# A Circuit Designer's Guide to 5G mm-Wave

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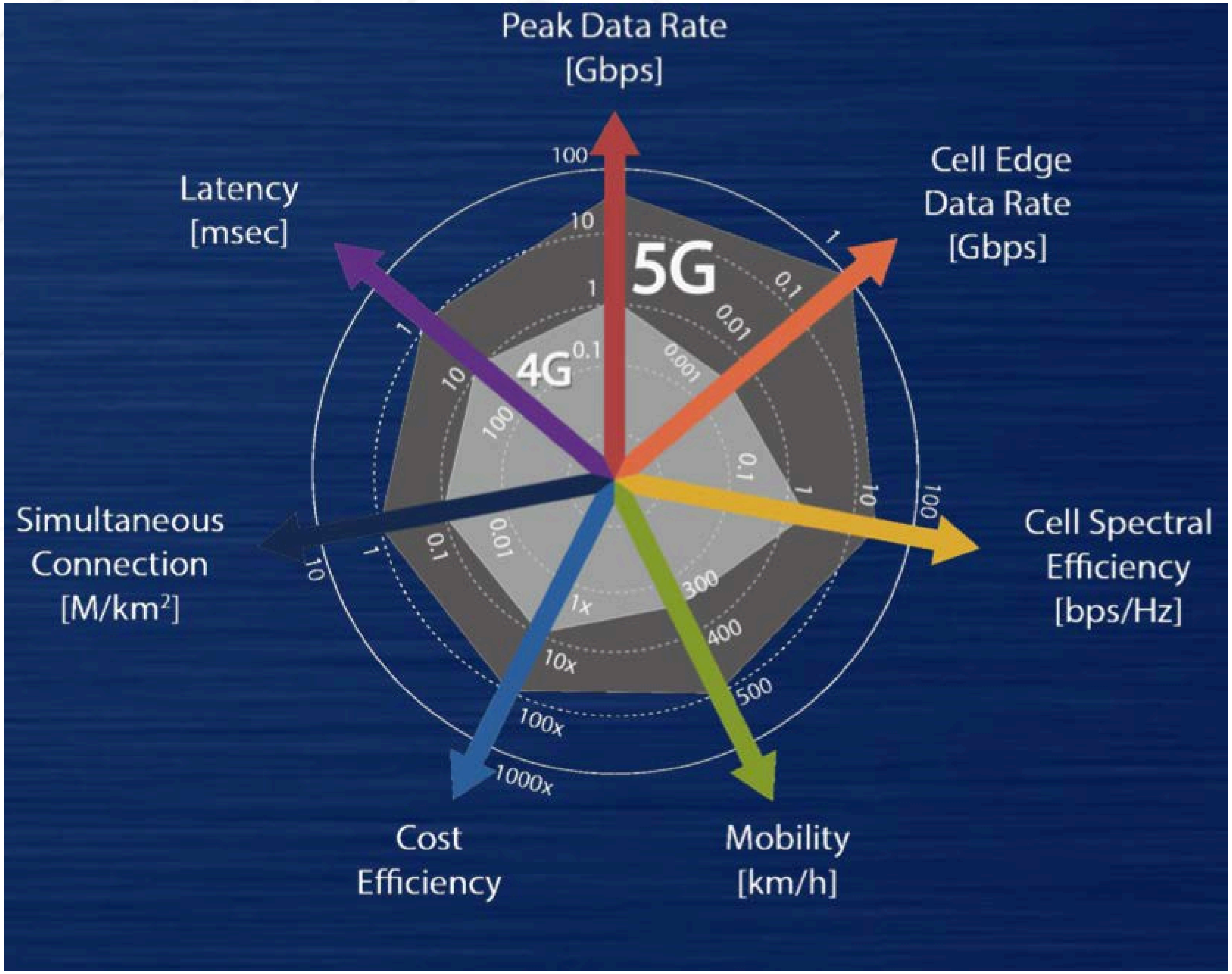
# Smartphones, tablets, IoT…

- 100,000% increase in data traffic inAT&T national wireless network: Jan 2007 – Dec. 2014
  - Source: Brooklyn 5G Summit
- Future:
  - IoT
  - More Internet media (audio, photos, video)
  - More video surveillance and monitoring
  - 3D telepresence
  - Control over wireless
  - More sensors everywhere



BWRC

# 5G Rainbow of Requirements

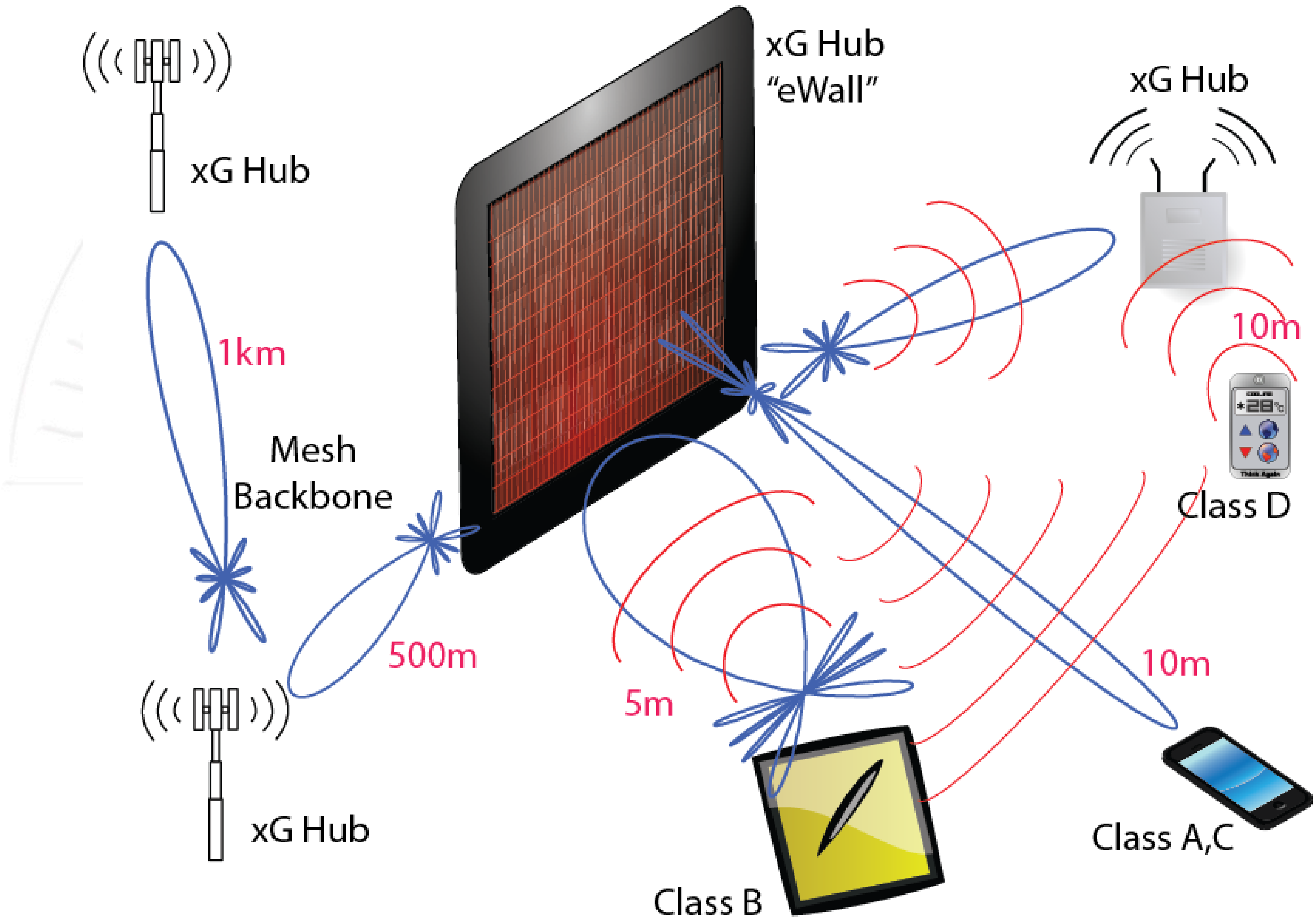



Source: Samsung, NYU 5G Workshop

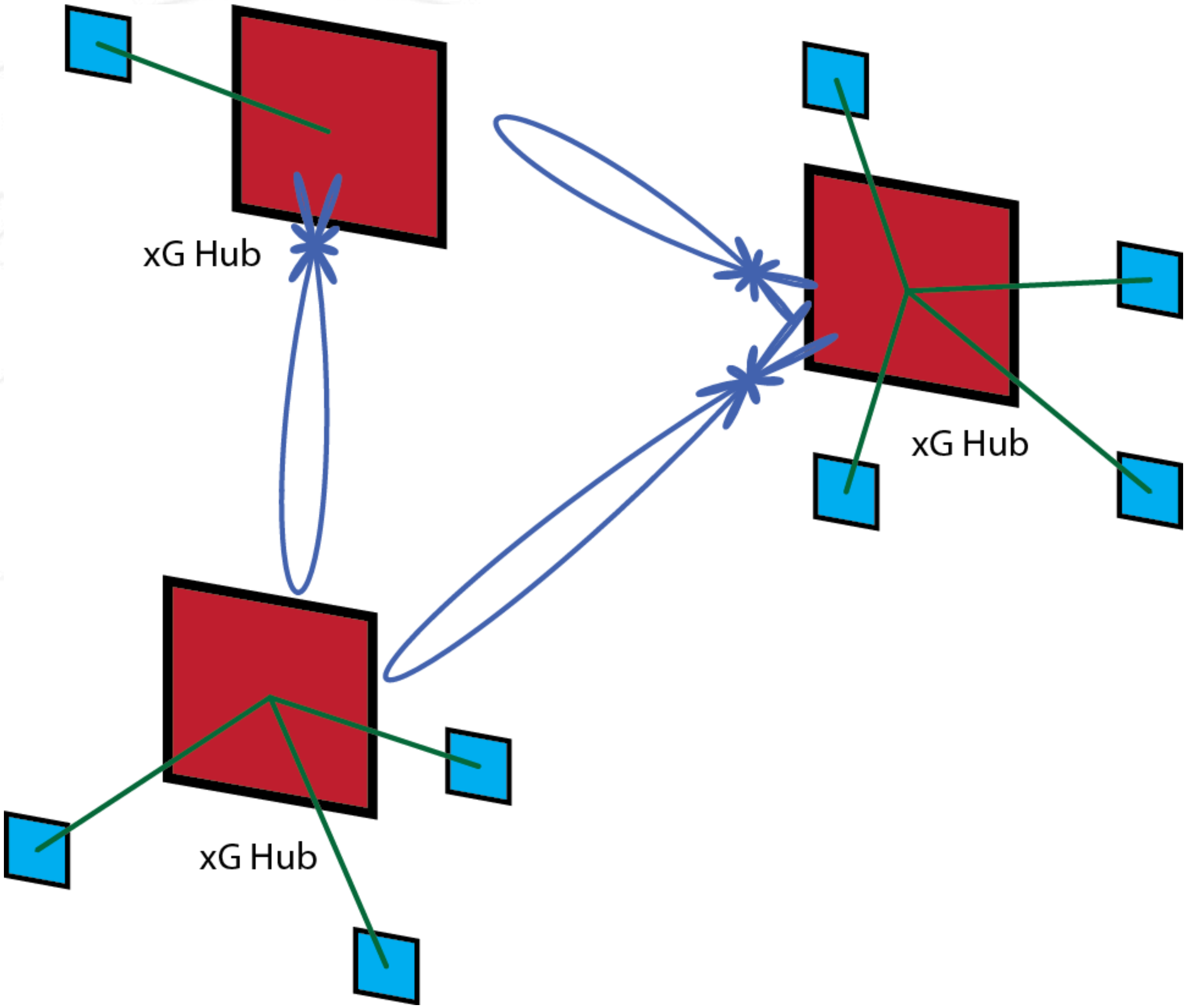
# What is 5G?

- A set of inter-related technologies that will enable orders of magnitude improvement in capacity, data rate, latency, and perhaps support IoT applications
  - Capacity is a must due to exponential increase in wireless traffic
  - Low latency enables new applications such as control over wireless
  - IoT applications today use a set of disparate wireless standards (Bluetooth, Zigbee, WiFi) and are disconnected from the cellular networks. Is it possible to link these devices using 5G?
- How to do it ?
  - Massive MIMO and extreme beam forming and nulling
  - Use of mm-Wave Spectrum from 10 GHz –100 GHz
  - 5G deployment over non-licensed spectrum (“absorb” WiFi)

# 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

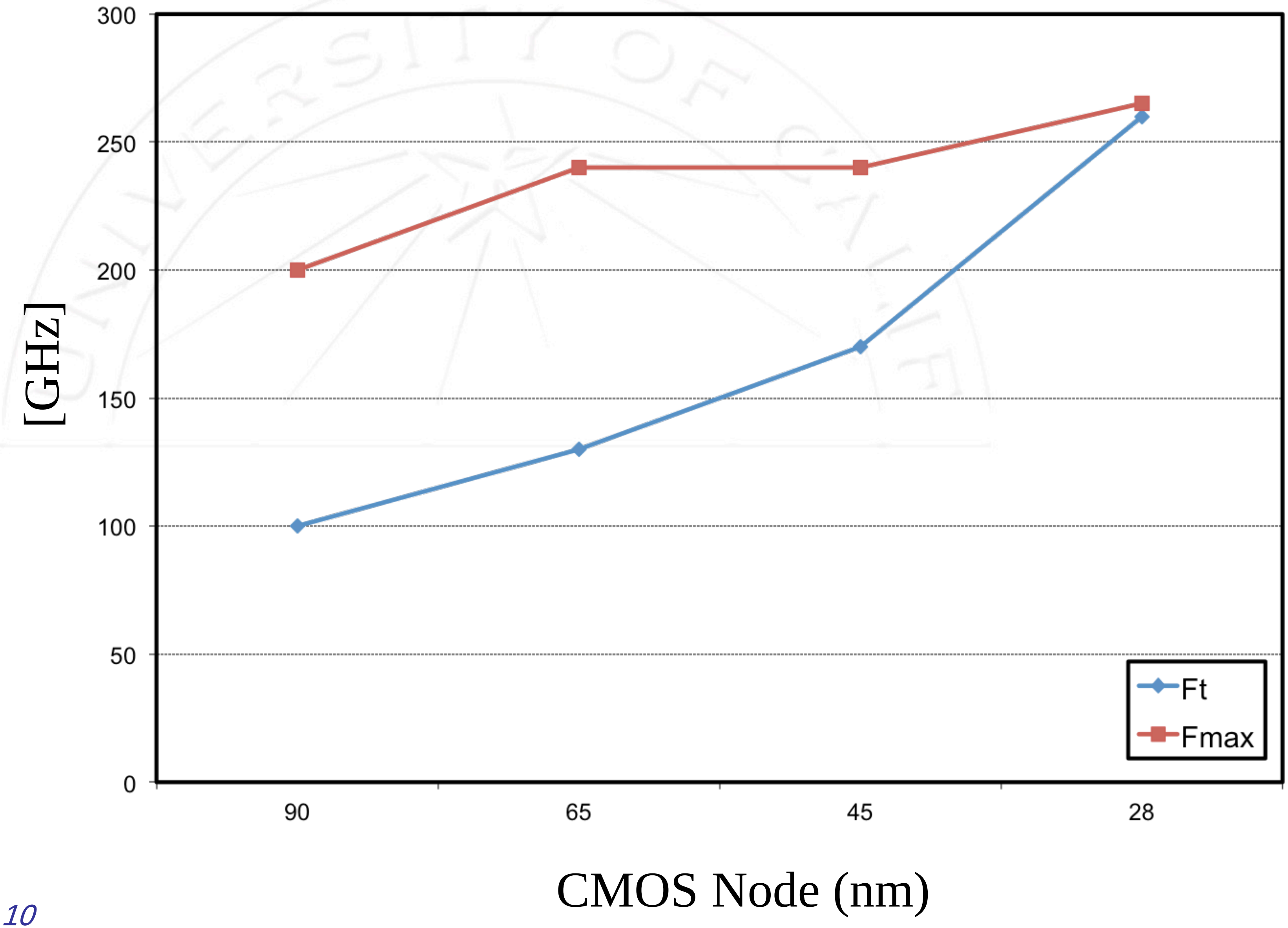
- Maxwell's equations are linear: waves just pass through each other
- Interference really happens because of the receiver's non-linearity
- Most radios today spray energy in all possible directions
- This is not only a huge waste of power, but it causes more interference!
- Solution: directivity!

