Implementational aspects of 6G transceivers

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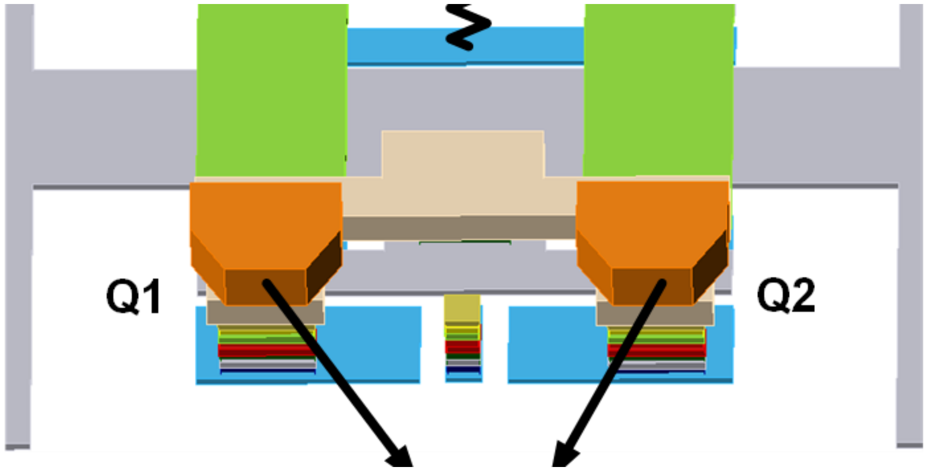
6G FLAGSHIP UNIVERSITY OF OULU

ACADEMY OF FINLAND

FLAGSHIP PROGRAMME

From devices to wireless systems



vs.

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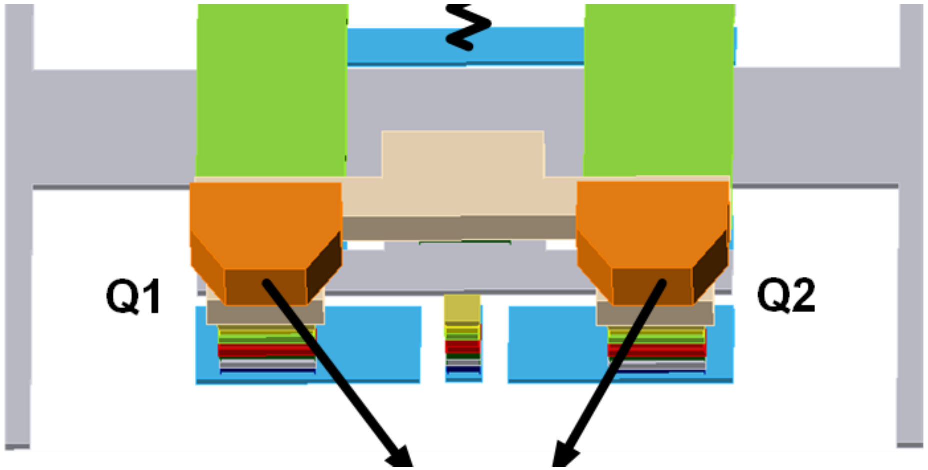

vs.

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

Stack of Wireless Systems

- Users and Applications
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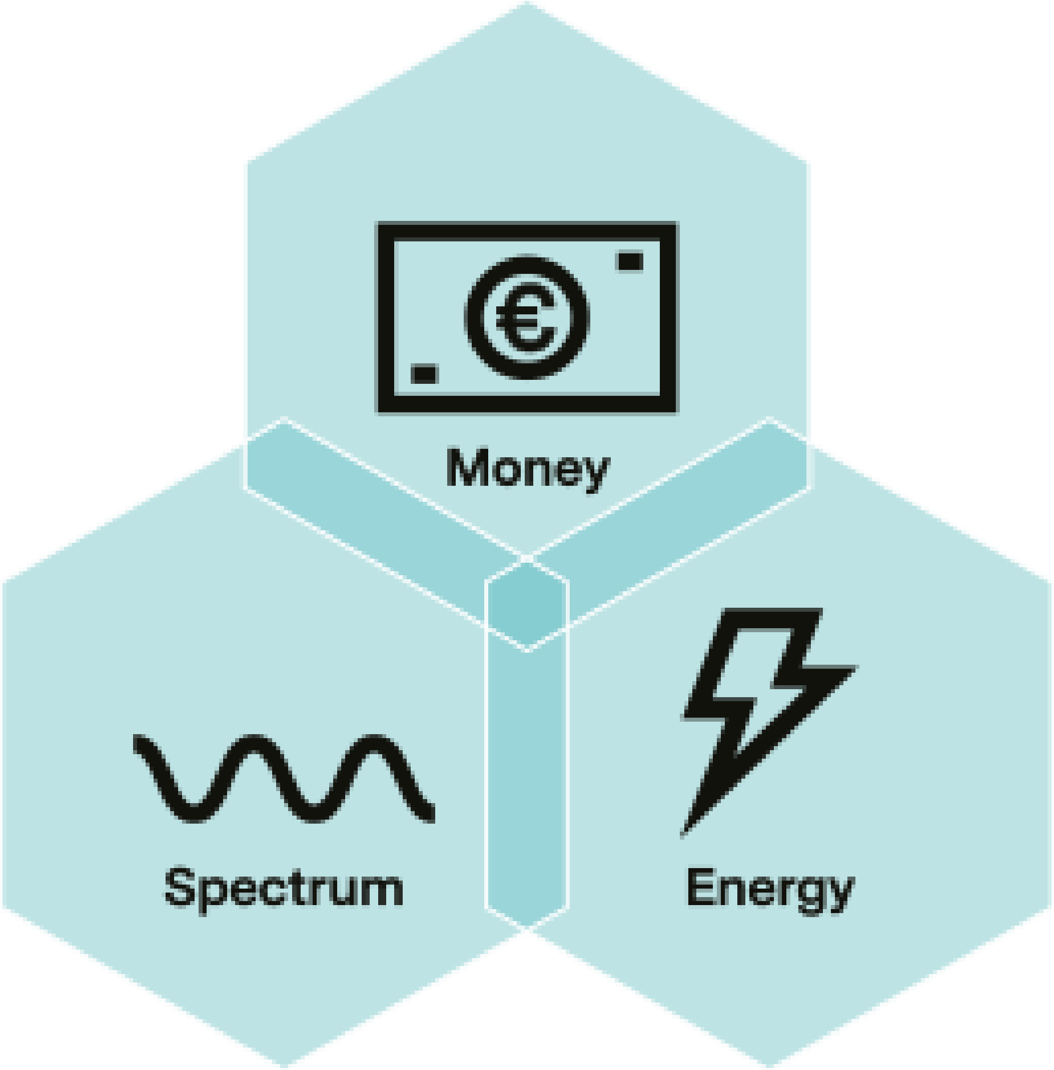
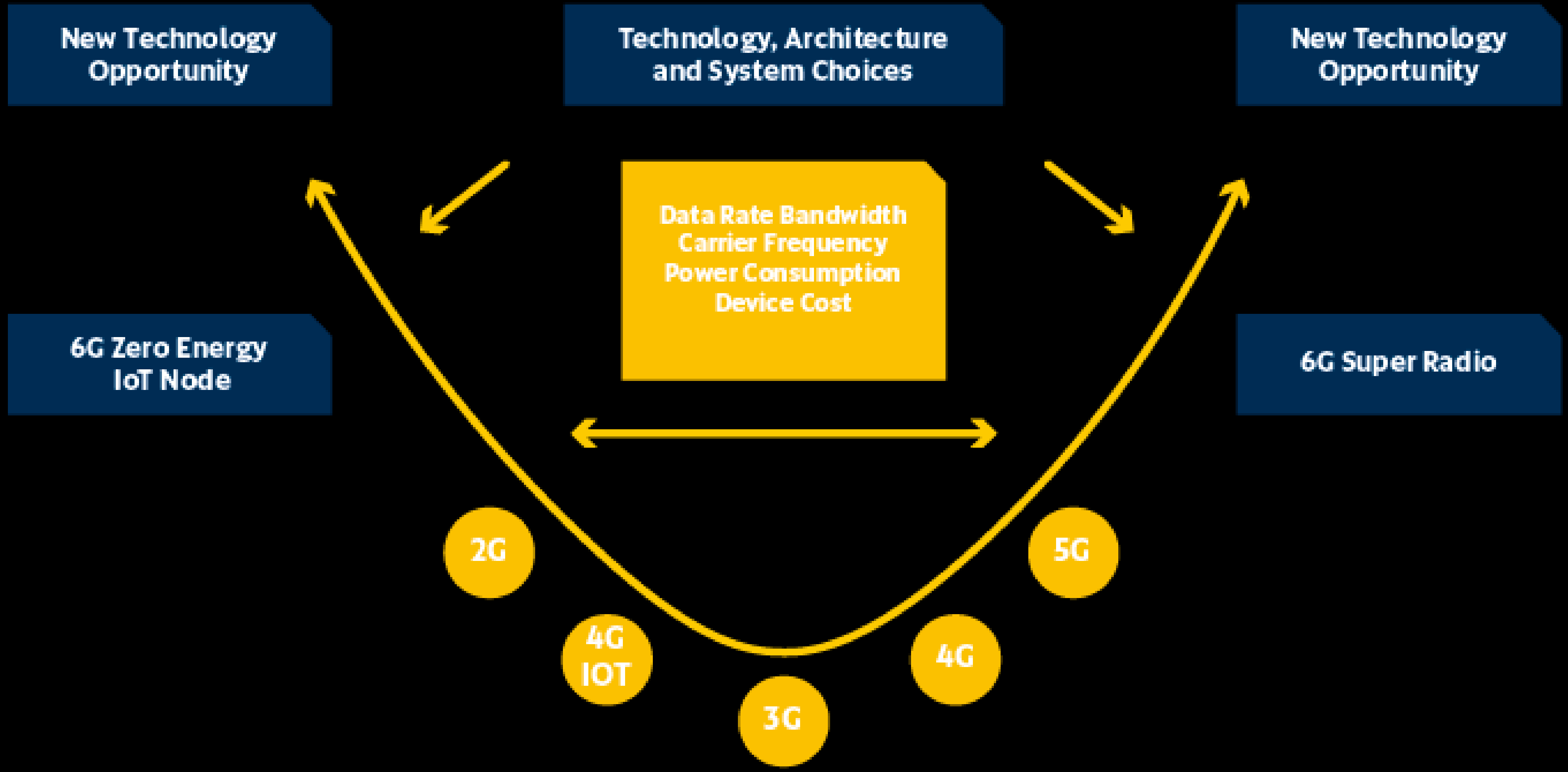
Constraints of wireless communications



What is challenging?



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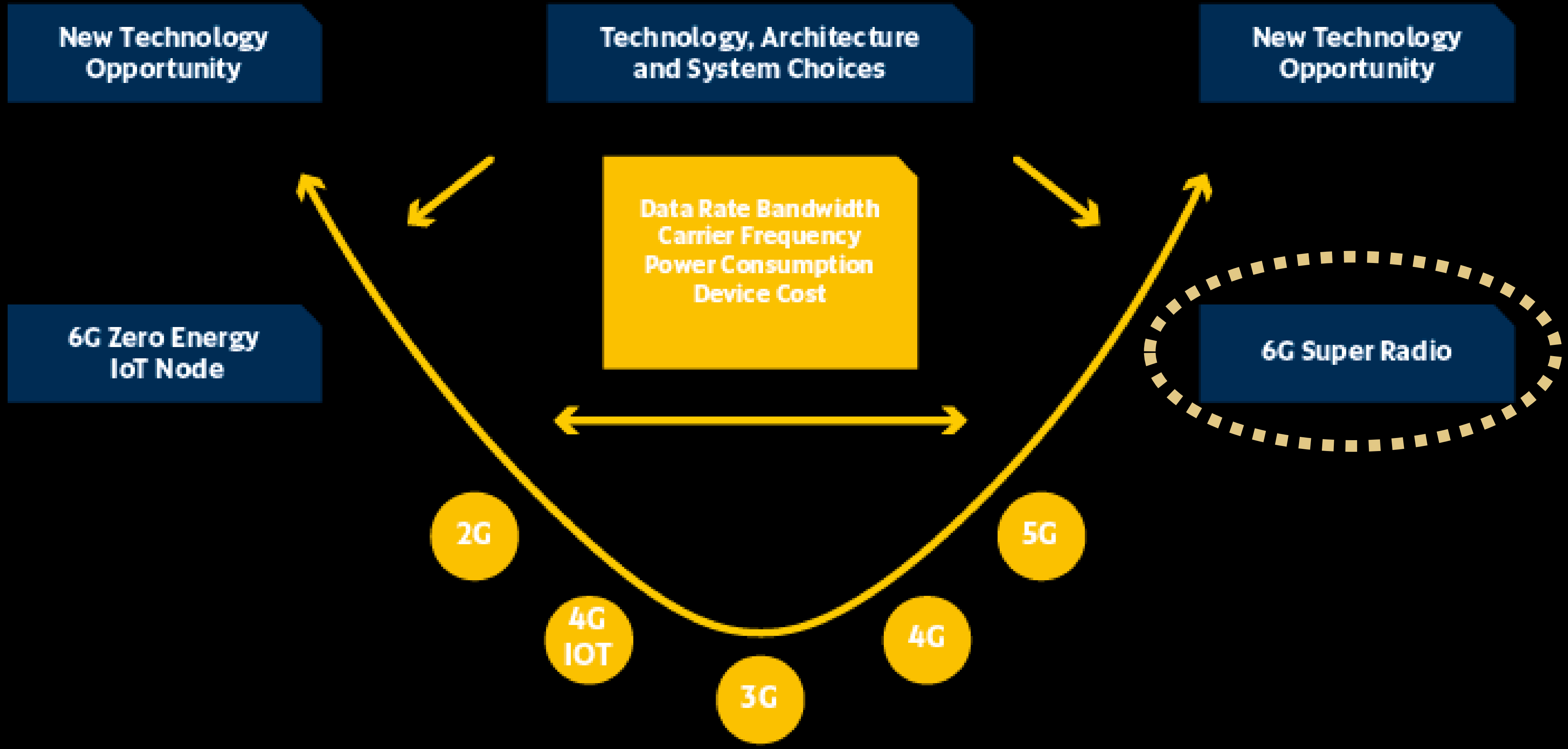


Exponential growth?

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

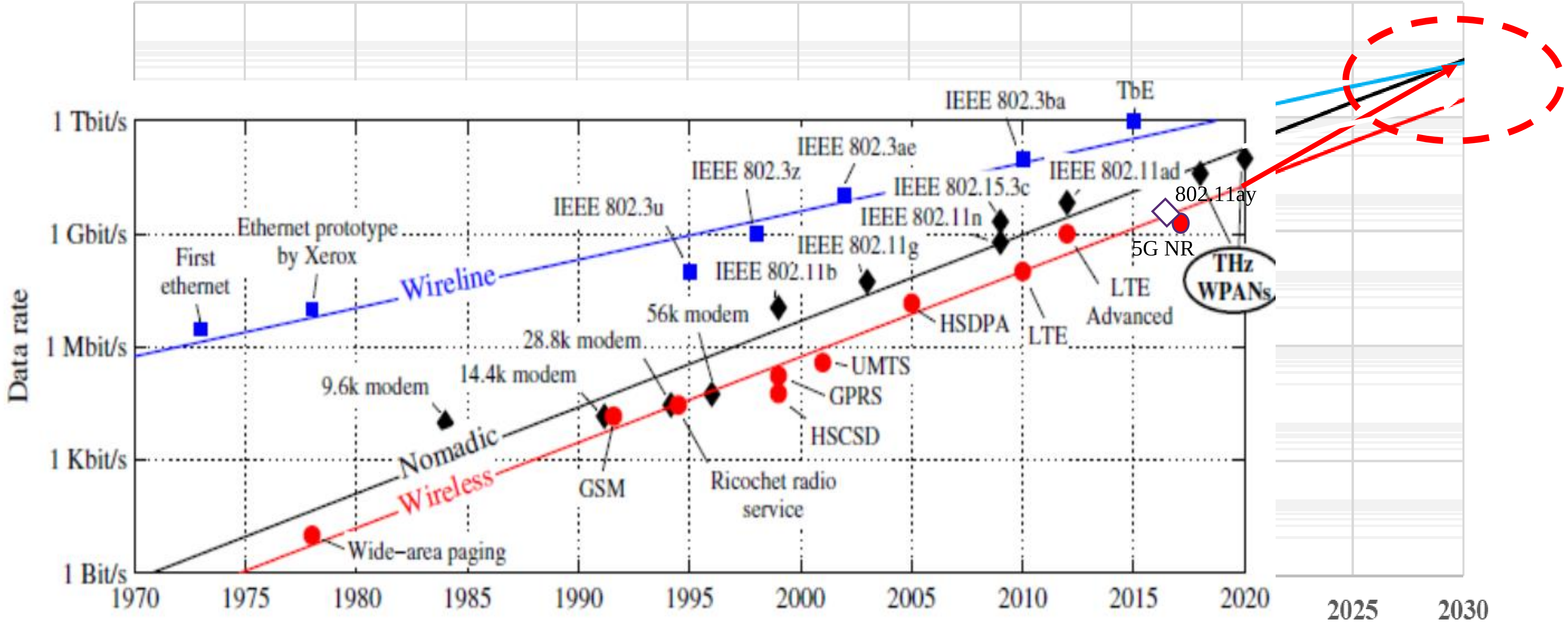


Figure 1 Development of data rates in wireline, nomadic and wireless systems (from [3])

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

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	Verticals?	CMOS/BiCMOS
6G	Improved Capacity	?	?

