Enabling 5G: mmWave Silicon Integration and Packaging

Bodhisatwa Sadhu

IBM Research
T. J. Watson Research Center

IBM

Why mmWave?

The only way to go is higher!

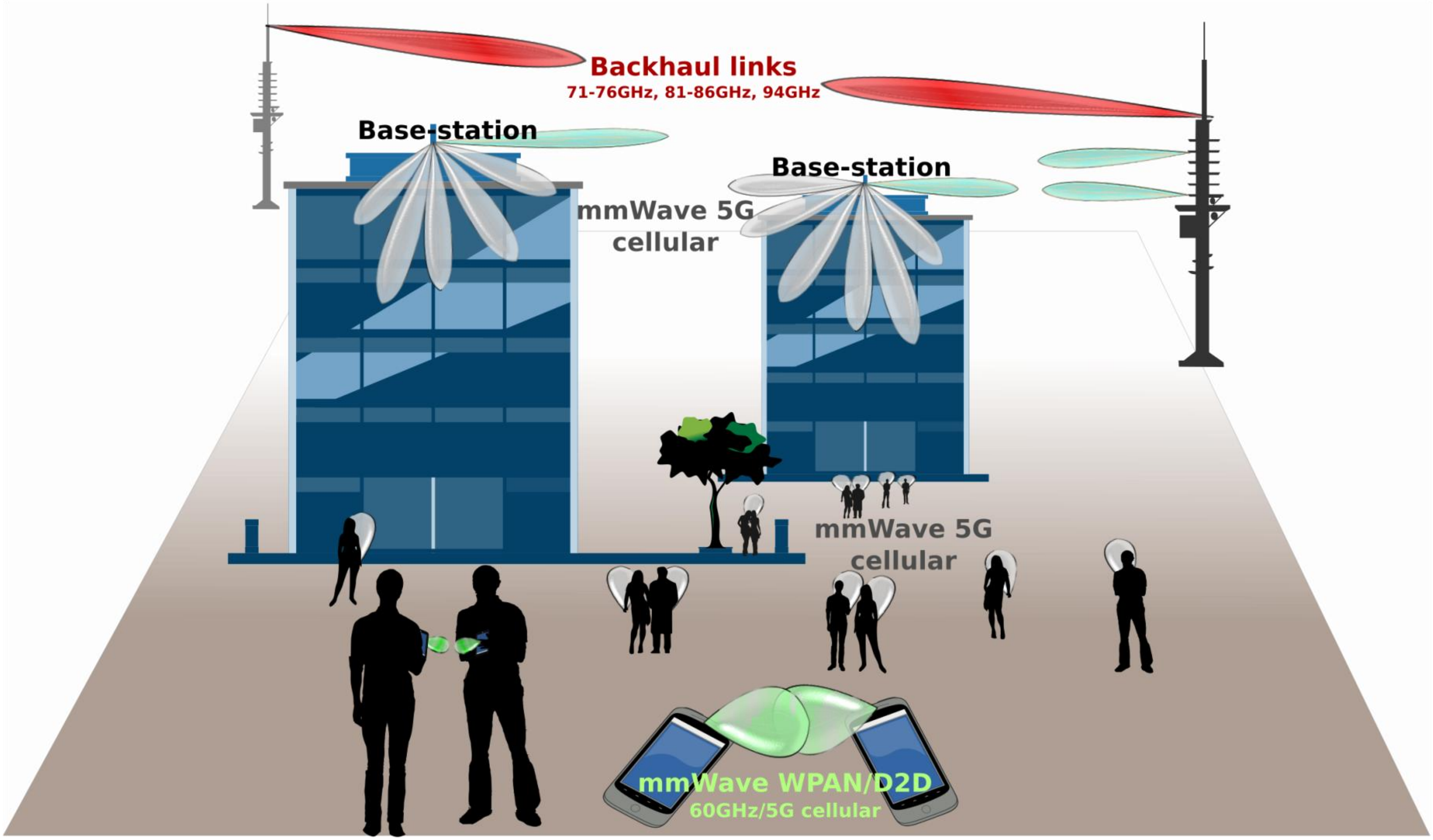
- Higher data rate
  - Larger bandwidth
  - Less interference

What's stopping us then?

