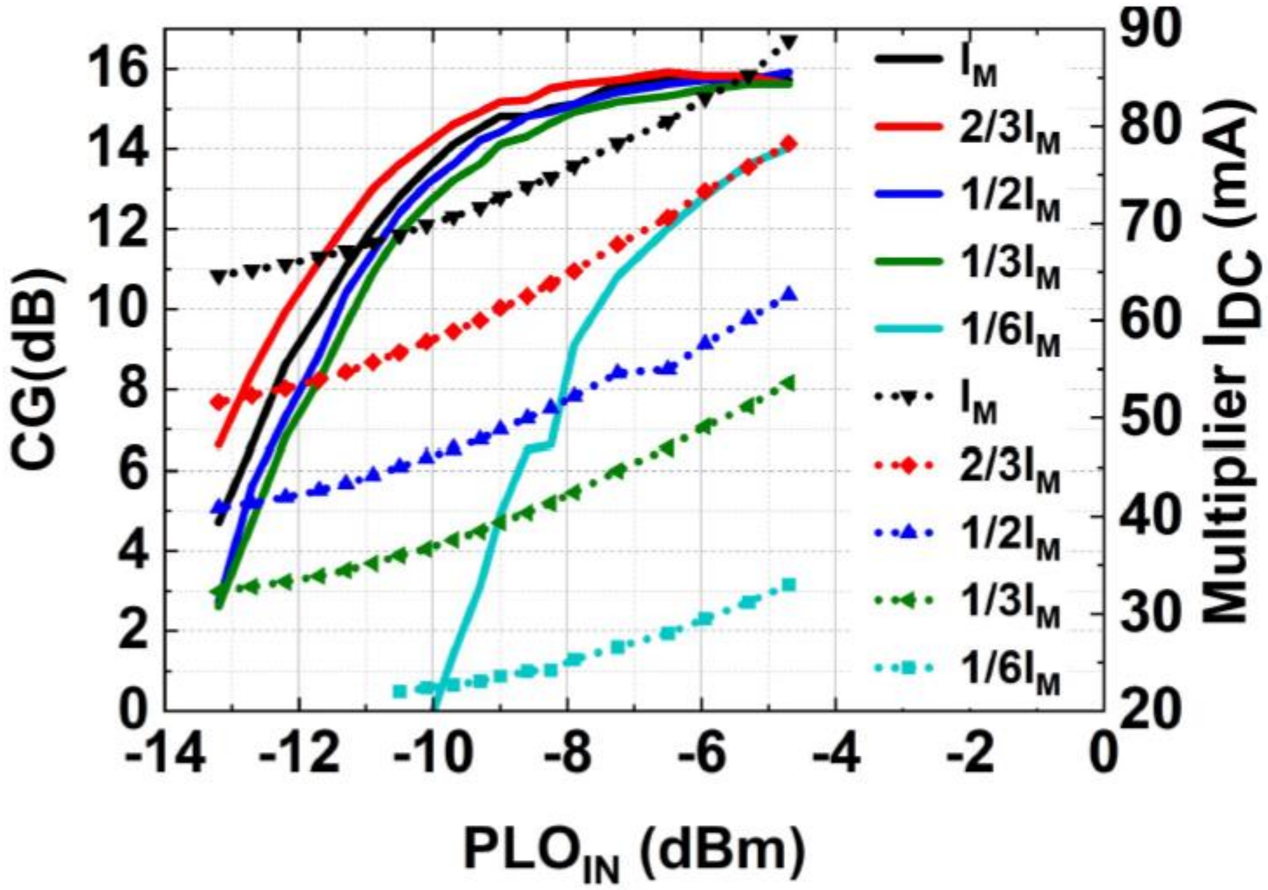
S. P. Singh, et al., OJSSCS, 2025

Slinding IF RX - Chip Micrograph

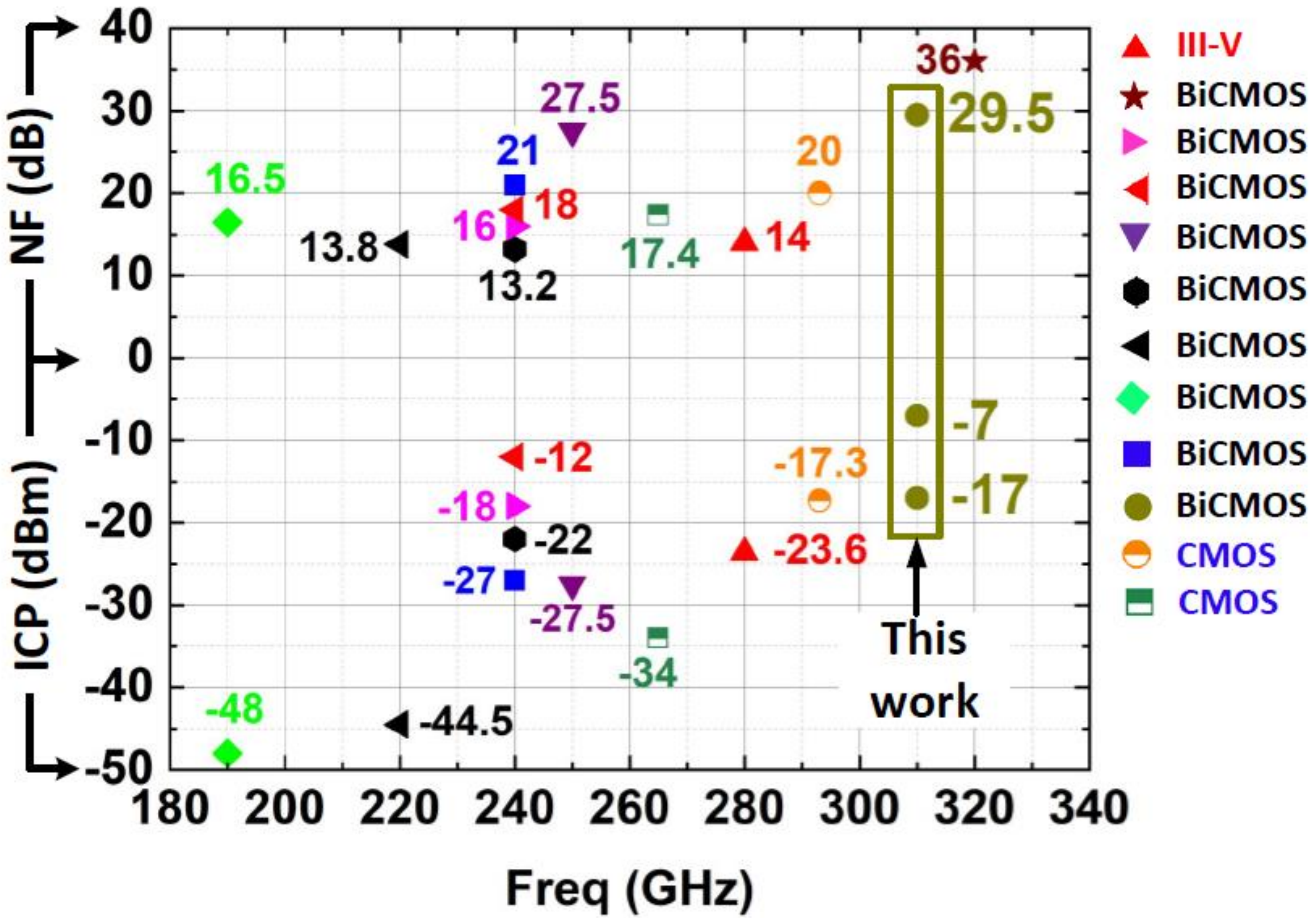