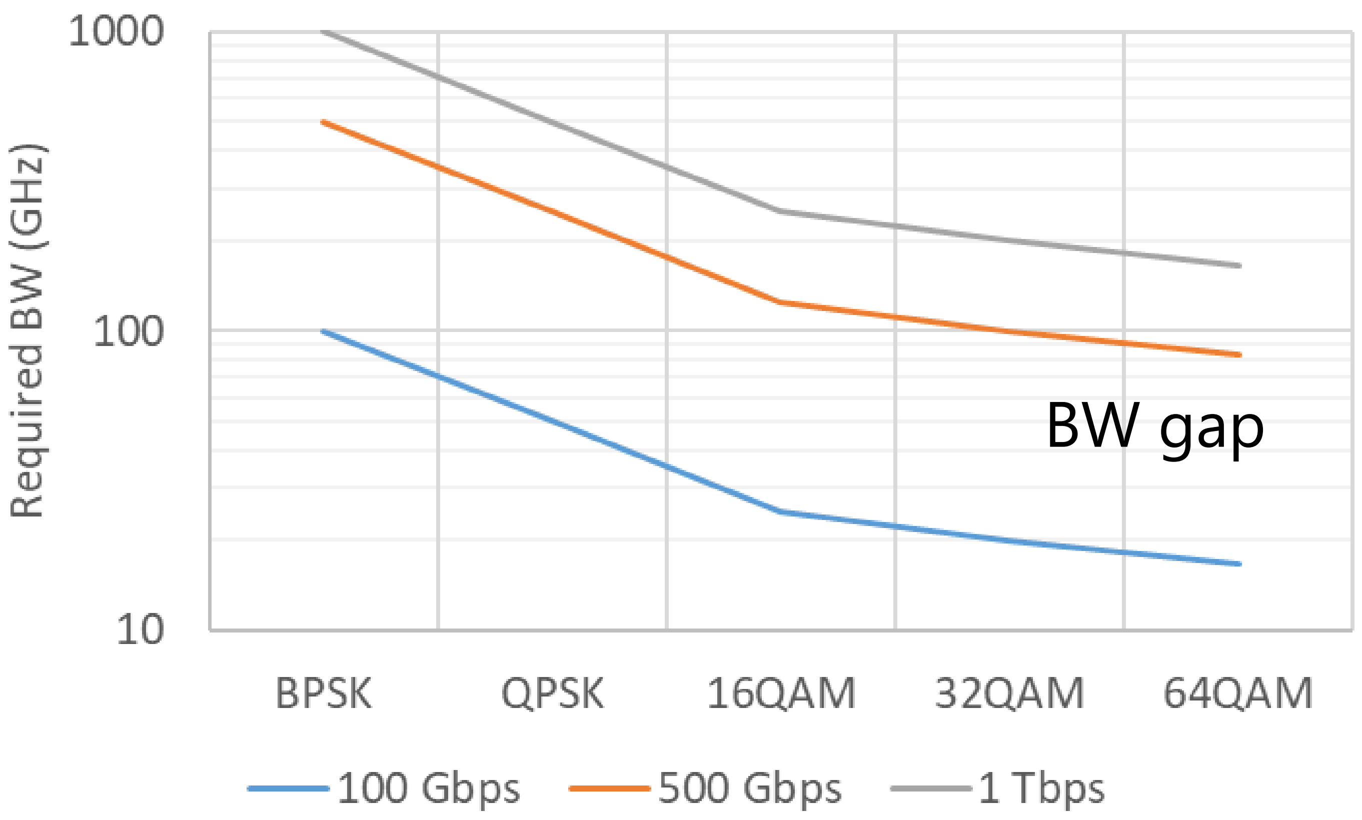
Initial Requirements for 6G Radio

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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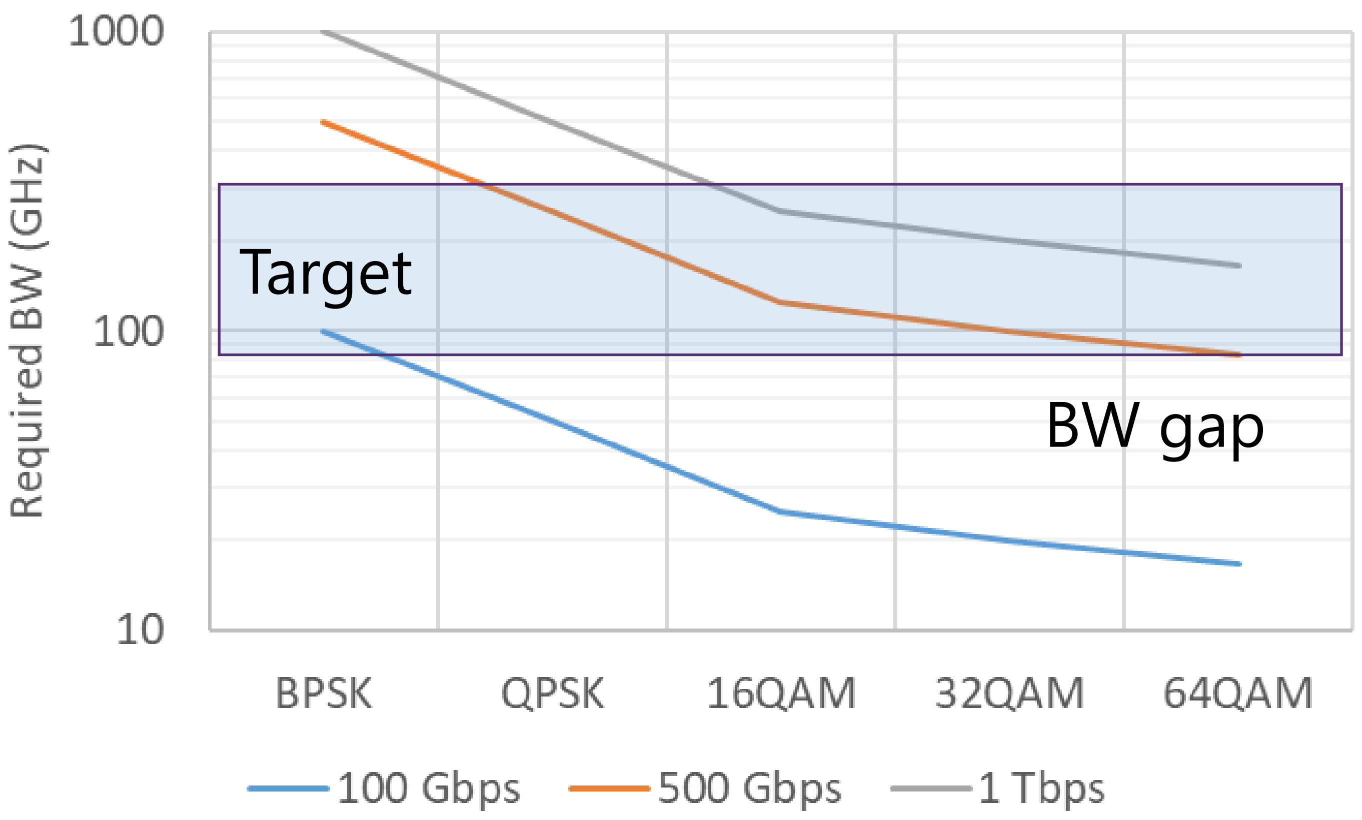

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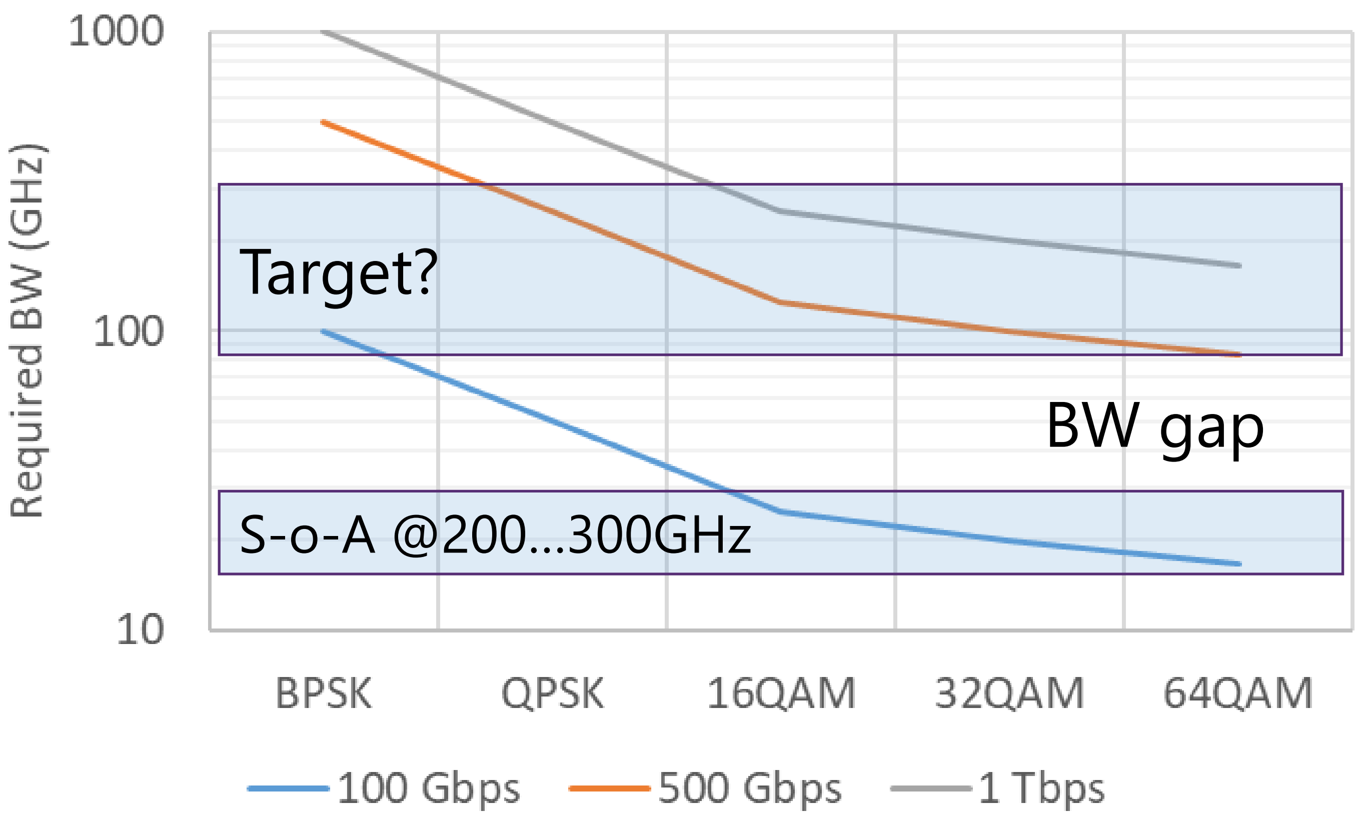
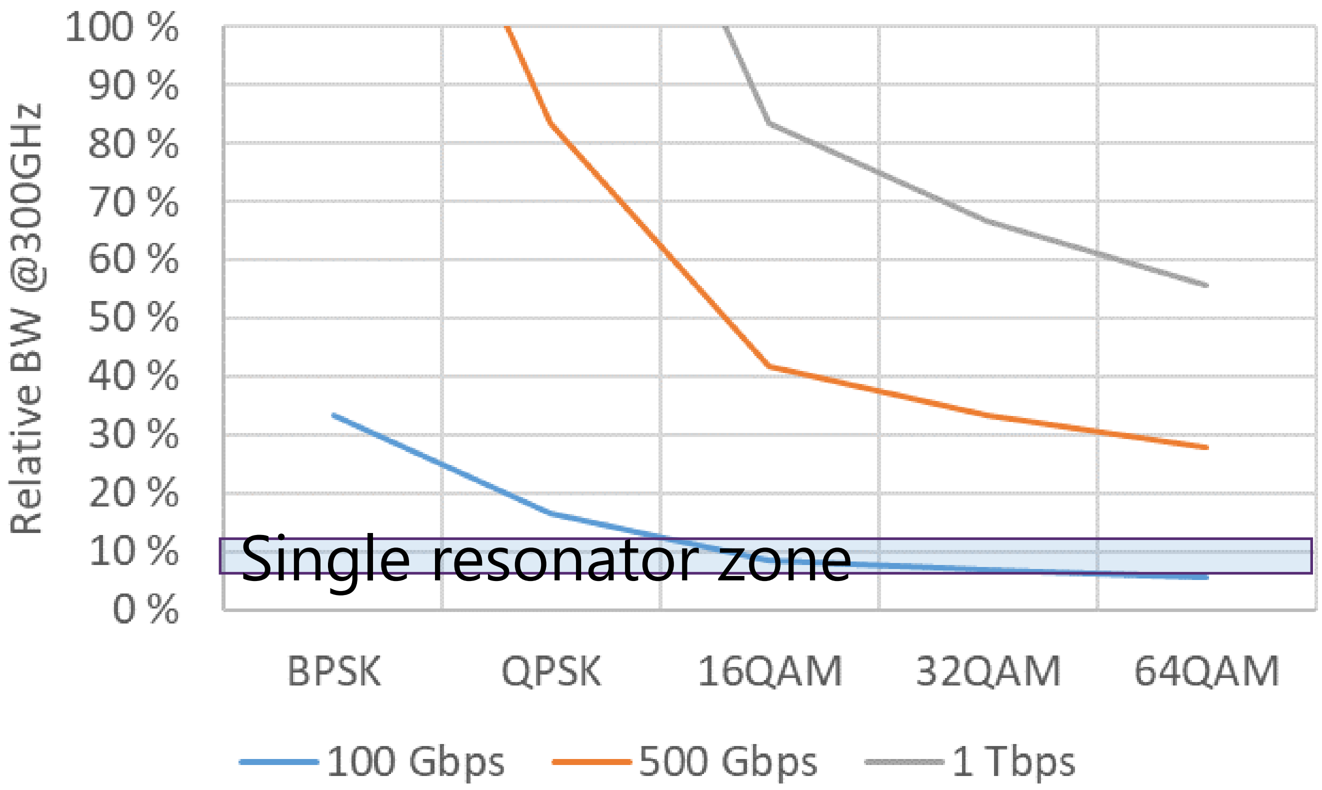


Relative Bandwidth for RF Design

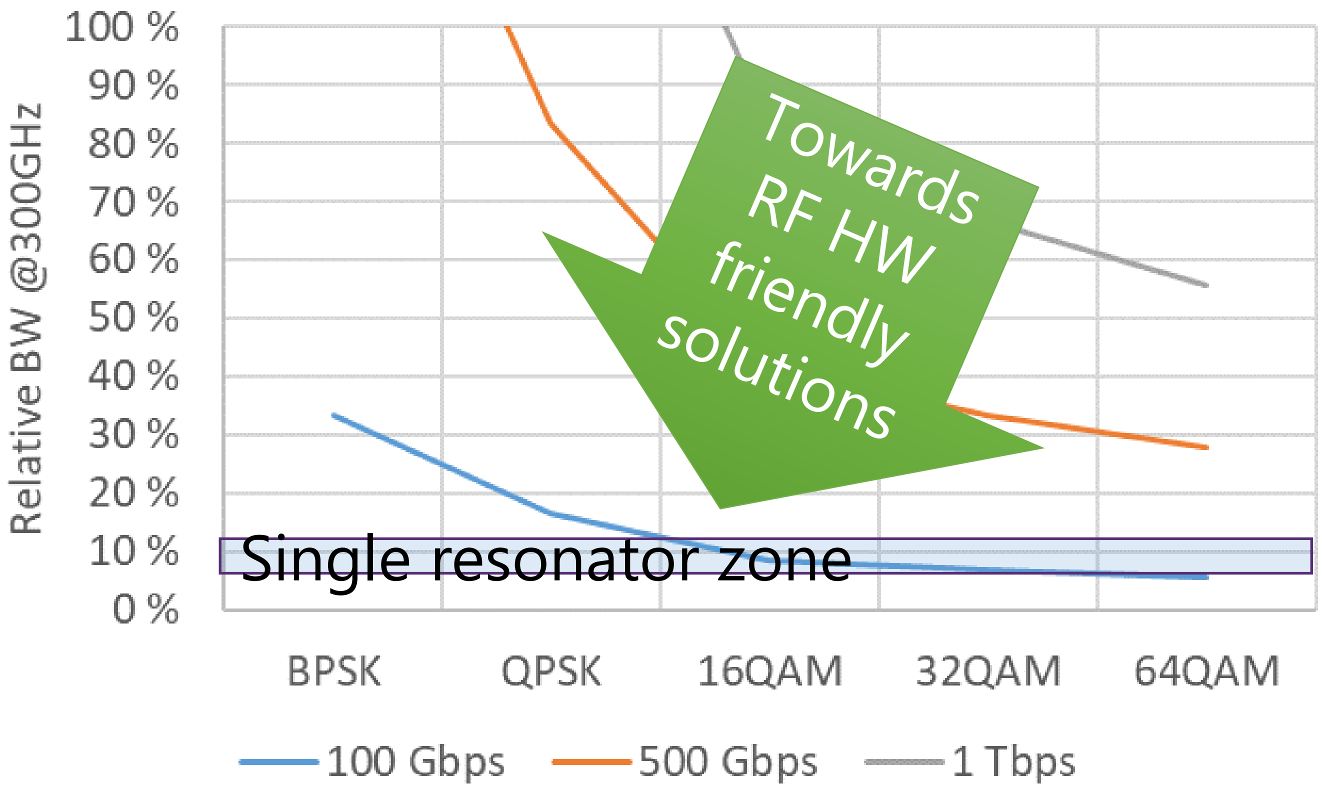
- Matters in RF design equally as absolute BW/carrier frequency
- Integrated resonators with Q~10



Example @300GHz

Relative Bandwidth for RF Design

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

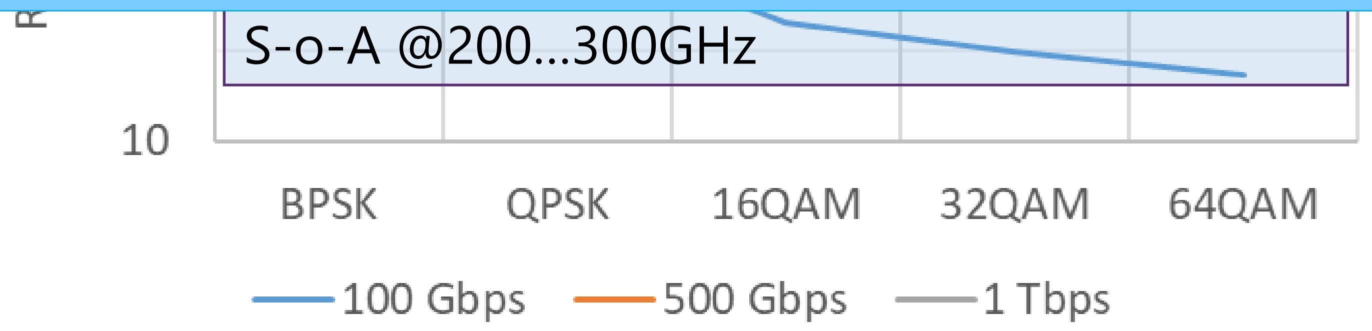


Number of orthogonal radio channels?

