WFB-1

Overview about RF and PA Requirements for 5G NR and Challenges for Hardware Implementation

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OUTLINE

- Introduction
  - Trends in communications and key characteristics
- RF Frontend Architectures for 5G
  - Massive MIMO Technology
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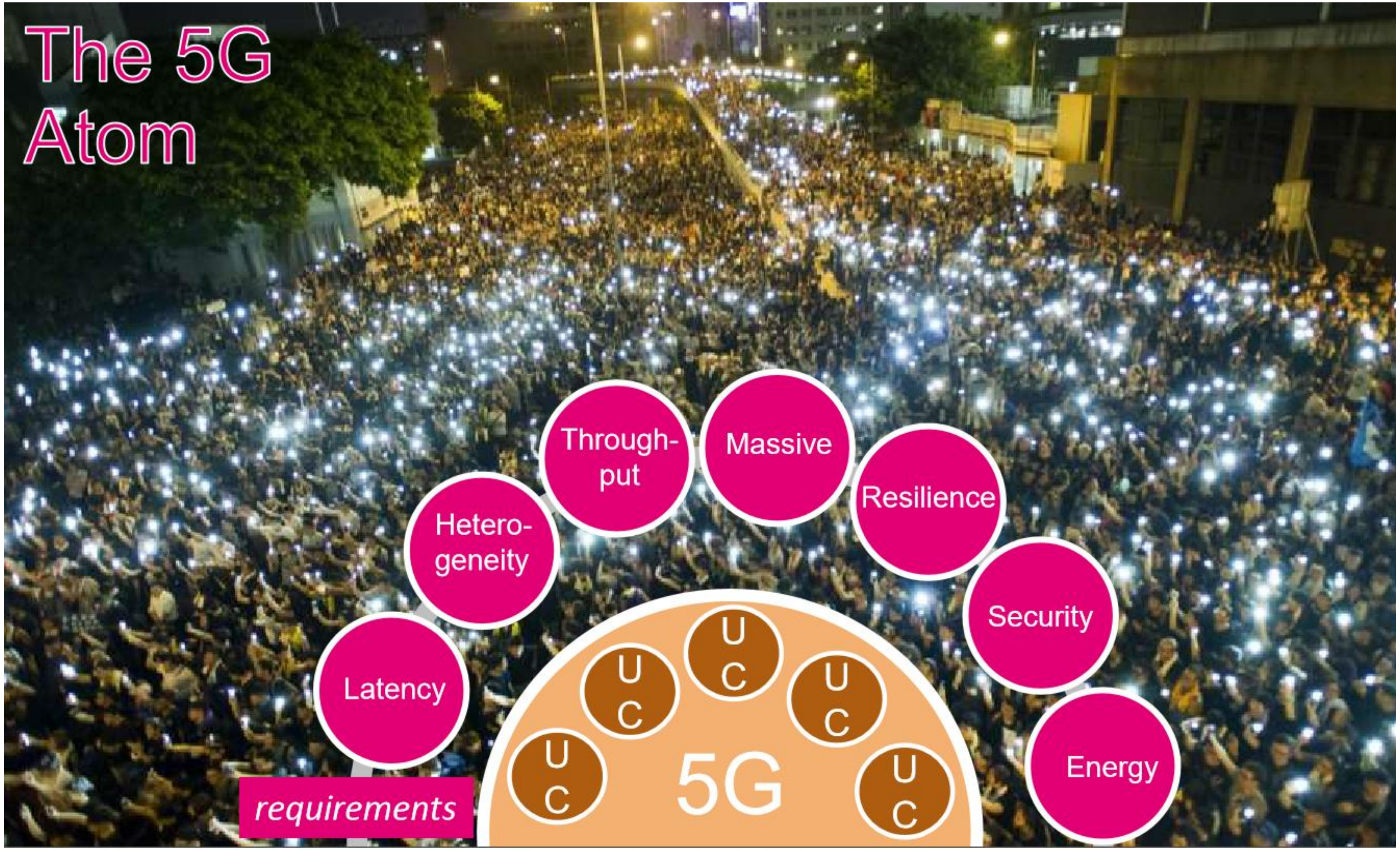
7 Billion Devices 2014 → 500 Billion Devices 2022



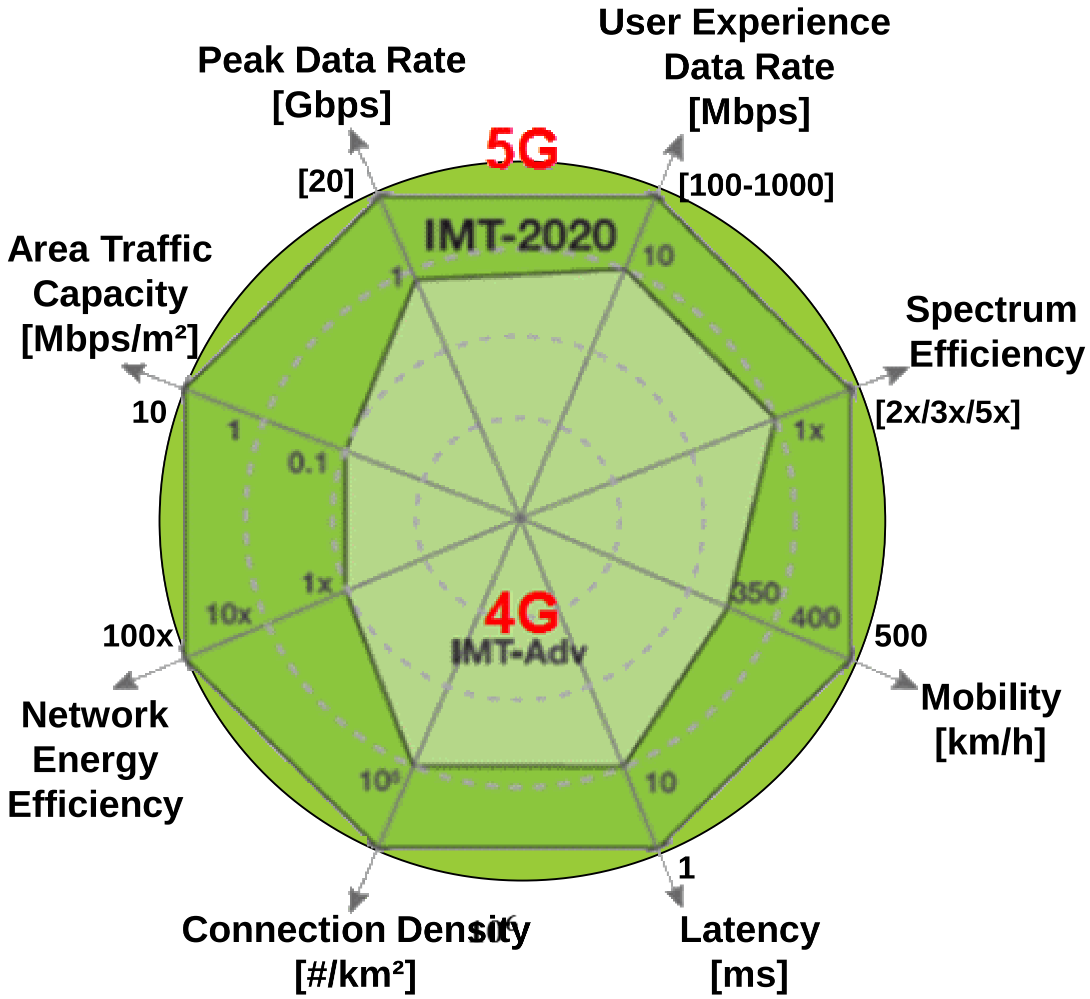
Courtesy Prof. Fitzek, TU-Dresden

In the headlines

- **Verizon hits 1.45Gbps 4G LTE speeds in New York** (With a little help from Nokia and Qualcomm)
- 5G mm-wave base station shipments: increased plans in the USA by AT&T and Verizon to pursue mobile 5G in the 24-39 GHz bands, not just fixed wireless.
- The China 5G ramp at 2.6 through 3.5 GHz was adjusted to account for new expectations from MIIT in China: Each of the three operators in China are expected to deploy 500,000 base stations within two years of receiving the 5G spectrum license.

Source: *dilbert.com*

ITU IMT-2020 5G Vision and Research Challenges



Data rates exceeding 10 GBps

Network latency under 1 millisecond

Capacity expansion by a factor of 1,000

Energy efficiency gains by a factor of 1,000 per transported bit

Source: *ITU and Ericsson Mobility Report*

Business impacts to semiconductor industry

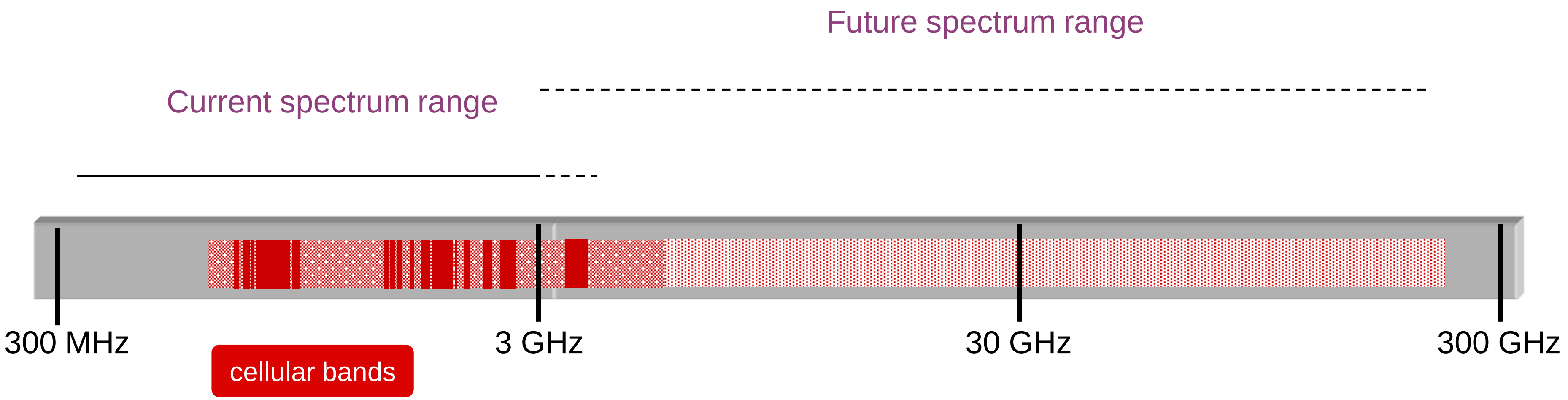
- Wireless major driver for semiconductor industry
- 5G expected to be the next major driver of wireless semiconductor market from 2020 onwards
- Challenges
  – Massive MIMO sells much more signal paths – what happens to cost
  – Cost per antenna
  – Can't be 100x more expensive
  – Moore's law – will it come to end and what is the impact to 5G
- Cost per unit very critical parameter for business success

Identification of Key 5G Characteristics and relevance for RF Architectures

- Massive MIMO
- RAN Transmission Centimeter and Millimeter Waves
- **New Waveforms**
- Shared Spectrum Access
- Advanced Inter-Node Coordination
- **Simultaneous Transmission Reception**
- **Multi-RAT Integration** & Management
- **D2D Communications**
- Efficient Small Data Transmission
- Wireless Backhaul / Access Integration
- Flexible Networks
- Flexible Mobility
- Context Aware Networking
- Information Centric Networking
- Moving Networks

