The Untethering of Information: Wideband High Throughput Wireless Communication in the mm-Wave Bands

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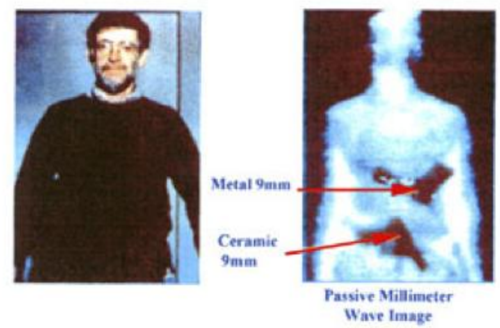
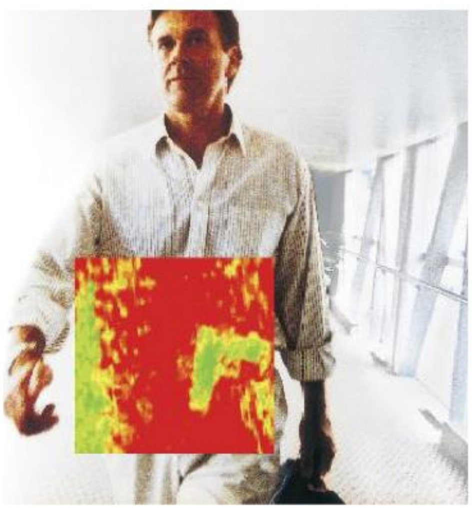
From the "Last Mile" to the "Last Inch"

Radar and Imaging

Passive "Camera" contains many receivers

QinetiQ Passive Array





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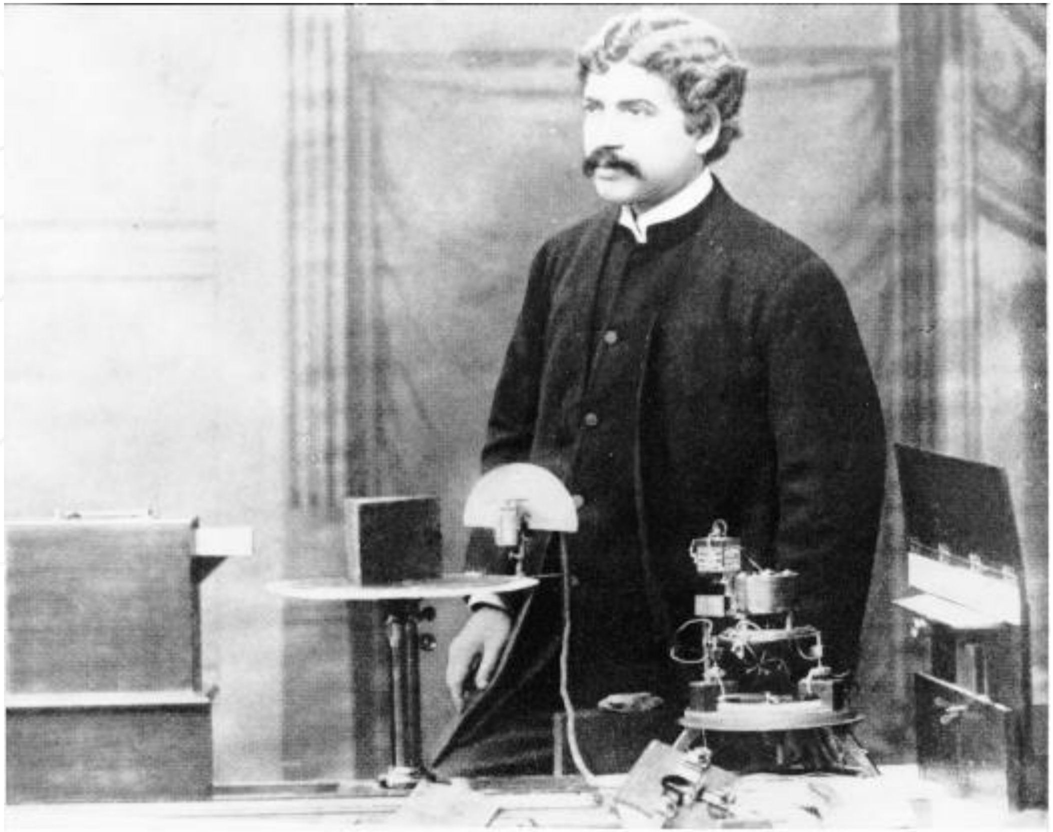
Outline

- Properties of mm-Waves
- Challenges
- Demonstrations
- What can we do tomorrow?

The Big Kahuna: Jagadis Chandra Bose



- "Just one hundred years ago, J.C. Bose described to the Royal Institution in London his research carried out in Calcutta at millimeter wavelengths. He used waveguides, horn antennas, dielectric lenses, various polarizers and even semiconductors at frequencies as high as 60 GHz…" (http://www.tuc.nrao.edu/~demerson/bose/bose.html)

