RFIC/Silicon-Based Phased Arrays and Transceivers for 5G

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UC San Diego
JACOBS SCHOOL OF ENGINEERING

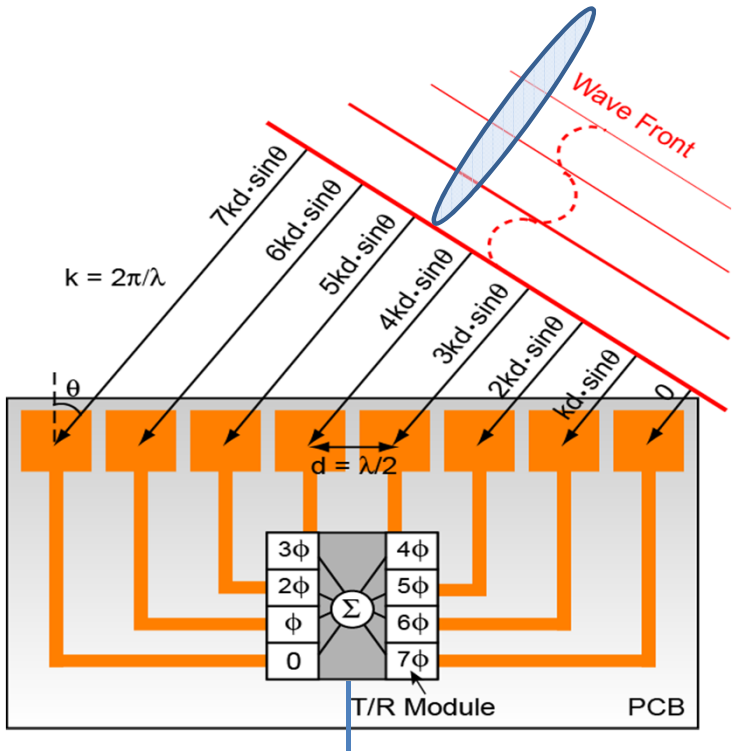
IMS
Connecting Minds. Exchanging Ideas.

HAWAI'I 5G Catch the Wave!

Outline of the Talk

- Phased-arrays and their architecture
- How silicon was introduced
- Technologies needed to make it happen
- 5G: How to increase data rates by 10x
- How to build 5G phased-arrays
- Some 5G examples at 28 GHz and 60 GHz
- Lowering the cost and other important things
- Conclusion

Phased-Array Basics



- Phase shifters at every element and sum the output (in RF or IF or DSP).
- Result in beamforming and electronic scanning
- Spatial power combining: (Array directivity ~ *N*)
- Higher Rx SNR: ~ *N* (dB)
  (Uncorrelated noise from receivers)
- Effective isotropic radiated power (EIRP=PtGt): ~ N^2 (directivity ~ *N*, power radiated ~ *N*).
- Total system improvement: N^3
- All of this is compared to a single element (which is not correct)
- For the same aperture size, the only advantage over a reflector (fixed beam) is electronic steering
- And lots of disadvantages (gain drop vs. scan angle, antenna impedance change, etc.)

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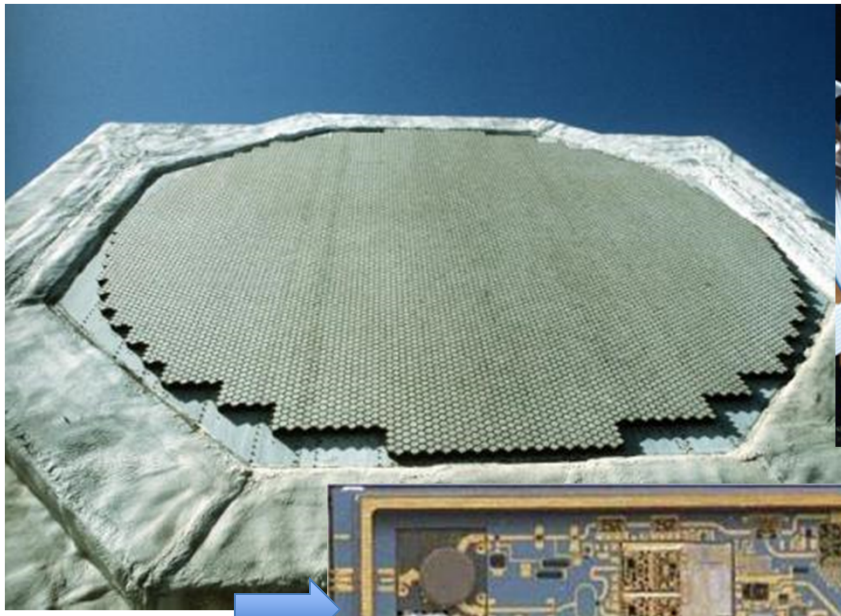
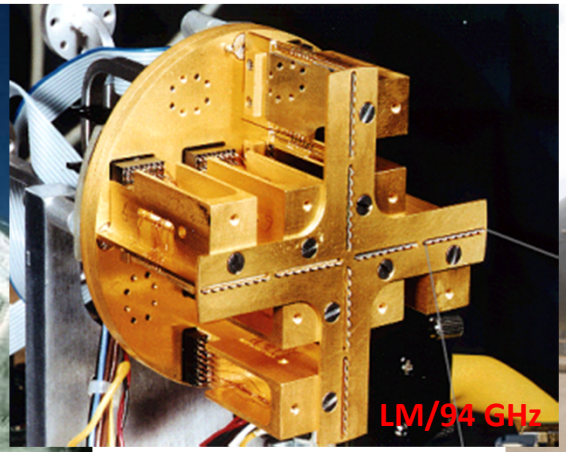
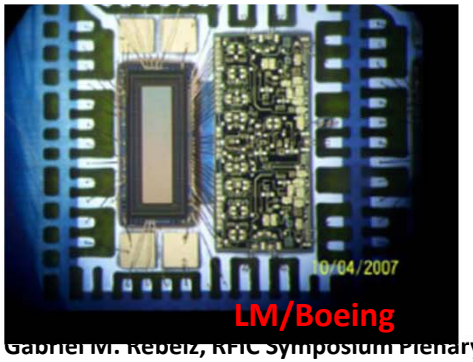
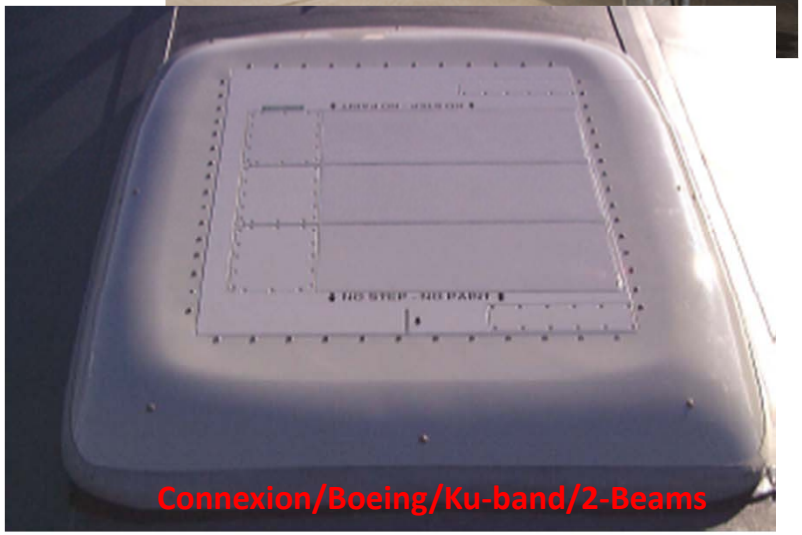
We Know How to Build Phased-Arrays





Cobham GaAs T/R Module

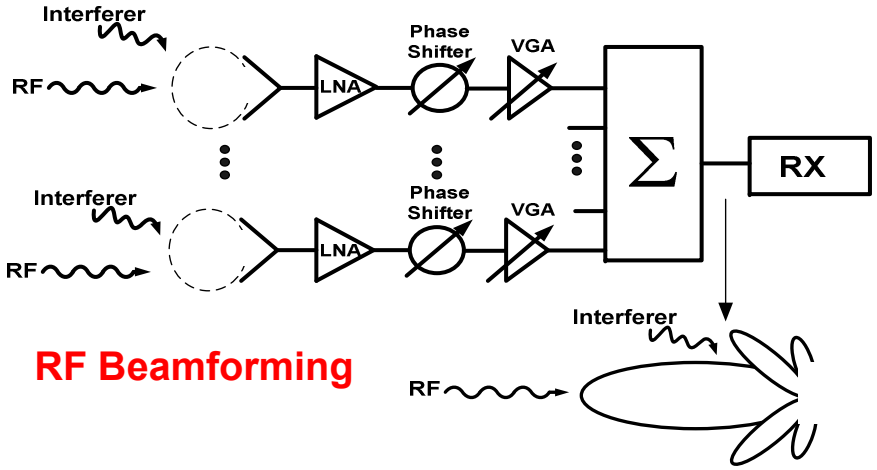




- Based on GaAs T/R modules
- Radars and high performance systems
- HOW TO REDUCE COST??