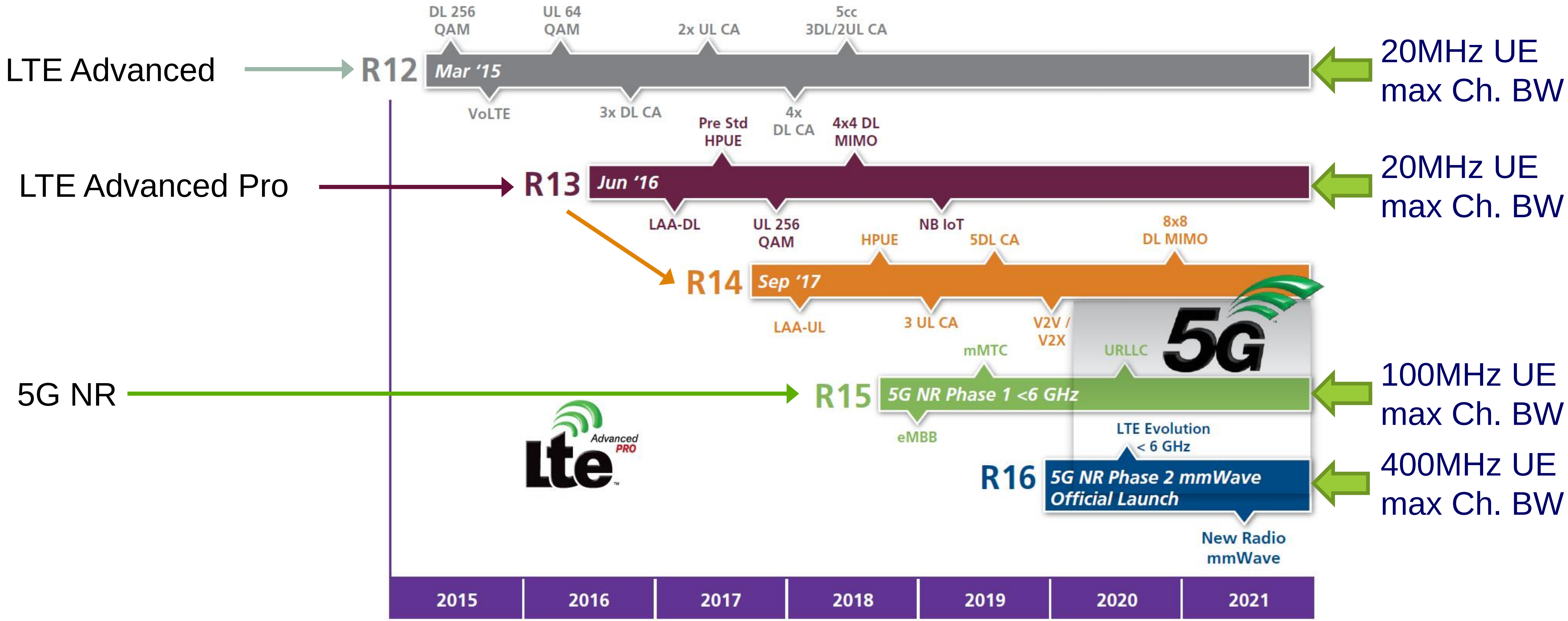
New Spectrum Scenarios

- Complementary use of alternative spectrum
  - Unlicensed spectrum, secondary spectrum usage, spectrum sharing,... „LAA“
- Usage of very high frequency bands (for 5G NR Phase 2)
  - Lots of spectrum available ➔ Extreme capacity and data rates
  - Small wave length ➔ Possibility for large array antenna solutions



Source: *Sven Mattisson, ISSCC-2016*

3GPP Time Line: LTE Adv. through 5G-NR



- **SKYWORKS** □ 2017 White paper: '5G in Perspective'

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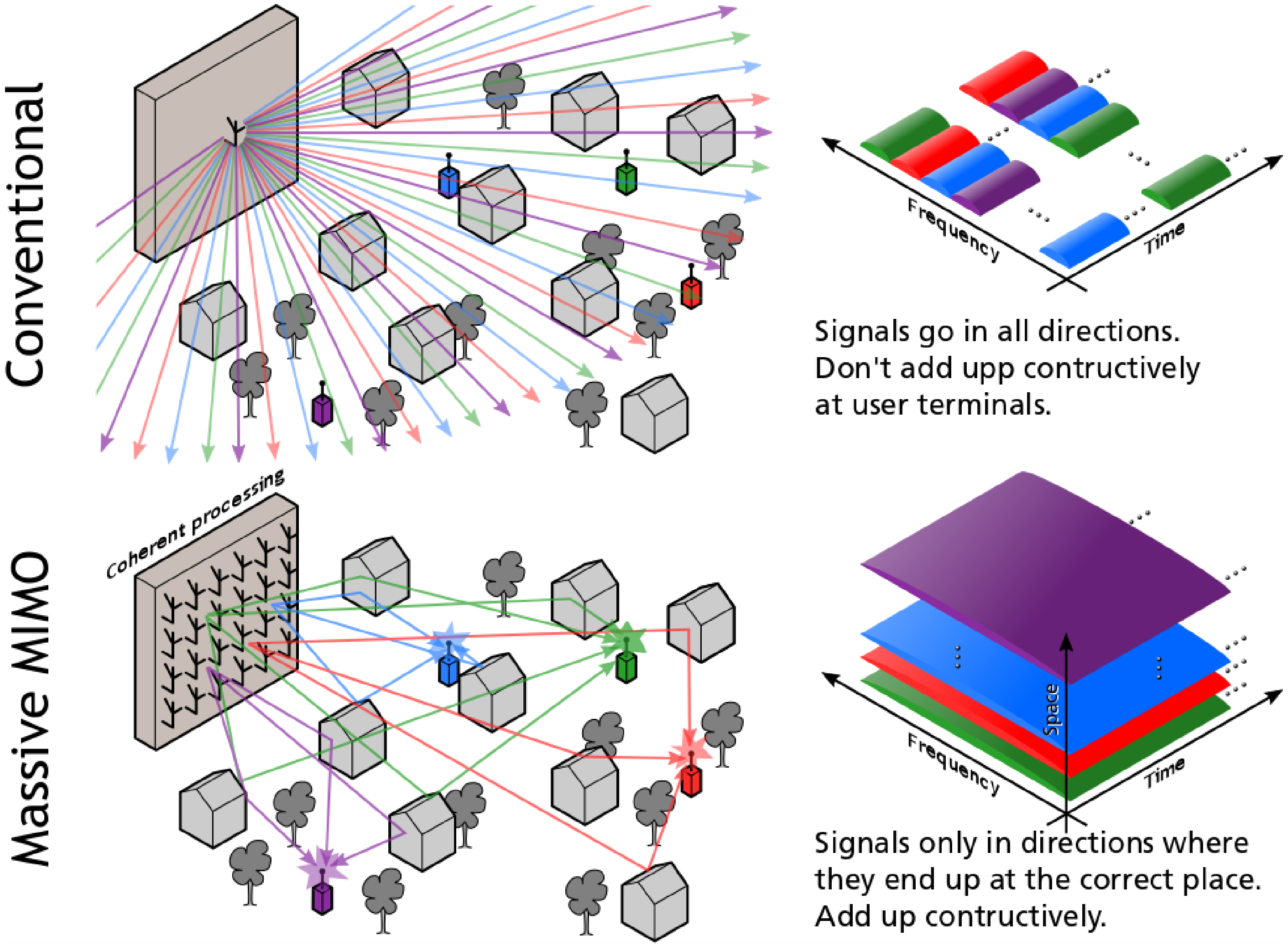
Array Antenna Systems / Massive MIMO



Signals go in all directions.
Don't add upp contructively
at user terminals.

Signals only in directions where
they end up at the correct place.
Add up contructively.

Massive MIMO is **multi-user** MIMO

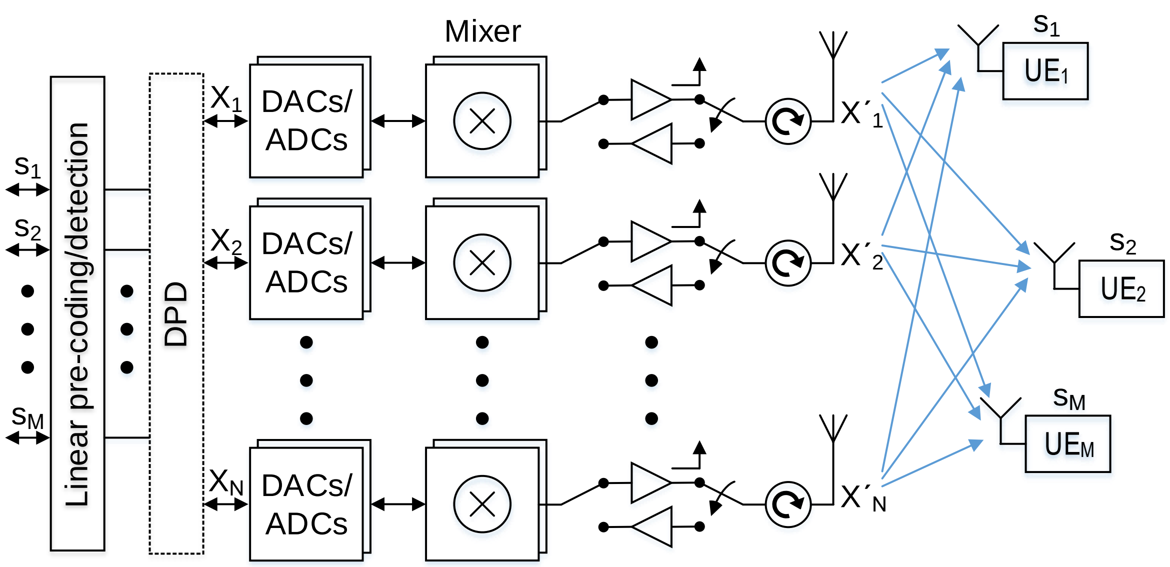
Impact is very demanding:

- 10 times increased capacity
- 100 times reduced radiated power
- **Overall: improvement in radiated energy efficiency (bits/J) > 1000 times, on the uplink & the downlink.**