It is hard…

Challenges of mmWave	Mitigation strategy
Greater propagation loss	Use phased array
Large loss in interconnects	Integrate antennas with IC
Technology limits	Co-design: IC, package, antenna, DSP
Expensive to test	Use on-chip testing infrastructure (DFT)

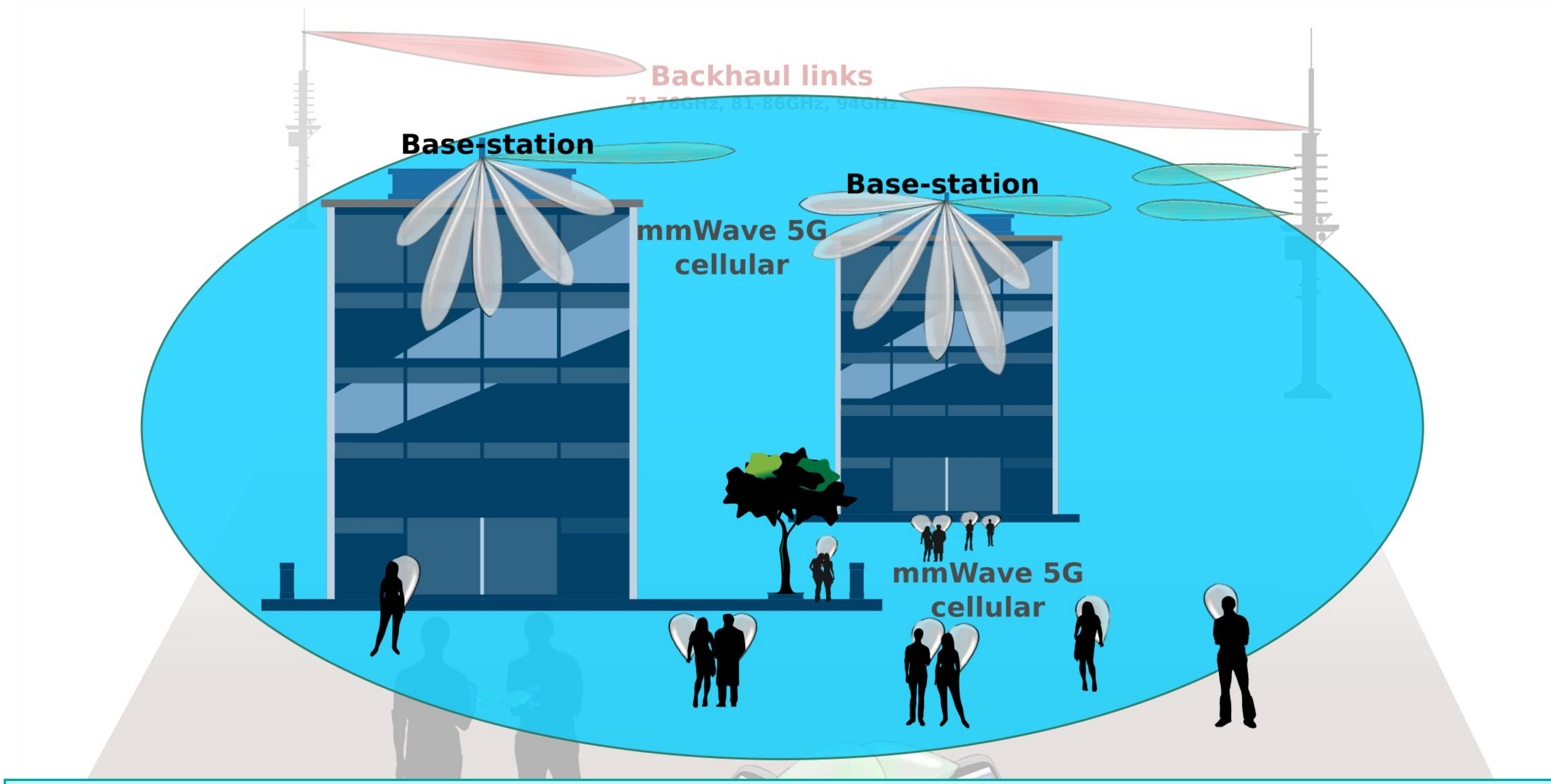
Gb/s mmWave Wireless Links:
Applications across the infrastructure stack



mmWave-based 5G network concept:
Ericsson: E. Dahlman, et al., “5G Radio Access,” Ericsson Review, June, 2014
Samsung: W. Roh, et al., "Millimeter-wave beamforming as an enabling technology for 5G cellular communications: theoretical feasibility and prototype results," in IEEE Communications Magazine, Feb, 2014

