IMS 2017 5G Summit: RFIC/CMOS Technologies for 5G, mmW and Beyond

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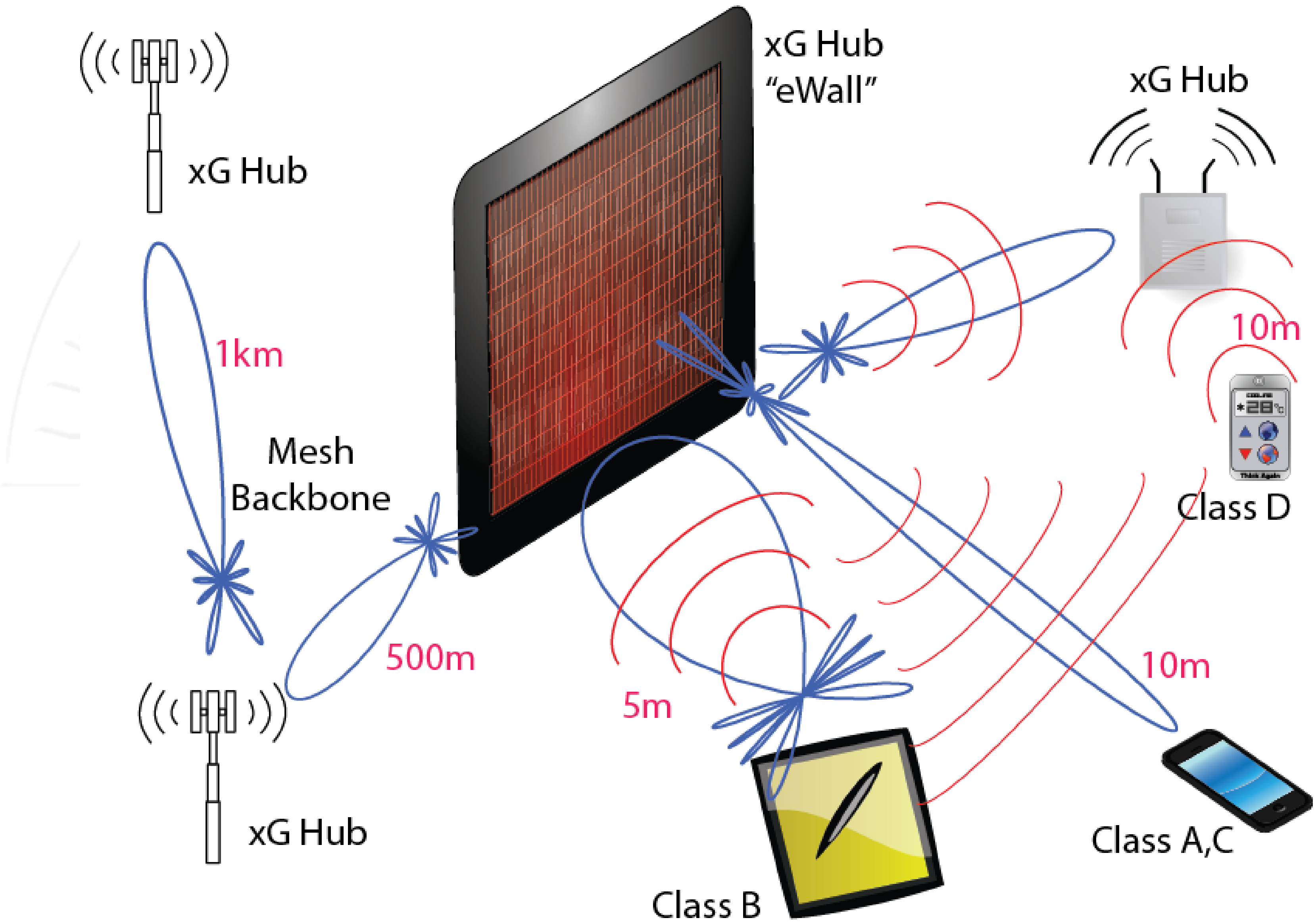
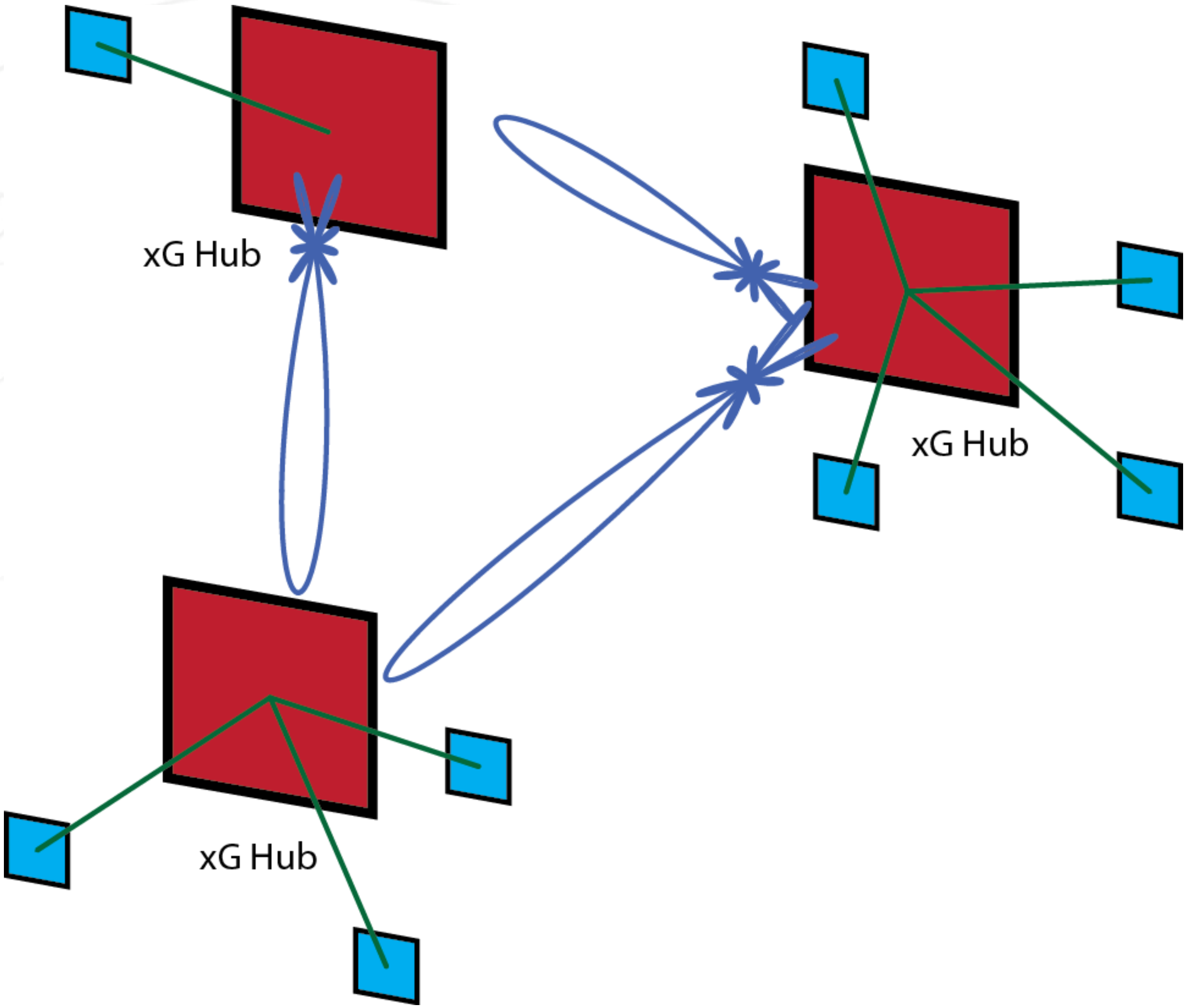
BWRC xG Vision (x >= 5)