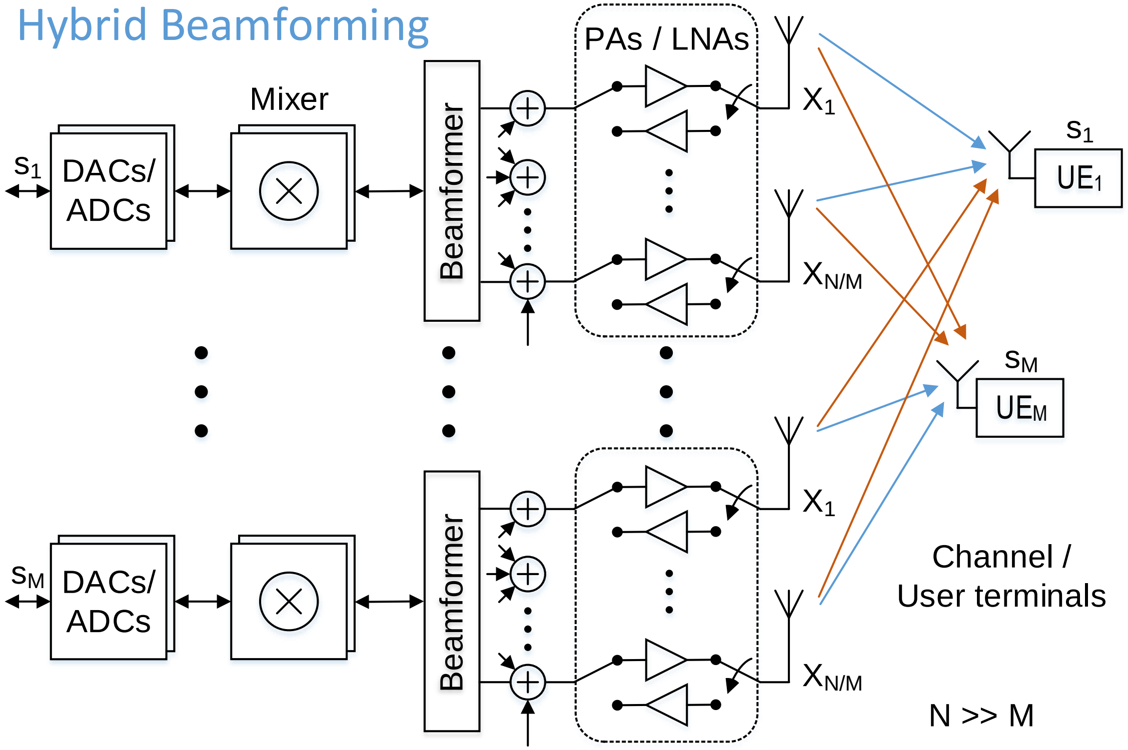
Source: *Ove Edfors, ISSCC-2019, Forum-1*

Beamforming/mMIMO options

Digital Beamforming



Hybrid Beamforming



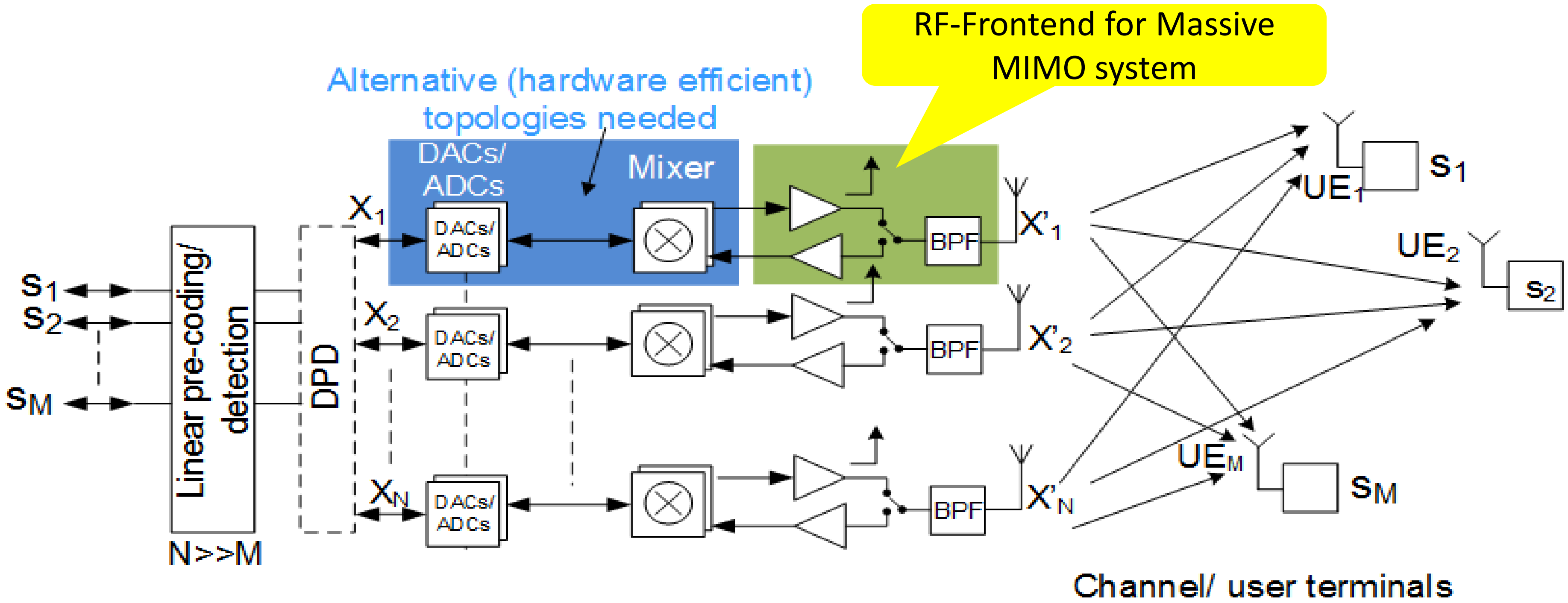
Digital beamforming/mMIMO
is used at sub 6GHz frequency bands today

Hybrid beamforming
is used at mm-Wave frequency bands today

Pros/cons investigation for beamforming options

	Simple BF	Digital BF	Hybrid BF	Complex Hybrid BF
Power Eff.	☺	☹☹☹	☺☺	☺☺☺
Area Eff.	☺	☹☹☹	☺☺	☺☺
Nr. of Streams	Single	Multiple	Multiple	Multiple
Flexibility	☹	☺☺☺	☺☺	☺☺
Complexity	☺☺	☹☹☹	☺	☹
Spectral Eff.	😐	☺☺☺	☺	☺☺

Full Digital Beamformer/mMIMO for sub 6GHz



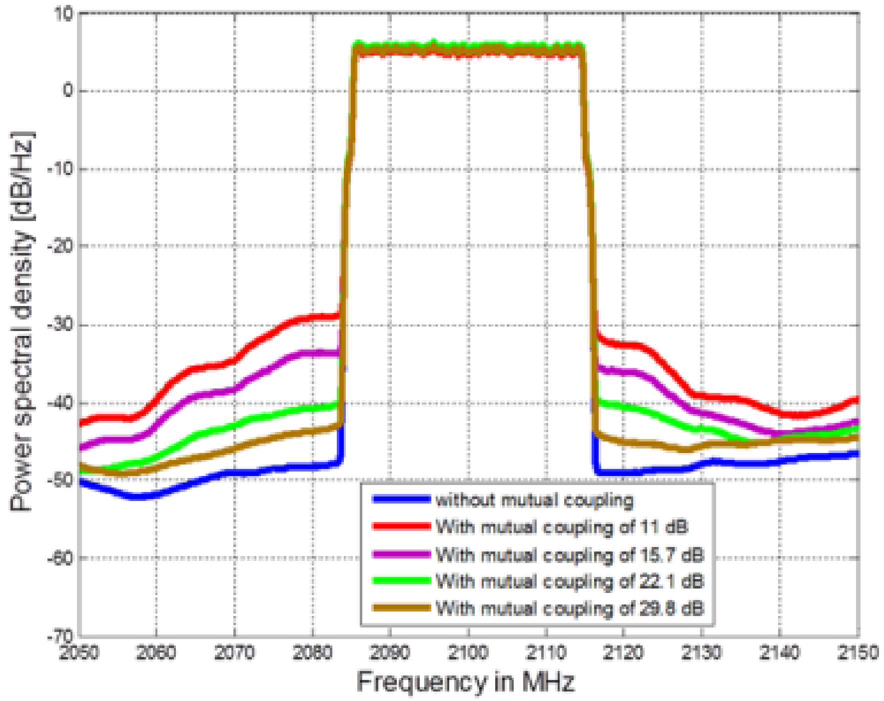
Near linear increase of area and power consumption with array size

- Traditional analog/RF approach becomes inefficient
- Efficient System in Package solution for: PA+LNA+Switch+Control
- Alternatives like all-digital transceiver to be considered like: PWM-based digital RF, RF-DAC, …

Analog/RF Requirements (some considerations)

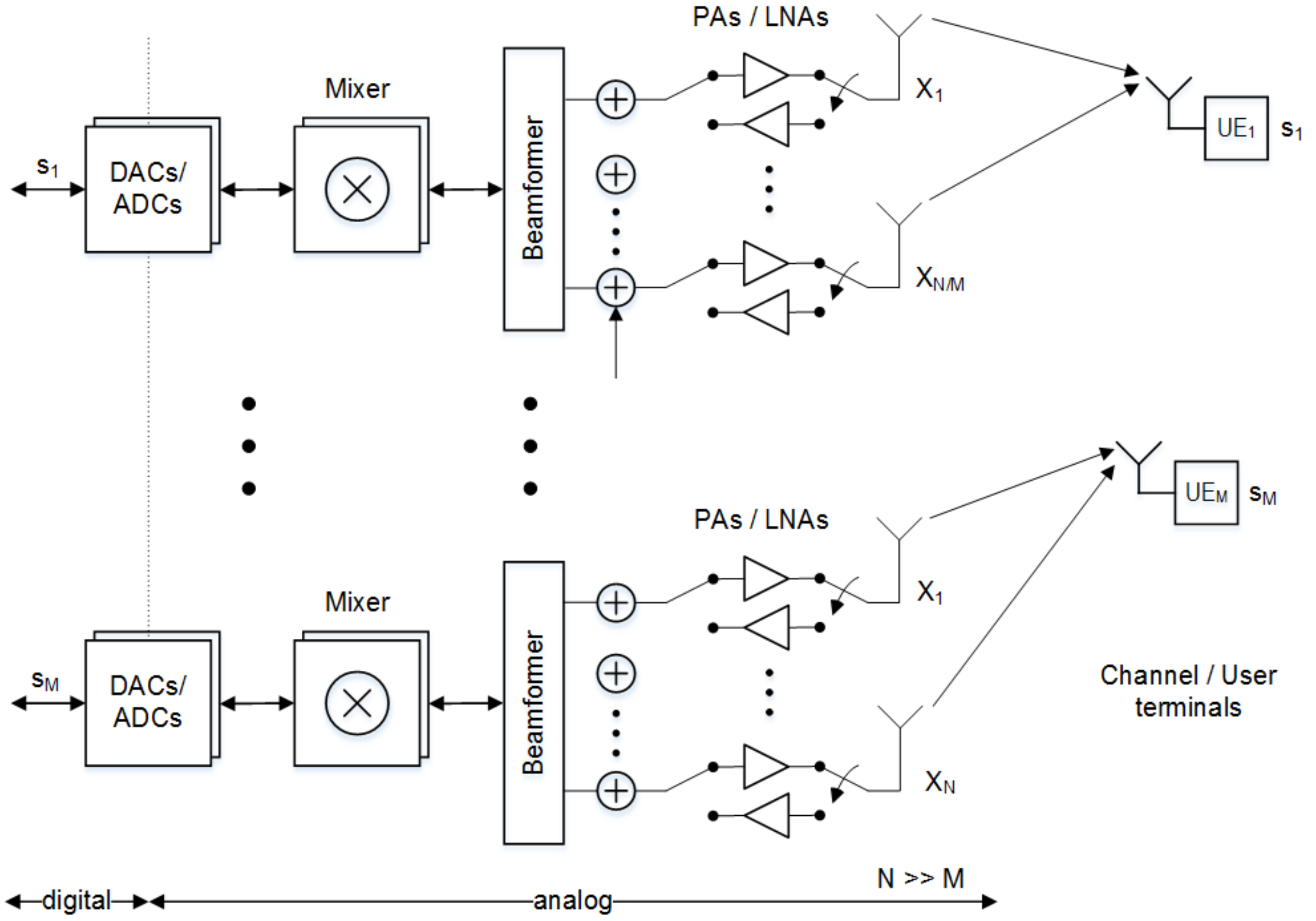
Establishing translations between circuit and radiated performance is challenging

- For bands below 6 GHz the requirements are in the same ball-park of existing systems
- The Tx output power per antenna element depends on EIRP and array size
- On the receiver side due to required coverage and cell-edge bitrates, the performance requirements like noise-figure are increasing.
- IBW requirement is increasing
- Beamforming and AAS/massive MIMO implies new challenges due to e.g. antenna cross talk etc.