Bandwidth for 1Tbps

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

6…30x multi-user gains needed for **1Tbps** network capacity @300GHz carrier and 30GHz channel BW depending on the waveform



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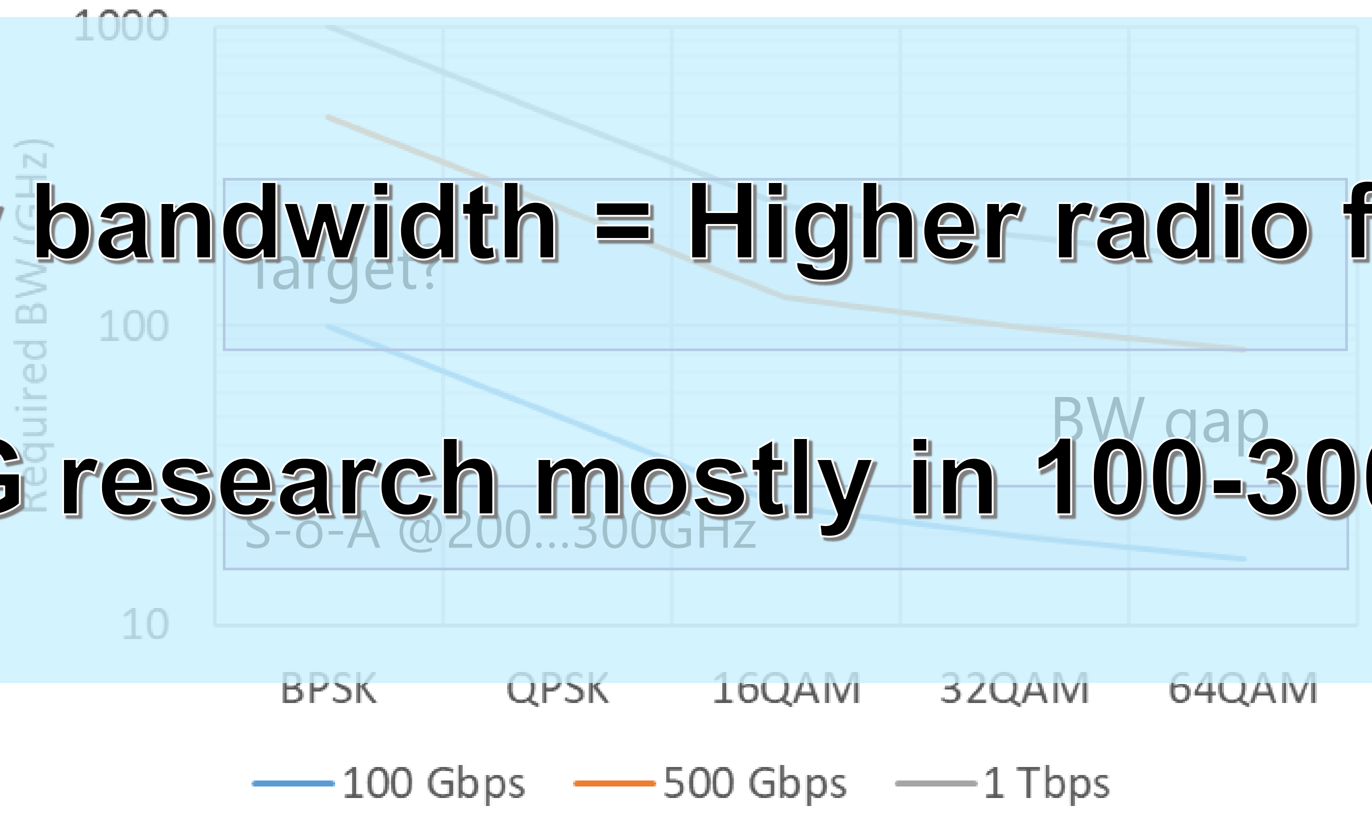
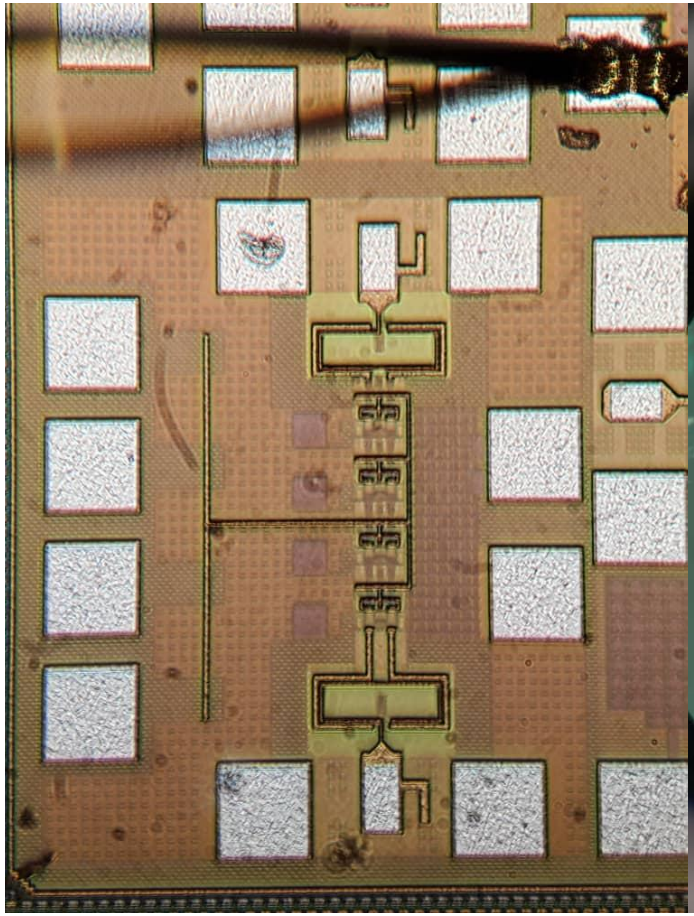


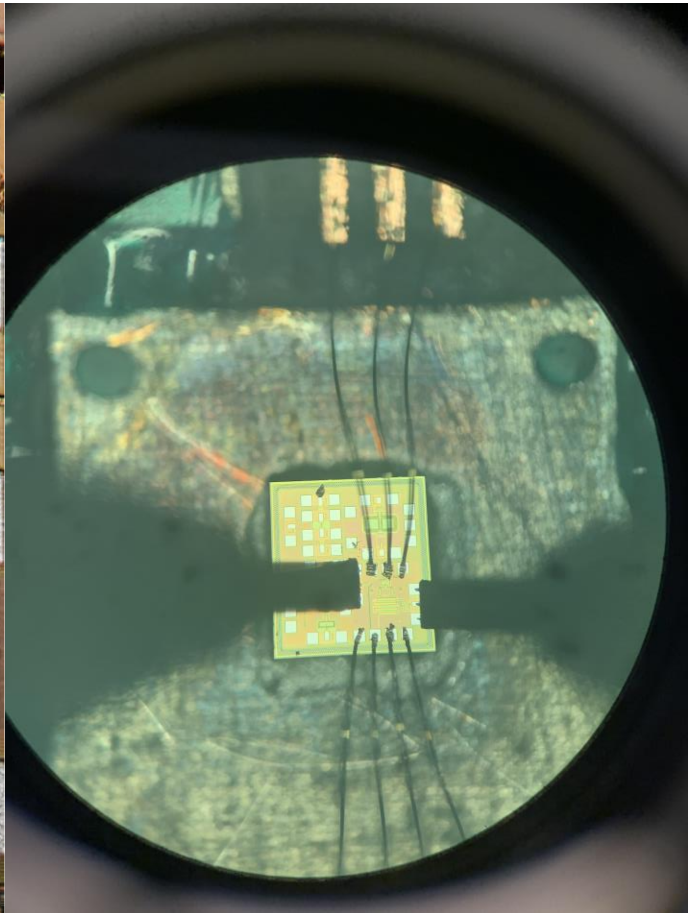
Larger bandwidth = Higher radio frequency

6G research mostly in 100-300GHz

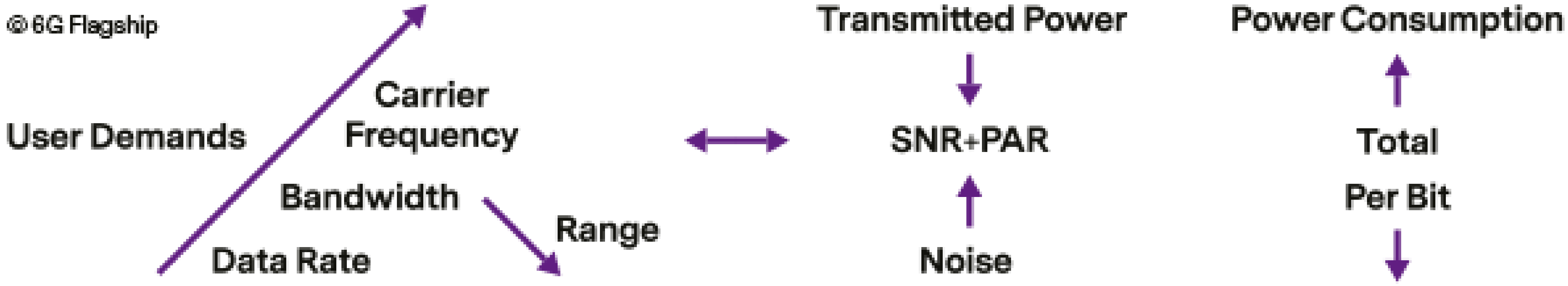
Enablers for wireless era

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



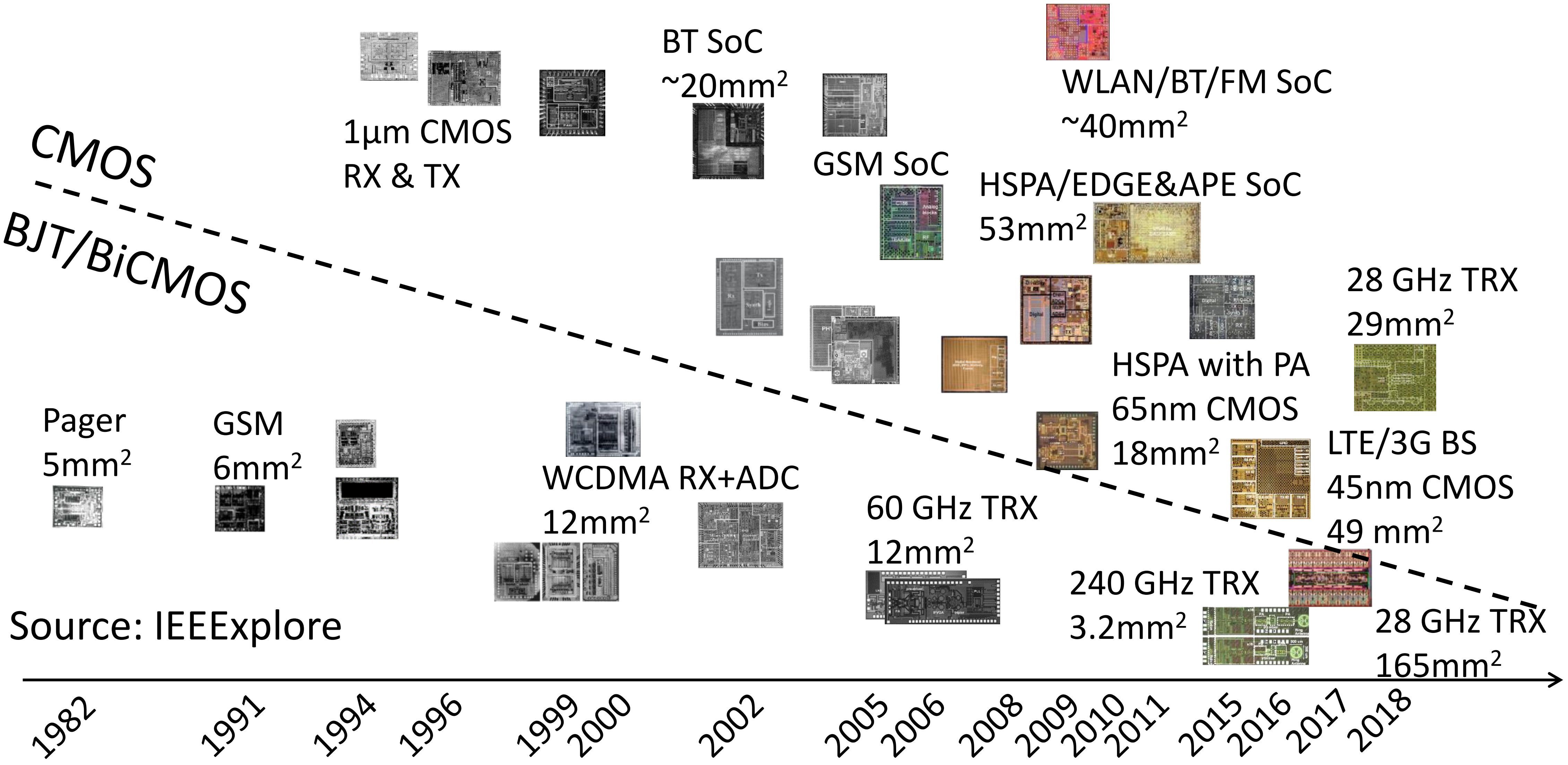


Tradeoffs

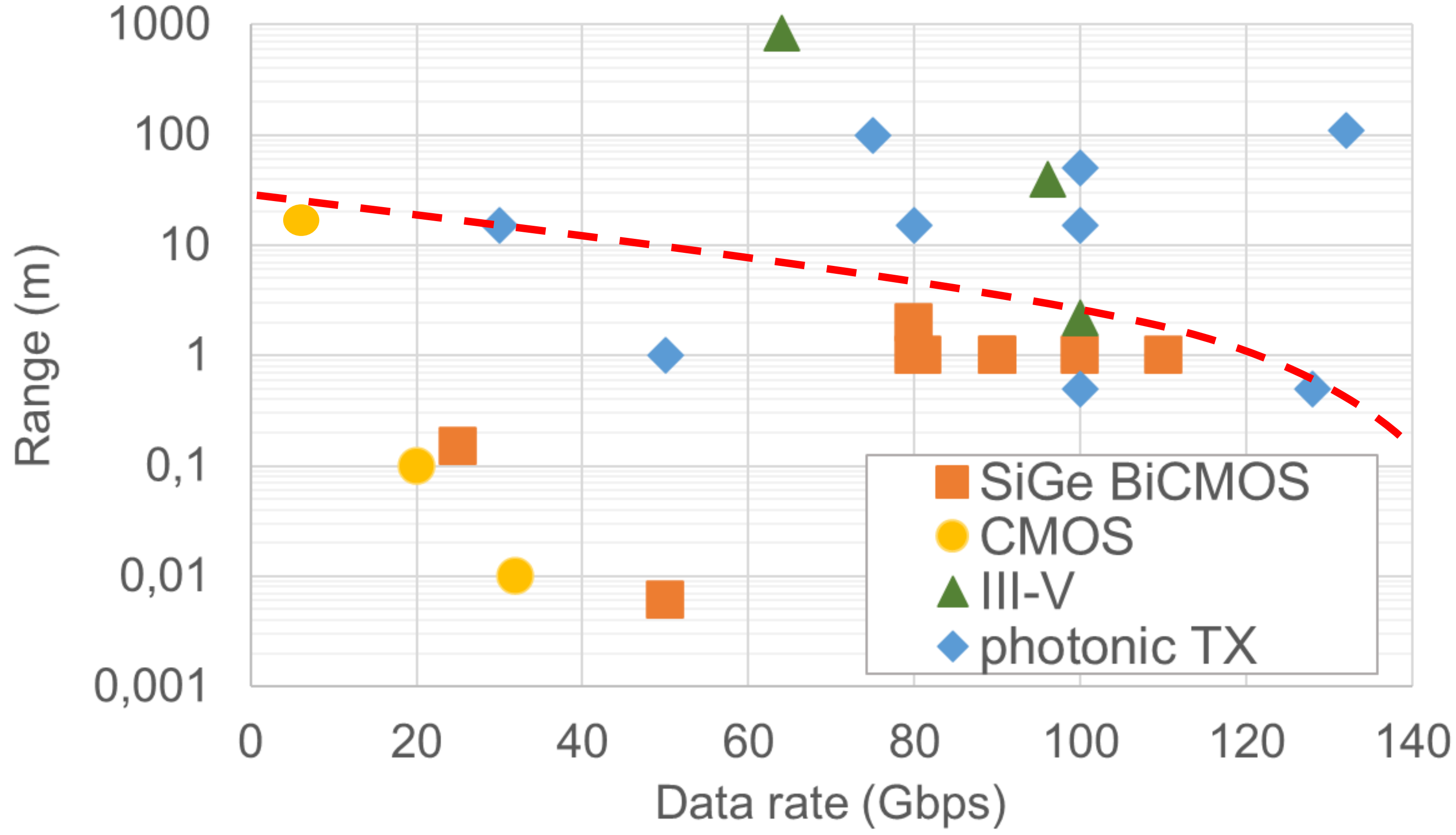


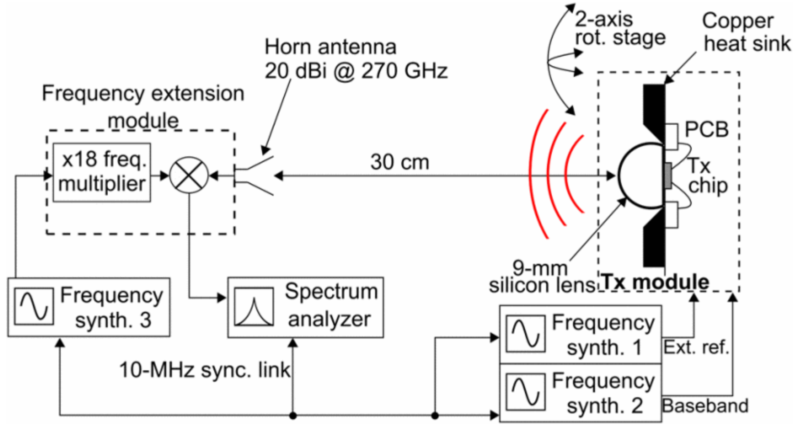
Key tradeoffs in radio system design toward higher data rates.

