Reconfigurable, Efficient, and Scalable Millimeter-Wave Systems

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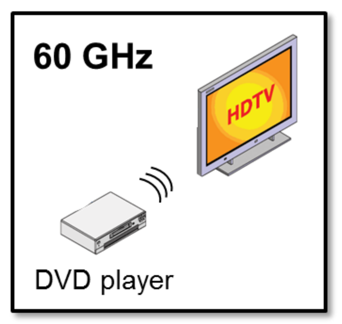
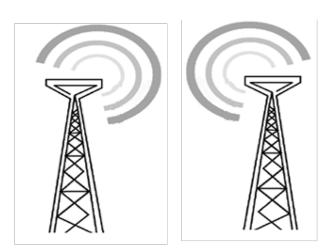
Motivation and Research Directions

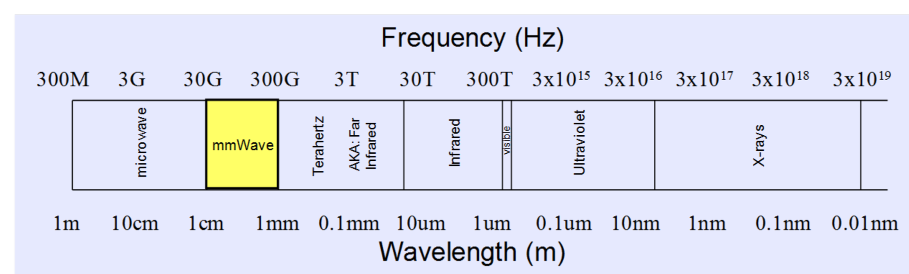
Millimeter-Wave Communications Opportunity



Cellular and WiFi communications (28GHz and 60GHz)



Point-to-point communications (60GHz, Licensed E-band 70/80GHz)



mmWave is defined as λ=10 mm to 1 mm or freq.=30-300 GHz

Higher Frequency

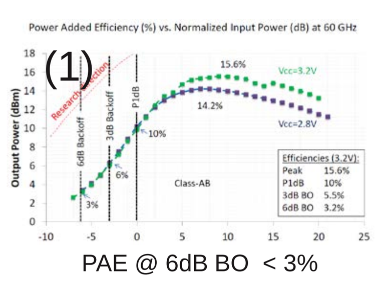
(1) More Bandwidth

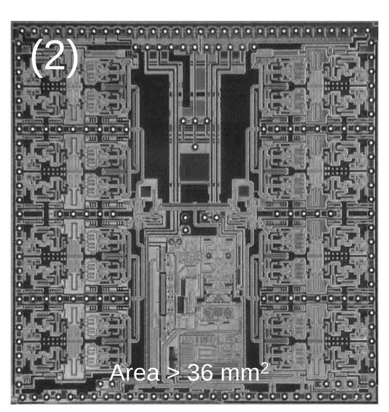
(5% @ 60 GHz = 3 GHz)
(5% @ 6 GHz = 0.3 GHz)

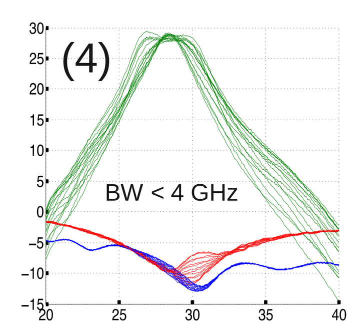
(2) Smaller Wavelength

+ Integrate antenna in package
+ Greater resolution radar/imager
- Smaller effective aperture

Challenges and Potential Solutions







(3)
2-Gbps Uncompressed HDTV Transmission over 60-GHz SiGe Radio Link

Data rate ~ Gb/s

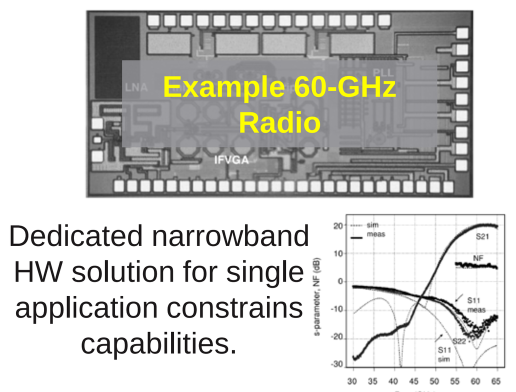
1. **Power efficiency of mm-wave transmit array is very low.**
2. **Arrays are large and expensive.**
3. **Performance delta of mm-wave radio over RF radio is too small.**
4. **Hardware solutions are specialized and not multifunctional.**