# One G to Unite Them All…

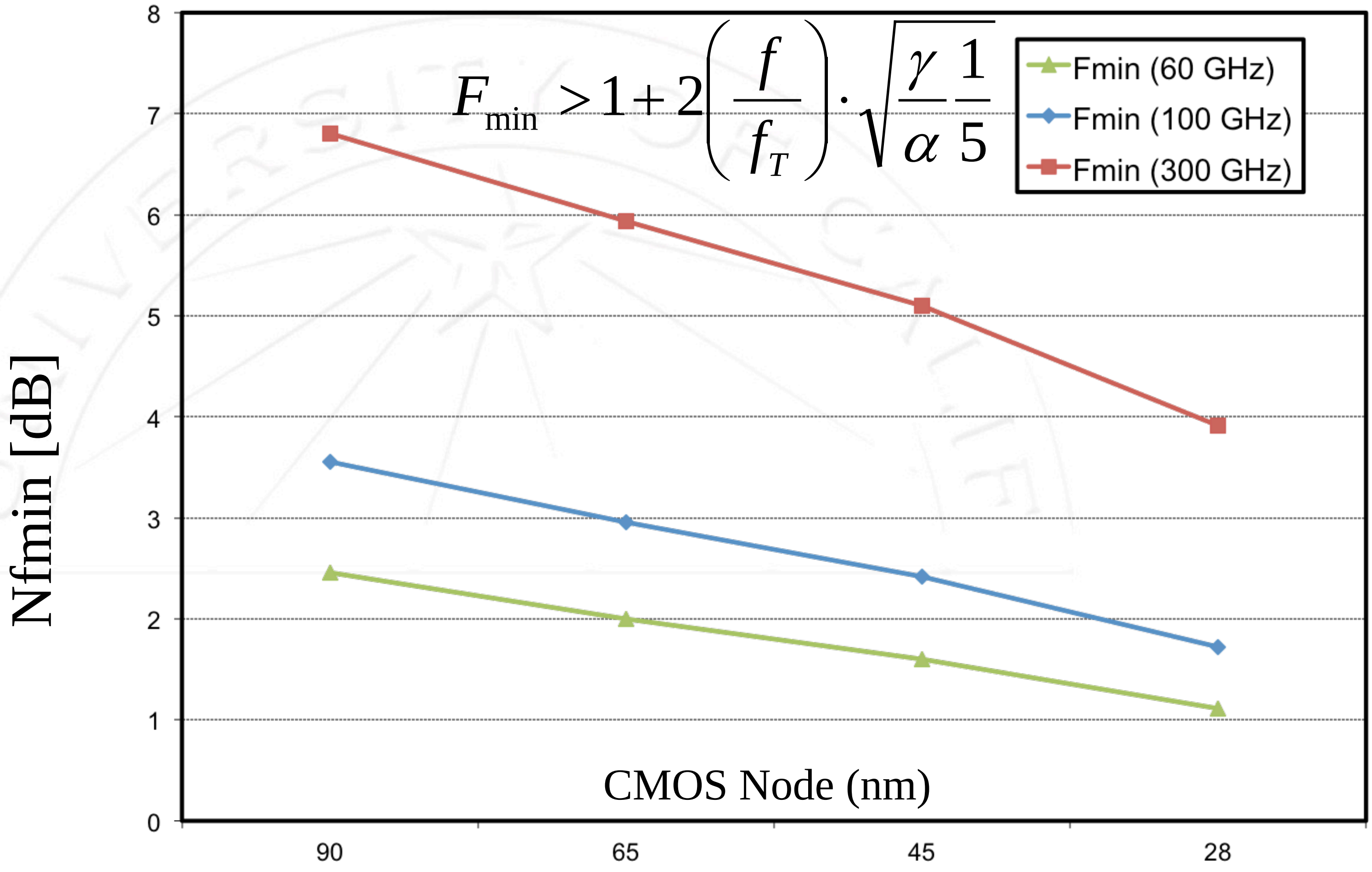
- xG = LTE + WiFi + Bluetooth + Zigbee + more
- Sum is more than the whole
- Must have universal communication between all modes
- Scale power from short range to long range
  - Range:  1cm – 1km
  - BW:  100’s Gb/s to 1 kb/s
  - Power:  100uW to 100 mW
  - NF:  10 dB to 2 dB
  - TX Power: -10 dBm to 27 dBm
  - Very good <u>sleep</u> power and wake on wireless functionality