Stay Wireless



- In Europe, ~50% of LTE base stations are wireless. Why not use the same technology for front- and back-haul

Interference Mitigation

- Maxwell’s equations are linear: waves just pass through each other
- Interference really happens because of the receiver’s non-linearity
- Most radios today spray energy in all possible directions
- This is not only a huge waste of power, but it causes more interference!
- Solution: directivity!

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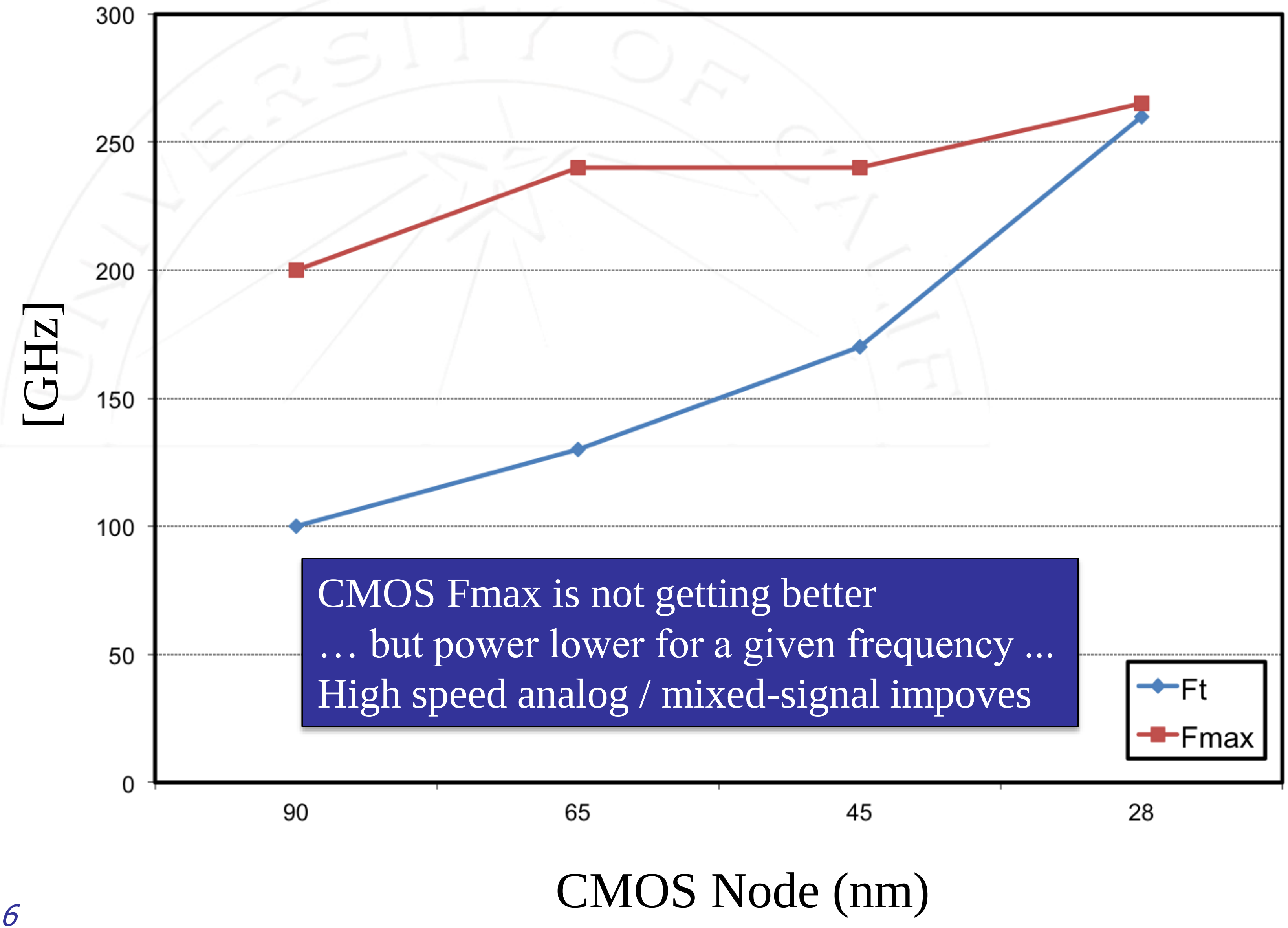
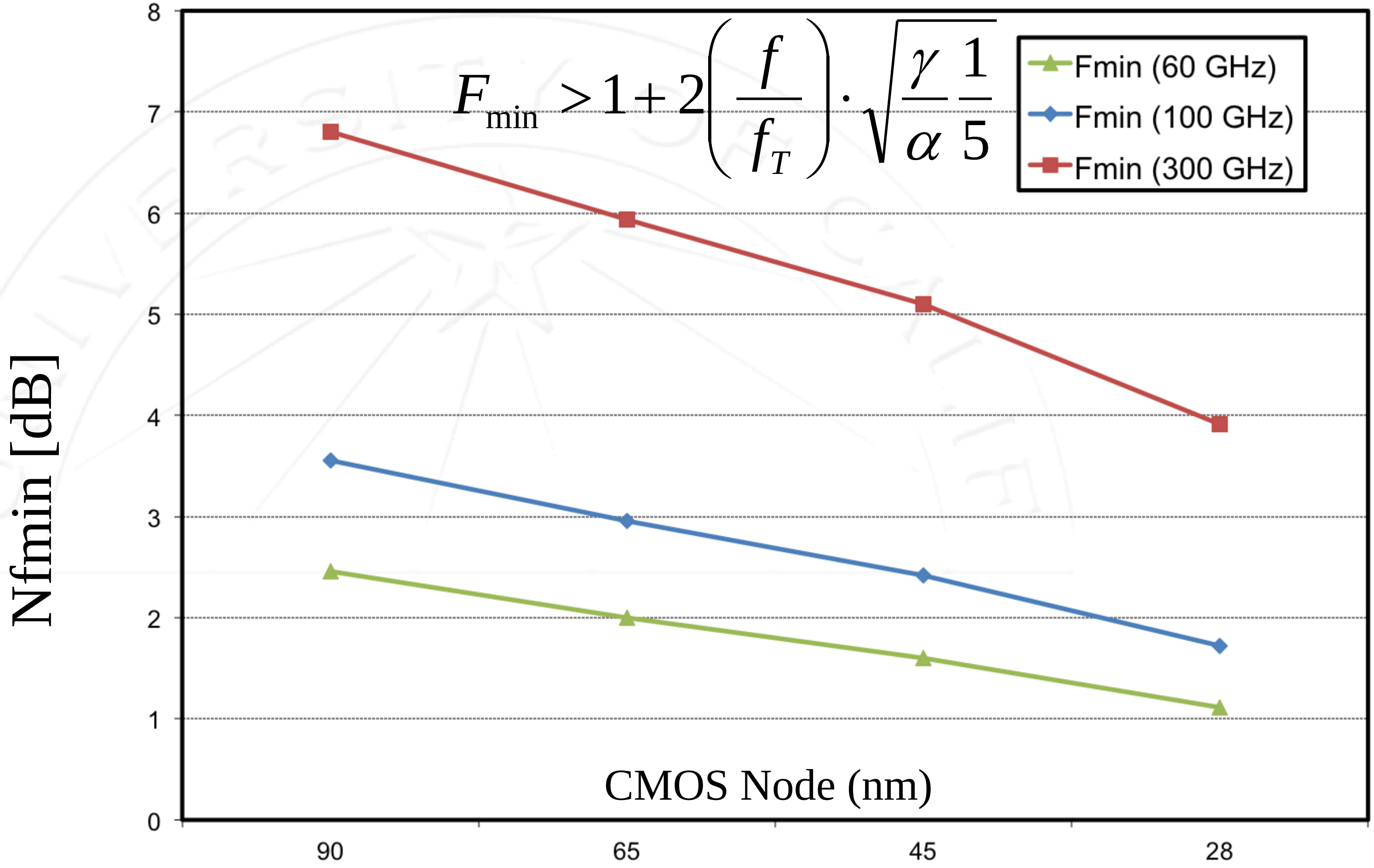
TECHNOLOGY TRENDS

