Designing 6G radios – challenge for RF?

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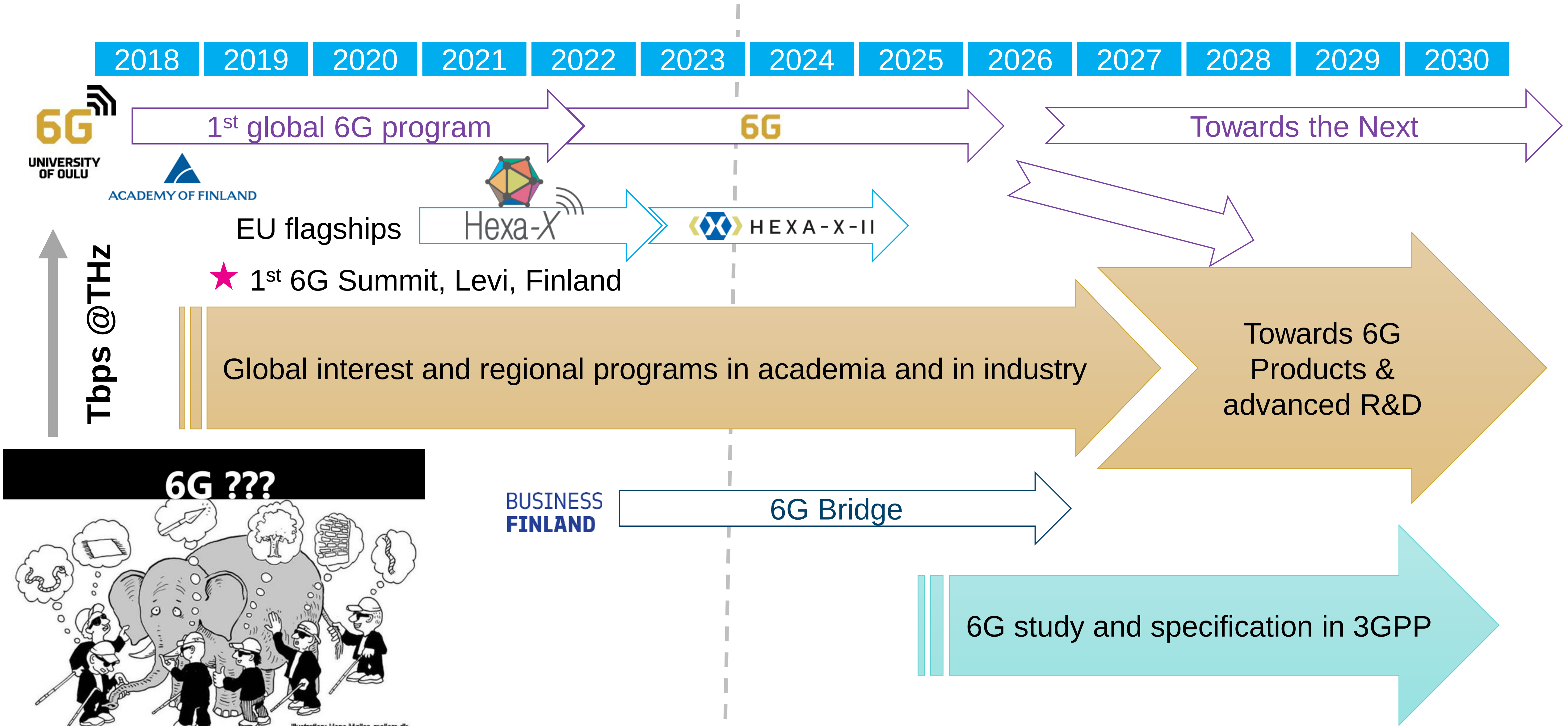
6G FLAGSHIP UNIVERSITY OF OULU

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?

Evolution of 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

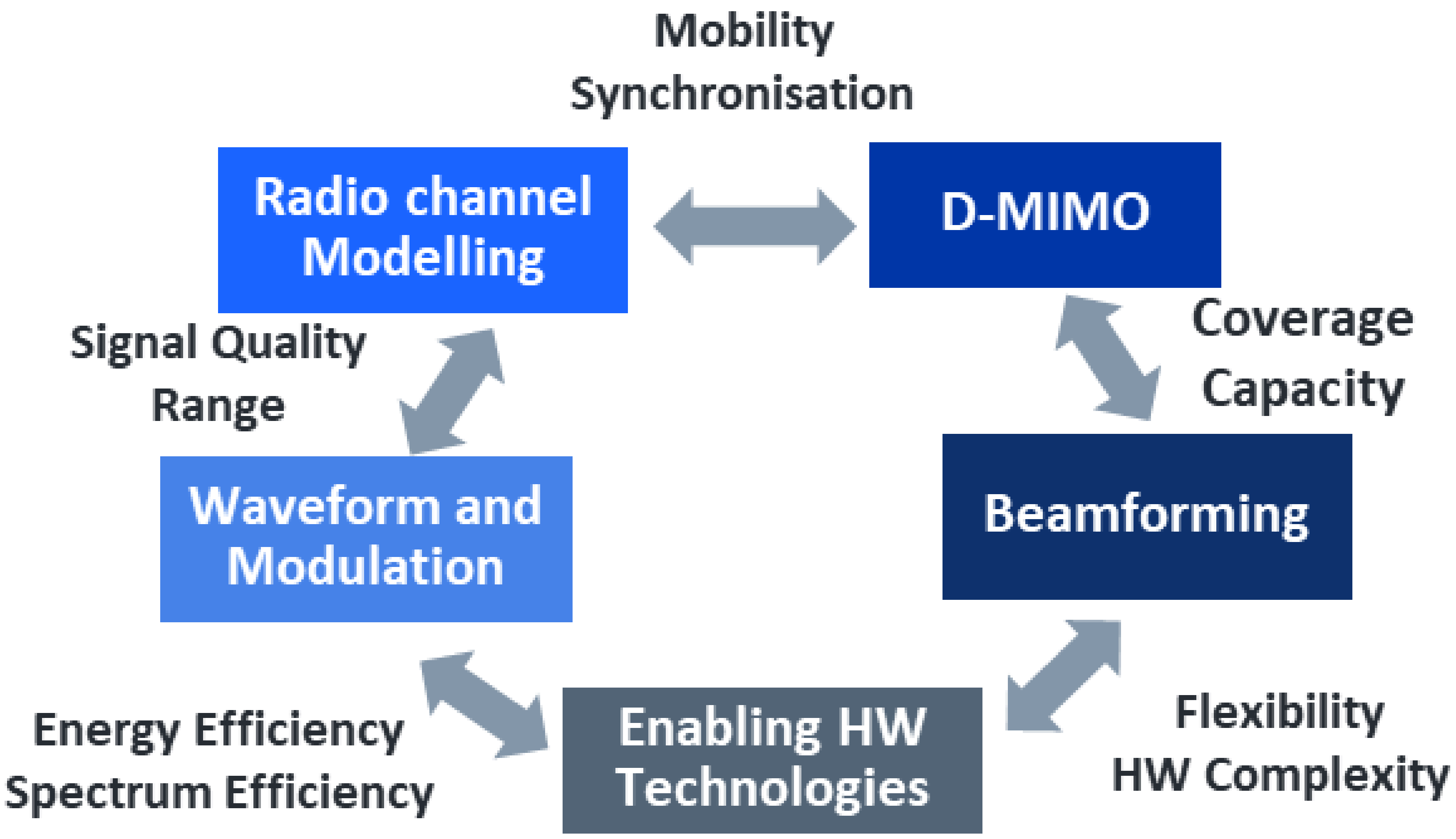
- 6G key technologies by Nokia

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

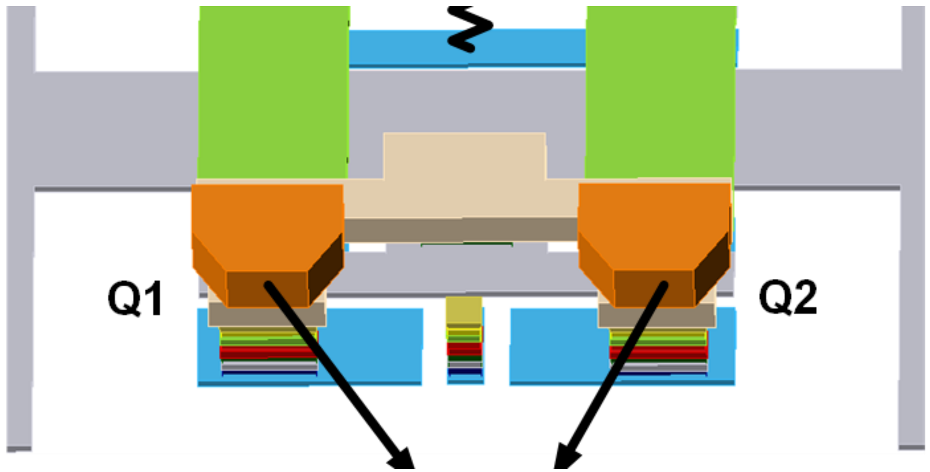
Nokia Bell Labs, “Envisioning a 6G future”

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

Hexa-x Radio performance towards 6G
- seemingly infinite capacity and data rate



From devices to wireless systems

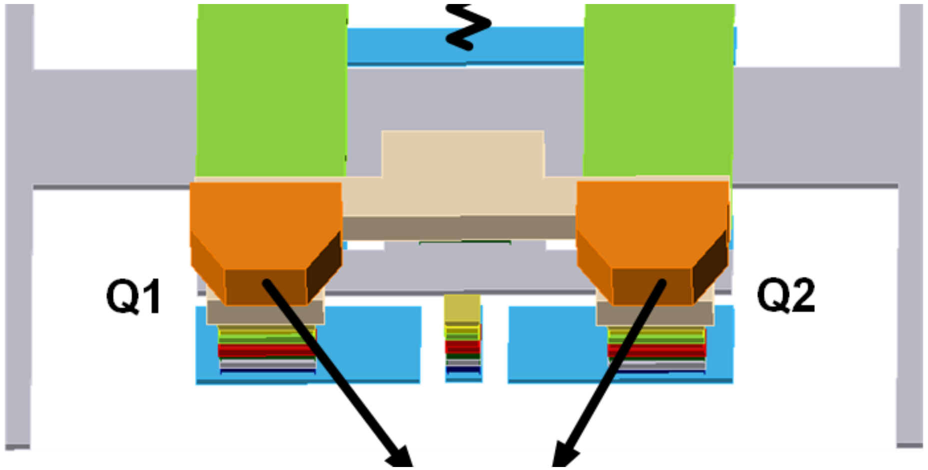


vs.

From devices to wireless systems

vs.

From devices to wireless systems



vs.

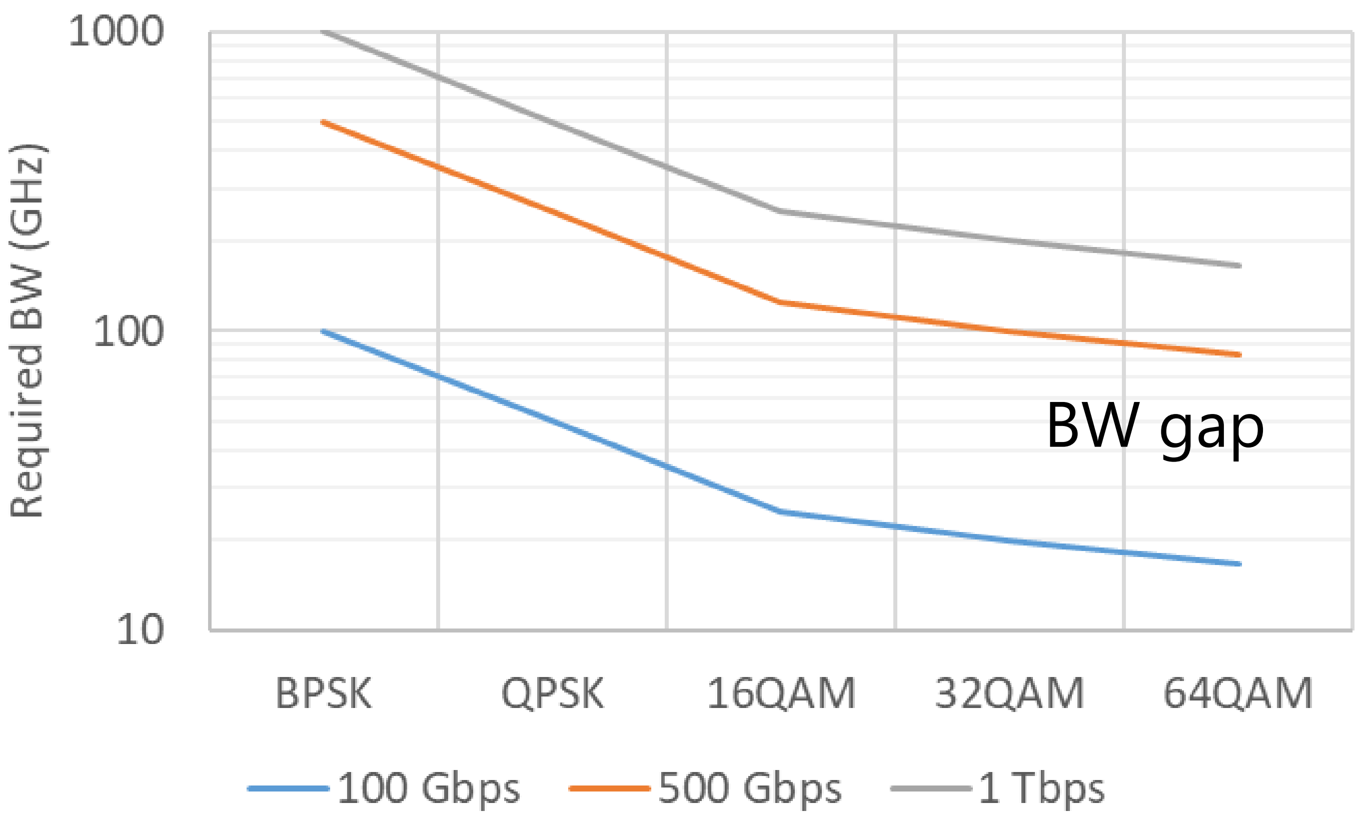
Initial Requirements for 6G Radio

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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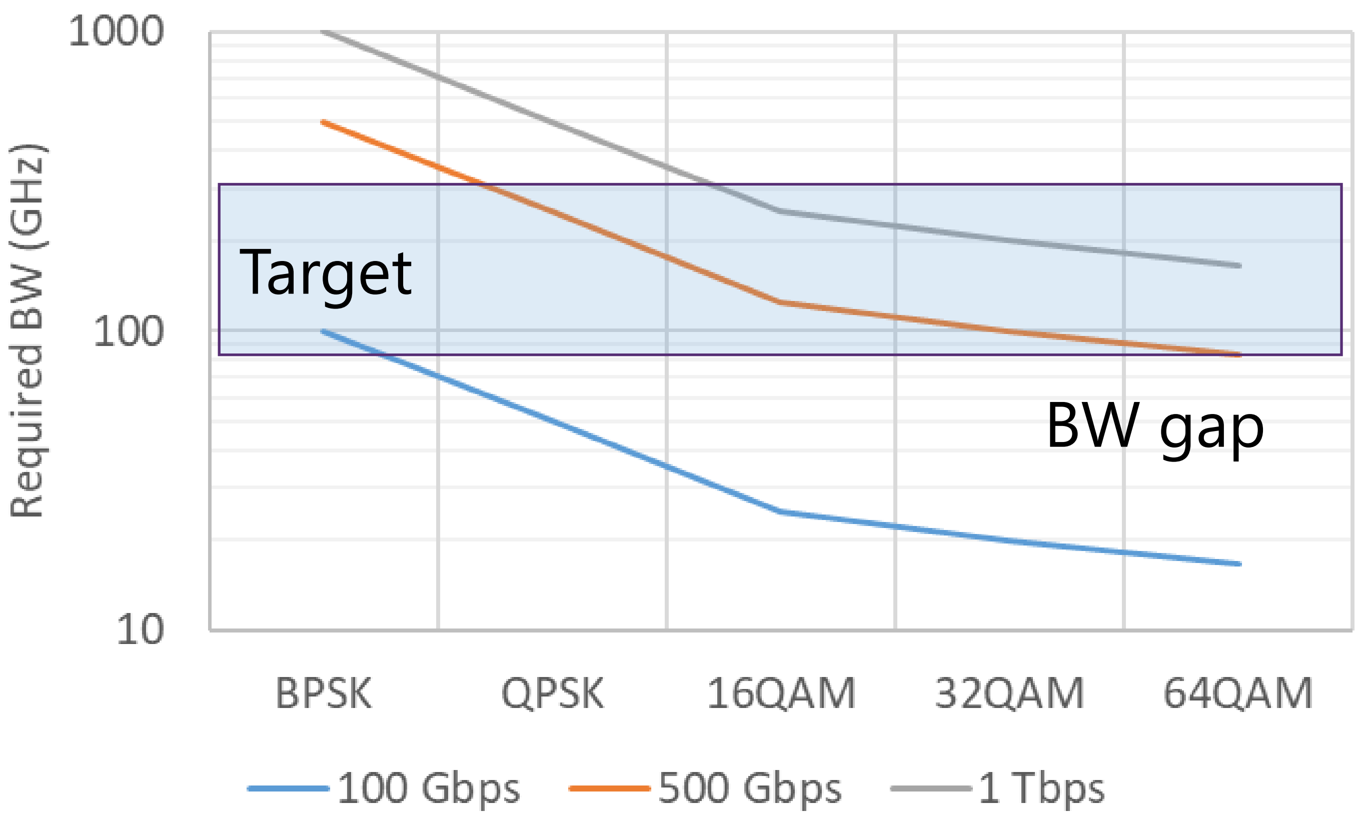

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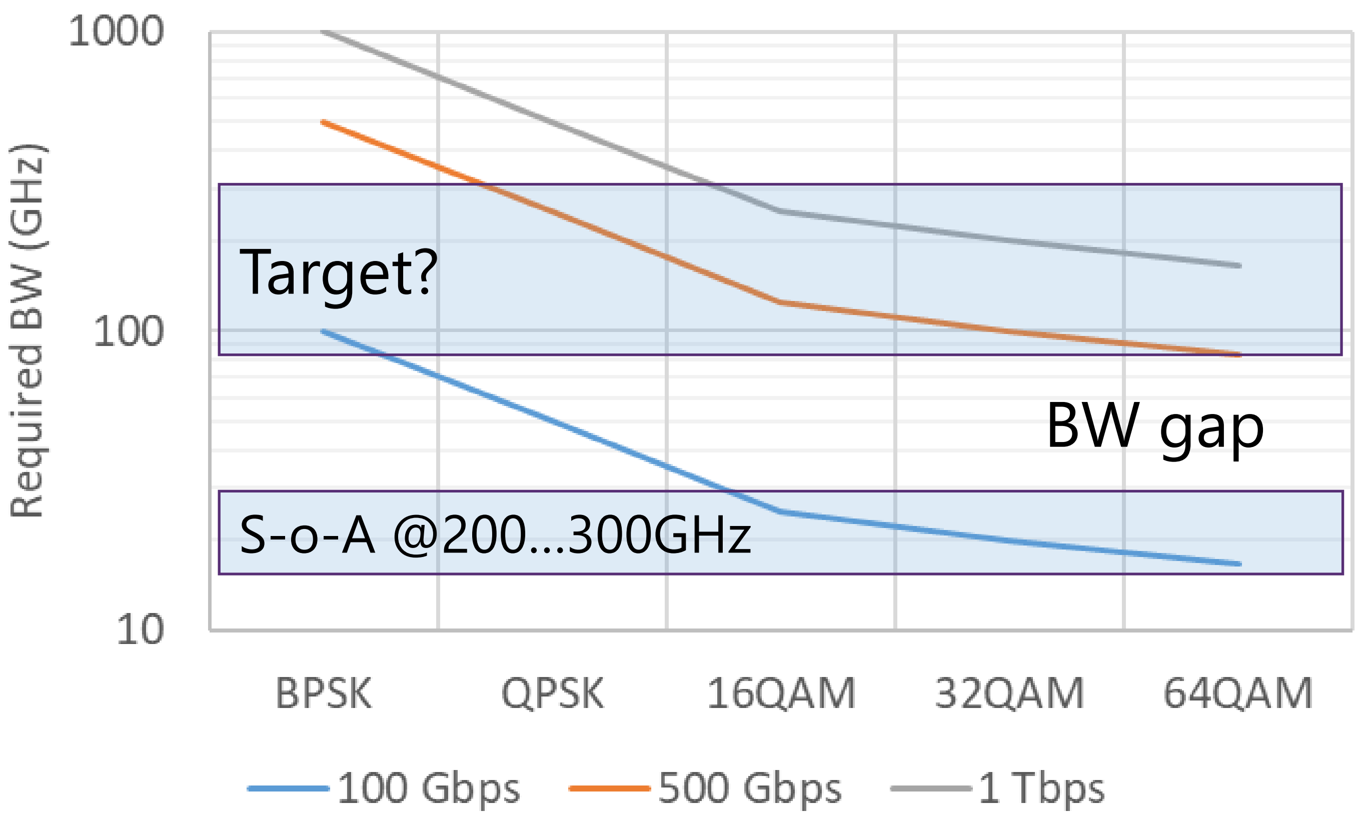

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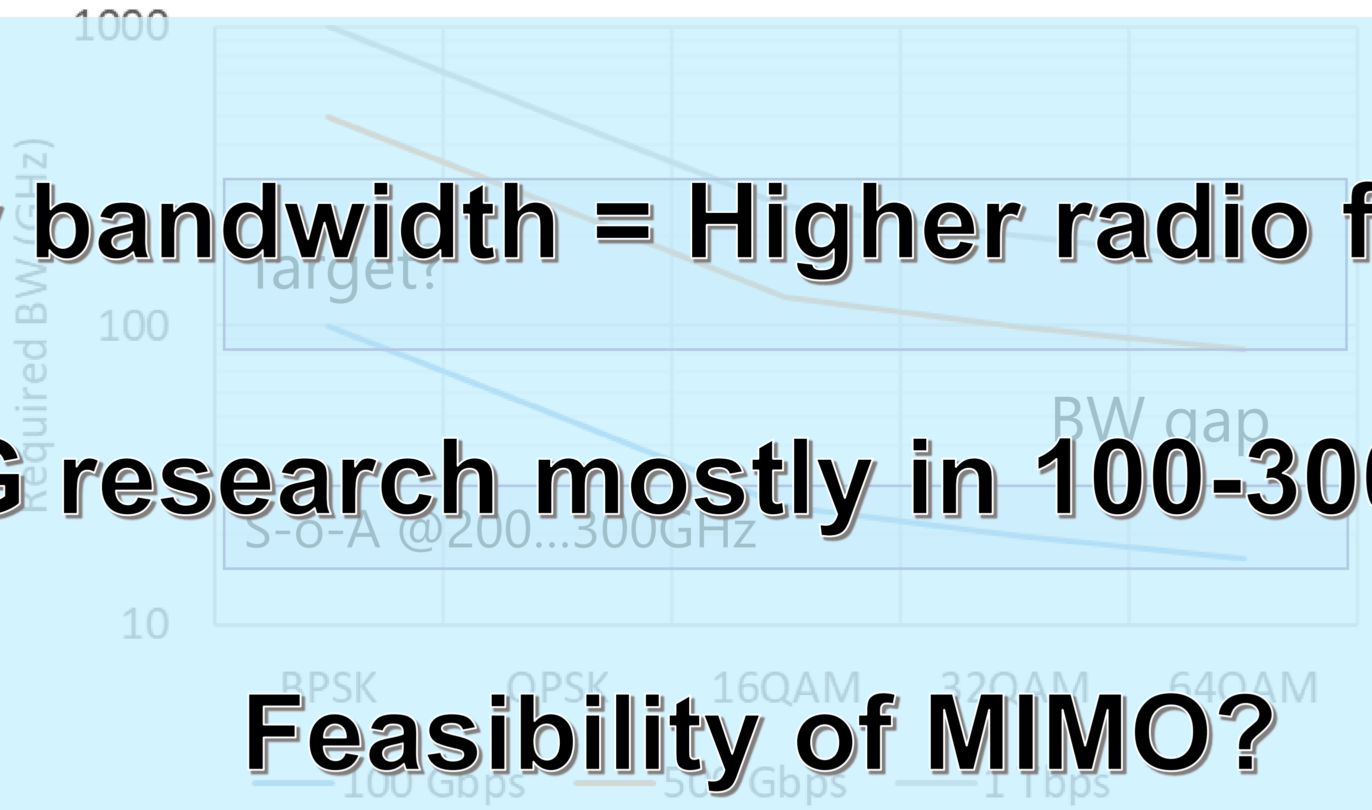


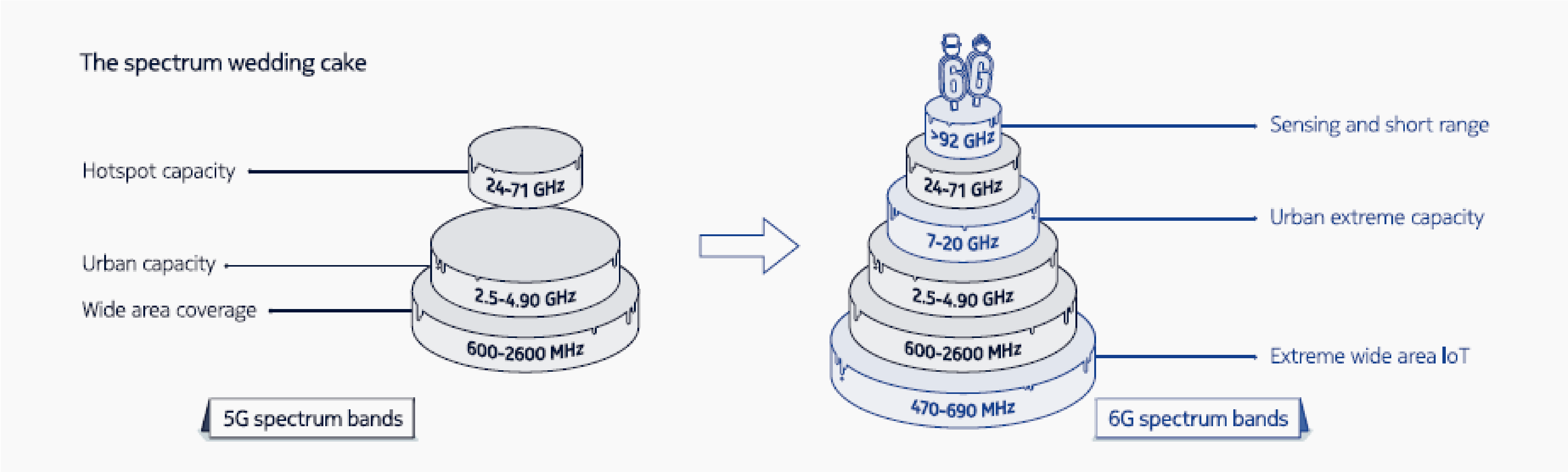
Larger bandwidth = Higher radio frequency

6G research mostly in 100-300GHz

Feasibility of MIMO?

What about realism?

- Most challenging use cases in ~100 Mbps…10 Gbps range
- Many of those 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

Do we finally need Tbps?

Size of object + resolution — Number of 'pixels' required in occupied volume

Block size of hologram after processing scan — In Mbits or Gbits depending on algorithm. 'Full parallax' requires much larger blocks

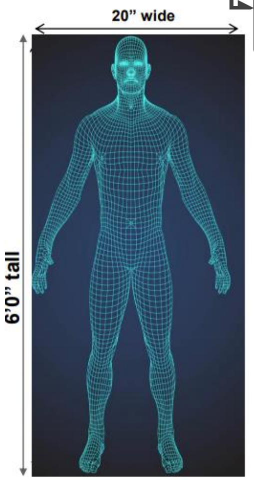
Color depth required — Say 24-bit color

Frames per second (fps) — 60 fps for smooth movement

+ measures to reduce speckle — 24 frames with random phase offset

=

Raw Data Rata before any compression



- 3" high 3D object (150M pixels), color, full parallax, 60 fps = 10Gbps*
- 10" high object, color, full parallax, 60fps = 60Gbps*
- **6' high full-size human = up to 4.3Tbps**

With 30GHz available spectral BW, using 16QAM waveform and 4 spatial streams, the max data rate we can achieve is (ignoring spectral efficiency etc):

30GHz x 4bits/Hz x 4 = **480Gbps** (over the air)

* X. Xu, Y. Pan, P. P. M. Y. Lwin and X. Liang, "3D holographic display and its data transmission requirement", *Proc. Int. Conf. Inf. Photon. Opt. Commun.*, pp. 1-4, 2011.

credit to Keysight

What about realism?