- **NCSU investigating ways to increase efficiency by >5X (or reduce area by >5X).**
- **NCSU investigating compact, wideband mm-wave arrays.**
- **NCSU investigating MIMO receiver for co-located antennas.**
- **NCSU investigating universal mm-wave transceiver for arrays.**

Towards Reconfigurable RF & Millimeter-Wave Systems

Research Need:

- mm-wave radios must offer disruptive capabilities over microwave radios.
- Need for reconfigurable, multi-antenna systems for multiple octaves → universal HW solution.

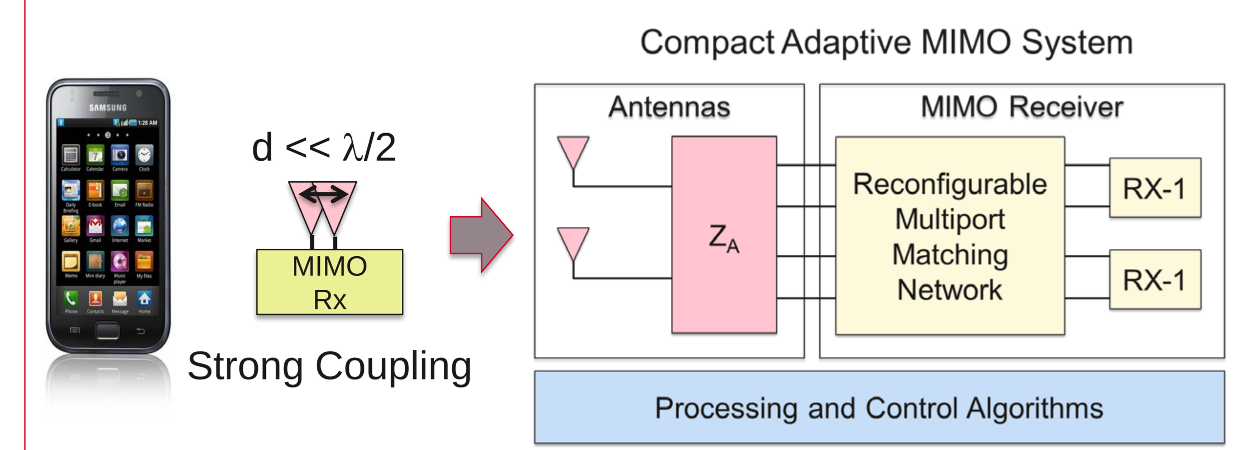


Dedicated narrowband HW solution for single application constrains capabilities.

NCSU Approach:

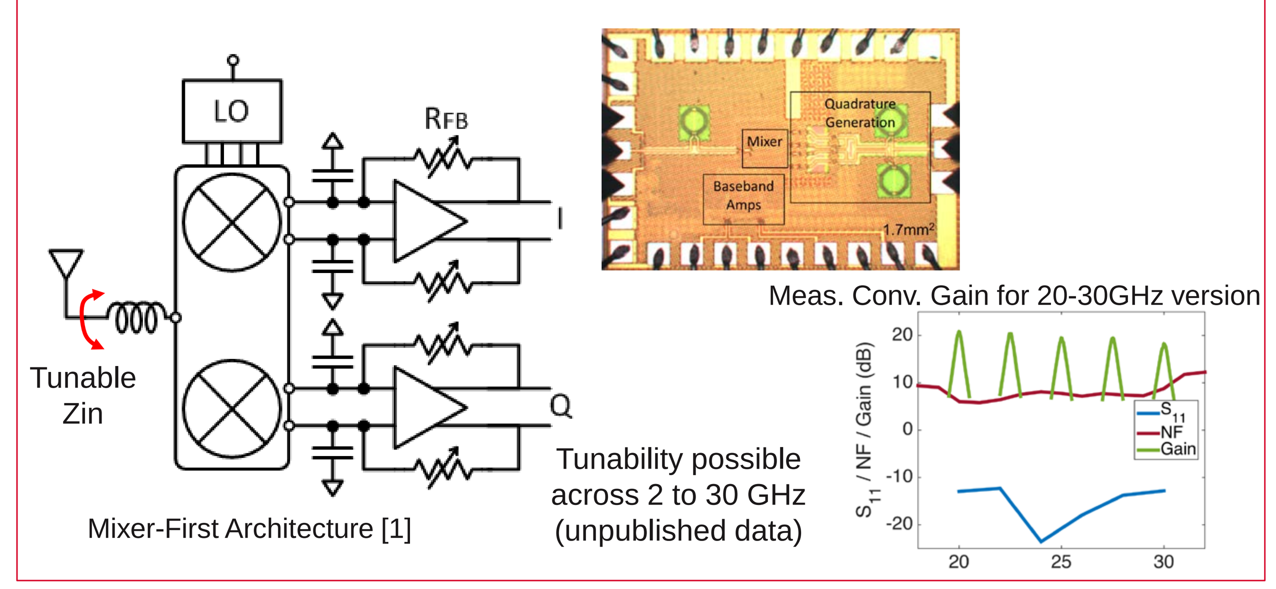
- *Mixer-first receivers for microwave through mm-wave.*
- *Embedded tunable matching, decoupling, BW.*
- *Decoupling of closely-spaced antennas → MIMO and/or extreme broadband apertures.*