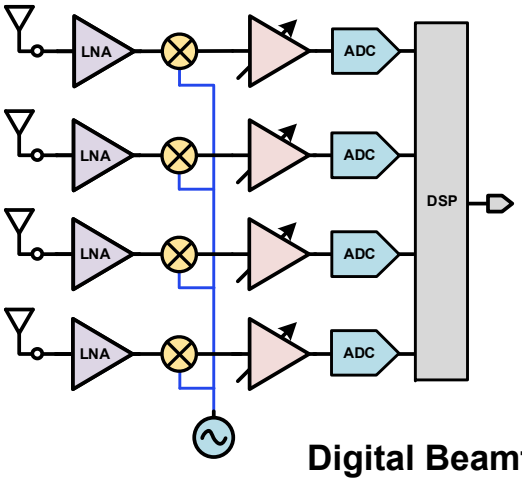
GaAs MMIC (V and H) and silicon controller

Phased-Array Architecture

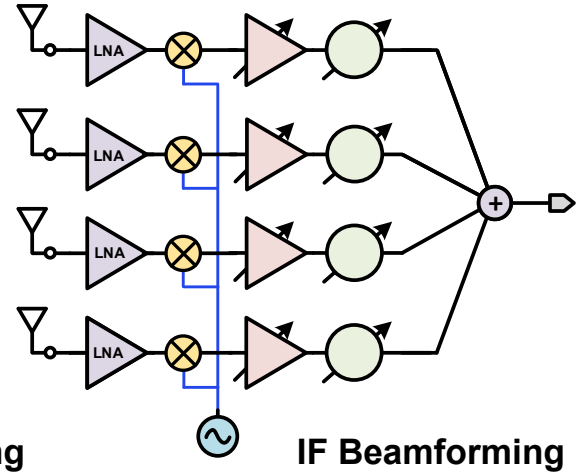


RF Beamforming

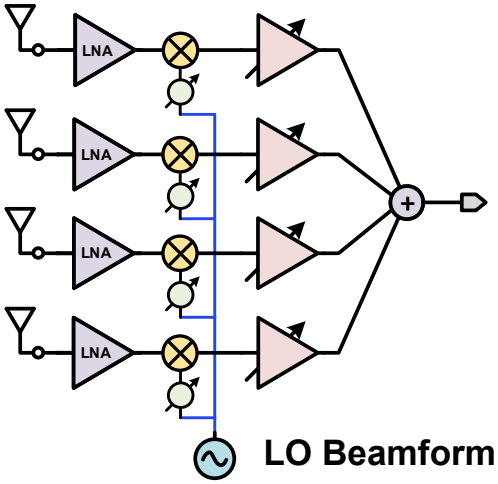
- RF beamforming allows for a sharp filter before the mixer
- Remember: S/N ratio at antenna is << 0 dB!!
- No interferers mixing at the element level
- No SSB filtering at the element level (for IF systems)
- No LO leakage (Direct conversion or IF)
- Most used topology (SATCOM, Radars, even 5G)
- Hybrid architecture (RF/Digital Beamforming) in 5G



Digital Beamforming



IF Beamforming



LO Beamforming

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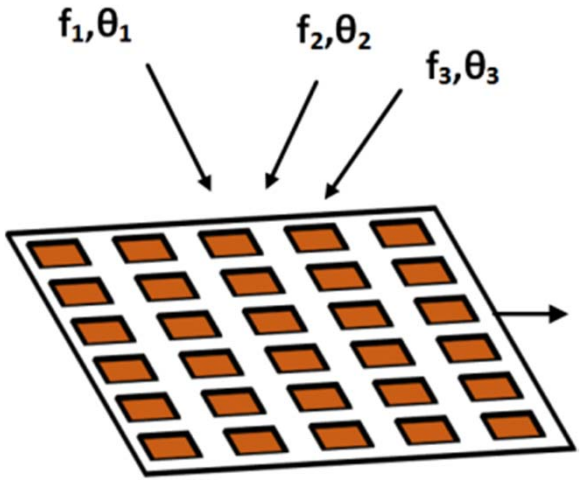
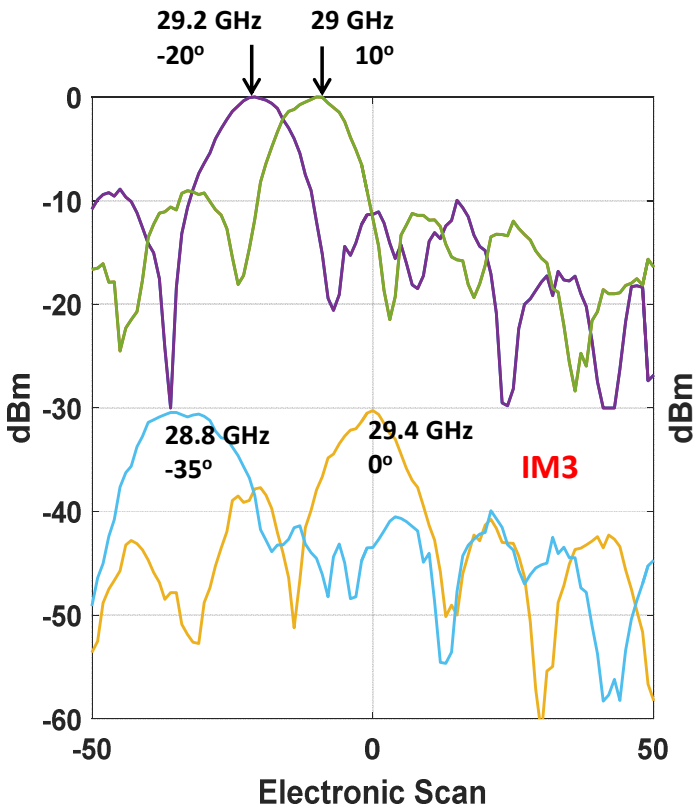
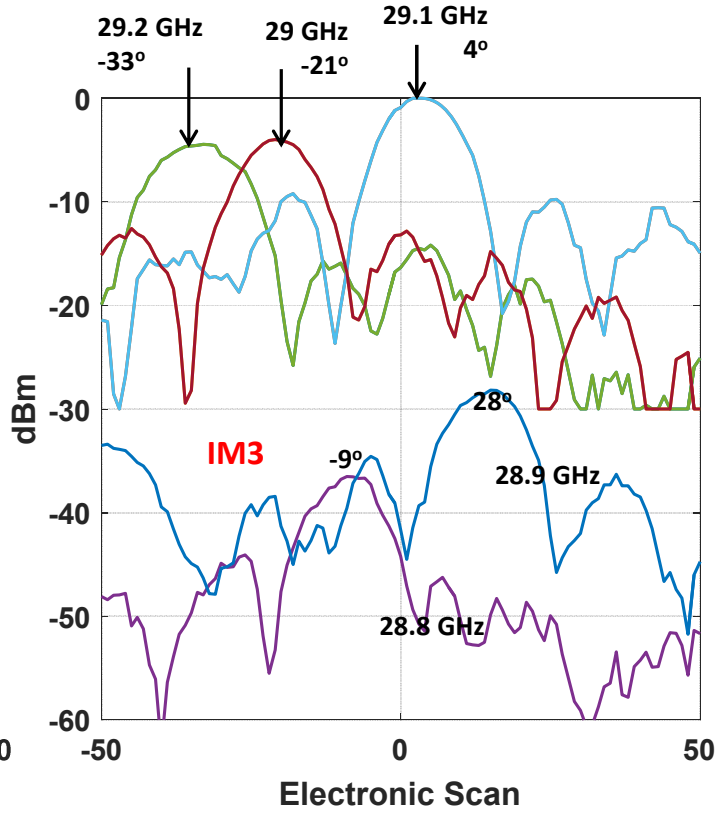
Interferes can kill you (and you do not know where they are!)







- IM3 from interferers occurs at an apparent angle, different than interferer incidence angles
- You cannot null the IM3 (create a zero in the pattern) – only filtering and linearity can save you
- This is why RF-Beamforming won – it is the most linear and allows for filtering before the mixer

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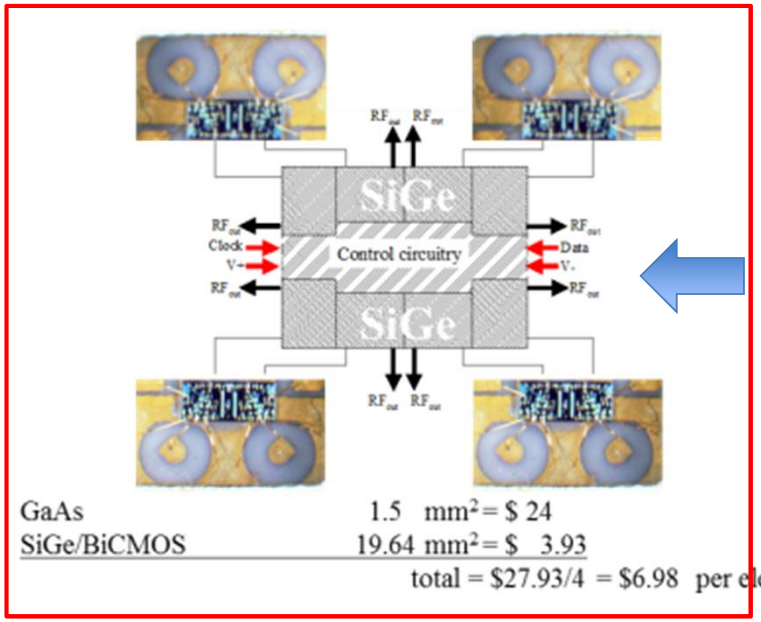
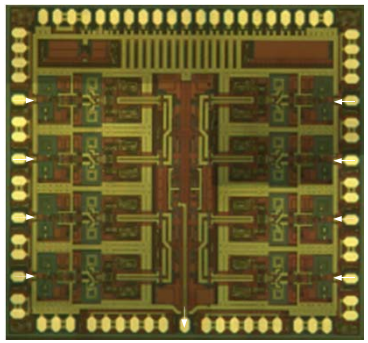
Lowering the Cost: Silicon to the Rescue!