mm-Wave Propagation

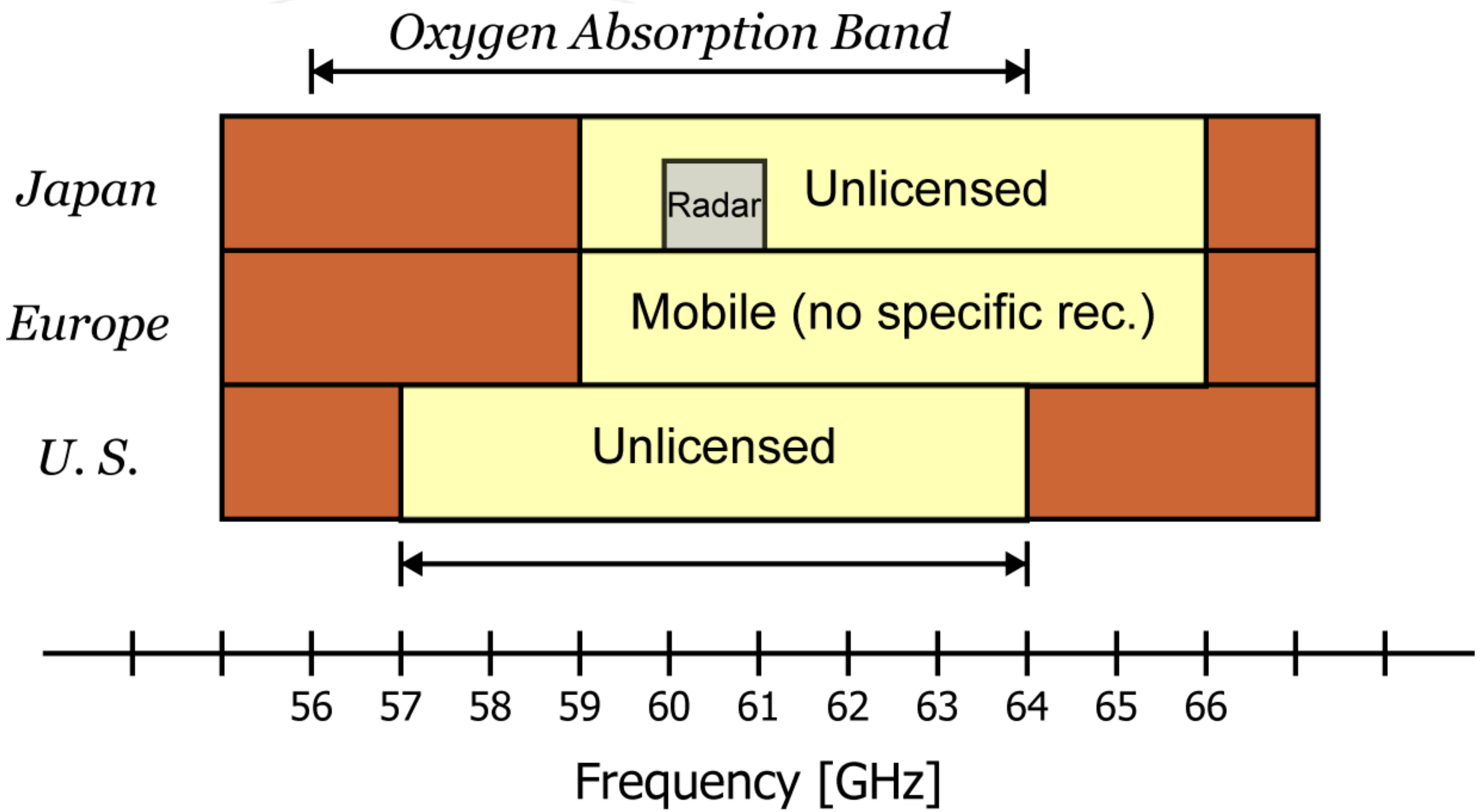
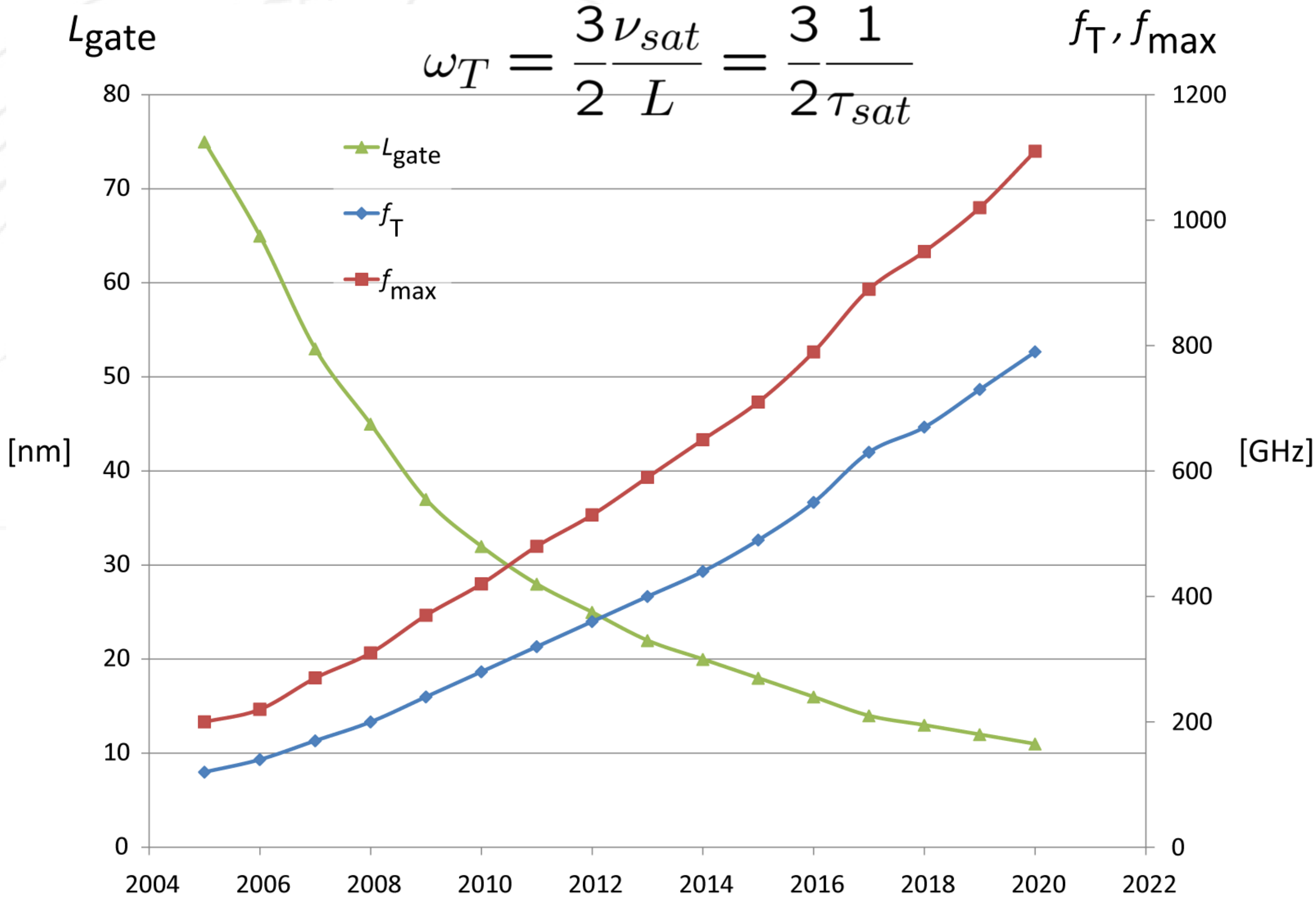


Fig. 1.9 The propagation attenuation characteristics [dB/km] versus frequency (wavelength) for earth's atmosphere under various conditions [7] (© IEEE 2003).

CMOS ITRS Scaling

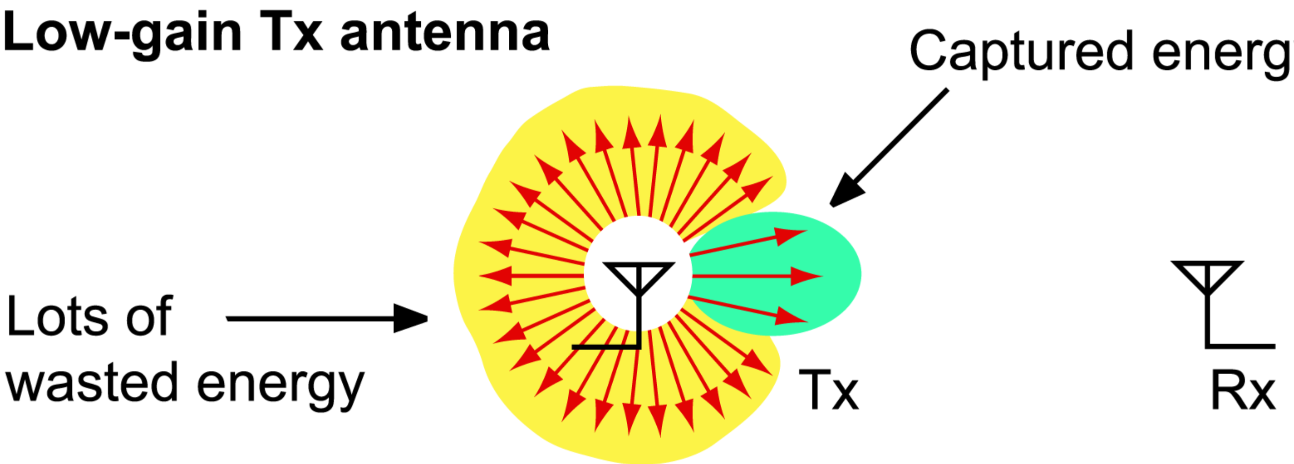
$$\omega_T = \frac{3}{2}\frac{\nu_{sat}}{L} = \frac{3}{2}\frac{1}{\tau_{sat}}$$



- Moore's Law: CMOS transistors have reached f_T ~ 200 GHz and f_{max} ~ $2f_T$ demonstrated

Challenges

Propagation Loss



$$\frac{P_r}{P_t} = \lambda^2 \frac{G_r G_t}{(4\pi r)^2}$$

$$G = \frac{4\pi A}{\lambda^2}$$

- Received signal is below detection threshold. Need gain at mm-wave frequencies. Must be careful to not add too much noise to signal.
- Carrier frequency is too high for detection, need to down-convert signal ("mix") with a local oscillator (need to synthesize a low phase noise reference.
- The propagation loss can be made up with a large aperture or an antenna array…