Allow MIMO Capacity Benefit from Co-located Antennas



1. Exploring compact **multi-port antennas** with low intrinsic coupling.
2. Exploring **information-theoretic wideband matching / decoupling** which can approach the capacity in uncoupled MIMO systems.
3. Exploring **adaptive receivers** to realize widely tunable broadband matching and decoupling functions with low noise and high linearity.

"Universal" Receiver for RF & mm-wave (2-30GHz)



Conclusions and Future Directions

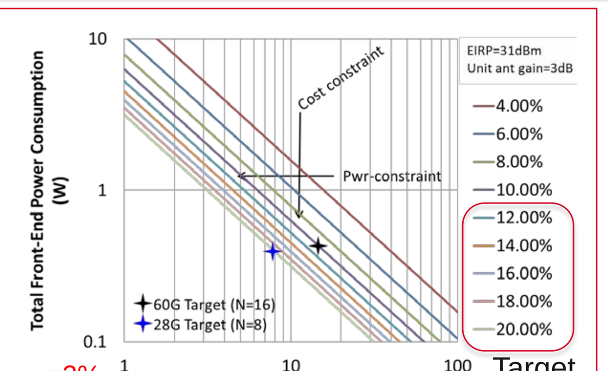
- *mm-wave radios must provide unique capabilities over microwave radios to displace entrenched soln.*
- Disruptive capabilities may include: massive MIMO, MIMO for co-located systems, widely tunable/extreme broadband radios.
- Mixer-first architectures in CMOS provide excellent platform for realizing disruptive capabilities.
- *Future direction: massive mm-wave MIMO (M4)*

[1] C. Wilson and B. A. Floyd, "A 20-30 GHz mixer-first receiver in 45-nm SOI CMOS," *IEEE RFIC Symp.* May 2016.

Towards Efficient Millimeter-Wave Systems

Research Need:

- Trade-off exists between array size and efficiency.
- 5X back-off efficiency improvement targeted to allow 5X reduction in size.

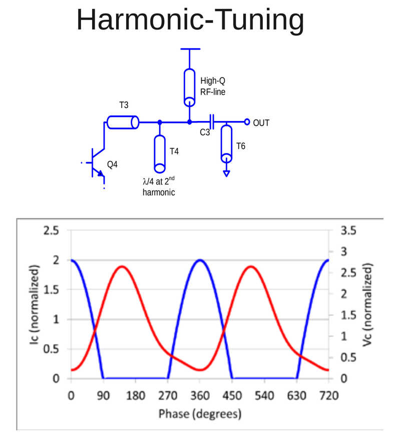


$$P_{DC} = \frac{EIRP/G_{el}}{\eta_{PE} N} + P_{overhead}$$

NCSU Approach:

- *Efficient single-unit PAs*: harmonic-termination [2].
- *Efficient multi-unit PAs*: Doherty & power-combined
- *Efficient transmitter architectures*: → Dual-Vector Doherty beamformer.