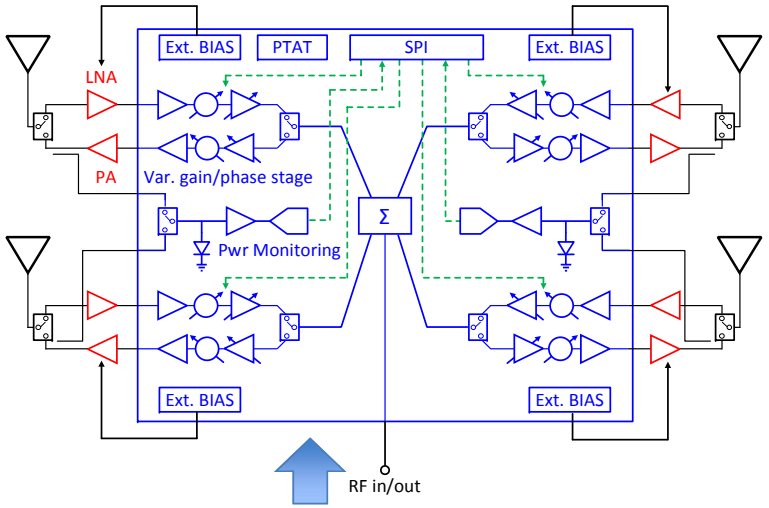
SATCOM

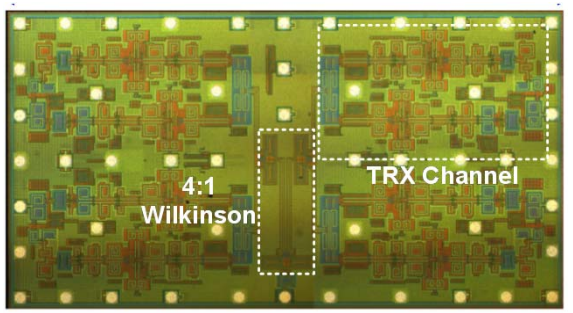


8-Channel Tx or Rx (2x2 dual Polarization)



RADAR or TDD/Comm





Proposed by Rebeiz and Navarro/Boeing 2001

- Use silicon where it makes sense (complexity, control, yield)
- Use GaAs where it makes sense (PA power, Ultra-low-noise)
- SiGe and CMOS are both good candidates

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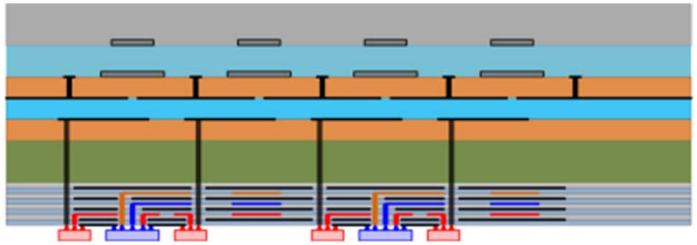
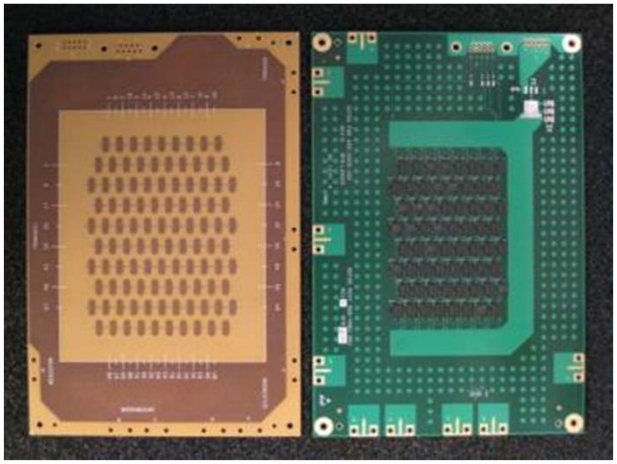
Silicon is Great (but need more technologies)!!

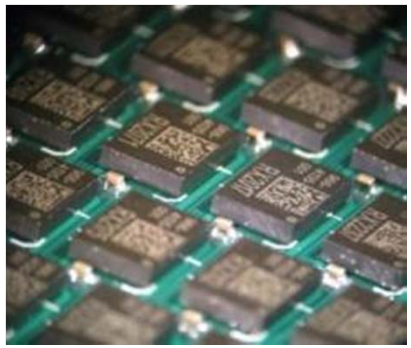
- Immense advances in highly dense, large area, multi-layer PCB boards
- Immense advances in packaging (QFN, BGA, WL-CSP)
- Immense advances in SiGe/CMOS microwave and mm-wave design
- Advances in planar antenna designs/ EM numerical solutions

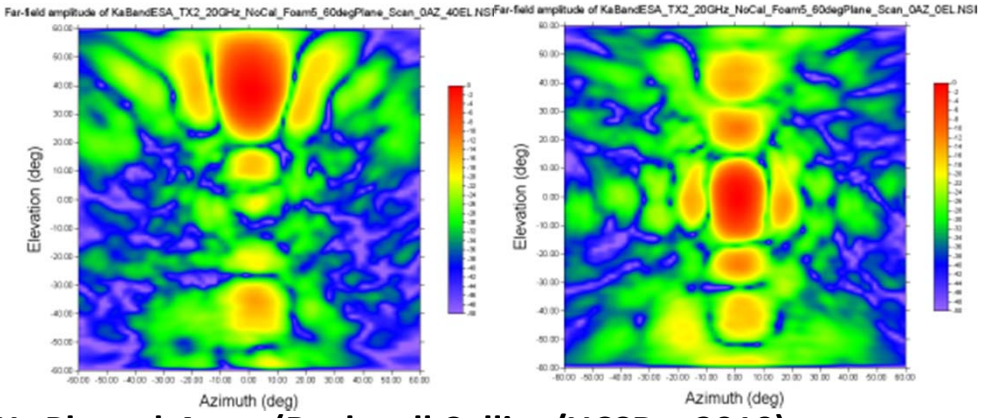
Put all four technologies together →

low-cost phased arrays and transceivers



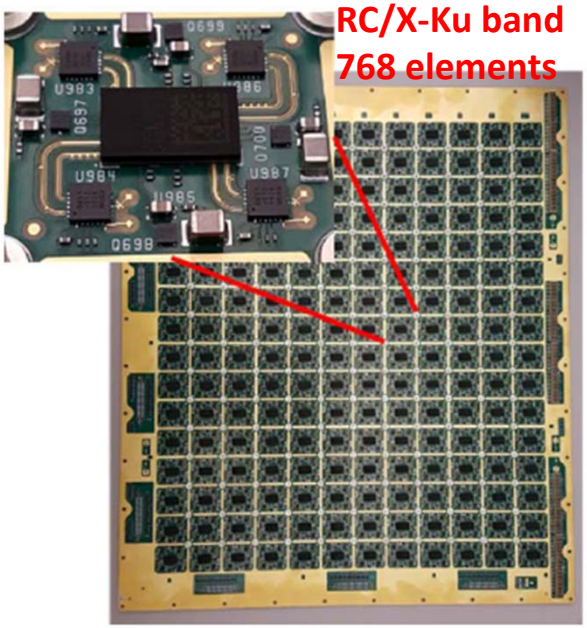


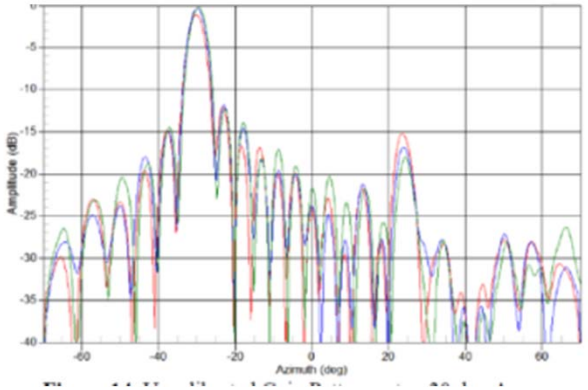


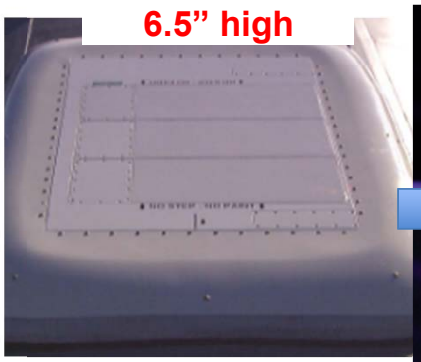


64-element 17-21 GHz Phased-Array (Rockwell Collins/UCSD – 2010)

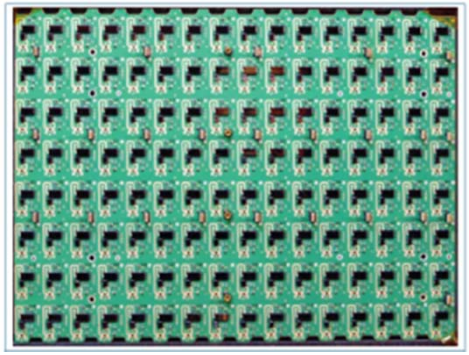
And.. Silicon has already changed several systems