# MM-WAVE BUILDING BLOCKS

# CMOS Technology Trends

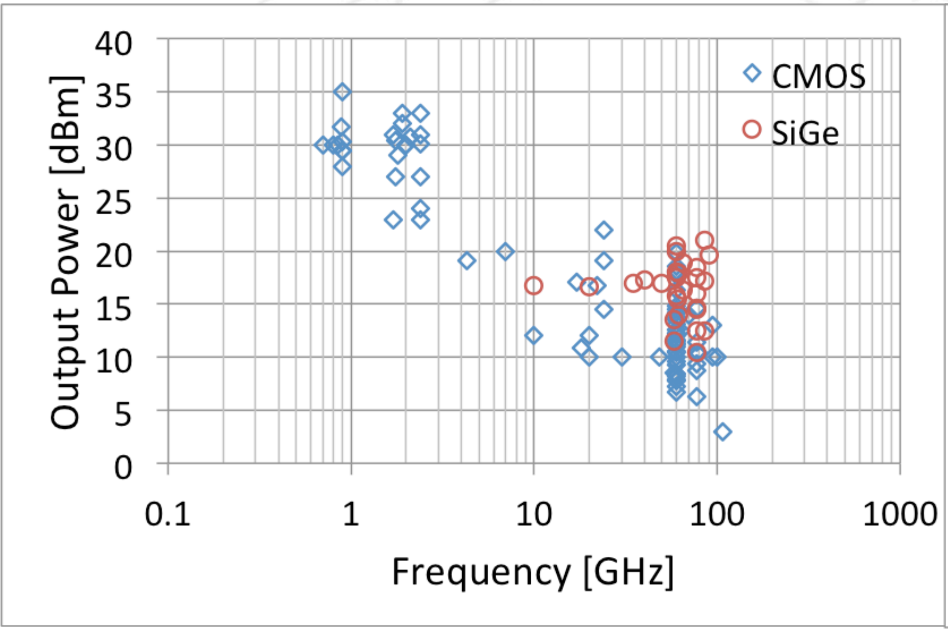


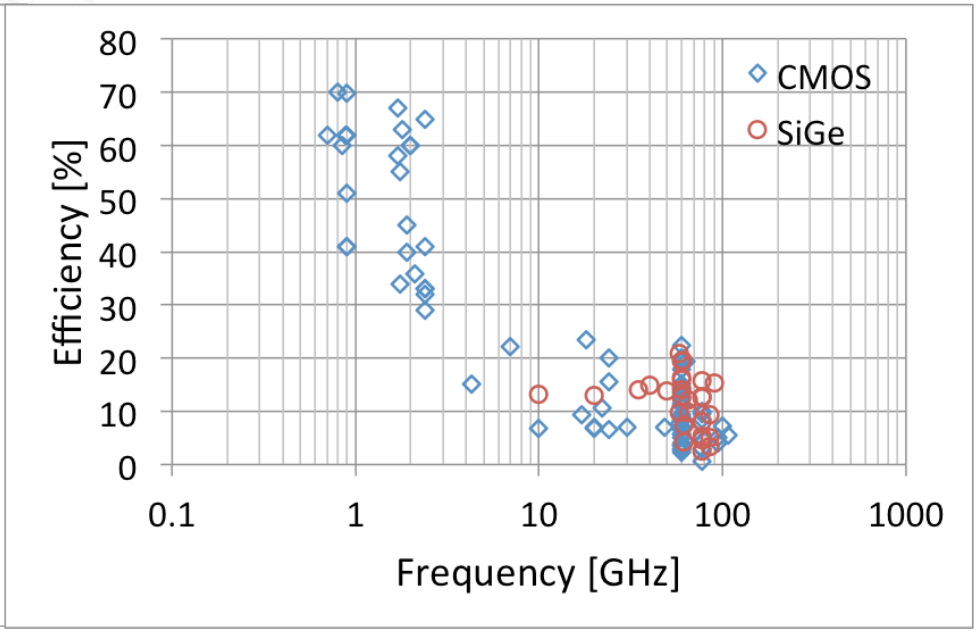
# Receiver Sensitivity




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

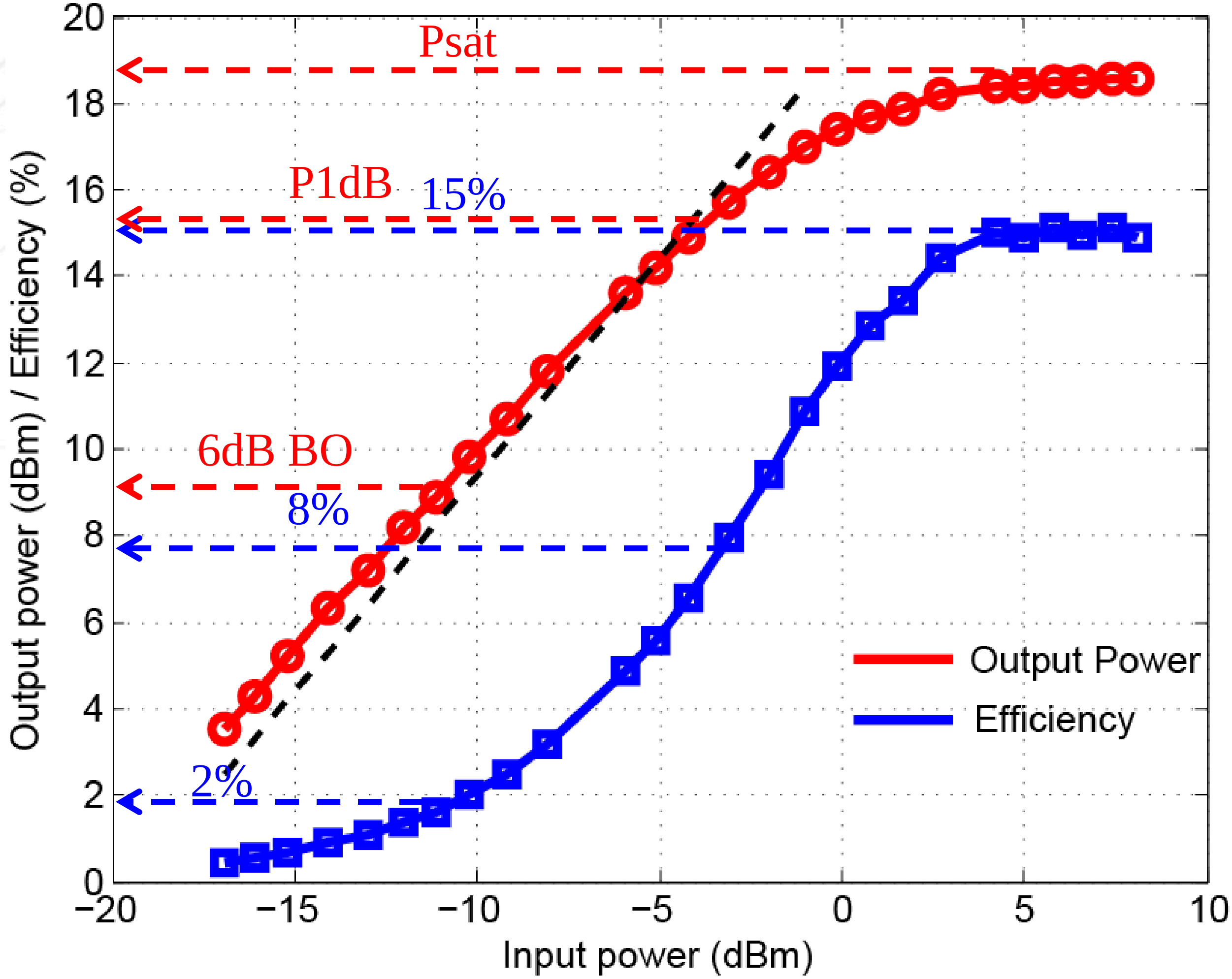
# Silicon Power Amplifier Performance




- 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

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

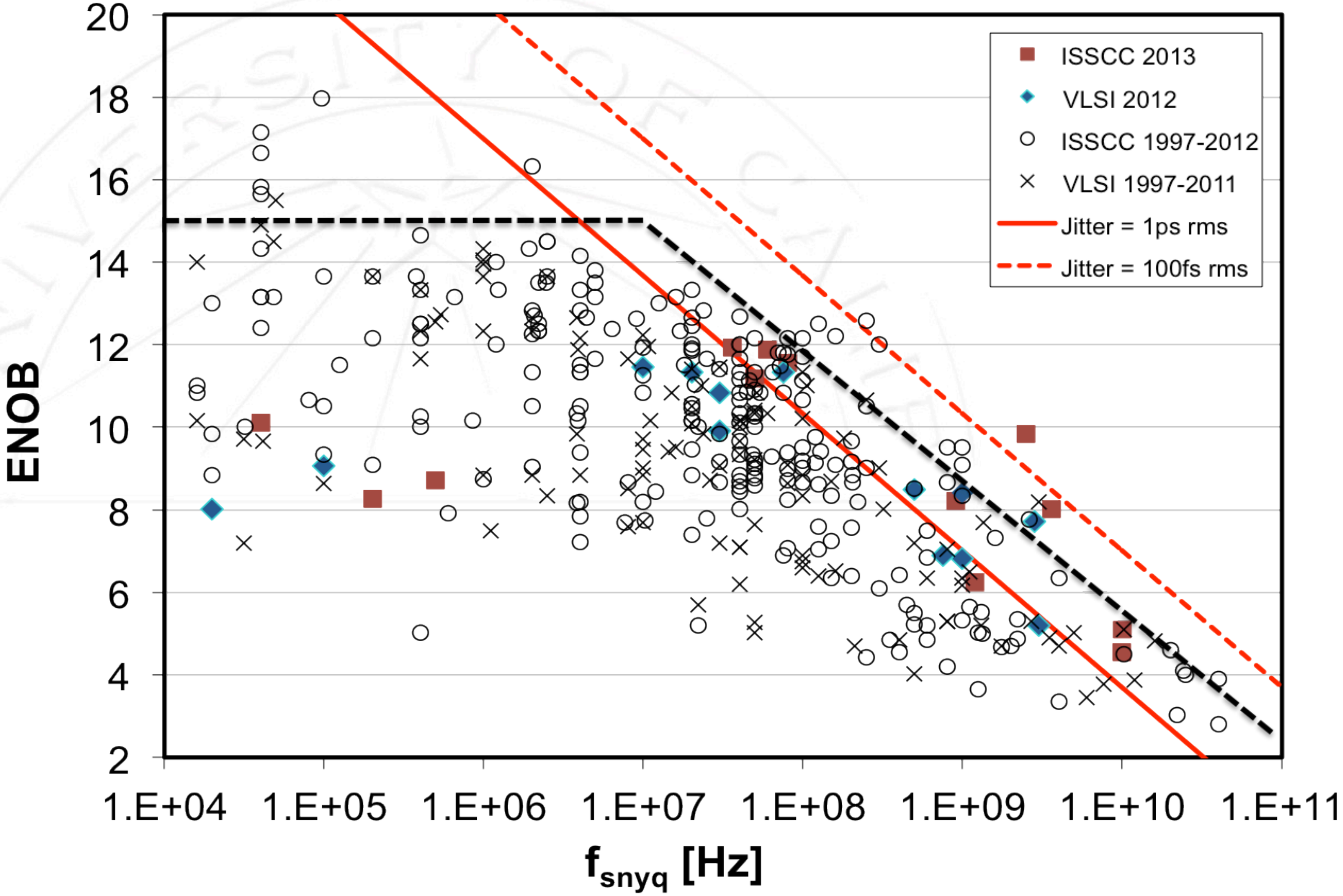


# Phase Noise

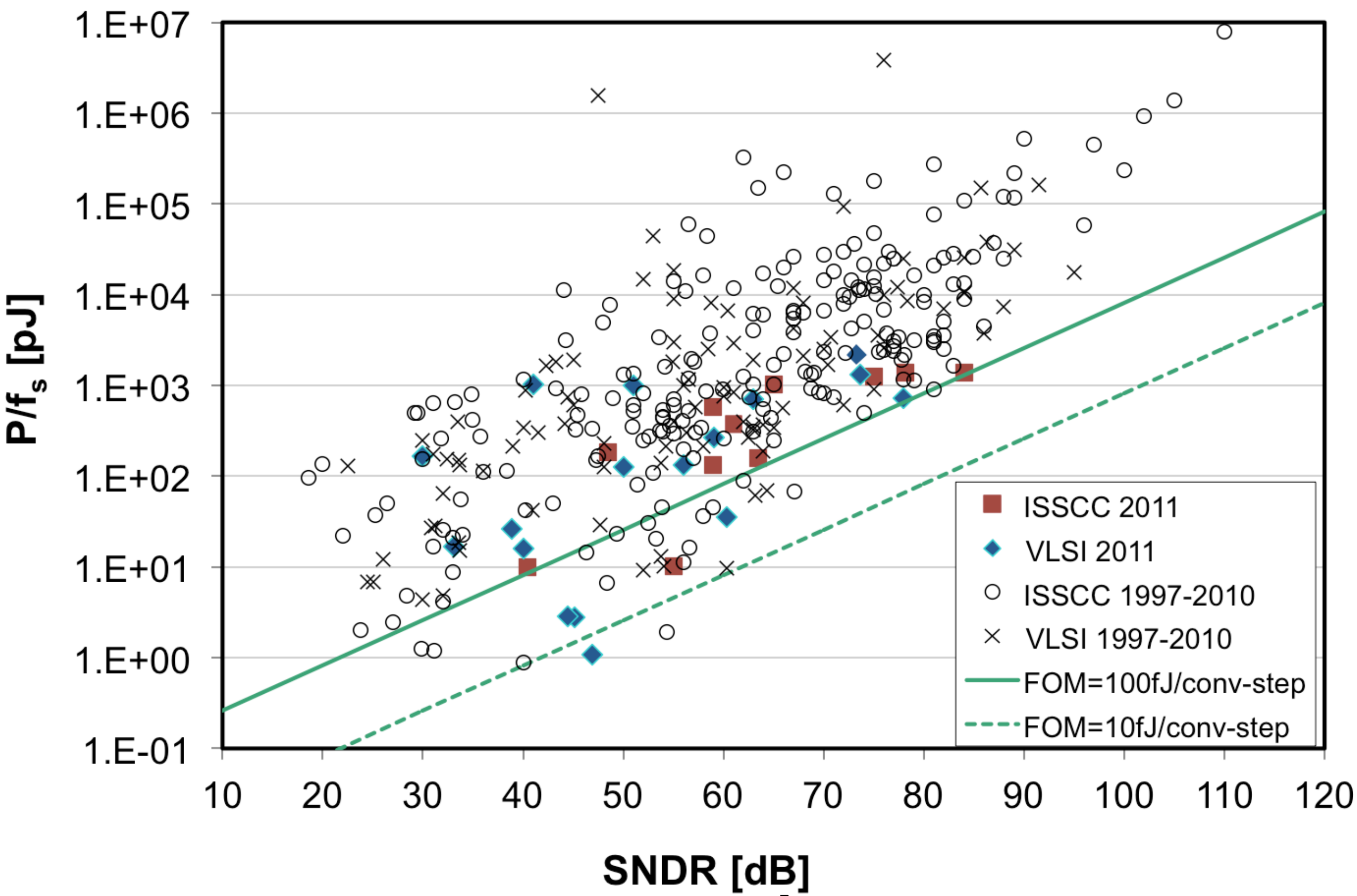
| | | RFIC15 [1] | JSSC13 [2] | RFIC08 [3] | ISSCC14 [4] | RFIC14 [5] | RFIC14 [6] |
|---|---|---|---|---|---|---|---|
| CMOS Technology | | 40nm | 90nm | 130nm | 40nm | 65nm | 32nm SOI |
| Type | | Harmonic extraction | Fundamental | Fundamental | Fundamental | Frequency tripling | Common-mode extraction |
| 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)

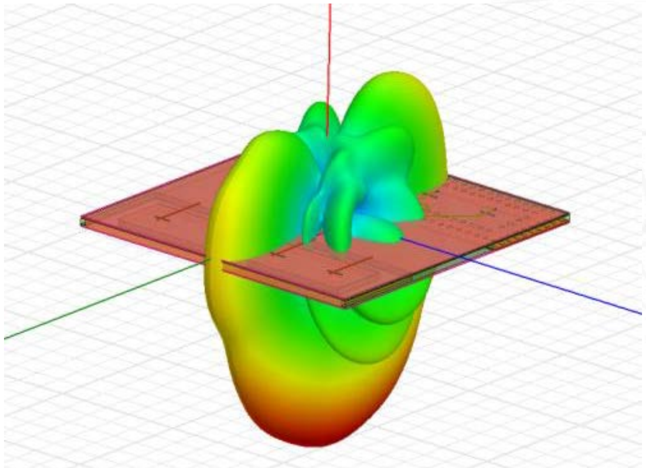


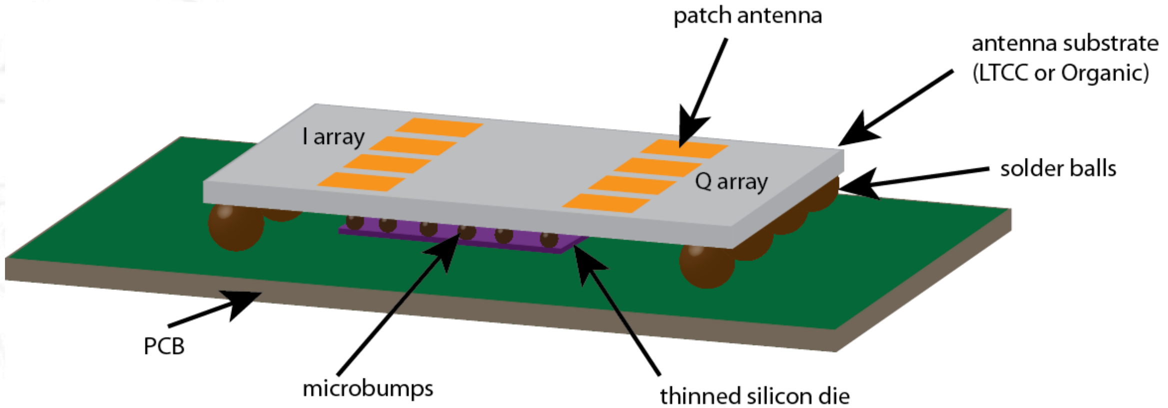
# ADC Power




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

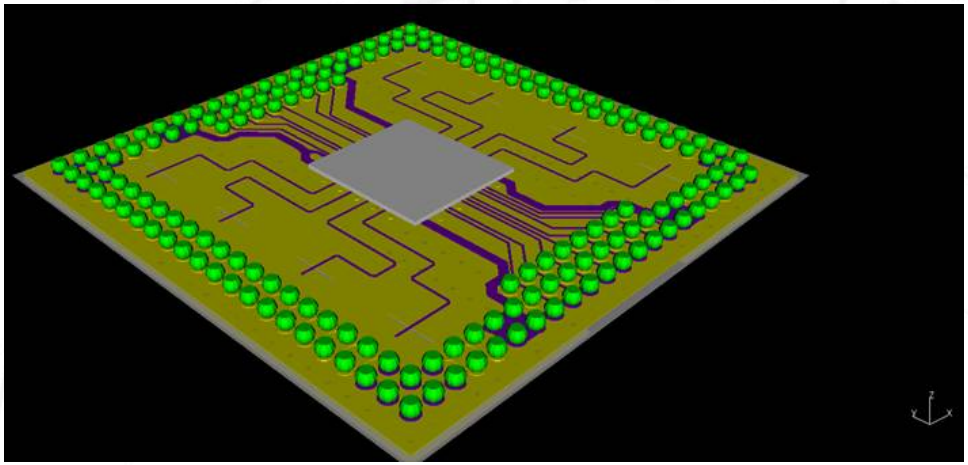
# Antennas and Packaging

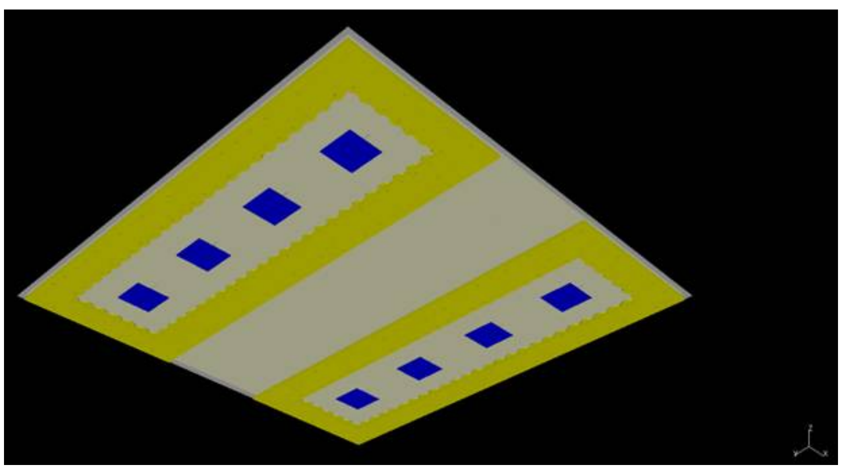




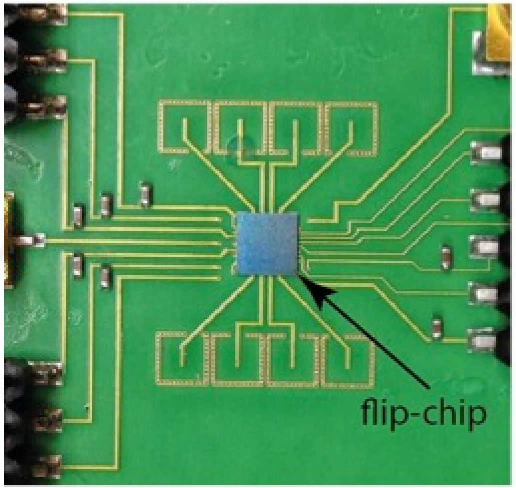

- Today cost of mm-wave components is dominated by packaging and testing, not the die cost
- A high volume solution requires low cost packaging and BIST (eliminate all mm-wave testing). Need the baseband integrated with the RF in the same technology.
- Flip-chip assembly is possible.  Must be ESD compliant.
- LTCC, HTCC, organic substrates, even FR4 or Rogers are possible depending on application

# Example Rogers Package

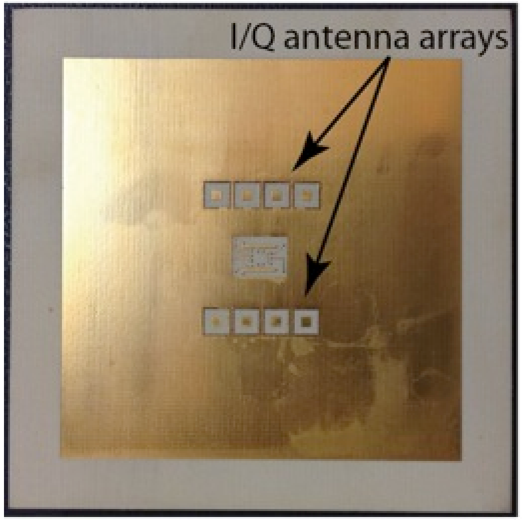




Package frontside




Package backside

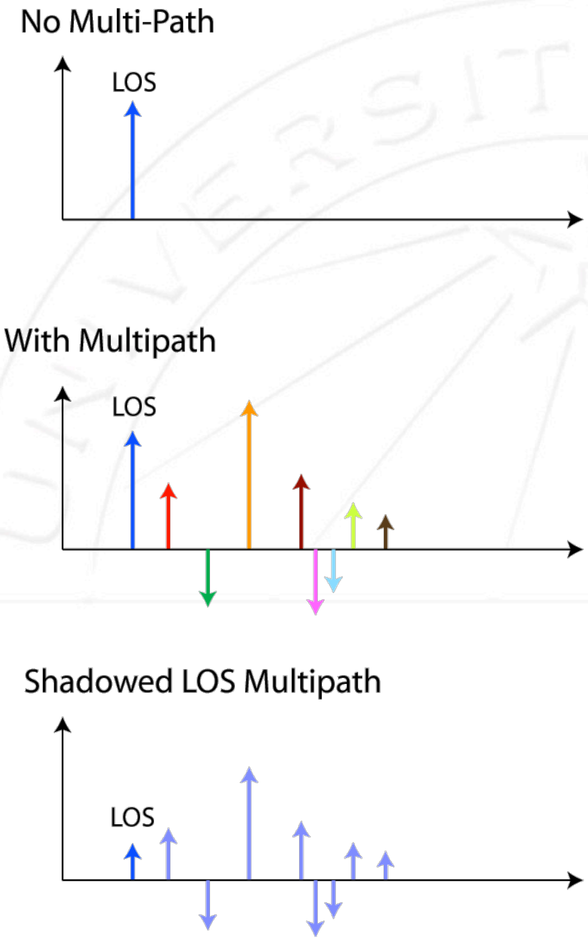


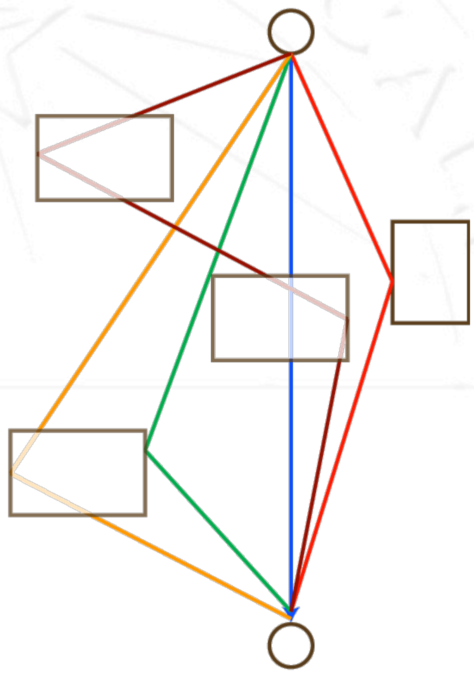
# MASSIVE MIMO AND MM-WAVE SYSTEM ARCHITECTURE

# Kilometer Scale Link Budget

| Link Budget Analysis | Downlink | Uplink |
|---|---|---|
| Transmiter power (dBm) | 40 | 23 |
| Transmit antenna gain (dBi) | 25 | 12 |
| Carrier frequency (GHz) | 30 | 60 |
| Distance (km) | 0.25 | 0.25 |
| Free space prop. Loss (dB) | -110 | -116 |
| Other losses (shadowing, fading) | 20 | 20 |
| Receive antenna gain (dB) | 12 | 35 |
| Received power (dBm) | -53 | -66 |
| Bandwidth (GHz) | 0.5 | 0.5 |
| Thermal noise PSD (dBm/Hz) | -174 | -174 |
| Noise figure | 7 | 5 |
| Thermal noise (dBm) | -80 | -82 |
| SNR (dB) | 27 | 16 |
| Implementation loss | 3 | 3 |
| Shannon spectral eff. | 8.0 | 4.4 |
| Data rate (Gbps) | 4.0 | 2.2 |

# Multi-Path Propagation



- Reflections, diffraction, and refraction for smooth objects
- Scattering for rough surfaces
- Depends on relative dielectric constants, angle and plane of incidence, etc.

**Key Observation**: Multi-Path components have a different angle of arrival. A phased array can therefore distinguish the desired signal from the clutter

# Modulation Schemes

| Modulation | OFDM-QPSK | High-order modulation (16-QAM) | Single-carrier QPSK | Constant Envelope (MSK) |
|---|---|---|---|---|
| $SNR_{req}$ (BER=$10^{-3}$) | 7dB | 12dB | 7dB | 7dB |
| $PAR_{TX}$ | ~10dB | ~5.5dB | ~3dB | 0dB |
| PA linearity req't | High | High | Moderate | Low |
| Sensitivity to Phase Noise | High (ICI) | High (Symbol Jitter) | Moderate | Low |
| Complexity of Multipath Mitigation Techniques | Moderate (FFT) | High (Equalizer) | High (Equalizer) | High (Equalizer) |

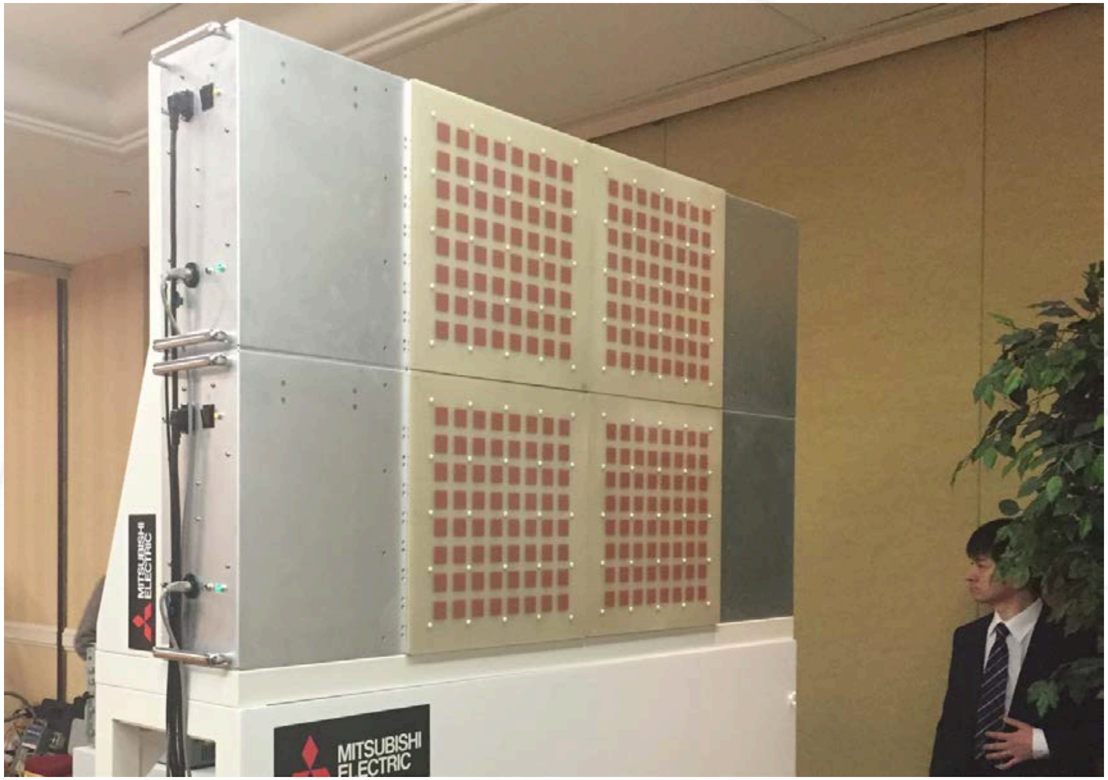
Source: Sobel (BWRC), "60GHz Wireless Link Design: Towards a mostly analog radio" (BWRC Retreat)

- Giving up 10 dB of transmit power for OFDM only makes sense if we can reduce the power of the equalizer by a commensurate amount.