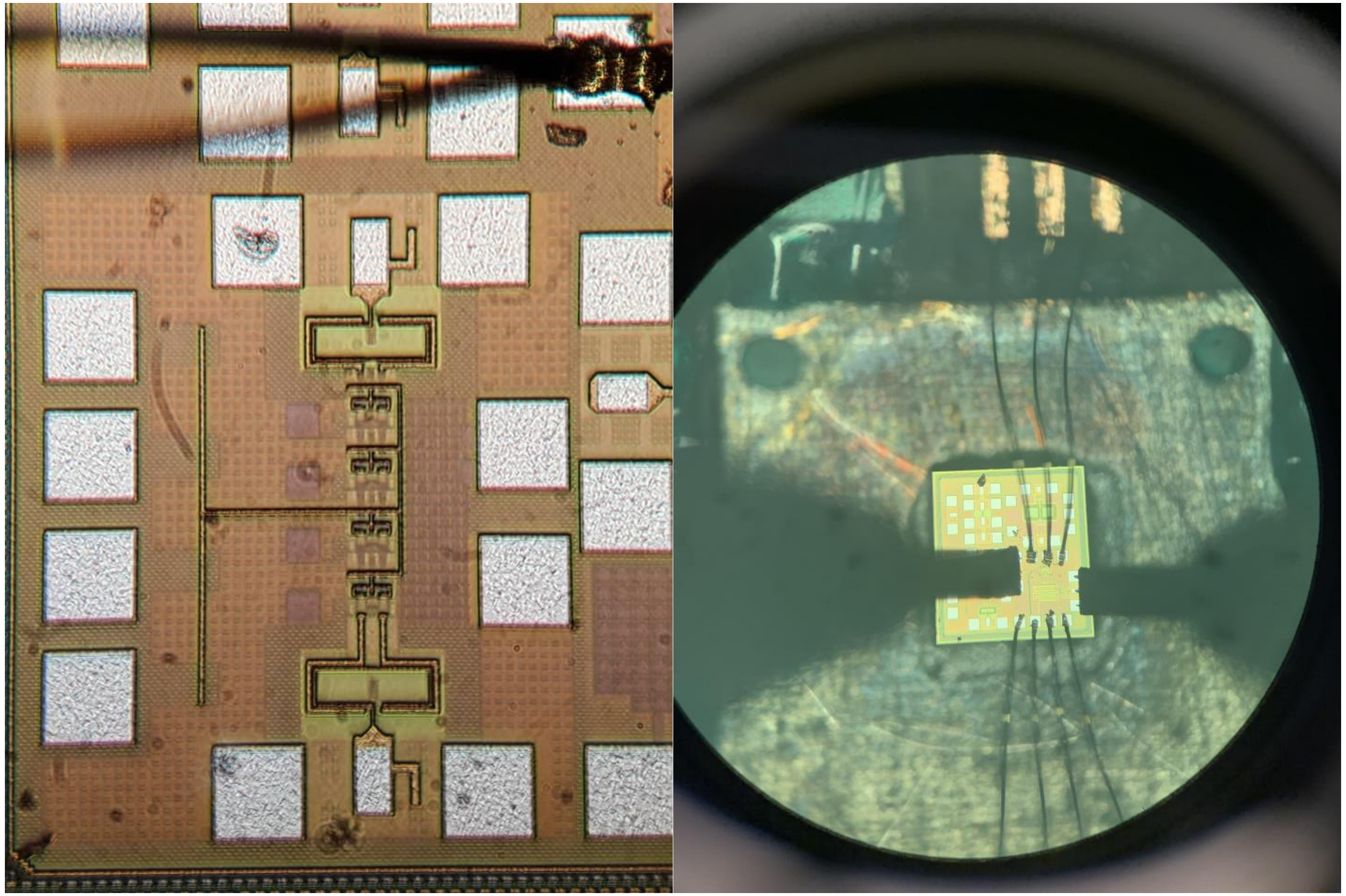
- Extreme speed and capacity?
- Minimalism?
- Ultimate scalability?

ALL OF THAT, THANK YOU!

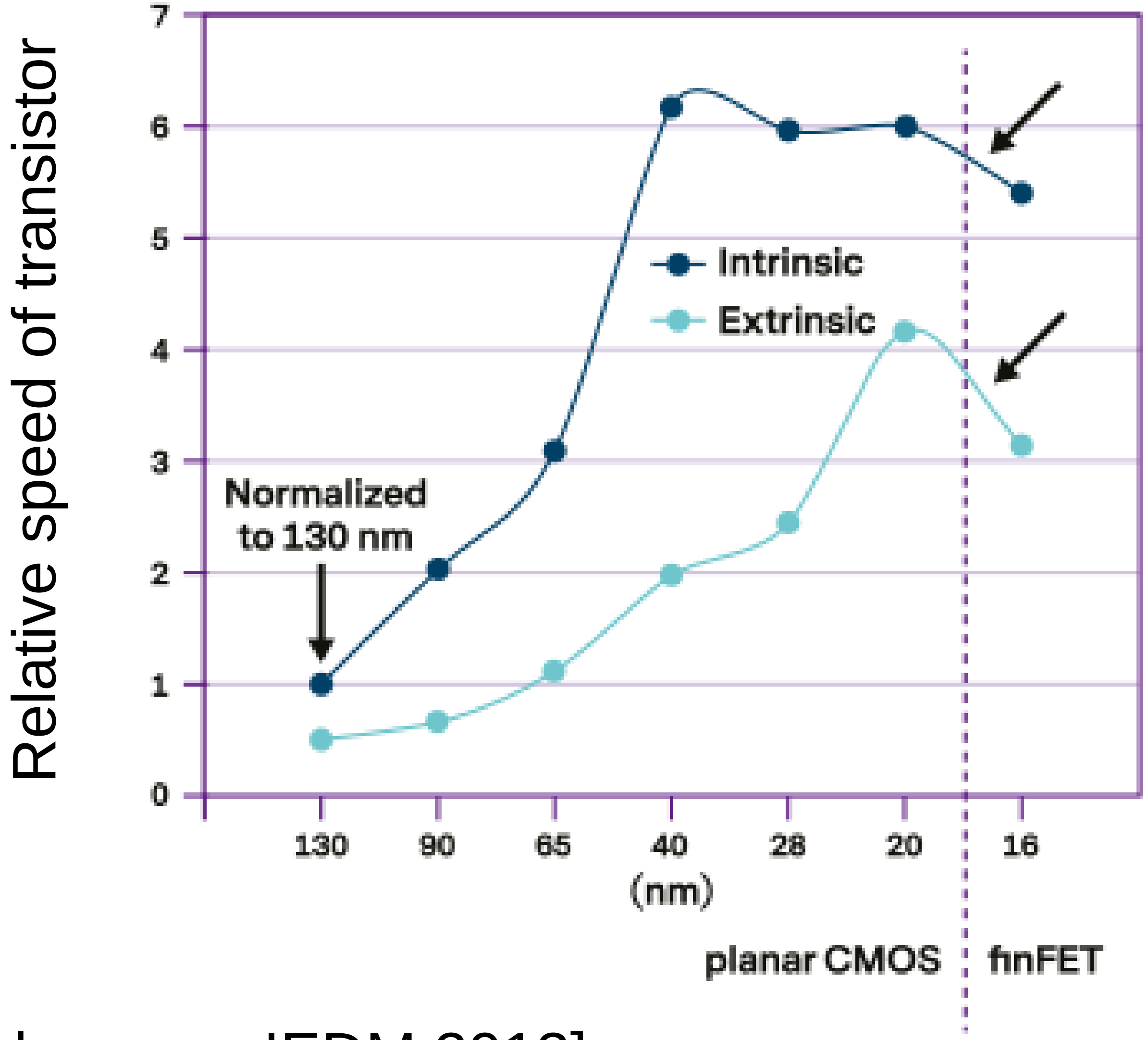
- With minimal complexity, power consumption and price?

Enablers for wireless era

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

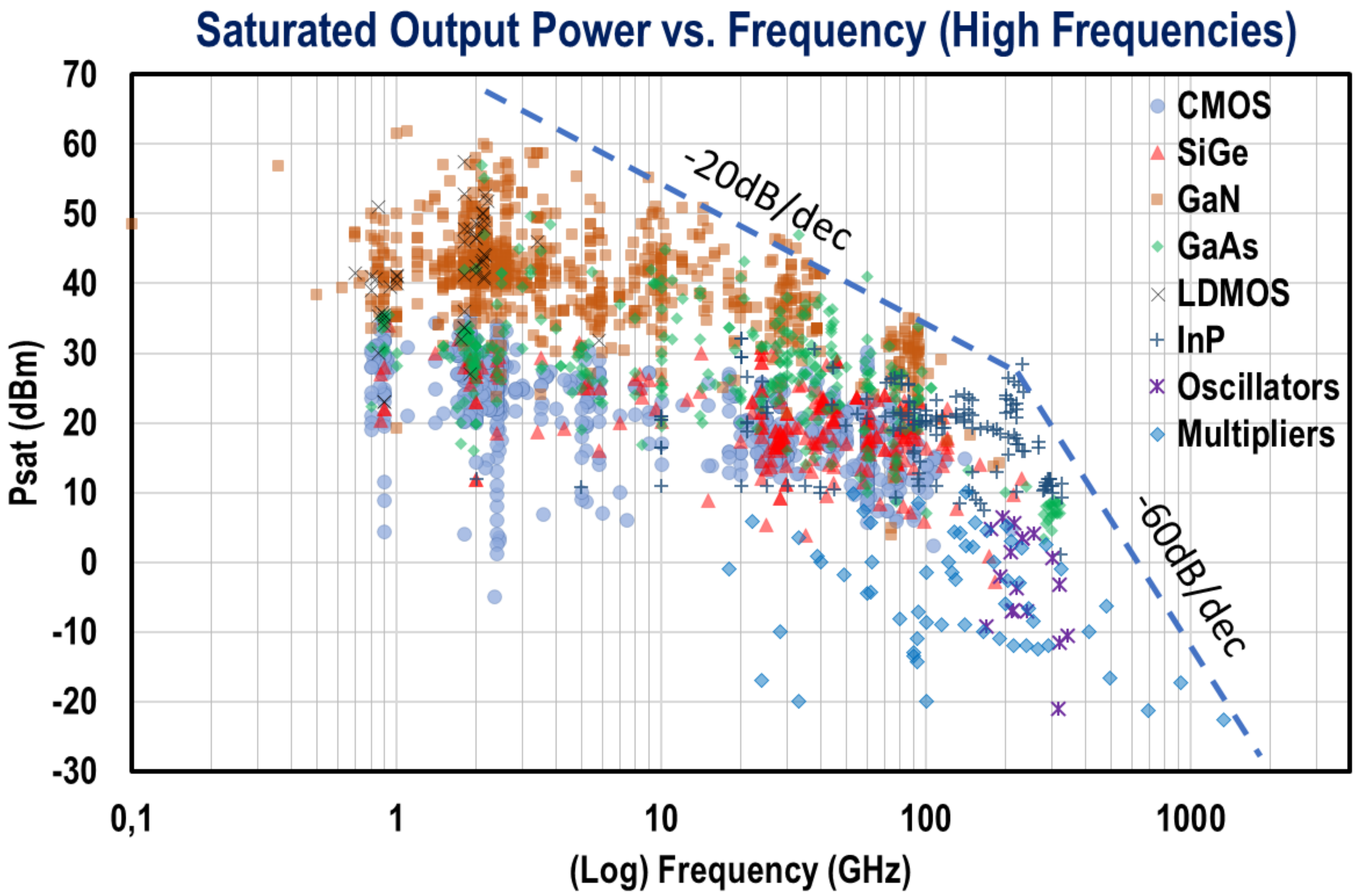


Semiconductor scaling not anymore generally granted



[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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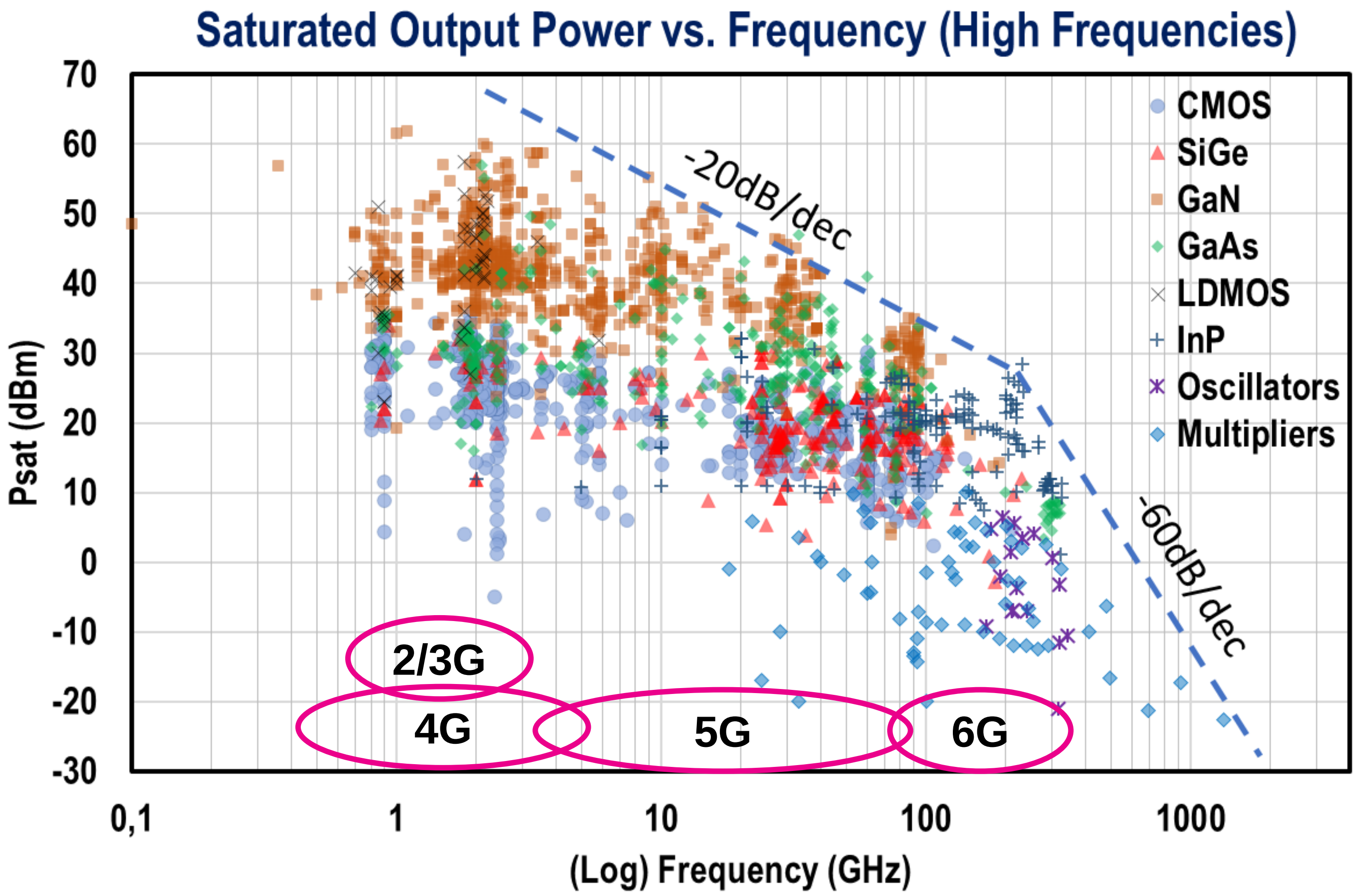
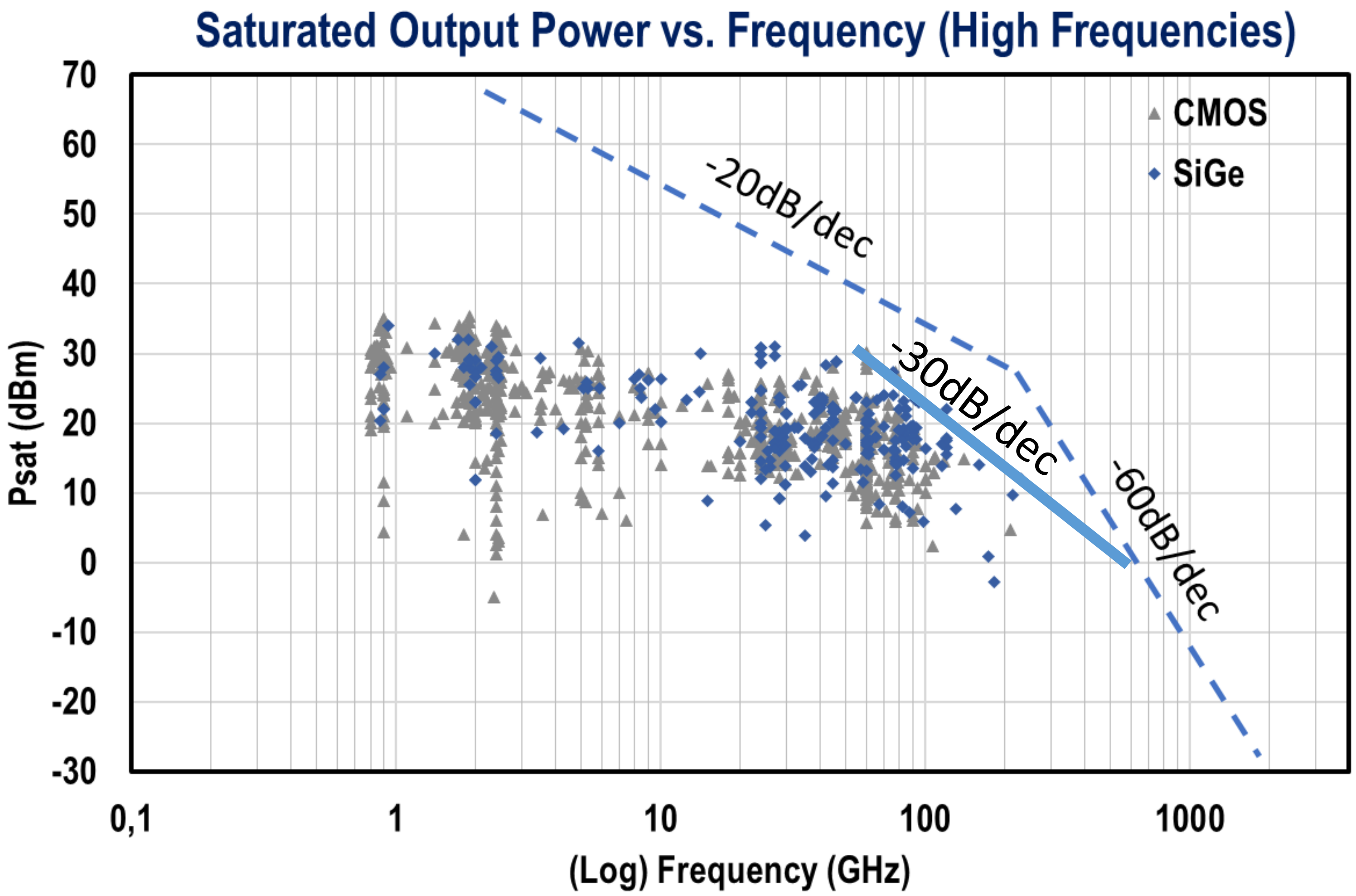


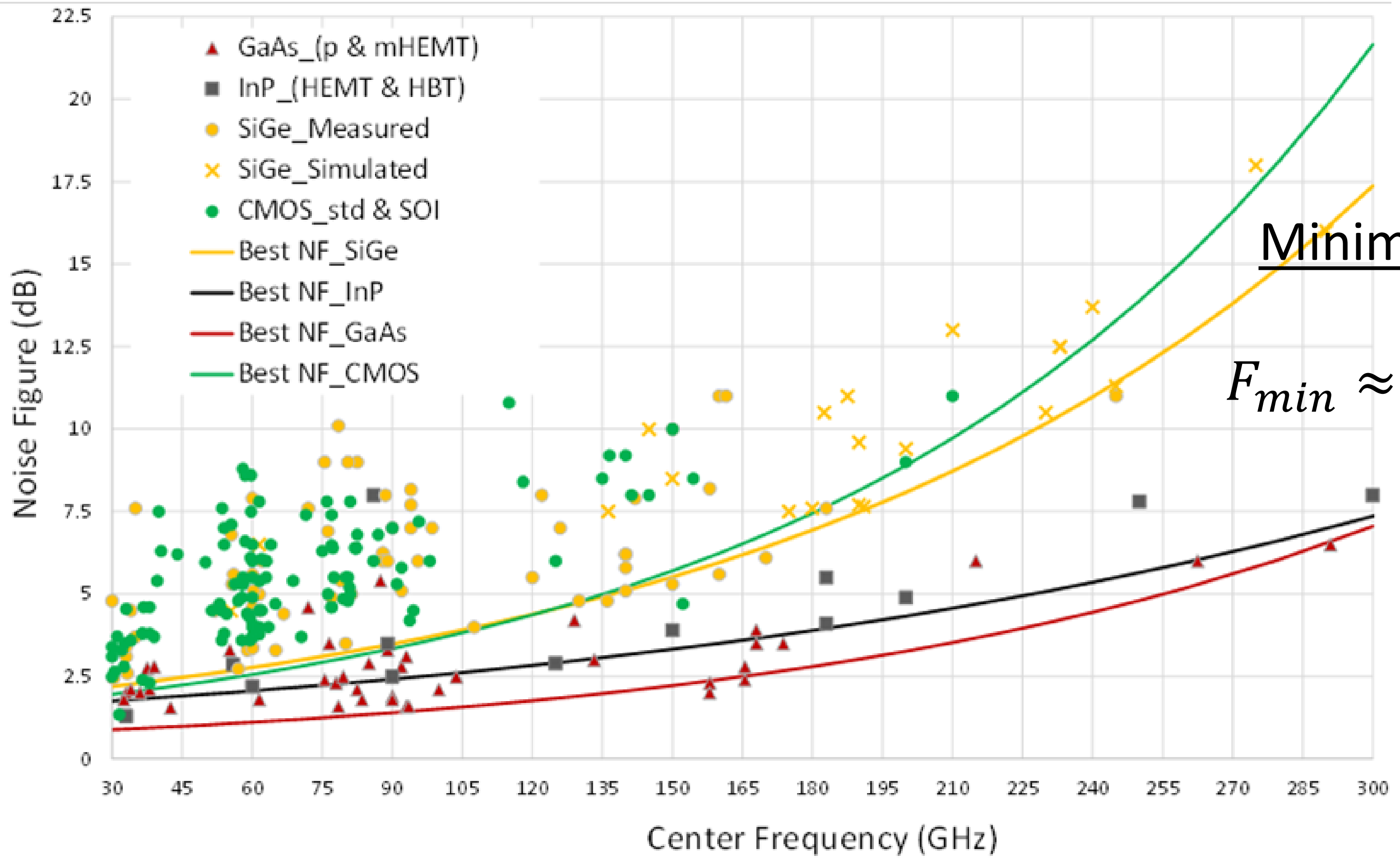
[H. Wang, et al., "Power Amplifiers Performance Survey 2000-Present," online] Available: https://gems.ece.gatech.edu/PA_survey.html

Output power – silicon



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

Performance Limits of LNAs



Minimum noise of a single transistor

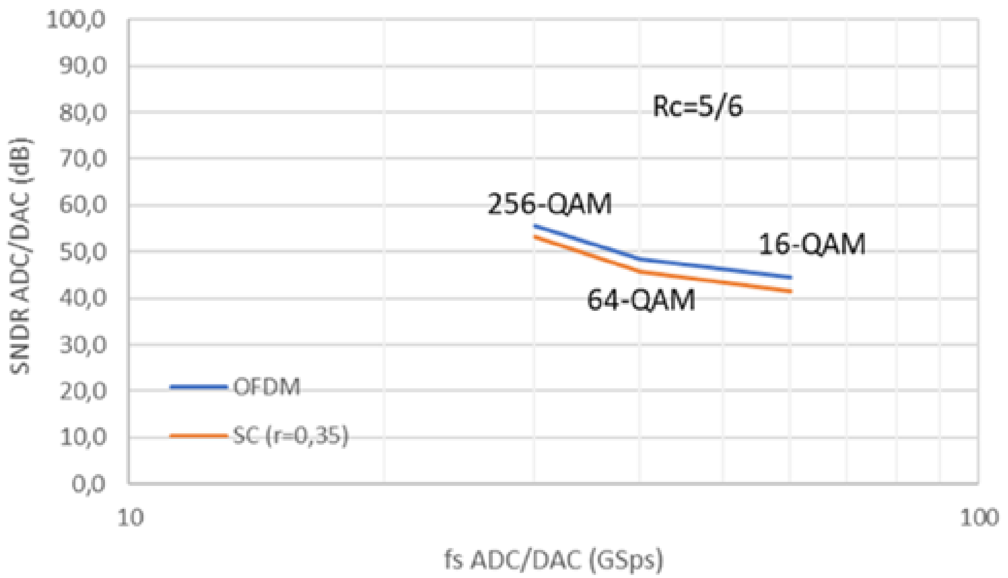
$$F_{min} \approx 1 + K \cdot \frac{\omega_0}{\omega_T} \sqrt{g_m(R_g + R_i + R_s)}$$

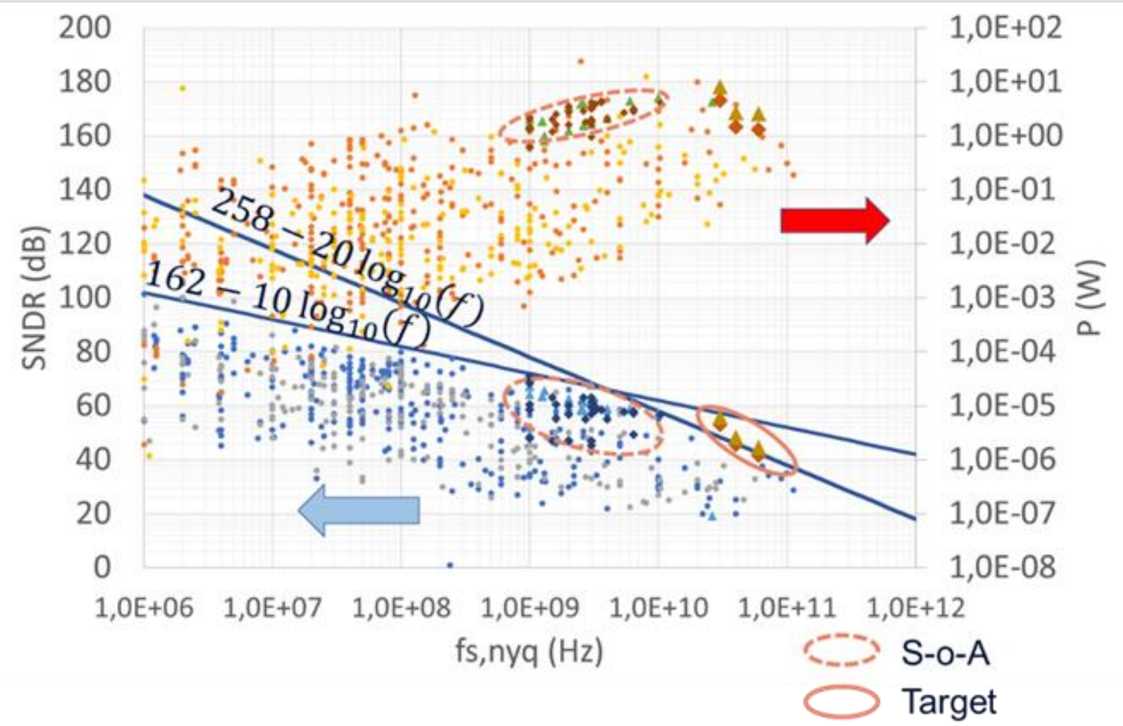
$$\approx 1 + 2.3\left(\frac{\omega_0}{\omega_T}\right)$$