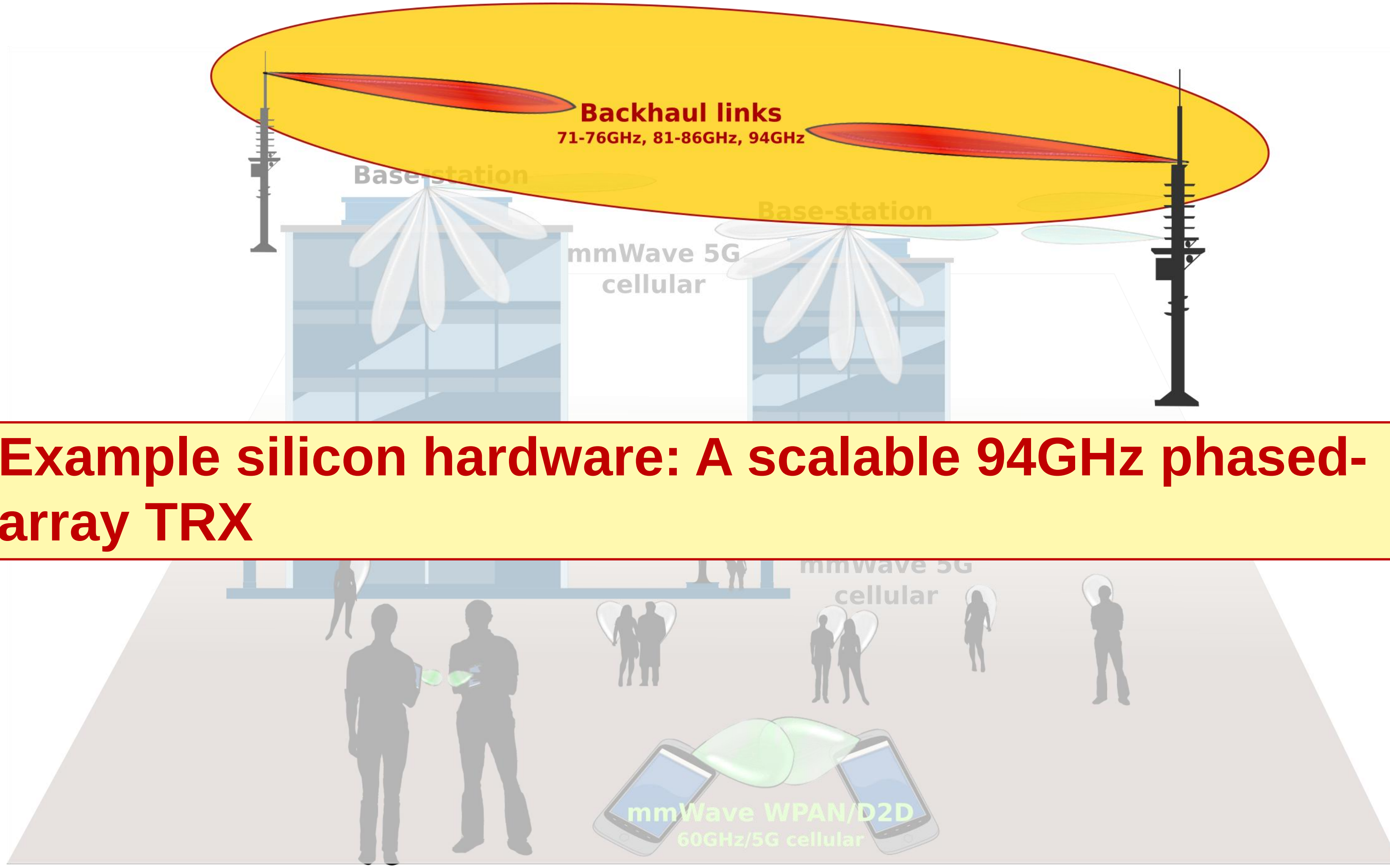
mmWave 5G cellular / WLAN

Packaged silicon hardware at IBM Watson labs



Example silicon hardware: A 60GHz 16-element phased-array TX and RX chipset