Efficient Unit and Multi-Unit PAs

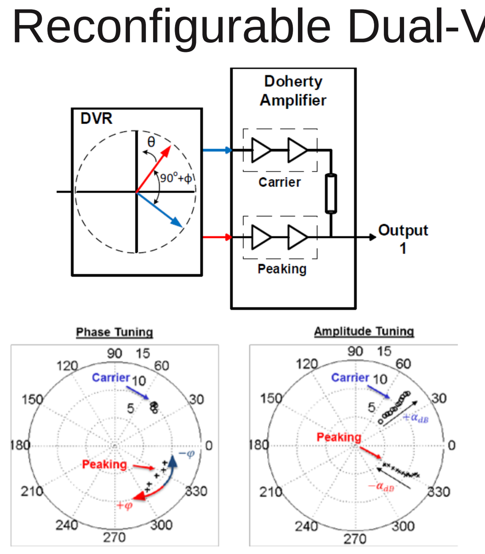


60-GHz PAs	Gen-1 (class AB)	Gen-2 (cont. mode)
Freq	60 GHz	60 GHz
Gain (dB)	29.6	19.5
oP_{1dB} (dBm)	+9.0	+13.3
P_{sat} (dBm)	+12.4	+15.4
Peak PAE(%)	15.6% ➡	25%
6-dB BO PAE	3.2% ➡	9.0%

Note: Larger improvements possible at 28 GHz.

- Evolution from traditional Class-AB to harmonic-tuned PA to Doherty PA **at 60 GHz**.
- Results in improved back-off effic. from 3% to 9.0%.

Reconfigurable Dual-Vector Doherty Beamformer (DVDB)



- Allows independent control of carrier and peaking amp.
- Embedded phase shifting for phased arrays.
- Can be configured in high-effic., reduced linearity mode or high-linearity, reduced efficiency mode.
  - Useful for range of modulations.
  - 60GHz results [3] show increased PAE_{6dB} from 4.2% to 7% (beamformer).

Conclusions and Future Directions

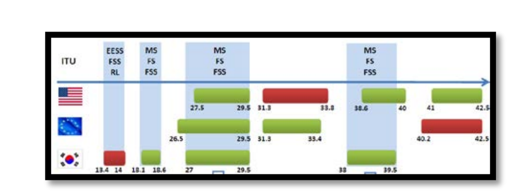
- *Increased back-off efficiency in beamformer is key to enabling lower cost, compact transmitters.*
  - → Transmitter architecture must support high BW at high linearity (challenge for polar architectures).
  - → Support of multiple modulation schemes suggests reconfigurable architecture desirable (DVDB, *left*).
- *Future: New (heterogeneous) approaches required which bridge devices, circuits, & signal processing.*

[2] A. Sarkar and B. Floyd "A 28-GHz harmonic-tuned power amplifier in 130-nm SiGe BiCMOS," accepted for publication, *IEEE Trans. Microwave Theory and Tech.*
[3] K. Greene, A. Sarkar, and B. Floyd, "A reconfigurable 60-GHz dual-vector Doherty beamformer," in revision, *IEEE J. Solid-State Circuits*, 2016.

Towards Scalable Millimeter-Wave Systems

Research Need:

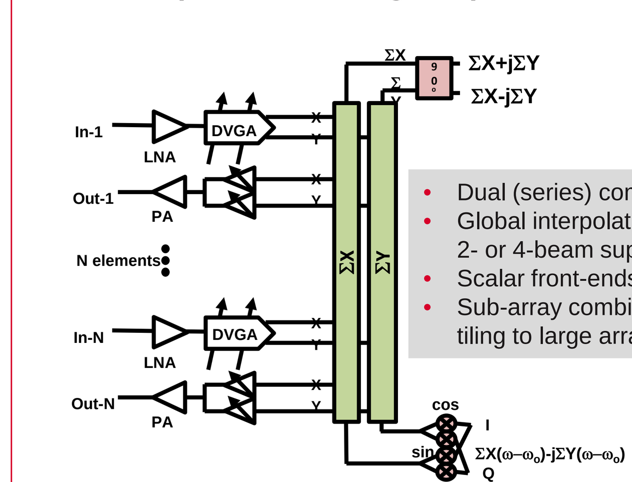
- Scalable architectures: "plug-and-play" for arrays.
- Multi-band/wideband solutions which can configure itself to take advantage of full mm-wave spectrum.