[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

ADCs for 6G signals

1-10W per ADC with SoA products





ADC dynamic range and sampling rate requirements for various combinations resulting to 100Gbps data rate

ADC dynamic range (SNDR) and power consumption (P) is compared to ADC dynamic range requirements for the OFDM and CW waveforms

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

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

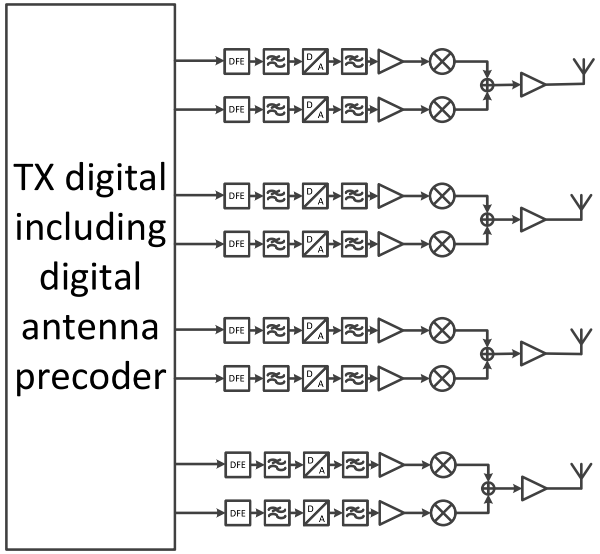
Parameter	Unit	LTE 20M	5G NR 200M	6G 20G?
Occupied BW	MHz	18.015	200	20000
Nth	dBm	-101	-91	-71
Modulation		64-QAM	64-QAM	64-QAM
Coding		1/3	1/3	1/3
Data Rate	Gbps	**0.036**	**0.4**	**40**
RX, SNRmin (with coding gain)	dB	**19.2**	**19.2**	**19.2**
Carrier Frequency (DL)	GHz	2.65	28	200
M_I (DSP margin) - 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**

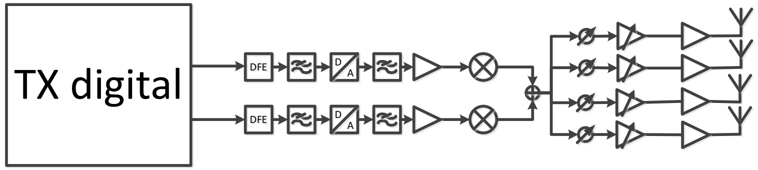
Simple (?) solution – increase antenna gain

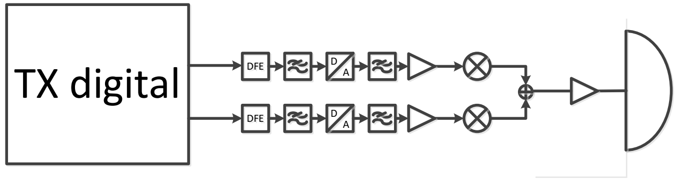
<u>MIMO</u>
- Full Flexibility
- RF & digital parallelism

<u>Phased array</u>
- Steerability
- RF parallelism per data stream

<u>Directive antenna</u>
- Large gain
- No parallelism
- Limited or no steering







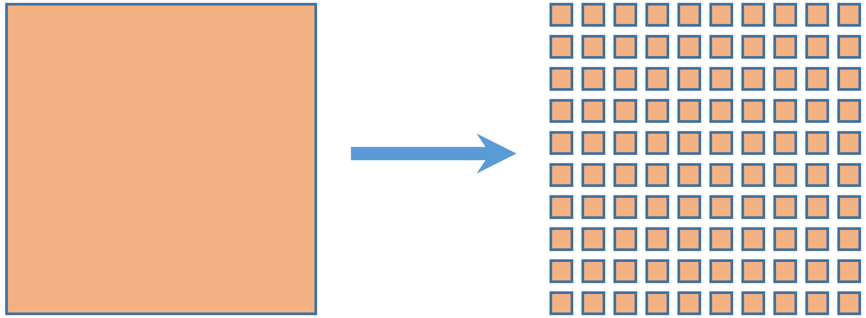
Link budget for phased arrays

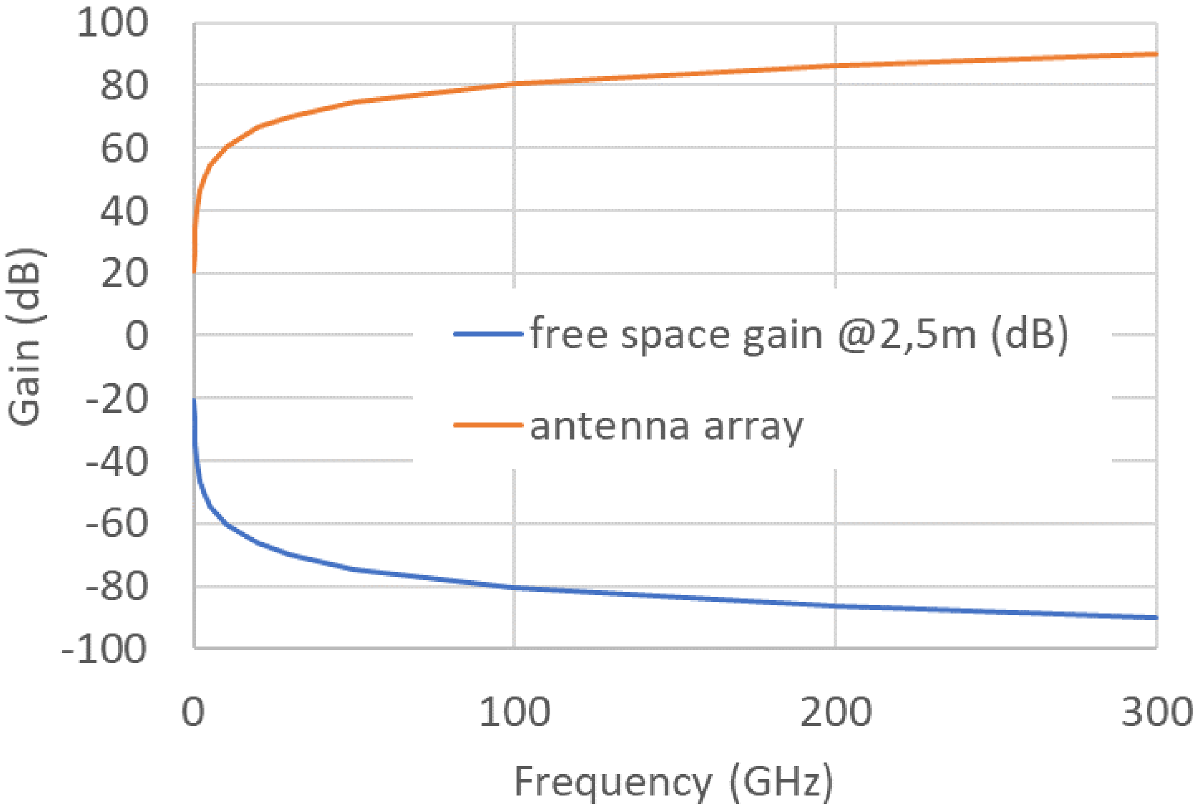
- Constant antenna aperture removes frequency dependency

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

$$G_{array} = 10\log_{10}(n_{ANT})$$

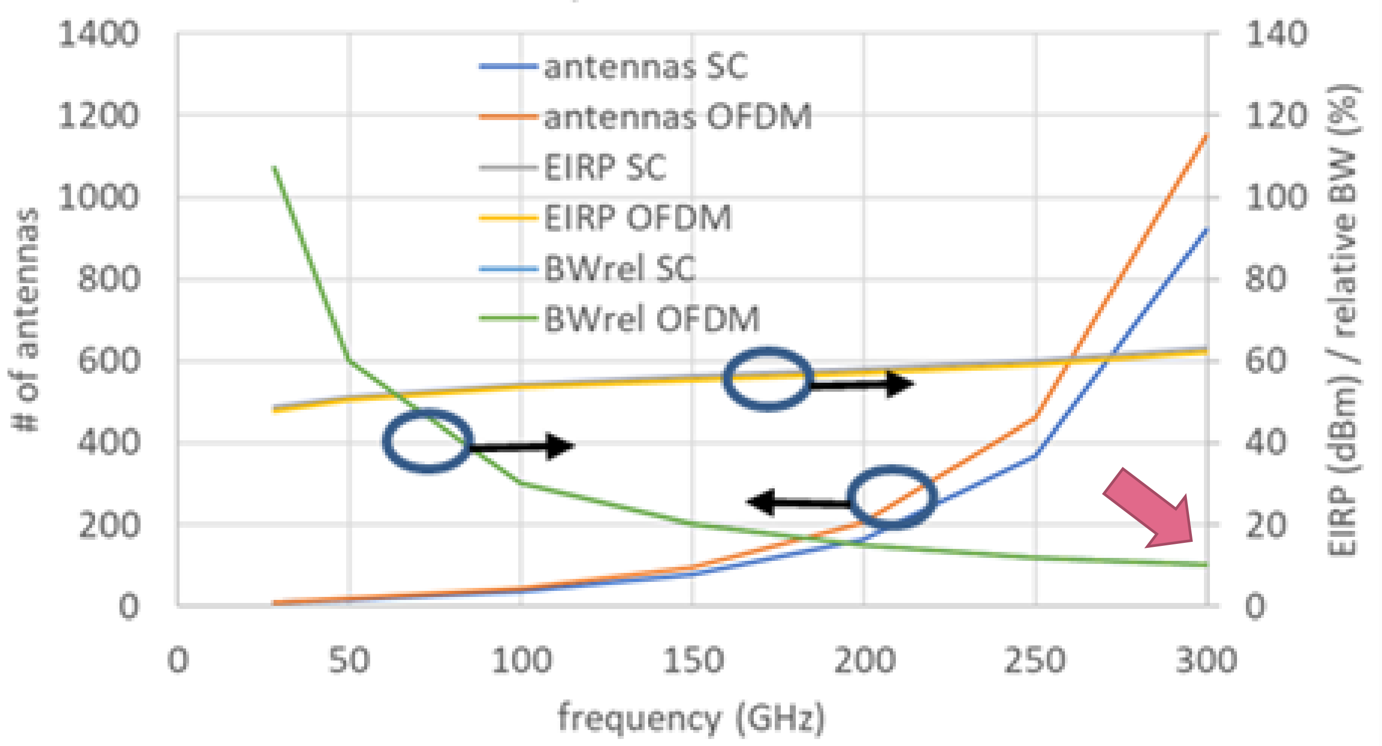
$$= 10\log_{10}\left(\frac{A}{(\lambda/2)^2}\right)$$





Impact of carrier frequency to radio performance with technology constraints

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

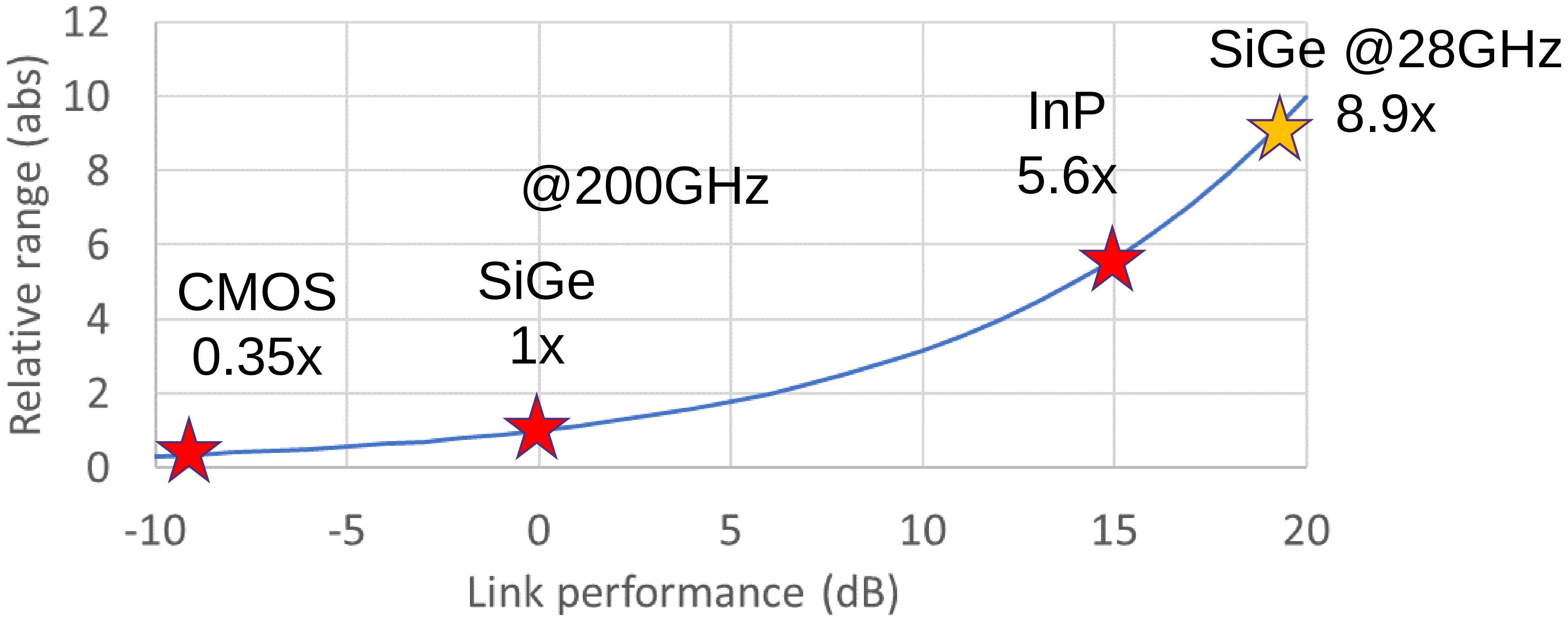


Number of antennas, EIRP and relative bandwidth as a function of frequency for 100 Gbps target data rate using single carrier or OFDM

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

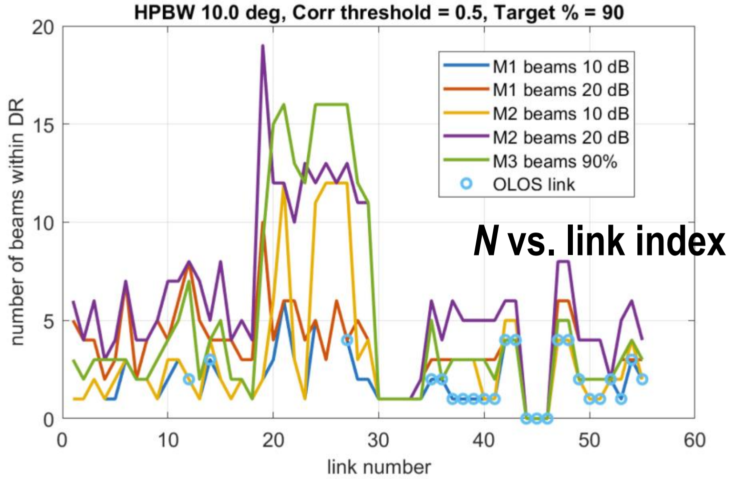
Choice of semiconductor technology?

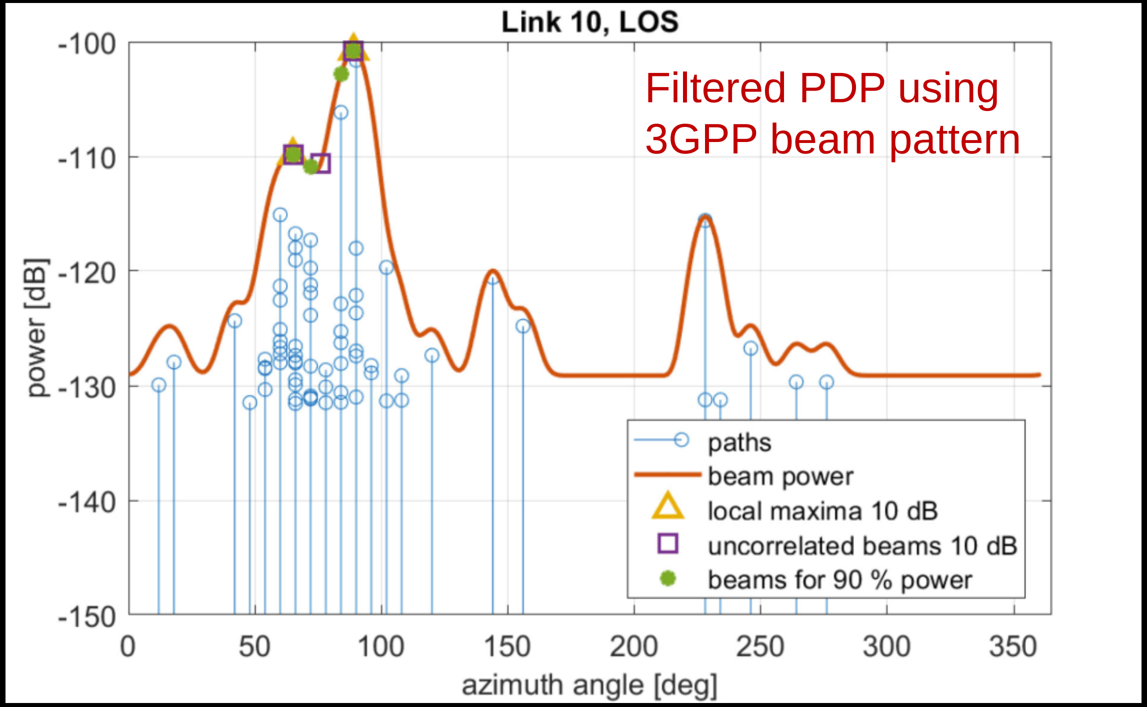
- We know the technology baseline of semiconductors towards 2030
- Being even close to 5G in 6G data rates requires
  - radical changes in our thinking
  - understanding of the semiconductors from transistors to complete wireless systems

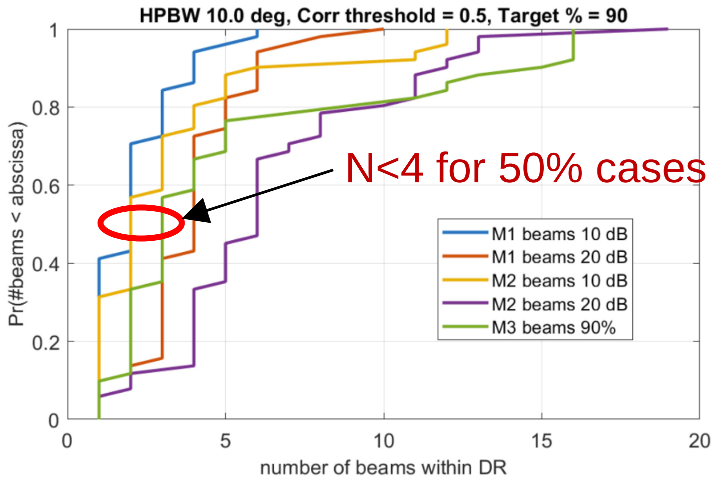


How Many Beams Does Sub-THz Channel Support?

- **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







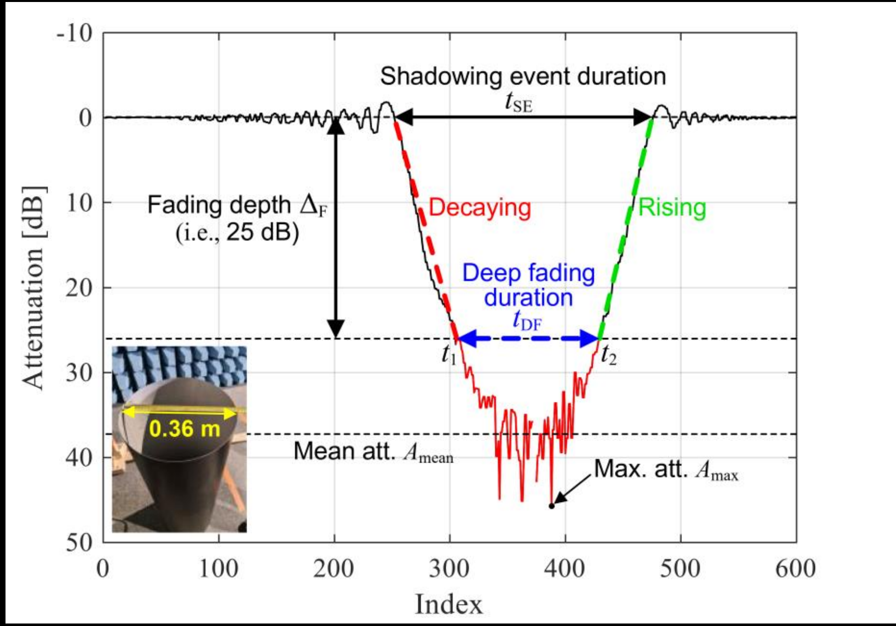
Pekka Kyösti, M. F. De Guzman, K. Haneda, N. Tervo and A. Pärssinen, "How Many Beams Does Sub-THz Channel Support?" ***IEEE Antennas Wireless Propag. Lett.***, vol. 21, no. 1, pp. 74-78, Jan. 2022

Aalto University

D-Band (140GHz) Human Body Shadowing

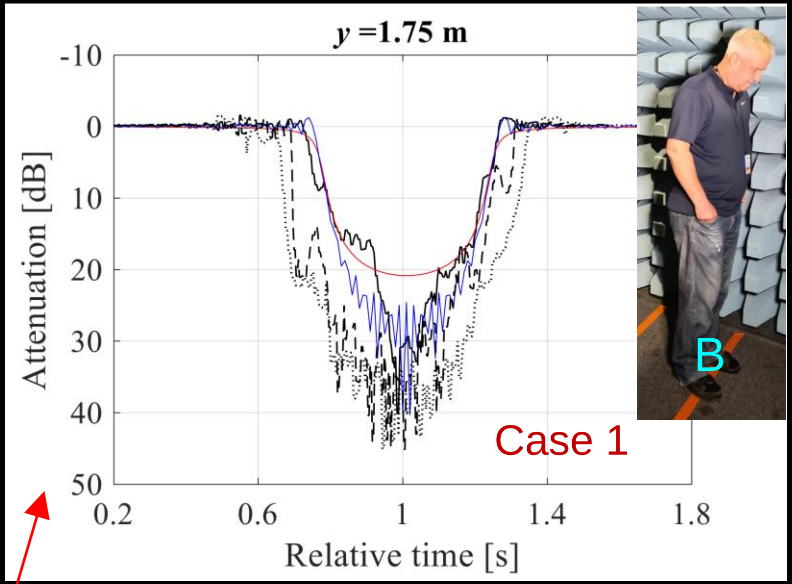
Results of Single-Person Human Blockage Effect

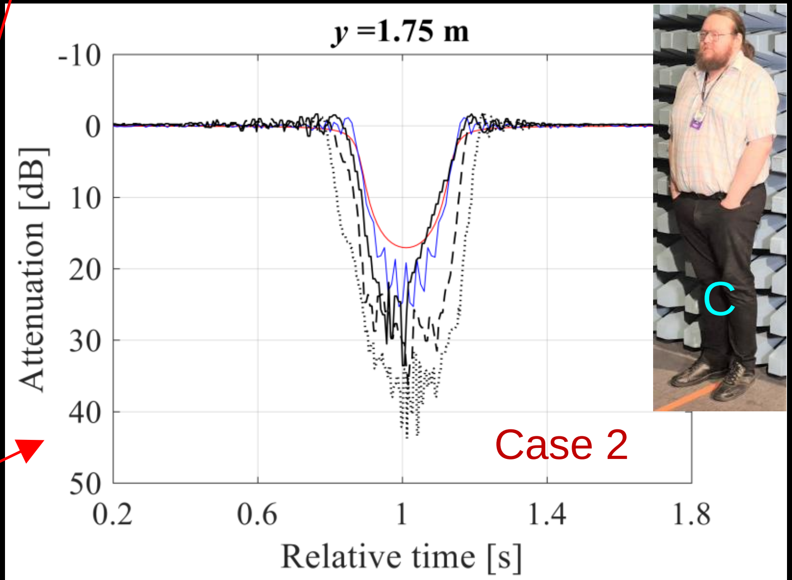
- ✓ Reference measurement results using standard cylinder
- ✓ Characterization of human body shadowing with volunteer A/B/C



Reference measurement with metallic cylinder

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.**





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

Impact of NLOS to HW complexity

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

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

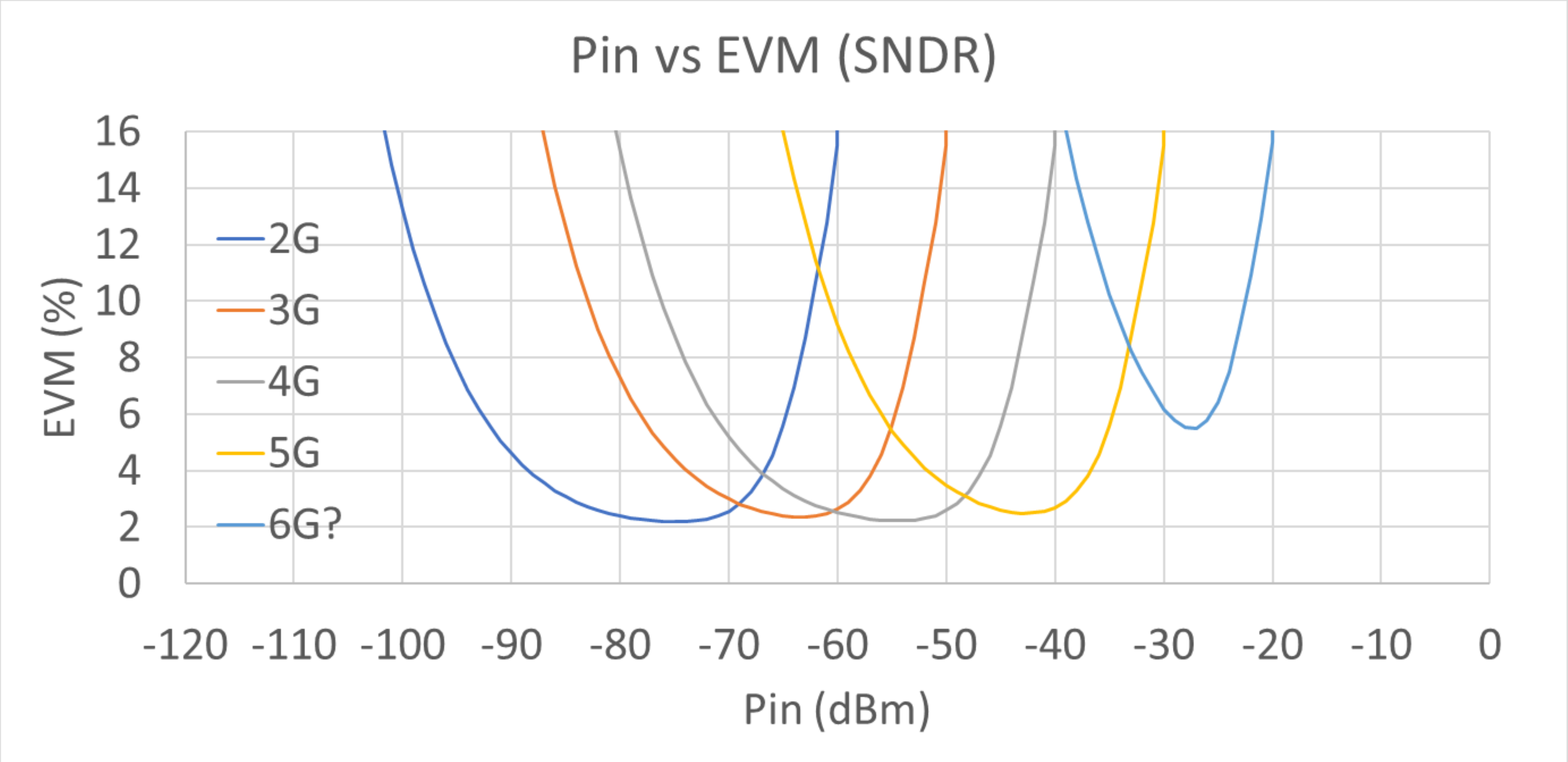
Additional path loss [dB]	Antenna increase (equal in TX&RX)	# of antennas with LOS (ref # 1000)
5	1,47x	1470
10	2,15x	2150
20	4,64x	4640
30	10x	10000
40	21,5x	21500

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

Dynamic range evolution

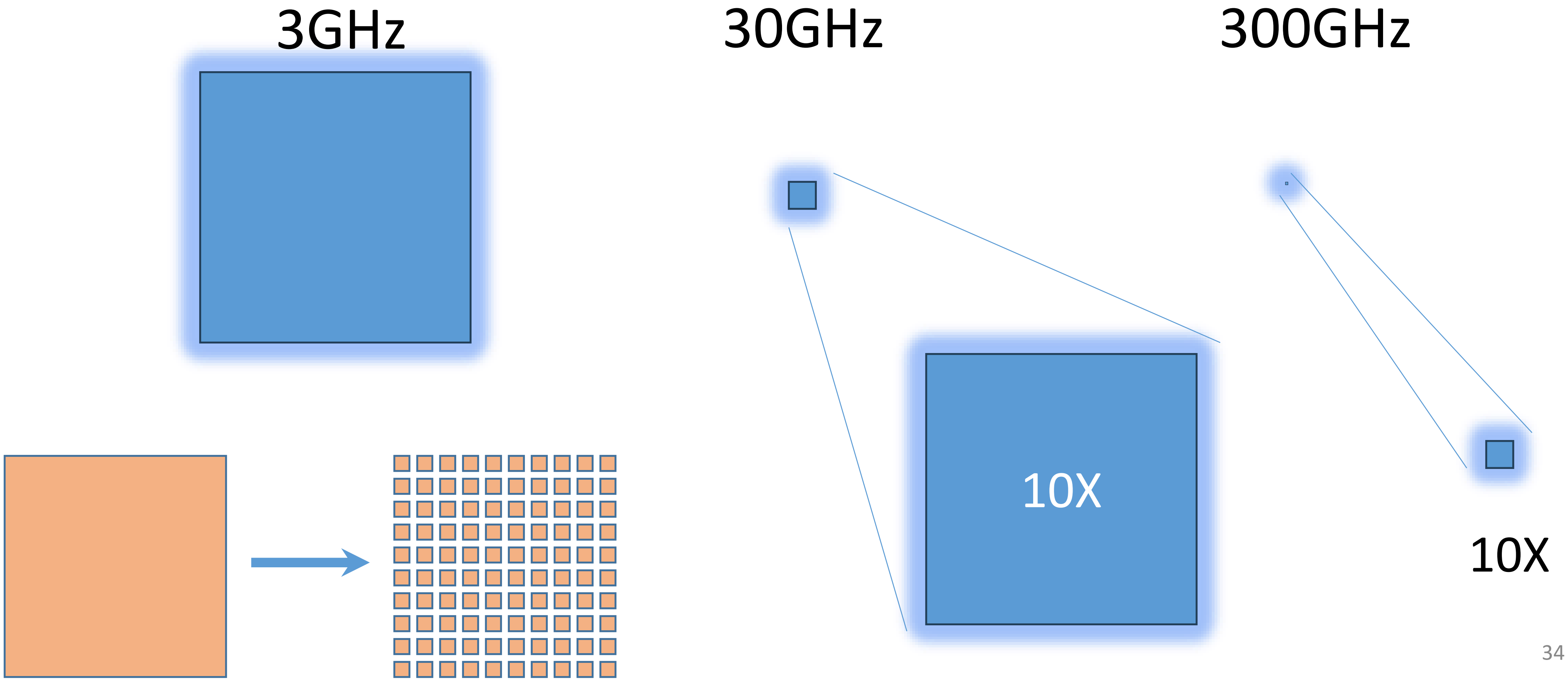
	2G	3G	4G	5G	6G?
ICP1 (dBm)	-60	-50	-40	-30	-20
EVM, flat (%)	2	2	2	2	2
NF (dB)	5	5	5	7	16
BW (MHz)	0,135	3,84	18,1	400	20000

Linearity will be a bottleneck with large antenna gains!