Transceivers and semiconductors up to early 5G

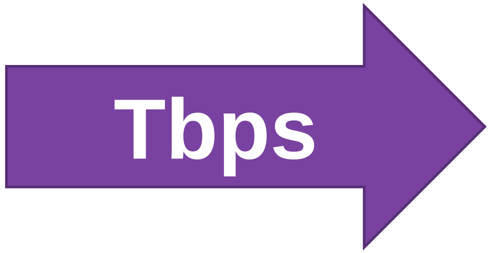


Test beds towards Tbps - technology comparison

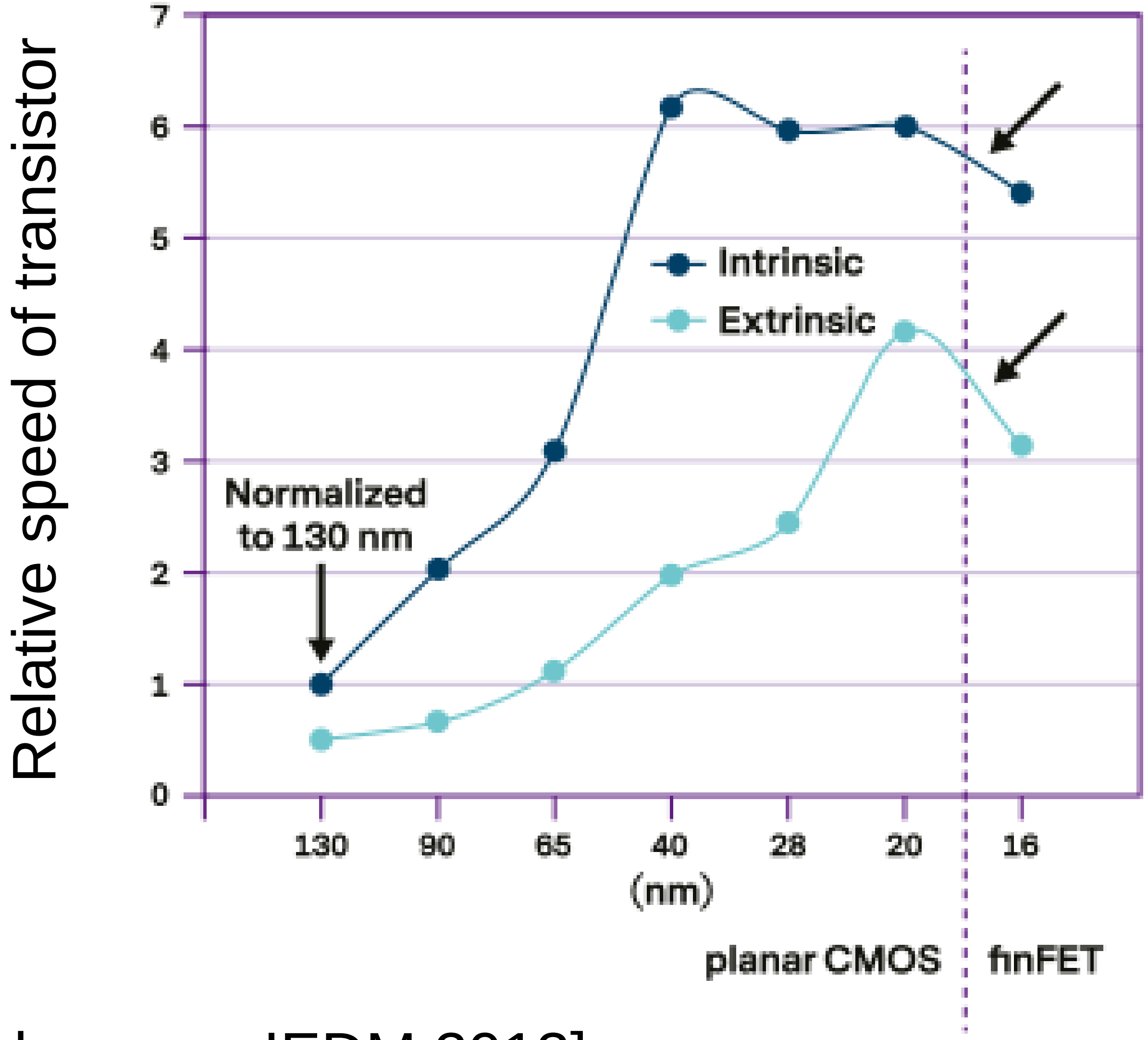




[Rodríguez-Vázquez, et al., 6G SUMMIT 2020]

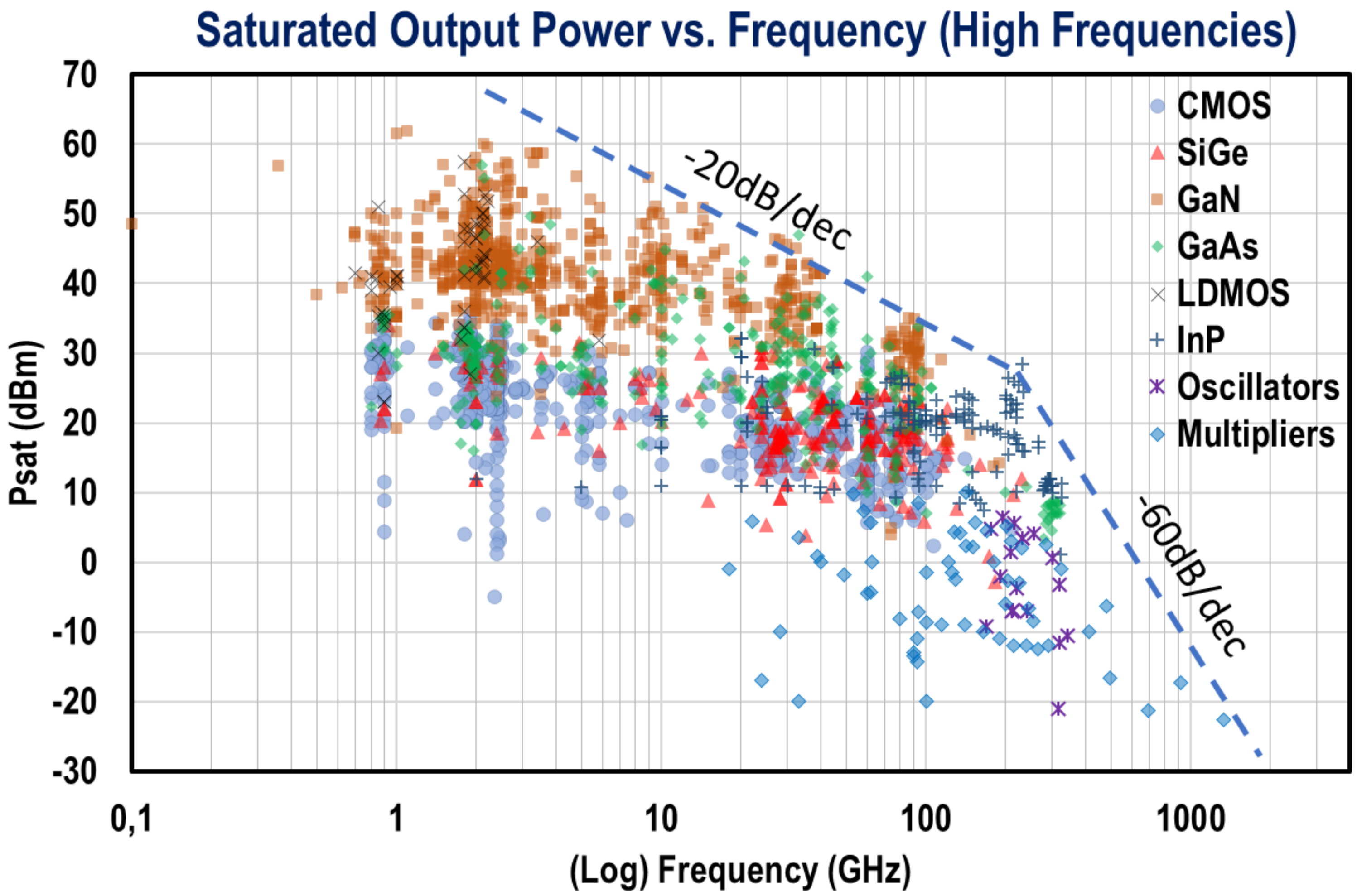


Semiconductor scaling not anymore generally granted



[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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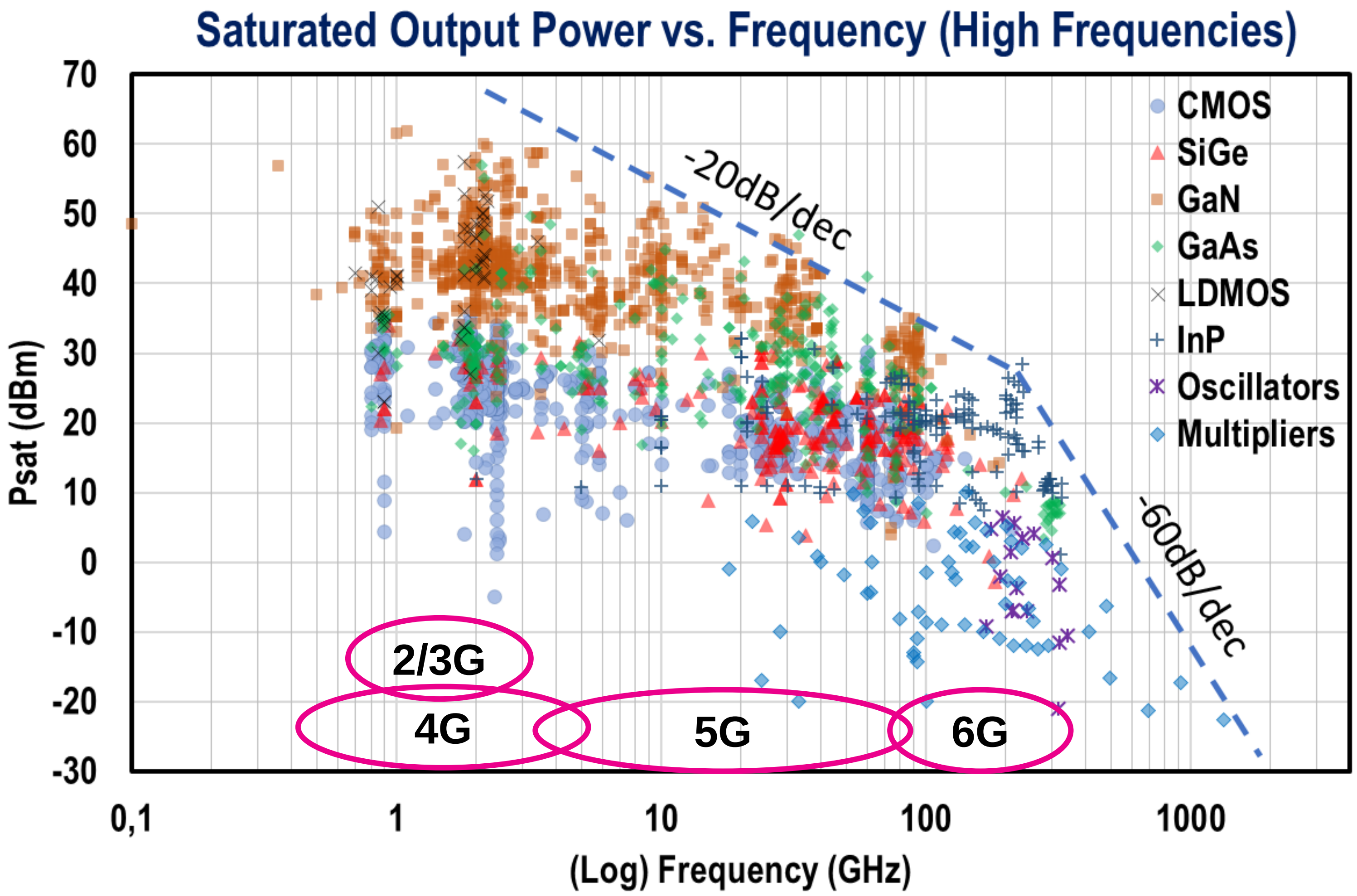

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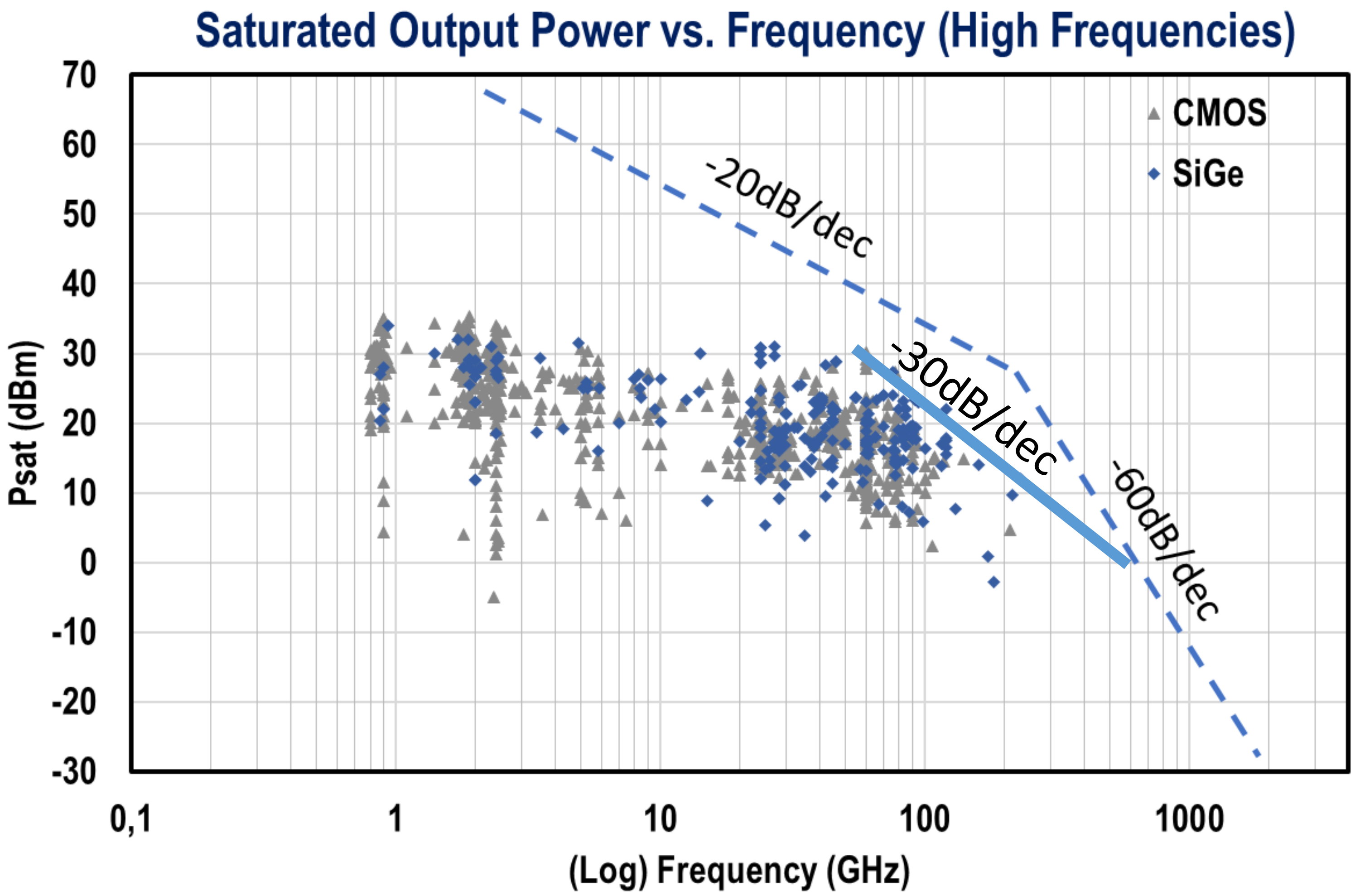
Output power – silicon



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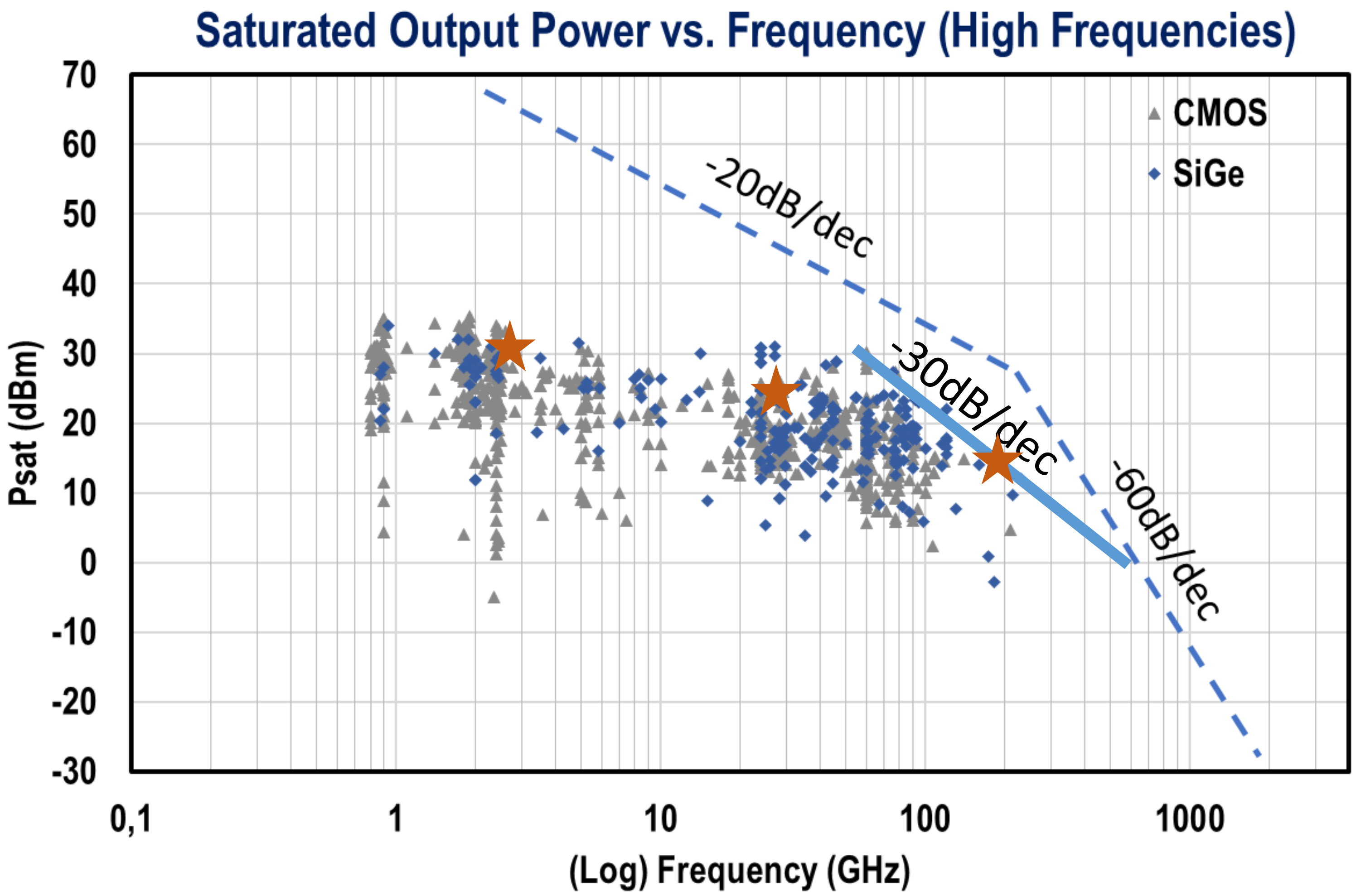
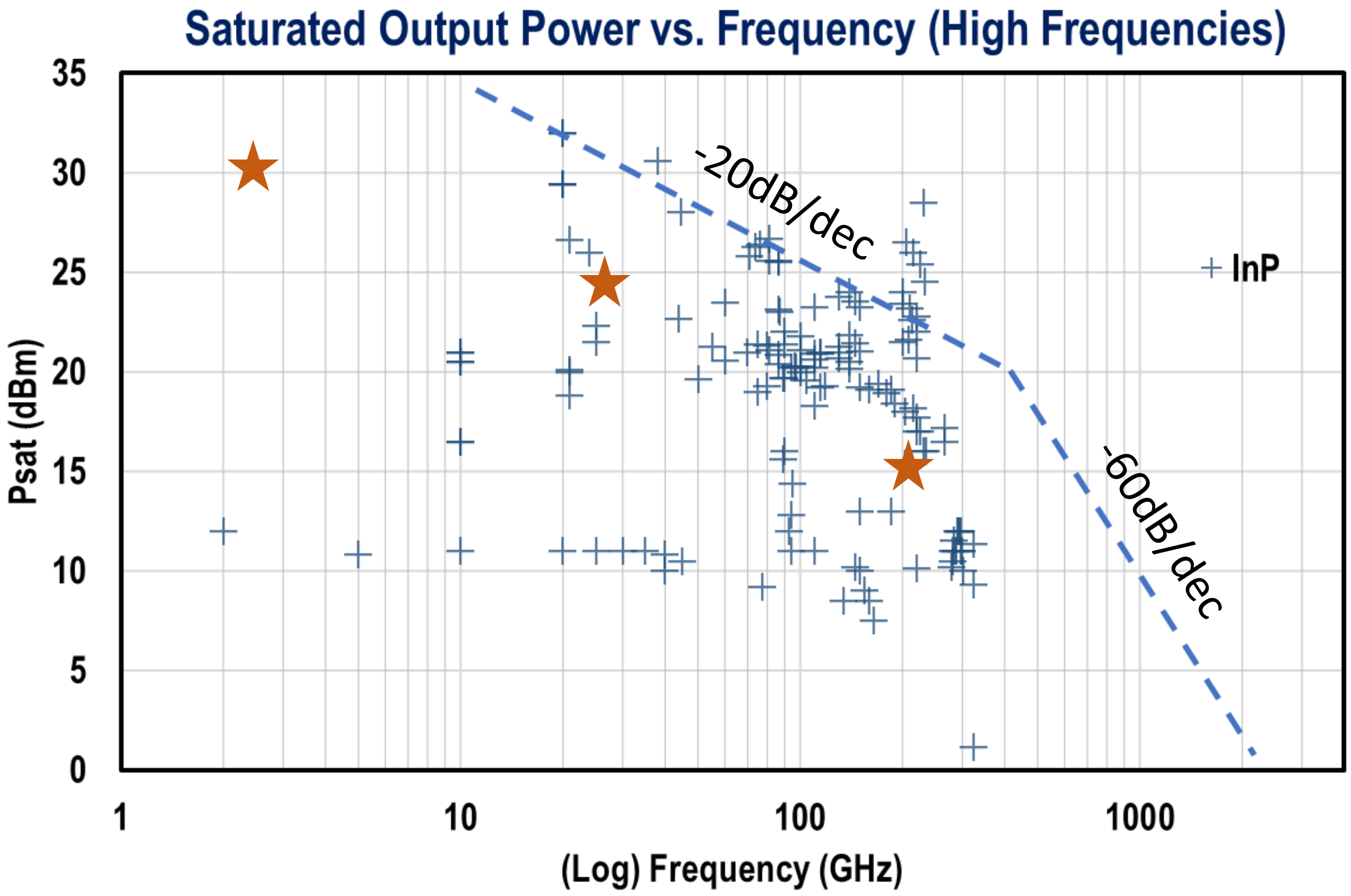