Raytheon/X-band



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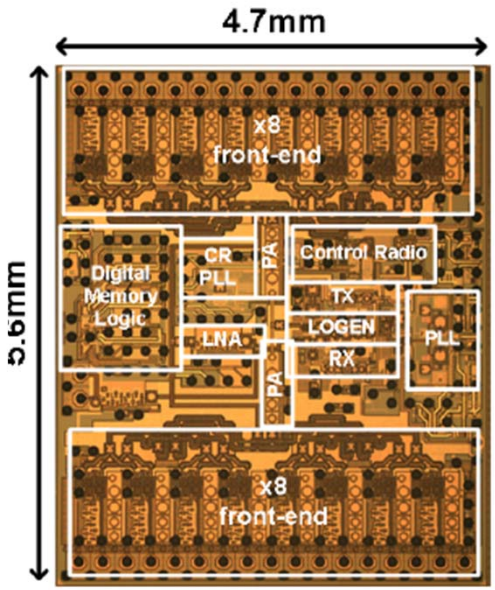
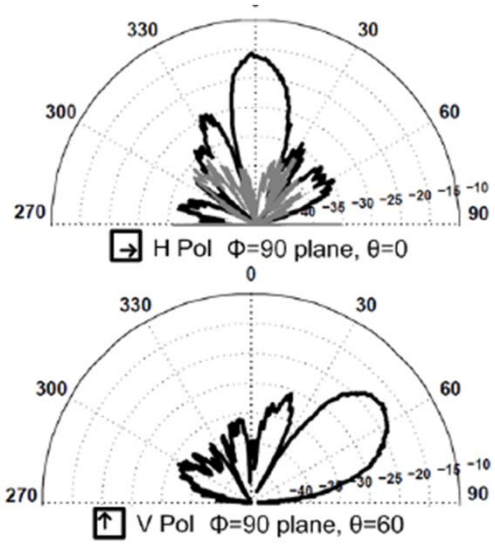
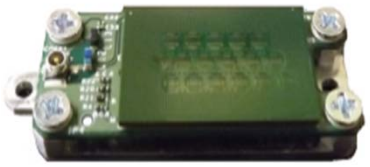
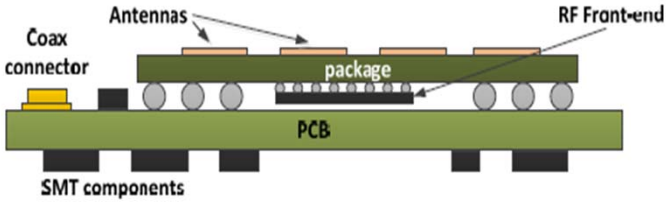
60 GHz Tx/Rx 8 to 16-Channel Phased-Array on Laminates

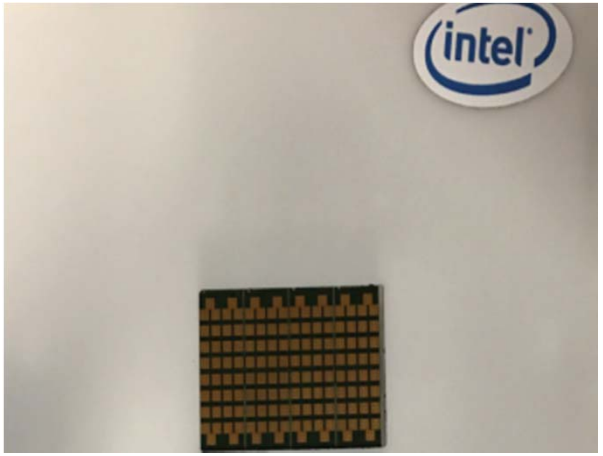


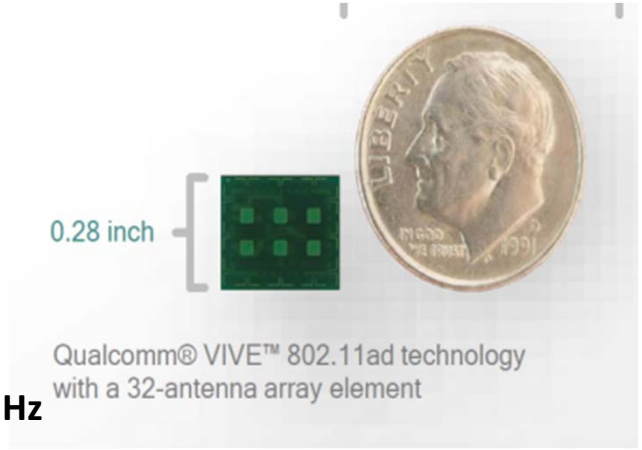
Broadcom











- **First major introduction of commercial silicon phased-arrays was at 60 GHz**
- **Large number of elements + transceiver on a single chip**

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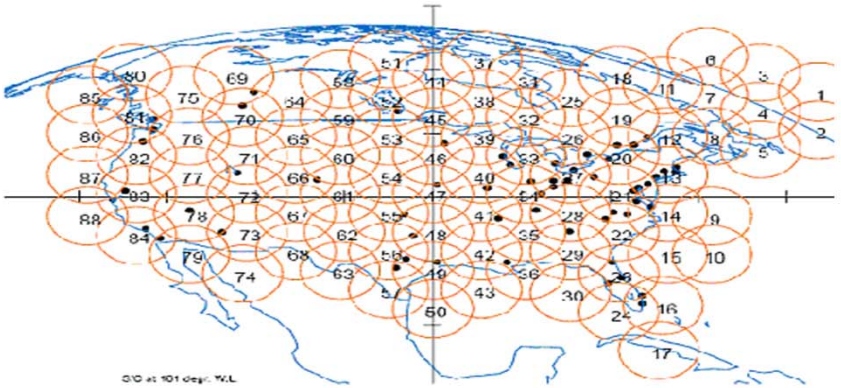
Let us look at mobile communications today

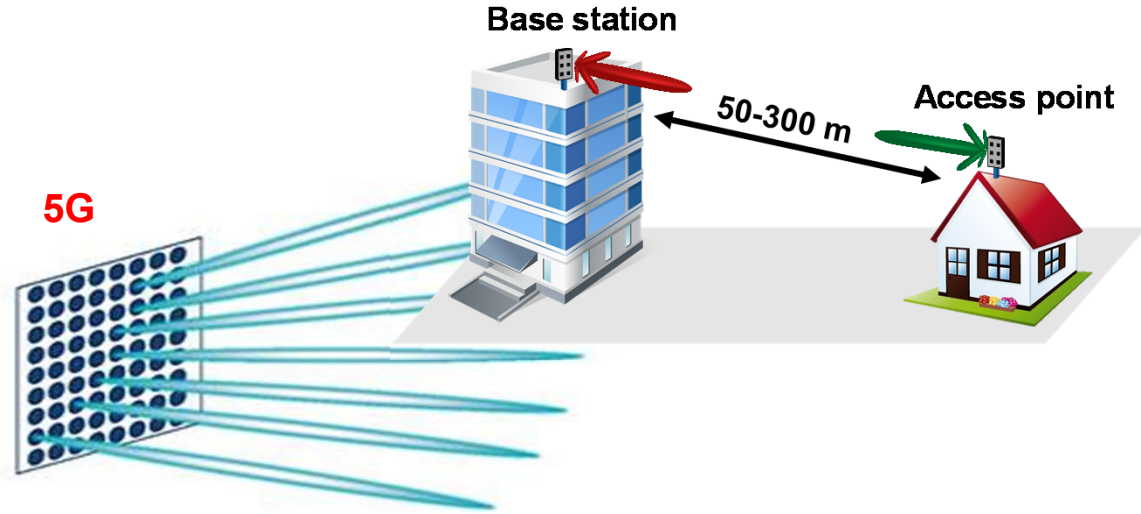
- All based on sectored base-station antennas to the mobile user (low gain/low gain)
- Low-gain to low-gain antennas (good for coverage/bad for data rate)
- How can we improve it? → **DIRECTIVE COMM. (Spatial diversity)**

Better communication systems: 5G

- Improving communication systems is a challenging problem:
  1) More Bandwidth: **Millimeter-waves (28 GHz, 39 GHz, 60 GHz, etc.)**
  2) Better Coding: We are (nearly) at our best
  3) Lower Noise Figure: We are at (near) theoretical limits
  4) PA power and efficiency: Again, near theoretical limits
  5) Spatial Diversity: **Phased Arrays/MIMO/Multiple Beams**

SATCOM knew this since a long time!!!