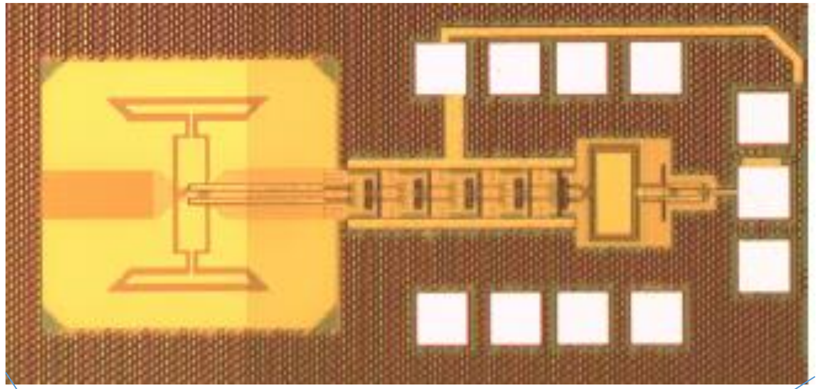
Form factor

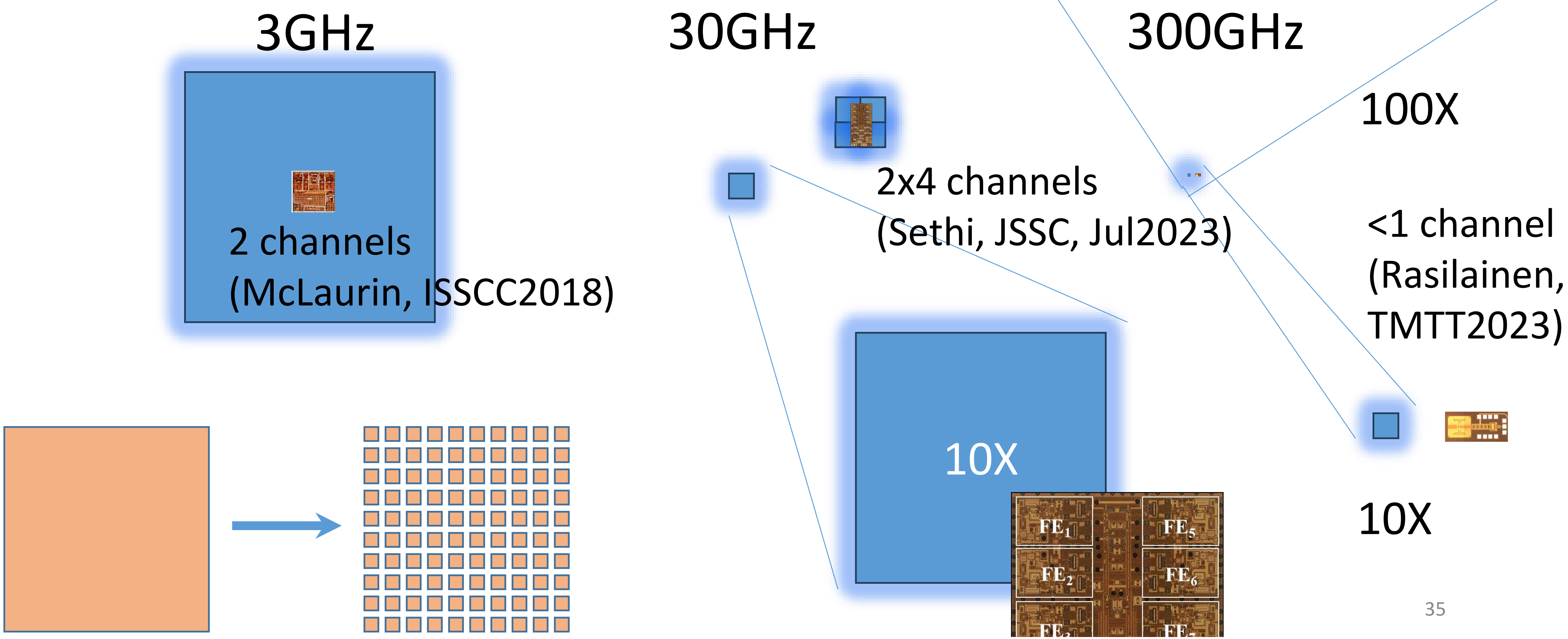
- Area for antenna at λ/2 distance



Form factor

- Area for antenna at λ/2 distance vs. IC





Hardware enabling communications and sensing

Mountains of Radio HW / RFIC

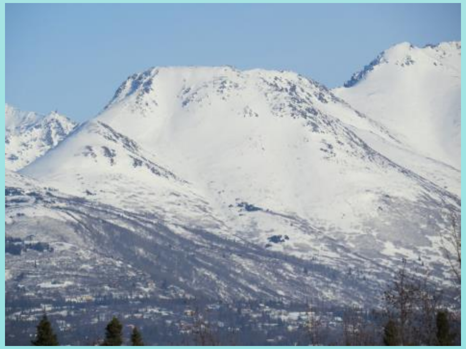
Mountains of Radio HW / RFIC

possibility
commodity
maturity
complexity

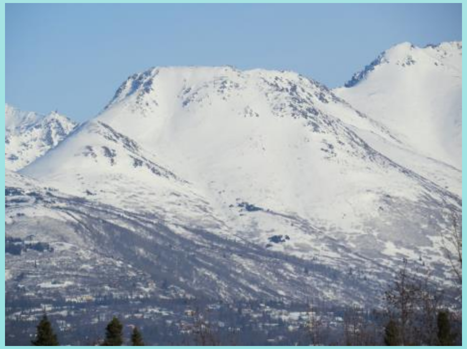
impossibility

missed dream

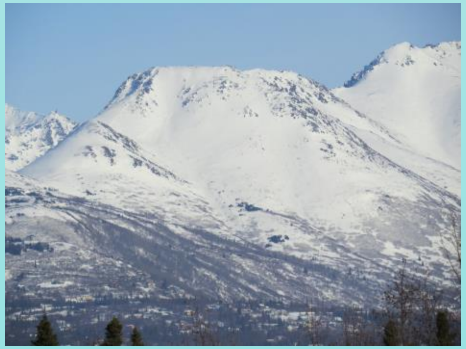
1-2 GHz
90’s feasibility
00’s large scale integration
10’s+ maturity and advances



Lower mmW
00’s feasibility
10’s large scale integration
20’s+ maturity and advances



Sub-THz?
10’s feasibility
20’s large scale integration
30’s+ maturity and advances

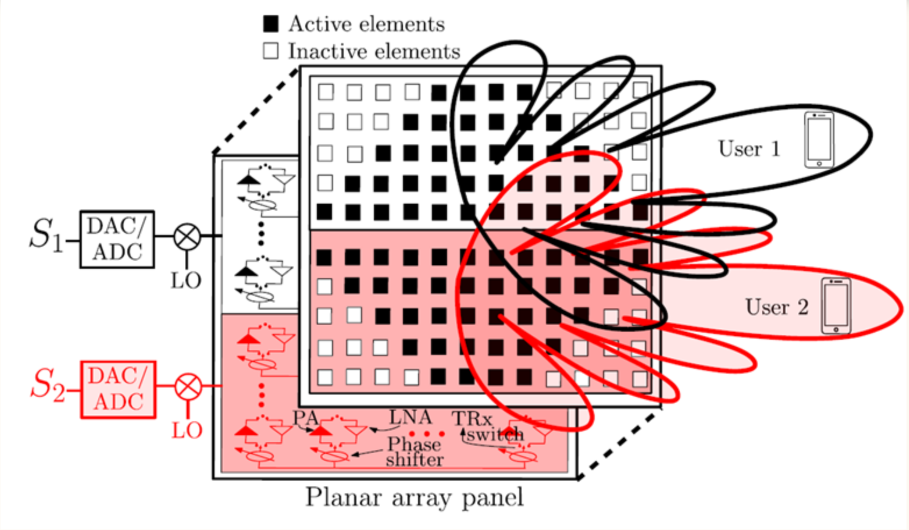


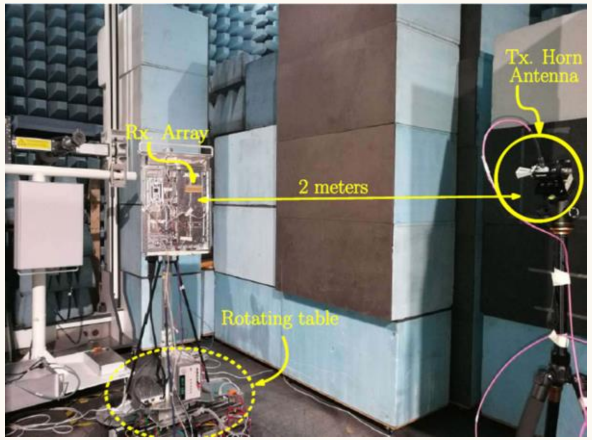
Advances in 5G at lower mmW region

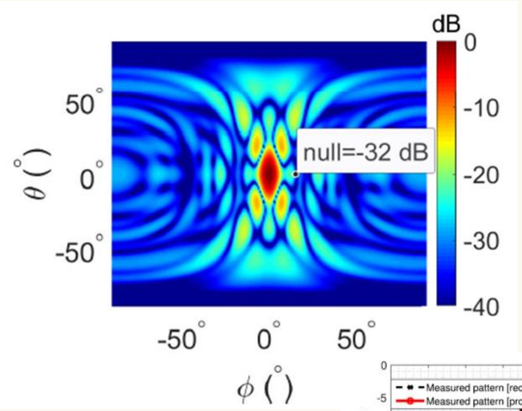
Case examples

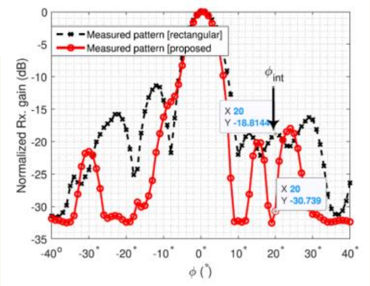
Spatial Interference Reduction by Subarray Stacking

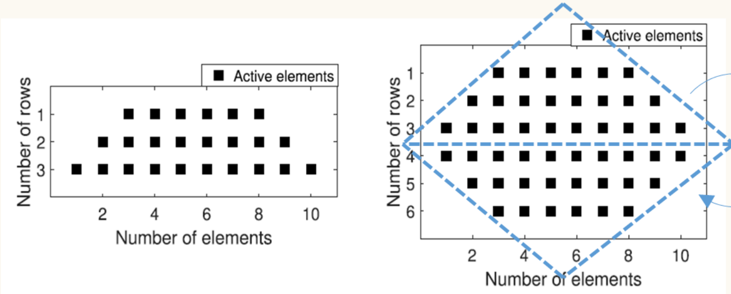
- Multi-beam transceivers and inter-beam interference (IBI)
- Interference reduction techniques for known and unknown interferers: amplitude tapering, thinning, spatial tapering, null forming
- Arbitrary directions











IEEE Transactions on Antennas and Propagation
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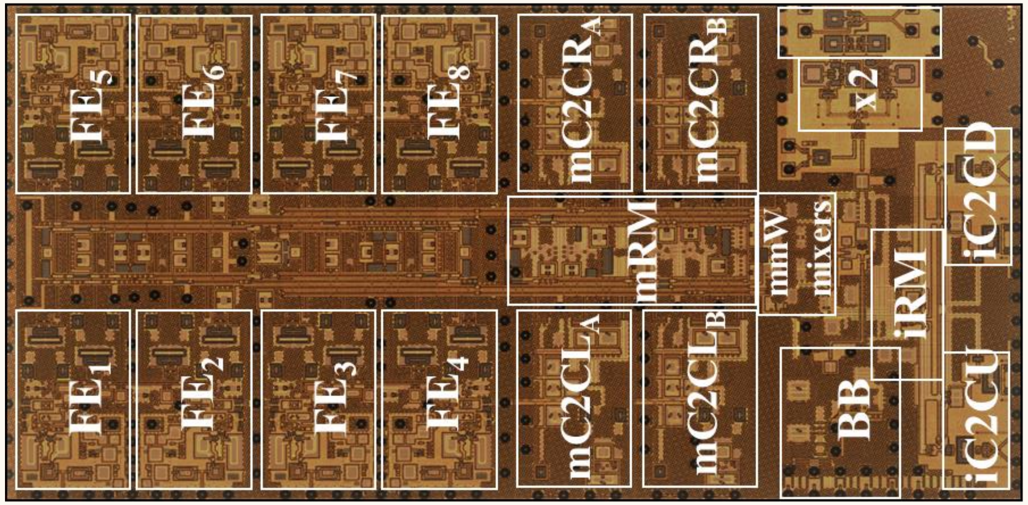
M. Y. Javed et al. propose a systematic approach for spatial interference reduction by subarray stacking in large two-dimensional antenna arrays. Their work received more than 400 full text views! ...see more

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, July 2021.

Large-Scale Highly Configurable mmWave Phased Arrays

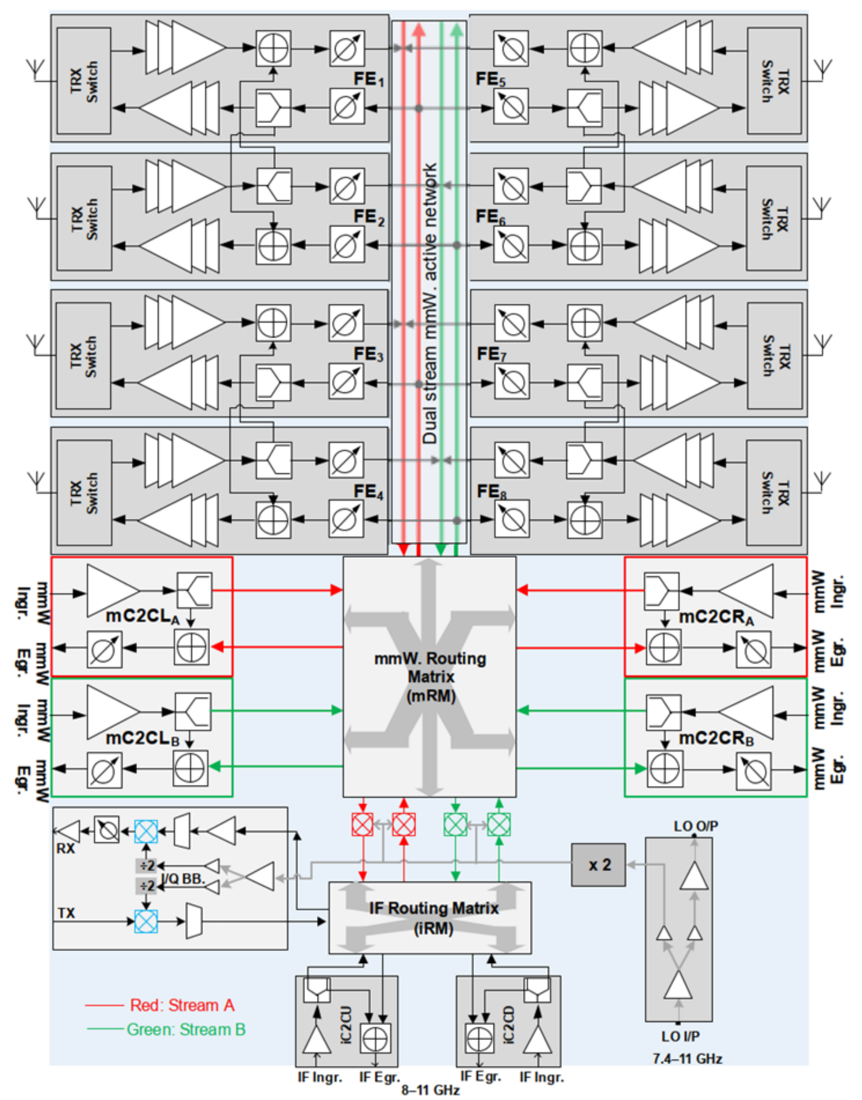
- Scalable phased array with flexible configurability for large scale arrays @28GHz
- Hybrid beamforming, several beams per panel
- GlobalFoundries 45nm RFSOI



8 x 4.4 mm2

64/256 QAM

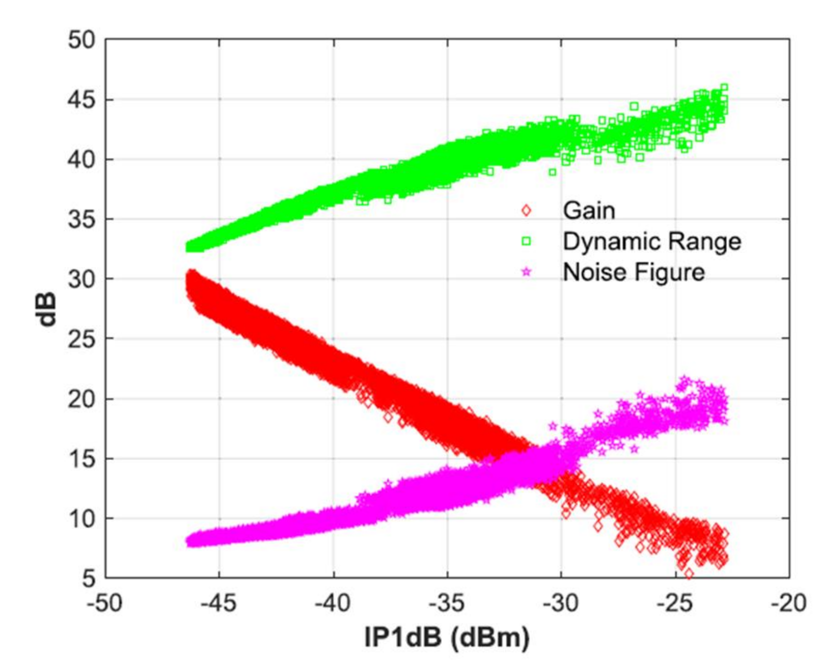
Tested up to 800MHz 5GNR signal

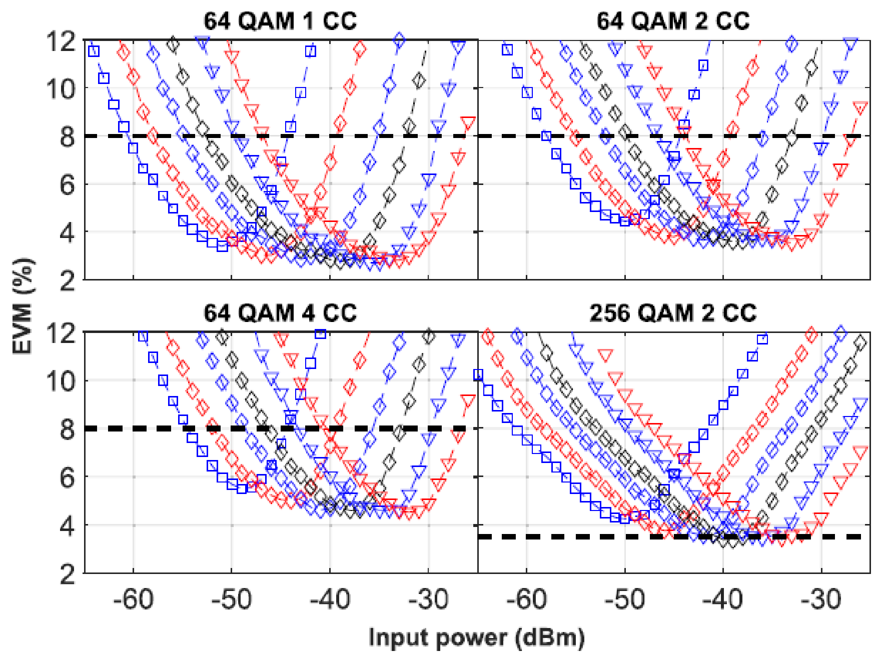


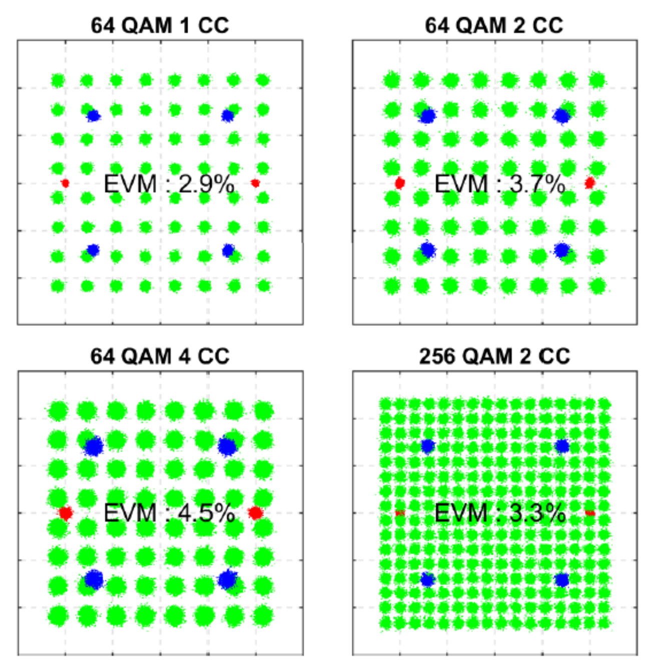
Sethi, et al., "Chip-to-Chip Interfaces for Large-scale Highly Configurable mmWave Phased Arrays," JSSC, Jul 2023.