How low power is possible - Conversion Gain

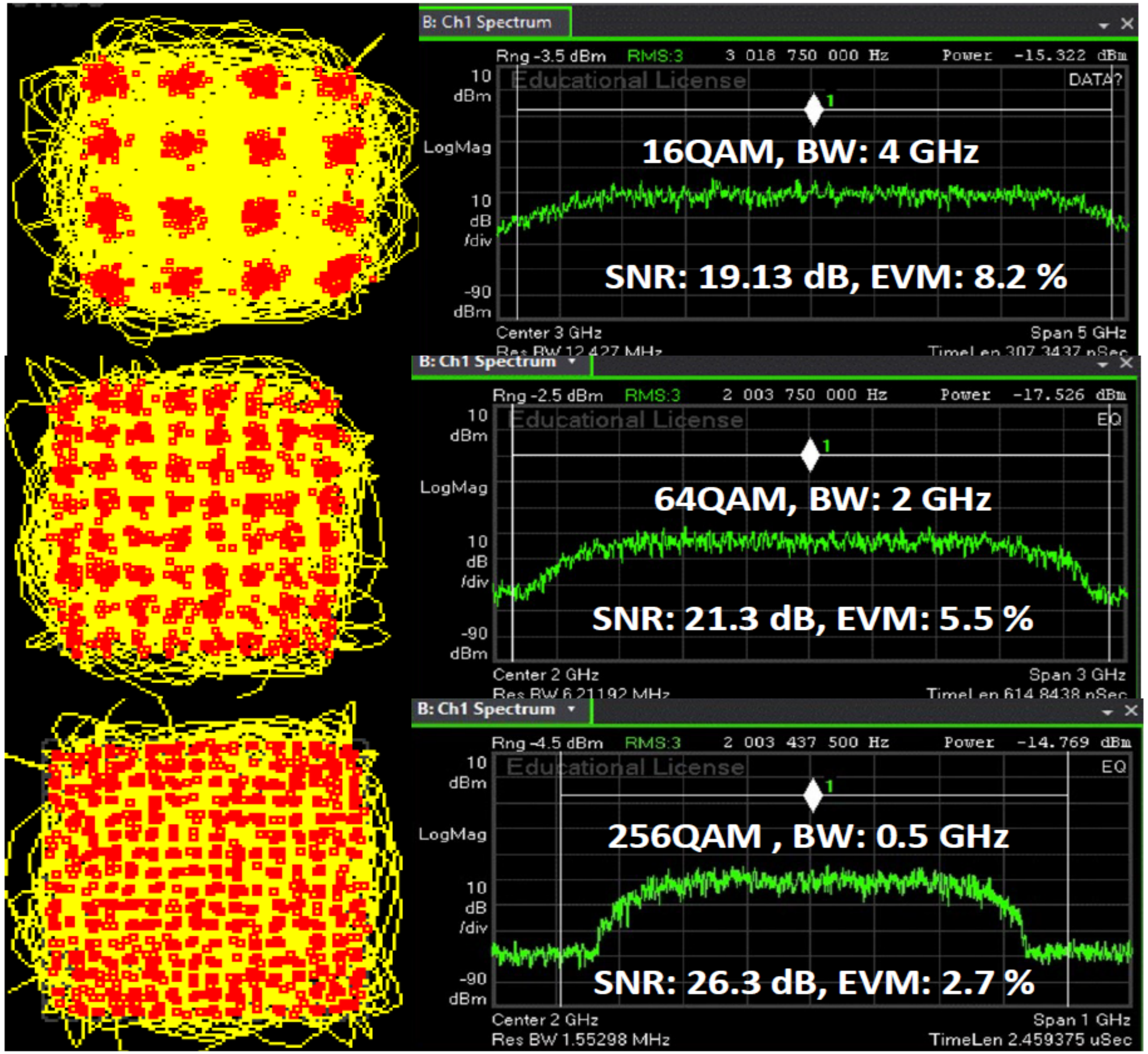




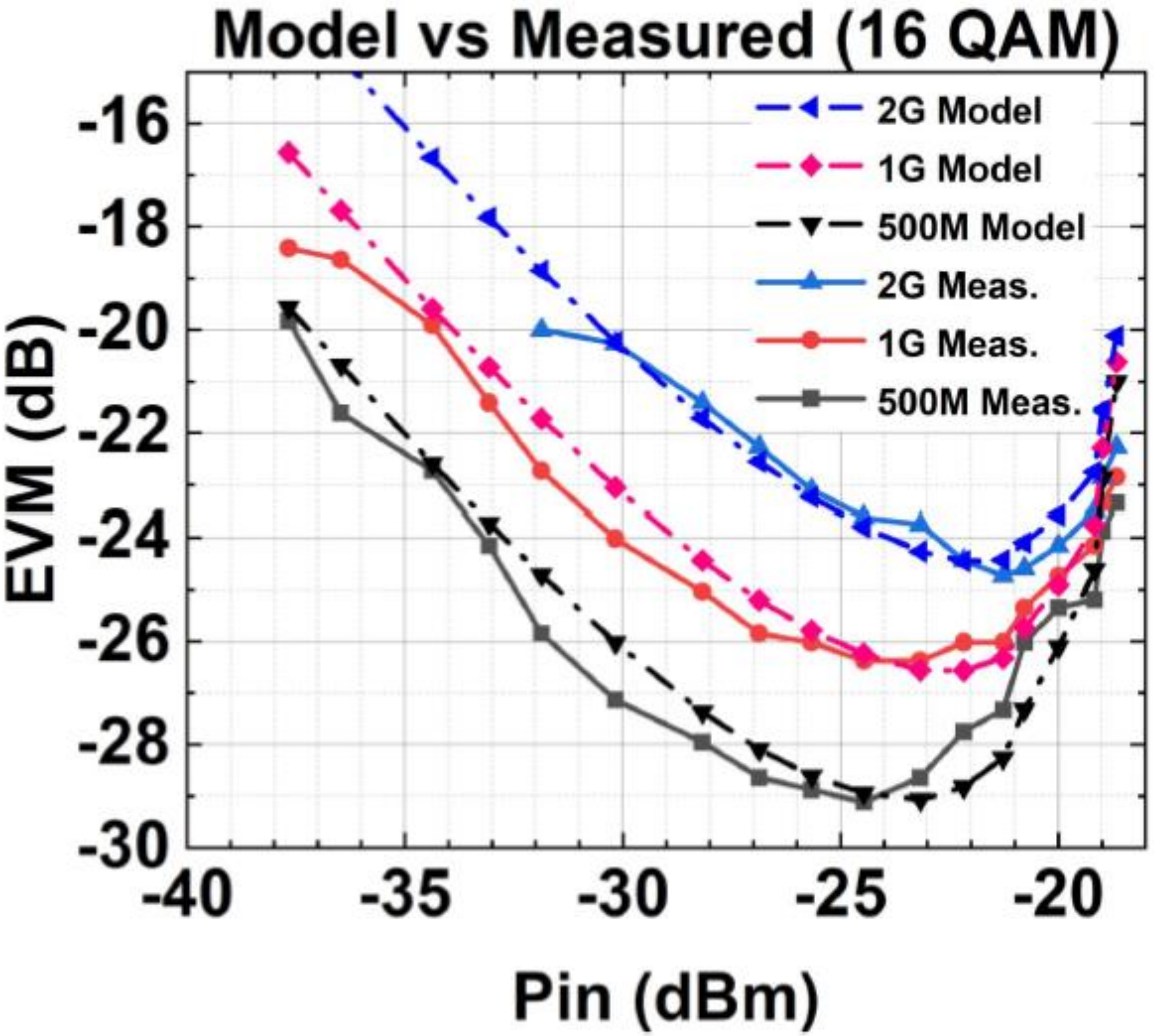