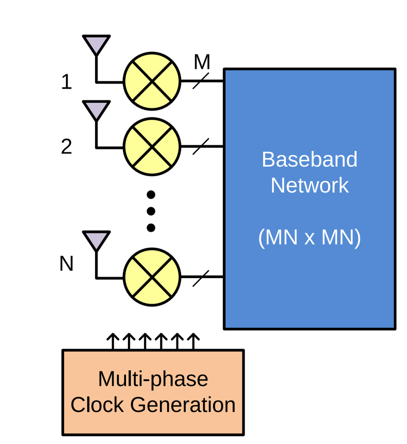


NCSU Approaches:

- Distributed Beamforming Architecture which eliminates BW limiting components and has extremely compact form-factor, supporting tiling.
- Mixer-first phased arrays (see above).

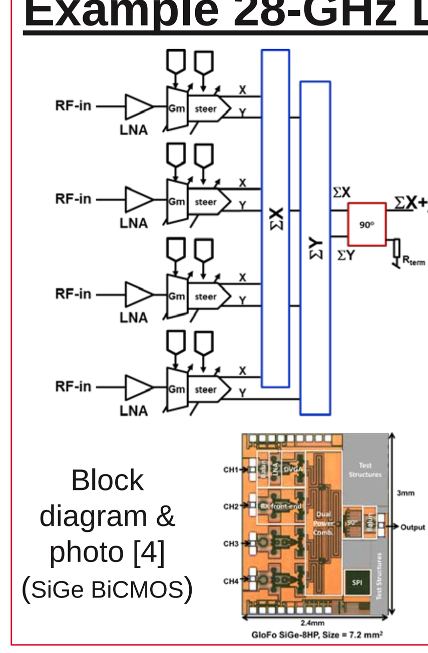
Hybrid Beamforming (RF+IF+digital) vs. Mixer-First Arrays





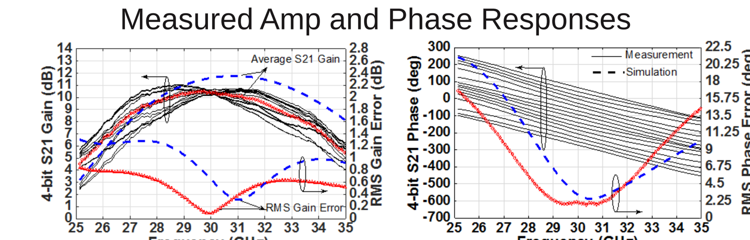
See "universal" Rx above

Example 28-GHz Dual-Vector Distributed Beamformer



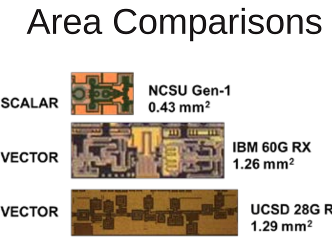
Block diagram & photo [4] (SiGe BiCMOS)

Measured Amp and Phase Responses



Performance of One-element RX Front-end	
Freq. band (GHz)	28-32
NF (dB)	5.1-8.5
In-band iIP3 (dBm)	-10.4 to -6.8
iP_{1dB} (dBm)	-16.4 to -12.9
DC Power (mW)	136.5
Front-end Area (mm²)	0.45
Performance of 4-element RX phased array	
Phase mis./iso. error (°)	<4.2
Gain mis./iso. error (dB)	<0.6

Area Comparisons



Conclusions and Future Directions

- *Multi-band, multi-beam phased-array solutions enable radio to take advantage of wide spectrum.*
- Hybrid beamforming (RF, IF, and digital) architectures, (combining aspects of RF, IF, and digital beamforming), may provide new capabilities and/or reducing bandwidth and size constraints.
- *Future: Mixer-first architectures which support beamforming and MIMO up through 40 GHz.*

[4] Y.-S. Yeh, B. Walker, E. Balboni, and B. A. Floyd, "A 28-GHz 4-channel dual-vector receiver phased array in SiGe BiCMOS technology," *IEEE RFIC Symp. Dig. Tech. Papers*, May 2016, pp. 352-355.