Large-Scale Highly Configurable mmWave Phased Arrays

- Experimental results



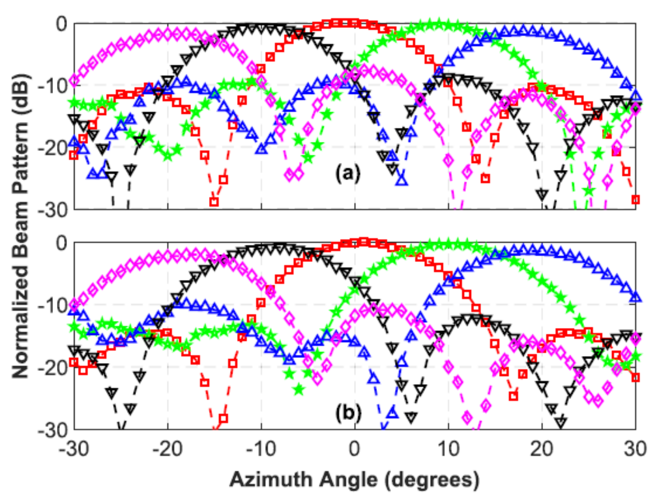


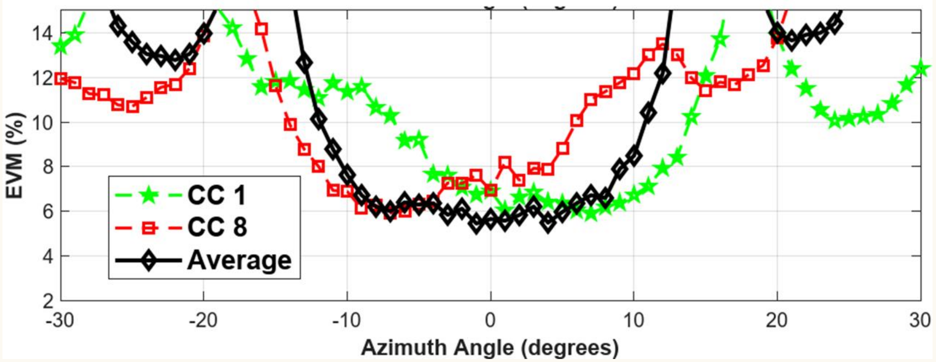


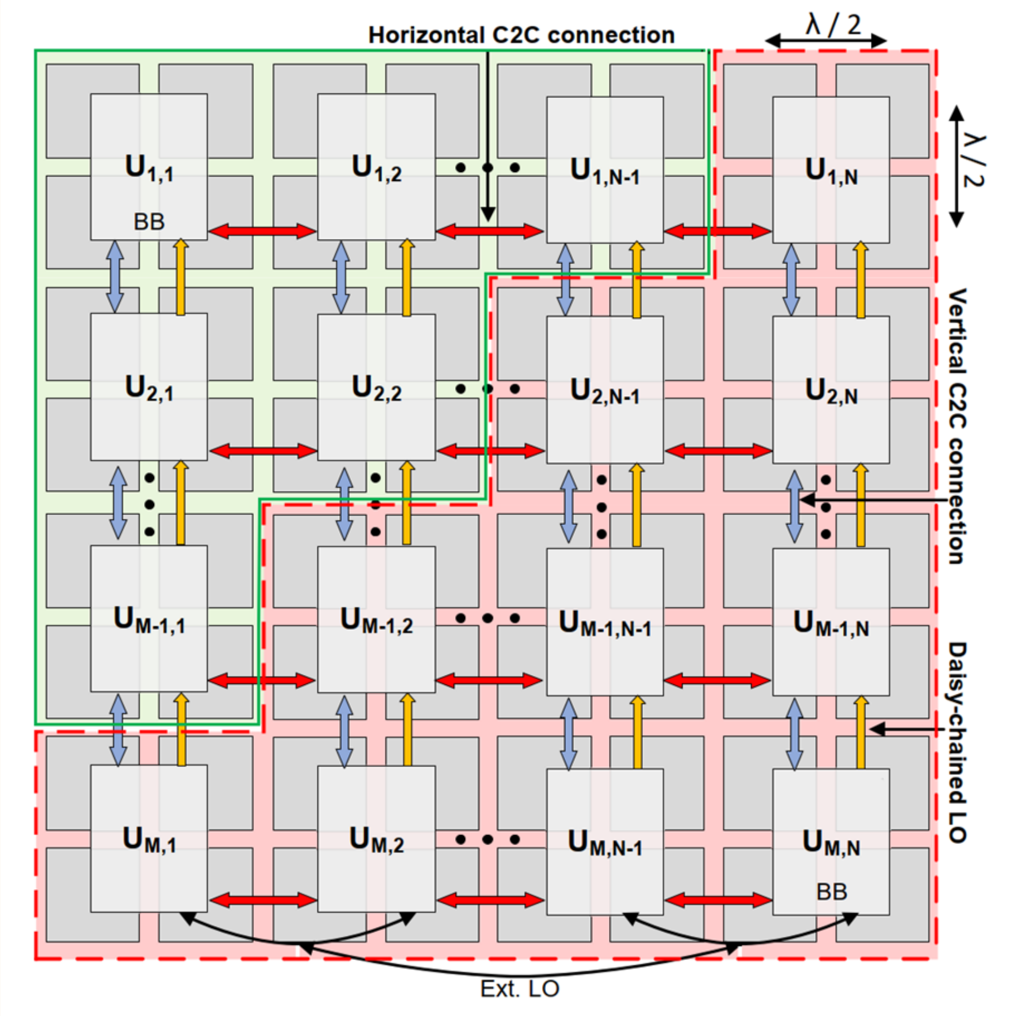
Sethi, et al., "Chip-to-Chip Interfaces for Large-scale Highly Configurable mmWave Phased Arrays," JSSC, Jul 2023.

Large-Scale Highly Configurable mmWave Phased Arrays

- Enabling non-uniform antenna array shapes



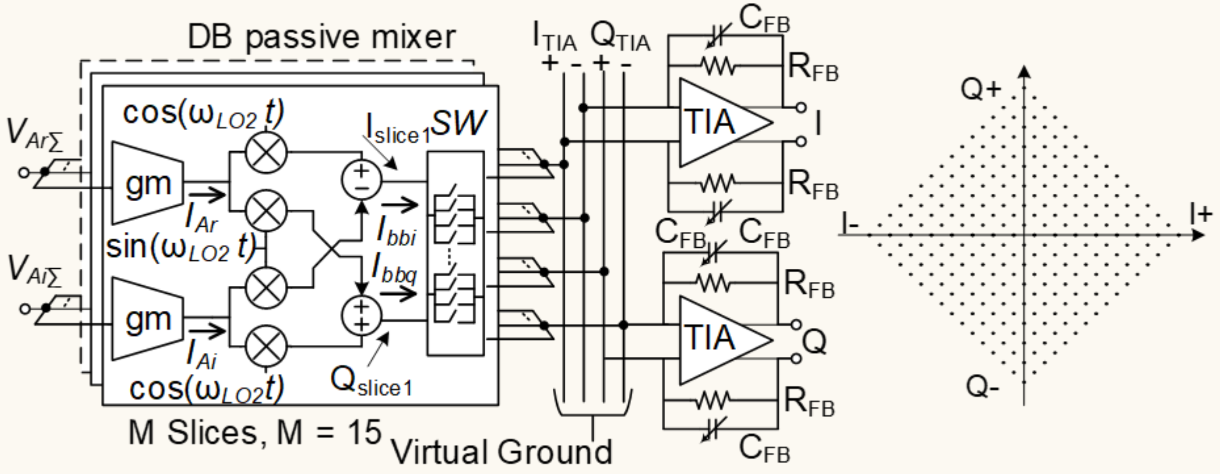


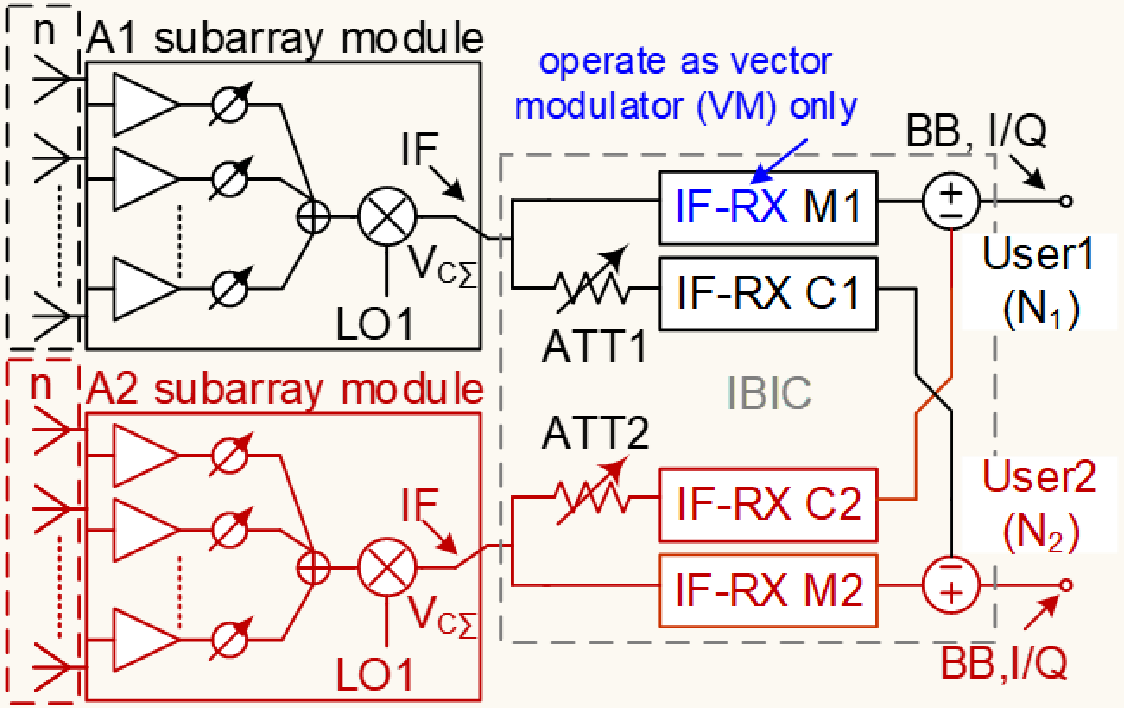


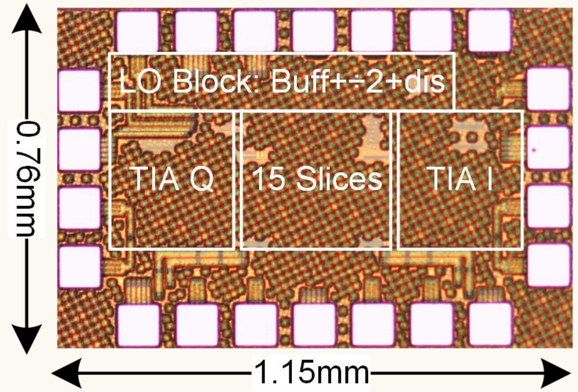
Sethi, et al., "Chip-to-Chip Interfaces for Large-scale Highly Configurable mmWave Phased Arrays," JSSC, Jul 2023.

IF Receiver for mmWave Sub-array Interference Rejection

- Analog interference canceller over 5G signals
- GlobalFoundries 45nm RFSOI



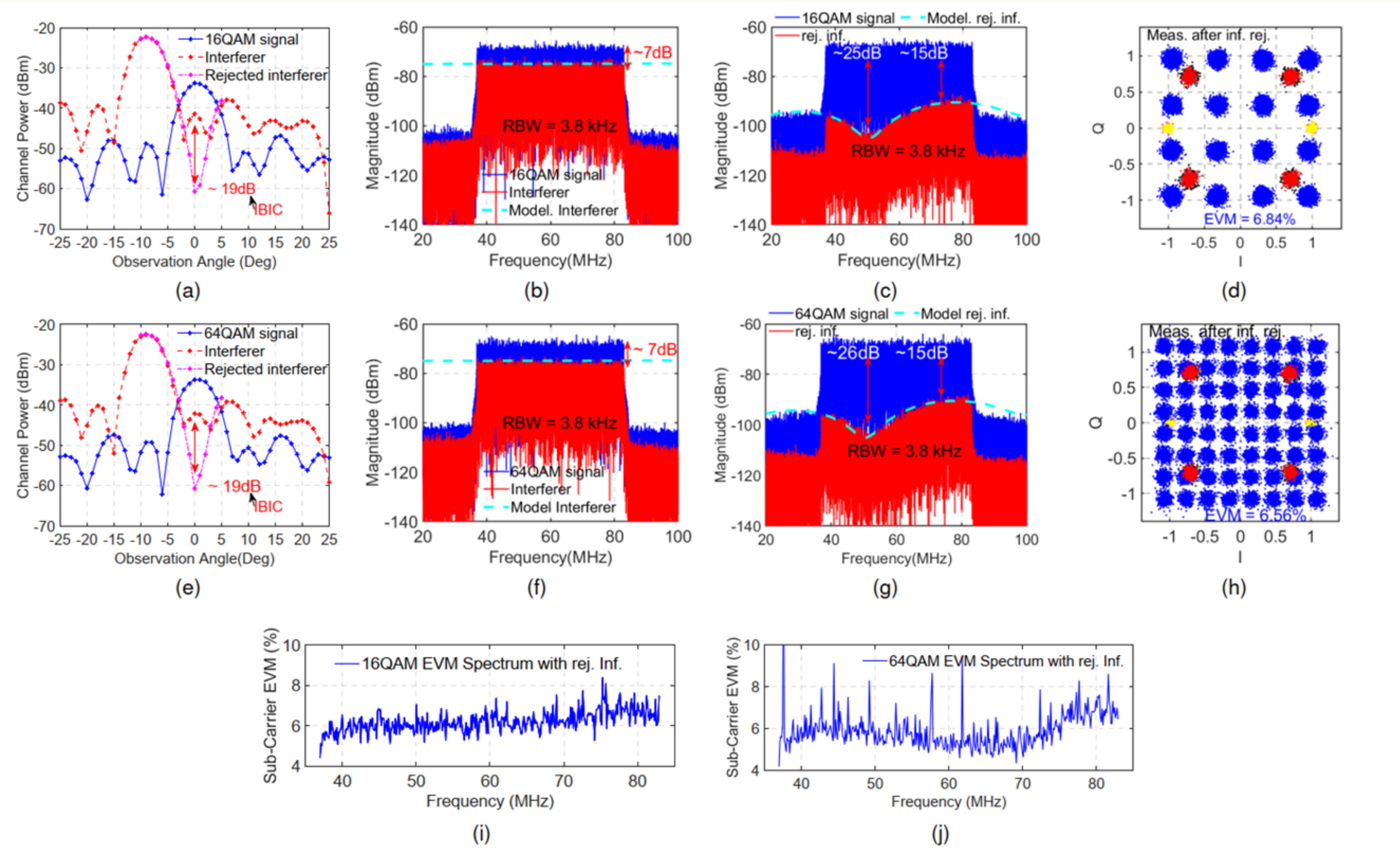




R. Akbar, et al., "A Wideband IF Receiver Chip for Flexibly Scalable mmWave Sub-array Combining and Interference Rejection," IEEE Trans. Microwave Theory and Tech., 2023.

IF Receiver for mmWave Sub-array Interference Rejection

- Spatial filter + IBIC
- 34-37dB interference rejection



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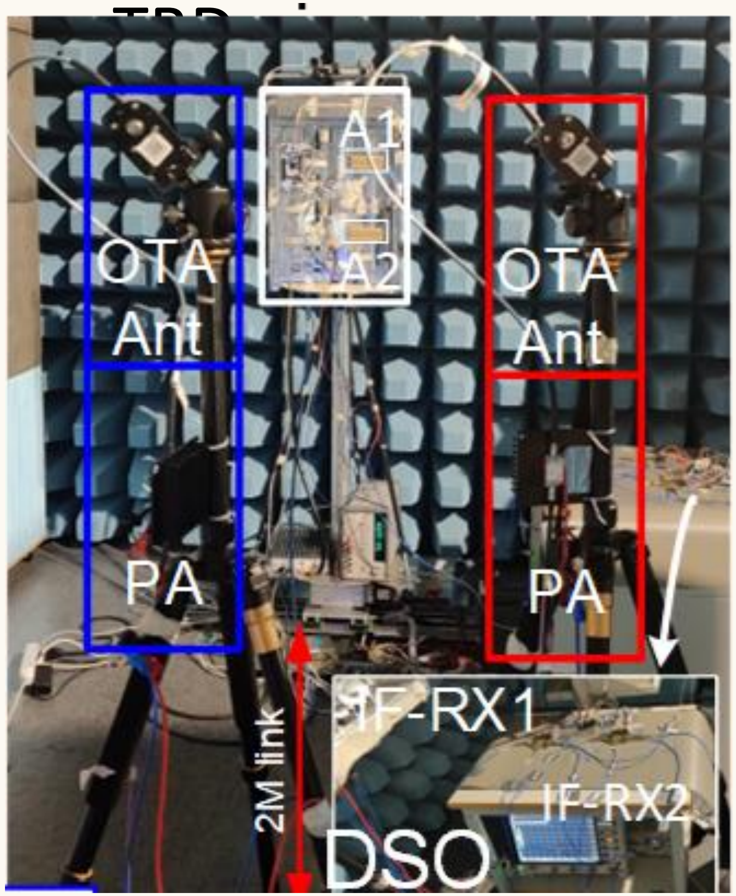
IF Receiver for mmWave Sub-array Interference Rejection



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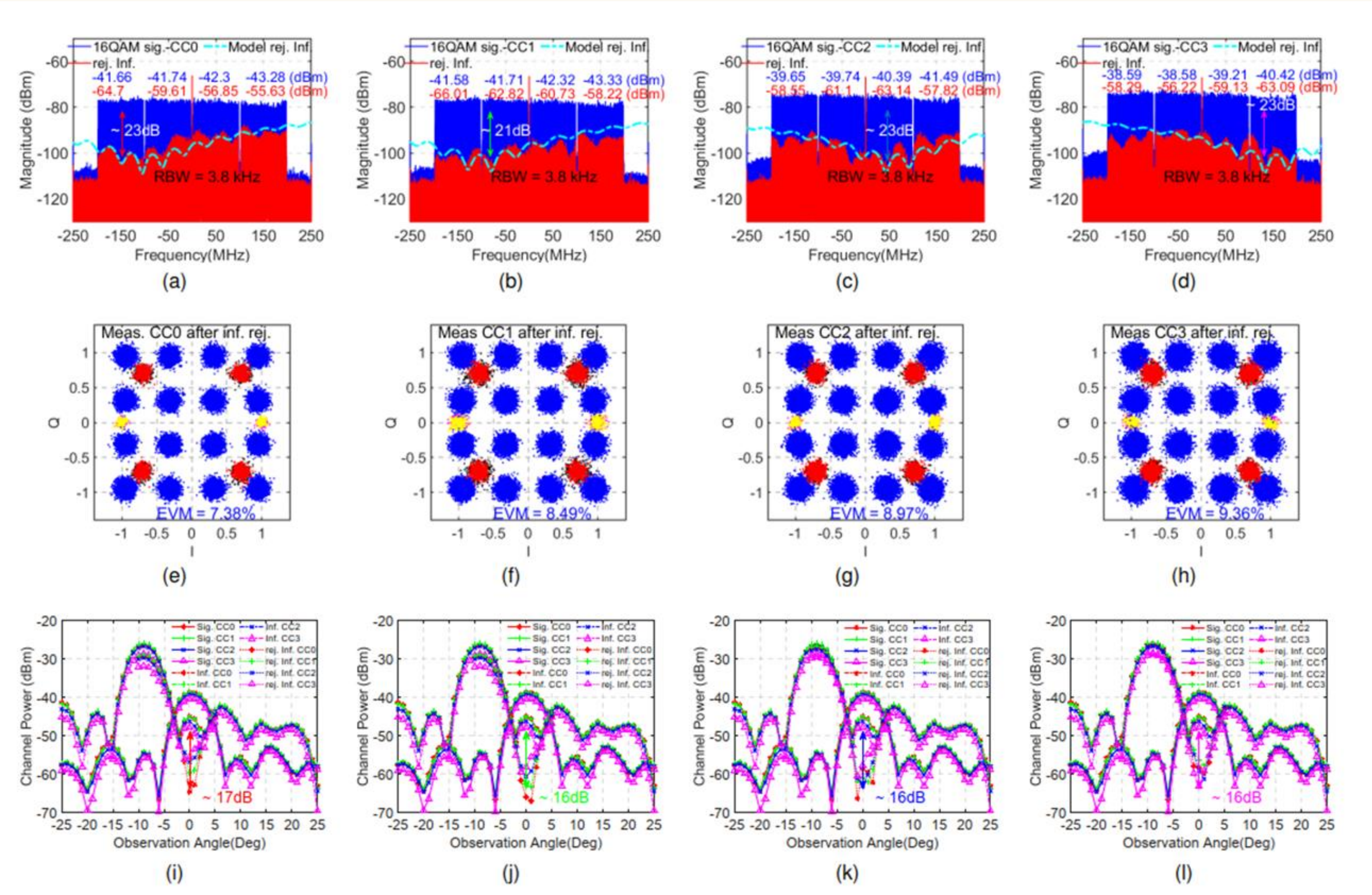


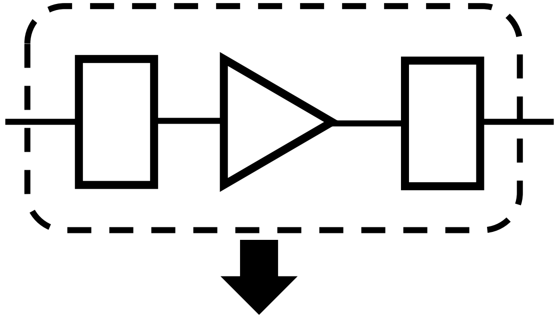
Circuits for 6G at upper mmW region

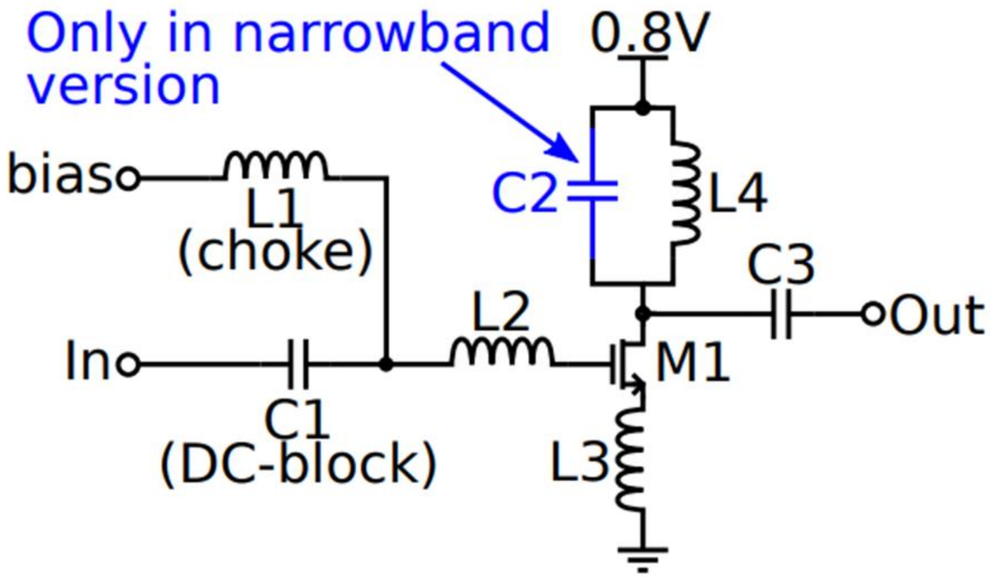
Case examples

LNA design with limited gain

- Typical target ~ 20dB
- Gain per stage
- Noise
  - Input device
  - Loss in matching
  - Loss in interconnects
- Example uses library models but ignores layout parasitics and EM effects

CS amplifier with matching networks

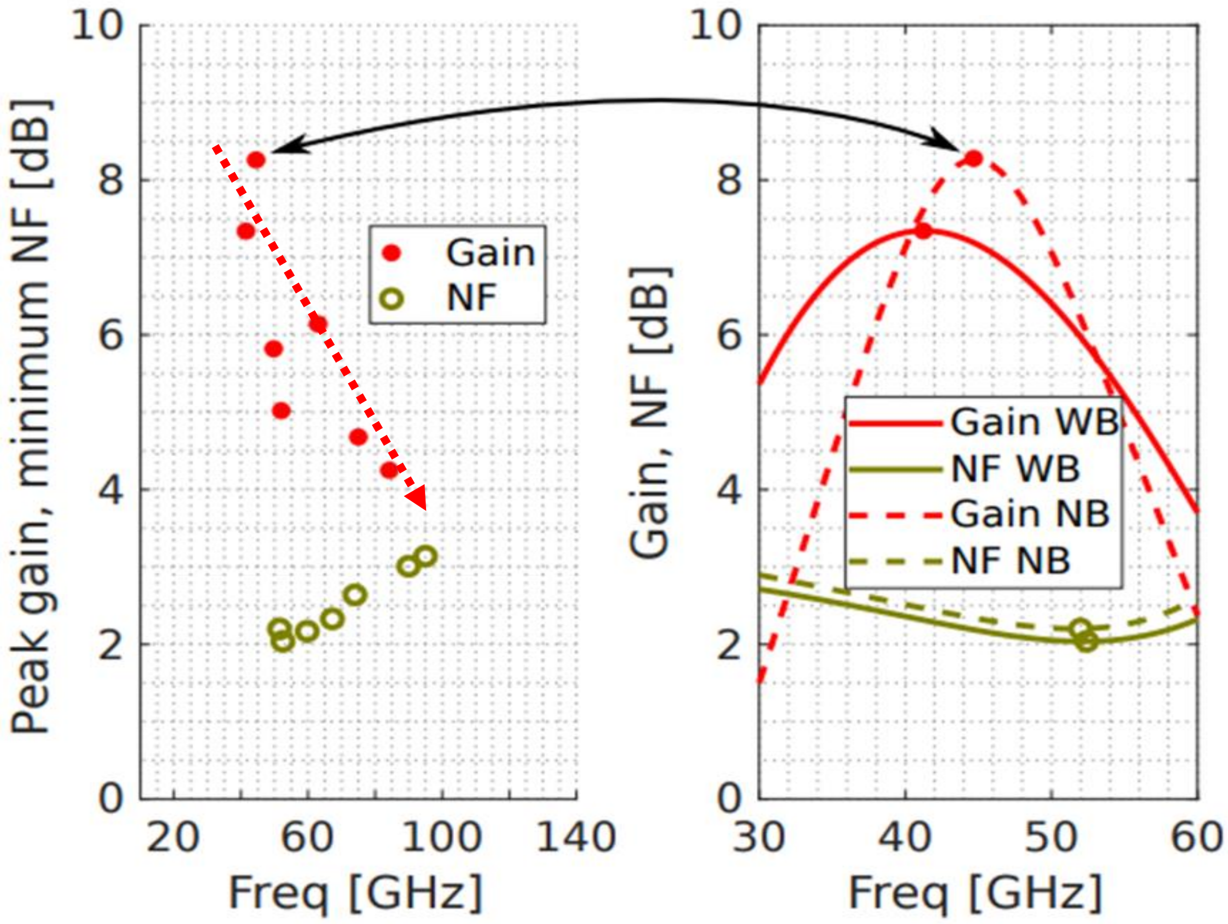




[Hietanen et. al, EuCNC/6G Summit 2021]

LNA design with limited gain

- LNA design tuned and optimized for various frequencies
- Input device the same
- 22nm CMOS SOI
- Bandwidth vs. gain
- Declining gain per stage
  - More stages @freq
  - More power consumption

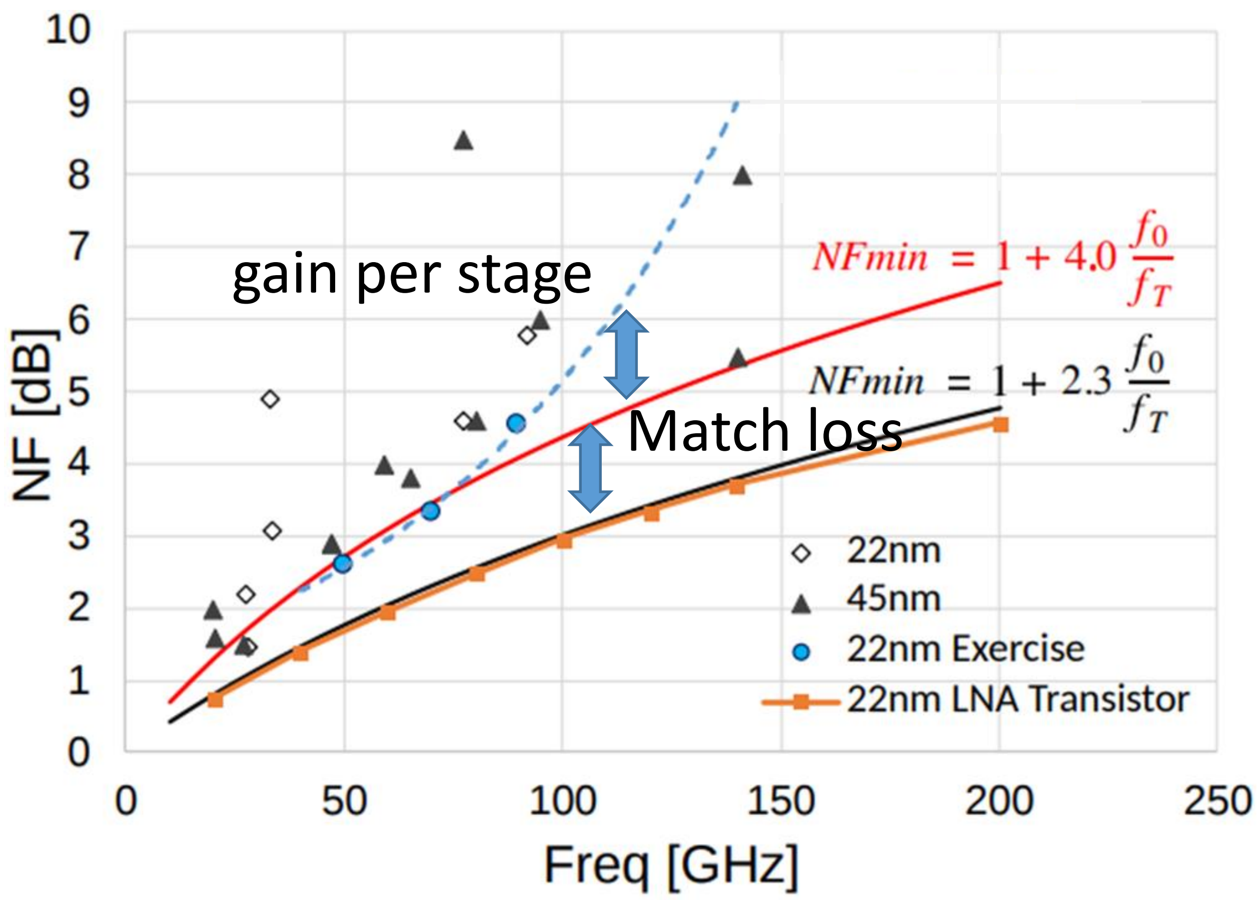


[Hietanen et. al, EuCNC/6G Summit 2021]