Comparision with State of the Art



EVM @300GHz – sliding IF RX

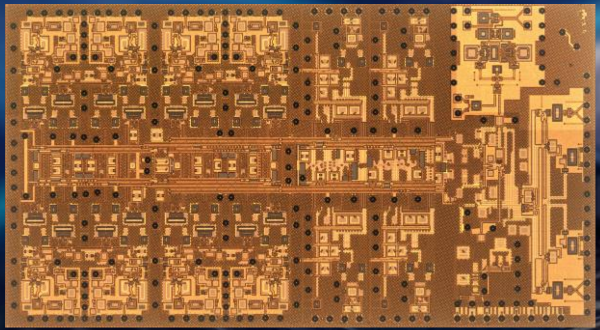


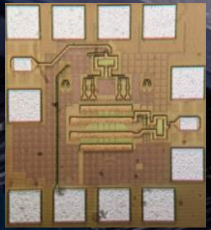
EVM @300GHz – sliding IF RX

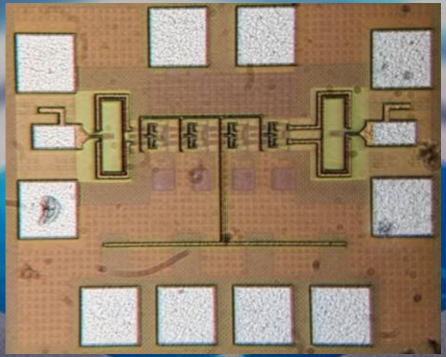


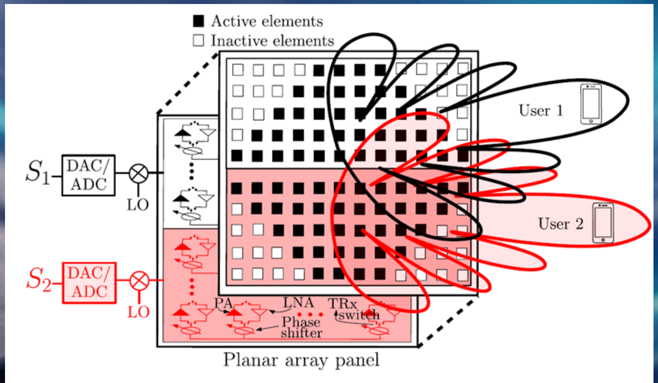
5G NR: 64 QAM, 800 MHz (0 IF)