mmWave Backhaul Links
Packaged silicon hardware at IBM Watson labs

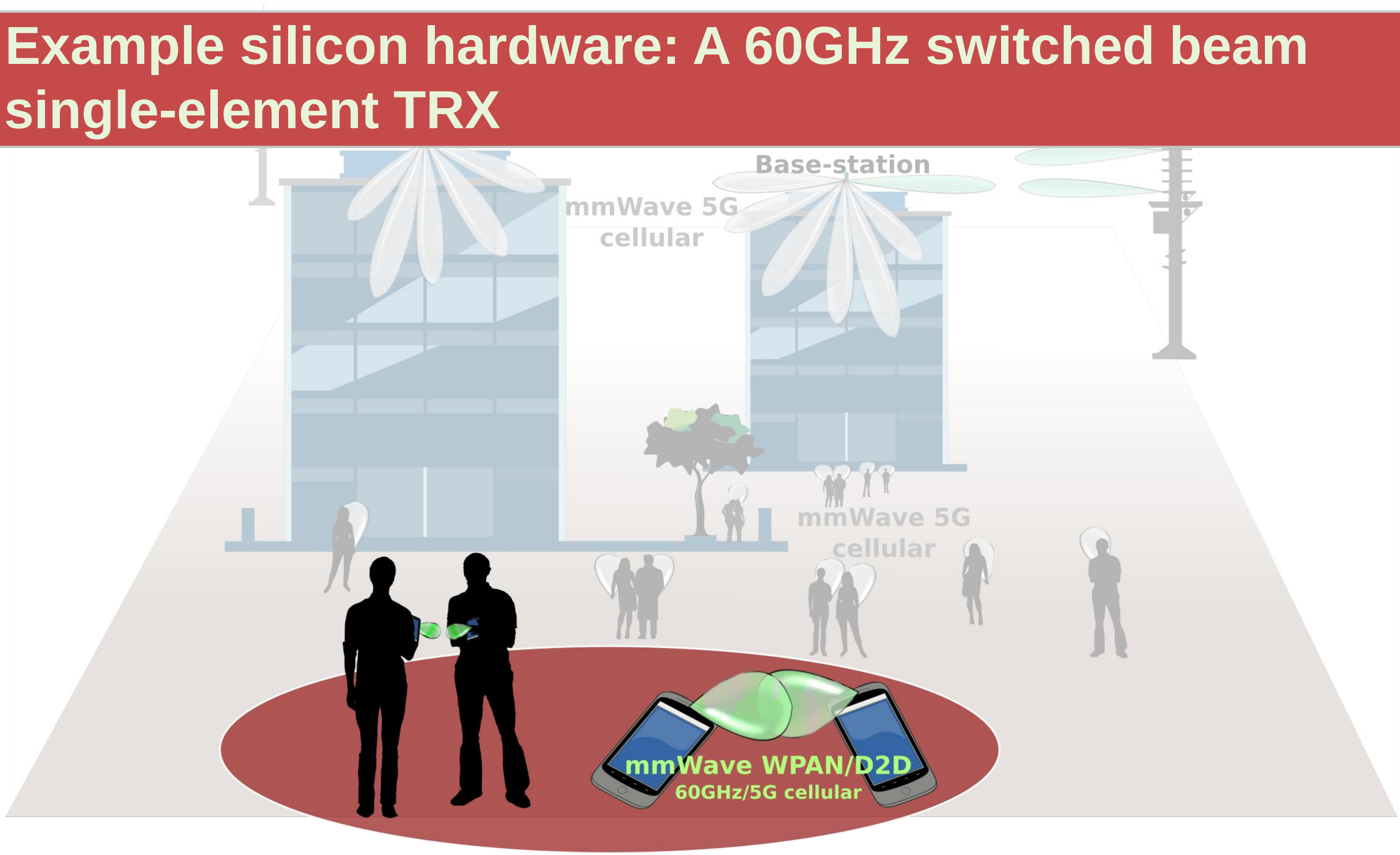


Example silicon hardware: A scalable 94GHz phased-array TRX

WPAN / Device to Device (D2D)