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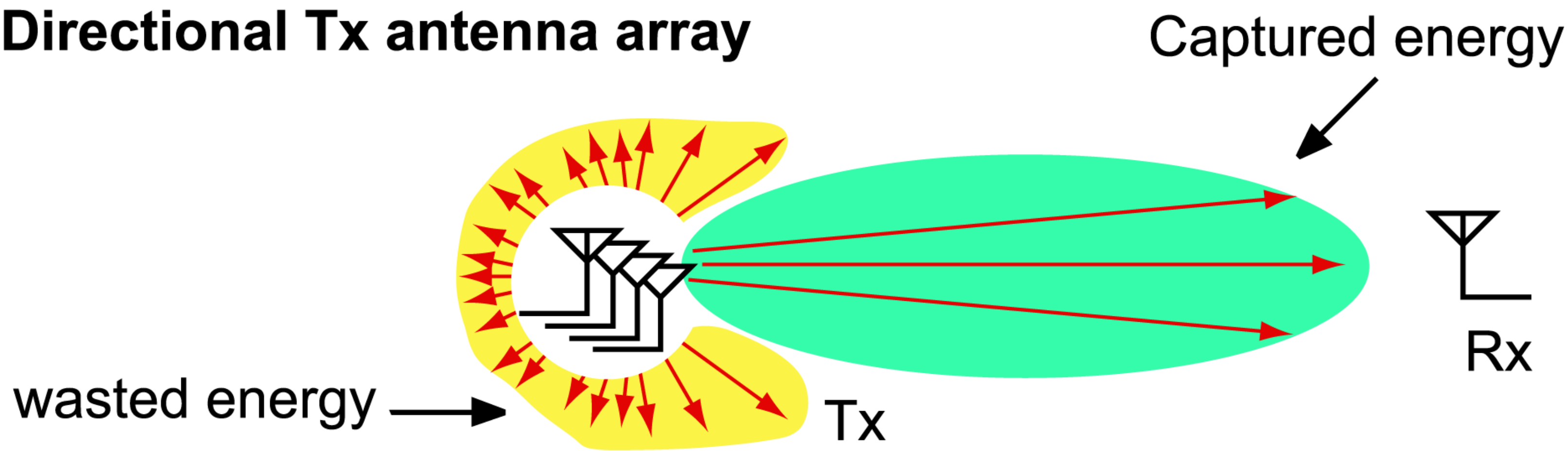
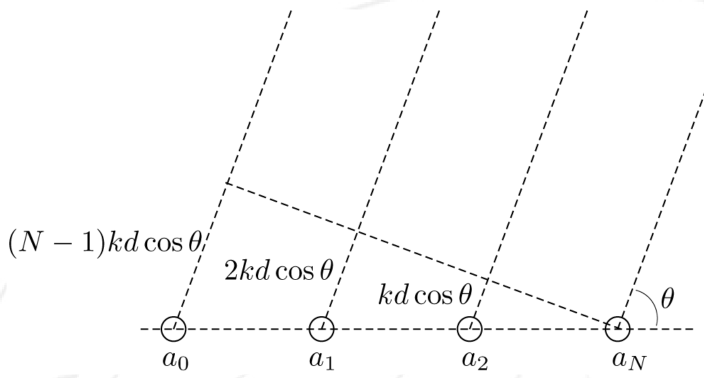
Antenna Array

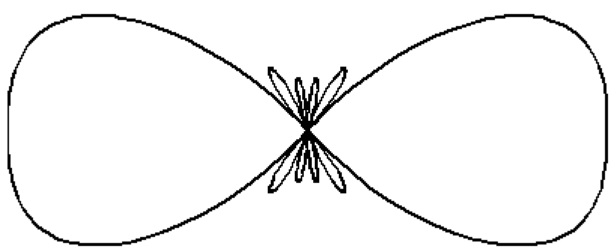


$$\frac{P_r}{P_t} = \frac{1}{\lambda^2} \frac{A_r A_t}{r^2}$$

- For a fixed aperture, going to higher frequencies offers higher gain.
- Parabolic dishes provide high aperture but the pencil beam is static and requires precision alignment.

Advantages of Phased Arrays

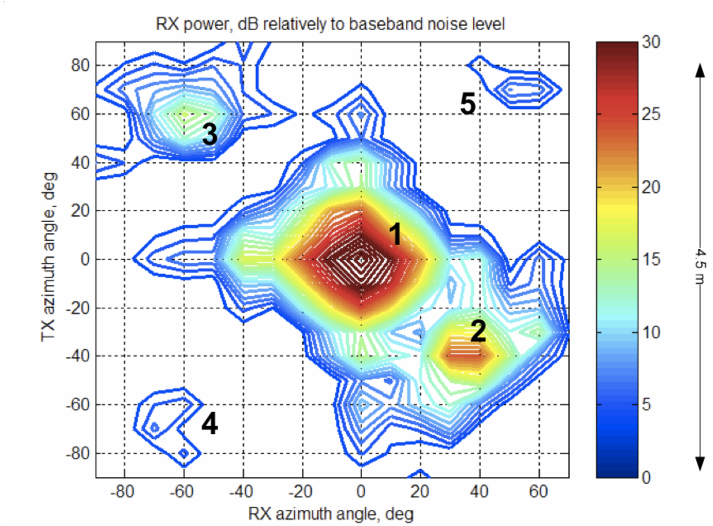


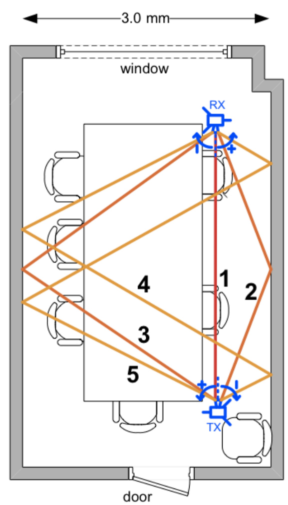


- Antenna array is dynamic and can point in any direction to maximized the received signal
- Enhanced receiver/transmitter antenna gain (reduced PA power, LNA gain)
- Improved diversity
- Reduced multi-path fading
- Null interfering signals
- Capacity enhancement through spatial coding
- Spatial power combining means
  - Less power per PA
  - Simpler PA architecture
  - Automatic power control

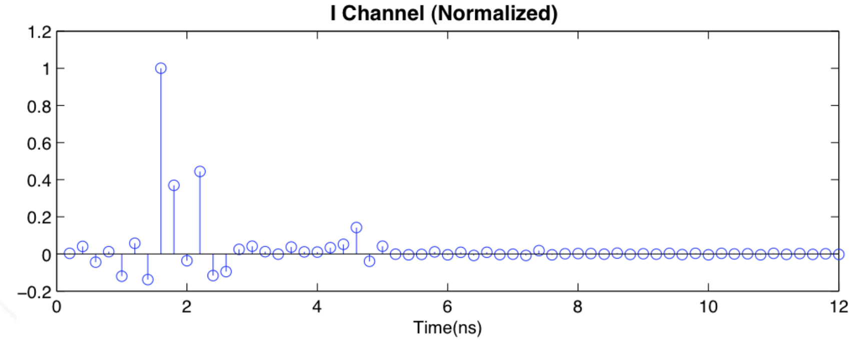
$$f(\theta) = a_0 e^{j(N-1)\overbrace{kd\cos\theta}^{\Psi}} + a_1 e^{j(N-2)\Psi} + \cdots + a_N$$

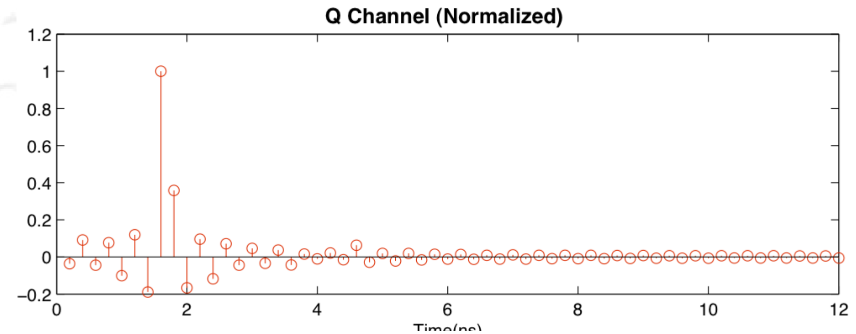
60 GHz Channel

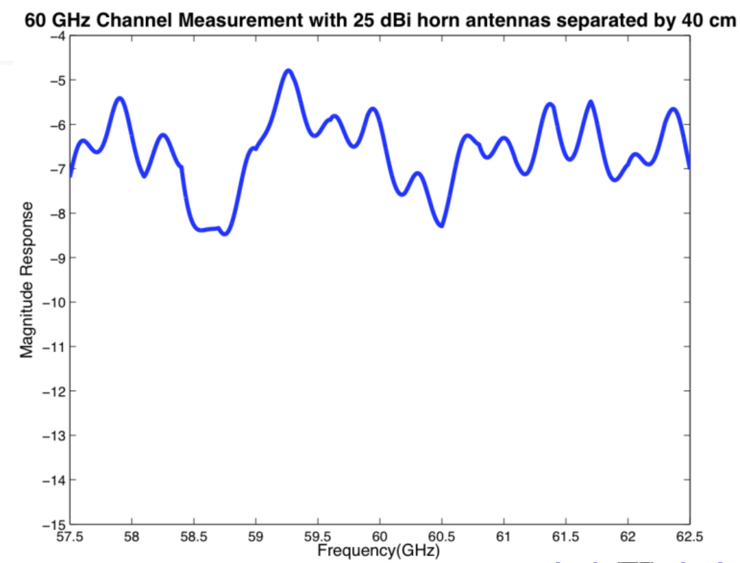




[Intel, Maltsev]