LNA design with limited gain

- LNA stages added to reach overall 20dB gain
- Input device matches well with the prediction
- Input matching loss gets more severe at higher frequencies

  2.3 → ~4

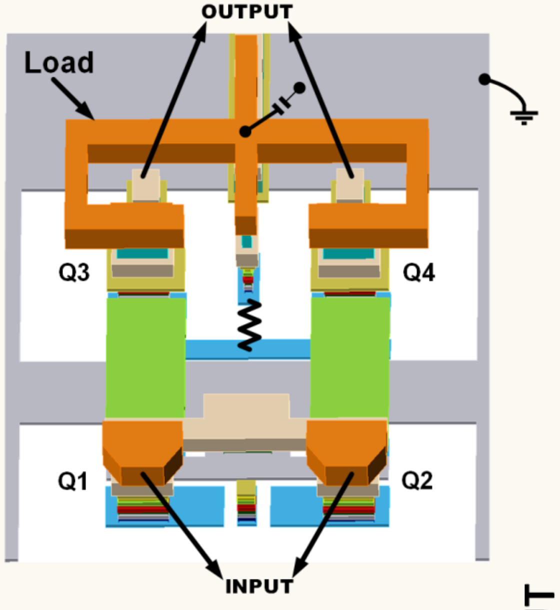


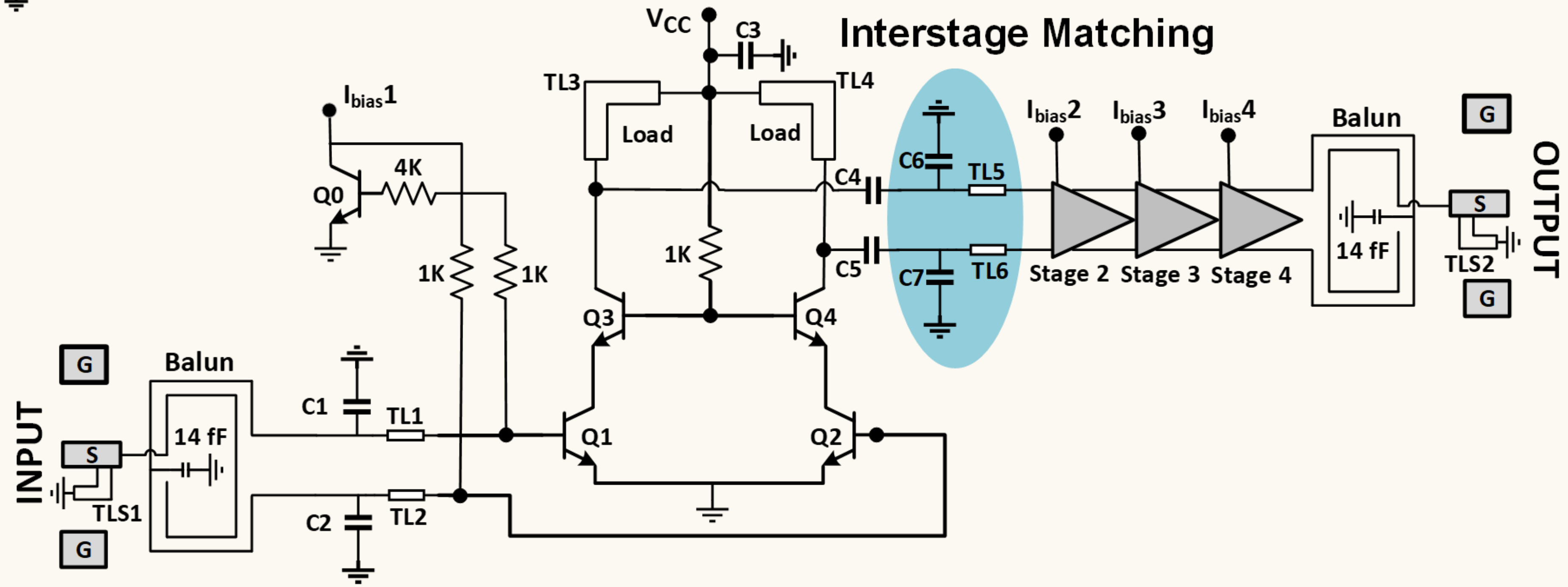
[Hietanen et. al, EuCNC/6G Summit 2021]

290GHz SiGe Low Noise Amplifier

- LNA at 2/3 of fmax is successfully implemented
- 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.

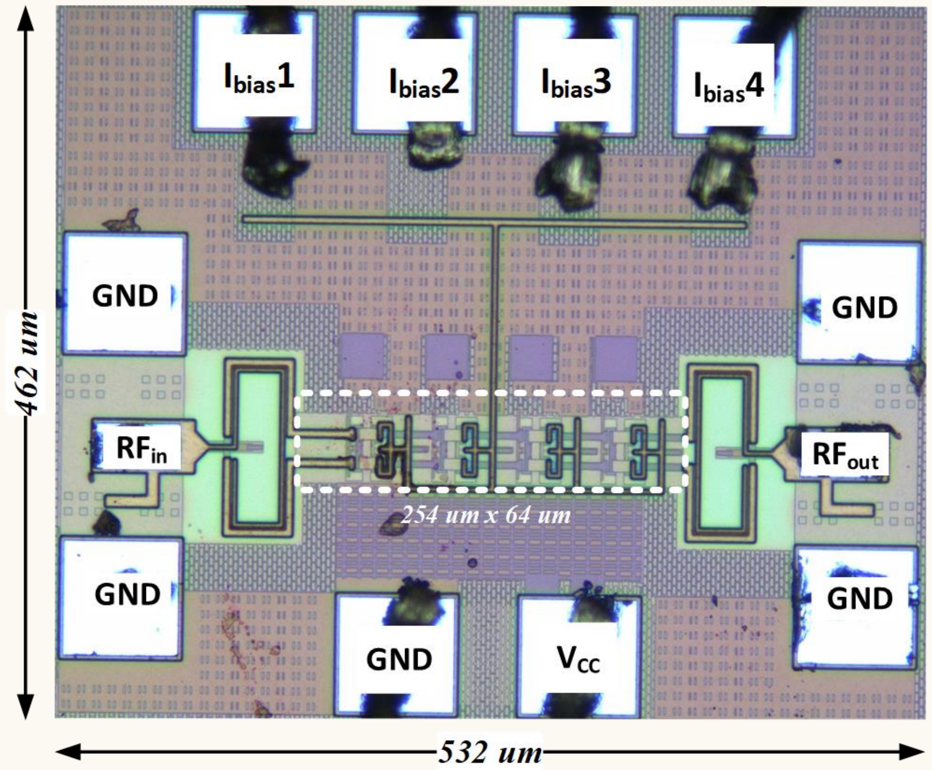


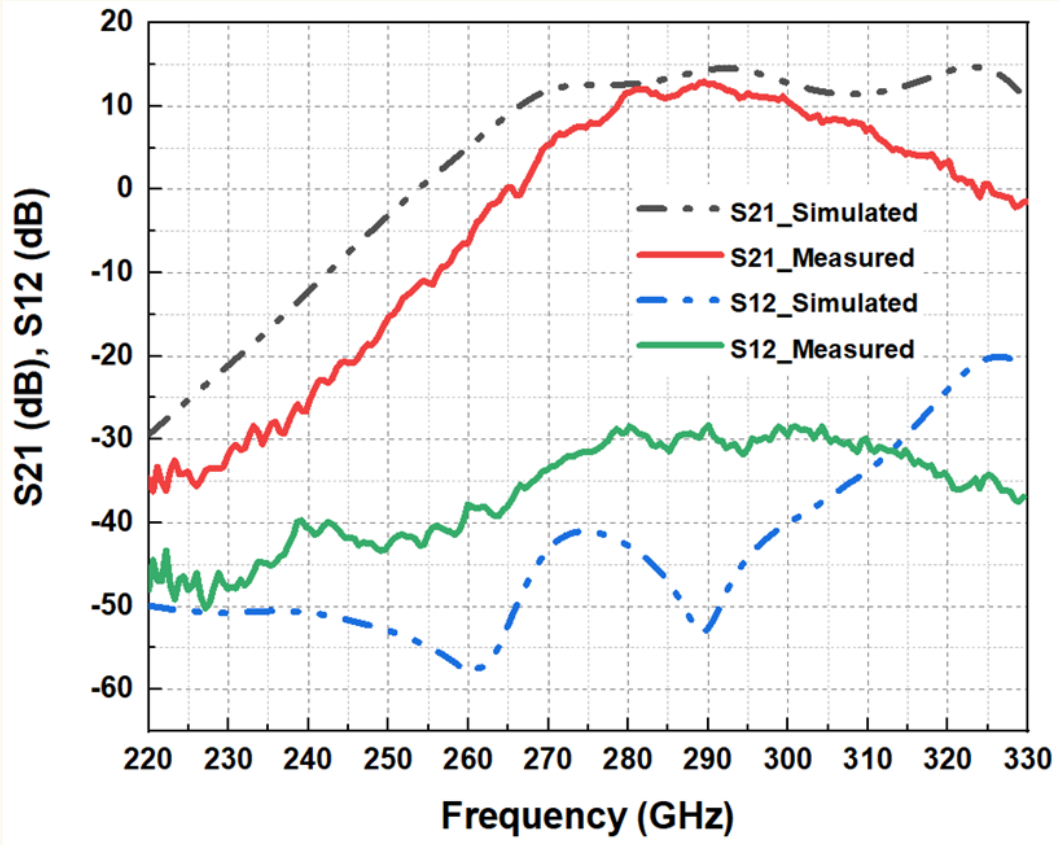


290GHz SiGe Low Noise Amplifier

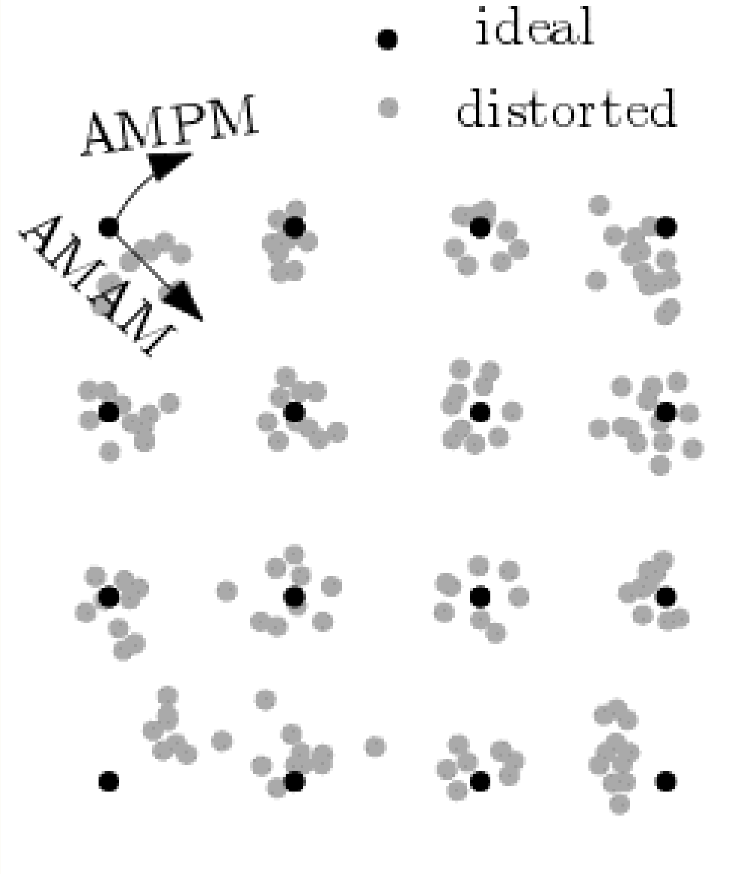
- LNA at 2/3 of fmax is successfully implemented
- Achieves gains of 12.9dB @290GHz and 11 dB @300GHz & NF of 16dB
- 0.53 x 0.46 mm²

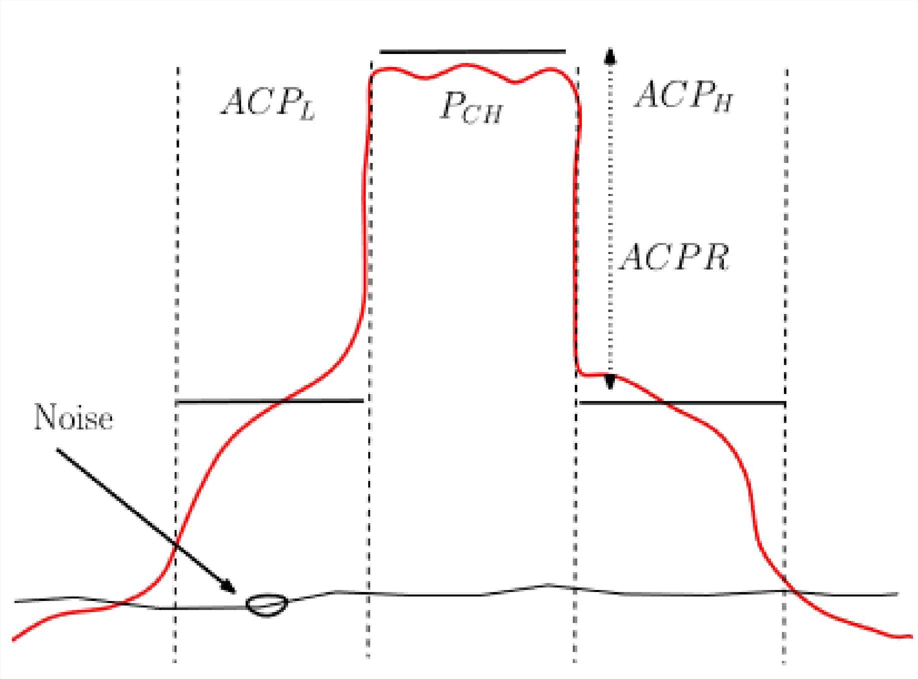
S. P. Singh, et al., "Design Aspects of Single-Ended and Differential SiGe Low Noise Amplifiers Operating above Fmax/2 in sub-THz/THz Frequencies," IEEE J. of Solid-State Circuits, 2023.





Modelling 300GHz amplifier nonlinearity





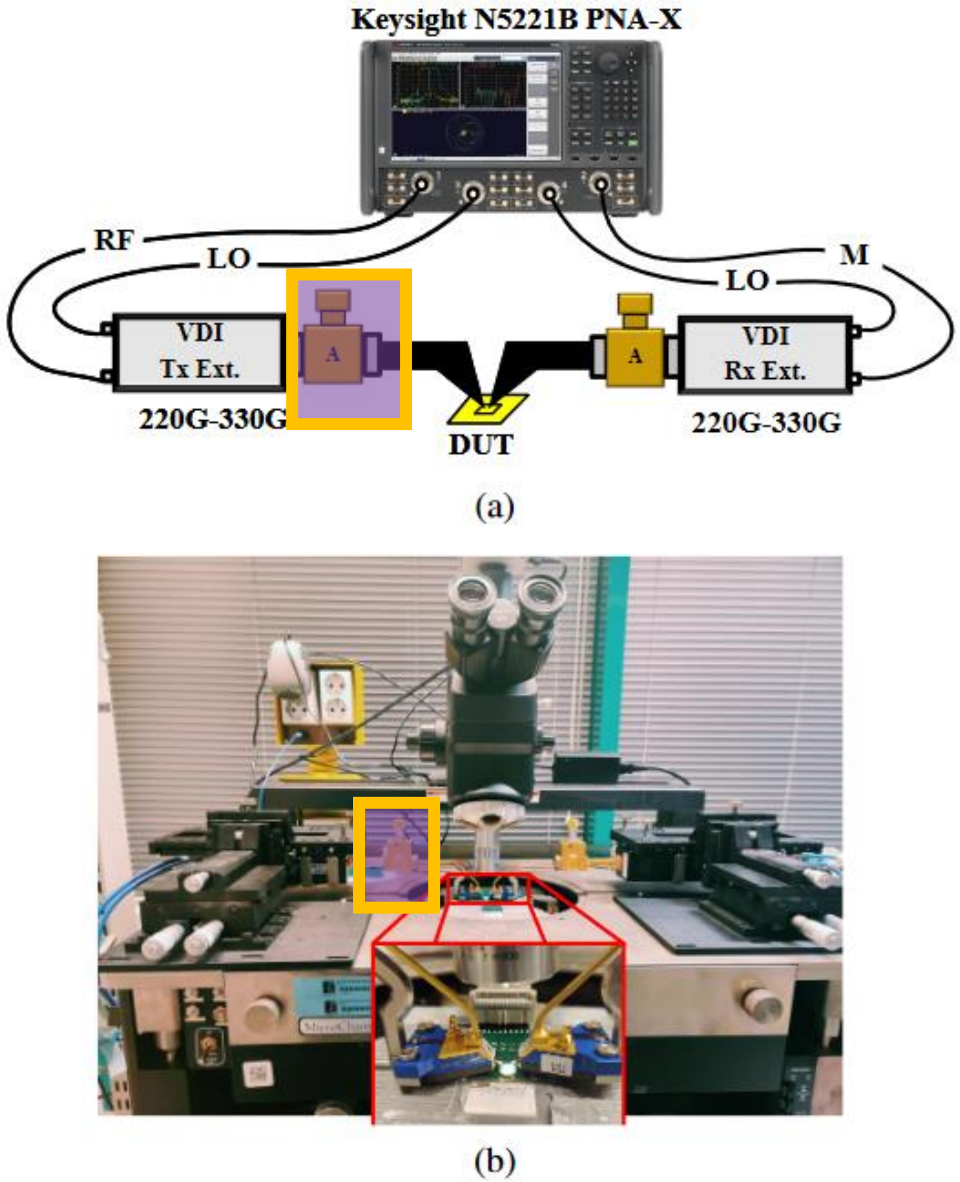
N. Tervo, et al., “Parametrization of Simplified Memoryless Amplifier Models at 300 GHz,” PIMRC23,

Some commonly used memoryless amplifier models…

Saleh	Modified Rapp	Ghorbani-model
$\lvert y(t)\rvert = \frac{a_s\lvert x(t)\rvert}{1+b_s\lvert x(t)\rvert^2},$	$\lvert y(t)\rvert = \frac{g_{\mathrm{r}}}{(1+(\frac{\lvert x(t)\rvert}{x_{\mathrm{sat}}})^{2s})^{\frac{1}{2s}}}\lvert x(t)\rvert,$	$\lvert y(t)\rvert = \frac{g_{\mathrm{r}}}{(1+(\frac{\lvert x(t)\rvert}{x_{\mathrm{sat}}})^{2s})^{\frac{1}{2s}}}\lvert x(t)\rvert,$
$\lvert y(t)\rvert = \frac{a_1\lvert x(t)\rvert^{a_2}}{1+a_3\lvert x(t)\rvert^{a_2}} + a_4\lvert x(t)\rvert,$	$\angle y(t) = \frac{\alpha\lvert x(t)\rvert^{q_1}}{1+(\frac{\lvert x(t)\rvert}{\beta})^{q_2}} + \angle x(t),$	$\angle y(t) = \frac{\alpha\lvert x(t)\rvert^{q_1}}{1+(\frac{\lvert x(t)\rvert}{\beta})^{q_2}} + \angle x(t),$

- Analytical models, typically used ”to get some nonlinear effects” to the system
- Can be parametrized against experimental data to make them more valid
- Are these okay for evaluating mmW/Sub-THz systems?

Experimental setup for extracting amplifier data

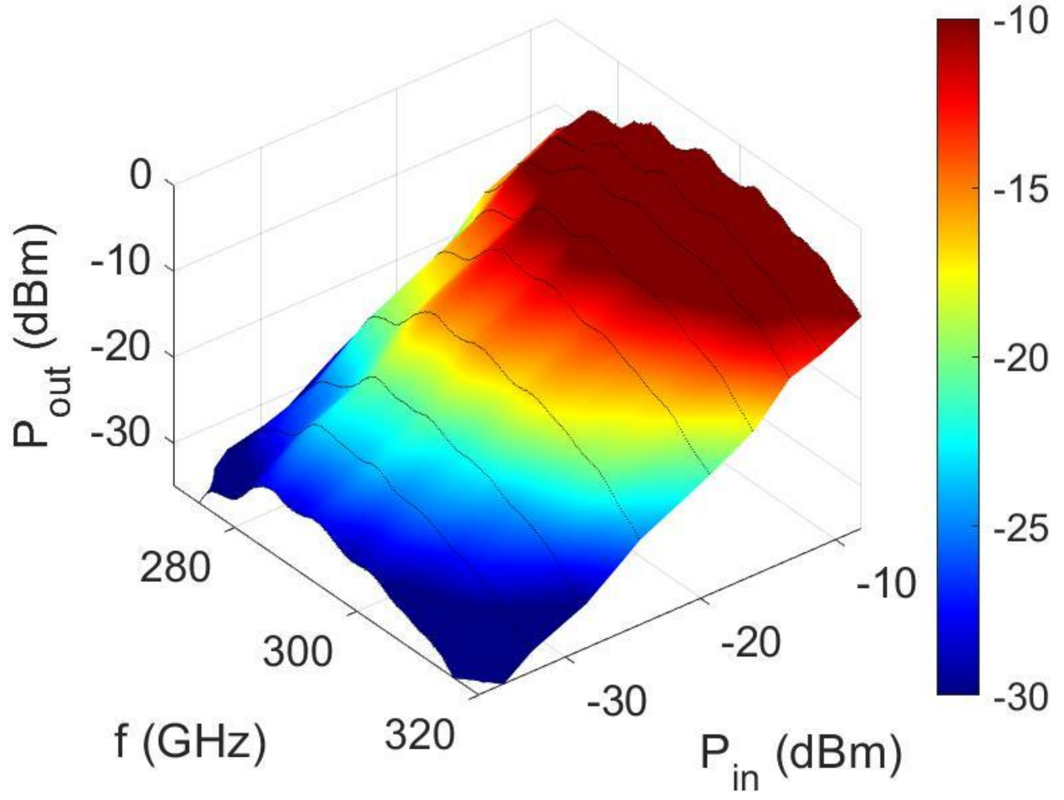


- S_{21} measurements (freq. response) in different input power levels
  - Extract AMAM/AMPM in different frequencies
- Used frequency extenders are very nonlinear!
  - Tunable attenuator used to vary input power level

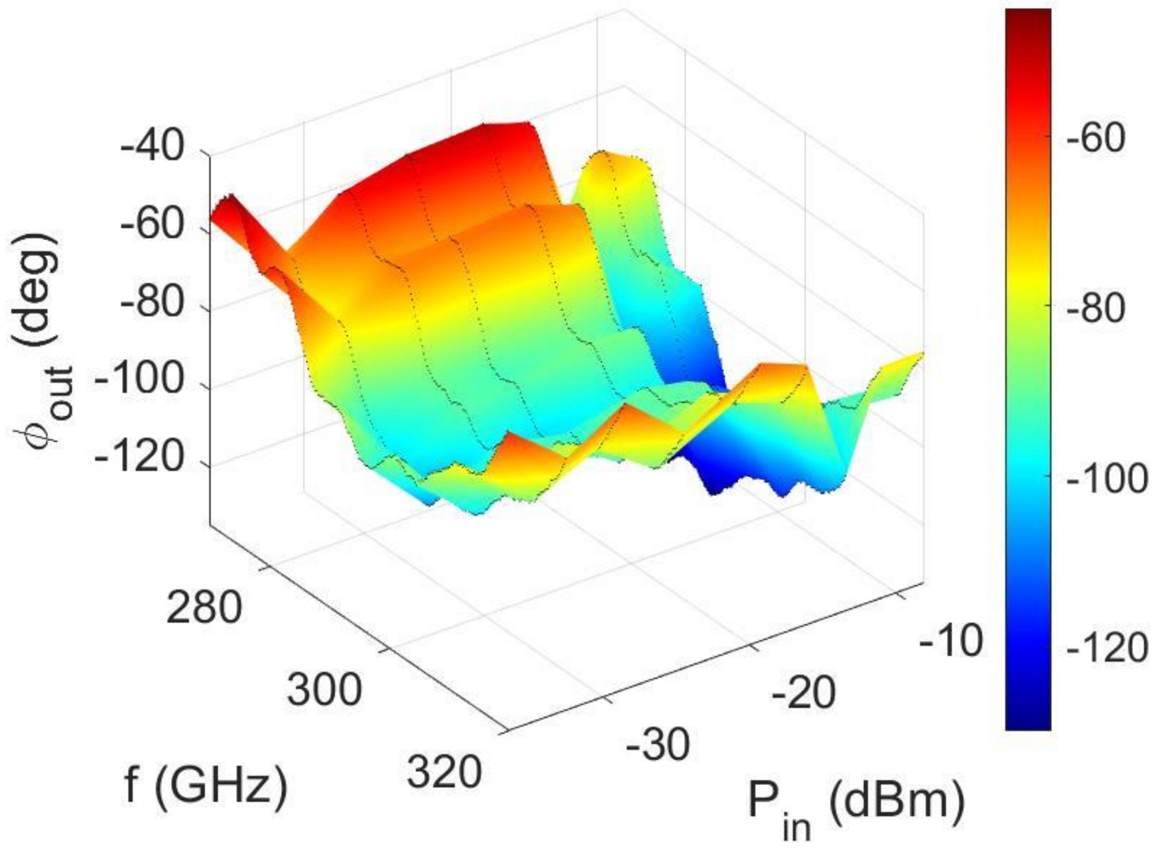
N. Tervo, et al., “Parametrization of Simplified Memoryless Amplifier Models at 300 GHz,” PIMRC23,

Raw AMAM/AMPM Data

AMAM data



AMPM data



N. Tervo, et al., “Parametrization of Simplified Memoryless Amplifier Models at 300 GHz,” PIMRC23,

AMAM/AMPM at 290 GHz: Vs. Circuit-level simulations

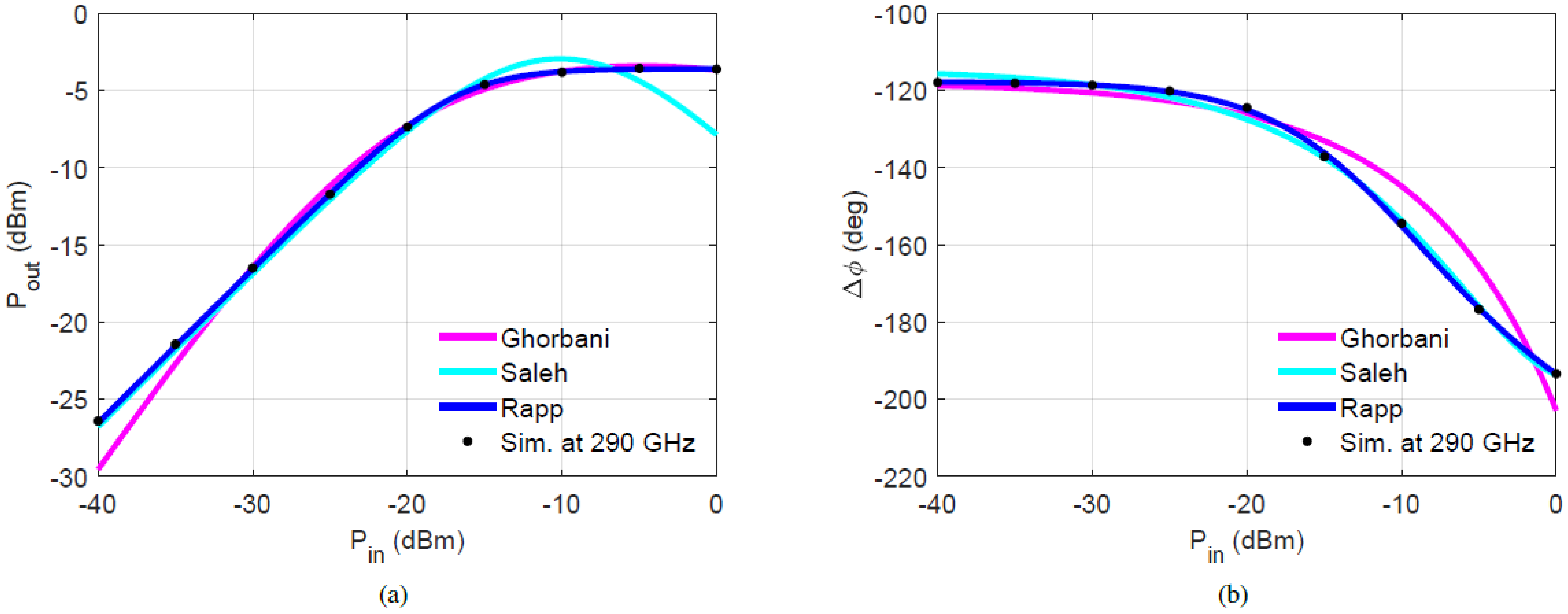


Fig. 3. (a) AMAM and (b) AMPM models with parameters fitted against a circuit level simulation data of the amplifier at 290 GHz.