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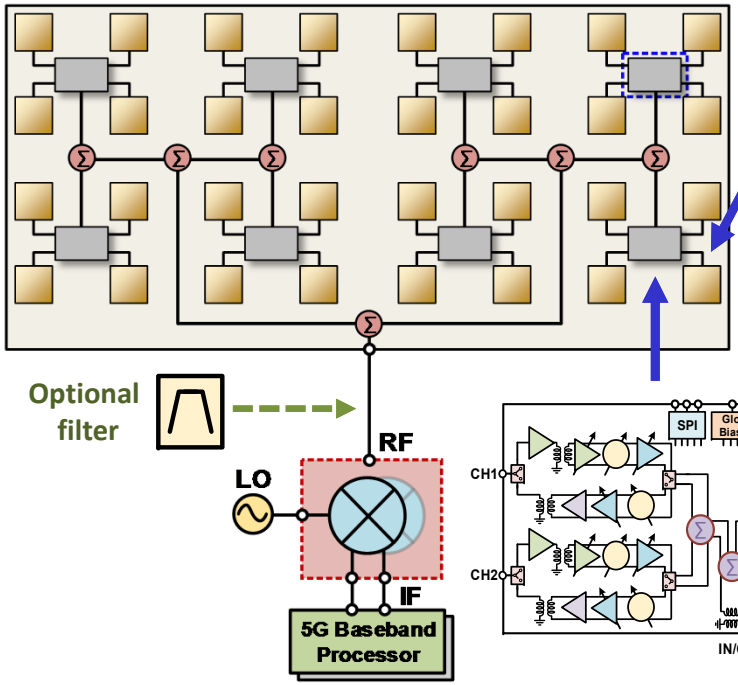
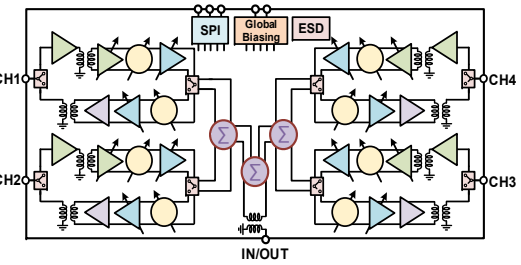
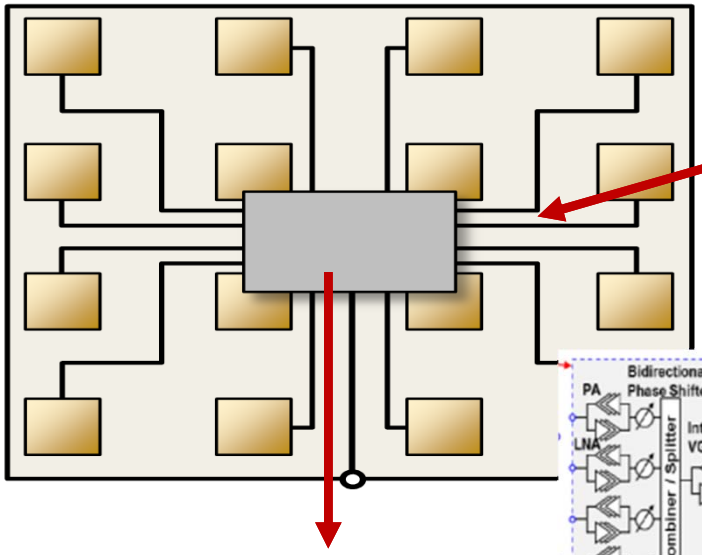
Which level of integration on the Silicon RFIC??



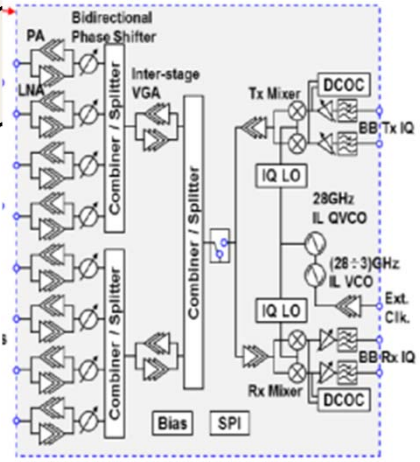


Equal feed lengths
Low loss



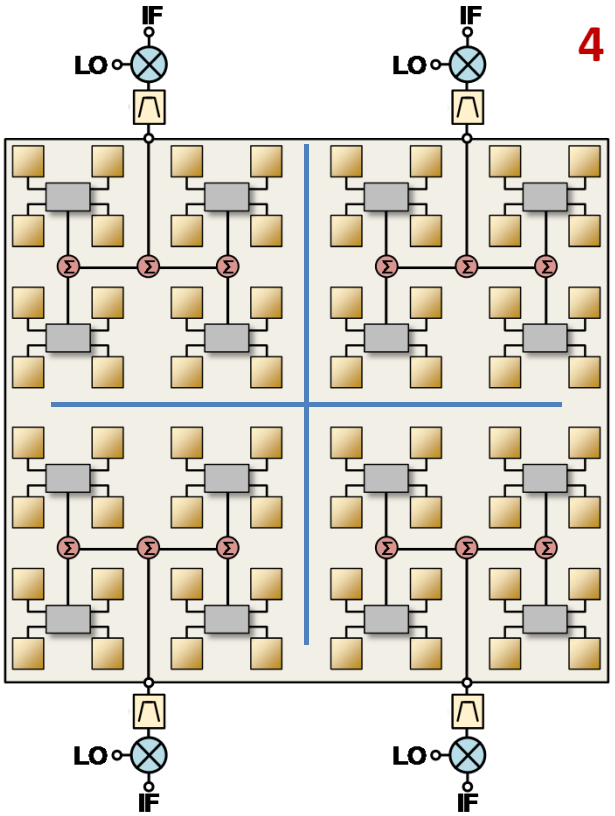
Unequal feed lengths
High loss

4x4 (or 4x8) TRX Chip: RF beamforming with a transceiver

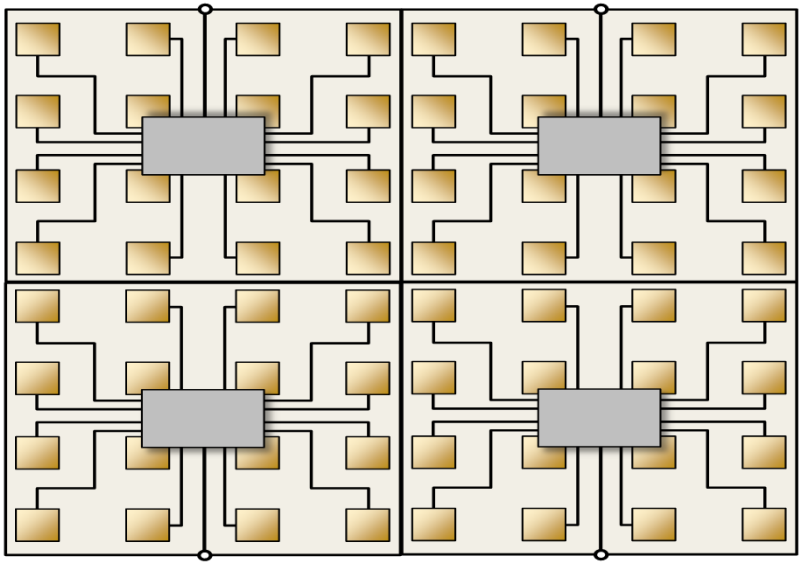


- Quad: Low chip to antenna loss, symmetric design ➔ no calibration required
- Quad: Low-cost PCB design possible (only 4 layers in certain designs)
- Quad: Uniform heat over phased-array, resilient to failures, mix/match technology (SiGe/GaAs, CMOS)
- 4x4 or 4x8: Lower cost (less chips), but more loss, more complex PCB, single-point failures, all CMOS
- **Both will be used: One in base-stations/UE, and the other in mobile**

How to Build MIMO Arrays?

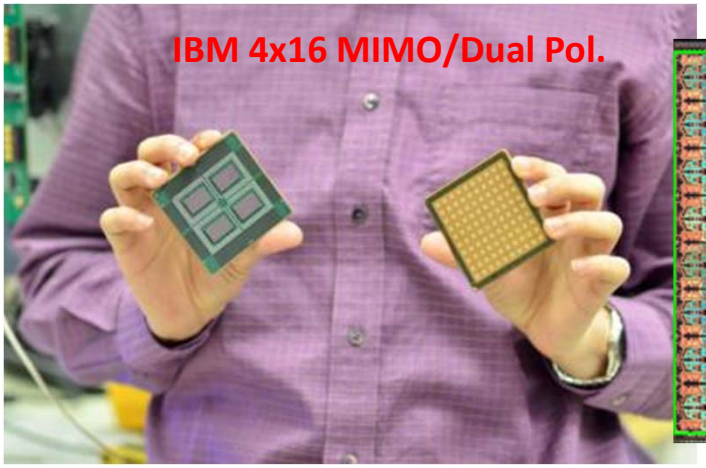


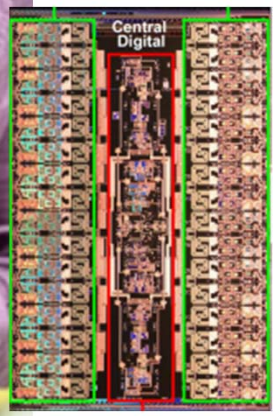
4 x 16-Element MIMO

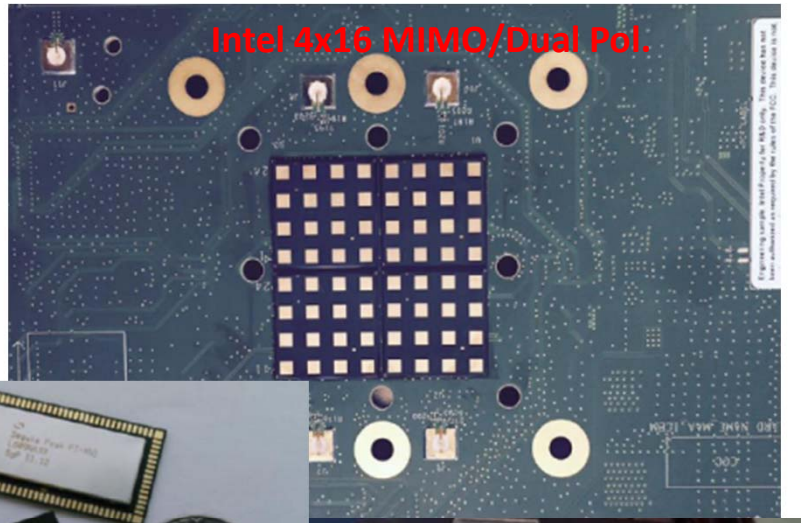


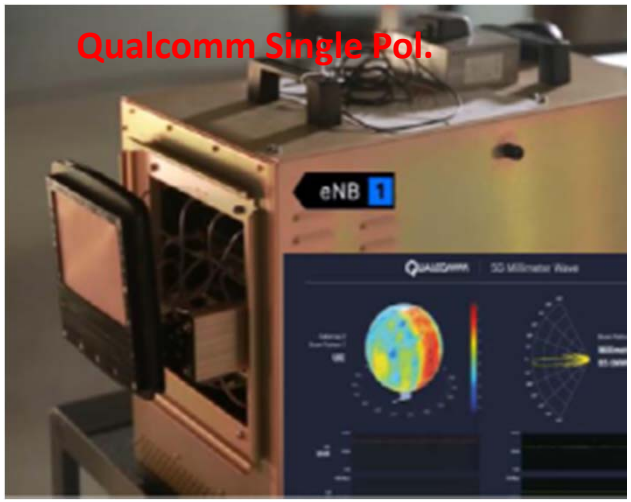
- MIMO arrays can be built using quad or higher chip-integration levels
- Same discussion as before (loss, technology mix/match, cost, heat distribution, resiliency)