- 60 GHz channel is very specular (as opposed to diffuse which occurs at lower frequencies)
- Spatial filtering very effective at reducing delay spread (multi-path propagation)

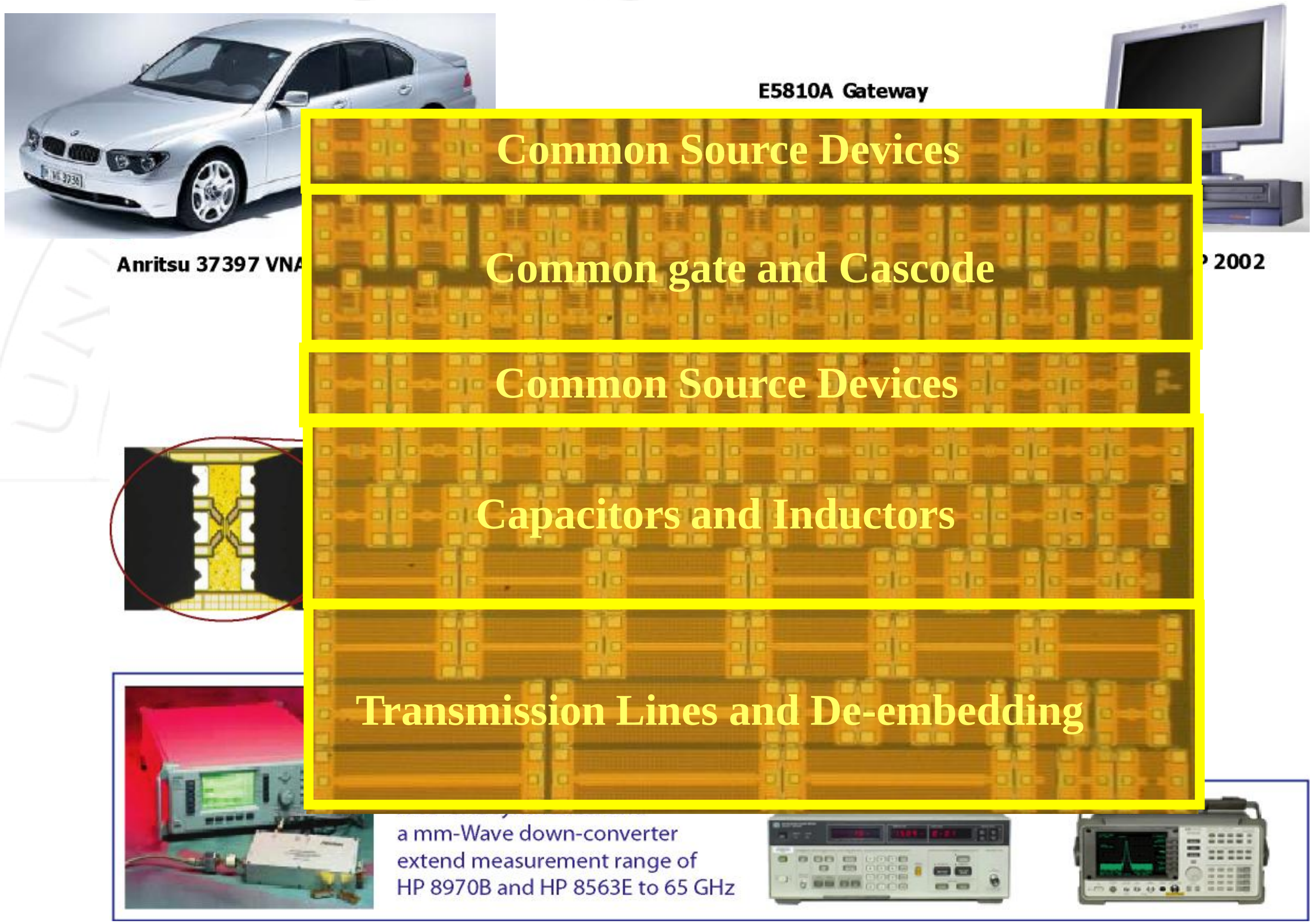
The Thorny Side of CMOS

- Low voltage breakdown and low power handling capability
  - P > 20 dBm difficult, low efficiency (< 20%)
- Lower gain (operation at ½ f_{max} in 90nm)
- Higher noise (operation close to f_T)
- Higher losses in passive elements
  - 1dB/mm T-lines, Q~20 inductors
- Typical mm-wave system cost dominated by packaging /testing

The Rosy for CMOS

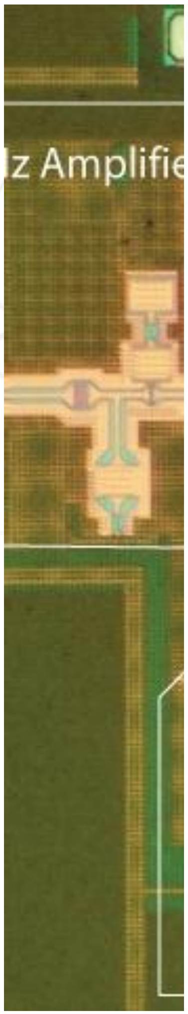
- **Scaling** provides higher gain or lower power
- CMOS is inexpensive and shrinking → higher speeds possible in 65nm, 45nm, and beyond
- Require total **system integration** for low cost testing; CMOS is the only viable low cost VLSI technology
- Inexpensive packages demonstrated for 60 GHz … consumer applications can tolerate performance loss
- Achievable NF (~6dB) and Power (17dBm) commensurate with link budget for short range link
- Fully integrated phased arrays can provide higher gain for long range links