# 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 …

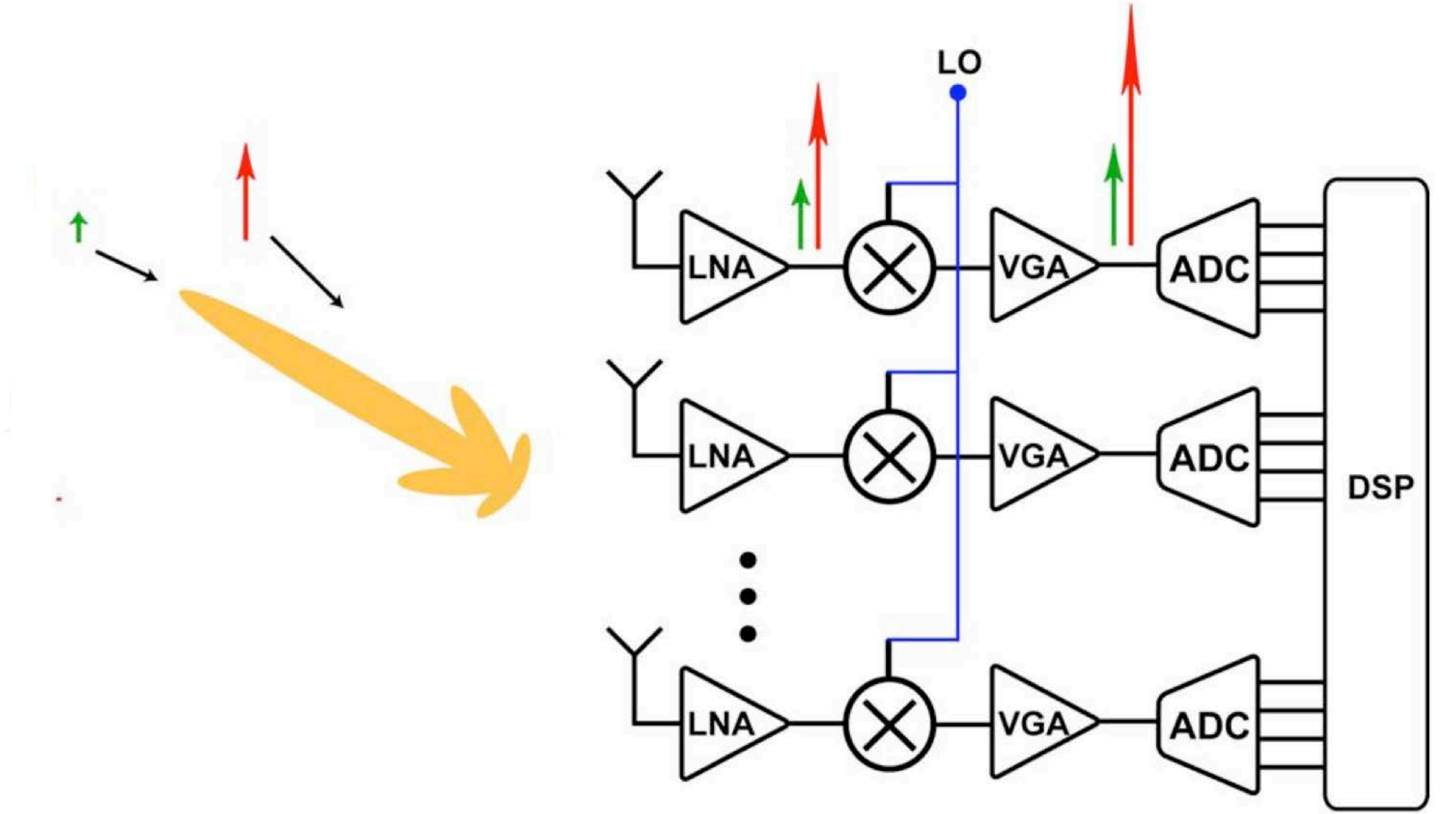
# Massive MIMO




- 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

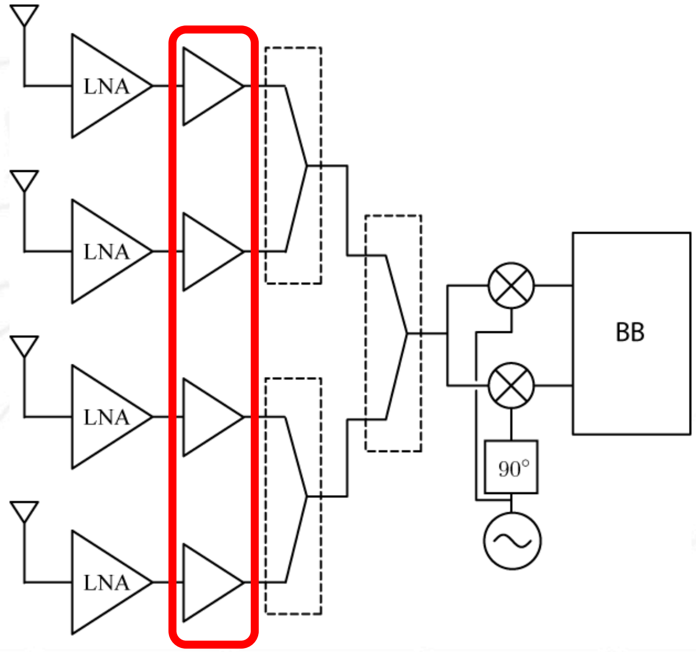
# Phased-Array Comparison






BWRC

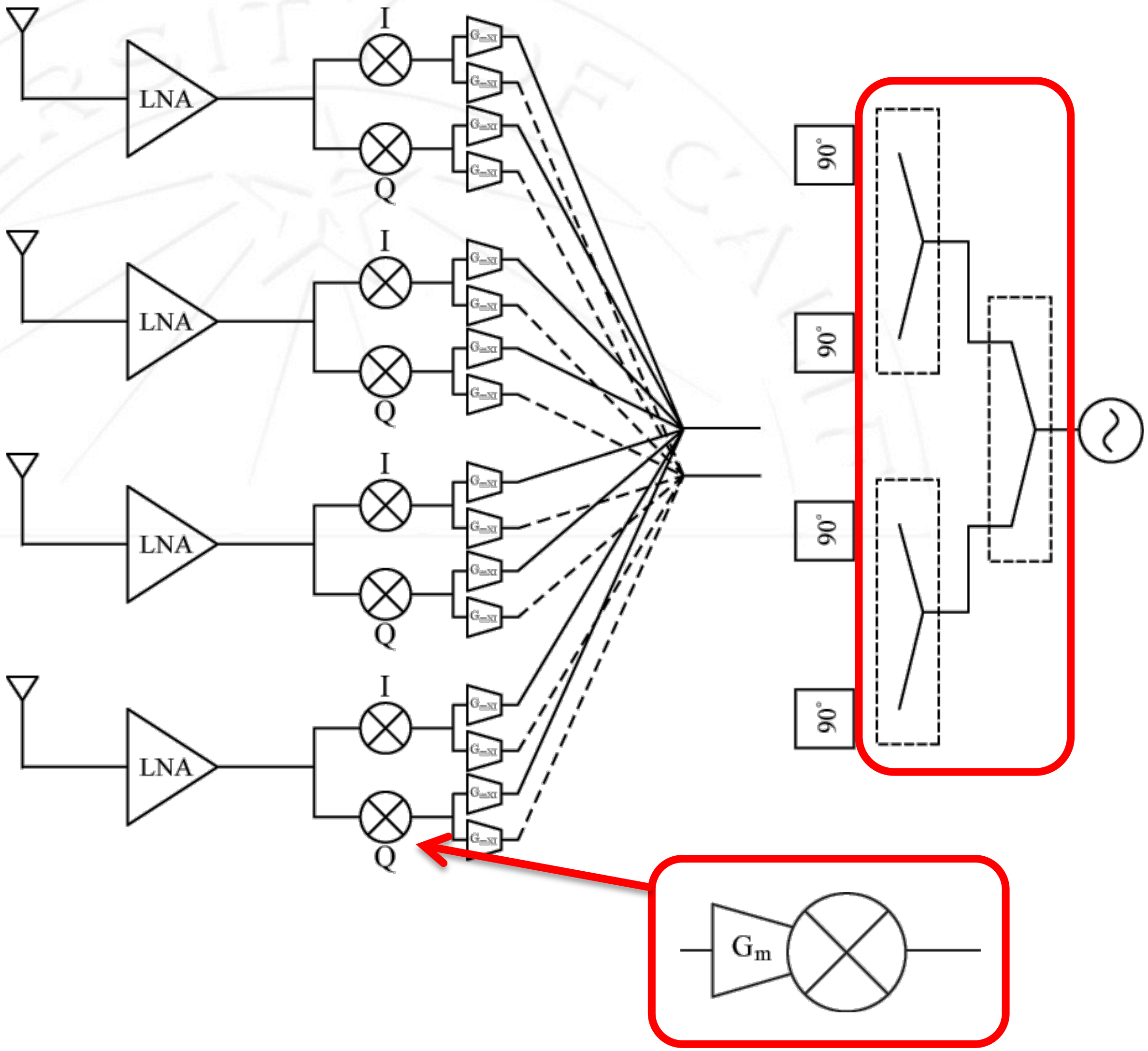
# RF Phase Shifter



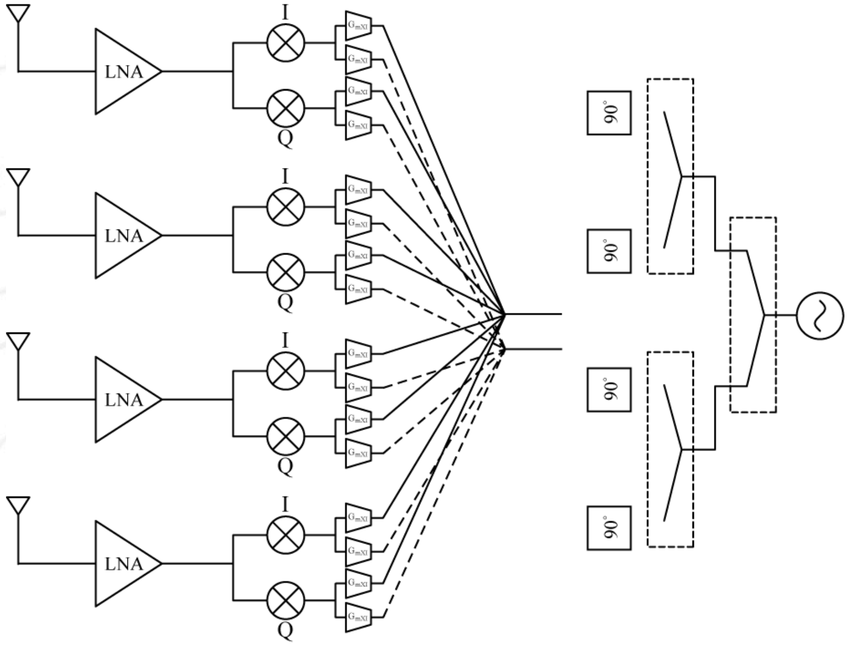

Amplifiers limit linearity and increase power

- RF combining is the most robust
  - Spatial filtering occurs before the mixer and relaxes requirements.
  - Only 4 LO signals are required (I/Q for RX and TX)
- Issues:
  - RF combiner is lossy and bulky
  - RF gain stage needed prior to signal combining (for noise reasons), which must meet tougher linearity specifications