CMOS Raw Speed

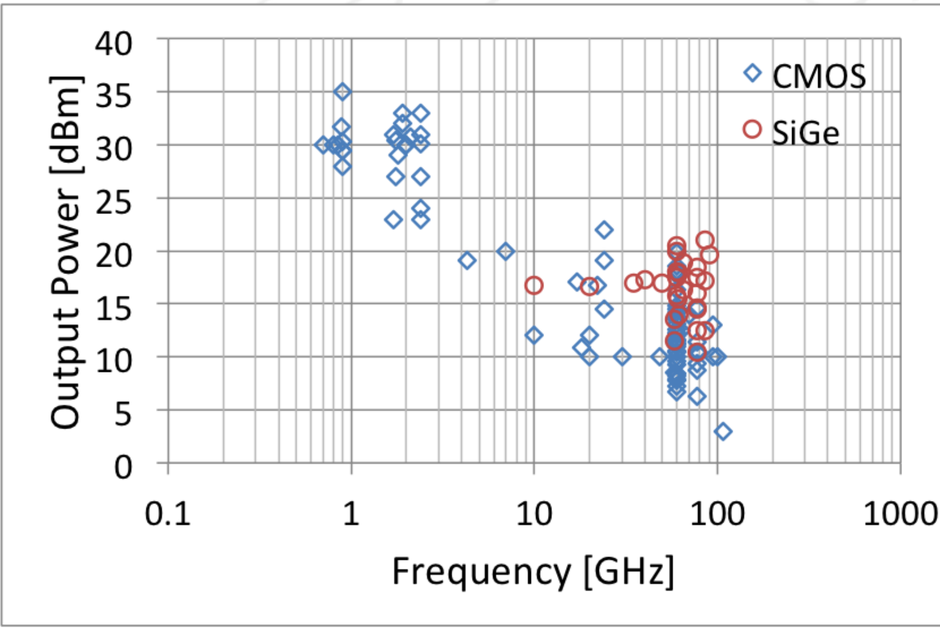


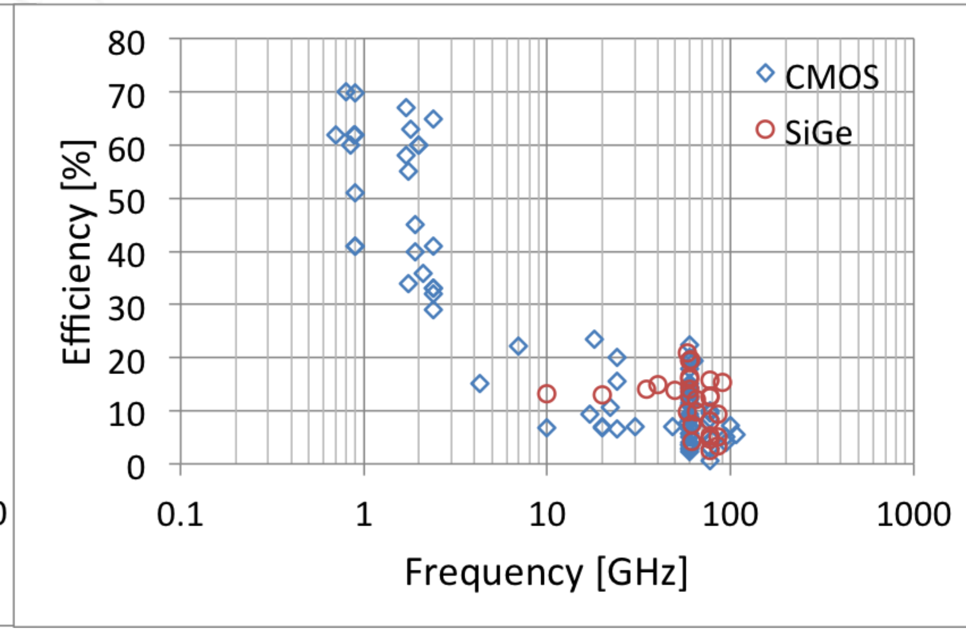
Receiver Sensitivity



- Receiver will have a noise figure ~ 3 dB higher than Nfmin of device
  - 28 nm: 4-5 dB NF at 100 GHz

Silicon Power Amplifier Performance





- Obvious trends: Power and Efficiency drop with frequency.
- Power can be improved by on-chip and spatial combining.
- Going beyond 17 dBm with CMOS difficult and inefficient
  - With modest array (64 elements), don't need much more power
  - Handset is key issue that would benefit from III-V (e.g. GaN)