Source: *Sven Mattisson, ISSCC-2016, Forum 3*

Hybrid beamforming for mm-Wave



Simple Hybrid beam-forming

- Beam-steering is sub-optimal
- Analog combiners are an issue

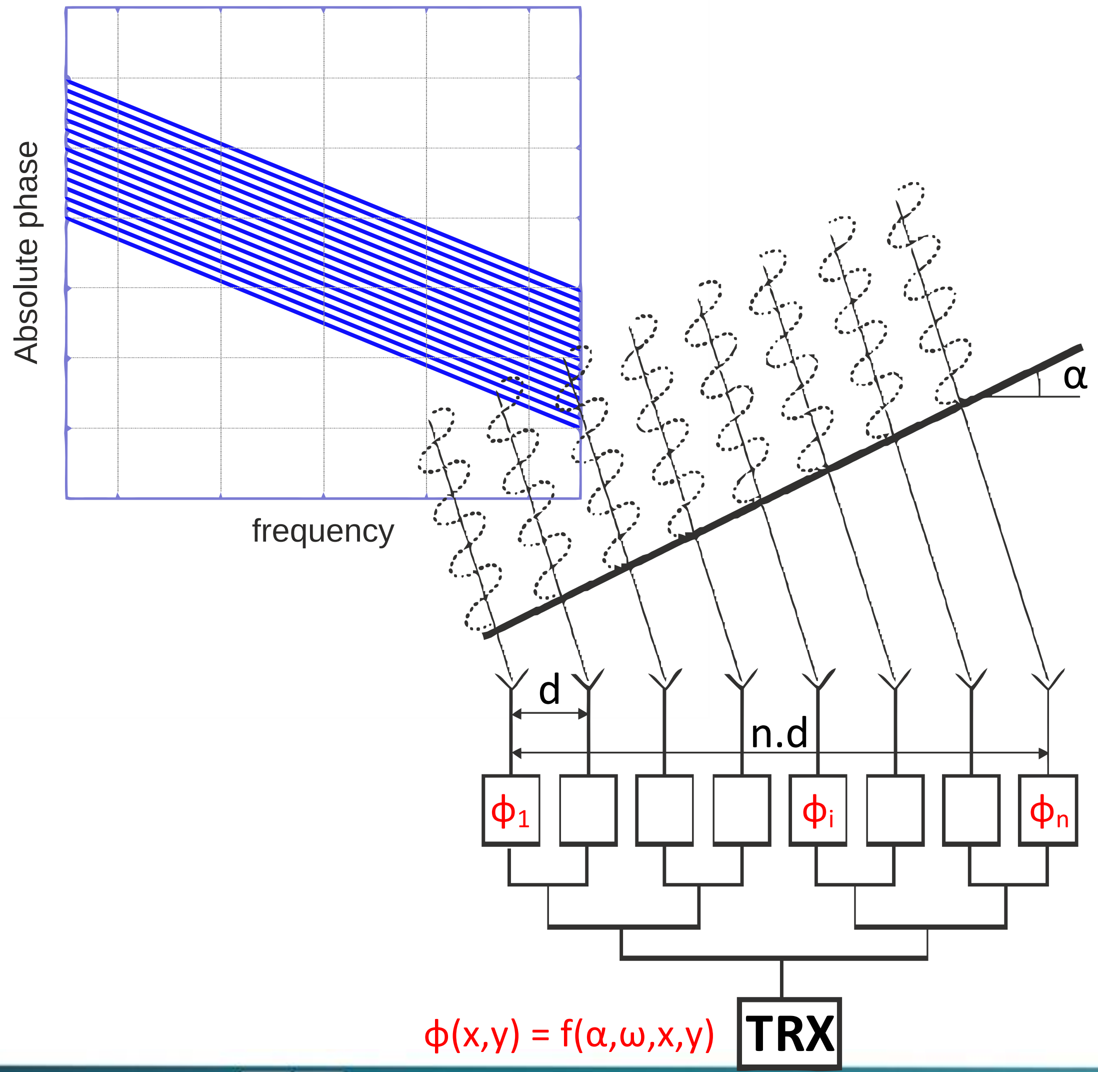
Complex Hybrid beam-forming

- Optimum performance – Equivalent to digital solution
- Analog combiners are an issue

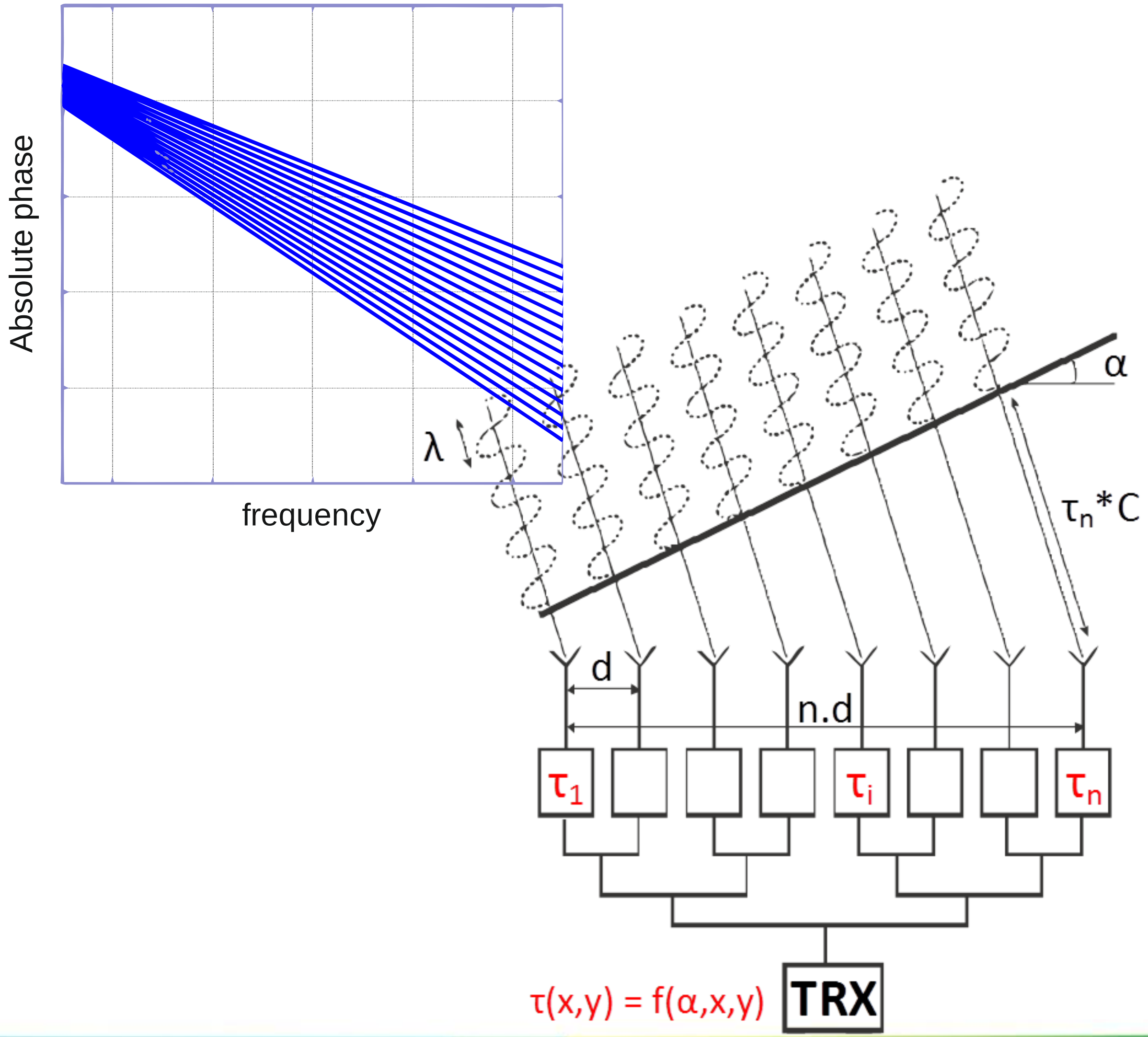
Design criteria for beamforming chip

- Number of channels
- Bandwidth
- Phase Shifter versus True Time Delay
- Rx performance like NF, phase/time resolution, Gain, Linearity, power consumption, ….
- Tx performance like of output power (P1dB, back-off,…), phase/time resolution, gain, evm, linearity, power consumption, …
- Phase shift or true time delay immune to temperature variation
- Phase invariant programmable gain
- Integrated test and calibration capabilities like LO-generation, signal injection and detection, …