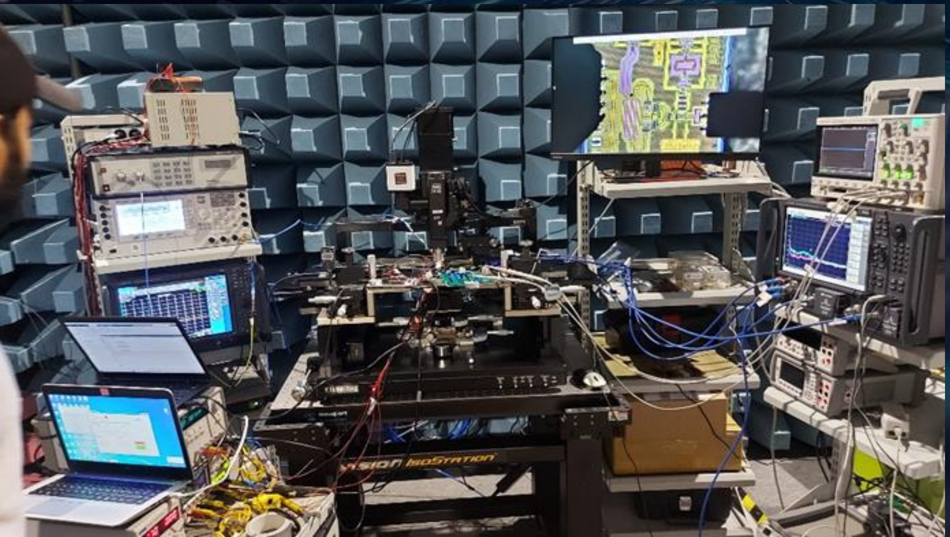
Hardware enabling communications and sensing