Packaged silicon hardware at IBM Watson labs

Example silicon hardware: A 60GHz switched beam single-element TRX



mmWave 5G cellular / WLAN

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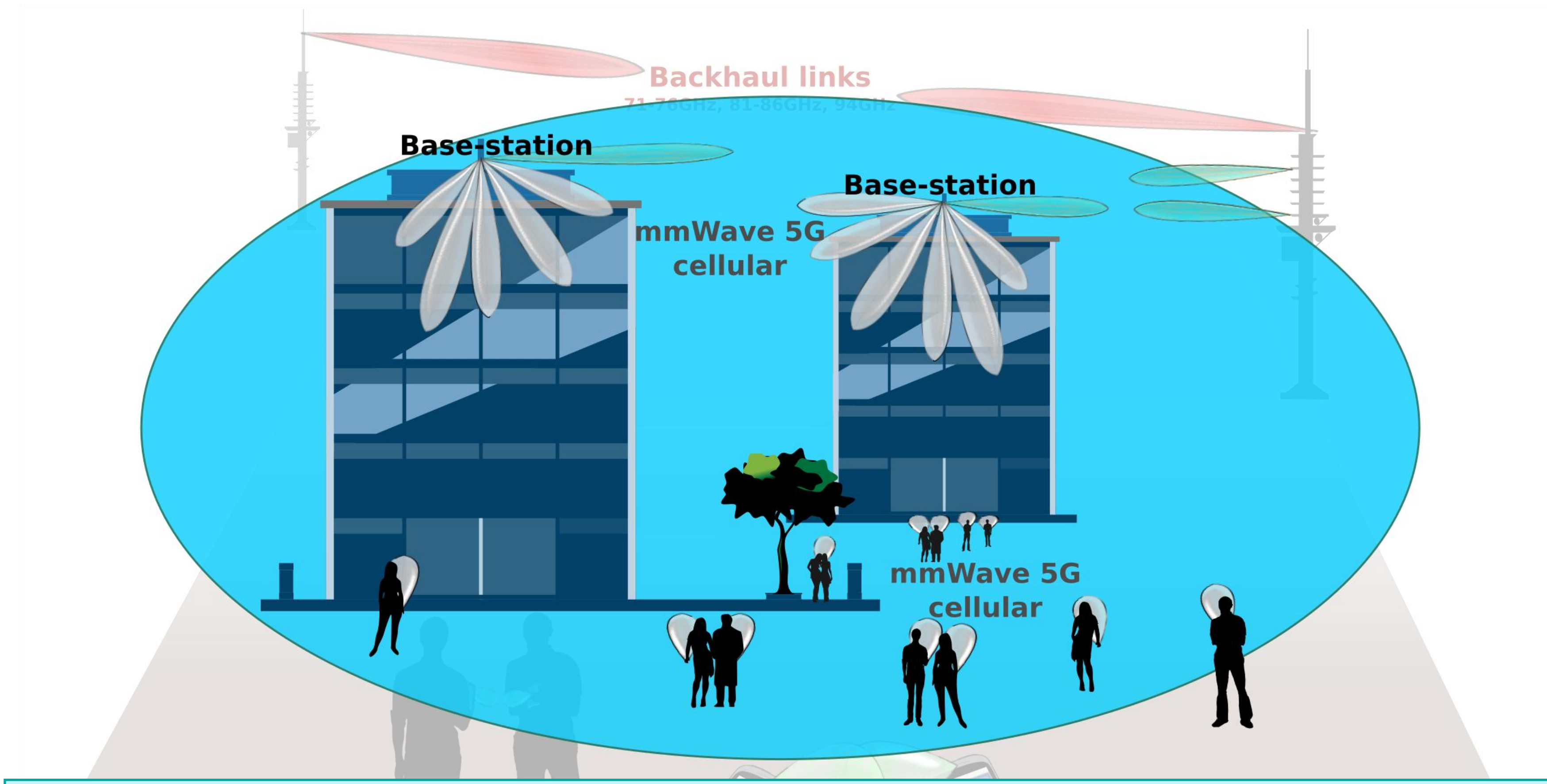
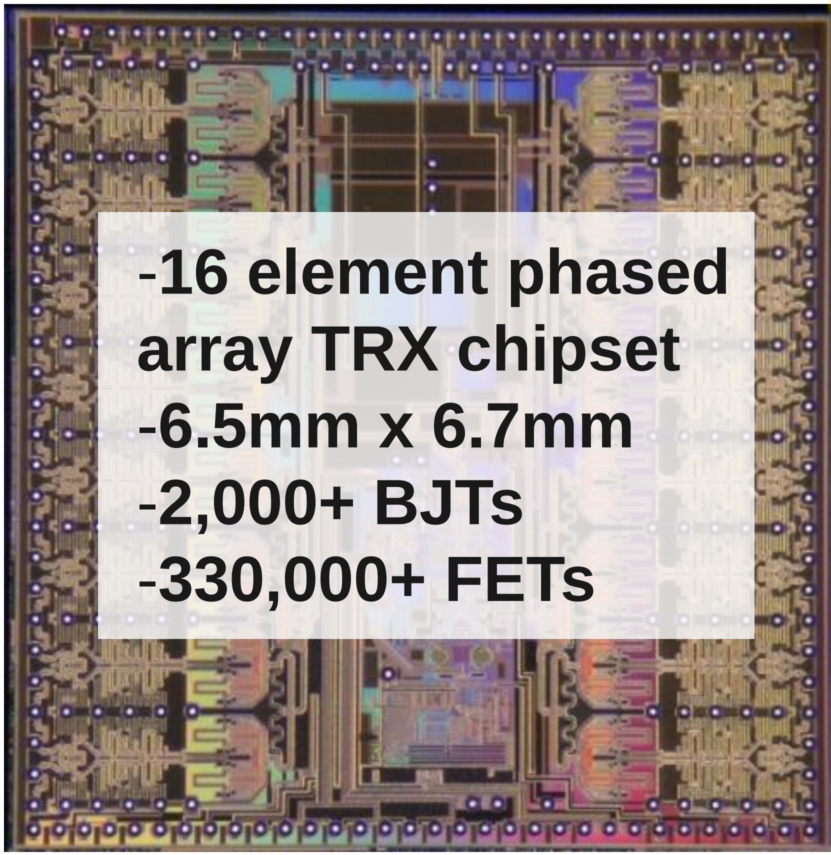