Phase Shifter versus True Time Delay



$\phi(x,y) = f(\alpha,\omega,x,y)$



$\tau(x,y) = f(\alpha,x,y)$

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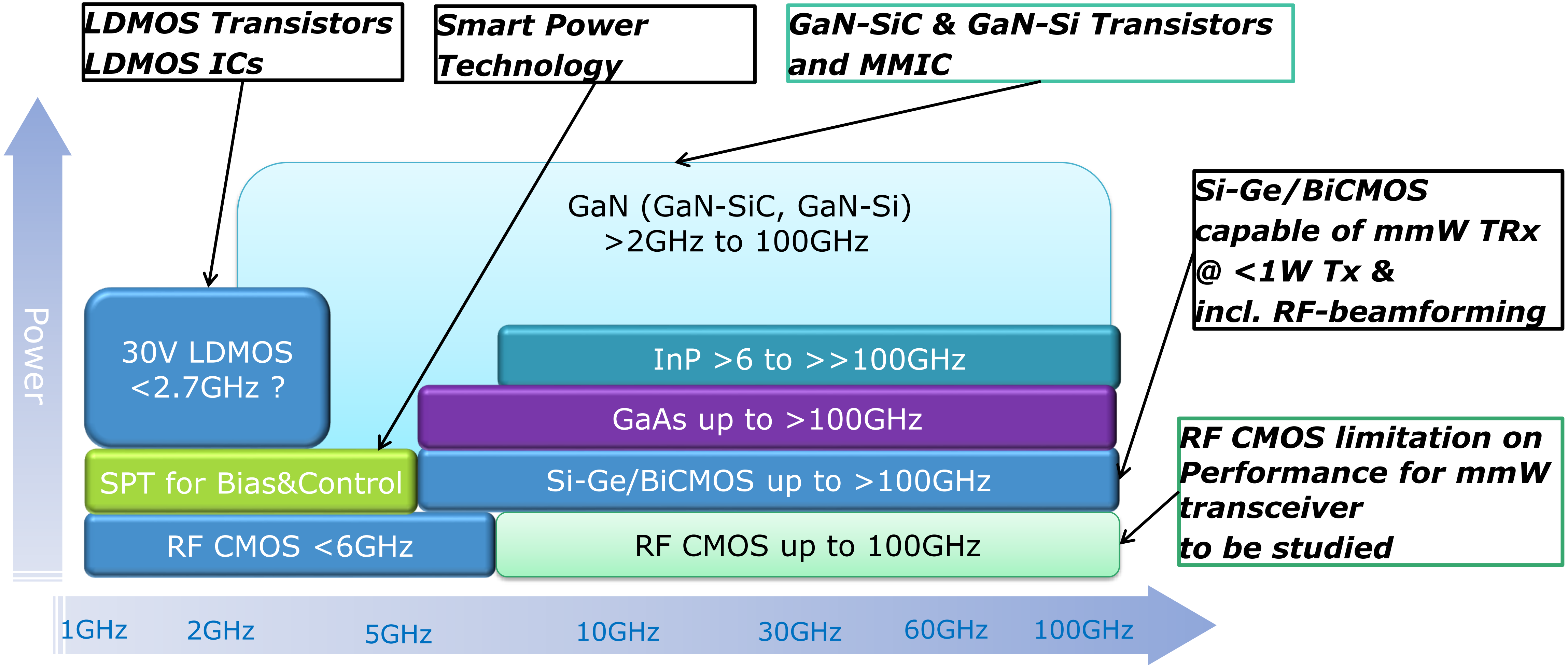
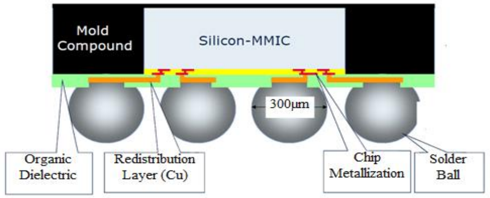
RF Transistor and RF-IC Technology Chart

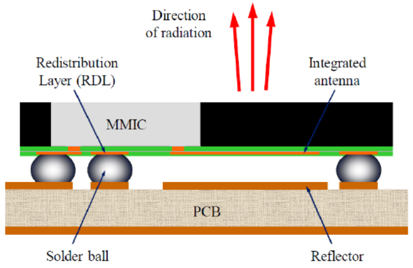


Packaging Technology Chart

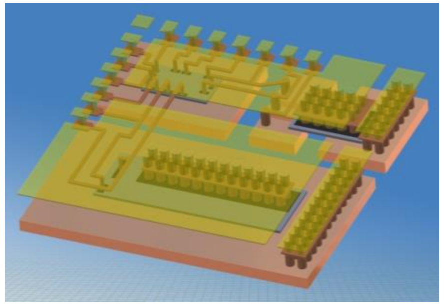
eWLB (embedded Wafer Level Ballgrid-Array) Packaging

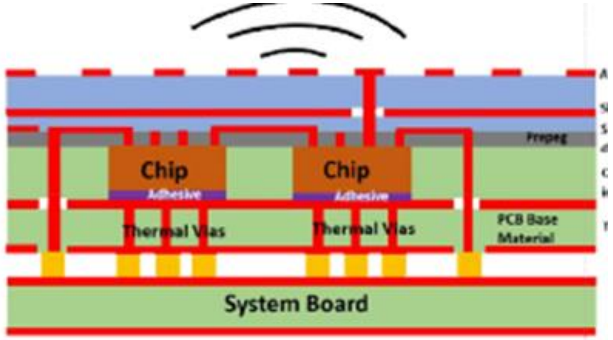


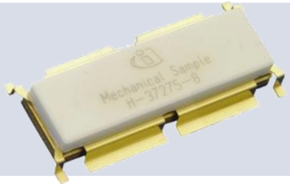
eWLB with Integrated Antenna



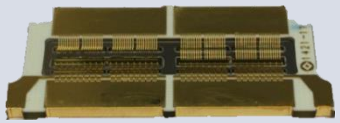
Under investigation: Packaging by 'Chip-Embedding'



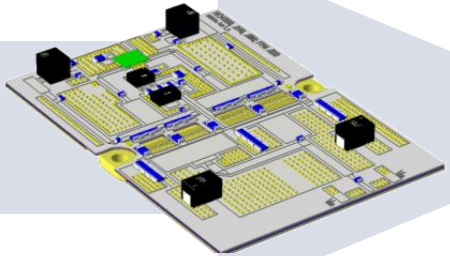




Ceramic Package



Cu Flange PCB based Package



Full RF-Power Module

Under investigation: Multilayer RF-laminate, plastic overmold

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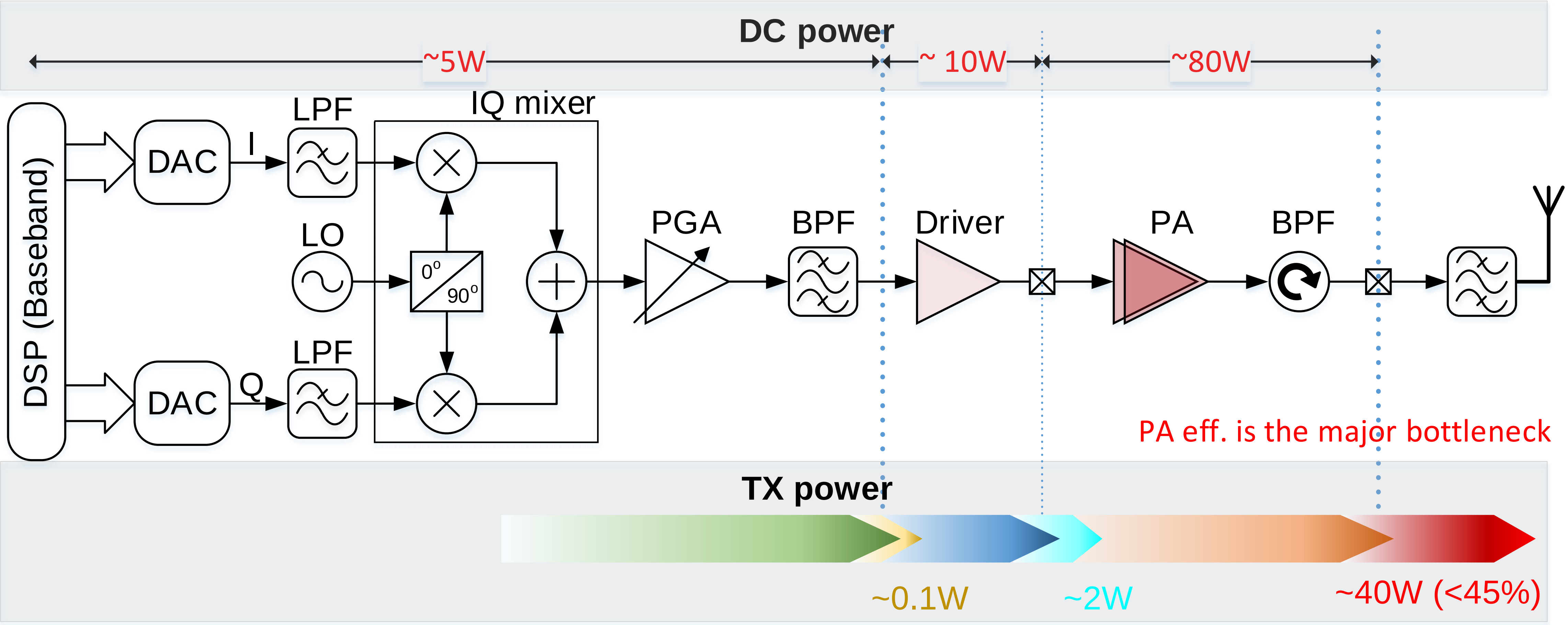
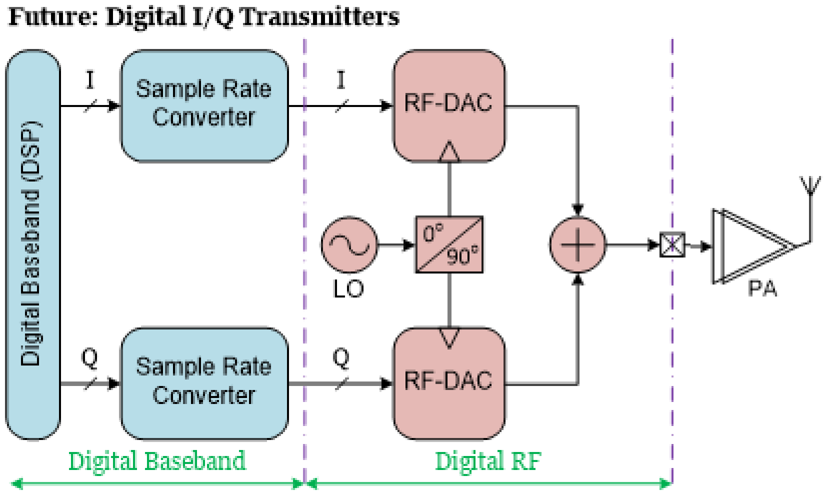
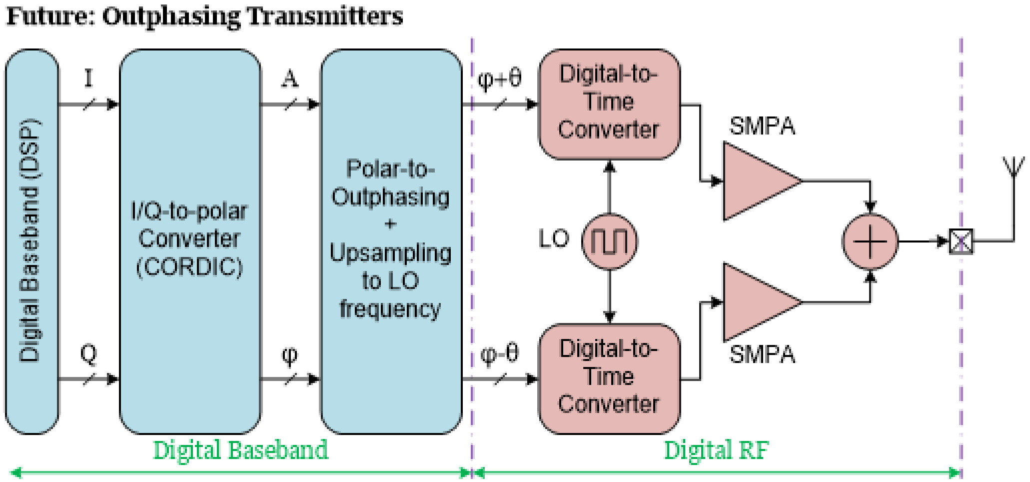
Traditional Transmitter line-up