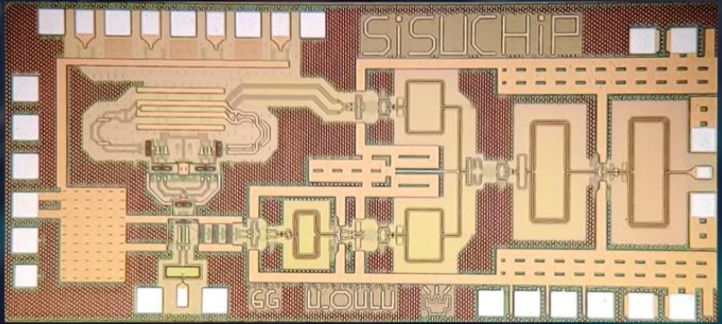


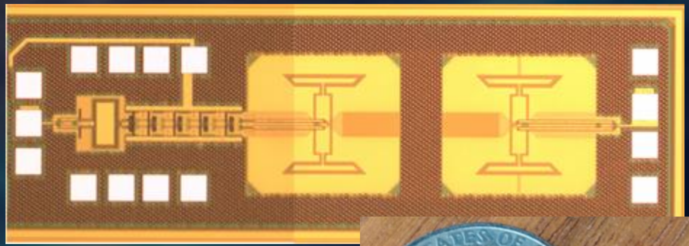






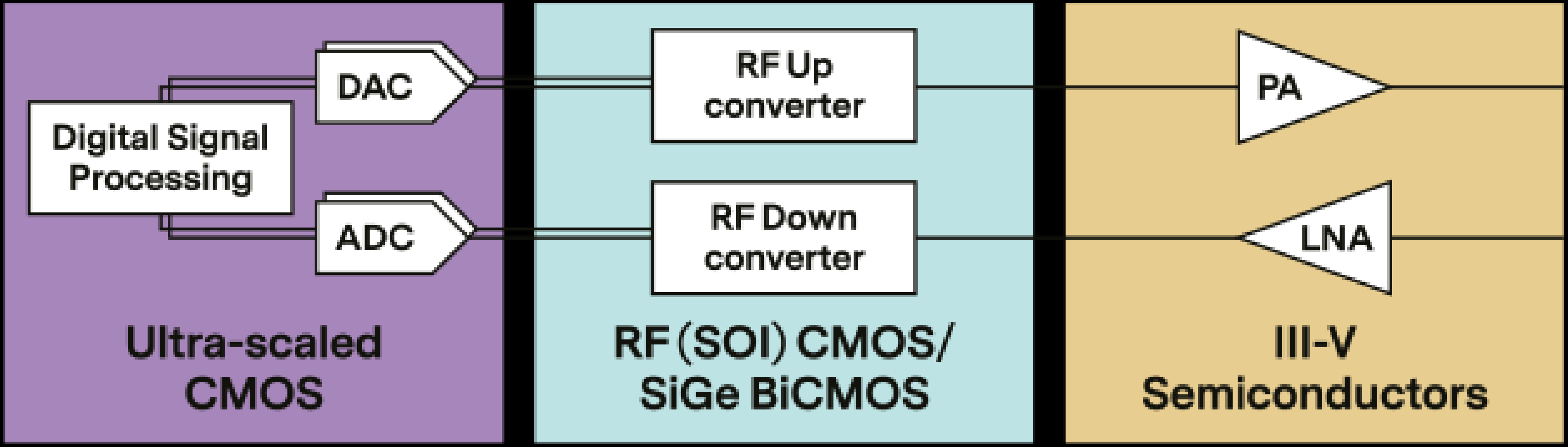






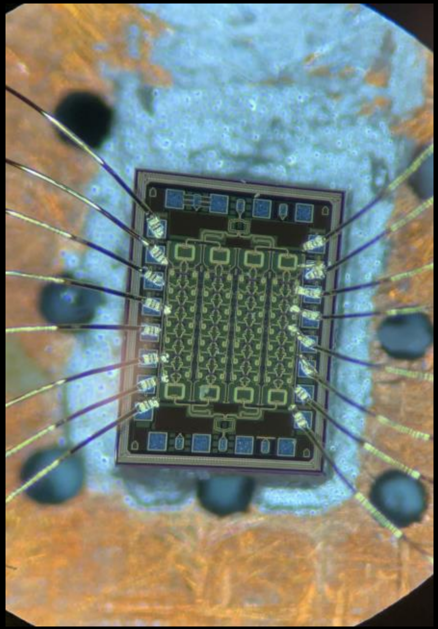
The Best Technology for Every Component?

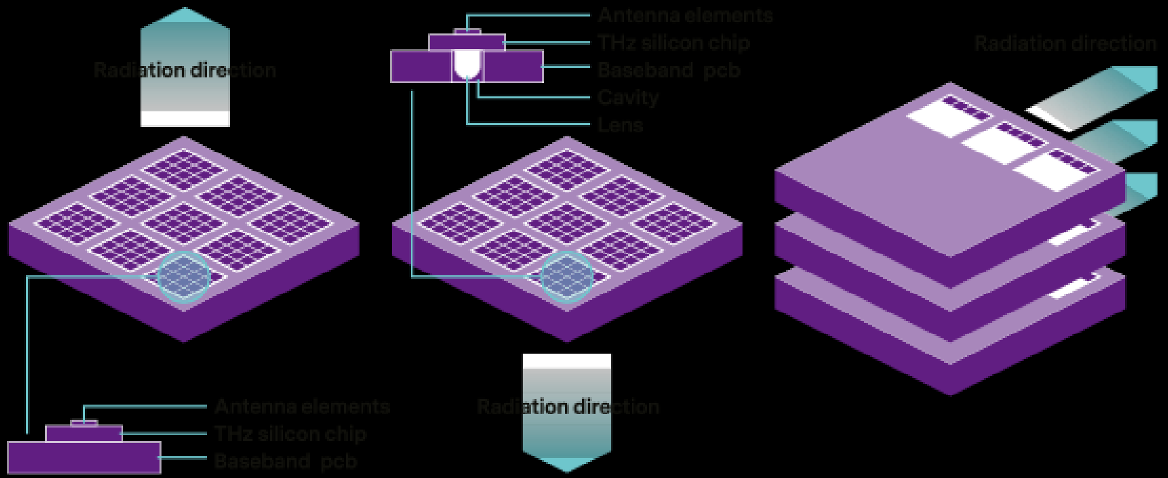
- Heterogeneous integration / 3D packaging / Chiplets