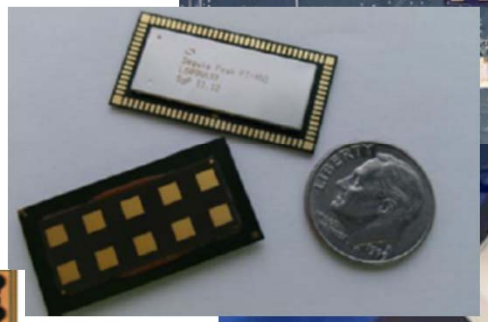
Industry has listened and we have 5G chips and systems



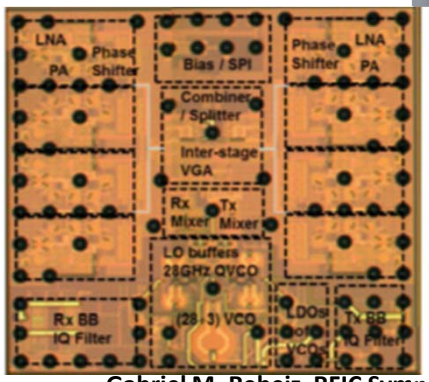


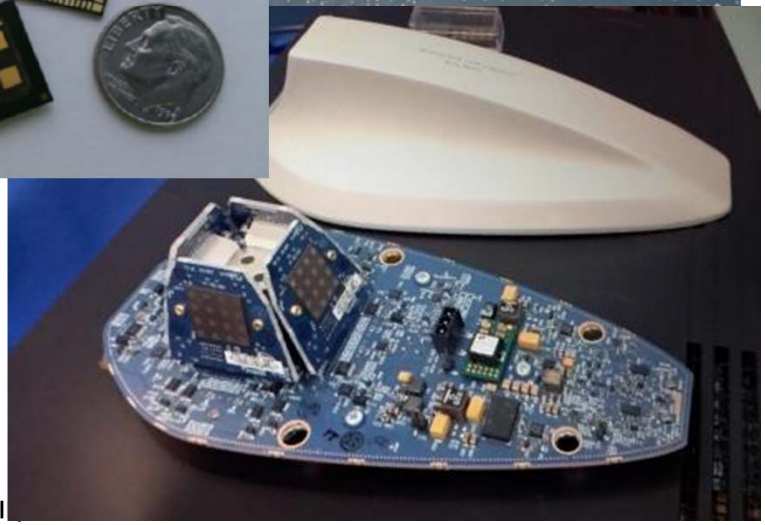






LG/RFIC '17





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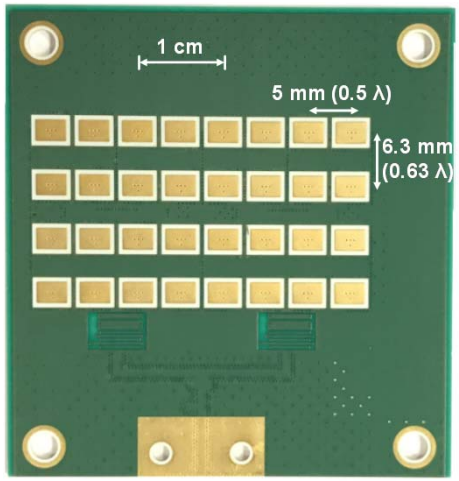
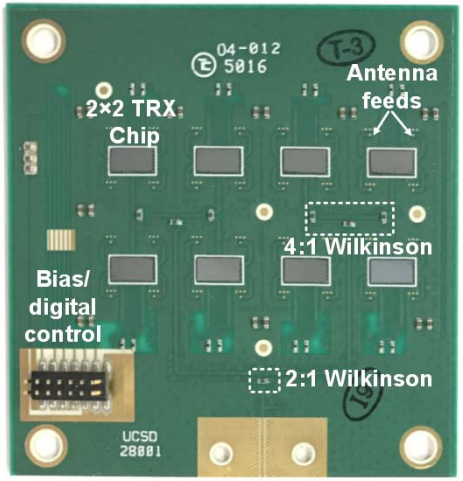
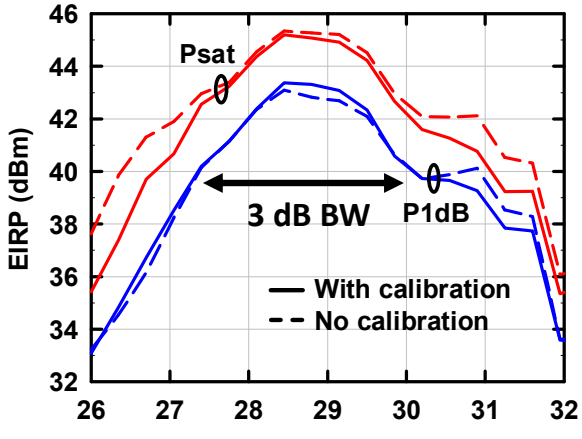
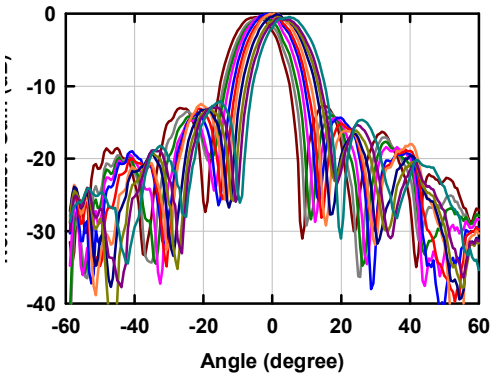
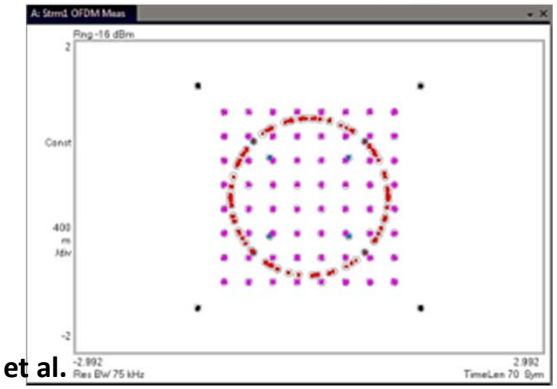
UCSD has demonstrated 5G systems

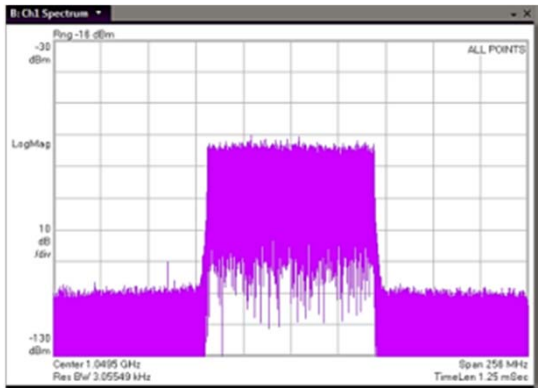


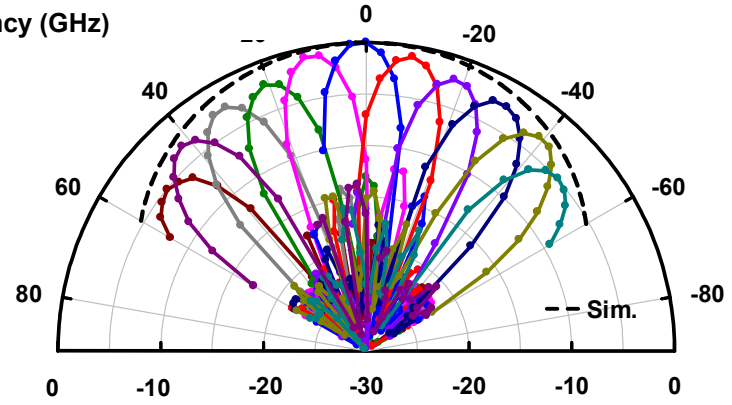












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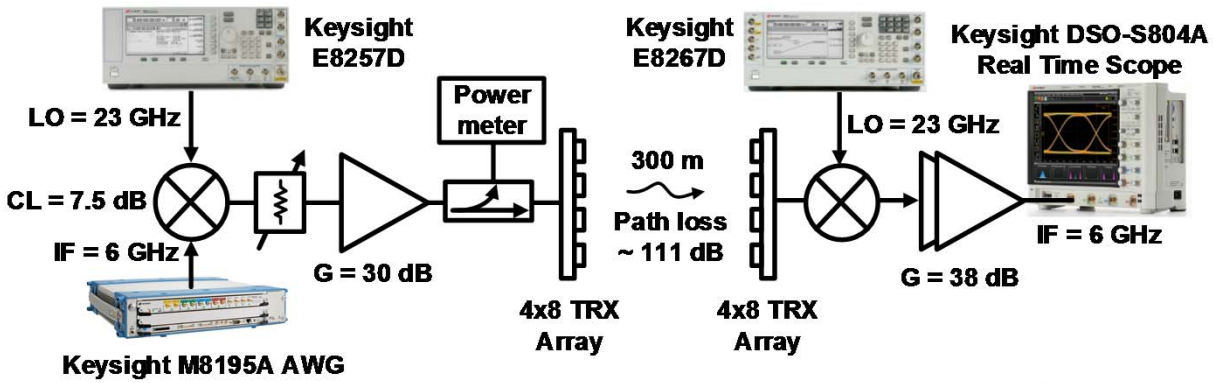
RFIC June 2017
IMS June 2017