Emerging RF architectures





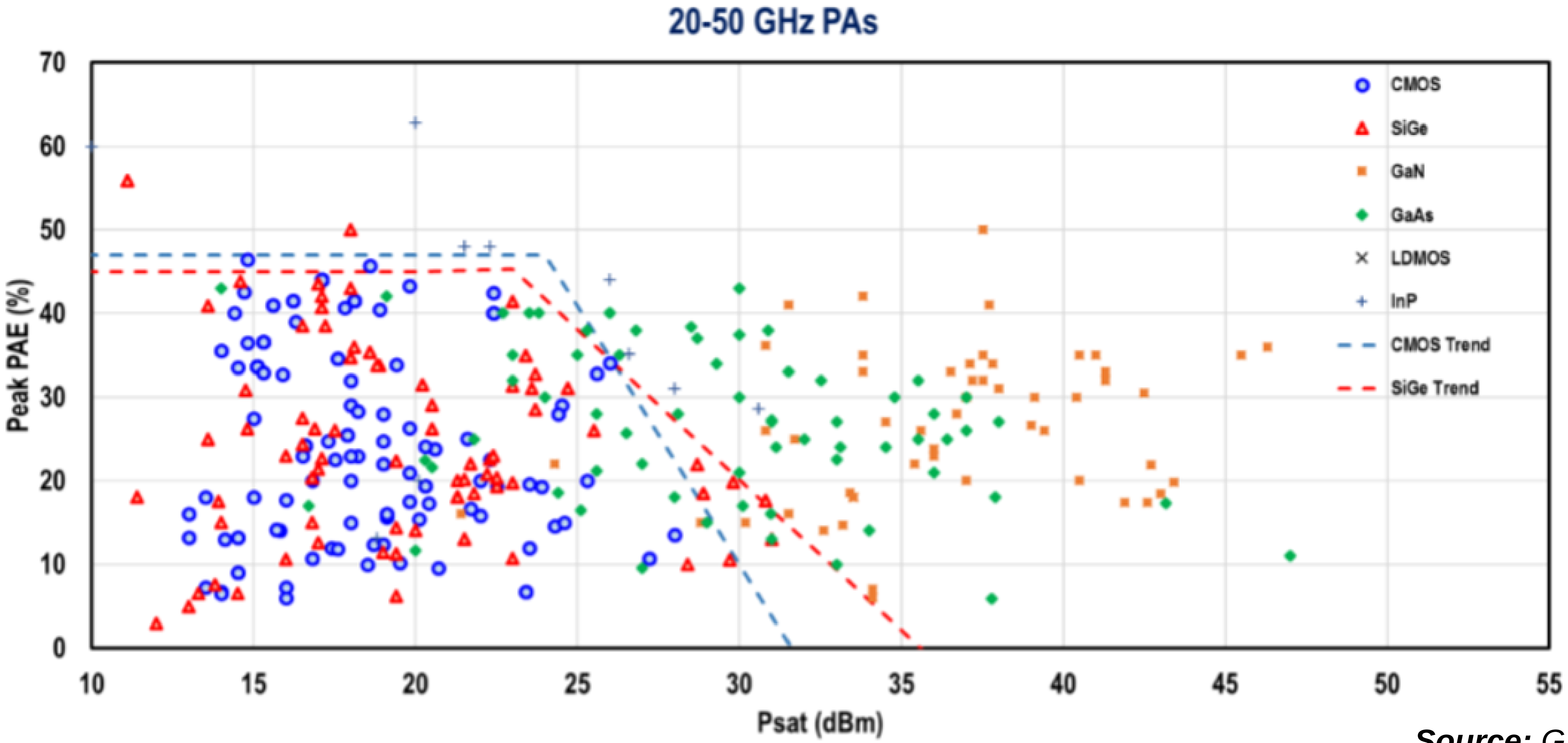
Digitally assisted RF

- **RF-sampled AD/DA converters and Doherty PA**
  - GHz-range, high resolution ADCs and DACs
- **Envelope Tracking**
  + RF path is broadband and reconfigurable
  + SMPA
  – Requires wideband and efficient supply modulator
- **Digital (PWM and outphasing) transmitter**
  + SMPA with high-efficiency e.g. Class-E PA
  + Reconfigurability
  – High resolution DTC for linearity (ACPR),
  – High bandwidth (IBW) requirement

GaAs, GaN, SiGe, or CMOS for the PA

- Choice of semiconductor process for the PA
  - Tricky balance of output power, linearity, and efficiency.
  - At 2,5-6 GHz, the PA process technology is likely to be GaN,
  - Above 20 GHz, the choice is more complex.
- mm-Wave (>24 GHz) PA's
  - Class-A, Class-AB in GaAs (used in many trials)
  - Huge heat load of several hundred Watt or higher.
  - Significant improvement needed for volume deployment
    - Fineline GaN technology
    - Doherty PA with RF predistortion
    - Relaxed ACLR specification

Comparison of CMOS, SiGe, GaAs and GaN for mmWave PAs



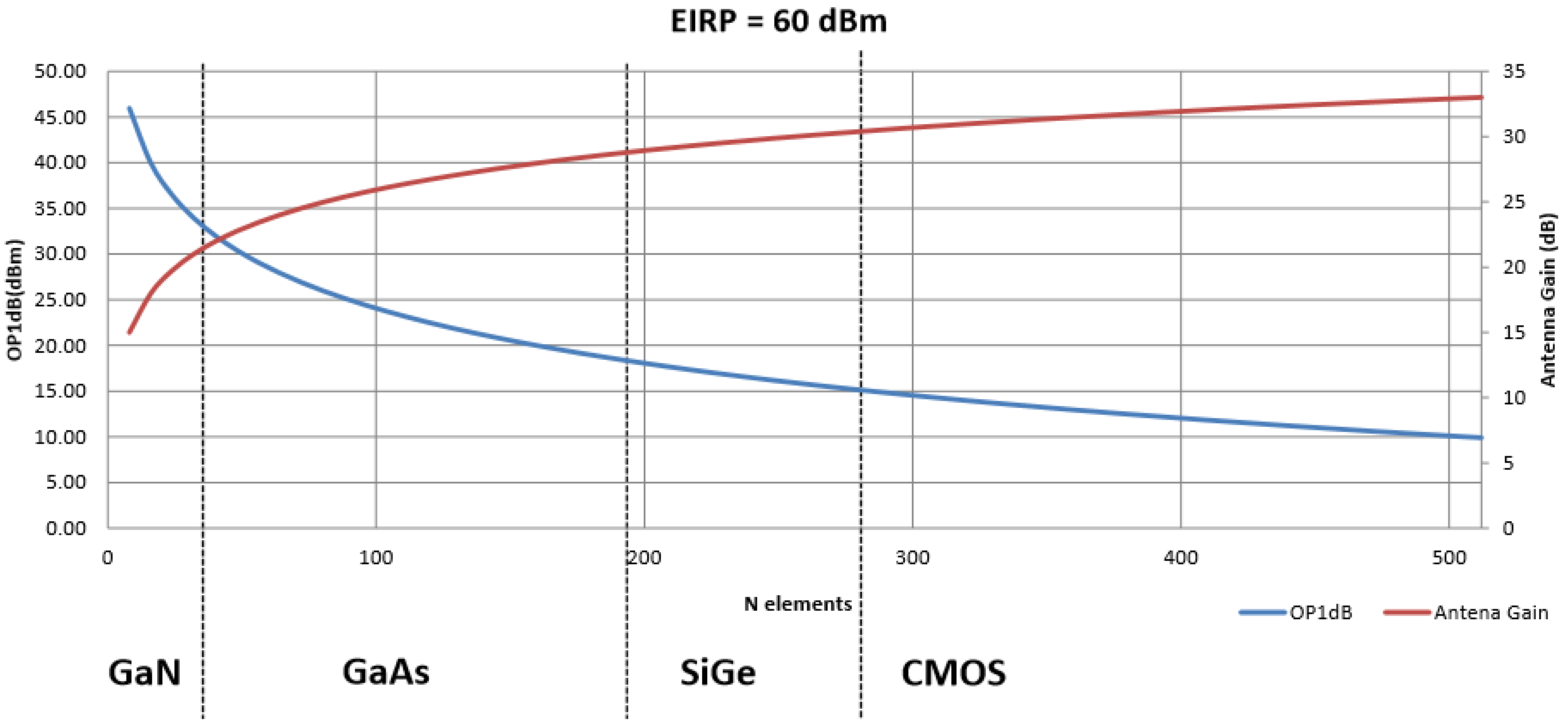
Source: *GA Tech*

A few assumptions for mm-Wave PA’s

- Peak-to-Average Ratio of the waveform of 10-12 dB.
- ACLR requirements likely to be set to about -30 dBc.
  - Ericsson’s input to the 3GPP RAN4 committee,
- ACLR requirements tighter than -35 dBc yield little benefit (and are probably not achievable in practical systems).
- Multiple deployment scenarios - different transmit power levels
  - Urban Deployment
  - Dense Urban Deployment
  - Indoor Small Cells
- Output power per PA depends on EIRP and number of antenna elements

Power Amplifier Technology Selection vs. Array Size

Backoff in the calculation below is 10dB



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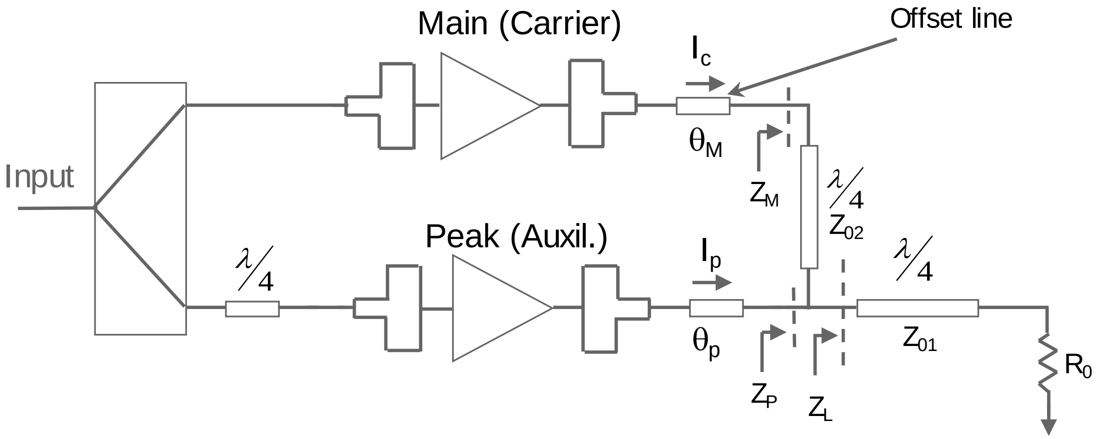
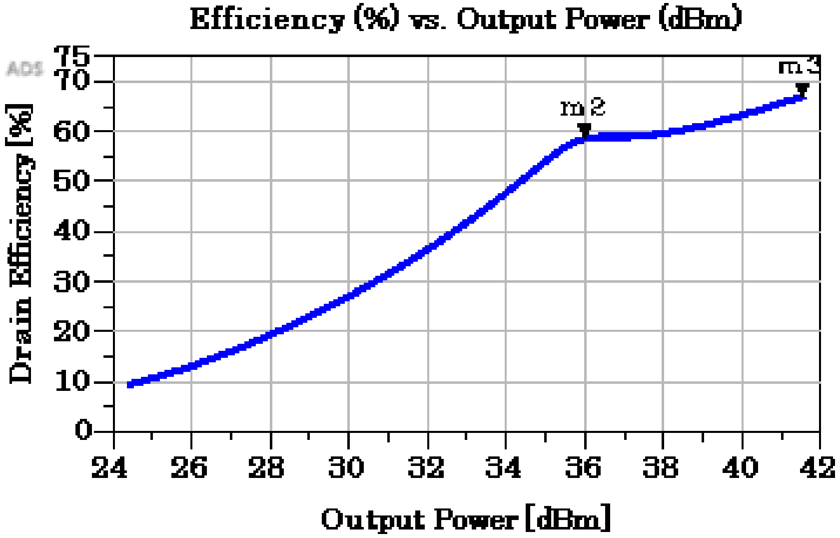
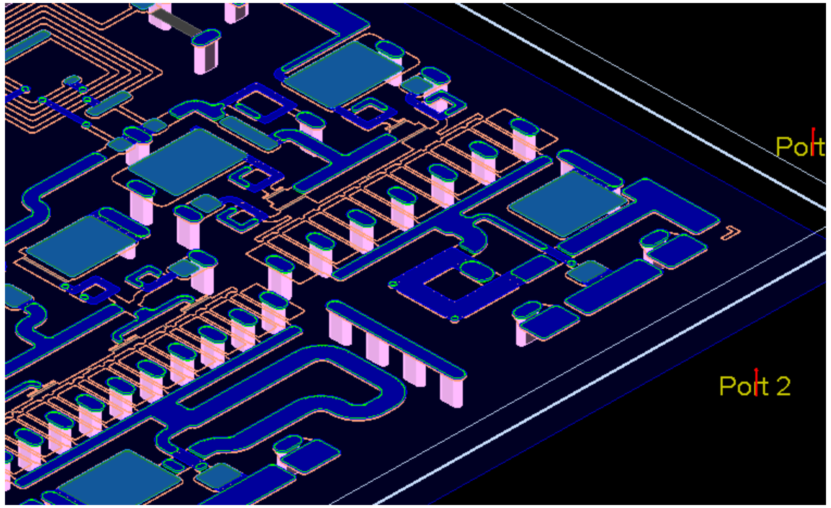
Case 1: Doherty PA for sub 6GHz