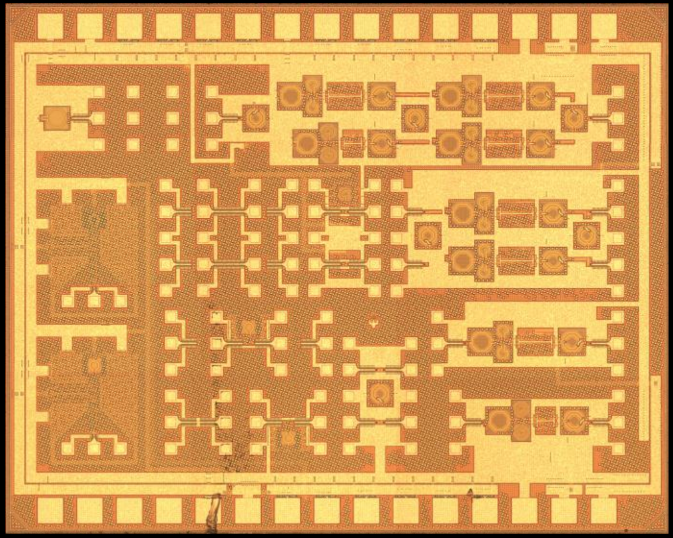


What? When? How?

- Technology will not automatically take us forward
- Multi-disciplinary perspective
- **HW aware (or even friendly) protocol design for 6G whatever the frequency will be**
- New use cases will come - after enablement

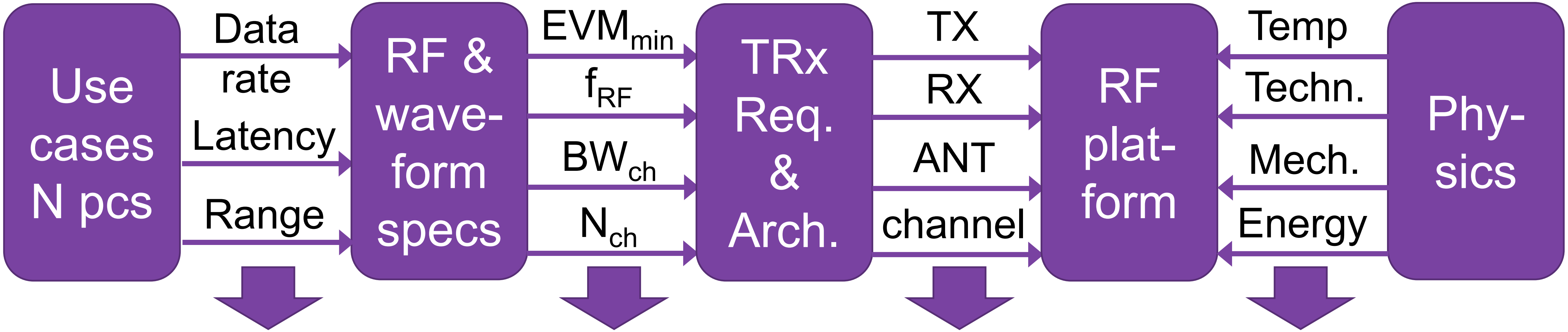


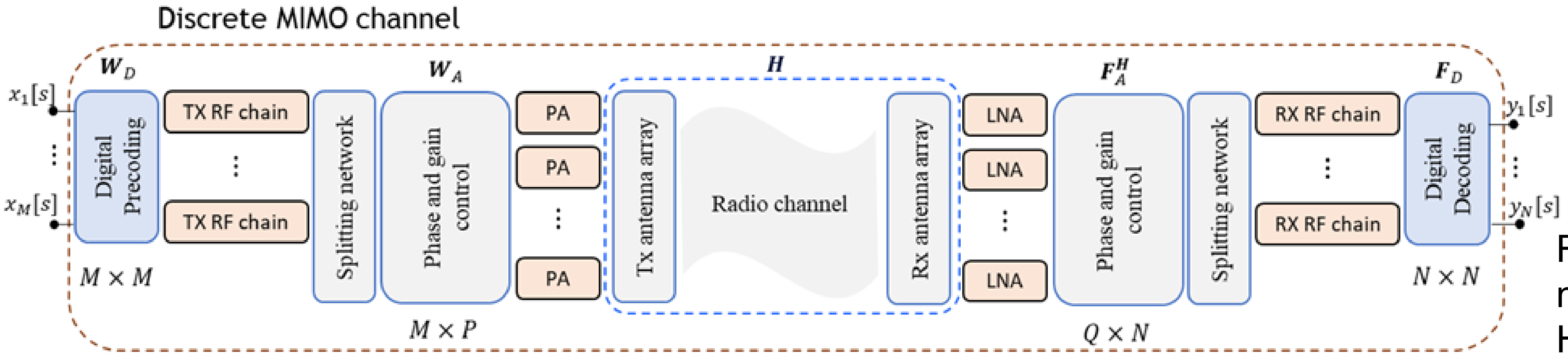




Simple when complex?