- Verizon pre-5G 64-QAM waveform/ S.C./100 MHz
- EVM = -41.7 dB (0.82%) at 8 dB backoff

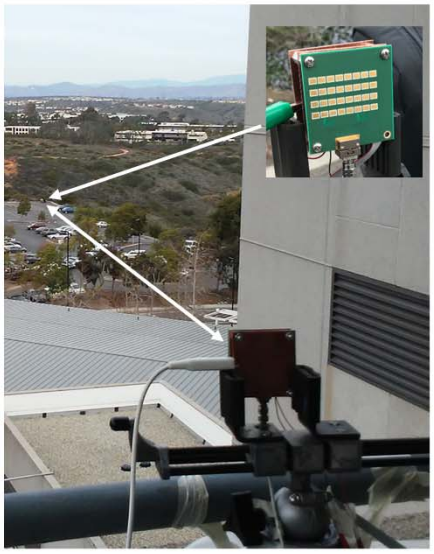
- -12 dB sidelobes with no calibration
- < 1 deg. scan angles possible

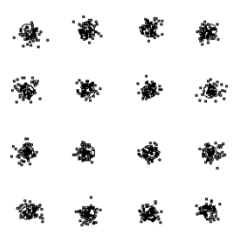
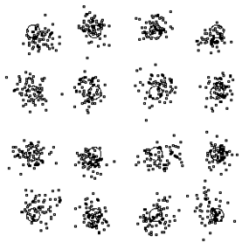
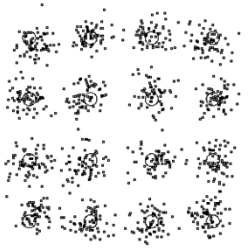
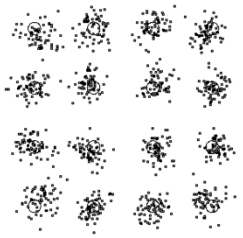
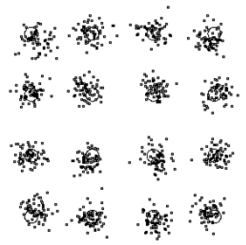
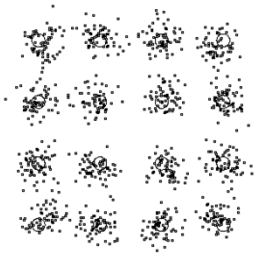
Gabriel M. Rebeiz, RFIC Symposium Plenary Talk, June 2017

300 meter link demonstrated at 1-1.6 Gbps



AWG and DSO scope makes testing easy



300 m Link		
		
0° scan 400 Mbps / 5.9%	+20° E-plane 1 Gbps / 10.3%	+50° H-plane 1 Gbps / 12.1%
		
0° scan 1.6 Gbps / 10.9%	-20° E-plane 1 Gbps / 9.6%	-50° H-plane 1 Gbps / 11.7%

No FEC, DPD or equalization

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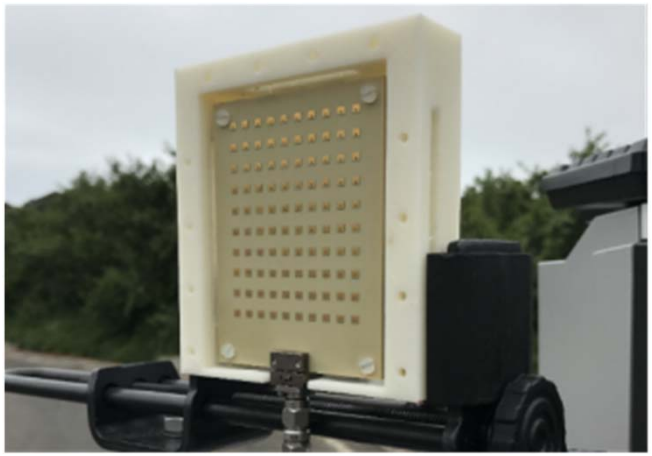
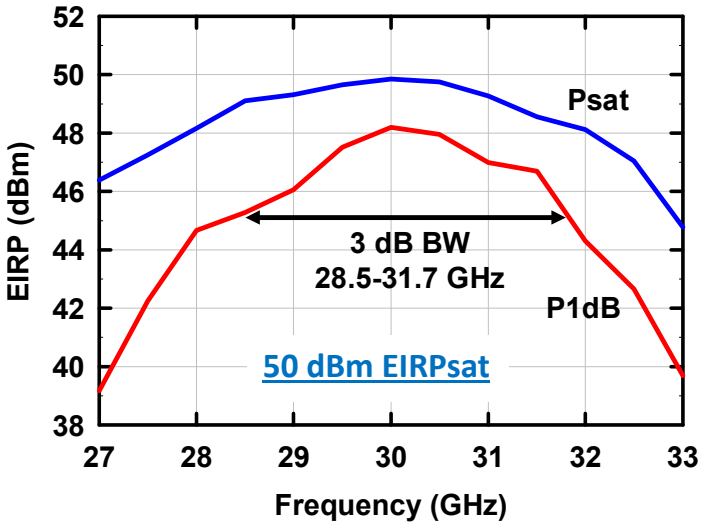
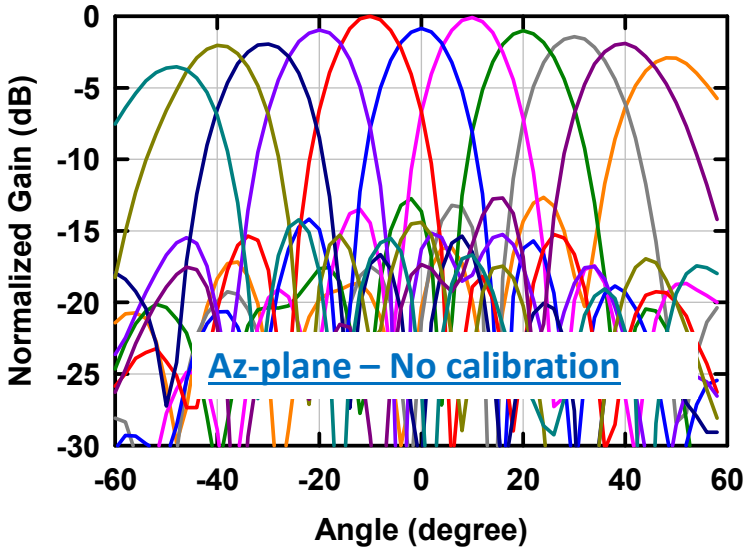
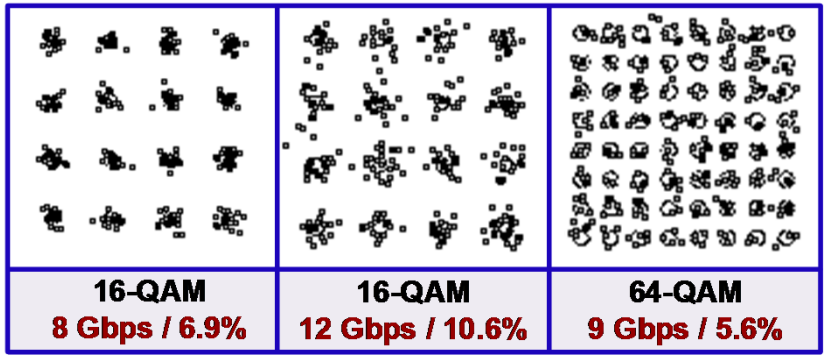
Record performance in 8x8 5G systems (UCSD)







±50° Scan Angle



300 Meter Link

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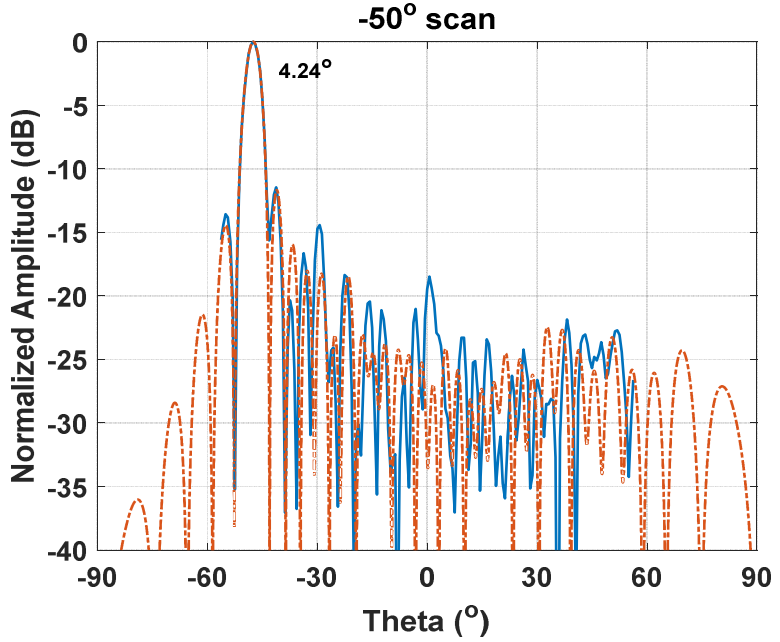
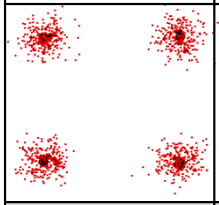
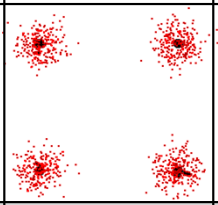
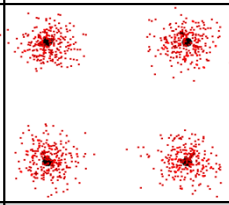
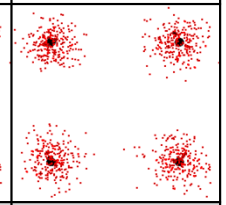
60 GHz Phased-arrays for 5G (29 dB Gain/UCSD)