Example silicon hardware: A 60GHz 16 element phased-array TX and RX chipset

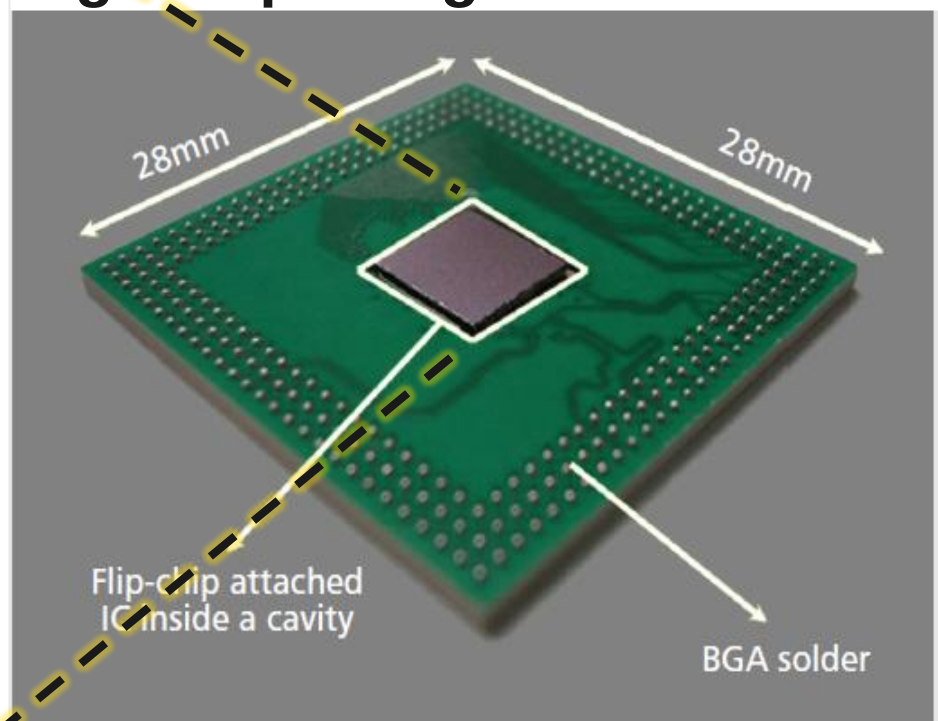
60 GHz 16-Element Phased Array TX and RX Chipset

Highly integrated IC and package co-design



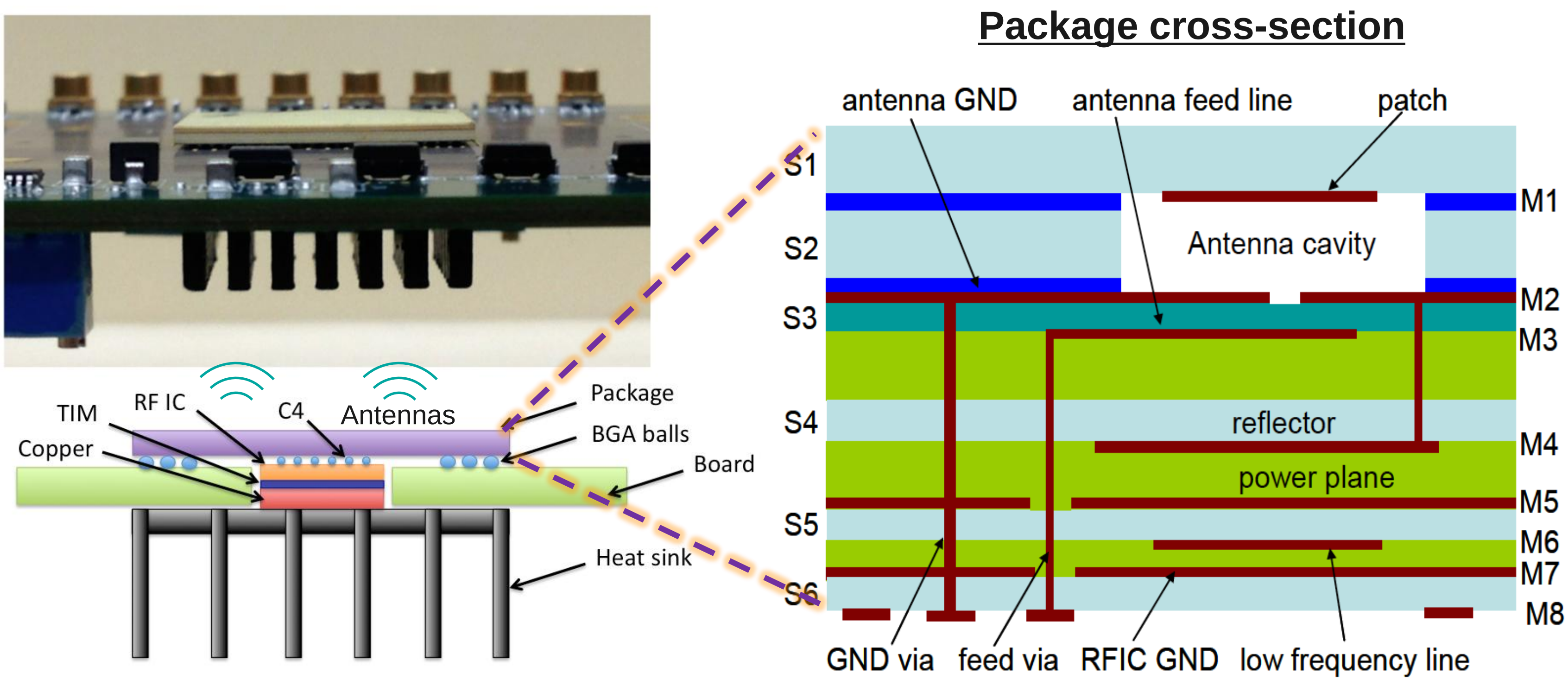
- -16 element phased array TRX chipset
- -6.5mm x 6.7mm
- -2,000+ BJTs
- -330,000+ FETs