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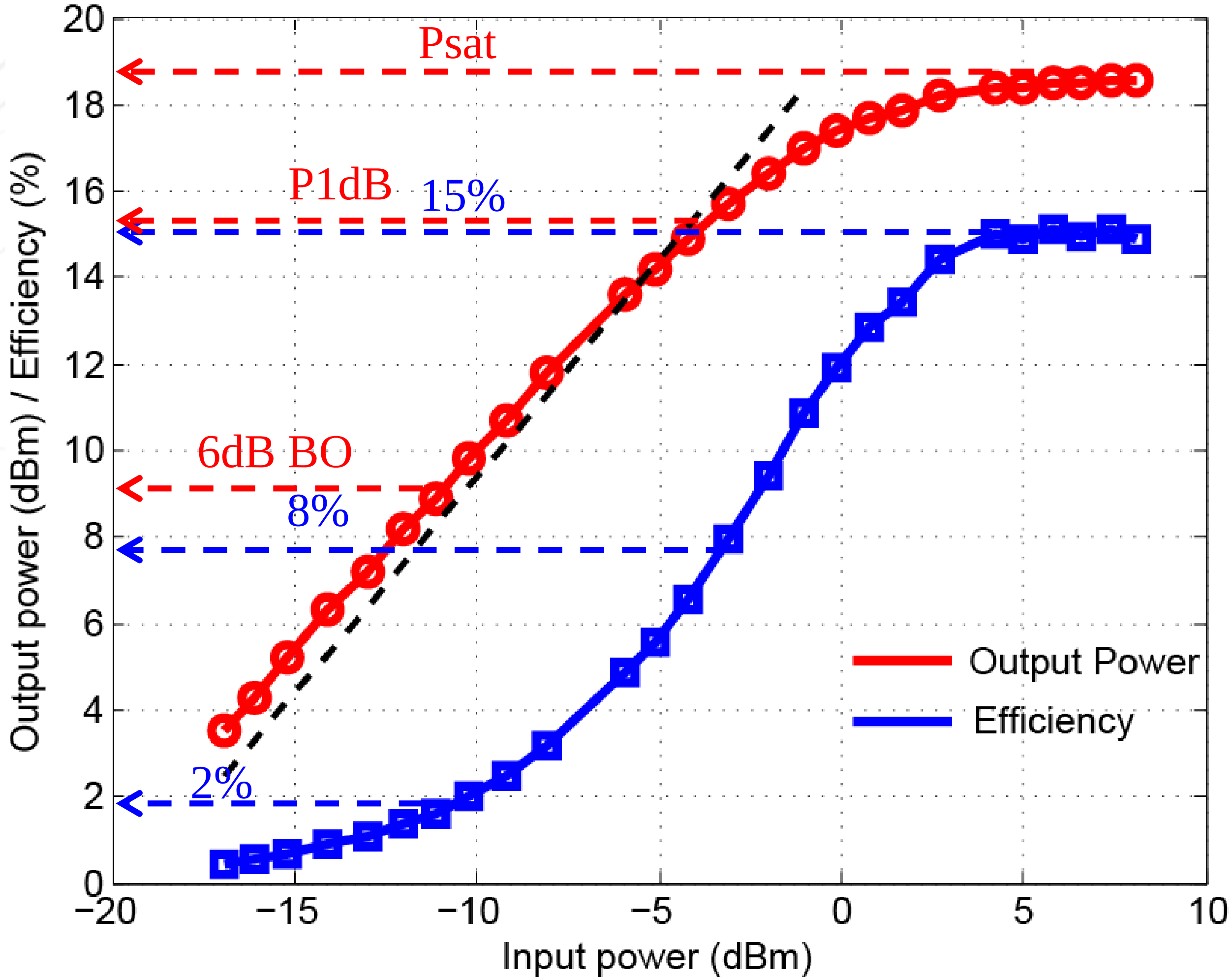
Typical mm-Wave Class-A PA Power/Efficiency Characteristics