Examples in system calc ★

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

Output power – InP



Examples in system calc ★

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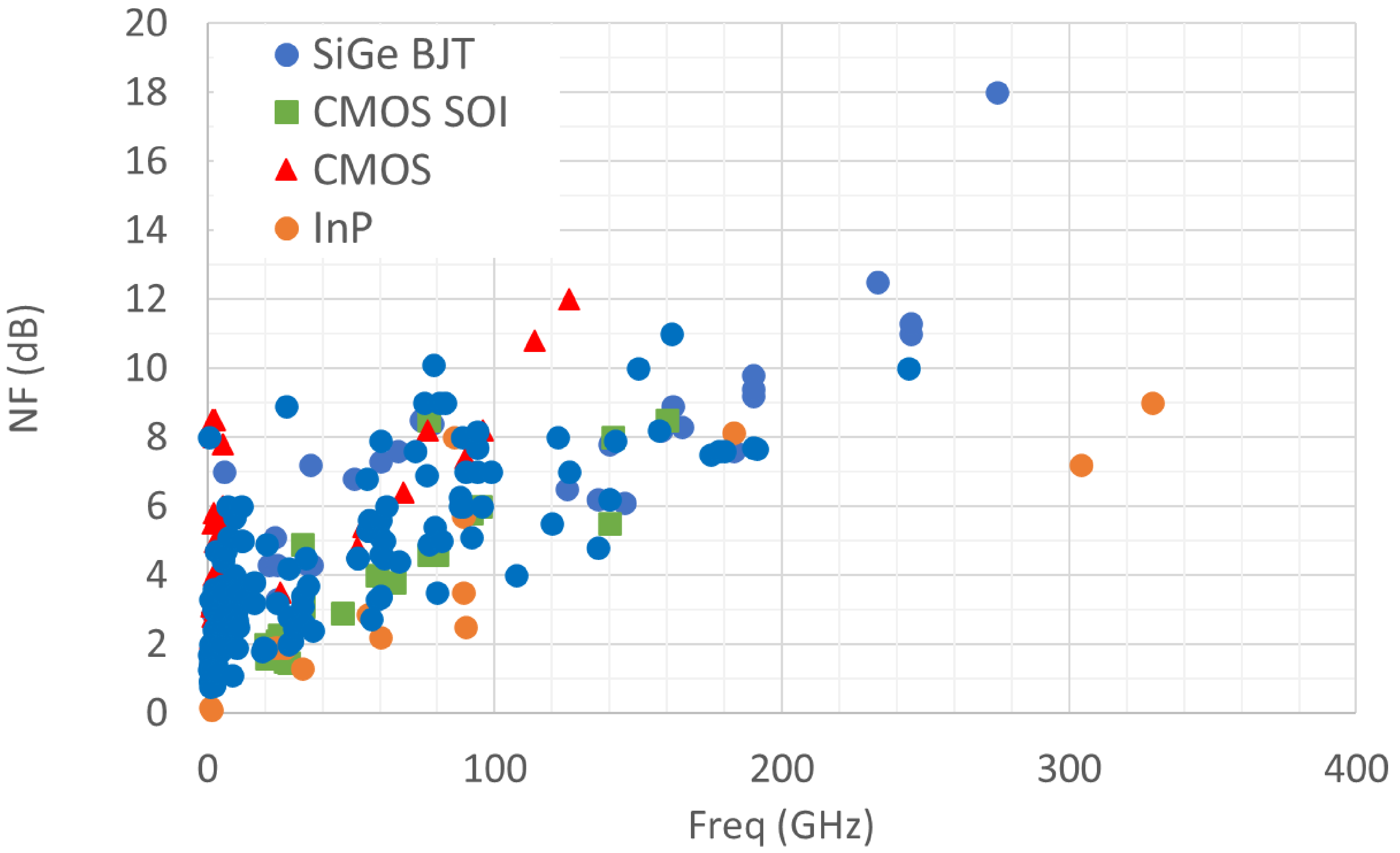
Performance Limits of LNAs



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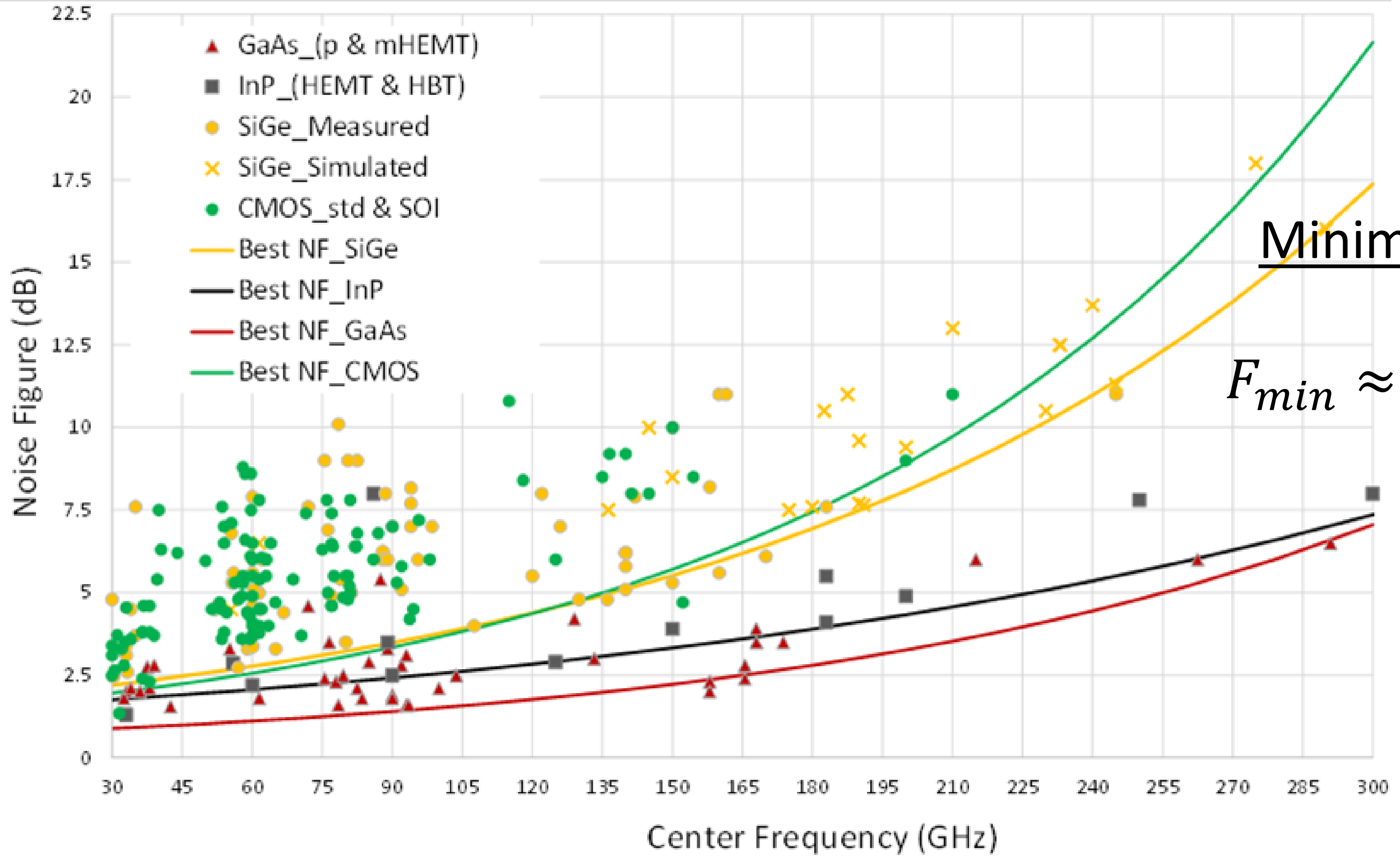


Minimum noise of a single transistor

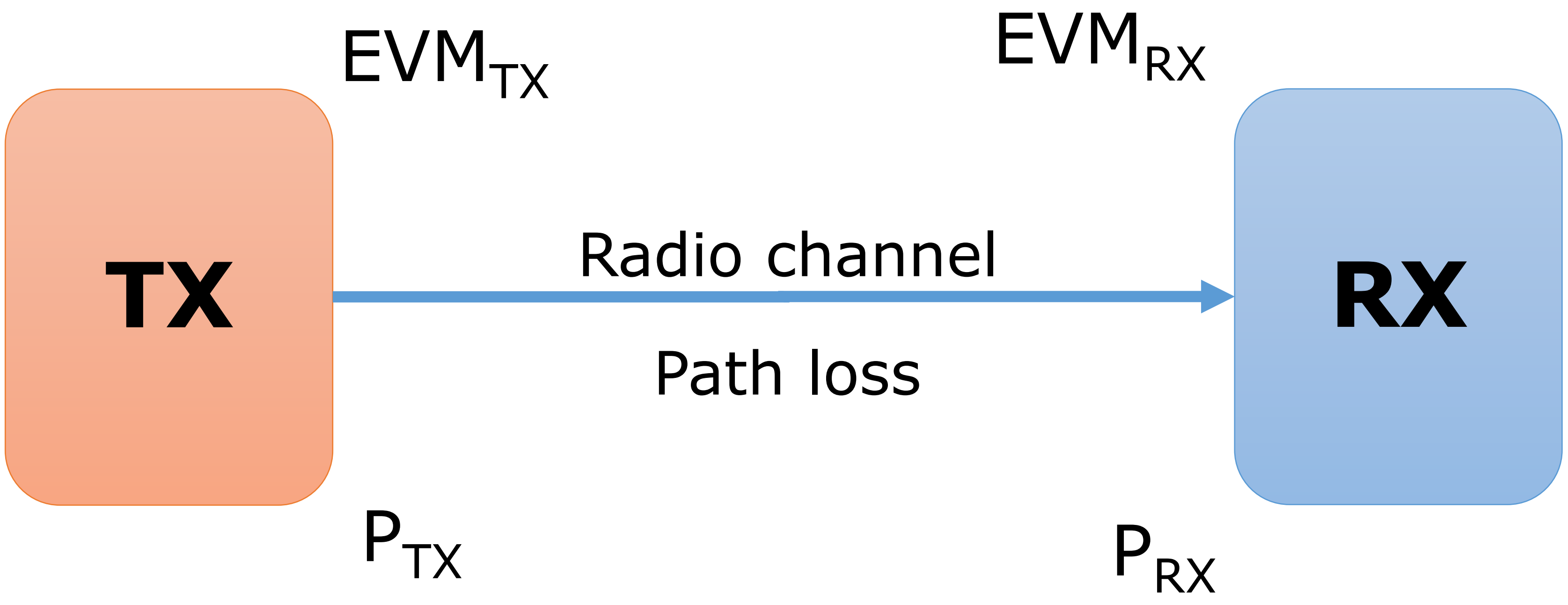
$$F_{min} \approx 1 + K \cdot \frac{\omega_0}{\omega_T} \sqrt{g_m\left(R_g + R_i + R_s\right)}$$

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

[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

Radio Link SNR/EVM

- Net impact of TX and RX for total link performance

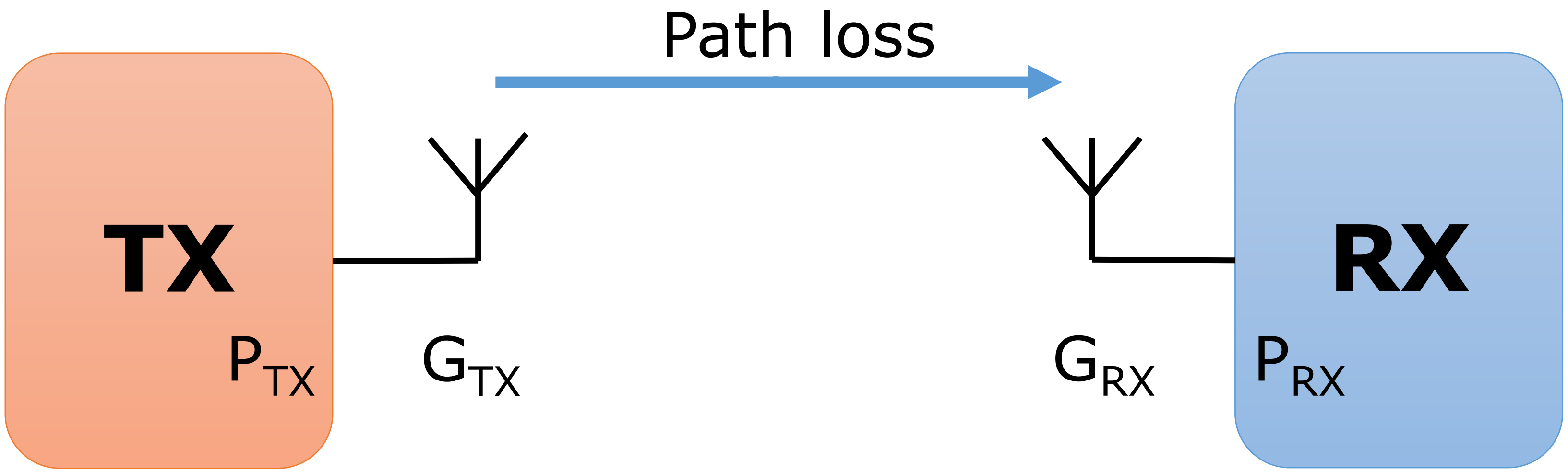


Link Budget

Received signal TX power antenna gains

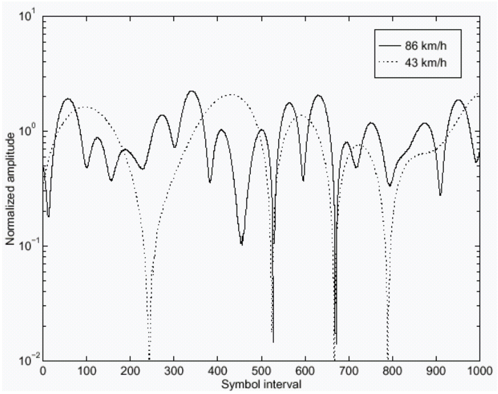
$$P_{RX} = P_{TX} - L_{path} - L_{fade} + G_{TX} + G_{RX}$$