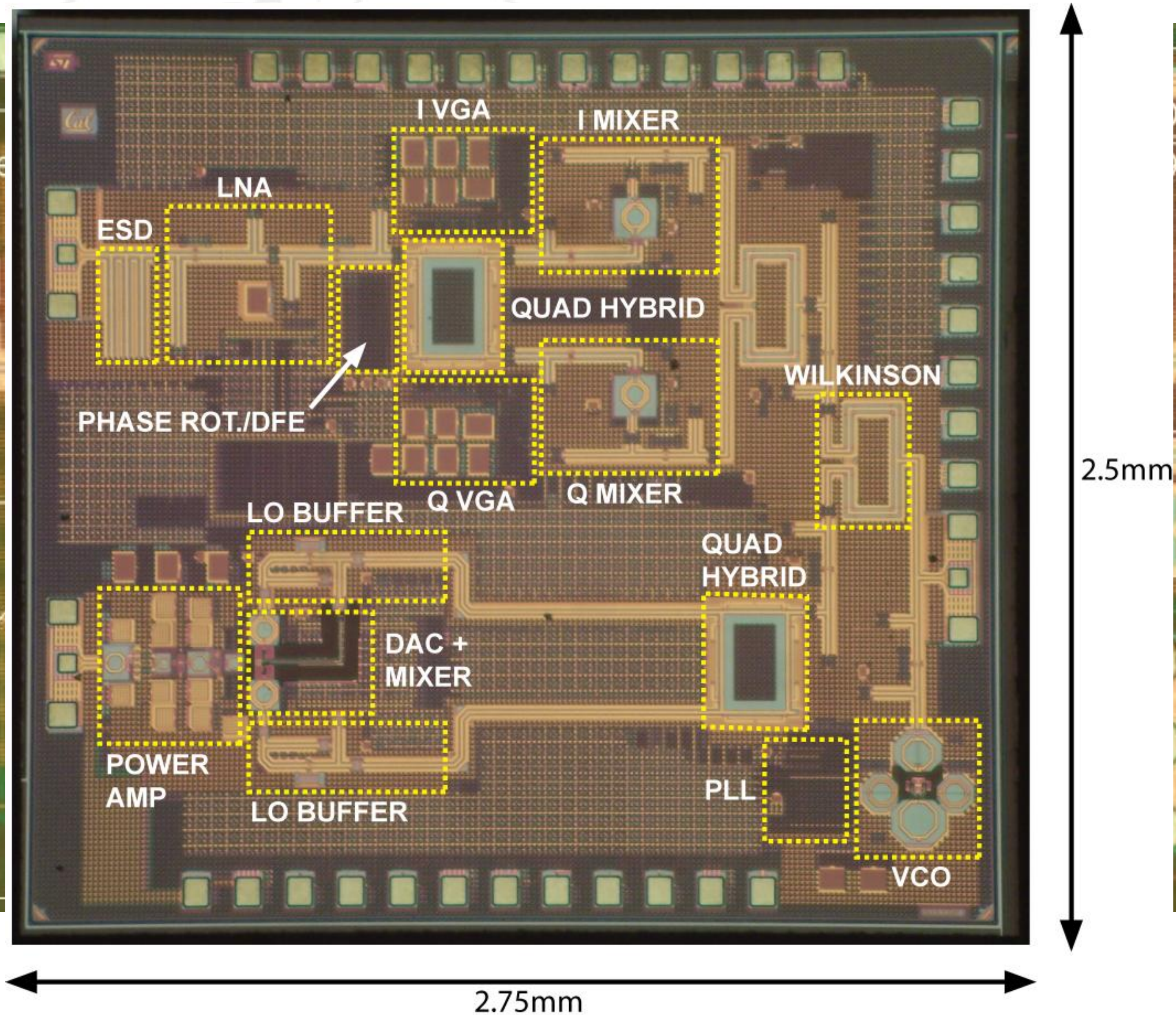
BWRC Measurement Setup



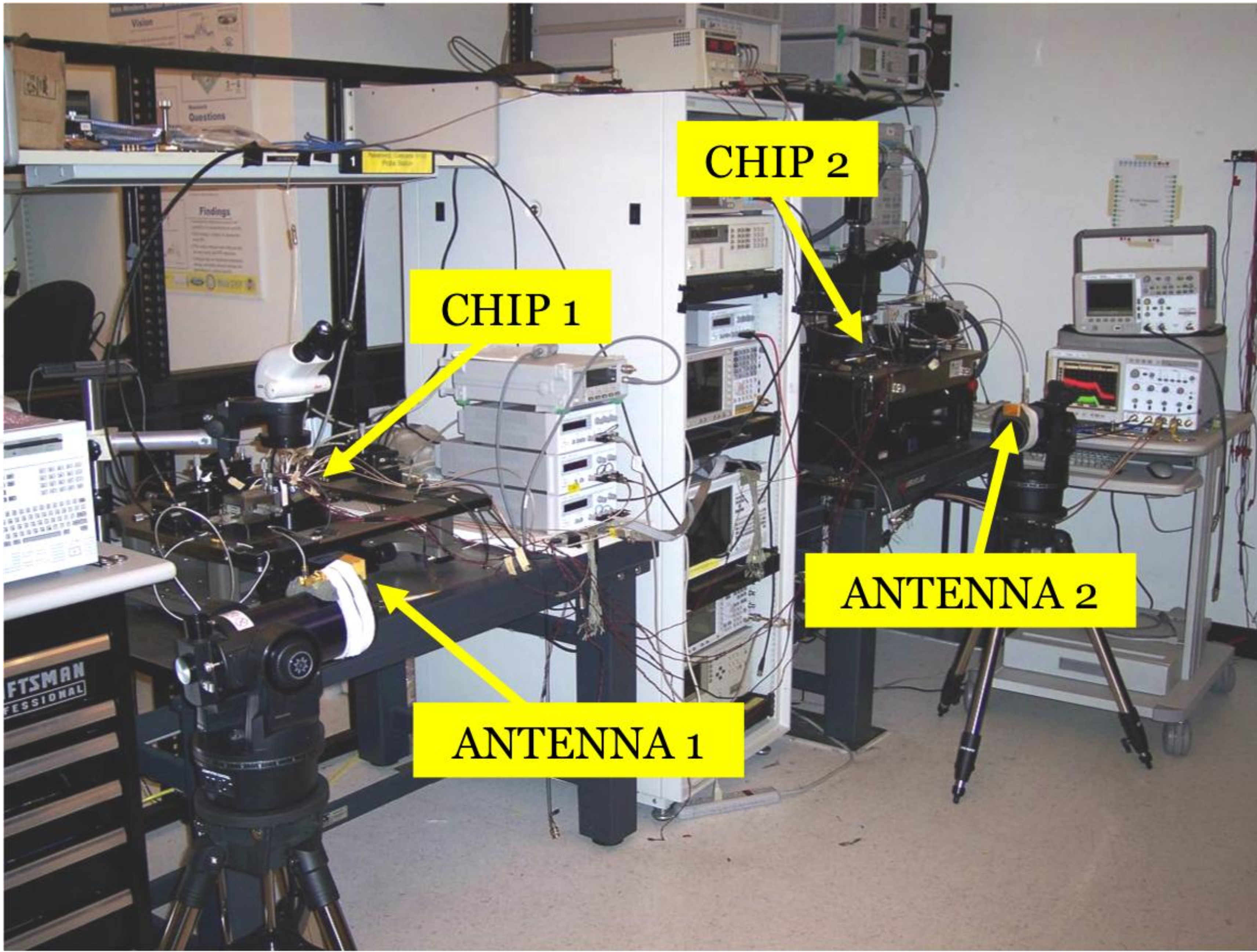
What can be done today?