Fully integrated multilayer organic package



A. Valdes-Garcia, et al., "Single-Element and Phased-Array Transceiver Chipsets for 60-GHz Gb/s Communication", IEEE Communications Magazine, April 2011

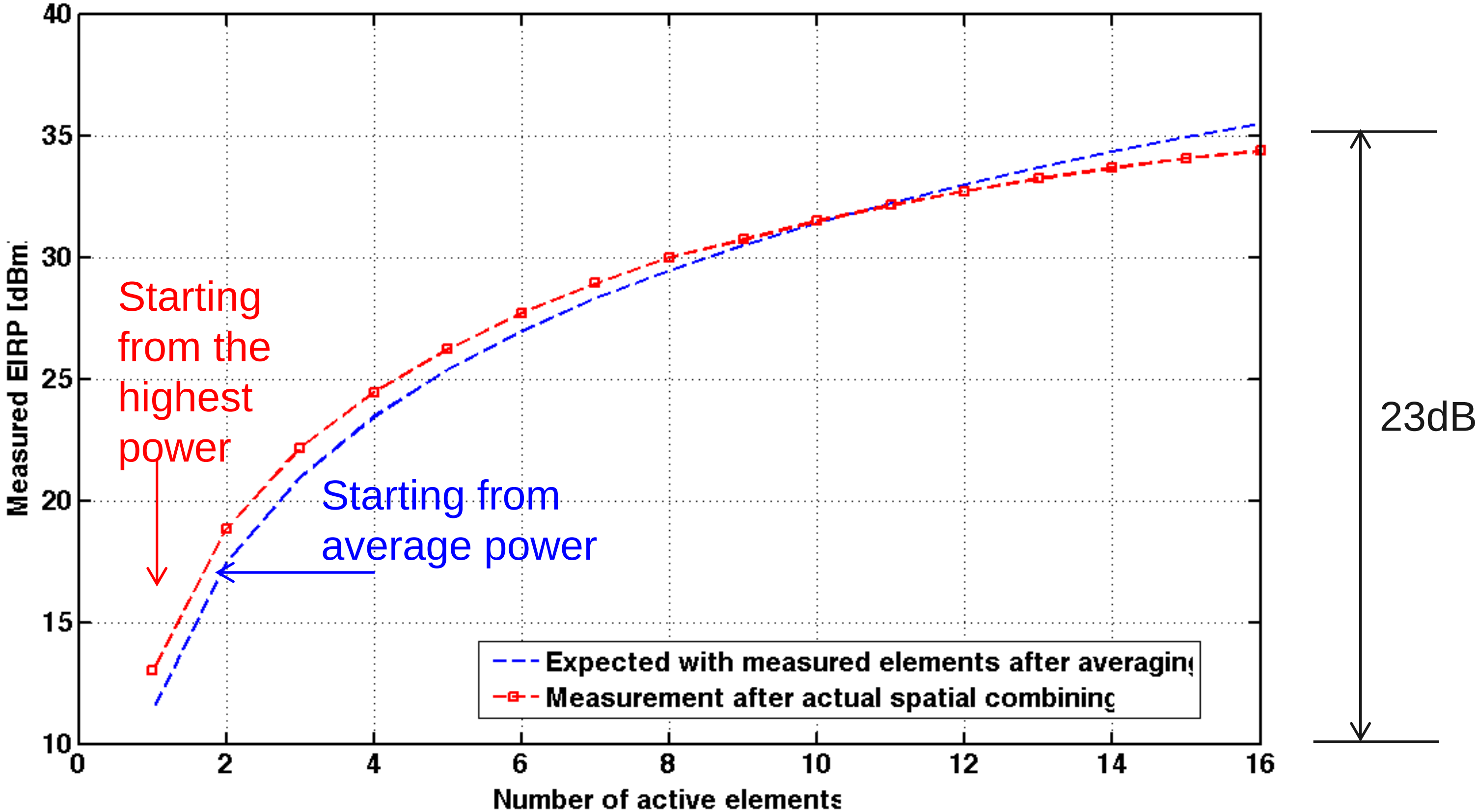
Tight Co-design of IC, Package, Board and Cooling Solution