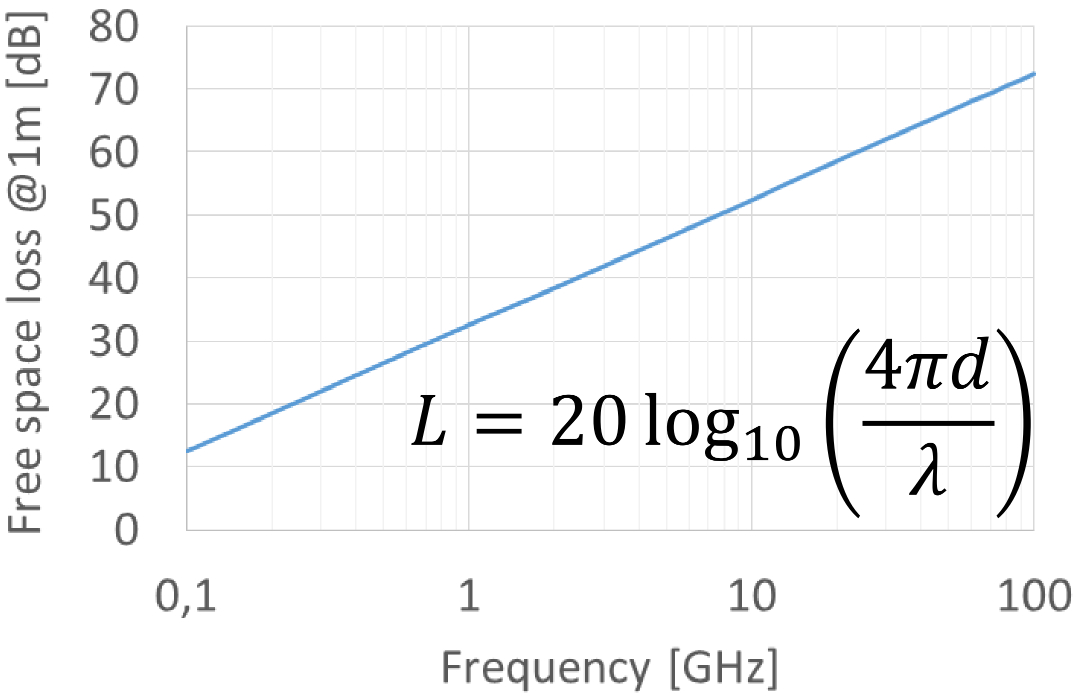
Path loss Fading margin



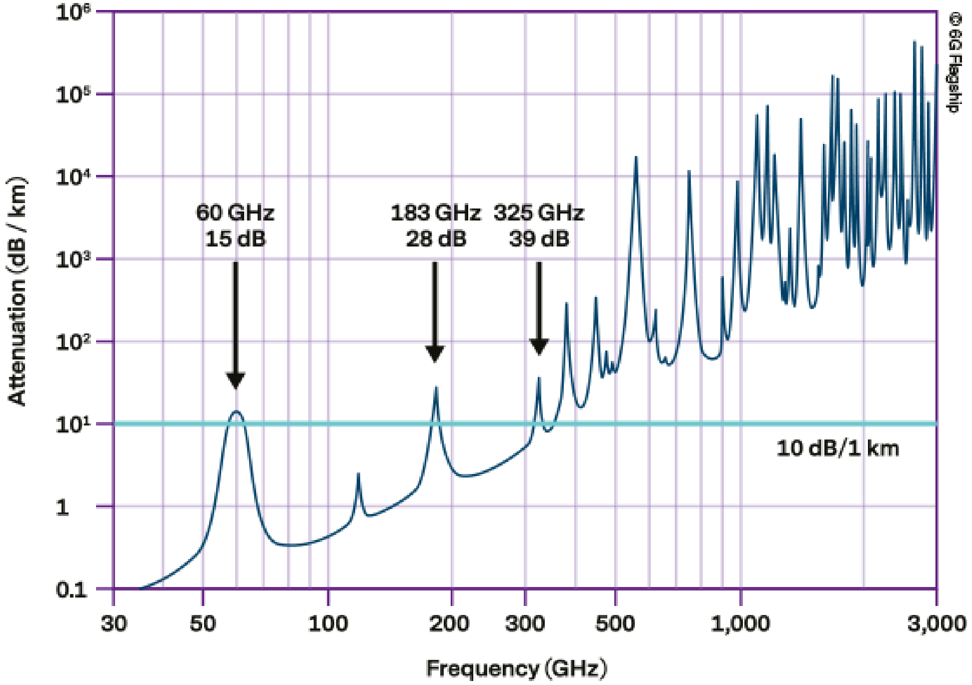
Radio Channel and Path Loss

• Free space & reflections & materials & fading





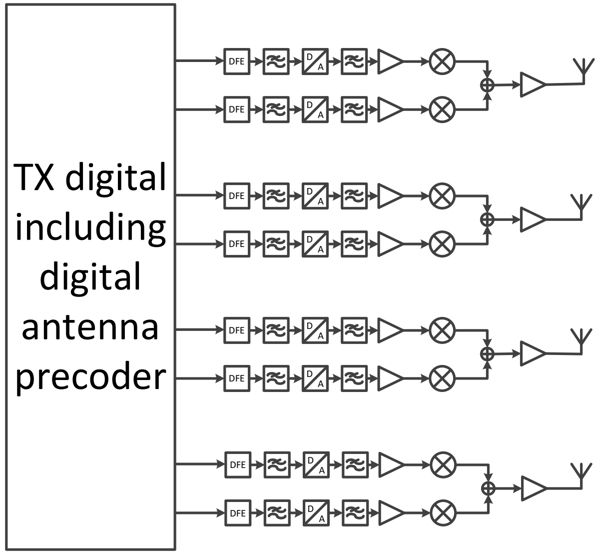
$$L = 20\log_{10}\left(\frac{4\pi d}{\lambda}\right)$$



Simple (?) solution – increase antenna gain

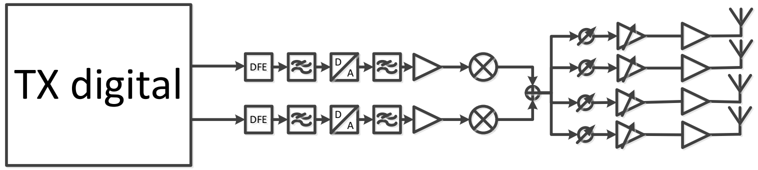
MIMO

- Full Flexibility
- RF & digital parallelism



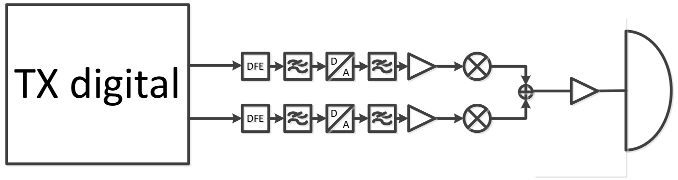
Phased array

- Steerability
- RF parallelism per data stream



Directive antenna

- Large gain
- No parallelism
- Limited or no steering



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Phased array

- Steerability
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Directive antenna

- Large gain
- No parallelism
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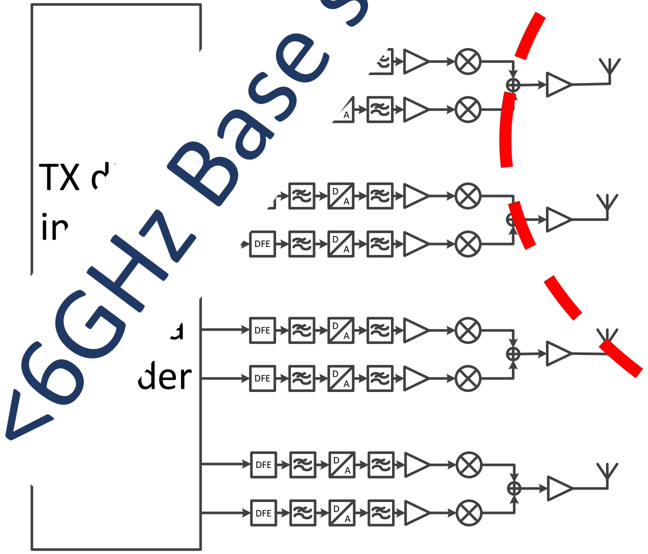
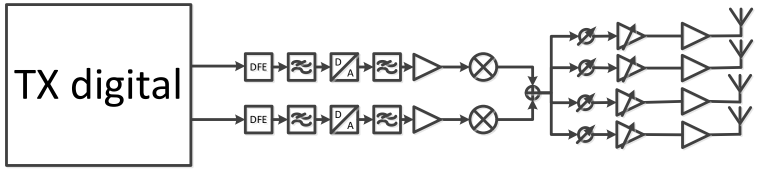
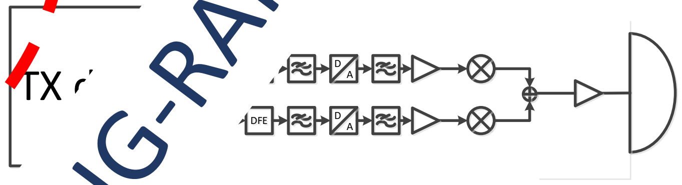
<6GHz Base station

compromizes needed

LONG-RANGE RADIO LINKS





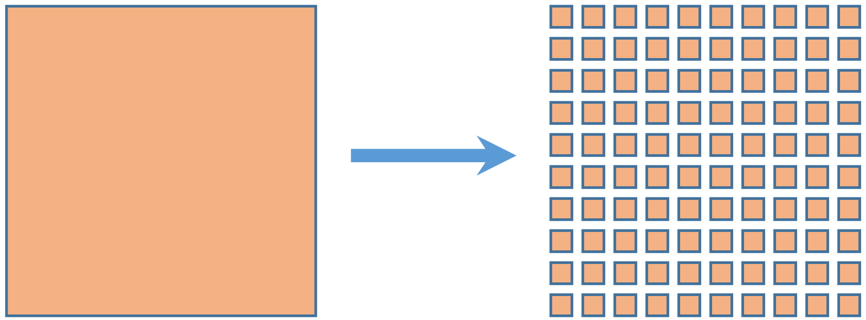


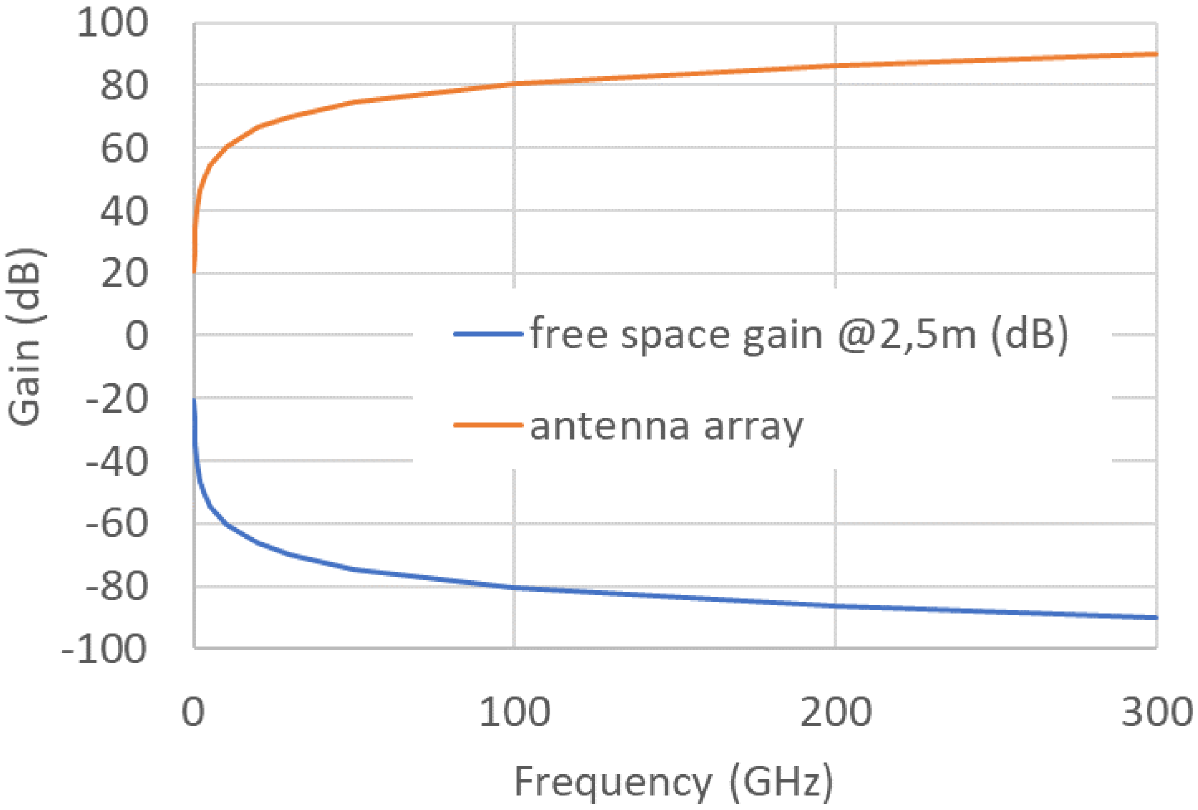
Link budget for phased arrays

- Constant antenna aperture removes frequency dependency

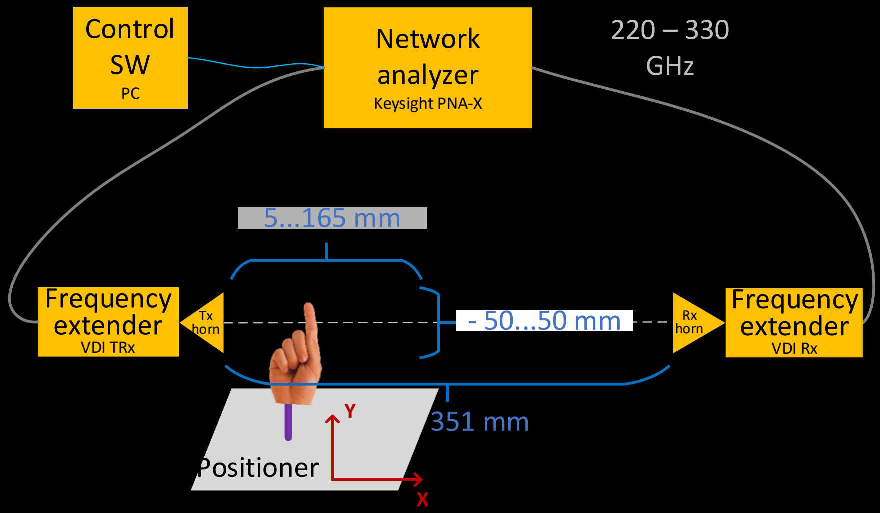
$$L = 20\log_{10}\left(\frac{4\pi d}{\lambda}\right)$$

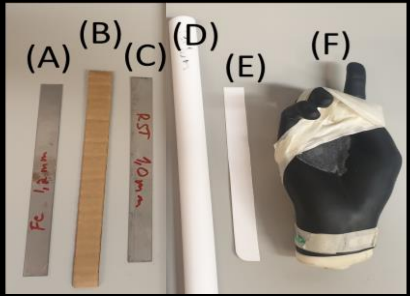
$$G_{array} = 10\log_{10}(n_{ANT})$$
$$= 10\log_{10}\left(\frac{A}{(\lambda/2)^2}\right)$$



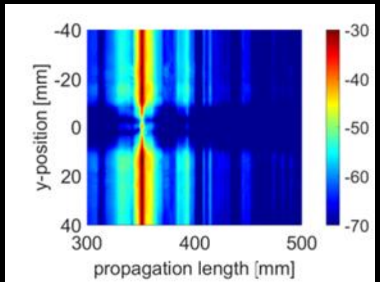


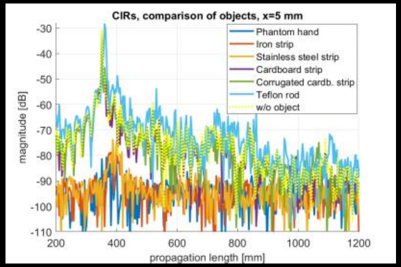
Radio channel from 100 to 330 GHz



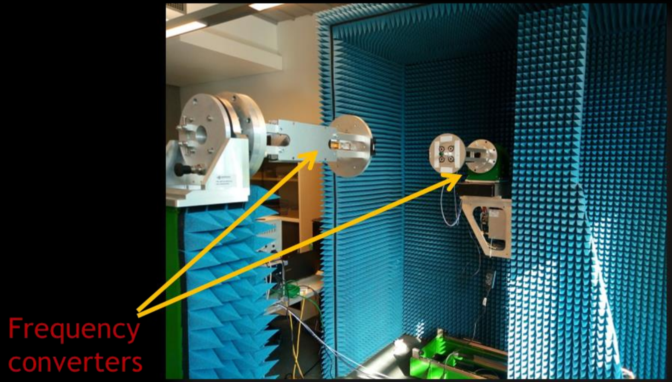


(A) *Iron strip*
(B) *Corrugated cardb. strip*
(C) *Stainless steel strip*
(C) *Nylon rod*
(E) *Cardboard strip*
(F) *Phantom finger*





- Measured Blockage Effect of a Finger at 300 GHz
- Above-100 GHz Wave Propagation Studies
- How many beams does sub-THz channel support?



P. Kyösti, M. F. De Guzman, K. Haneda, N. Tervo, A. Pärssinen, "How many beams does sub-THz channel support?," in IEEE Antennas and Wireless Propagation Letters, Jan. 2022.

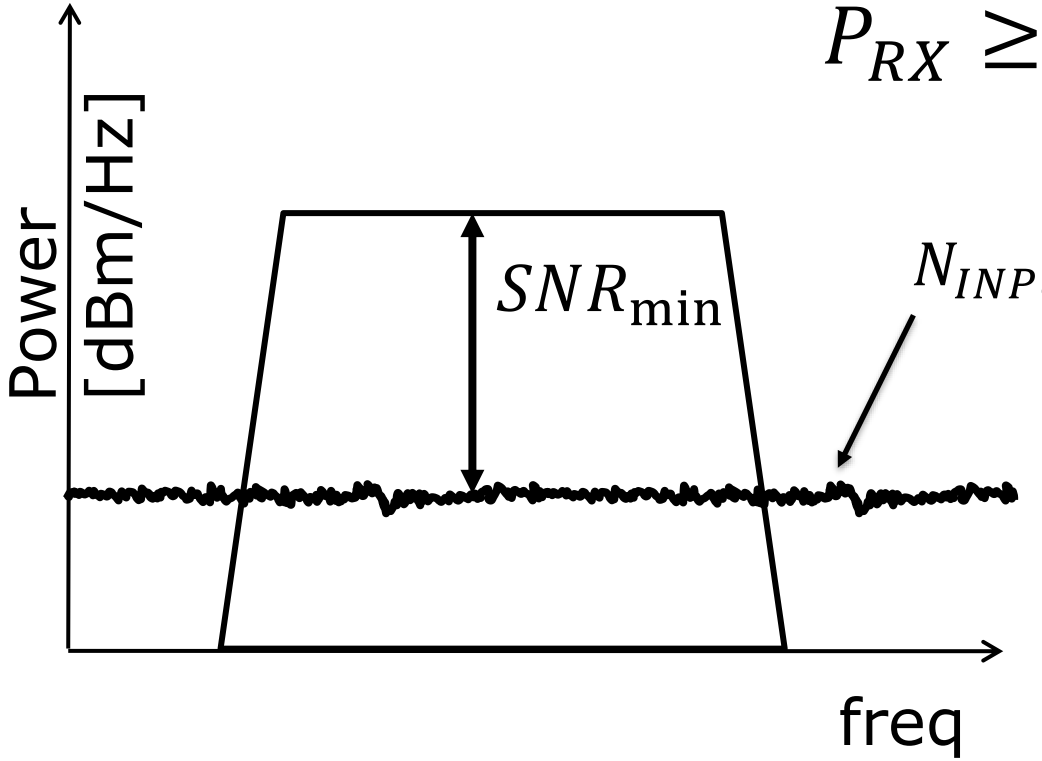
P. Kyösti, K. Haneda, J.-M. Conrat, A. Pärssinen, "*Above-100 GHz Wave Propagation Studies in the European Project Hexa-X for 6G Channel Modelling*," EuCNC & 6G Summit, 2021.

P. Kyösti, N. Tervo, M. Berg, M. E. Leinonen, K. Nevala, A. Pärssinen, "*Measured Blockage Effect of a Finger and Similar Small Objects at 300 GHz*," EuCAP, 2021.