Berkeley's 60 GHz Chips

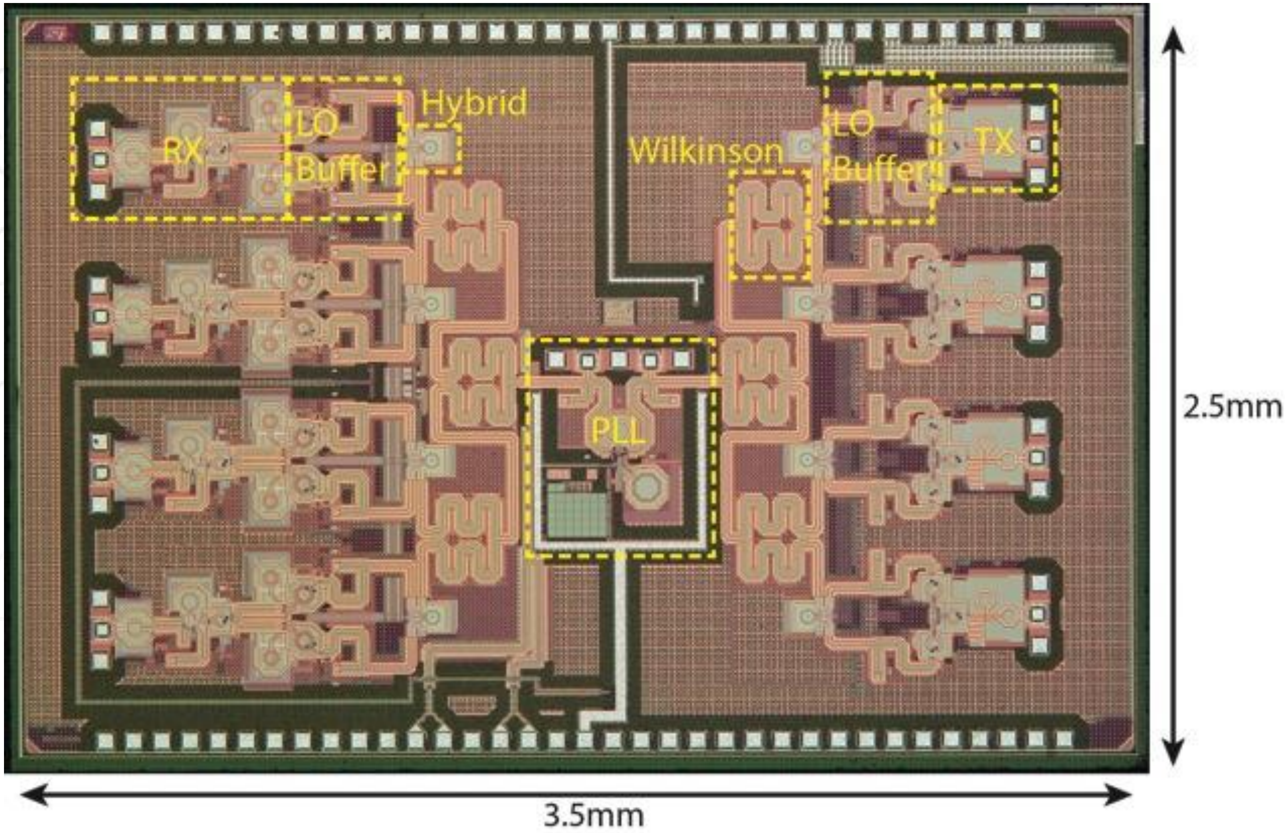




Data Transmission

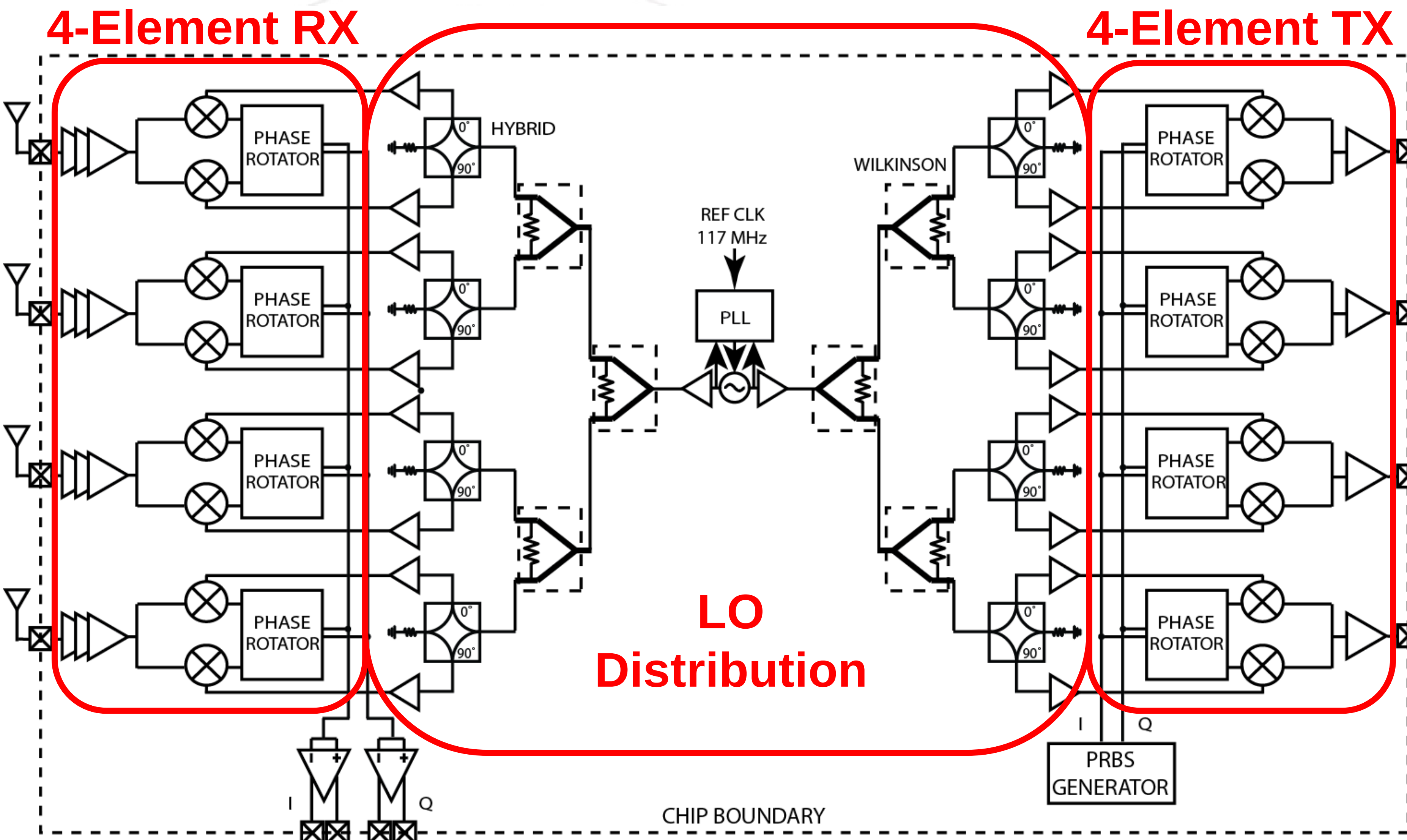


“Medium” Range 60 GHz Phased-Array



- A complete phased-array transceiver including RX, TX, and PLL/LO distribution
- Flexible IF combining architecture can be extend to many channels (prototype 4-channels)

4-Element IF Phased Array Transceiver



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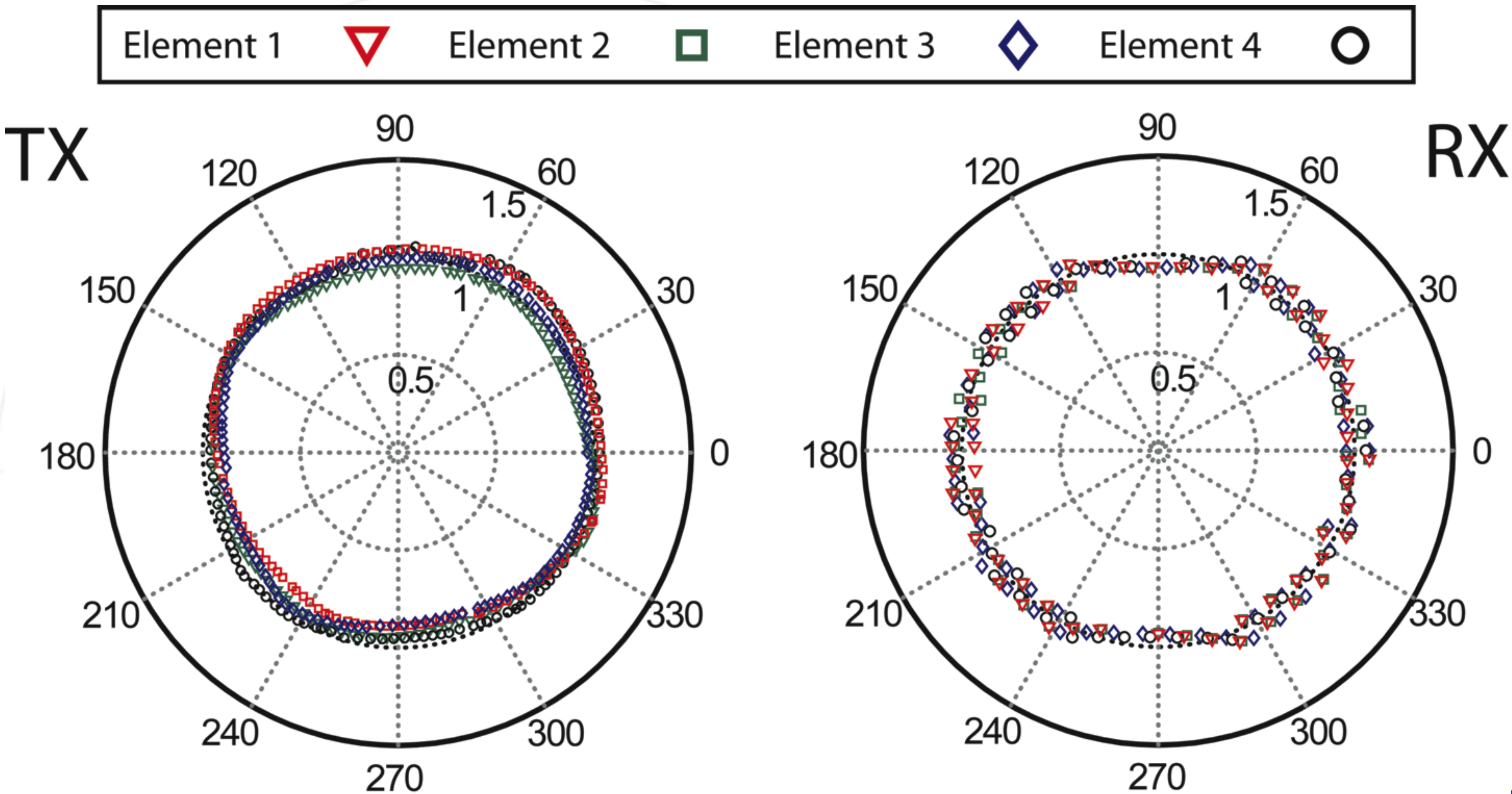
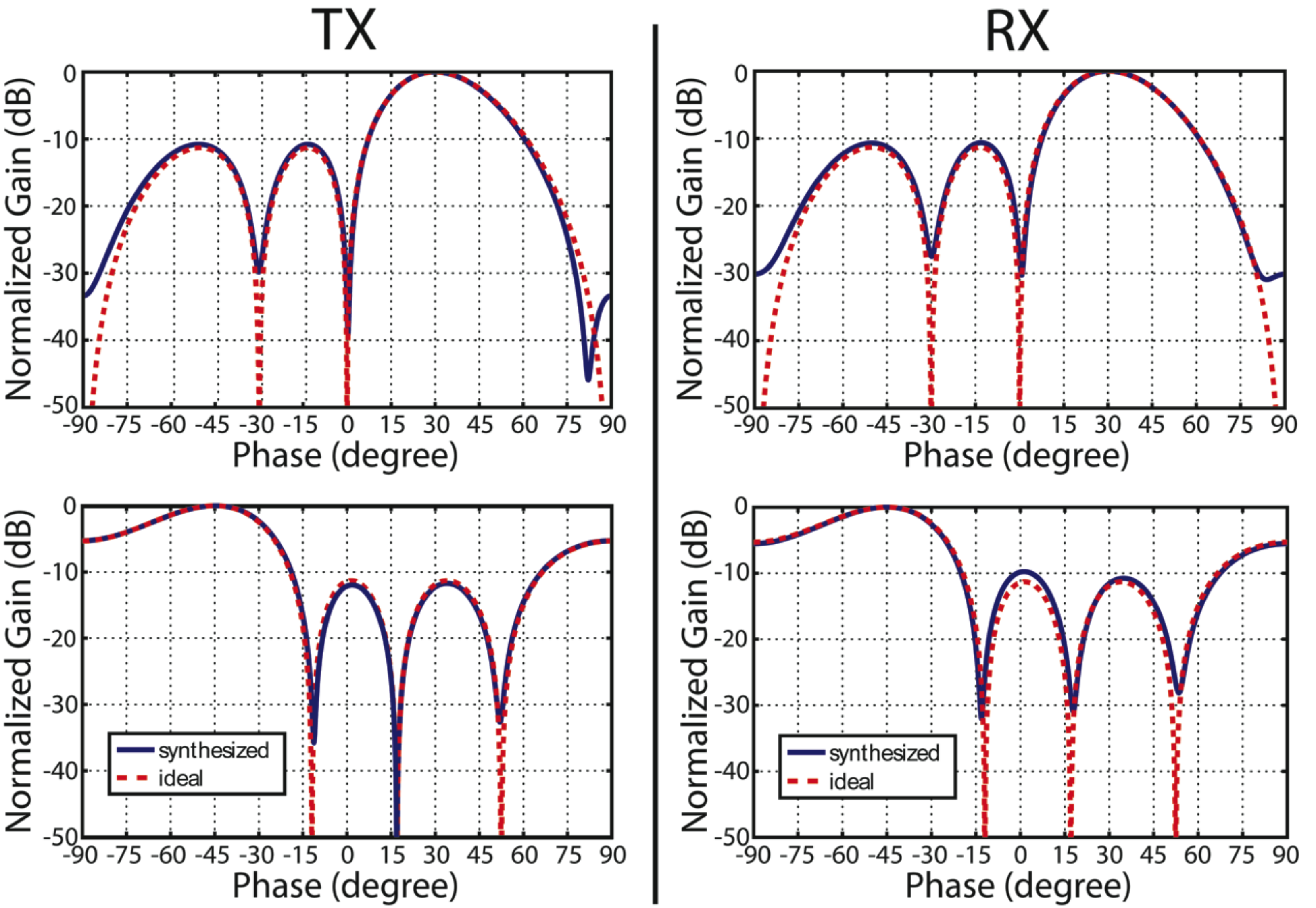
Measured TX/RX Constellation