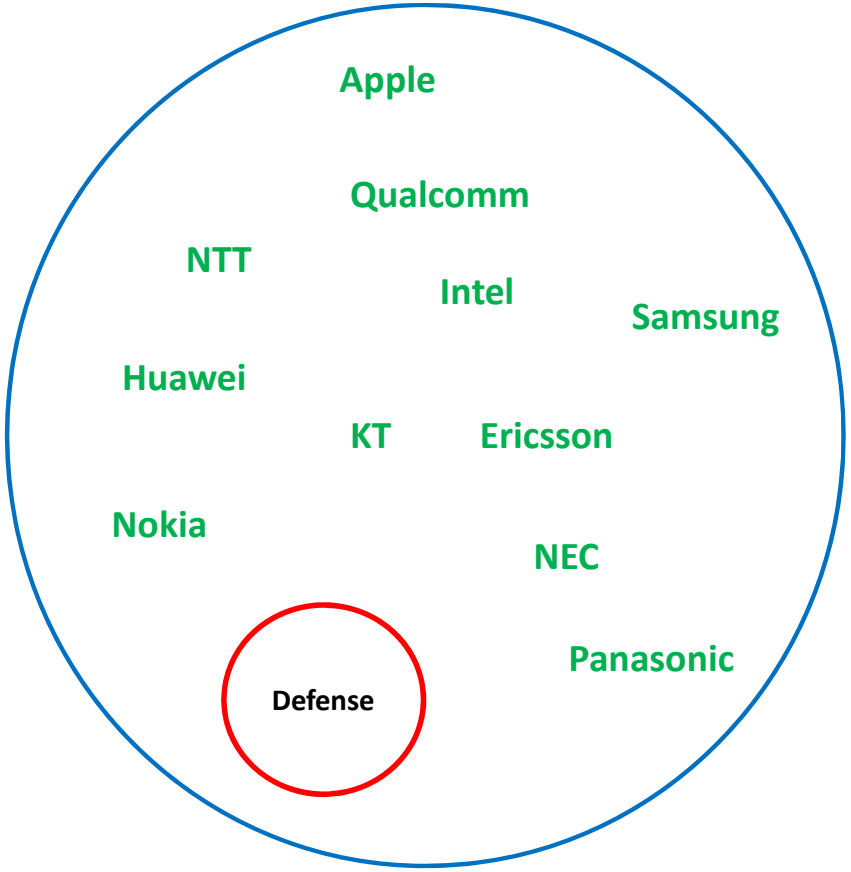
- **Unlicensed band**
- **VR applications**
- **All SiGe or CMOS**
- **32 and 64-elements**

B. Rupakula et al.
IMS June 2017



EVM/Scanning with 1 Gbps QPSK/300 meters			
+30°	-30°	+45°	-45°
			
17.4%	17.23%	21.2%	22%

In the near future...



- Defense remains the same
- Commercials increase a lot
- Defense does what it does best:
  - High power
  - High linearity
  - Ultra-wideband
- Commercials do everything else
- This happened before:
  - Radios (Apple, Samsung, Qualcomm, Intel)
  - Photonics
  - Satellites
  - Aviation
  - Nuclear science
  - etc.

Gabriel M. Rebeiz, RFIC Symposium Plenary Talk, June 2017

We are far from done....

- We still have to learn on how to use phased-arrays with complex modulation (they were used in radars or QPSK communications only)
- We need to greatly lower the cost of these systems: silicon RFICs (great enabler), but also at the PCB level and with self-calibration.

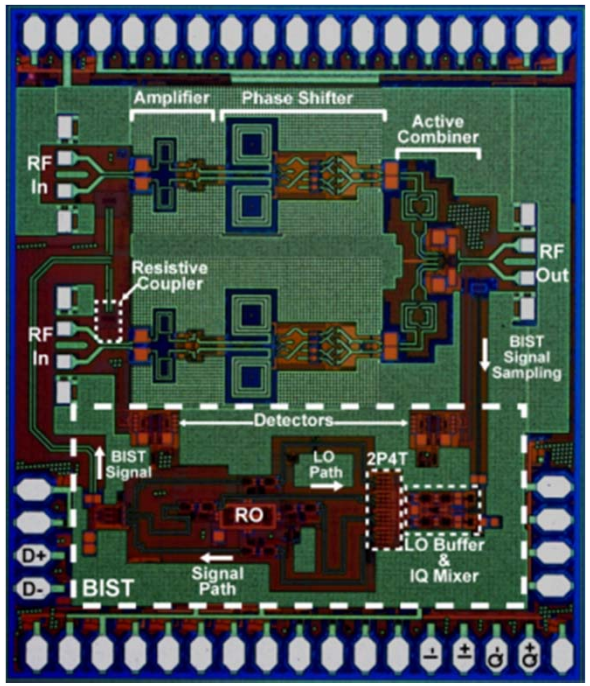
- Research in:
  - Phased-Arrays: No calibration whatsoever (chip level, antenna level). Lower cost.
  - Better silicon: Lower current (higher ft, fmax), lower NF.
    → Silicon needs to come close to GaAs (Pout, NF)
  - Power Amplifiers: High-order modulation, DPD, back-off, efficiency.
  - Millimeter-Wave Antennas: Wideband, efficient, stable active impedance.
  - Linearity: Base-station interference, mitigation.
  - Production Tests: Meet FCC requirements at minimal cost.
  - SAR: How to handle SAR with 43 dBm and 65 dBm EIRP?

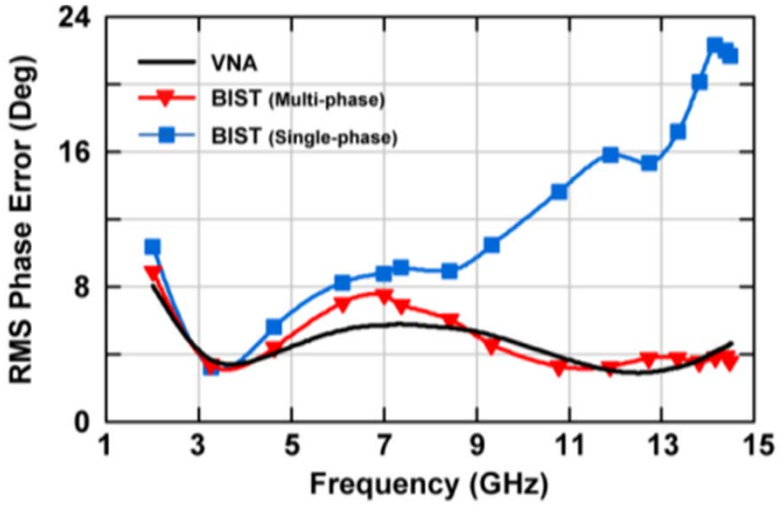
Built-in-self-test for lowering the cost

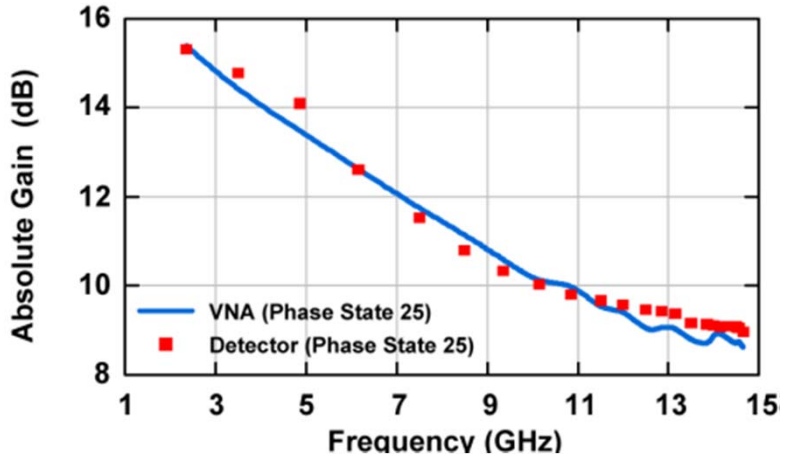
- Integrated self-correcting VNA covers 2-16 GHz
- Integrated RO to generate BIST signal
- Wideband couplers at input and output ports
- Integrated power meters for absolute power gain meas.

T. Kanar et al.
T-MTT, Dec. 2016

BIST area







We should thank...

- DARPA: Funded all the initial work to make 5G possible
- Universities: Did the early mm-wave designs, trained students and industry

- Foundries: Listened to mm-wave designers and made their process better
- Test Systems: Easier to use at mm-waves, can do complex modulation tests quickly
- Software: Cadence, HFSS, Sonnet, etc. are much better and easier to use

- RFIC and microwave designers: The heroes of 5G. Nothing is impossible to them.

THE END OF THE MARCONI ERA IS NEAR (1920-2020). WE ARE NOW ENTERING INTO THE DIRECTIVE COMMUNICATIONS ERA, and soon, we will look back at the Marconi era as we look back at the old analog TVs today ☺