N. Tervo, et al., "Parametrization of Simplified Memoryless Amplifier Models at 300 GHz," PIMRC23,

AMAM/AMPM at 290 GHz: Vs. Measurements?

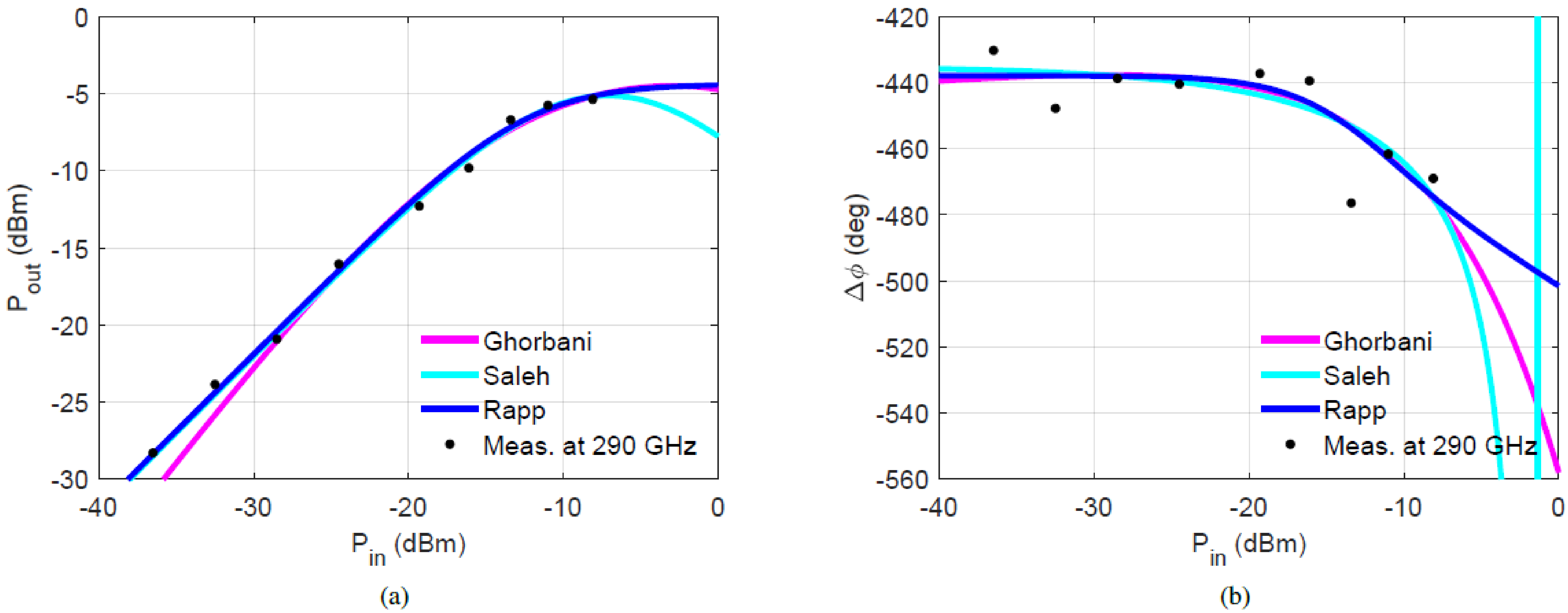


Fig. 2. (a) AMAM and (b) AMPM models with parameters fitted against a measurement data of the amplifier at 290 GHz. Note that only the Rapp model gives smooth compression characteristics outside the measurement range.

- **<u>NOTE:</u>** PURPOSELY PLOTTED OVER THE MEASUREMENT RANGE TO SEE THAT ONLY SOME MODELS CAN BE USED OUTSIDE THIS RANGE…. NEED TO BE CAREFUL☺

Conclusions & lessons learned

- On-wafer CW-measurement data in these frequencies is subject to errors & inaccuracies
  - Just because it is measured, does not mean that it is the reality!

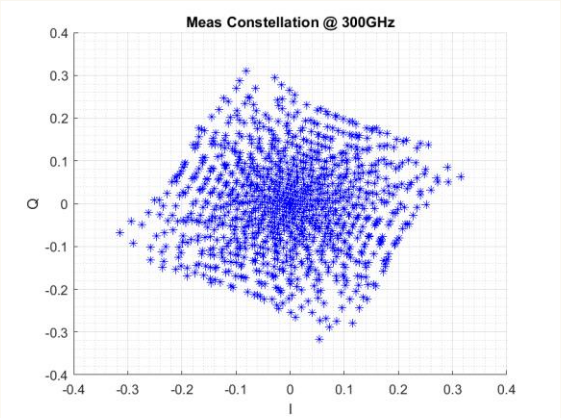
- Commonly used memoryless modeling principles seem to capture the nonlinear effect also in higher frequencies
  - Model parameters are also a function of design choices, PA class (biasing), and topology.

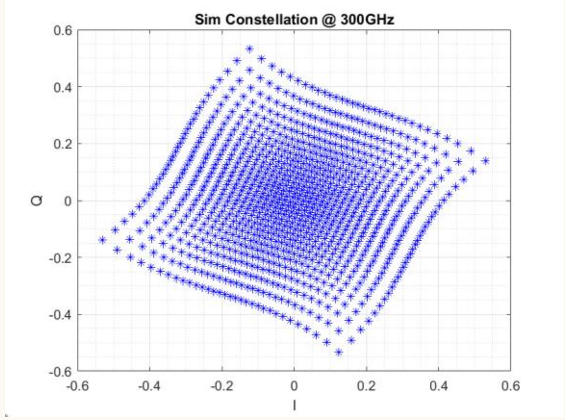
- All models are subject to errors if used across entire input/output power range of signal samples
  - Remember to plot your model and check how you use it!

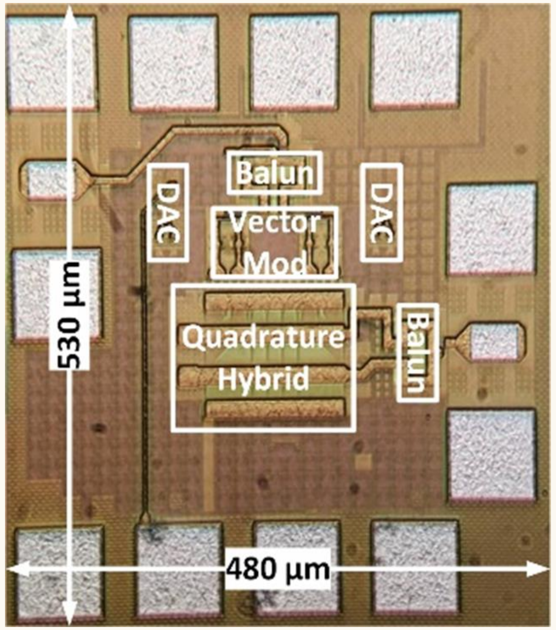
N. Tervo, et al., “Parametrization of Simplified Memoryless Amplifier Models at 300 GHz,” PIMRC23,

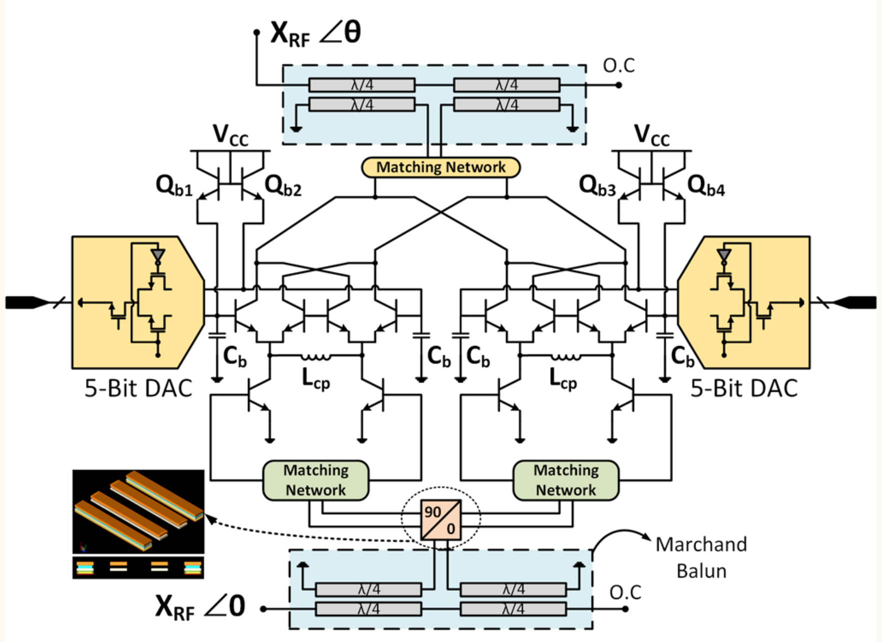
270-330GHz SiGe Phase Shifter

- Vector modulator with digital control
- Achieves <1° phase error
- BiCMOS having ft /fmax 300GHz/450GHz
- 0.48 x 0.53 mm^2





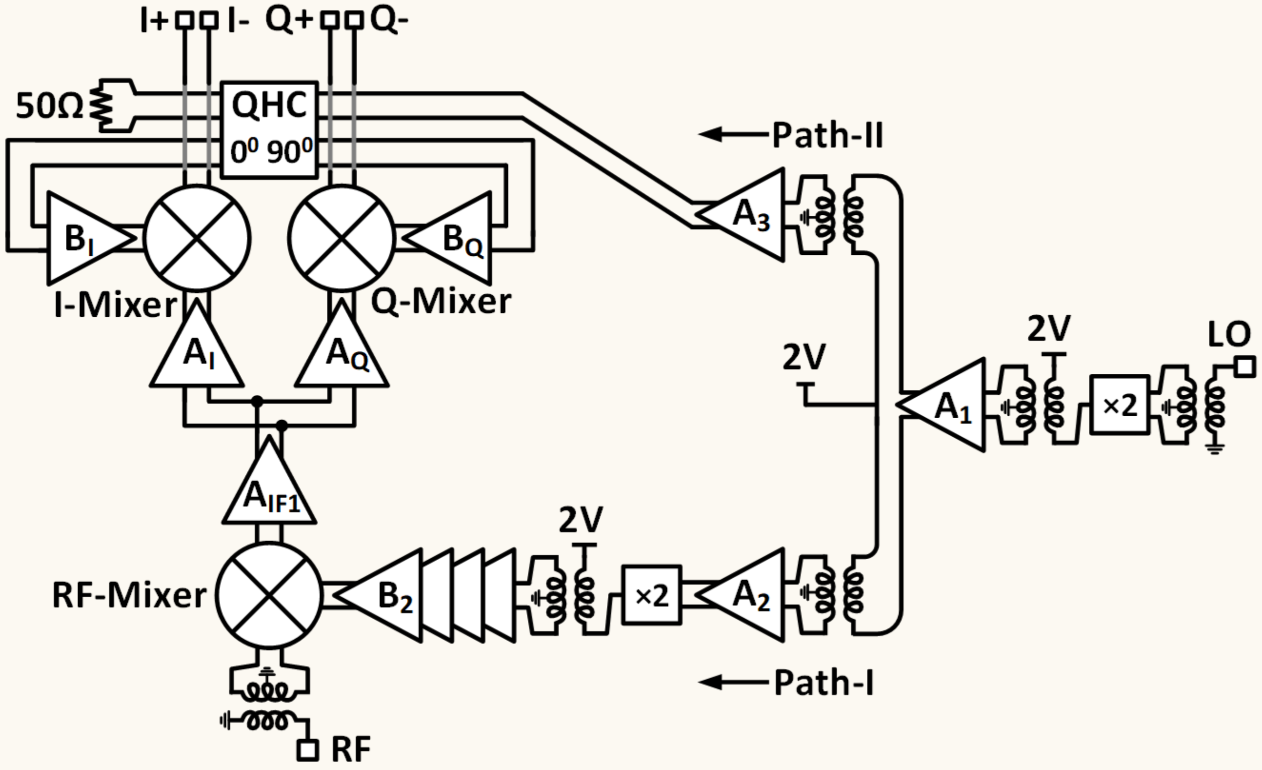


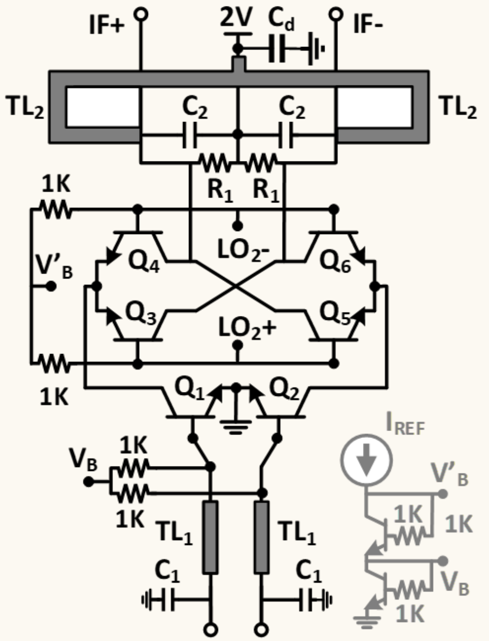


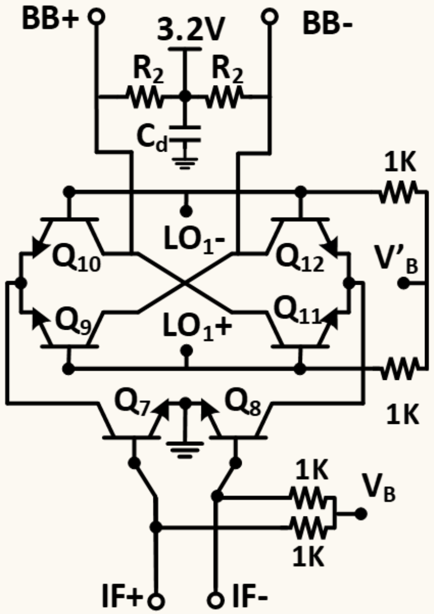
M. Montaseri, et al.,, "A 270 – 330 GHz Vector Modulator Phase Shifter in 130nm SiGe BiCMOS," EuMIC) 2022.

A 300-320 GHz Sliding-IF I/Q Receiver Front-End

- 130nm SiGe BiCMOS

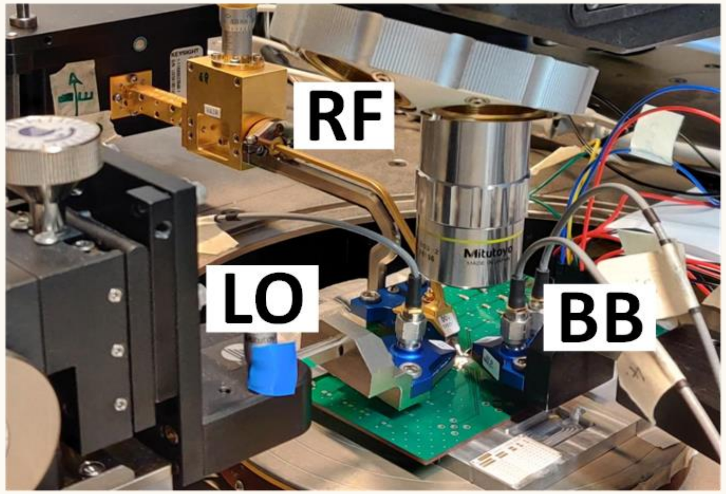


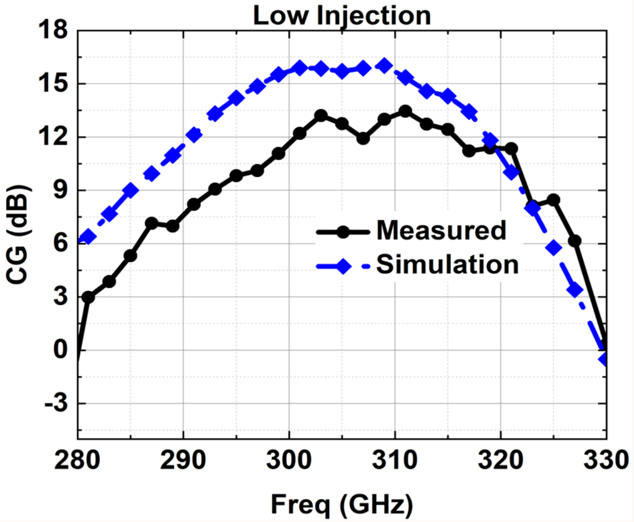


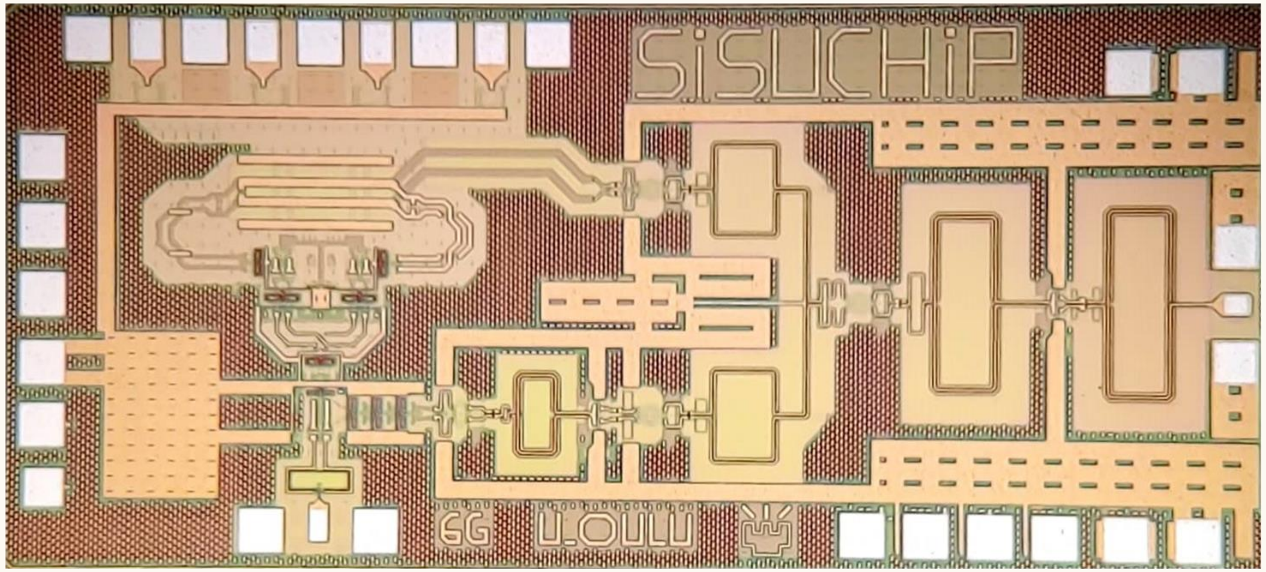


S. P. Singh, et al., "A 300-320 GHz Sliding-IF I/Q Receiver Front-End in 130 nm SiGe Technology," IEEE RFIC Symp., 2023.

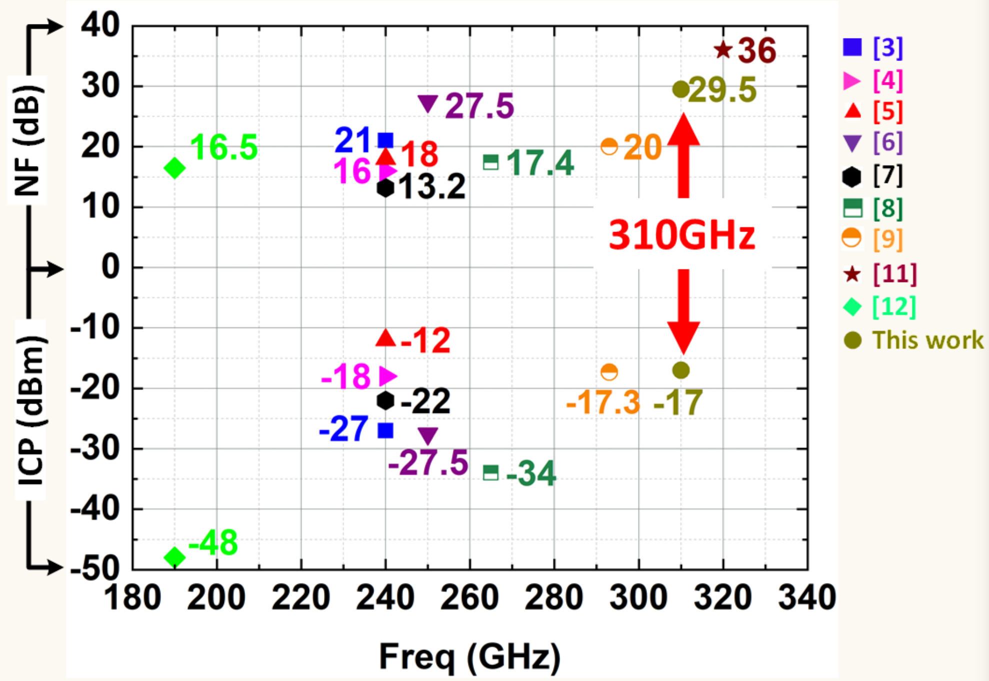
A 300-320 GHz Sliding-IF I/Q Receiver Front-End







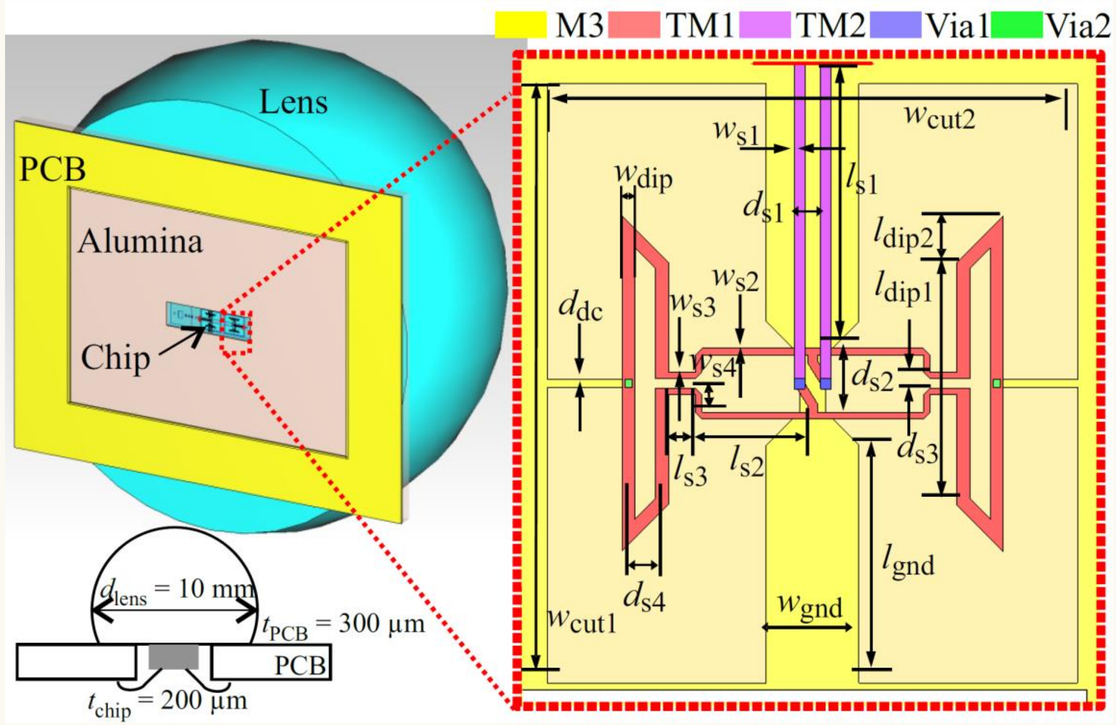
- 130nm SiGe BiCMOS
- 2.14 x 0.94 mm^2

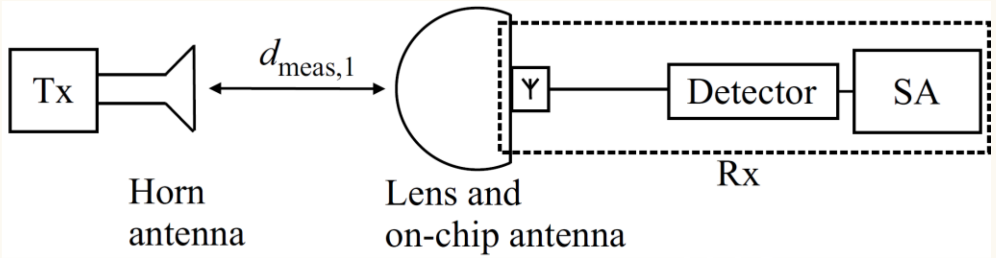


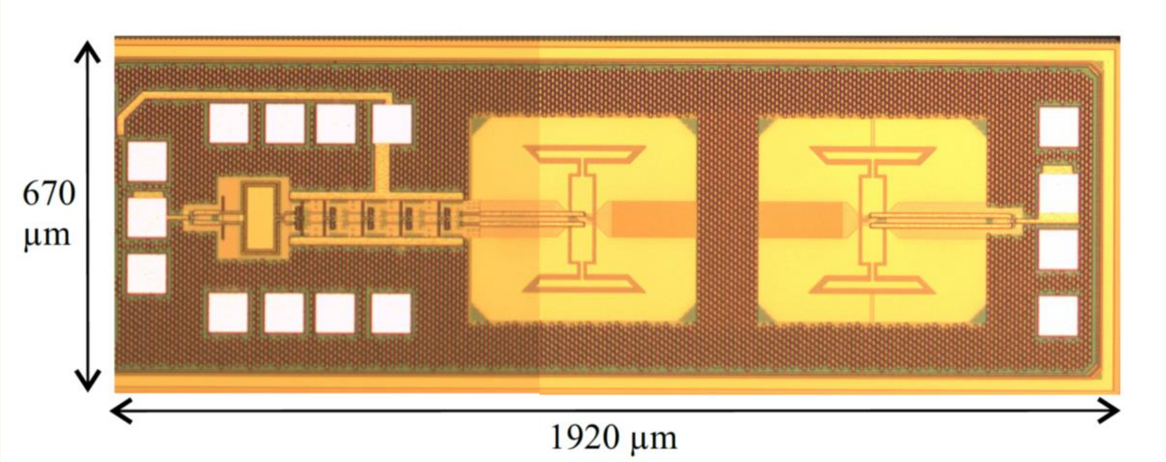
S. P. Singh, et al., "A 300-320 GHz Sliding-IF I/Q Receiver Front-End in 130 nm SiGe Technology," IEEE RFIC Symp., 2023.