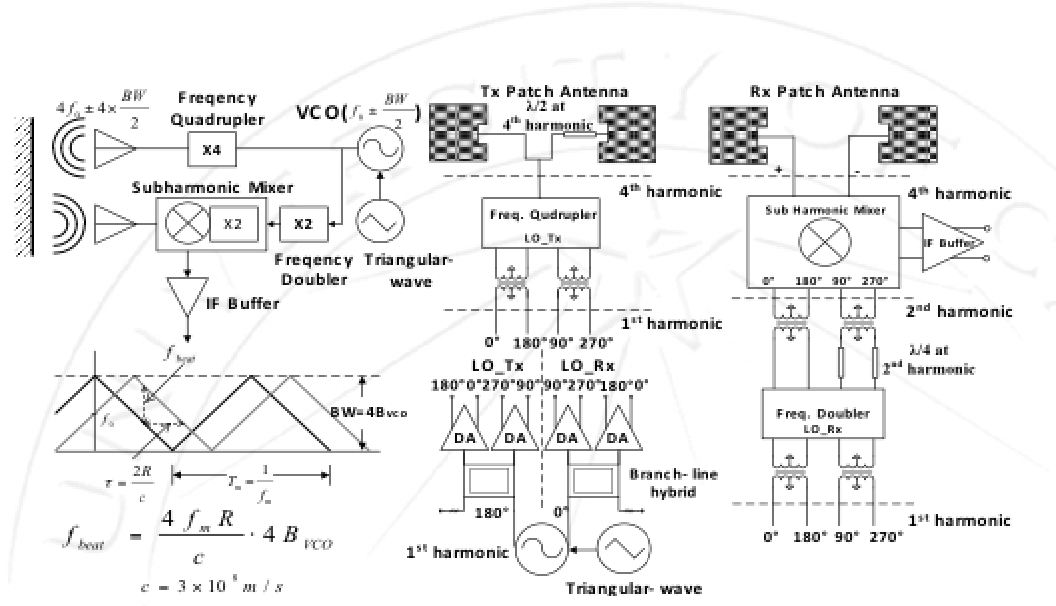
- Phase shifter resolution: RX=11° and TX=5.6^0 (with +/- 0.5dB gain variation across phase settings and elements)