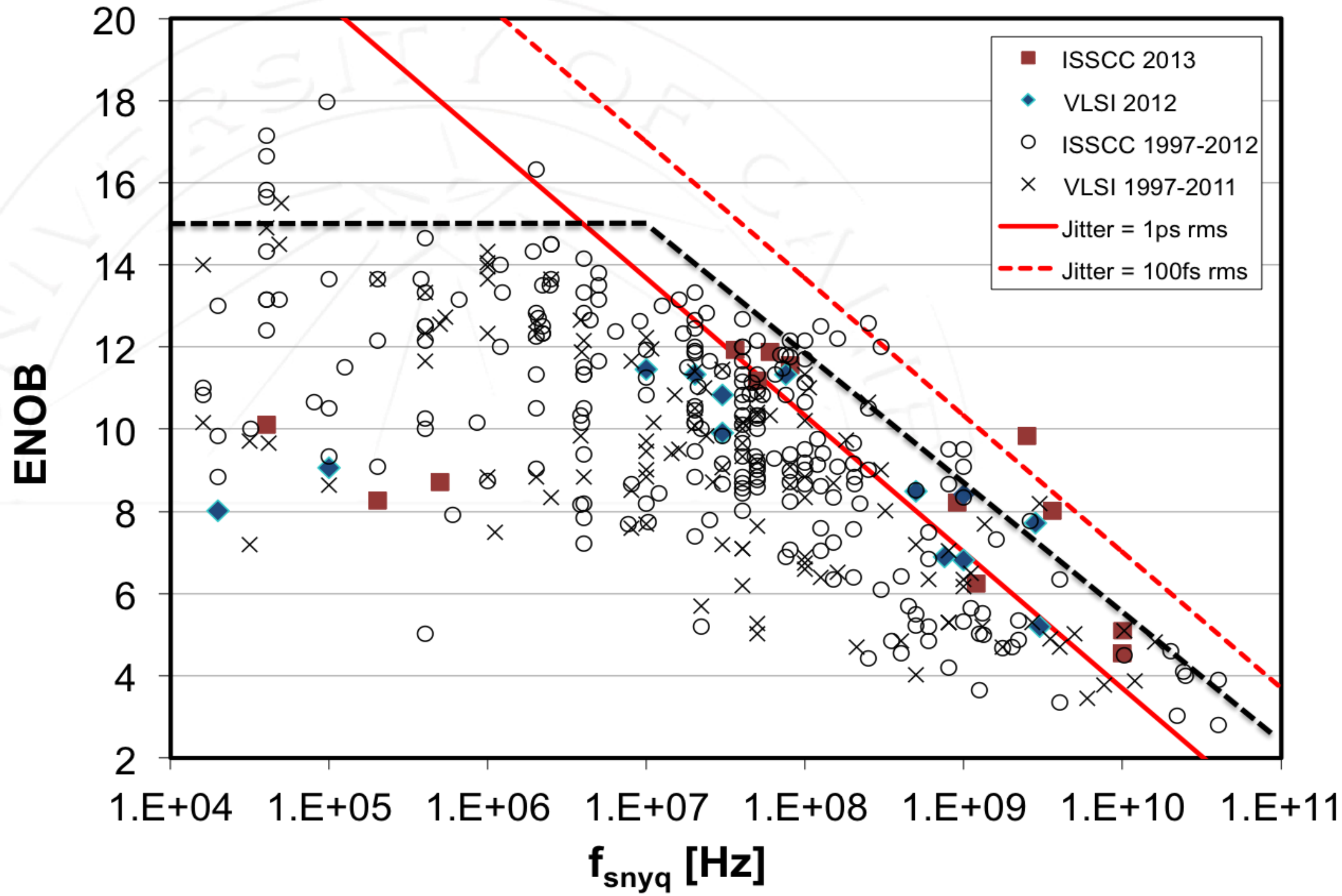


Phase Noise

		RFIC15 [1]	JSSC13 [2]	RFIC08 [3]	ISSCC14 [4]	RFIC14 [5]	RFIC14 [6]
CMOS Technology		40nm	90nm	130nm	40nm	65nm	32nm SOI
Type		Harmonic extraction	Fundamental	Fundamental	Fundamental	Frequency tripling	Common-mode extraction
Quadrature output		No	No	No	Yes	Yes	No
P_{DC} (mW)	Oscillator	13.5	14	3.9	30	10.6+14[(a)]	35
	Buffer	10.5	NA	NA			
Supply voltage (V)		0.7/1	1.2	1	0.9	1.2	1
Tuning range (GHz)		48.4-62.5 (25.4 %)	55.8-61.6 (9.75 %)	59-65.2 (10 %)	57.9-68.3 (16.2 %)	58.3-65.4 (11.5%)	46.4-58.1 (22.4 %)
Phase noise (dBc/Hz)	1MHz	-100.1	-94	-95 / -91[(c)]	-92.5	NA	-89[(b)]
	10MHz	-122.3	NA	NA	NA	-115[(b)]	-118[(b)]
FoM (dBc/Hz)	1MHz	181.5	177.7	185 / 181	173.1	NA	168.5
	10MHz	183.7	NA	NA	NA	176.9	177.5
FoM_T (dBc/Hz)	1MHz	189.6	177.9	185 / 181	177.3	NA	175.5
	10MHz	191.8	NA	NA	NA	178.1	184.5

[Courtesy of Masoud Babaie]

ADC Resolution (ENOB)



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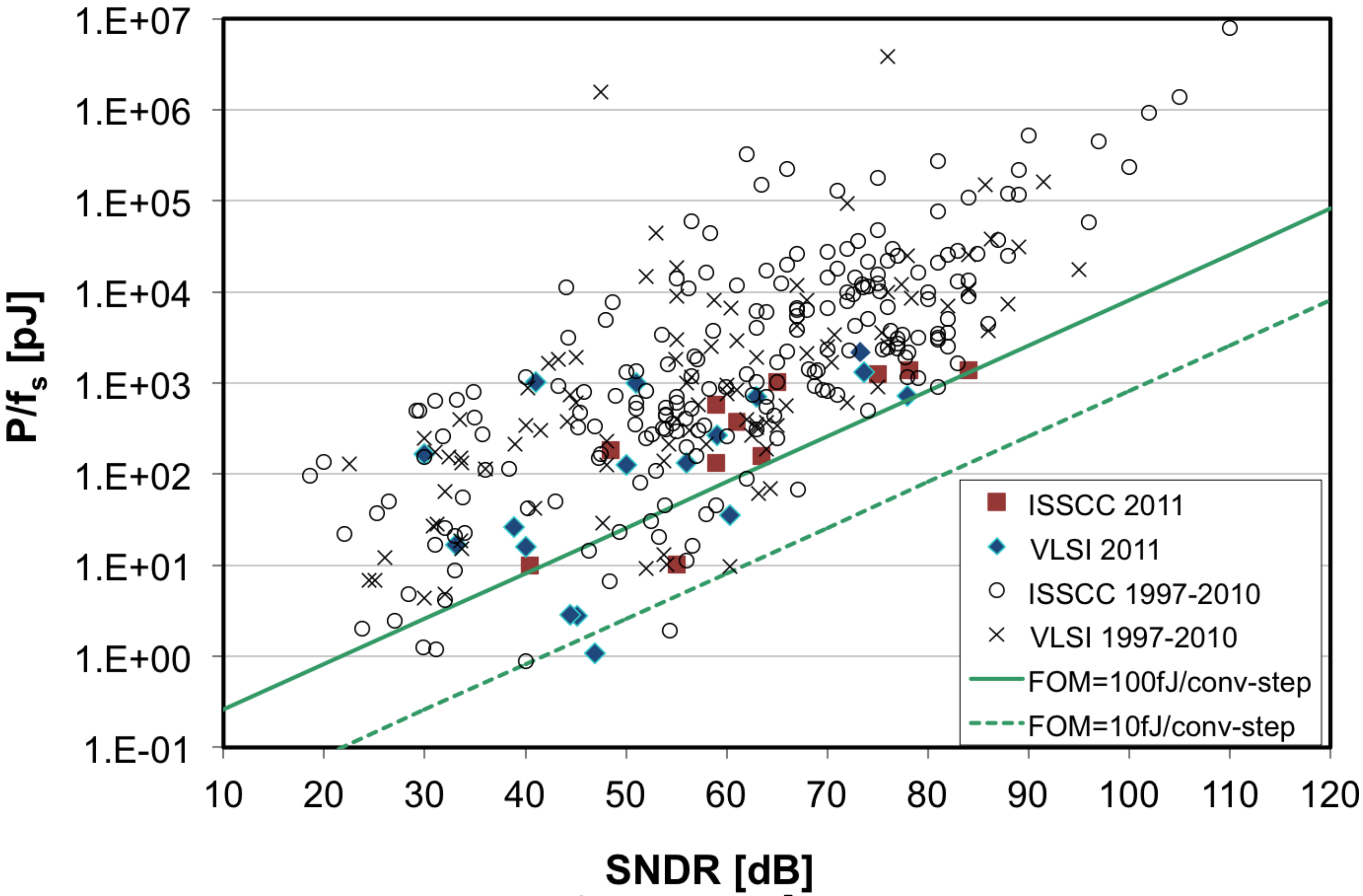
ADC Power



- 2 GS/s, 8-bits @ 100fJ/conv → 50mW
- Clock jitter requirements (0.5 ps), ADC buffer (especially SAR), reference buffer …