# IF Phase Shifter

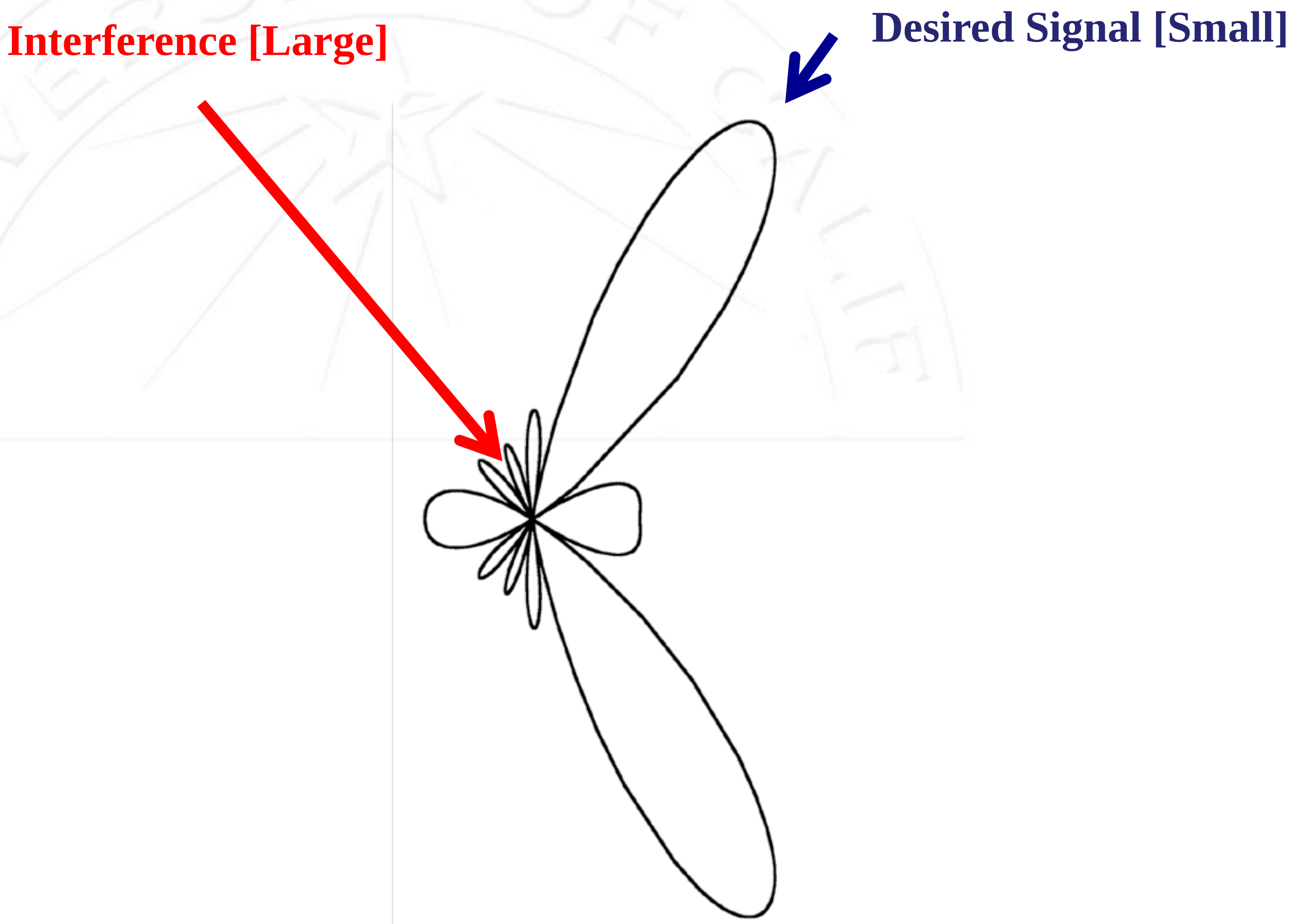


# IF Phase Shifter Issues

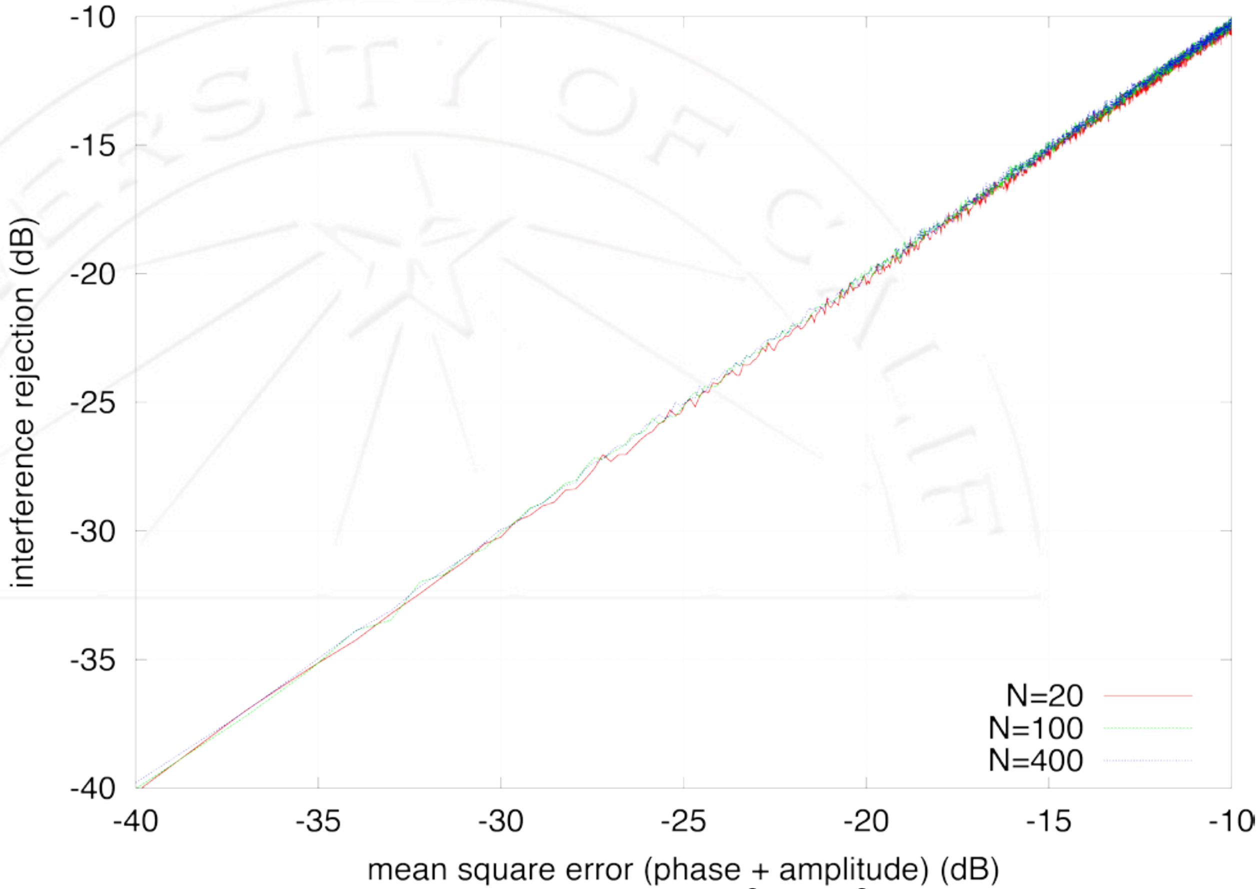



- Power loss in RF path is transferred to LO path (energy neutral).
- Gm non-linear of mixer device is also the same as the second stage of the RF gain stage (distortion neutral)
- IF stages can be combined in a flexible manner
- Issues: Need to keep power of mixers low → scale devices

# Interference Nulling



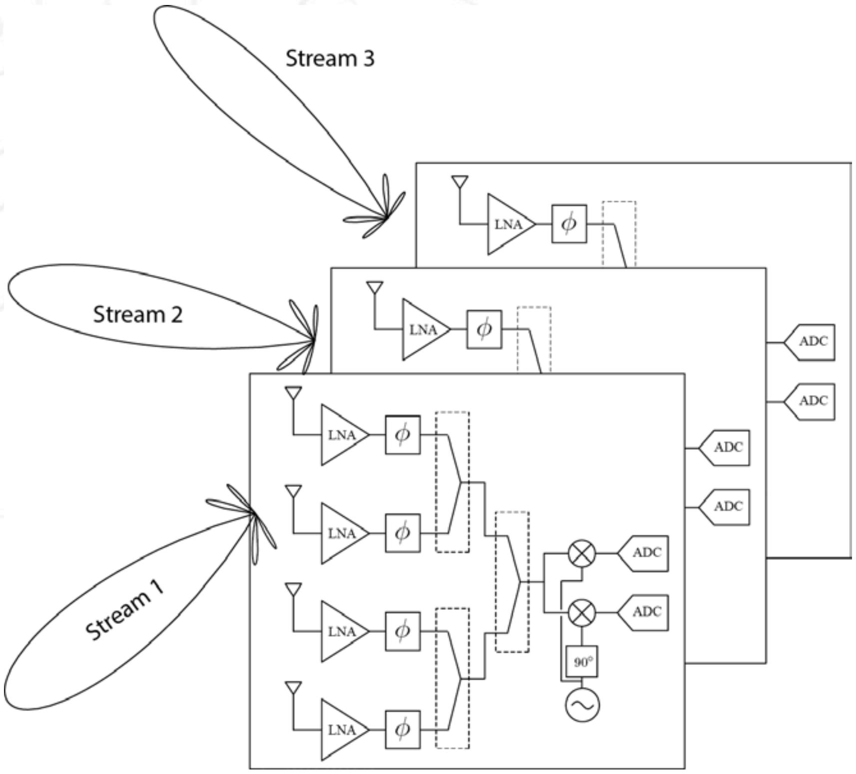
# Beam Nulling vs. Resolution




$$10\log(\sigma_\epsilon^2 + \sigma_\delta^2)$$

- Unlike the peak directivity, beam nulling is very sensitive to phase and amplitude errors.
- The result is independent of array size

# Hybrid Beam Forming

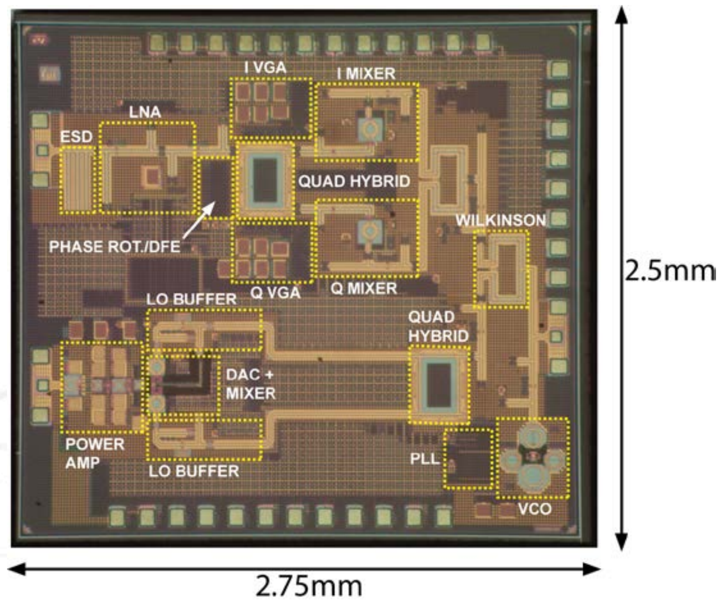


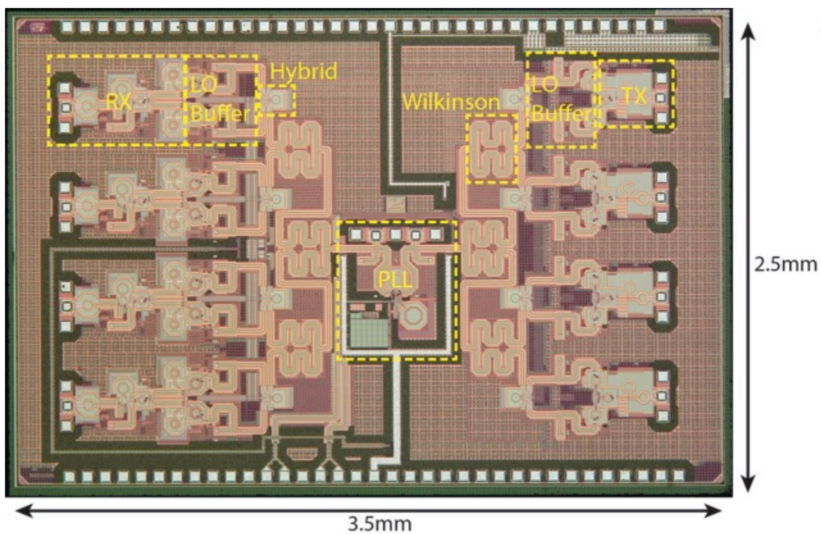

- Digital beam form a limited number of elements (polarization diversity or a few reflections)
- Analog beam form to form a large number of streams

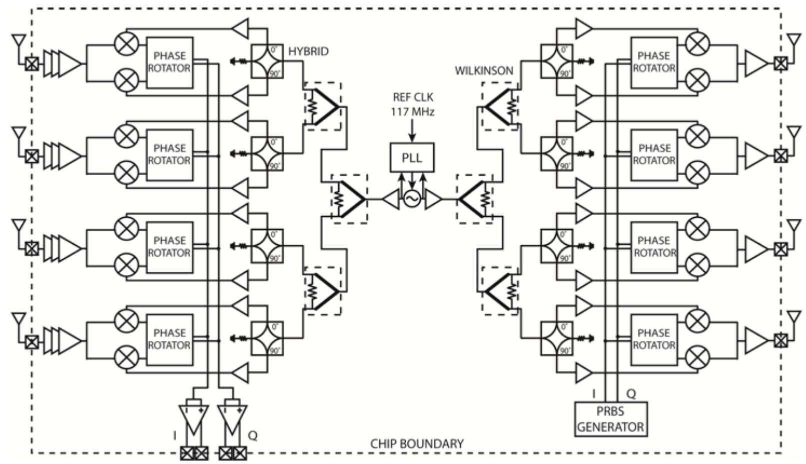
# EXAMPLE MM-WAVE SYSTEMS

# BWRC 60 GHz Transceiver Demos

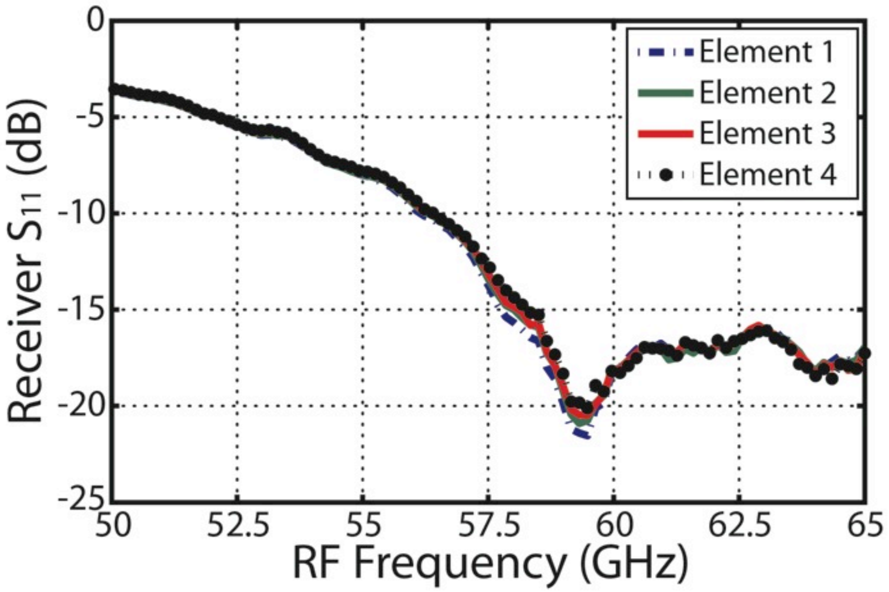
- 10 Gbps at 10 m wireless range
- About 30mW per channel !
  - 3pJ/bit for short range (< 1m)
  - 30pJ/bit for medium range (< 10m)
- Build next generation to allow flexibility to realize a large array…