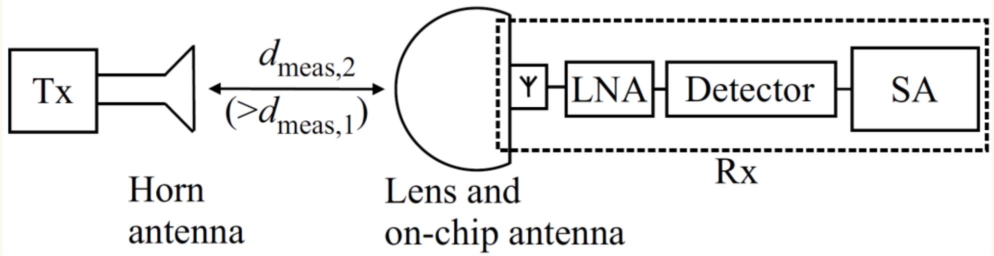
Sub-THz antenna & OTA measurement system

- **On-chip antenna feeding a lens @300GHz**









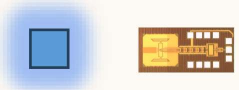
K. Rasilainen, et al., *EuCAP*, 2023

K. Rasilainen, et al., *ARFTG Microwave Measurement Conference*, 2023

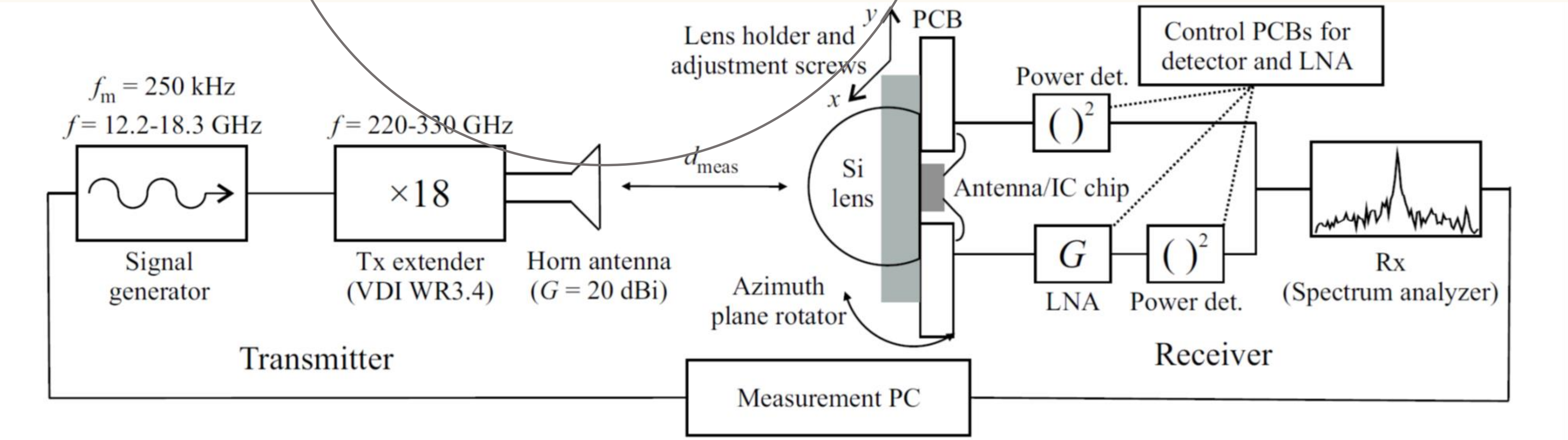
K. Rasilainen, et al., accepted to Trans. Microwave Theory and Tech., 2023

Sub-THz antenna & OTA measurement system

- **Lens & on-chip antenna combo measured using a power detector ~300GHz**
- **10mm silicon lens with >20dB gain**



10X



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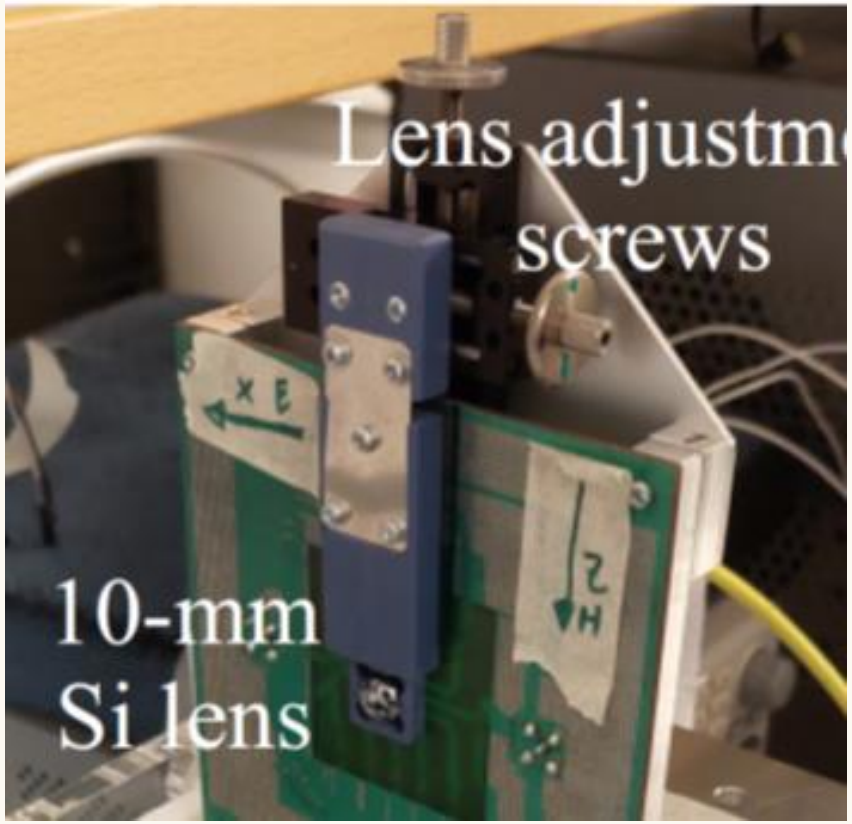
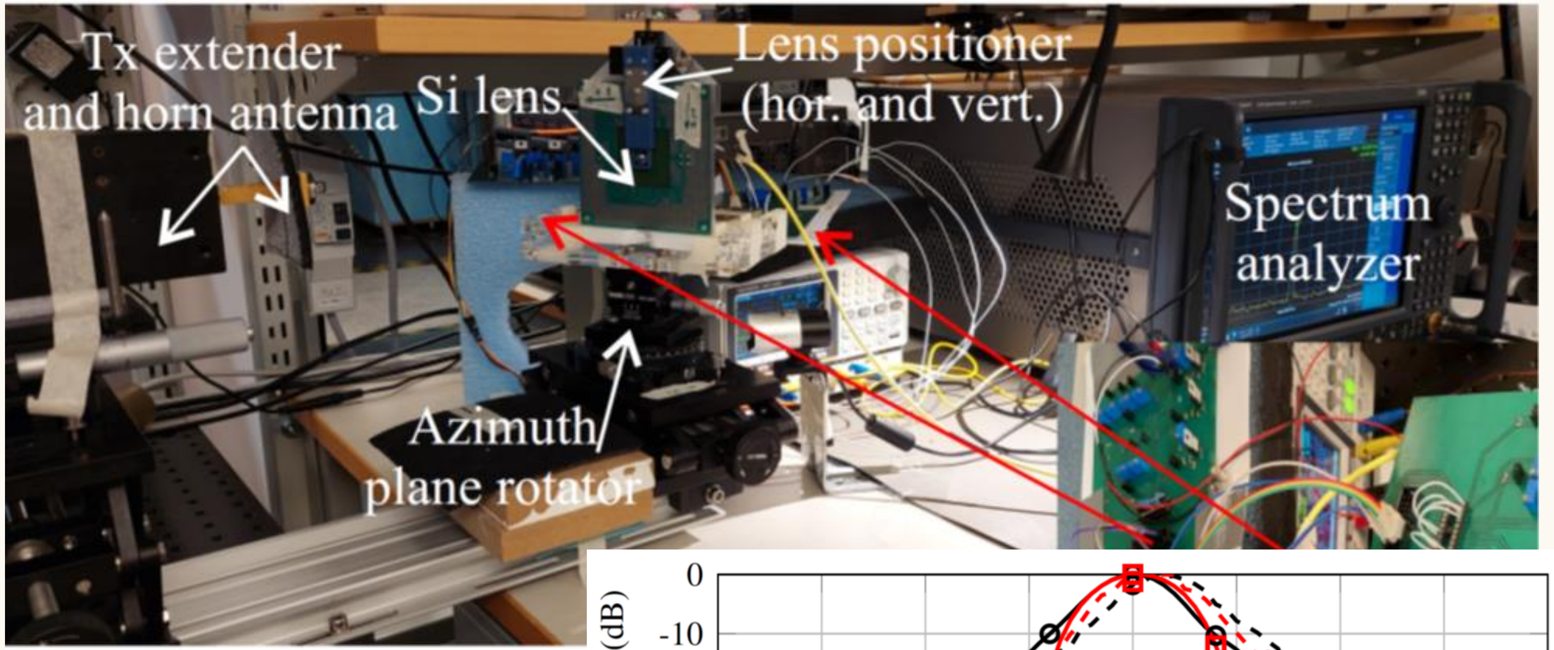
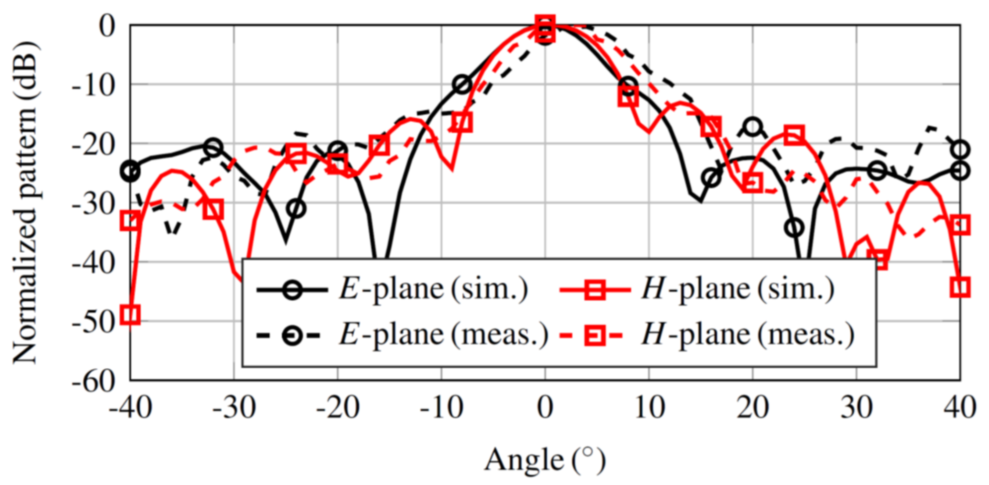
Sub-THz antenna & OTA measurement system

- **Lab setup and beam patterns**







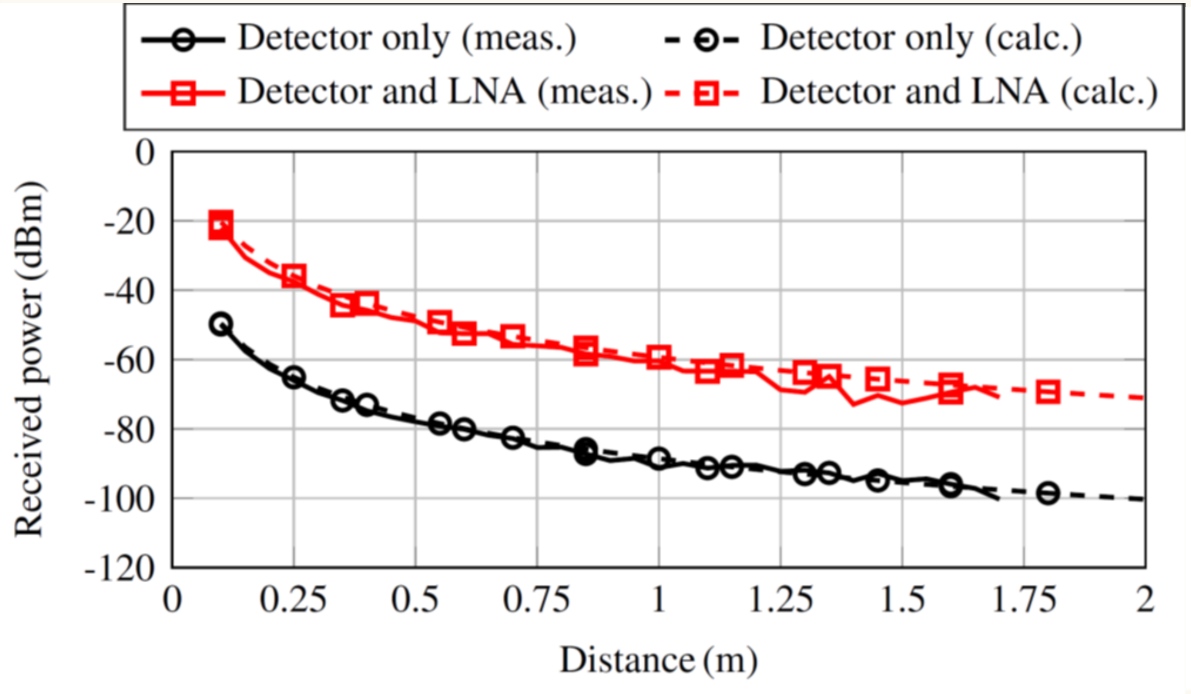
K. Rasilainen, et al., *EuCAP*, 2023

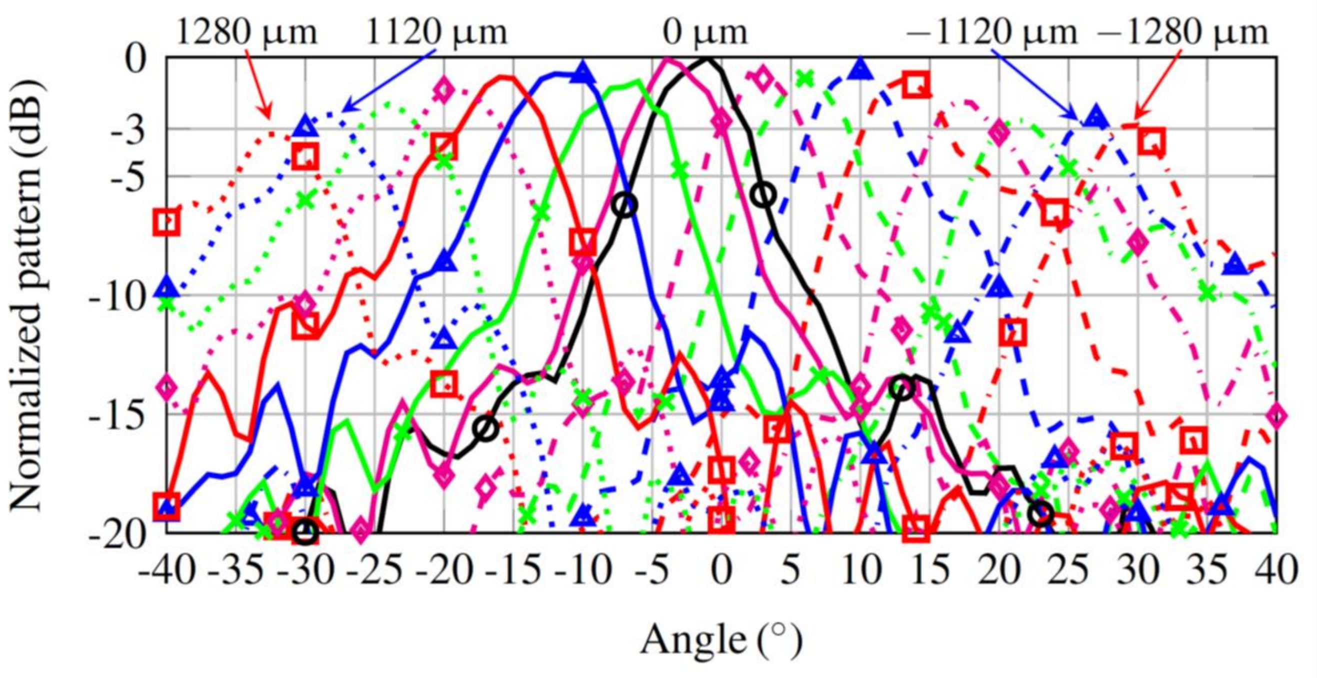
K. Rasilainen, et al., *ARFTG Microwave Measurement Conference*, 2023

K. Rasilainen, et al., accepted to Trans. Microwave Theory and Tech., 2023

Sub-THz antenna & OTA measurement system

- **Measured and analyzed received powers for system with and without LNA**
- **Mechanical beam steering**





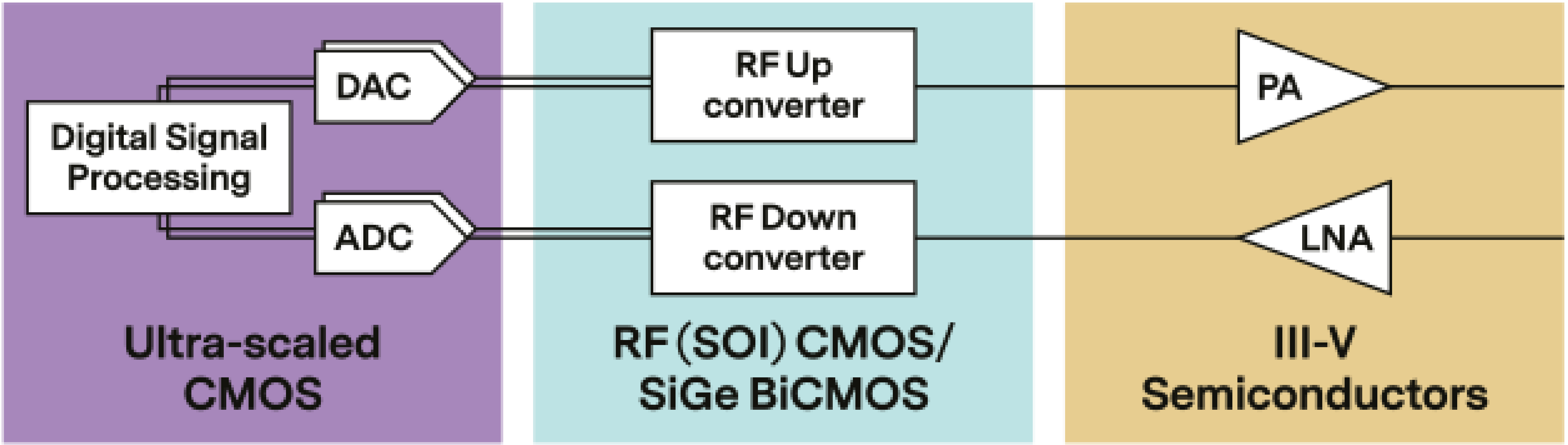
K. Rasilainen, et al., *EuCAP*, 2023

K. Rasilainen, et al., *ARFTG Microwave Measurement Conference*, 2023

K. Rasilainen, et al., accepted to Trans. Microwave Theory and Tech., 2023

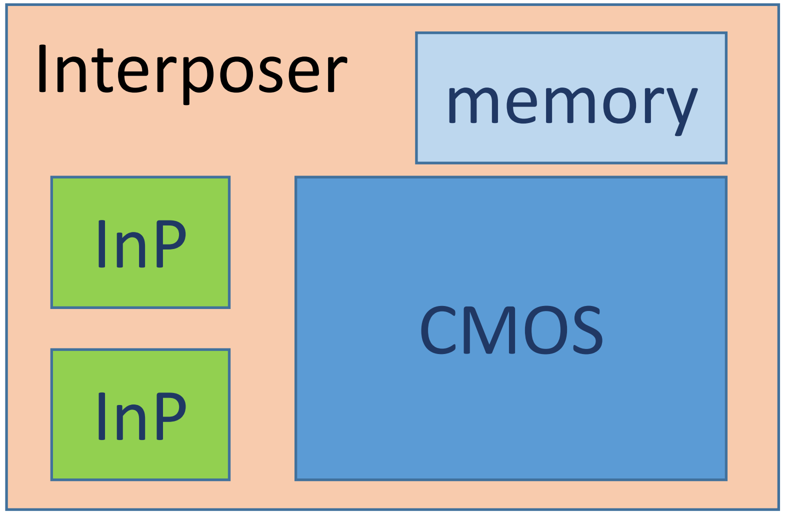
The Best Technology for Every Component?

- Heterogeneous integration / 3D packaging?

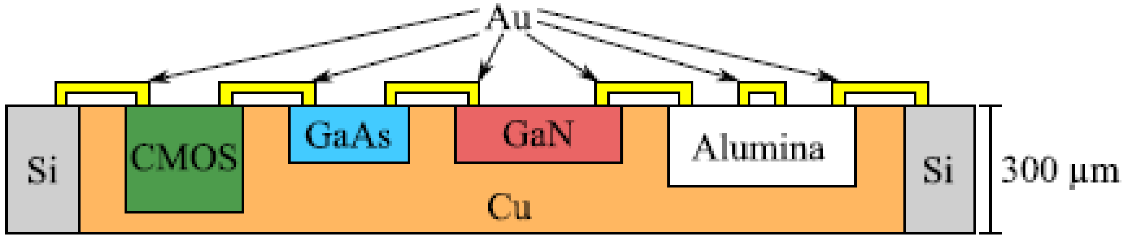


Chiplets and packaging

- 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>**



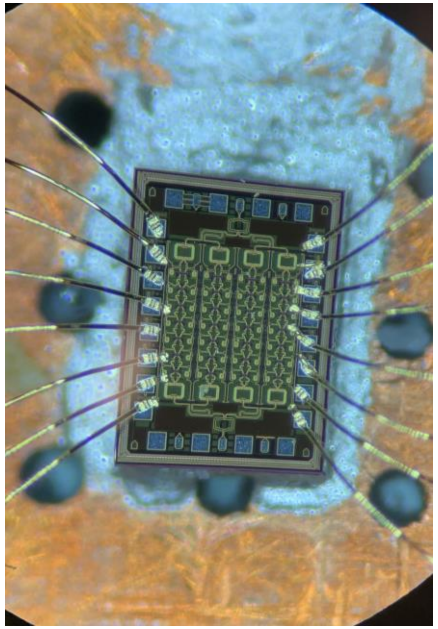
Photolithographically defined Au interconnects

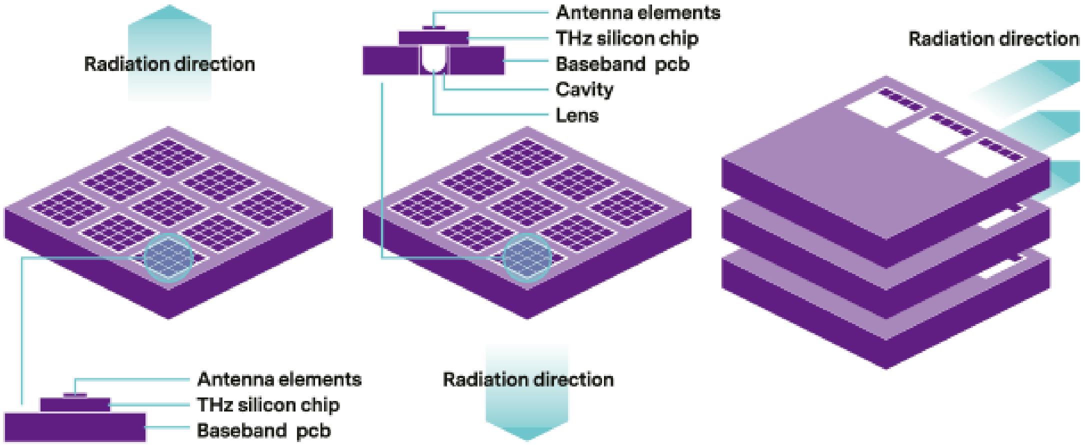


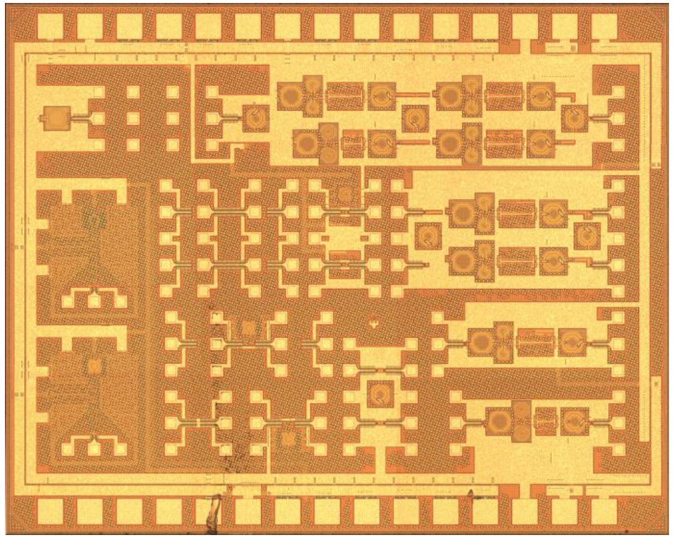
[Estrada et. al, IEEE TMTT Sep 2019]

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**
- Forward-looking thinking
- New use cases will come - after enablement
- Now with research - next with products

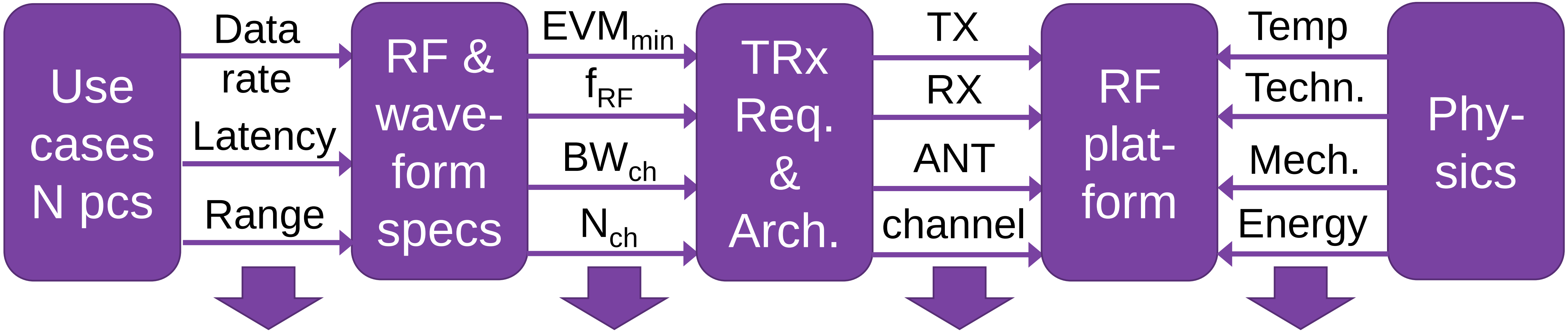


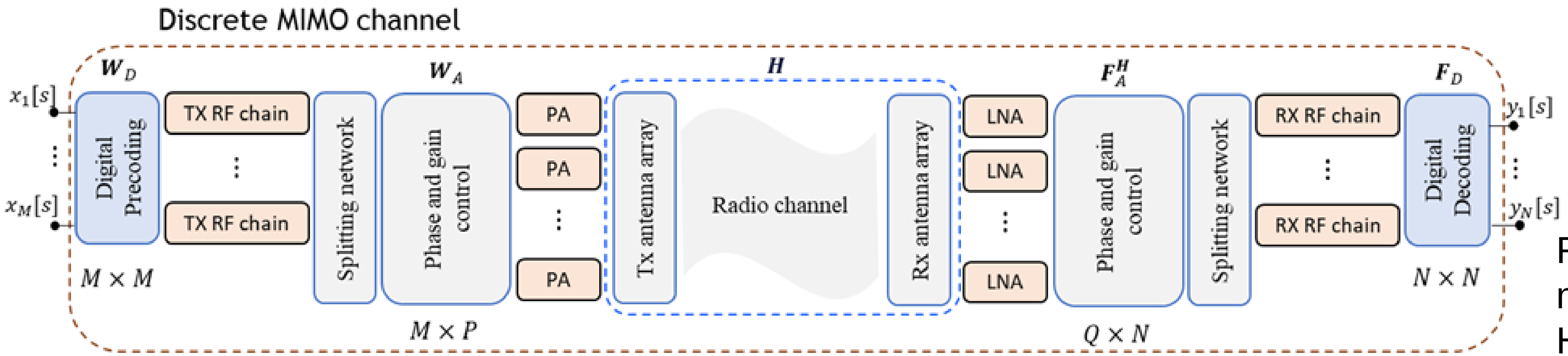




Simple when complex?

- 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
- Try to make RF TO LOOK IDEAL for the rest of the system as always – Maybe this is too much to asked this time

6G ?

Vision

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Thank you!

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