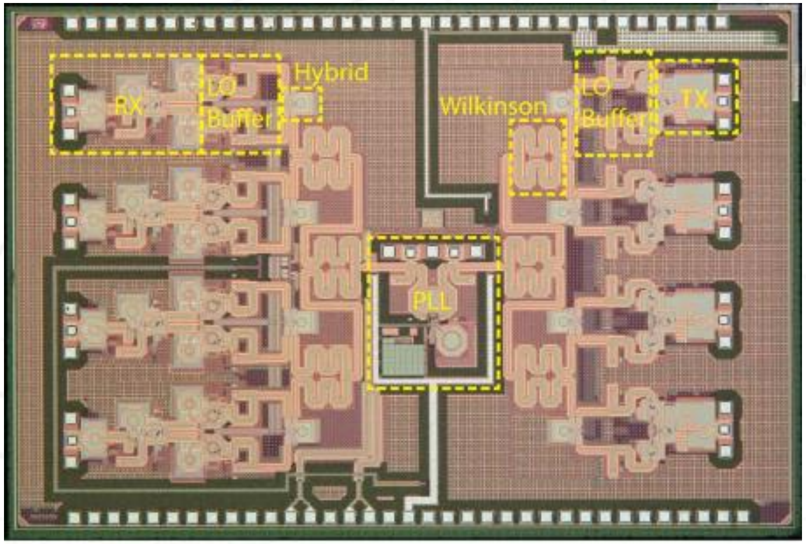
Technology Trends Summary

- Operation up to 100 GHz possible with CMOS / SiGe
- Receiver noise figure not an issue
  - Especially in an array
- Phase noise is dominated by reference noise
  - 64-QAM at 1 Gb/s at 28 GHz possible
- Tx efficiency a major issue
  - < 5% with current techniques at 6-dB back-off
  - Composite signals (multiple streams) may require 10-dB backoff !
- ADCs getting better … especially moderate resolution @ 1 Gb/s (4-6 bits)

MASSIVE MIMO AND MM-WAVE SYSTEM ARCHITECTURE

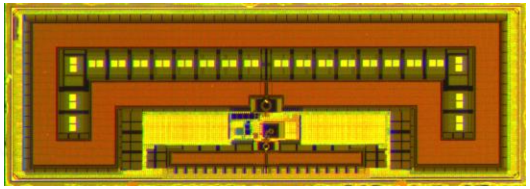
BWRC Past mm-Wave Chips

[Tabesh et al, ISSCC 2011]

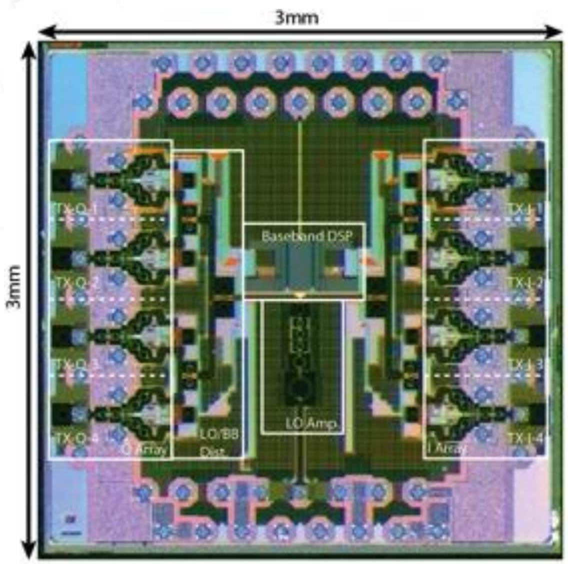


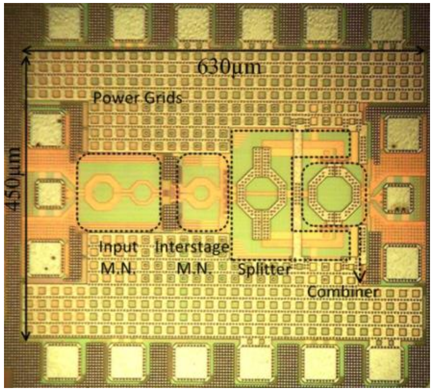
4 Elements (Separate TX/RX)
137 mW Total (Rx or Tx mode)

[Tabesh et al, VLSI/JSSC 2015]



24/60 GHz RFID; 12 Mbps; 1.5 uW





[Chen et al, ISSCC 2011]
18.6dBm 60GHz Power Amplifier in 65nm

[Chen et al, ISSCC 2013]
Peak Tx efficiency 17.4%.
Maintains > 7% efficiency while transmitting 6 Gbps (16-QAM)

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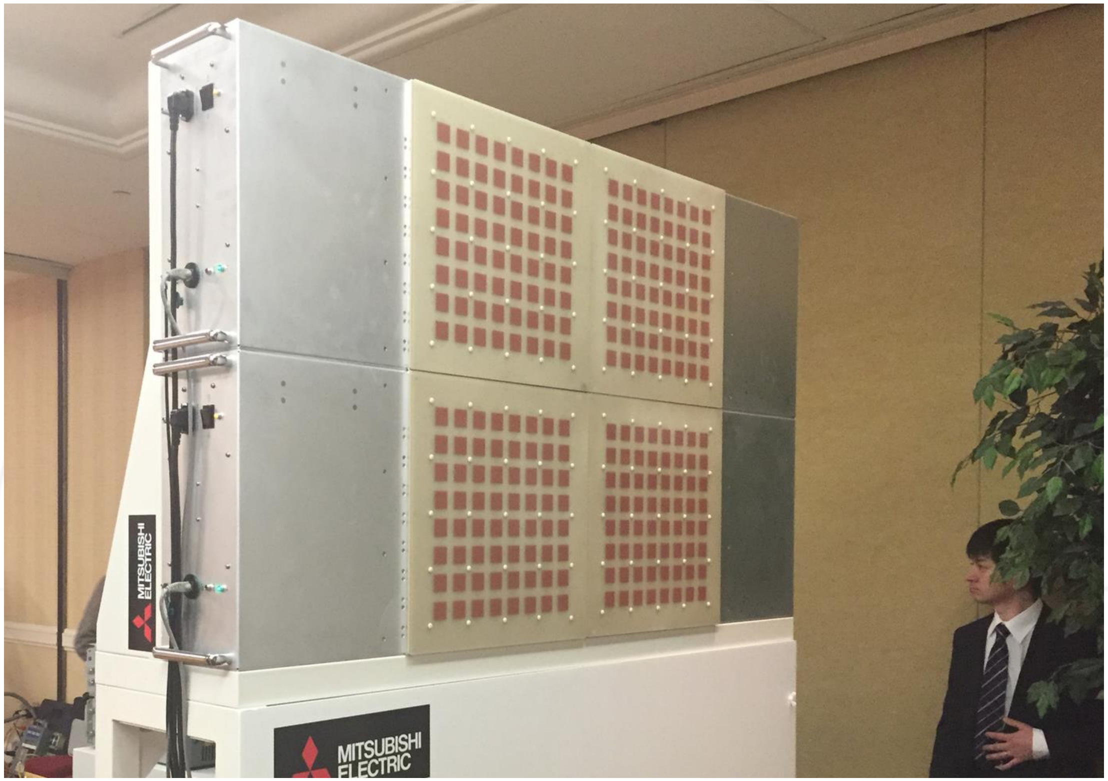
MIMO vs. Beamforming