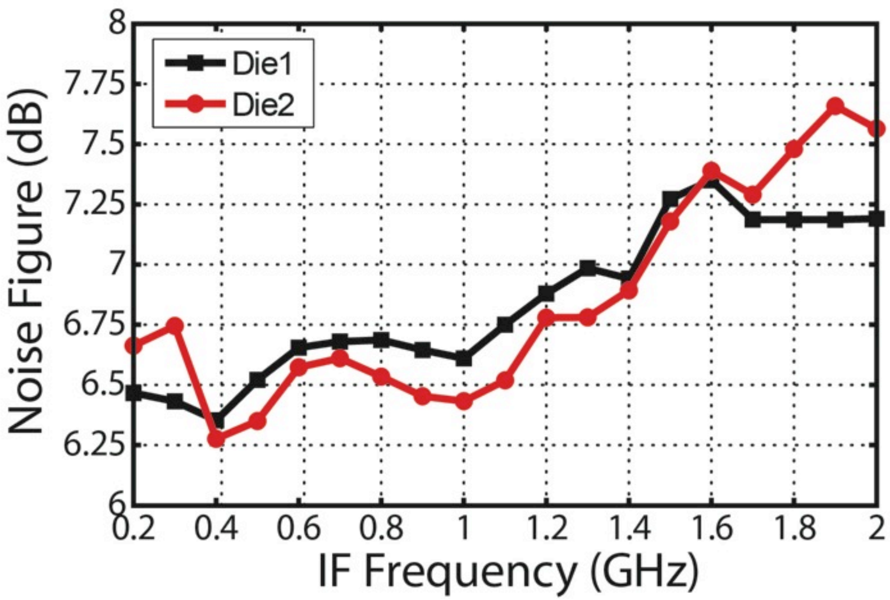


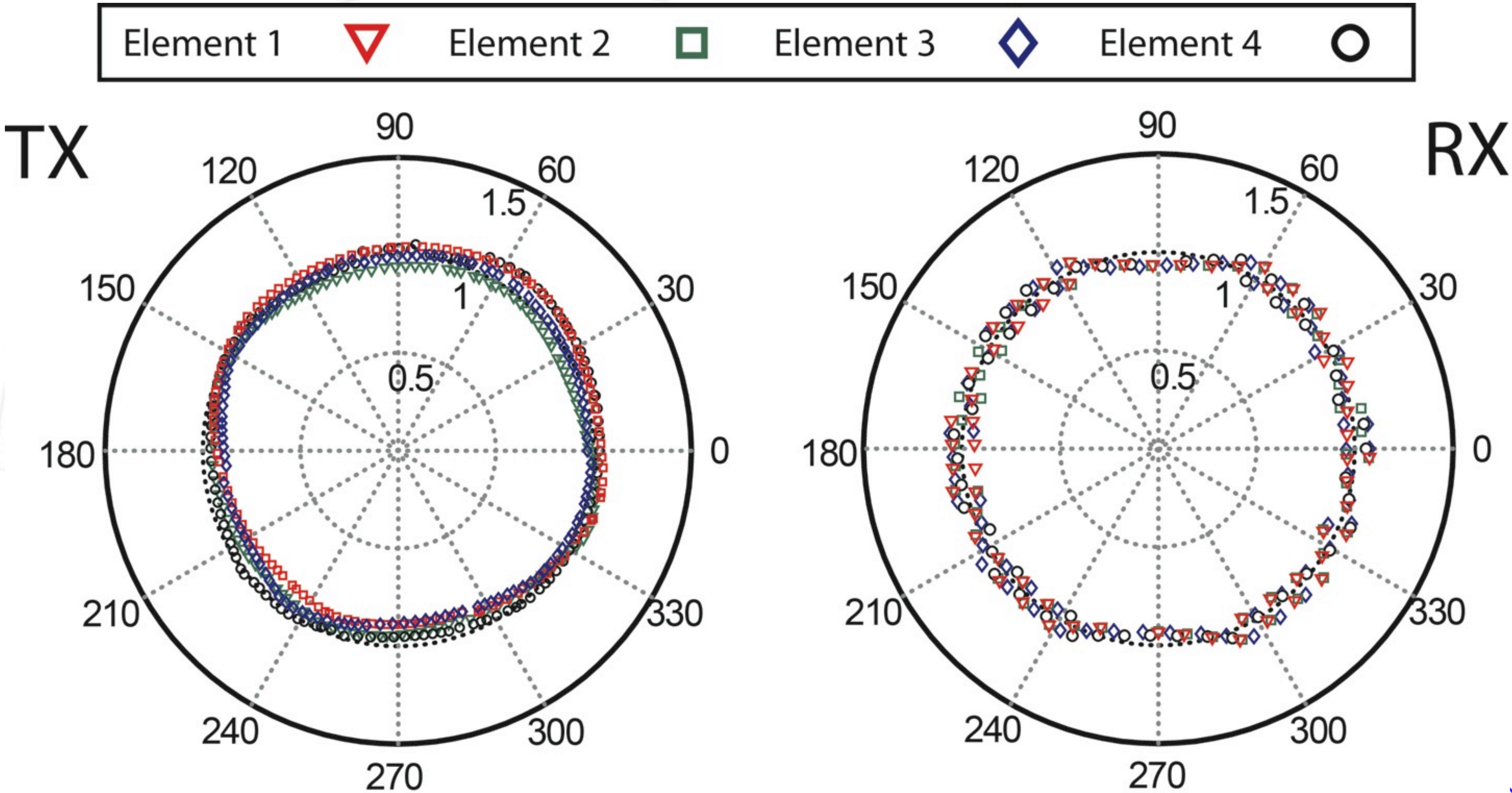
# Receiver Measurements



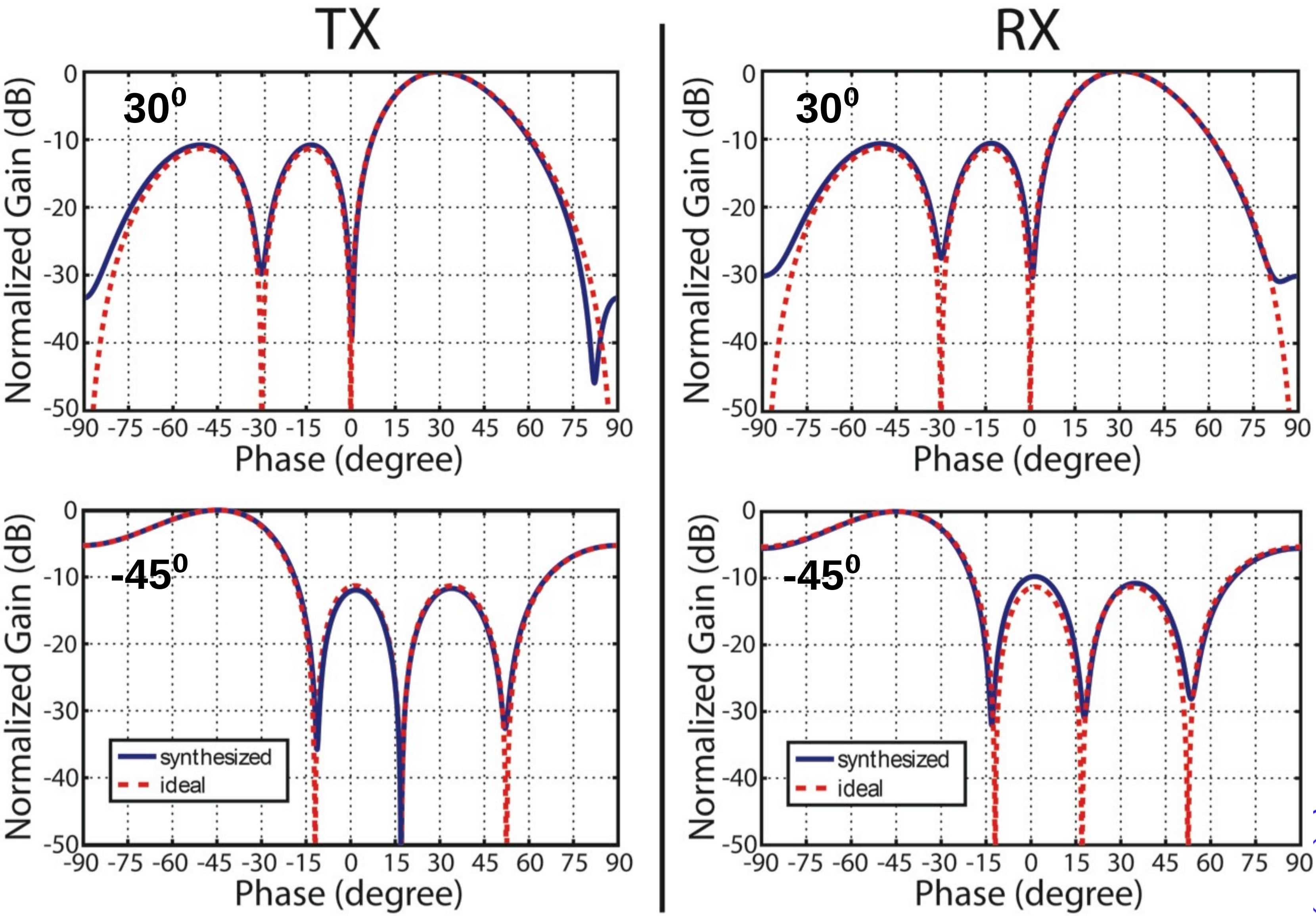

- Broadband input match due to use of transformer in matching network
- Average noise figure of 6.8dB across 2GHz IF band including ESD protection at LNA input

# Measured TX/RX Constellation



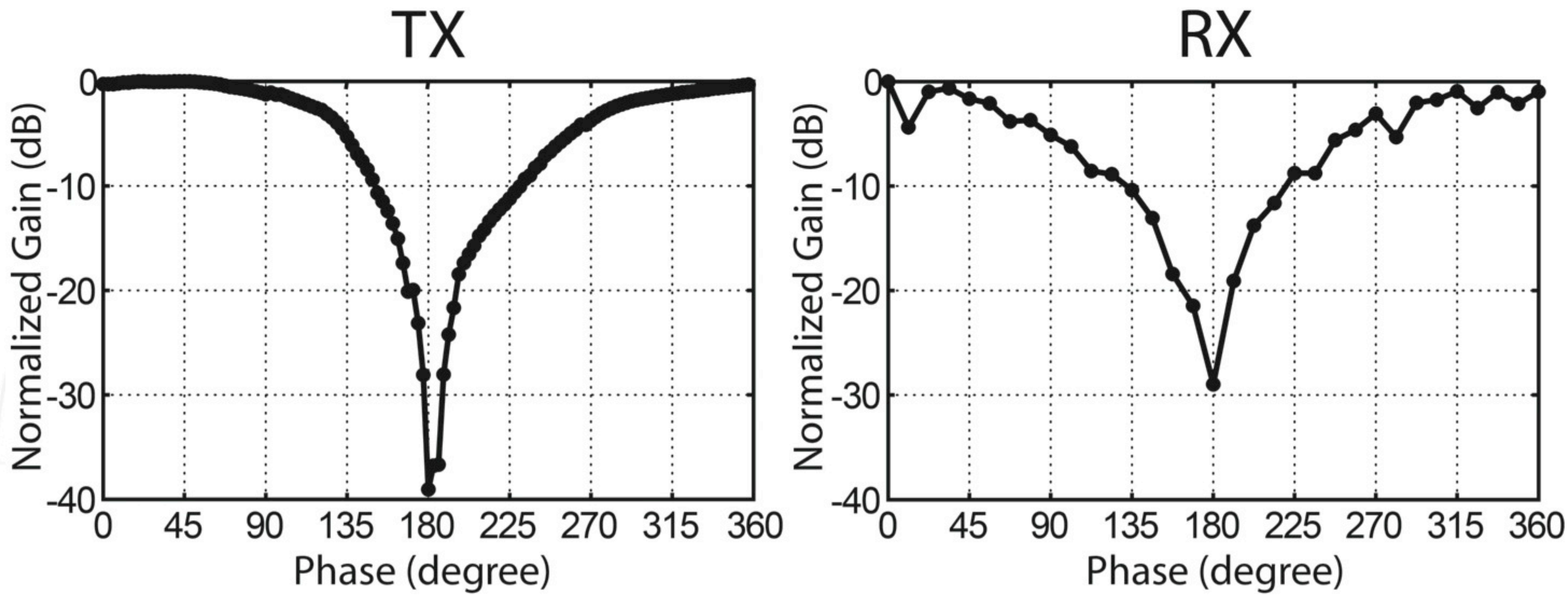

- Phase shifter resolution: RX=11º and TX=5.6º (with +/- 0.5dB gain variation across phase settings and elements)

# Synthesized 4-Element Array Pattern



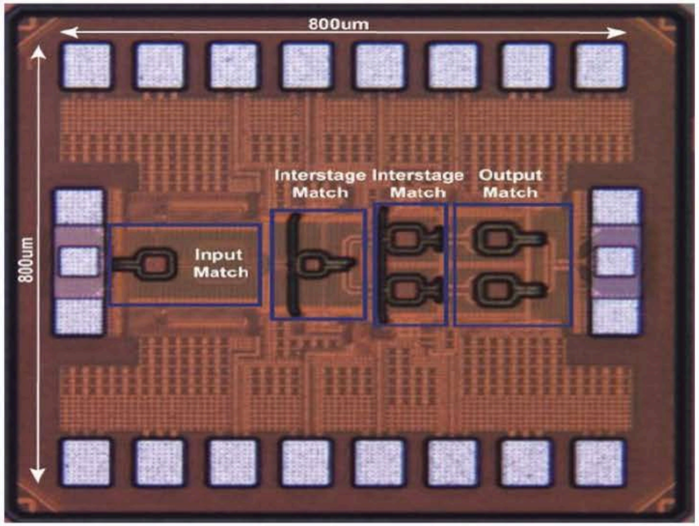

Array pattern synthesized based on all four element phase/gain measurements

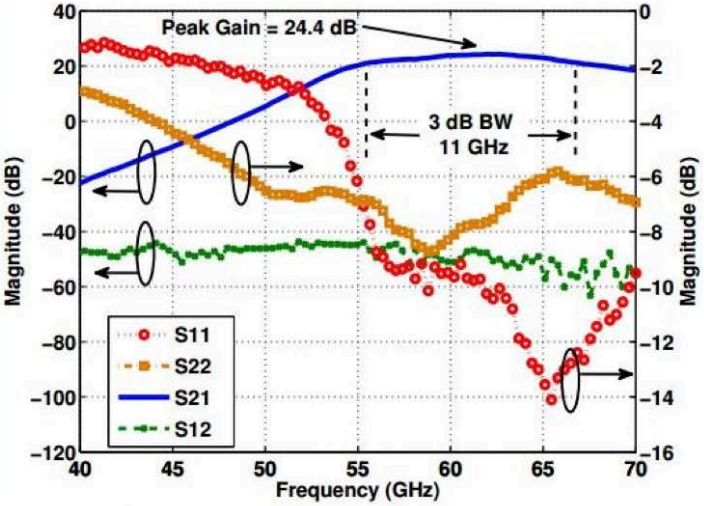
# Two-Element Measurement

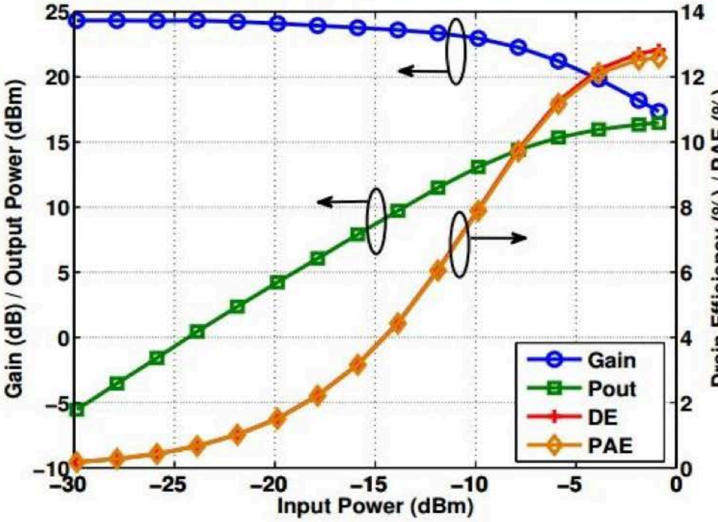


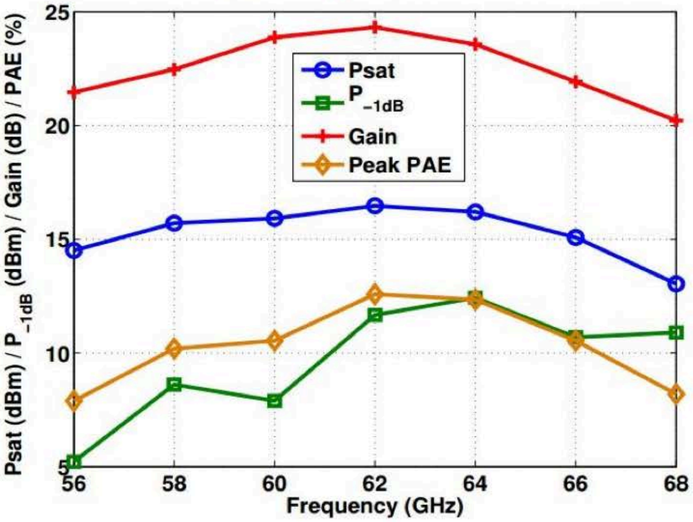

- Measurements performed using a dual GSG probe
- Measured 2-element peak-to-null ratio:
  - TX peak-to-null ratio: 40dB
  - RX peak-to-null ratio: 29dB

# PA Design in 28nm CMOS

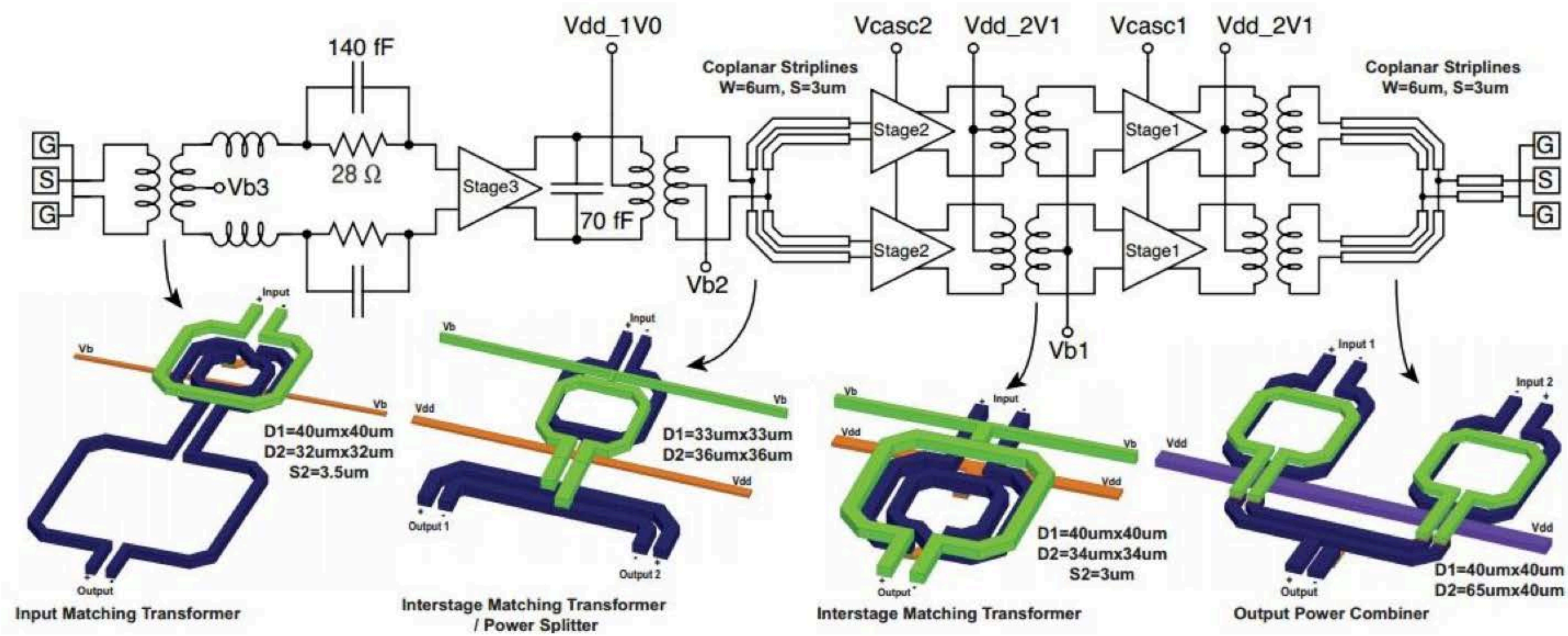


# Power Combining On-Chip

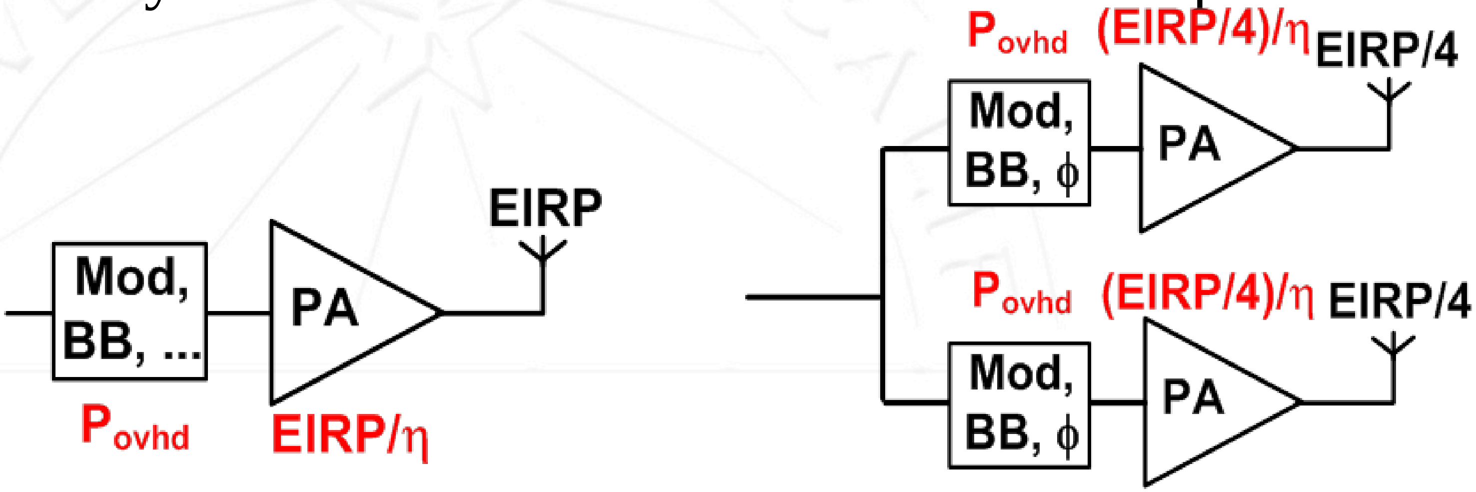


# Optimal PA Power

- Given that PA efficiency is low, we prefer to realize EIRP with many elements
  - Can we eliminate the PA and use hundreds of antennas ?
- In practice we can reduce the power below 10 dBm and use dozens of antennas on handset and hundreds in basestation
- Active research on the design of low overhead transmitters to maximize efficiency for fixed EIRP