RX Sensitivity

- Minimum detectable signal (MDS): modulation, BW, coding

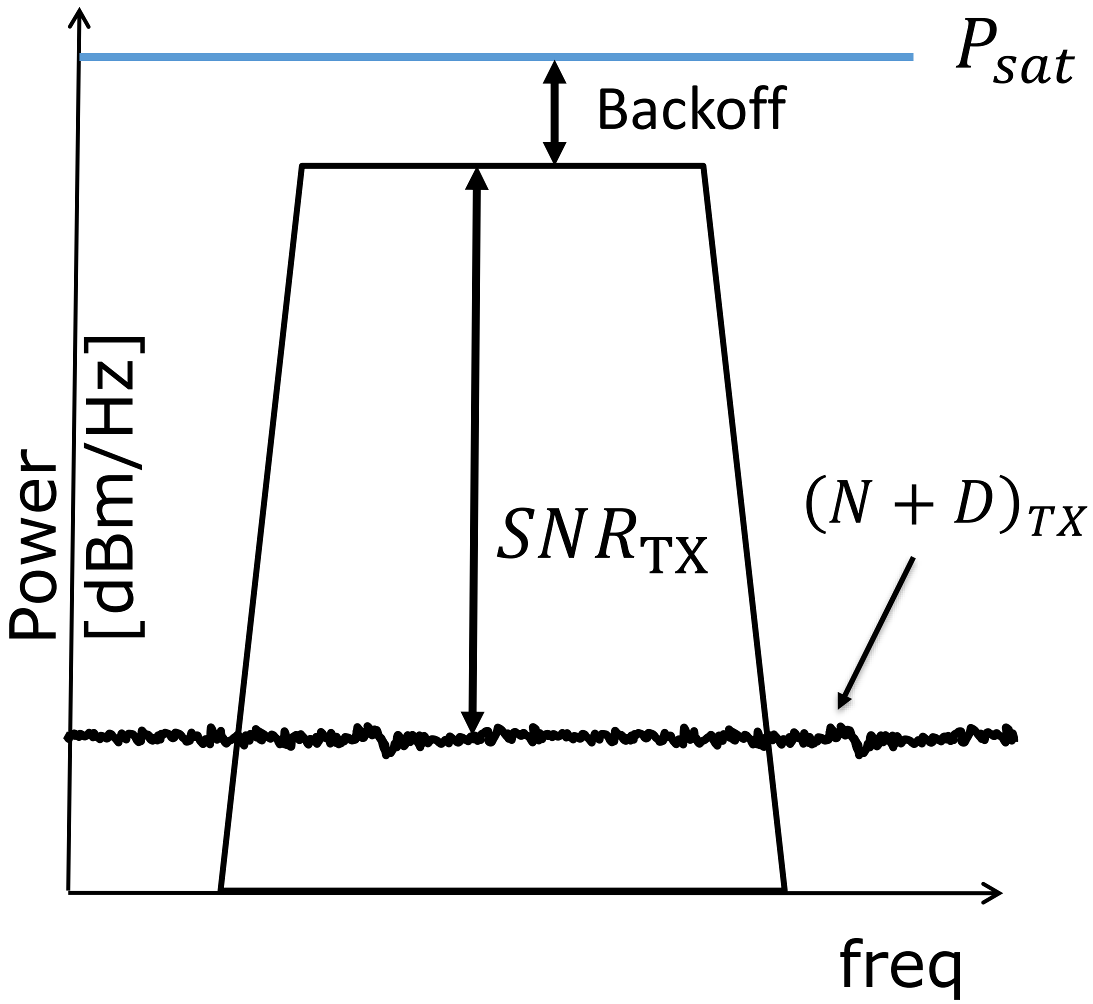
$$P_{RX} \geq MDS = N_{INPUT} + SNR_{\min} - G_{DSP}$$



$$\begin{aligned} N_{INPUT} &= N_{TH} + NF \\ &= kTB_n + NF \end{aligned}$$

B_n = noise bandwidth
T = temperature in K
k = Boltzmann constant
(~1.38×10^{-23} J/K)

TX Output Power and SNR/EVM



- Typically, $\mathrm{SNR}_{\mathrm{TX}} \geq \mathrm{SNR}_{\mathrm{RX}}$
- SNR indicates here
  - noise
  - distortion
  - all other non-idealities
  - i.e. EVM
- Backoff needed from Psat for signals with non-constant envelope depends on
  - modulation
  - technology
  - circuit design

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**

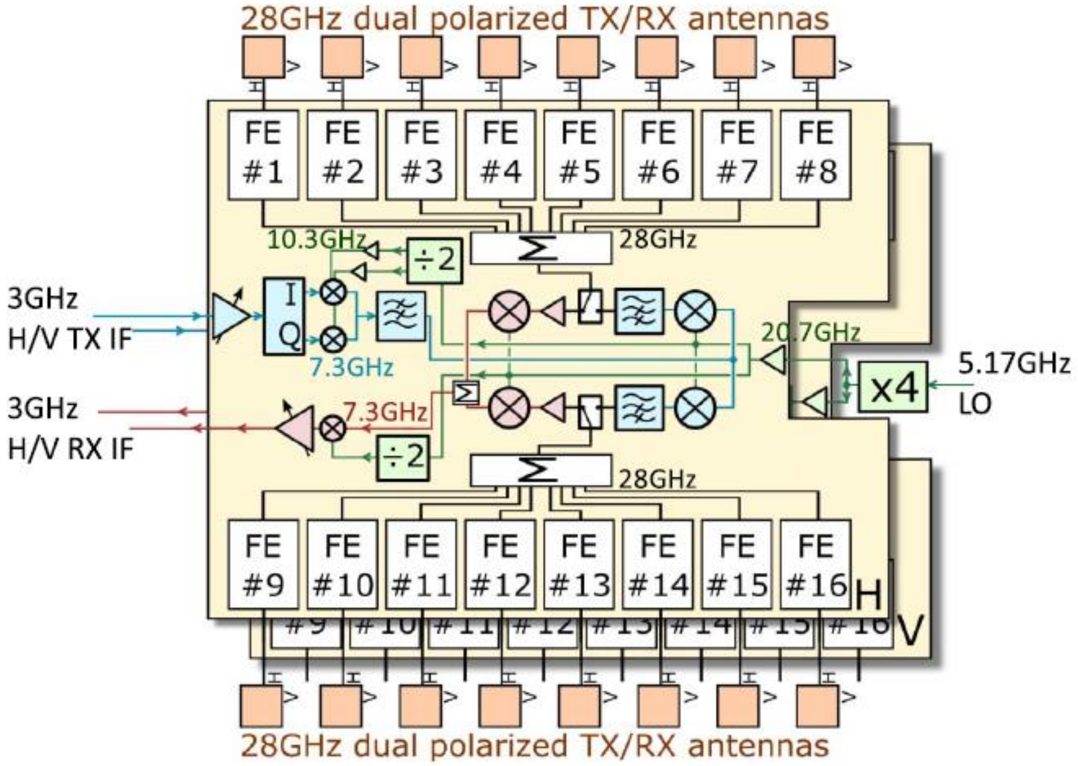
From 36Mbps to 40Gbps

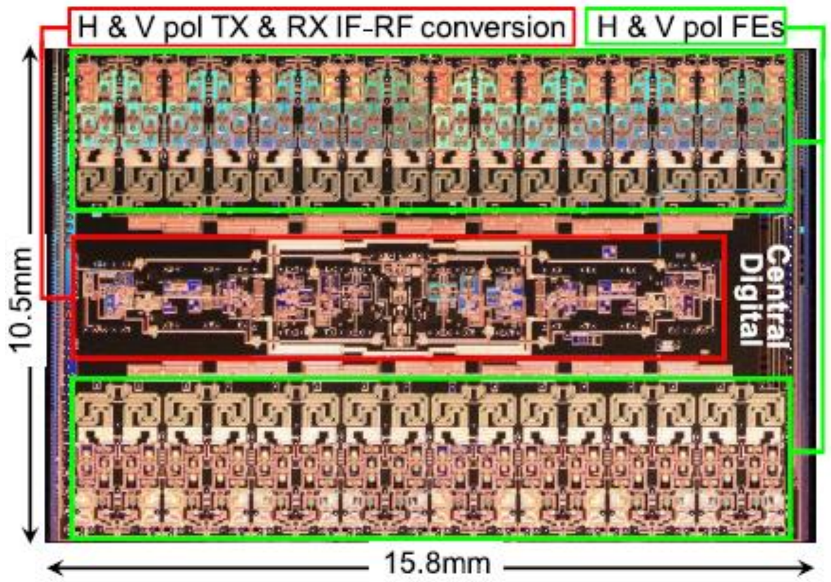
Parameter	Unit	LTE 20M	5G NR 200M	6G 20G?
Link Distance (line-of-sight)	m	**411**	**3.3**	**0.013**
Equal link distance	m	**411**	**411**	**411**
Free space loss	dB	93.2	114	131
P_{out}, PA	dBm	20	12	5
Sensitivity, 64-QAM (FDD)	dBm	-73.2	-59.7	-35.7
Margin to compensate	dB	0	41.9	90.0
Number of RX and 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 ~1mm² per antenna

28-GHz 32-Element TRX Phased-Array

- 0.13-µm SiGe BiCMOS (f_T/f_{max}=200/280 GHz)

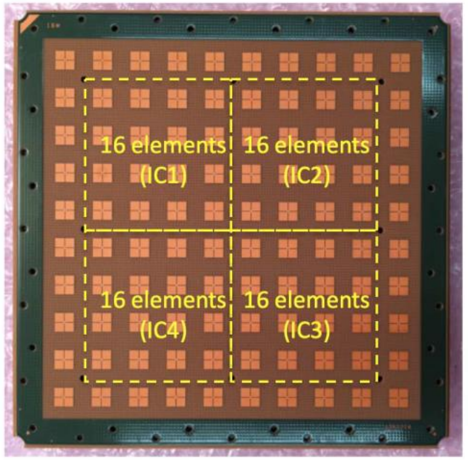


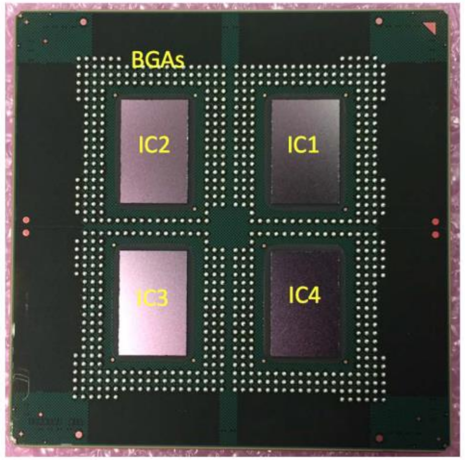


[B. Sadhu et al., JSSC Dec. 2017 & X. Gu et al., TMTT July 2019]

28-GHz 32-Element TRX Phased-Array

Modulation		64QAM
Bandwidth	GHz	0.8
Lens antenna gain	dBi	N/A
Data rate	Gbps	20.64
Range	m	50
Area (IC x1)	mm^2	166
P_{DC} (TX/RX)	W	4.6/3.3

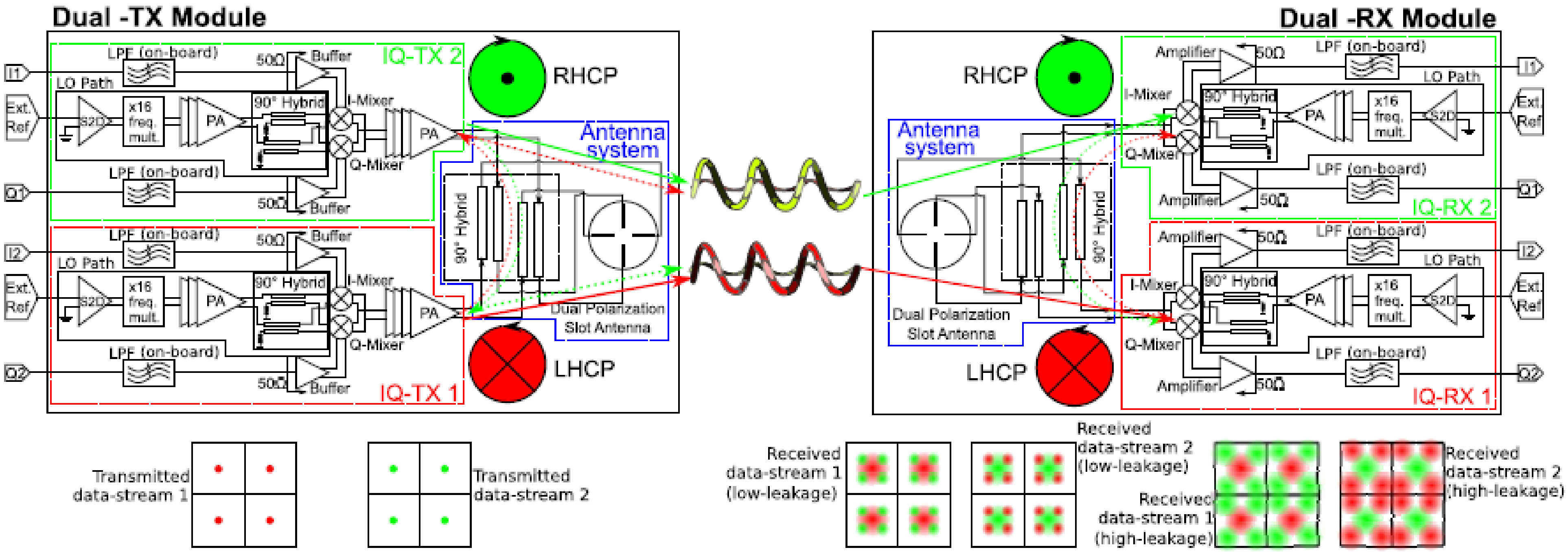




[B. Sadhu et al., JSSC Dec. 2017 & X. Gu et al., TMTT July 2019]

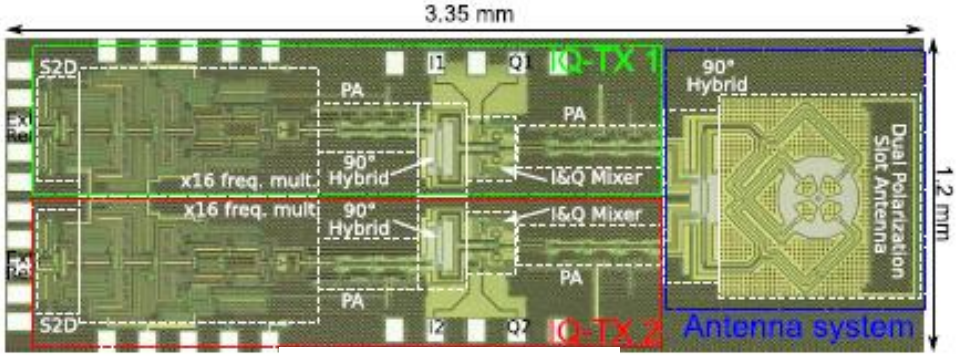
SiGe HBT - 110-Gb/s Polarization-Diversity MIMO Wireless Link @220–255 GHz

- 0.13-µm SiGe HBT (f_T/f_{max}=350/550 GHz)
- On-chip, dual-polarized antennas and lens

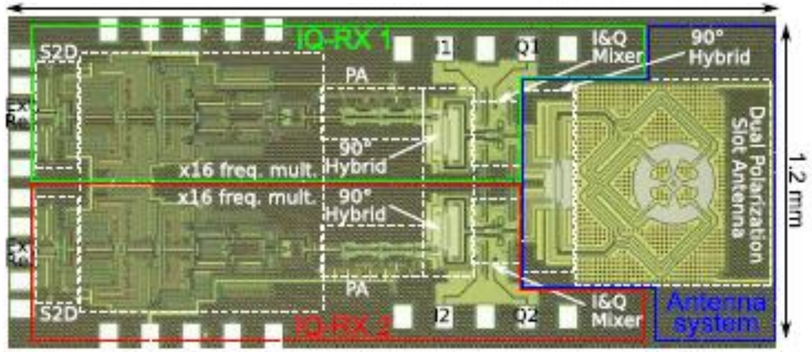


[Rodriguez-Vazquez et. al, TMTT Sep2020]

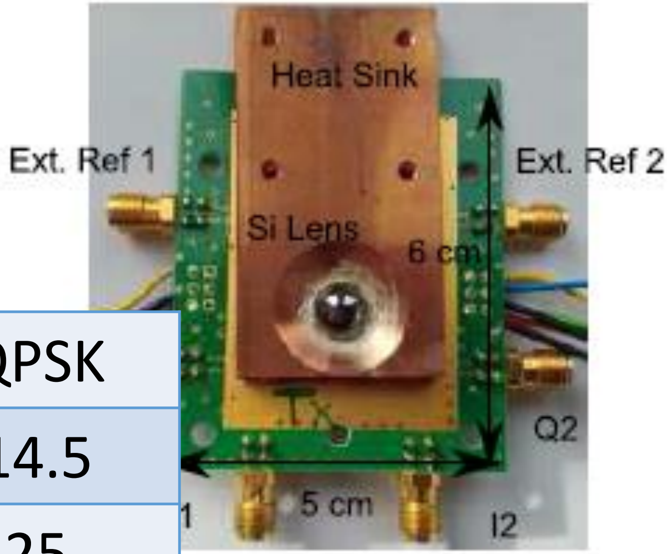
SiGe HBT - 110-Gb/s Polarization-Diversity MIMO Wireless Link @220–255 GHz