- A fully digital MIMO allows us to trade-off spatial diversity of channel in various ways
  - Higher capacity through multiple streams
  - Beam forming, Multi-user beam forming
  - Spatial diversity
  - But MIMO requires ADC/DAC per element
- Analog/RF beamforming requires only phase shifters, which can be done in the analog / RF domain → lower power transceivers, arguably reduced performance requirements from analog/baseband blocks (ADC)
  - Grating lobes can be reduced with tapering
  - Time-division multiple beam access for multi-user
- A hybrid solution is desirable
  - Long range beams, short range multi-beams …

Massive MIMO



- A very large number of antennas, much larger than the number of user beams; form "beams" from the basestation to users simultaneously
- Computation of channel matrix simplified in TDD systems if we invoke reciprocity. FDD is problematic

Can choose beamforming coefficients either using beam forming (peak gain in the direction of desired user) or Zero Forcing (ZF) – nulls in the direction of other users, which reduces gain but improves multi-user capacity

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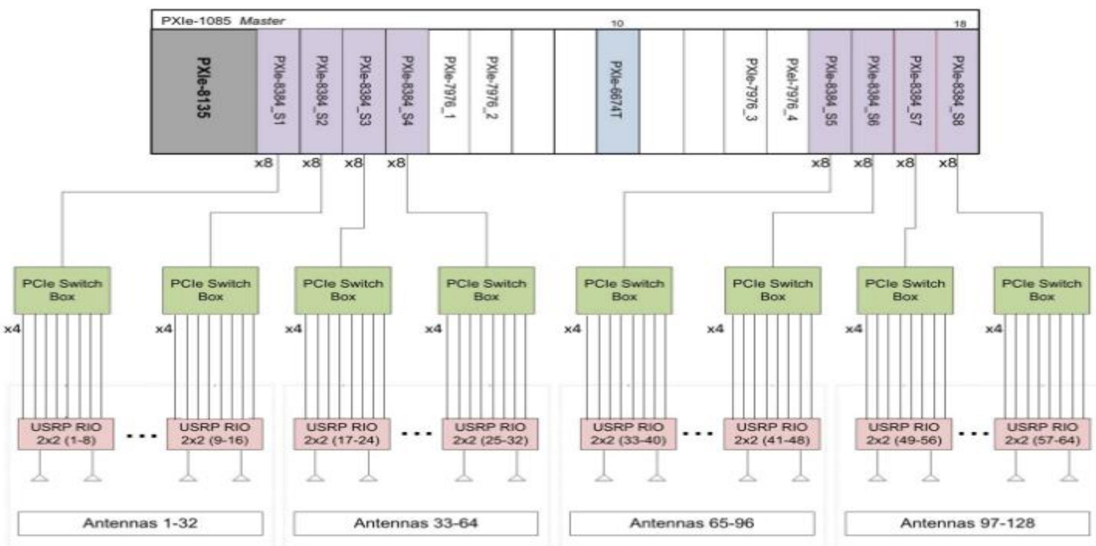
State-of-Art Massive MIMO

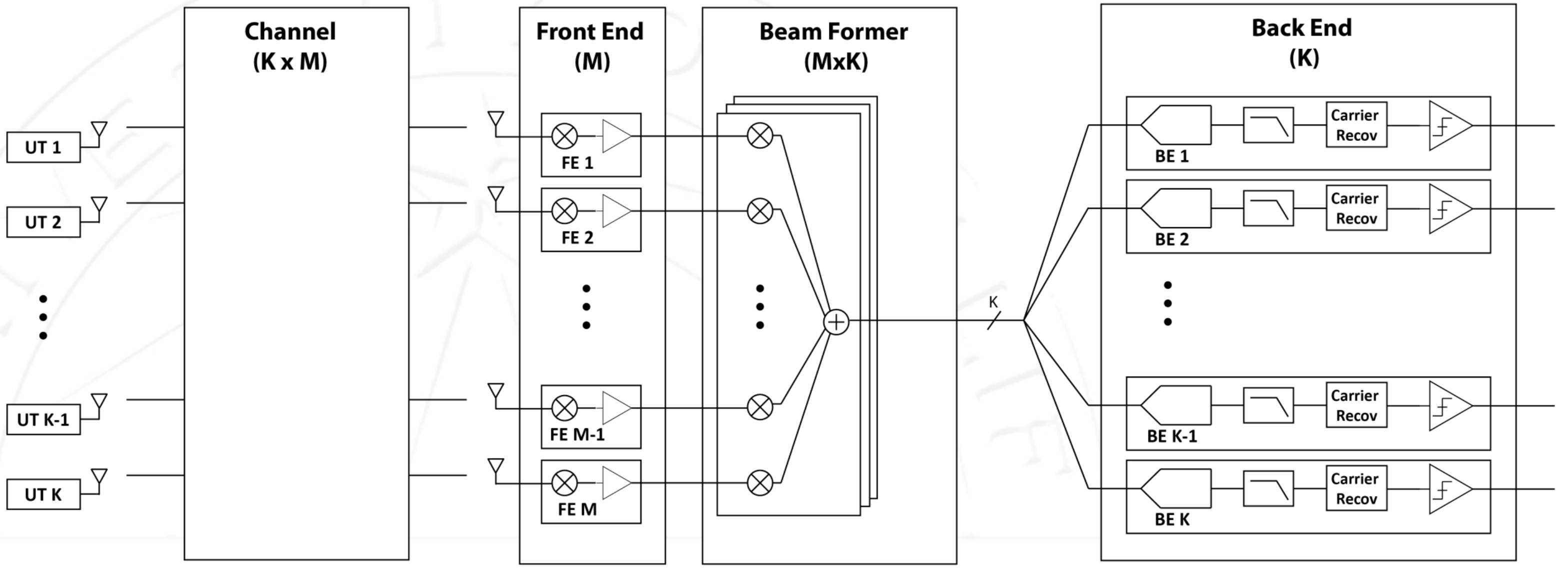
- 128 antennas
- 20 MHz of channel bandwidth
- 125 Gbit/s aggregated into central bas



What happens when we need 100x more throughput??