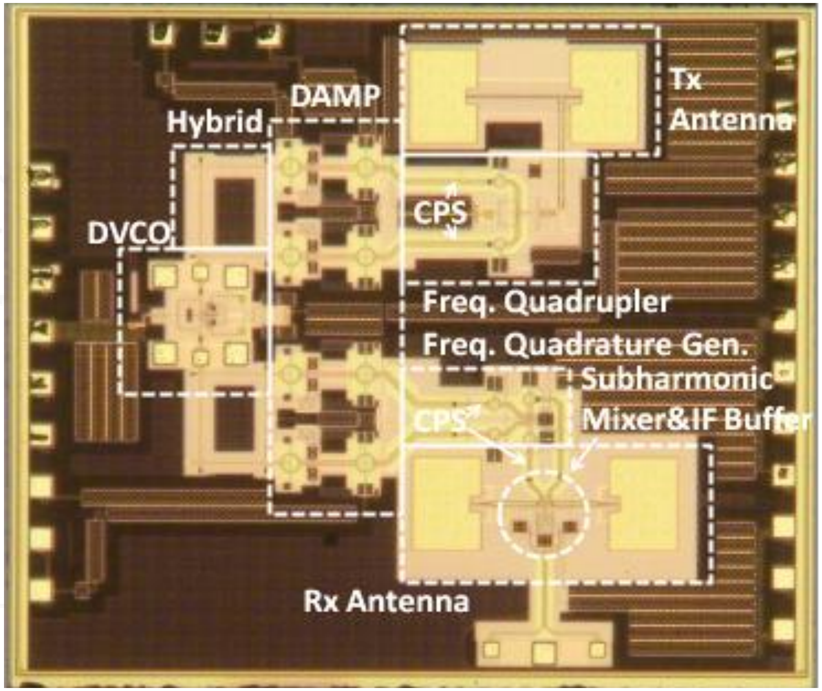
Synthesized λ/2-Spaced Array Patterns



Let's dream a little…

"THz" Radar Demonstration





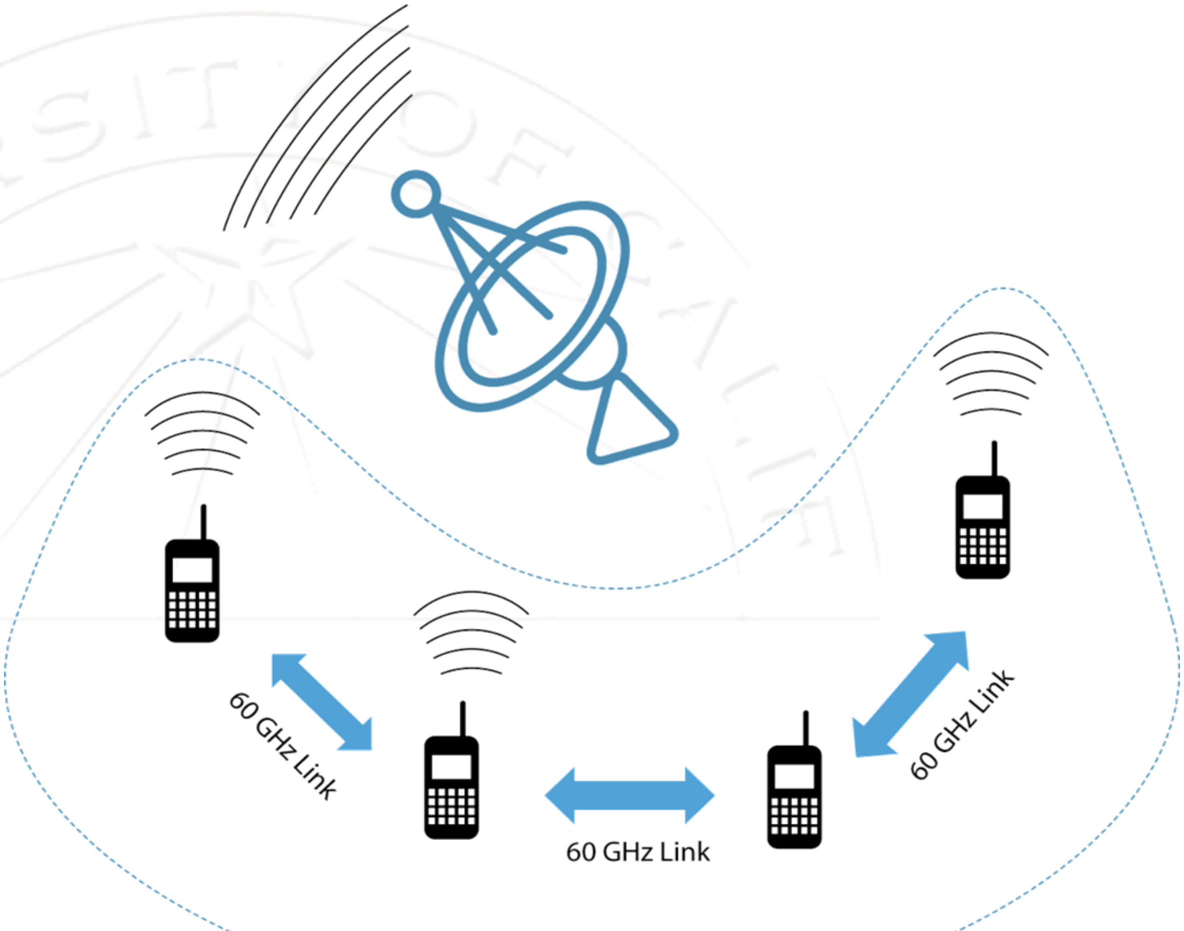
- Proof of concept "THz" (380 GHz) radar in 130nm SiGe
- Complete system includes TX and RX on same die, including antennas. Receiver uses a sub-harmonic mixer.
- Power is 360 mW and RX NF ~ 35 dB (estimate)
- Radar measurements confirm operation at 380 GHz

To be presented at VLSI 2011

Very Short Range Wireless

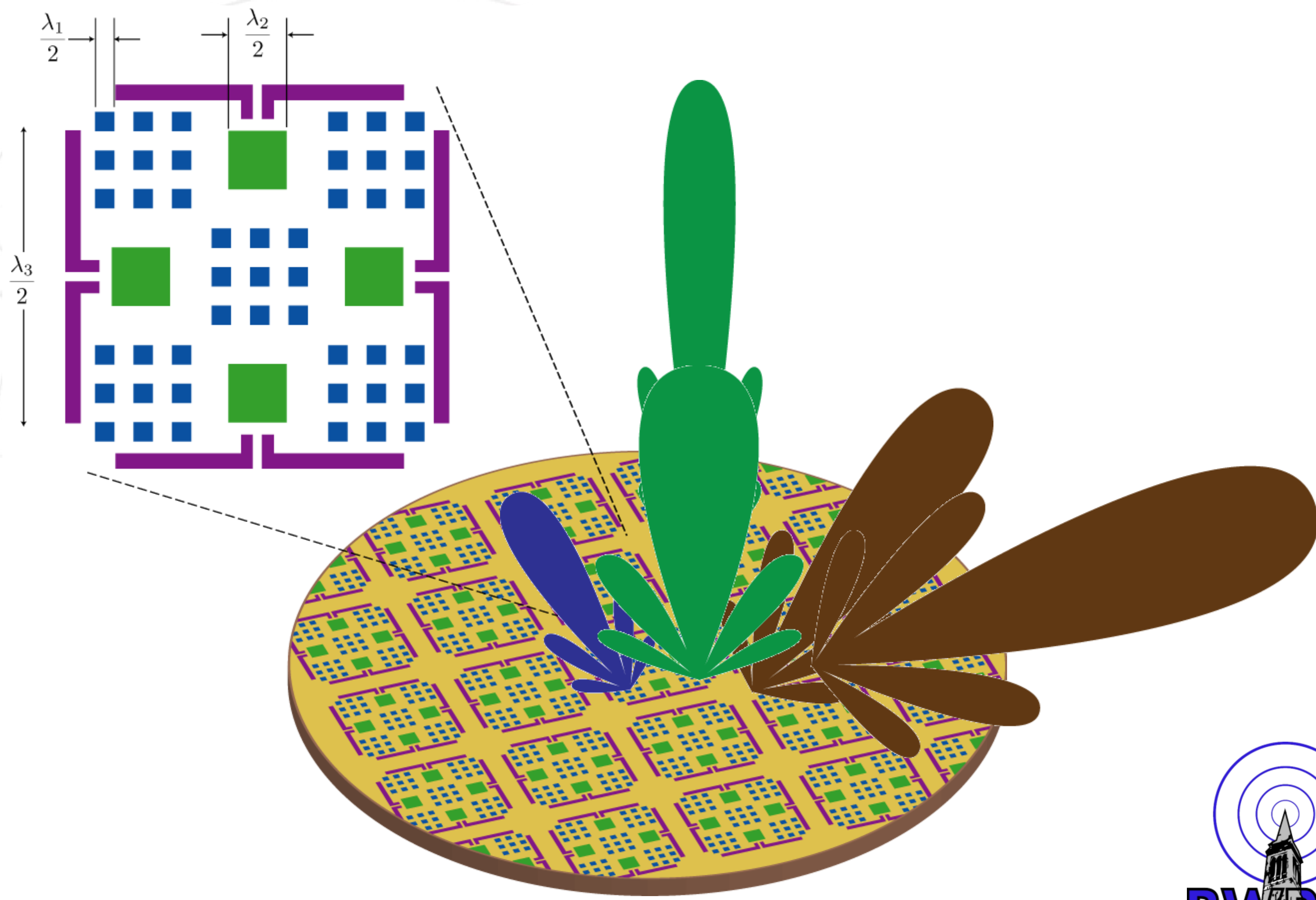
- If the bandwidth of a wireless bus is sufficiently high, there are many interesting applications for such a technology (chip-to-chip communication)

Distributed MIMO



- Use 60 GHz band for local communication and form a MIMO at cellular bands using a cluster of radios.

Multi-Band Antenna Array



Conclusion

- mm-Waves have many interesting and useful applications for communication and imaging (and medicine)
- Today's CMOS technology is a competitive candidate for realization of the entire system. Remaining challenges include power reduction (baseband, ADC, decoders), cost reduction (packaging, testing), and system design (phased-array)
- Emerging applications such as chip-to-chip at "THz" and wafer scale radios are very exciting but require much more research
  - Generate > 0 dBm at 300 GHz in CMOS?
  - Do a low noise receiver ? NF < 20 dB?
  - Realize on-chip antennas with moderate efficiencies (> 40%)

Acknowledgements

- BWRC sponsors and member companies
- DARPA TEAM Program
- FCRP Focus Center for Circuit and System Solutions (C2S2)
- Chip fabrication donated by ST Microelectronics
- Berkeley Design Automation
- Cascade Microtech
- NSF Infrastructure Grant No. 0403427