# A Good "Bad" Transmitter

- Arrays can actually reduce total power
  - But only if careful about "overhead" – TX example:




$$P_{tot} = \frac{EIRP}{\eta} + P_{ovhd}$$

$$P_{tot} = 2\left(\frac{EIRP / 4}{\eta} + P_{ovhd}\right)$$

$$P_{tot} = \left(\frac{EIRP}{2\eta} + 2P_{ovhd}\right)$$

*L. Kong, Ph.D. thesis, Dec. 2012

# Low *Overhead* Transmitters

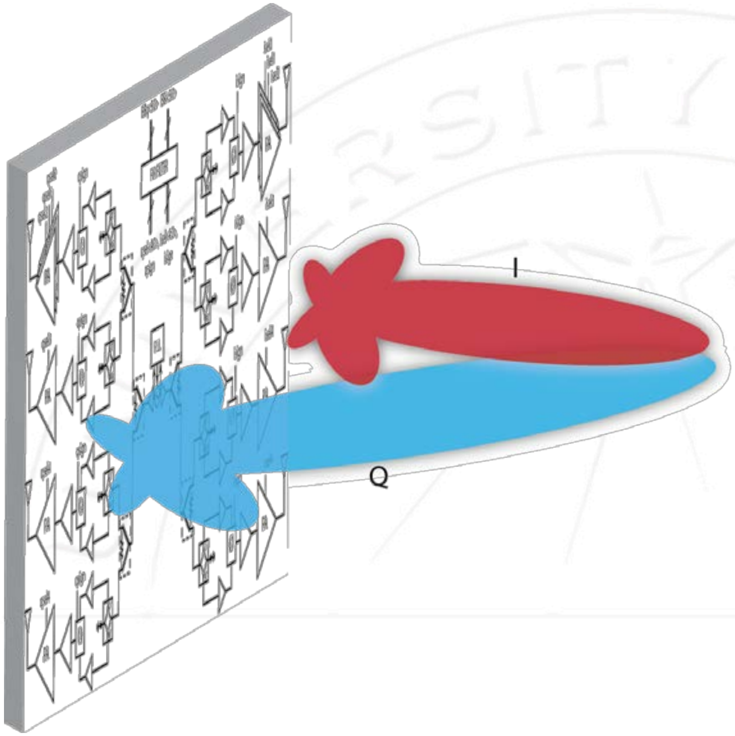
- Overhead power actually sets overall optimal number of elements and hence power:

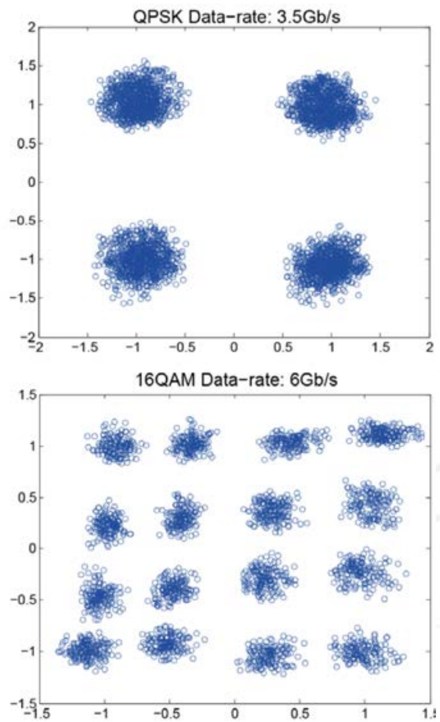
$$P_{tot} = \left( \frac{EIRP}{N_{elem}\eta} + N_{elem} P_{ovhd} \right)$$

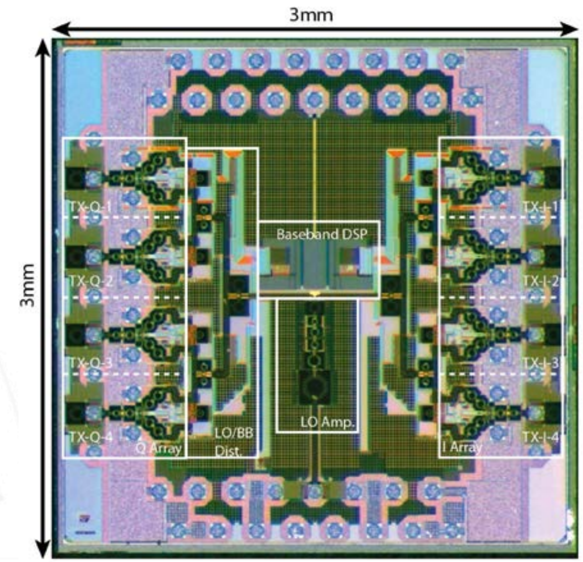
$$\boxed{P_{tot,\min} = 2\sqrt{\frac{EIRP}{\eta} P_{ovhd}}} \qquad \boxed{N_{elem,opt} = \sqrt{\frac{EIRP}{\eta P_{ovhd}}}}$$

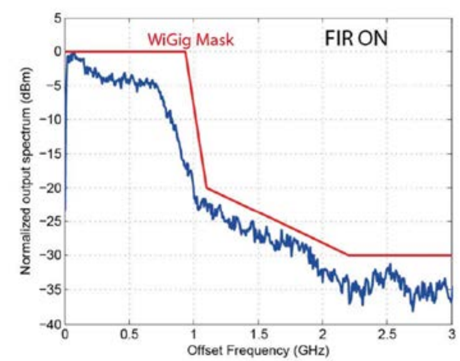
- **In an array, <u>power is cheap</u>. What is key is the <u>overhead</u> for a given power.**

# 60 GHz Spatial Modulation



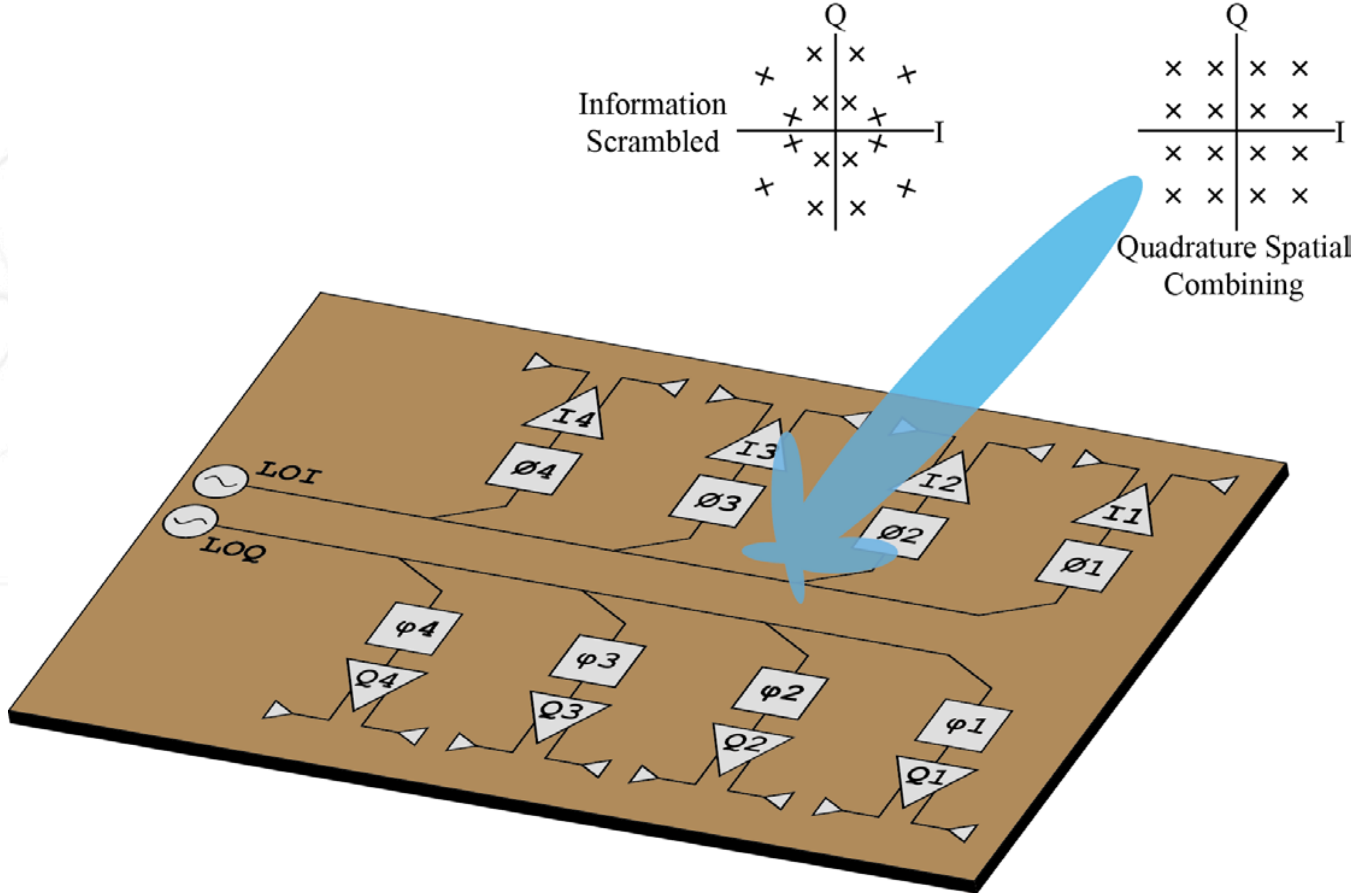



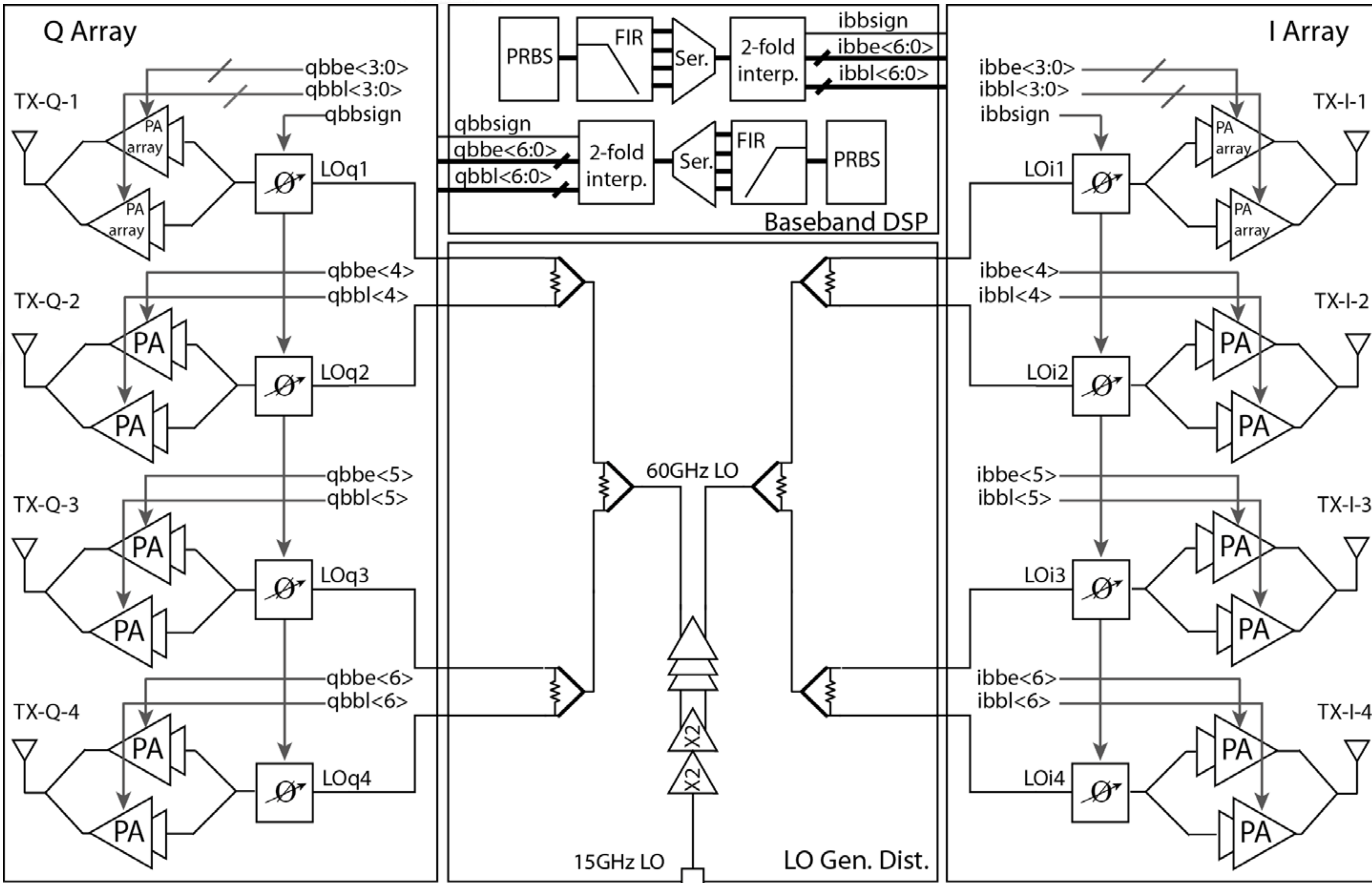

- Based on spatial I/Q combining of “digital” signal, effectively modulating the data in space
- Prototype:   65nm CMOS, 4 I and 4 Q channels, Rogers antenna array
- Peak Tx efficiency 17.4%.  Maintains > 7% efficiency while transmitting 6 Gbps (16-QAM)

# Digital Quadrature Spatial Combining

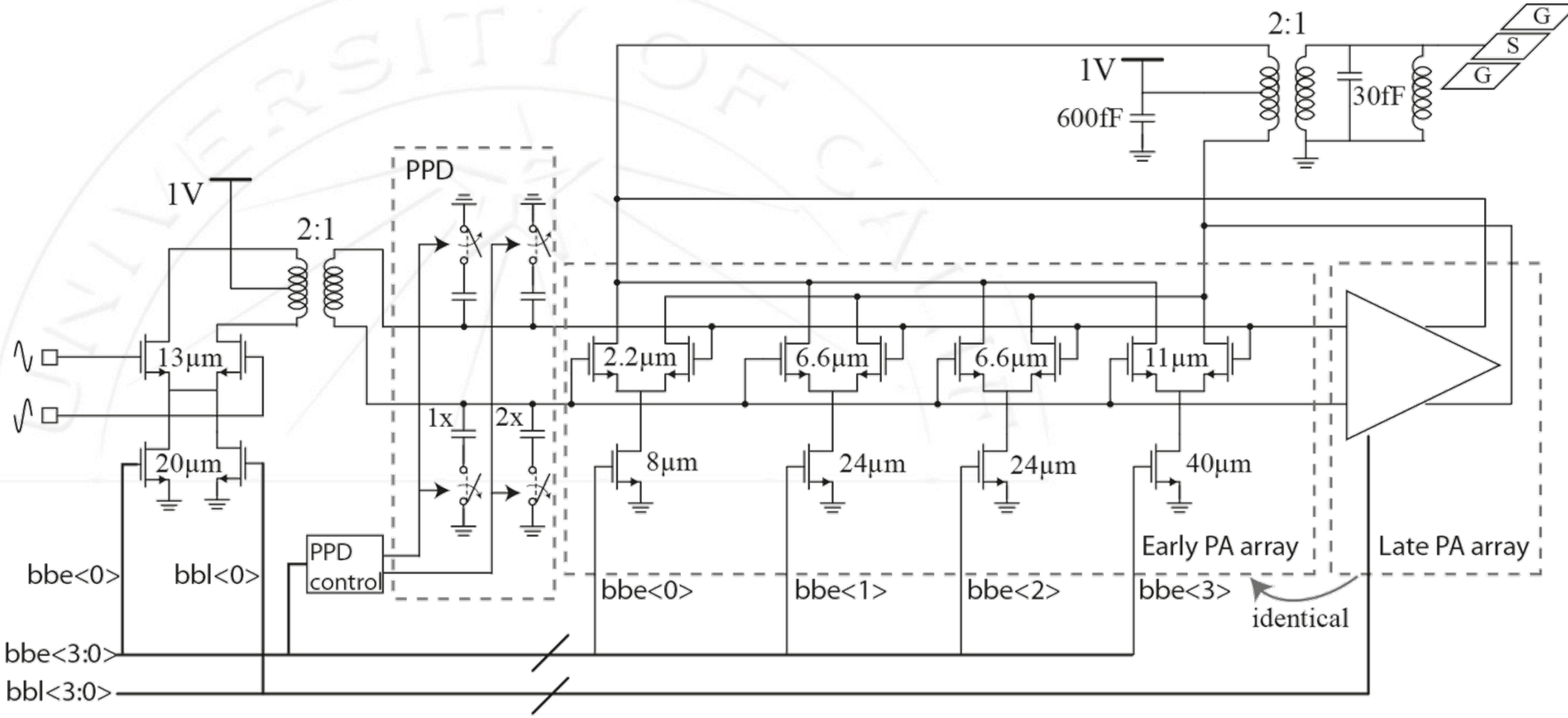



- Each antenna element can be switched on/off based on constellation.
- Digital spatial I/Q combining results in low loss signal summation and high backoff efficiency.