- MBSE: Layered and structured design and interaction





RF system model Hexa-x

Towards 6G

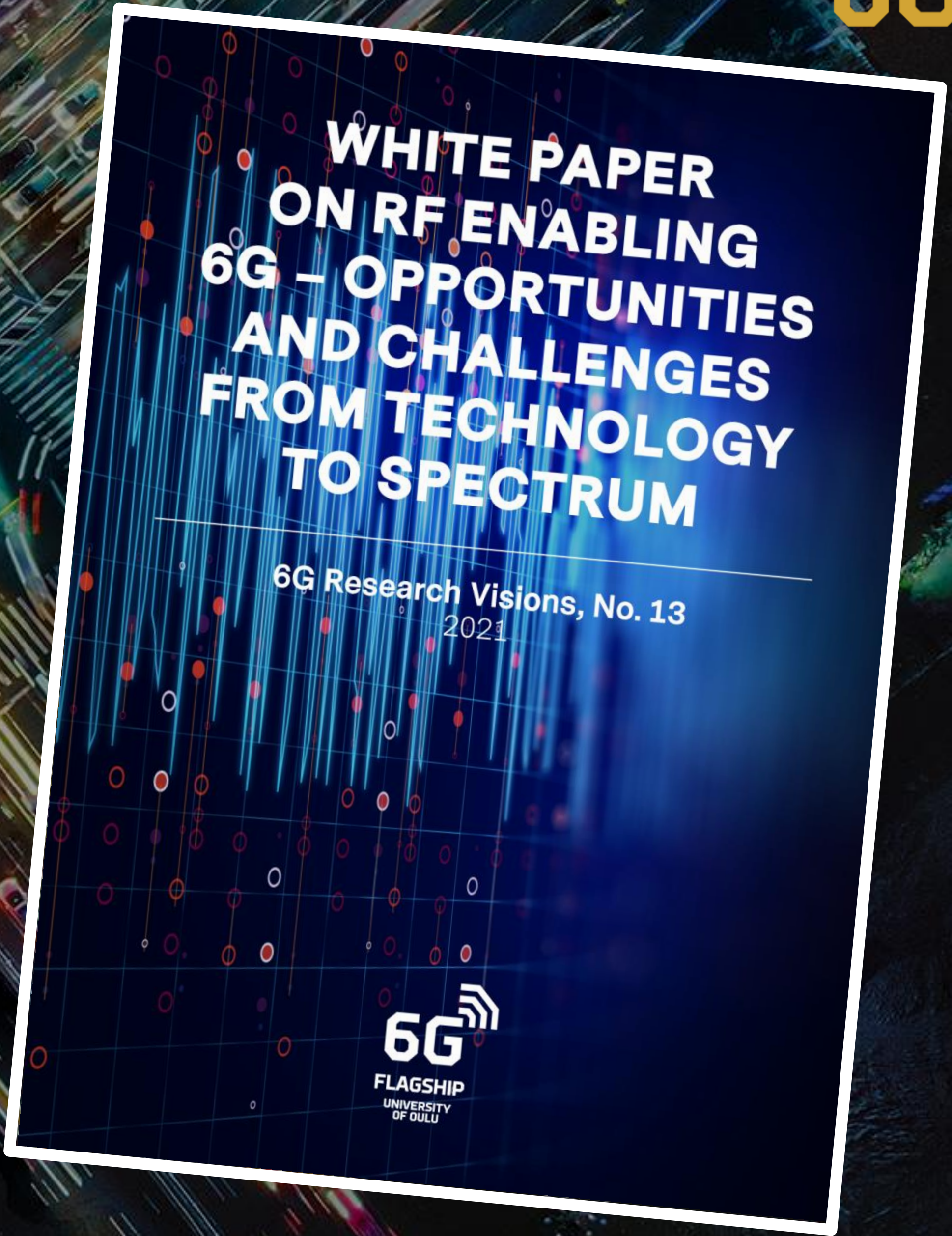
- Entropy tends to increase from business to technology
- Take all out from existing and make it better
- Create something that is not obvious
- Role of AI in HW?
- RF TO LOOK IDEAL ????

6G ?

What will be finally picked to 6G standards?

Vision

6gflagship.com



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