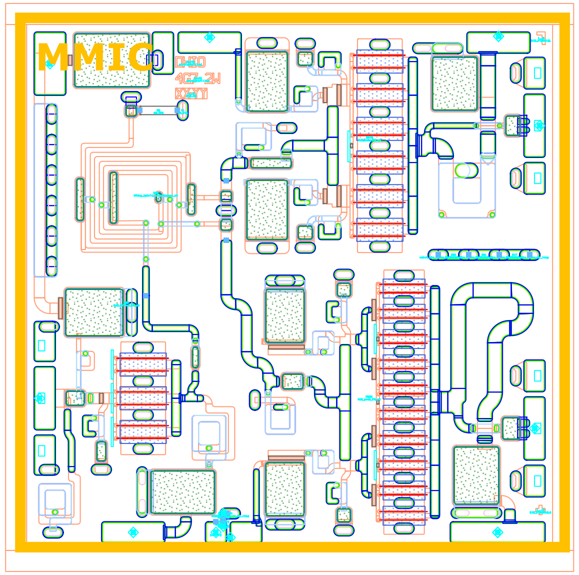


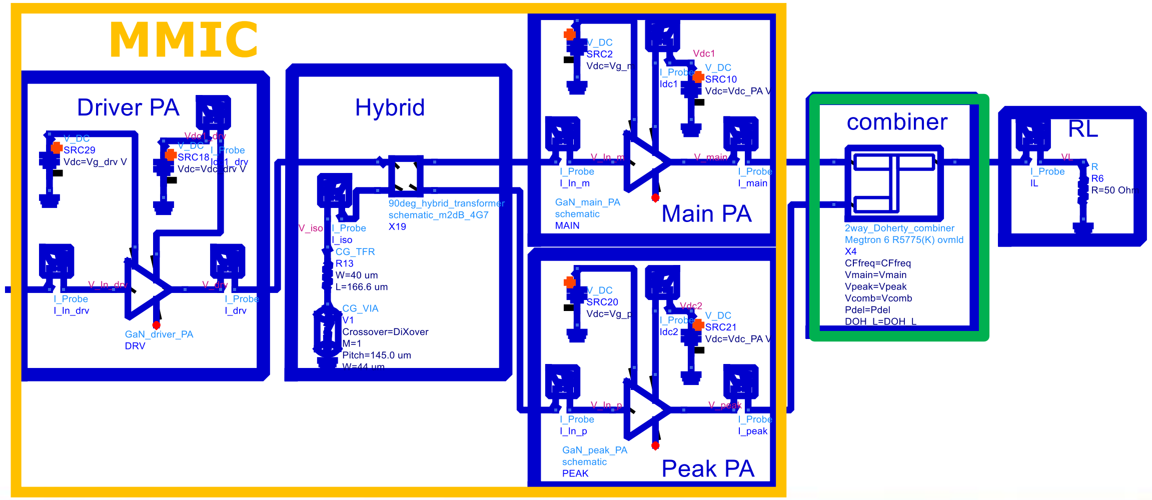


- Multi-carrier cellular signals have high PAPR (~ 8dB after CFR)
- PA architecture
  - **Doherty is best in efficiency at deep back-off**
  - Linearization is a must in order to meet both power and emissions requirements: predistortion is a must
- Discrete or MMIC integration

4.5GHz Doherty MMIC research in GaN-MMIC







Area:
2,5x2,5mm

Design targets:

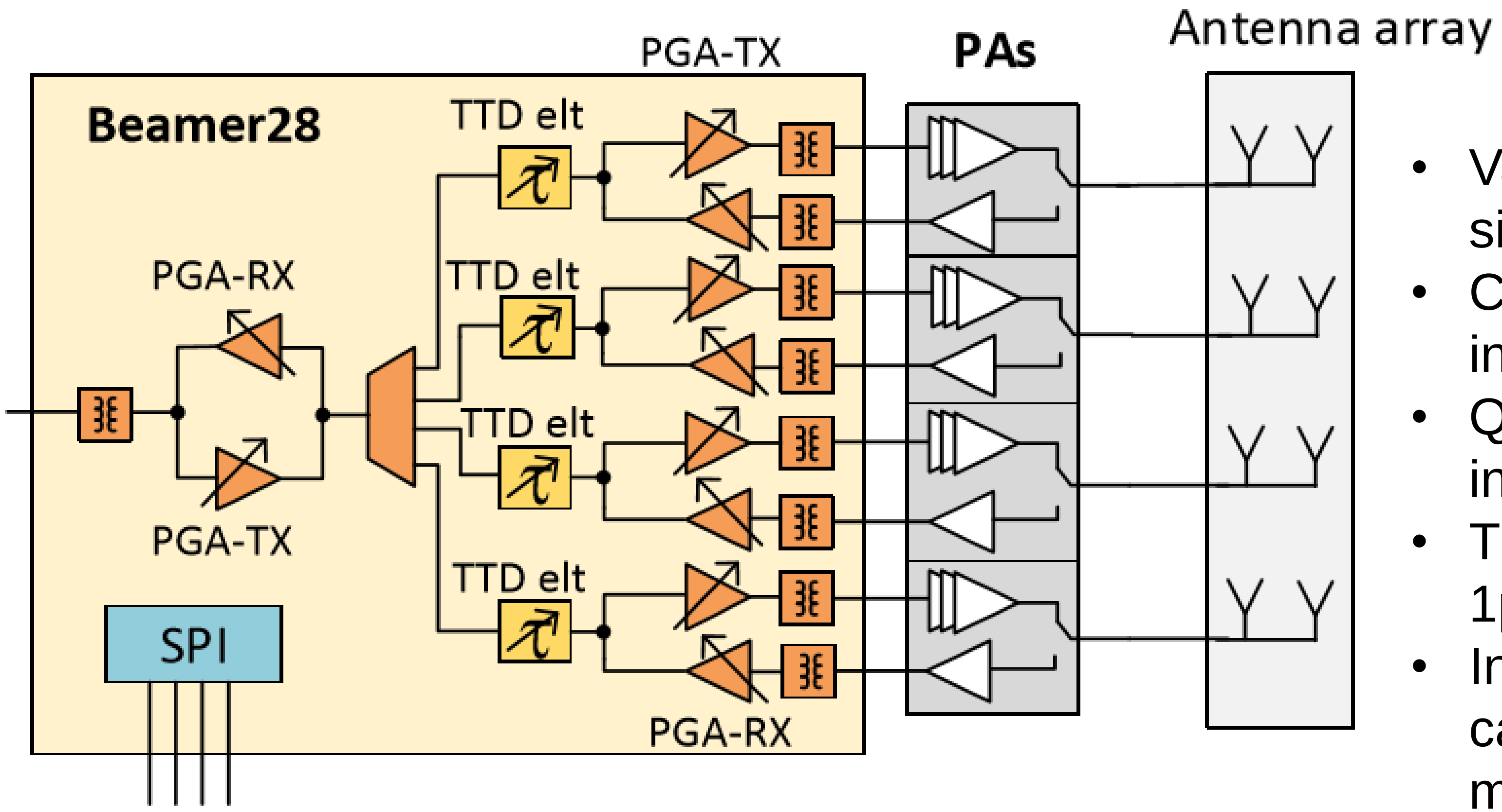
- Frequency: 4,5GHz
- IBW: 400 MHz
- PAE: >40%
- Pout: >33dBm
- PAPR: 9dB
- Gain: 30dB
- Supply: 28V

Case 2: mm-Wave RF beamforming example

- For current mm-wave amplifiers and beamformers:
  - – PAE < 4% (@10dB back-off)
  - – Beamforming cost ~ 250 mW/channel

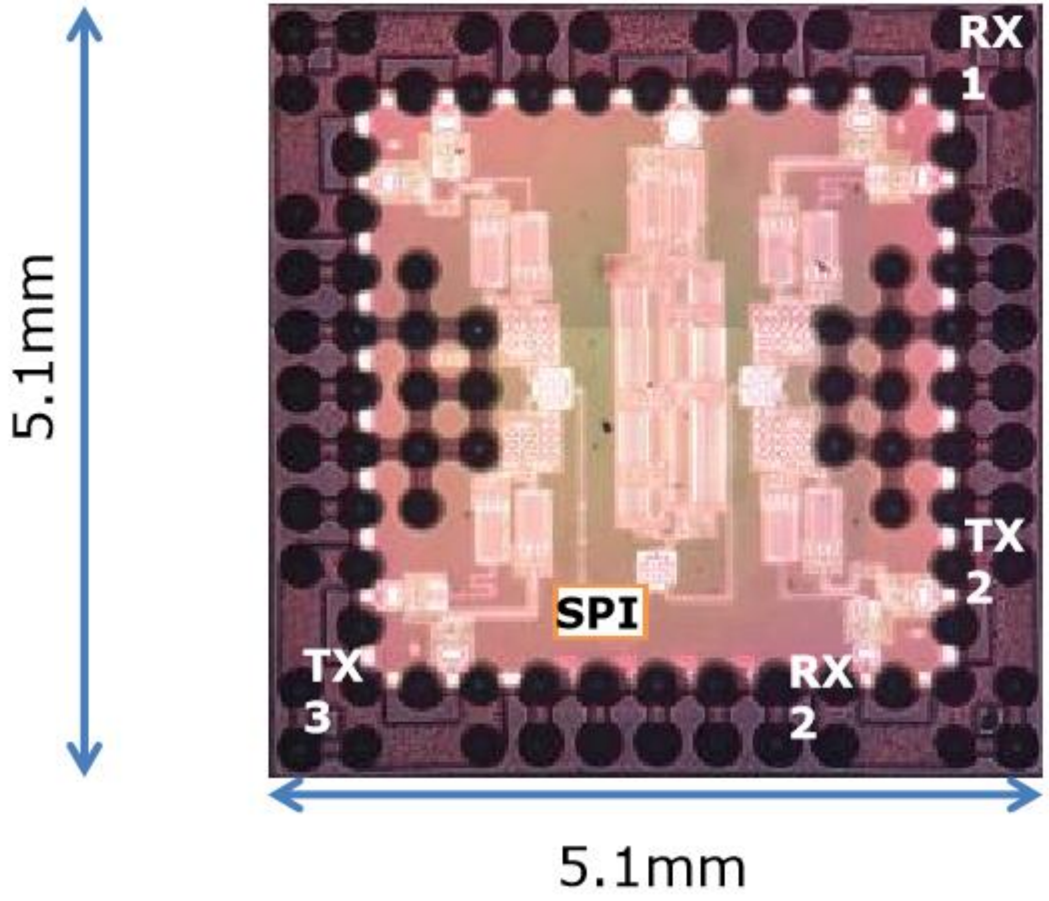
- "Optimum" array configuration:
  - – 200 elements (14 x 14)
  - – 10 dBm average power per element @ 4% PAE → 50 W
  - – 250 mW/element beamforming → 50 W
  - – **Total per antenna array = 100 W** just for the RF front-end …