Need less of a "brute force" architecture

BWRC's Hydra: Massive mm-Wave MIMO



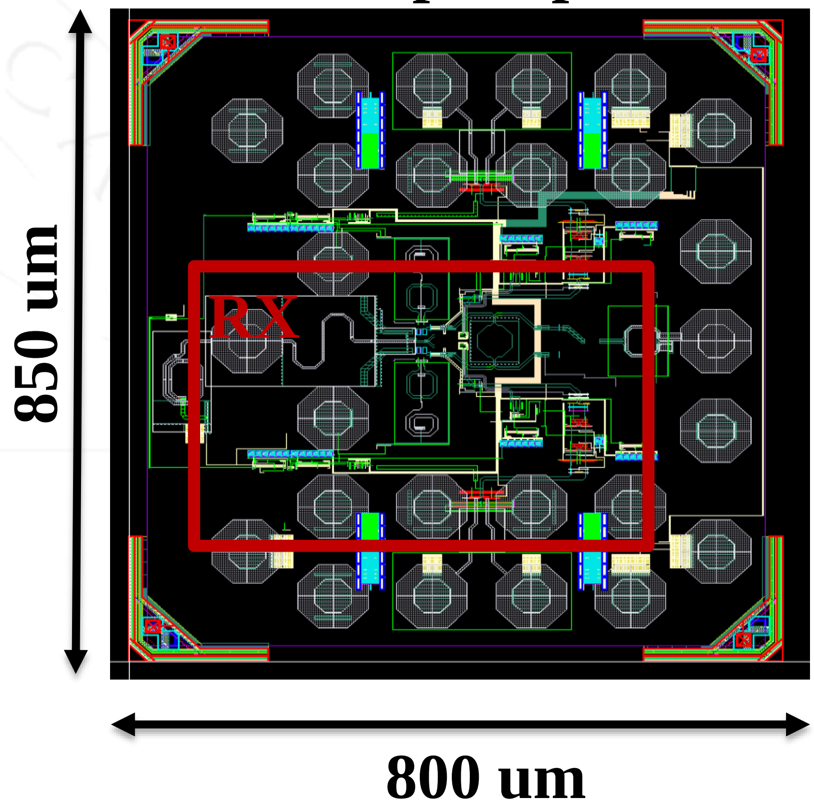
- Many more elements at base station than users (M>>K)
- Users are simple and ignorant of channel matrix
- FE circuitry has relaxed noise performance due to array averaging
- Multipliers in BF also have relaxed noise performance

First Prototype Receiver (Sim)

f0	75 GHz
BW,BB	2 GHz
AC Gain	21-22dB
NF	8-10 dB
Input P1dB	-18 dBm
Pdc	8 mW
Area	200x450um^2

- Goal is low power per channel
- Mixer first receiver ; IF multi-user phase shifting
- Trade-off noise but don't give up linearity

V2: flip-chip



Tech: CMOS 28nm

xG "Array" Publications

INVITED PAPER

Design of Energy- and Cost-Efficient Massive MIMO Arrays

This paper discusses how multiuser massive microwave and mm-wave MIMO can support communications among many users over a given allocation of spectrum, along with manageable array form factors and power consumption.

- A. Puglielli, A. Townley, G. Lacaille, V. Milovanovic, P. Lu, K. Trotskovsky, A. Whitcombe, N. Narevsky, G. Wright, E. Alon, B. Nikolic, A. M. Niknejad, "Design of energy and cost efficient massive MIMO arrays," *Proceedings of the IEEE*, vol. 104, no.3, pp. 586-606, March 2016.

- A. Puglielli, G. LaCaille, A. Niknejad, G. Wright, B. Nikolic, E. Alon, "Phase noise scaling and tracking in OFDM multi-user beamforming arrays," presented at the *IEEE International Conference on Communications*, ICC'16, Kuala Lumpur, Malaysia, May 23-27, 2016.

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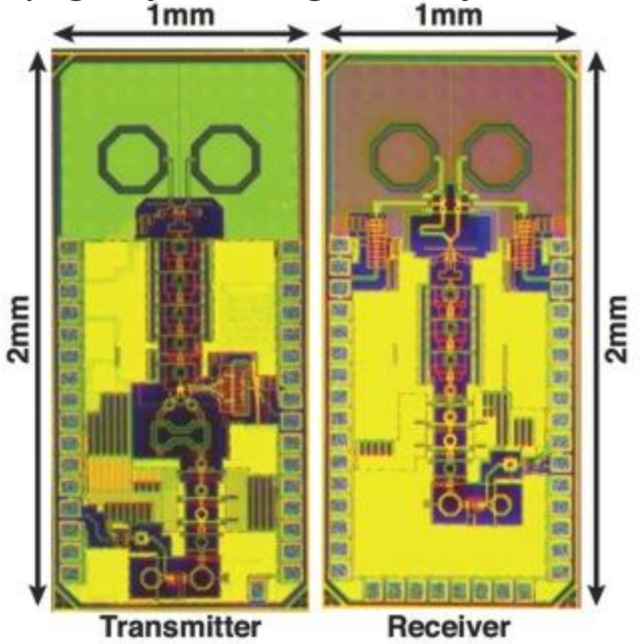
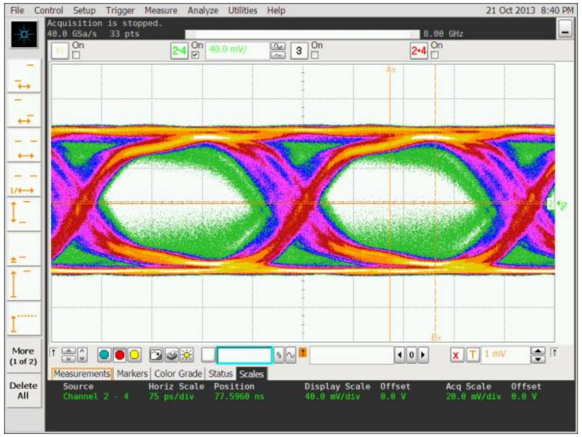
"THz" Communication

[Thyagarajan, Kang, Niknejad, RFIC 2014]





- We demonstrated 240 GHz with 16 Gbps (65nm)
  - On-chip antennas
  - QPSK: Modulate at 80 GHz → Tripler
  - 14 pJ/bit Tx + 16 pJ/bit Rx
  - Up to 1 meter range with dielectric lenses
- Can we improve energy efficiency with technology scaling?
- Highest achievable data rate / energy efficiency ?
  - More complex modulation schemes?

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Conclusion

- Massive MIMO:
  - Beam forming, beam nulling
  - 10X higher spatial capacity
- Mesh networking and wireless backhaul
- mm-Wave
  - 10 GHz →100 GHz for up to 1 km
  - > 100 GHz for shorter ranges
- Design the entire array, not individual blocks
  - PA output power reduced per element
  - Receiver noise figure can trade-off with array
  - Need to carefully consider phase noise / coherence across array

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Acknowledgements

- Collaborators: Elad Alon, Bora Nikolic
- Our research vision comes from years of research funded by NSF, DARPA, the UC Discovery Program, and our industrial sponsors at BWRC
  - DARPA TEAM program (60 GHz)
  - DARPA Wafer Scale Radio Seedling
  - DARPA RF-FPGA Program
  - UC Discovery Program:
    - CMOS "Digital" Transmitters
  - FCRP-C2S2 Program
- And many continuing programs!
  - NSF EARS
- And of course industry collaborations.

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