Transmitter



Receiver

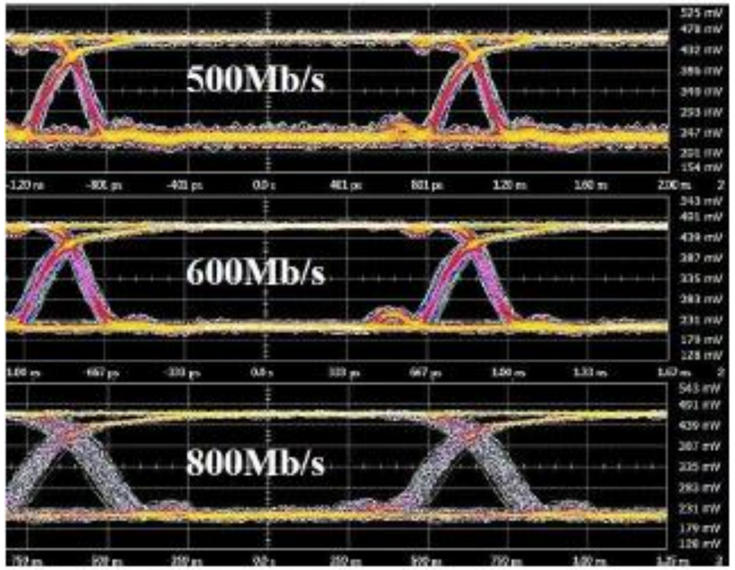


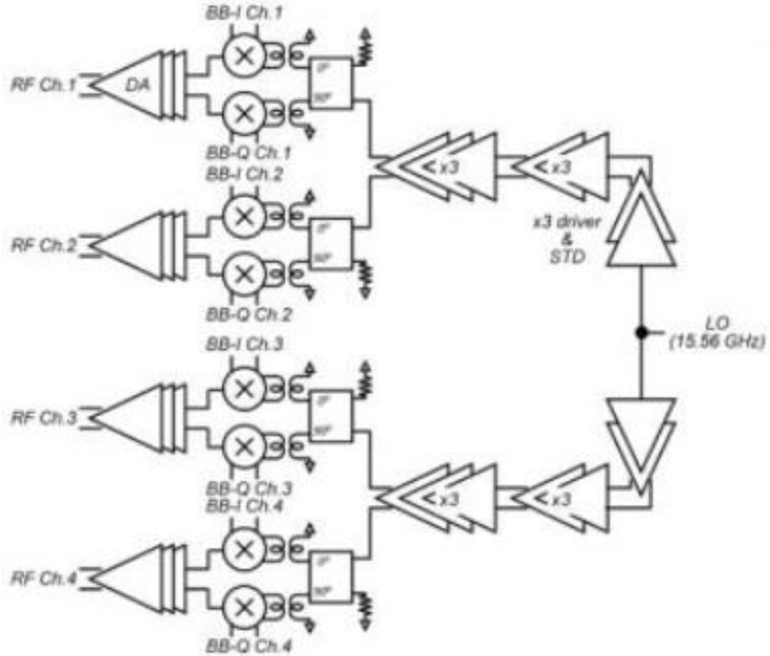
Modulation		QPSK
Bandwidth (max.)	GHz	14.5
Lens antenna gain	dBi	25
Data rate	Gbps	100/80
Range	m	1.0/2.0
Area (TX & RX)	mm^2	7.4
P_{DC}	W	2.85

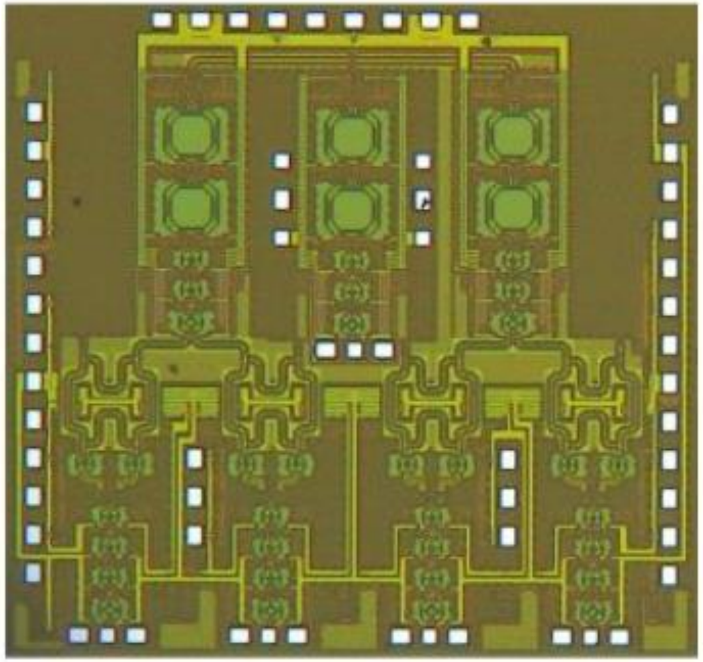
[Rodriguez-Vazquez et. al, TMTT Sep2020]

140 GHz Wireless Link Demonstration

- 45nm CMOS SOI
- Beam steering

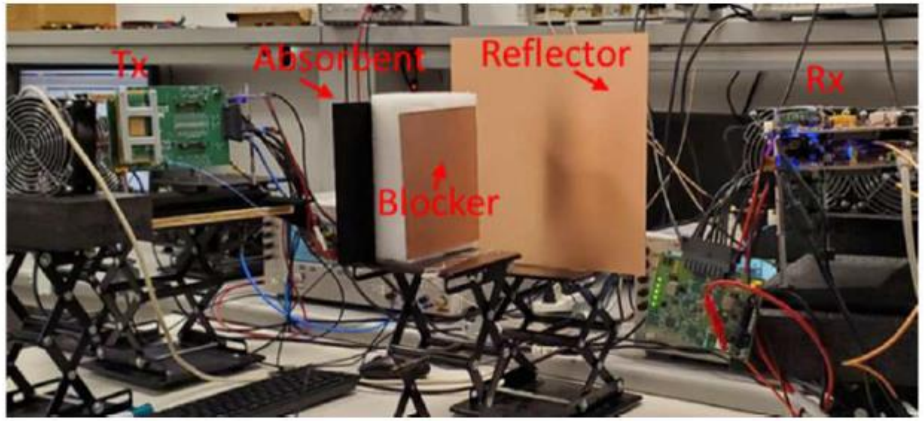


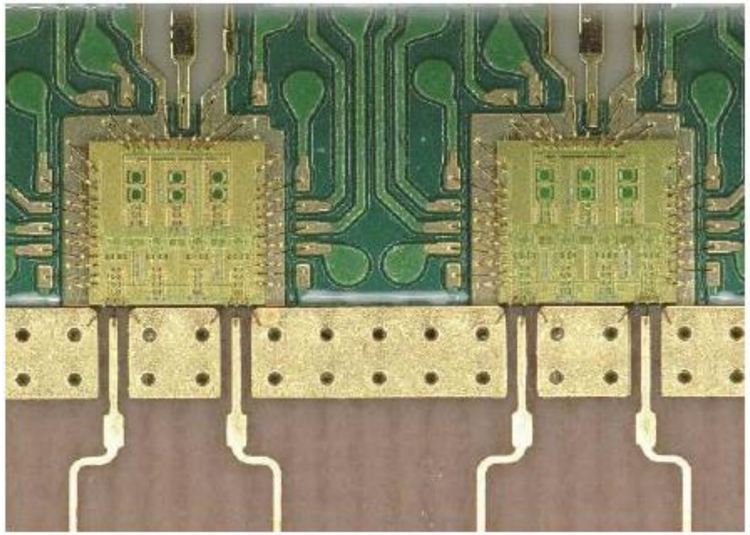




[S. Simsek et al., BCICTS 2018]

140 GHz Wireless Link Demonstration



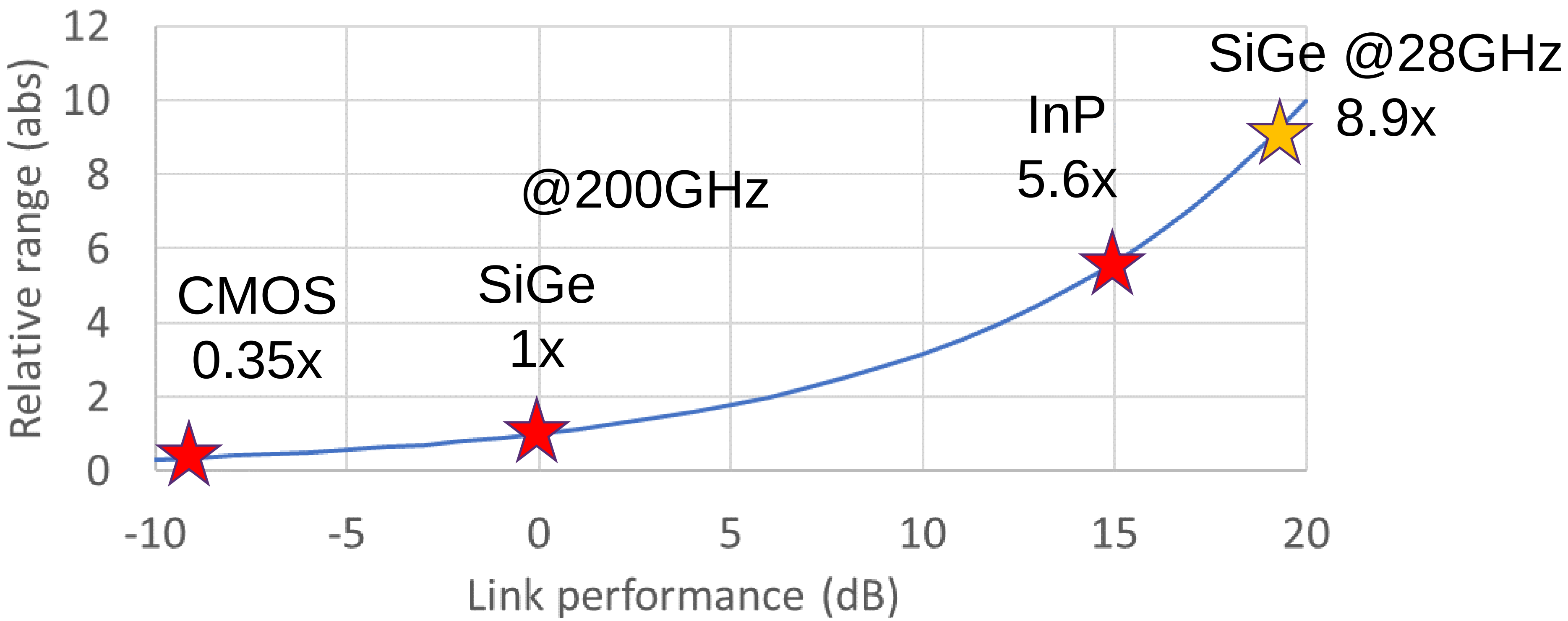


		4xTX + 4xRX	Lens TX + 8xRX
Modulation		QPSK	16-QAM
Bandwidth (max.)	GHz	2	2
RX/TX antenna gain	dBi	17	19/42
Data rate	Gbps	3.19	6.3
Range	m	1.0	15
Area (TX & RX)	mm^2	5.9	
P_{DC}	W	0.96	

[S. Abu-Surra et al., ICC 2021]

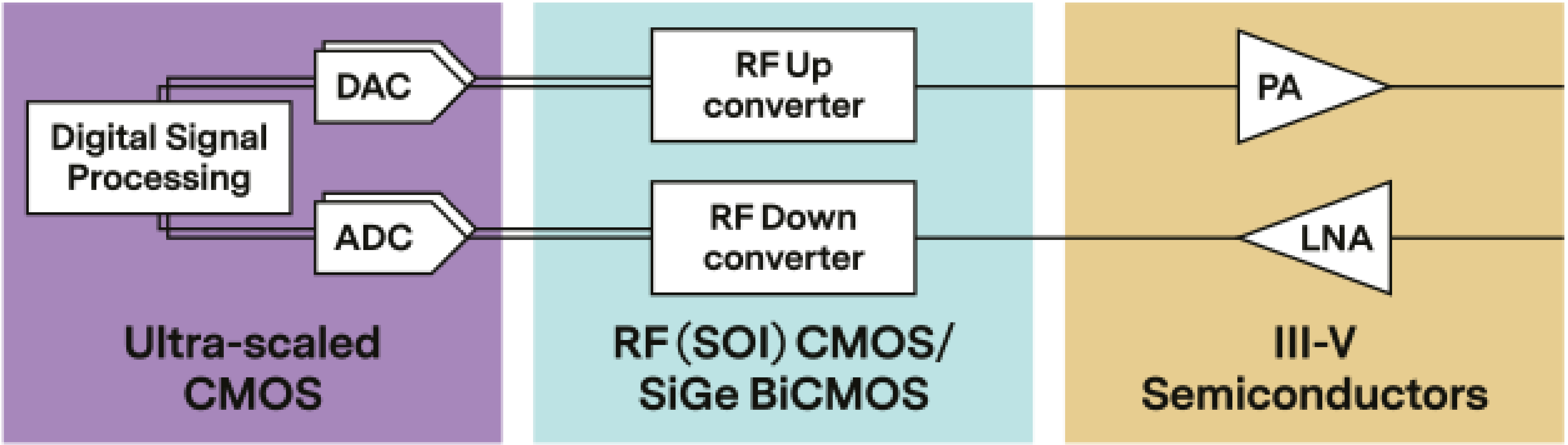
Choice of semiconductor technology?

- 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



The Best Technology for Every Component?

- Heterogeneous integration / 3D packaging?



Heterogeneous integration

- Multiple chips on the same interposer (chiplet) or bonding dies of different technologies together (oxide-to-oxide)

CMOS / BJT

- Compatibility to high-density digital logic (CMOS)
- Integrated control
- More limited frequency range
- Lower output power
- Moderate noise

III-V GaN/InP

- Lowest noise
- Highest output power
- Additional step in integration
- Yield?
- Additional losses between dies?

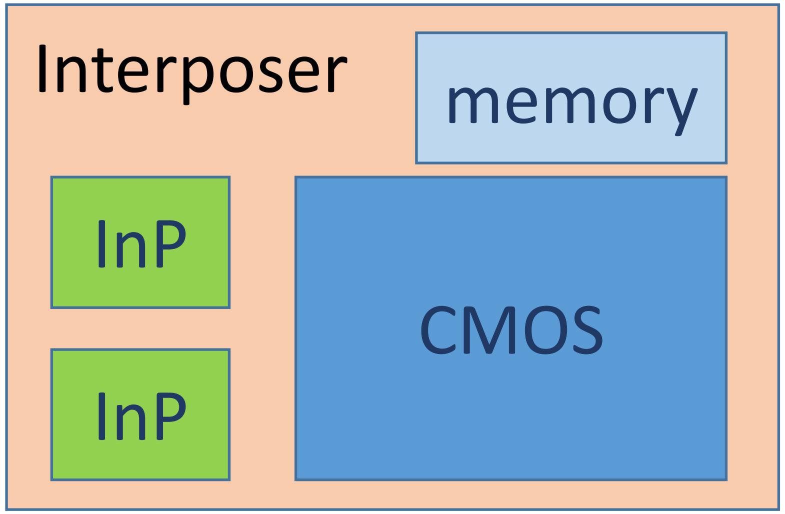
Heterointegration of semiconductors

- Many techniques with compromises to goals
- Epitaxial integration with device-layer islands (Ex. InP with silicon)
  - Lateral proximity
  - Change in Si process flow

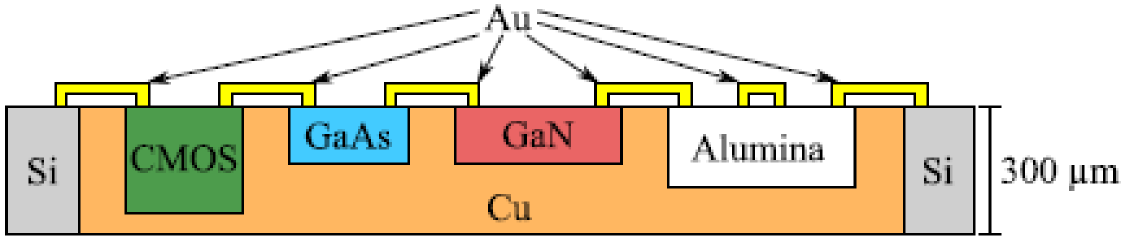
- Wafer-to-wafer or chip-to-wafer bonding
  - Separate processes and thus IPs
  - Chip-to-chip/via alignment
  - Heat distribution
  - Small size / 3D packaging

Chiplet

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



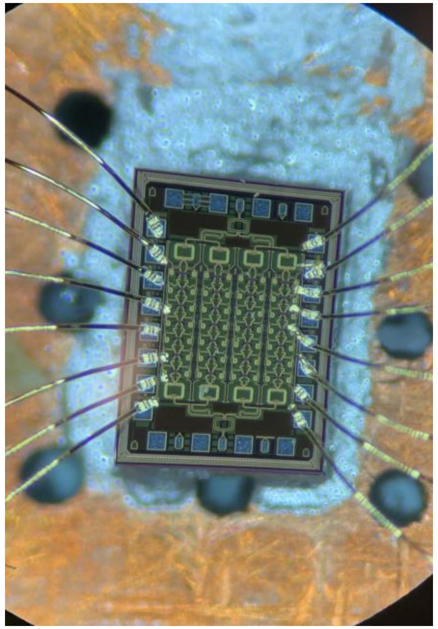
Photolithographically defined Au interconnects

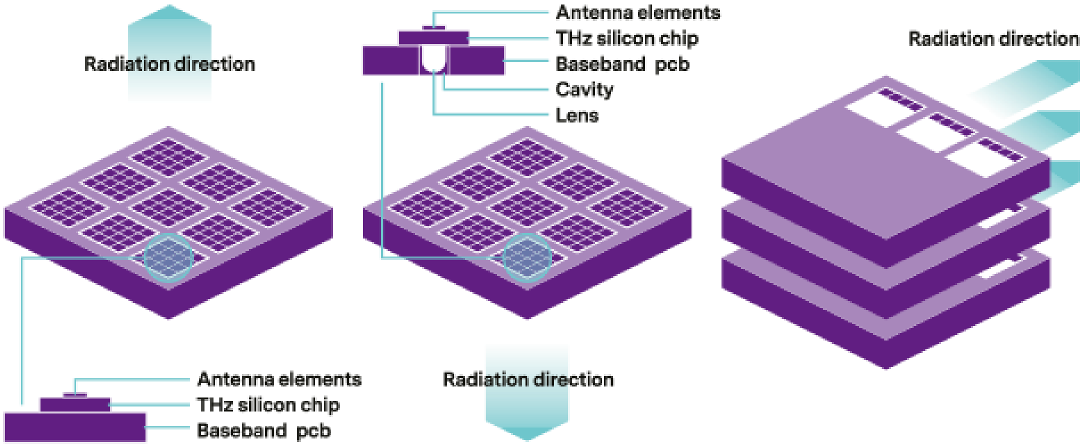


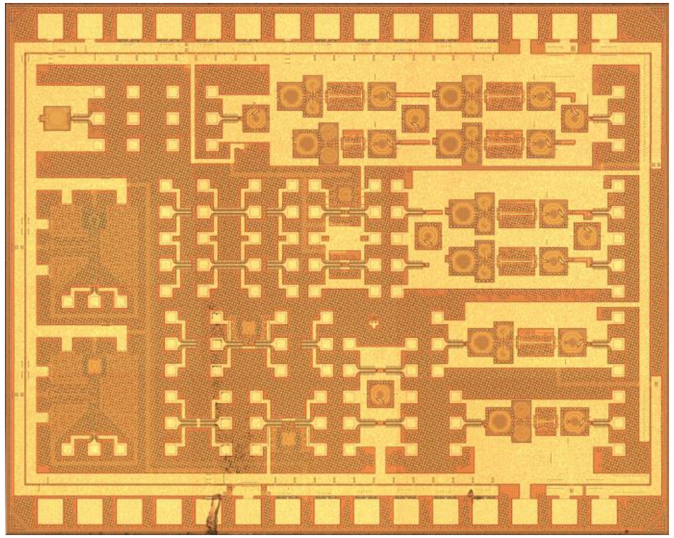
[Estrada et. al, IEEE TMTT Sep 2019]

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







Vision

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