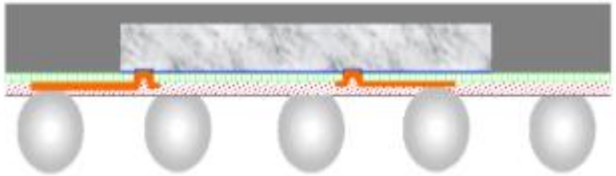
Beamer 28 RFIC Block Diagram



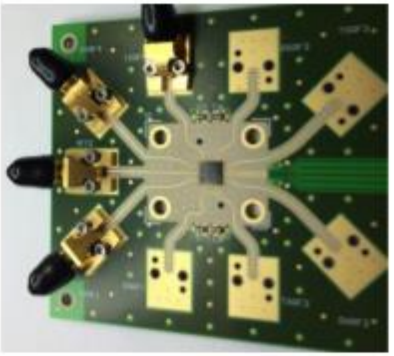
- Variable TTD supports wideband signals
- Center frequency 28…32 GHz, instantaneous Bandwidth 800MHz
- Quadruple bidirectional channels including Wilkinson splitter/combiner
- True time delay range 180ps and 1ps resolution
- Integrated BITE for Test and calibration (RF signal generation and monitoring)

Beamer 28 RFIC Microphotograph and eWLB Package

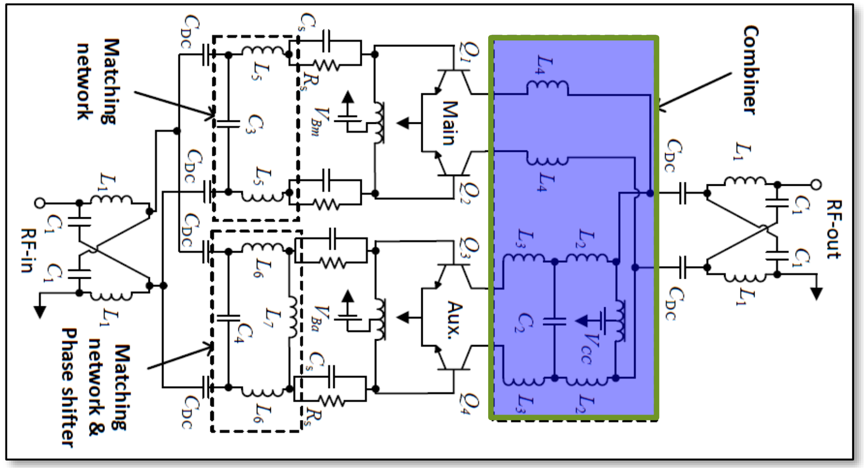


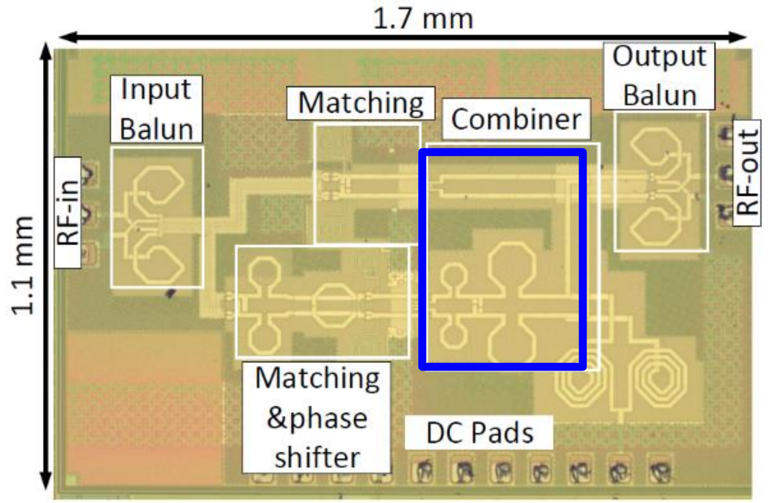


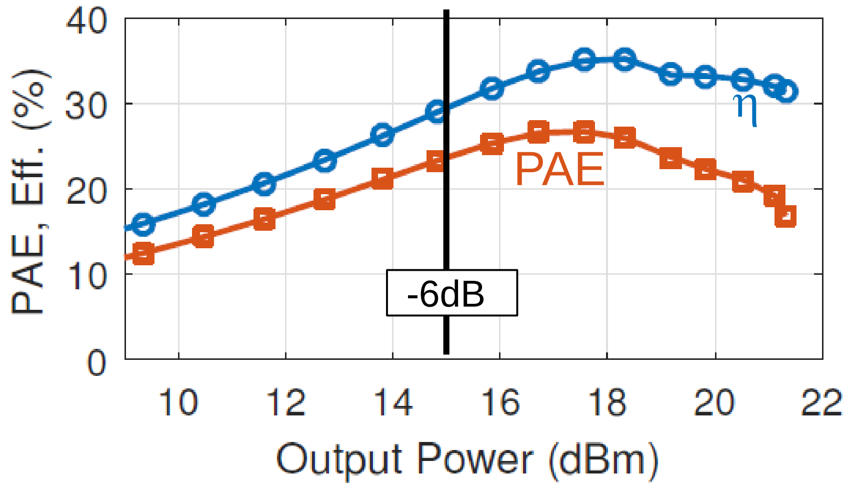
- Automotive qualified
- 400μm ball pitch
- RF Co-design for best thermal behavior

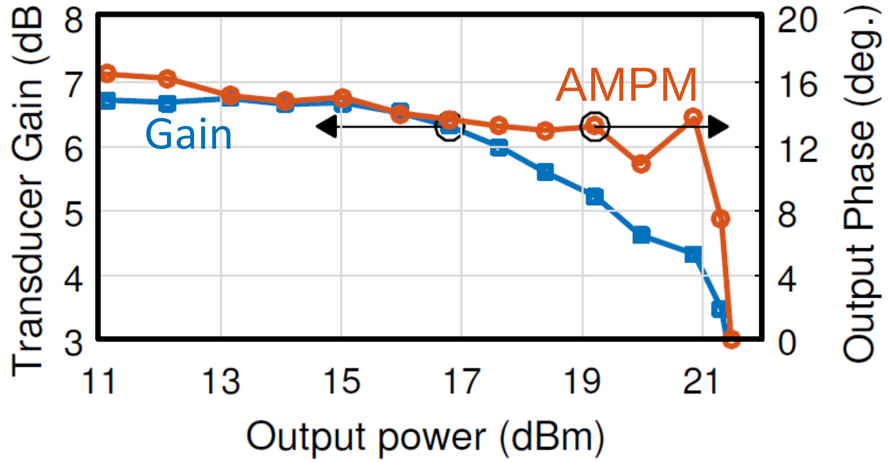


Case 3: Efficient 30 GHz Doherty PA design in SiGe









Source: *Mustafa Ozen, Christian Fager, ISSCC-2019, Forum 1*

Comparison Table

	Infineon	[1] Tokyo IT	[2] Qualcomm	[3] IBM	[4] UCSD
Technology	SiGe 130nm	CMOS 65nm	CMOS 28nm	SiGe 130nm	SiGe 180nm
Freq. [GHz]	24.25-30.5	28 (n257)	28 (n257)	27-29	28-32
Channels	4	4 (4xH-BF, 4xV-BF)	24x TRX	16/pol (16xH/16xV-TRX)	4 (4xH-BF, 4xV-BF)
Area [mm²]	19.4	12	27.8	165.9	23
Package	eWLB	–	Flipped on PCB	Laminate	Flipped on PCB
RX P_{dc} [W]	1.6 (0.4/path)	0.6 (0.112/path)	0.042/path	3.3/pol (0.206/path)	0.15/path
TX P_{dc} [W]	1.8 (0.45 @P_{1dB}/path)	1.2 (0.252 @11.3 dBm/path)	0.119 @11 dBm/path	4.6/pol (0.319 @16.4dBm/path)	0.22/path
RX NF [dB]	4	4.2	4.4 – 4.7	6 (Front-end)	4.8
BITE	YES	NO	NO	NO	NO

[1] J. Pang *et al*., "21.1 A 28GHz CMOS Phased-Array Beamformer Utilizing Neutralized Bi-Directional Technique Supporting Dual-Polarized MIMO for 5G NR," *2019 IEEE International Solid- State Circuits Conference - (ISSCC)*, San Francisco, CA, USA, 2019, pp. 344-346.
[2] J. D. Dunworth et al., "A 28GHz Bulk-CMOS dual-polarization phased-array transceiver with 24 channels for 5G user and basestation equipment," 2018 IEEE International Solid - State Circuits Conference - (ISSCC), San Francisco, CA, 2018, pp. 70-72.
[3] B. Sadhu et al., "A 28-GHz 32-Element TRX Phased-Array IC With Concurrent Dual-Polarized Operation and Orthogonal Phase and Gain Control for 5G Communications," in IEEE Journal of Solid-State Circuits, vol. 52, no. 12, pp. 3373-3391, Dec. 2017.
[4] K. Kibaroglu, M. Sayginer, A. Nafe and G. M. Rebeiz, "A Dual-Polarized Dual-Beam 28 GHz Beamformer Chip Demonstrating a 24 Gbps 64-QAM 2×2 MIMO Link," 2018 IEEE Radio Frequency Integrated Circuits Symposium (RFIC), Philadelphia, PA, 2018, pp. 64-67.

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SUMMARY

- Demanding performance of the emerging 5G NR solutions require a new approach from system architecture down to circuits and technologies involved
- Massive MIMO and mm-Wave frequencies are required to achieve the ever increasing communication demand
- This leads to increased hardware complexity: cost and power are exploding
- PA becomes the bottleneck and has to be addressed at all levels including technology selection and architecture

Thank you for your attention