# 60GHz Beamforming Transmitter for WiGig

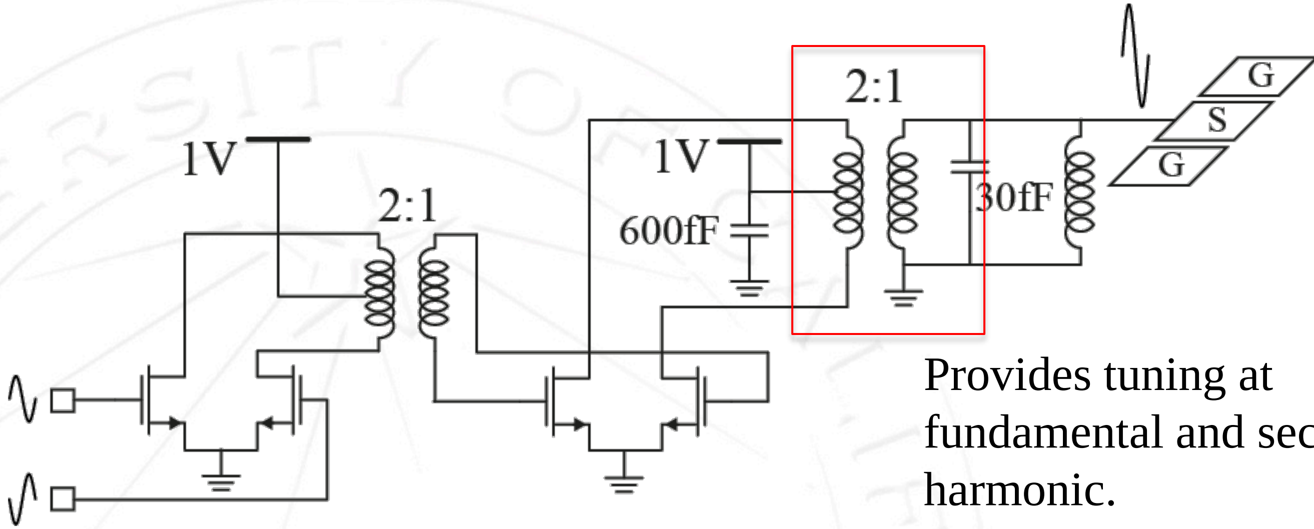


# 2-bit PA-DAC

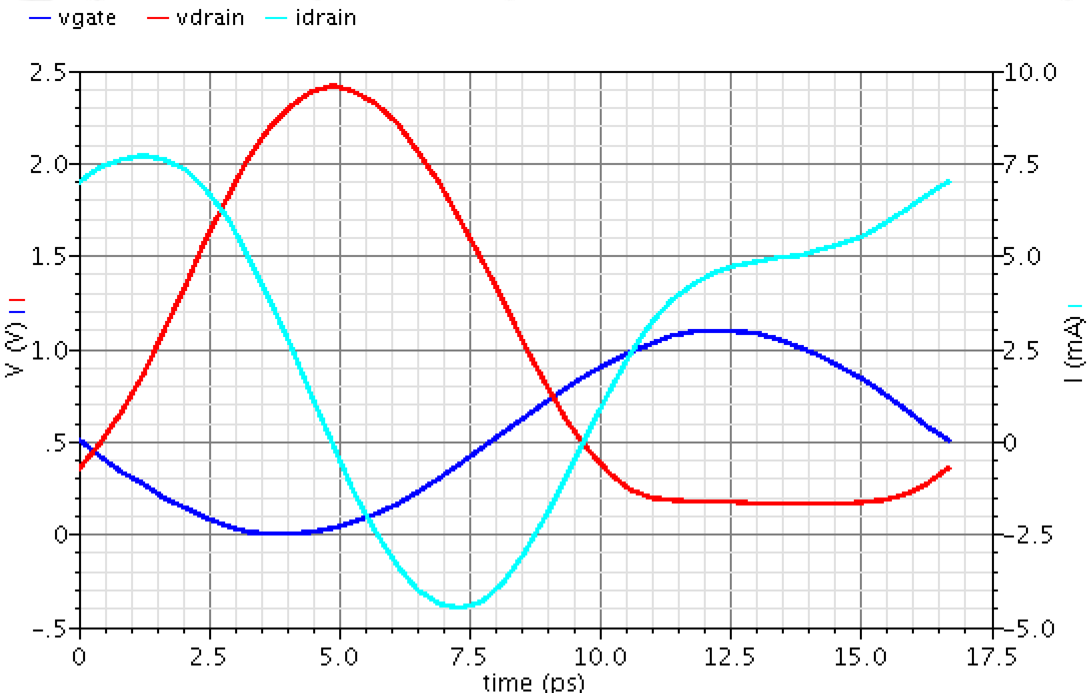



- Pout = 9.9 dBm
- Drain efficiency (output stage): 43%
- Drain efficiency (two stages): 34%

# Class E/F2 Switching PA Design




Provides tuning at fundamental and second harmonic.




Transformer loss ~ 1.2dB

@ 1.1V sine-wave input
Pout: 11dBm
Efficiency: 46%
Gain: 10dB

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# A “Good” Bad Receiver

- Unfortunately, in a receiver the improvement in SNR is only proportional to the number of elements, which comes at a power penalty, thus offering no direct benefits for power consumption.

$$SNR = \frac{M^2 E_s}{M\sigma_c^2 + M\sigma_{rx}^2} = \frac{M\frac{E_s}{\sigma_c^2}}{1 + \frac{\sigma_{rx}^2}{\sigma_c^2}}$$

Environmental noise

Rx noise

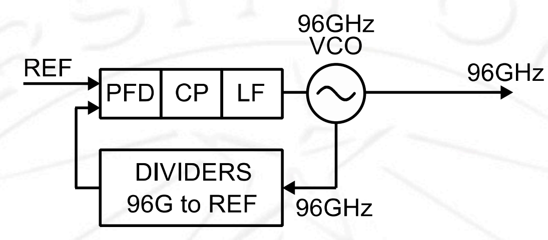
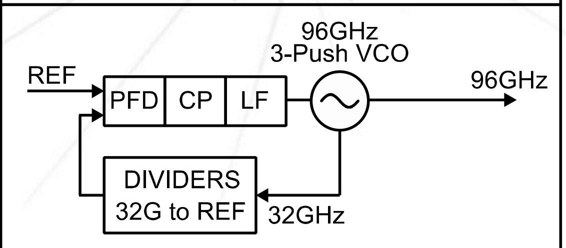
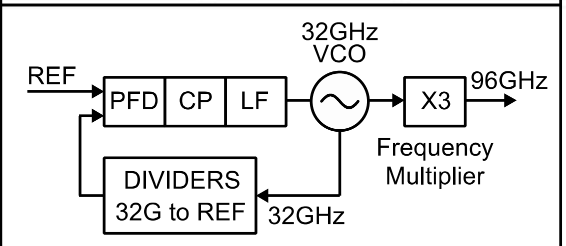
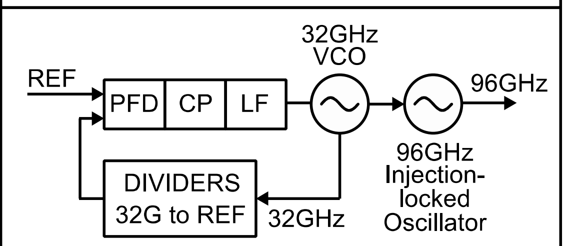
$$NF_{elem} = NF_{arr} = 1 + \frac{\sigma_{rx}^2}{\sigma_c^2}$$

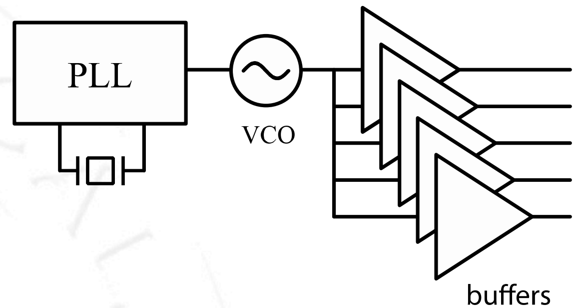
- Even though environmental noise is correlated across the array, the spatial filtering reduces the incoming noise (assuming source is isotropic)

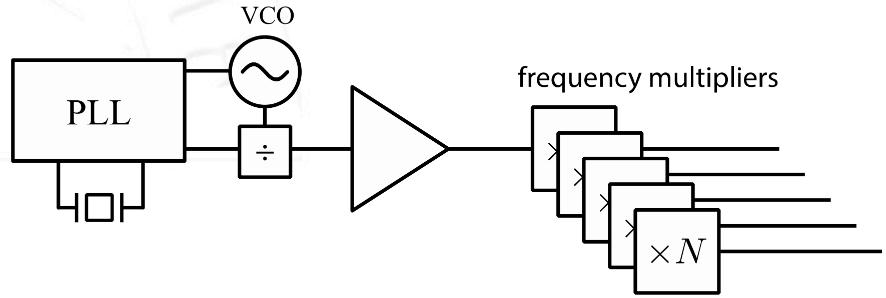
# Receiver Design

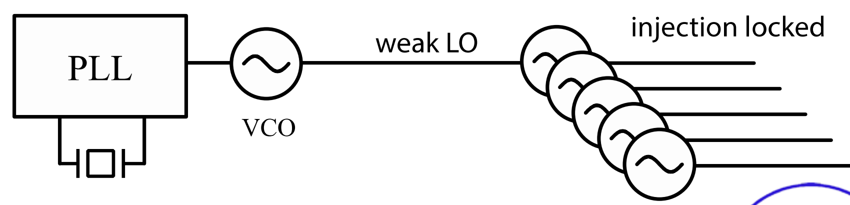
- For the RX, the main motivation is the spatial filtering / aperture gain.
- To make a large array energy efficient, must scale power consumption of each element aggressively
- Due to averaging of errors, can afford to sacrifice performance such as noise (but not linearity)

# LO Generation / Dist Options

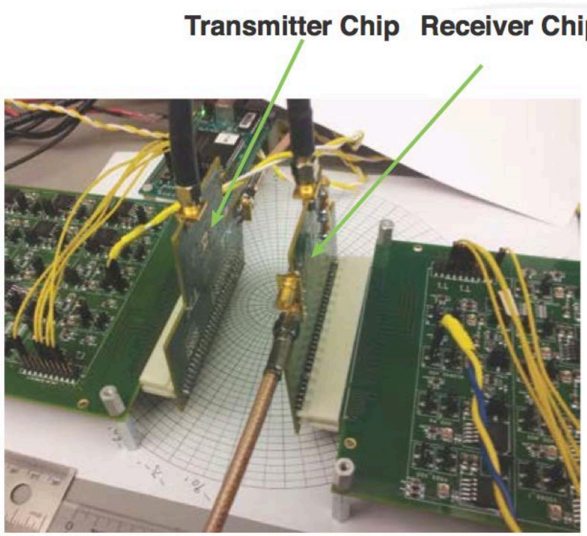
| | |
|---|---|
| (a) PLL with a Fundamental VCO |   |
| (b) PLL with an N-Push VCO |   |
| (c) PLL and a Frequency Multiplier |   |
| (d) PLL and an Injection-locked Oscillator |   |

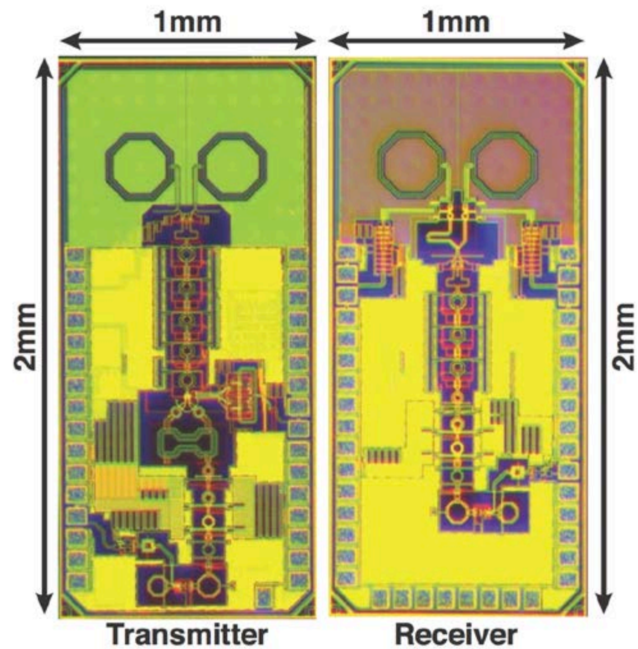


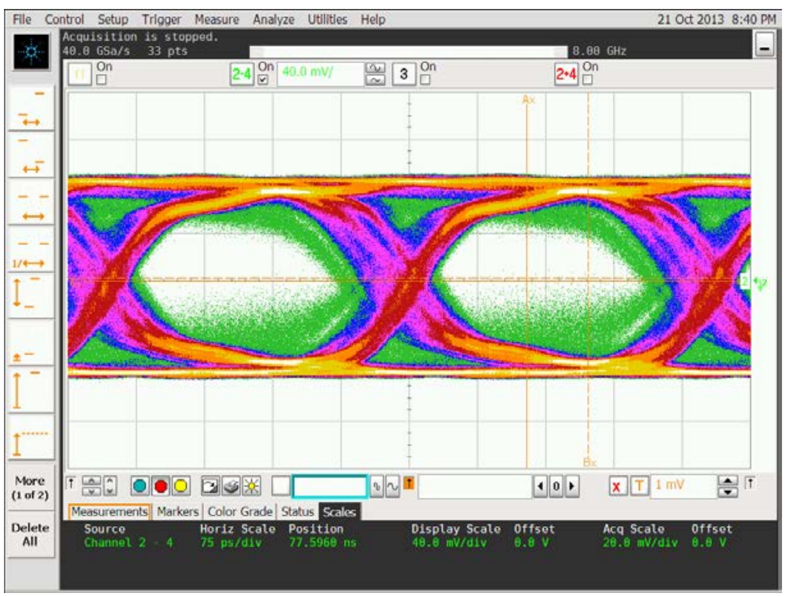



# The Small Internet




- Why pollute the spectrum for short range high data rate communication?
- 240 GHz link has 16 Gbps and energy efficiency of 30pJ/bit

[Thyagarajan, Kang, Niknejad]

BWRC

# Key Points

- Massive MIMO:
  - Beam forming
  - Beam nulling
- 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 and efficiency can be improved if we adopt new spatial modulation.

# Conclusion

- Technology: The sky is the limit. We can build low cost CMOS radios from 100 MHz to 100 GHz.
- Stop obsessing with bandwidth scarcity. Let's start taking advantage of spatial diversity (antennas!) and higher frequencies and there's enough bandwidth for all for a long time to come …
- Key mm-wave technology enabler is large arrays that can be manufactured at low cost and deployed widely

# Acknowledgements

- 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
  - UC Discovery Program:  CMOS “Digital” Transmitters
  - FCRP-C2S2 Program

- And many continuing programs!
  - NSF THz Chip-to-Chip
  - DARPA RF-FPGA


- And of course industry collaborations.
- Thanks!