- The MLO package houses the IC and the 16 element phased array antennas

X. Gu et al.,"Enhanced Multilayer Organic Packages with Embedded Phased-Array Antennas for 60-GHz Wireless Communications", IEEE ECTC 2013

Phased Array EIRP Grows as (# of Elements)^2
Overcomes mmWave path loss

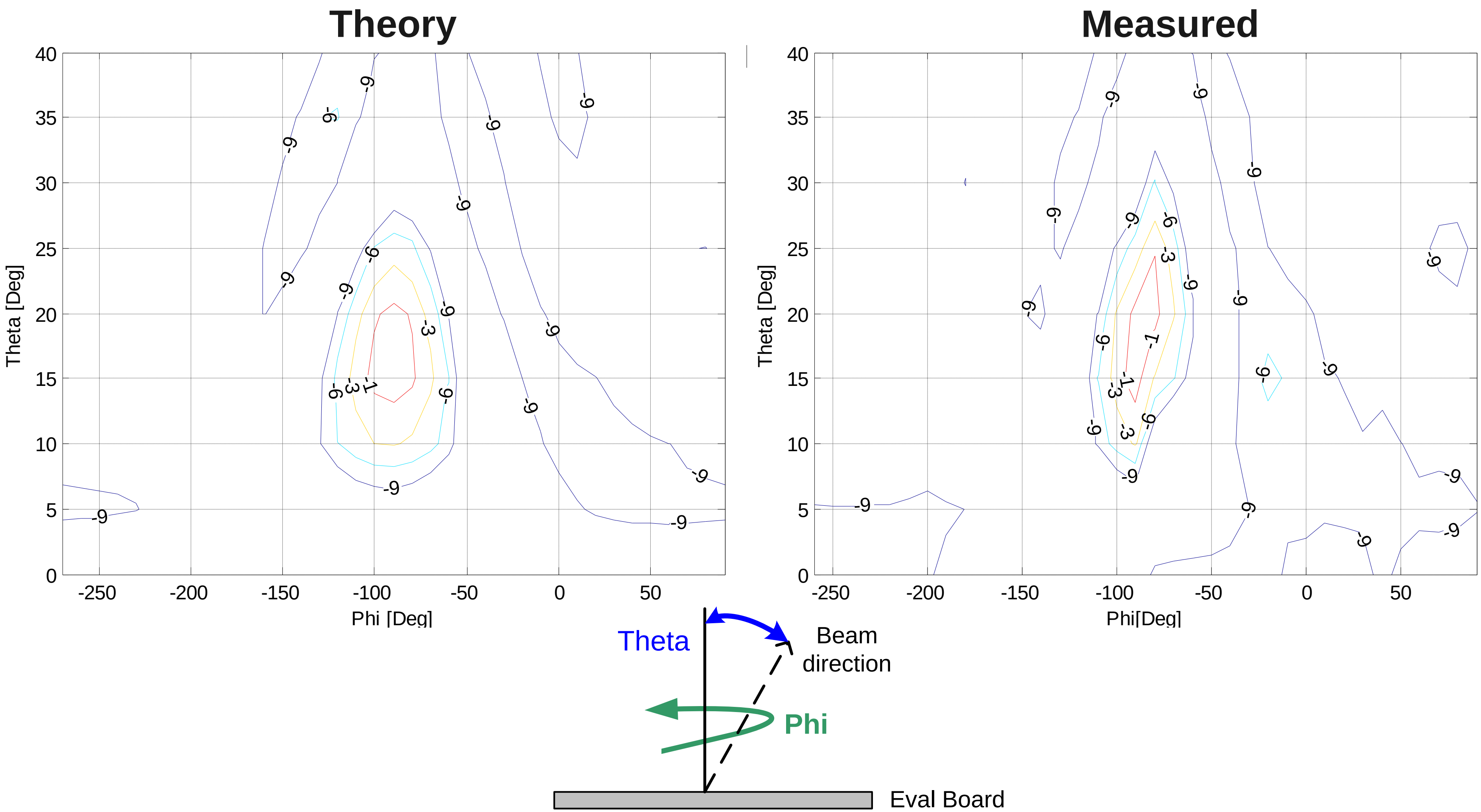


- *V1.0*: 42dBm equivalent isotropically radiated power while consuming 3.4W
- *V2.0*: 34dBm equivalent isotropically radiated power while consuming 2.7W
- 23dB increase from spatial combining [20log(16) = 24dB expected from theory]

A. Valdes-Garcia, et. al. "A Fully Integrated 16-Element Phased-Array Transmitter in SiGe BiCMOS for 60-GHz Communications ", IEEE JSSC, 2010

16-Element Tx Radiation Patterns

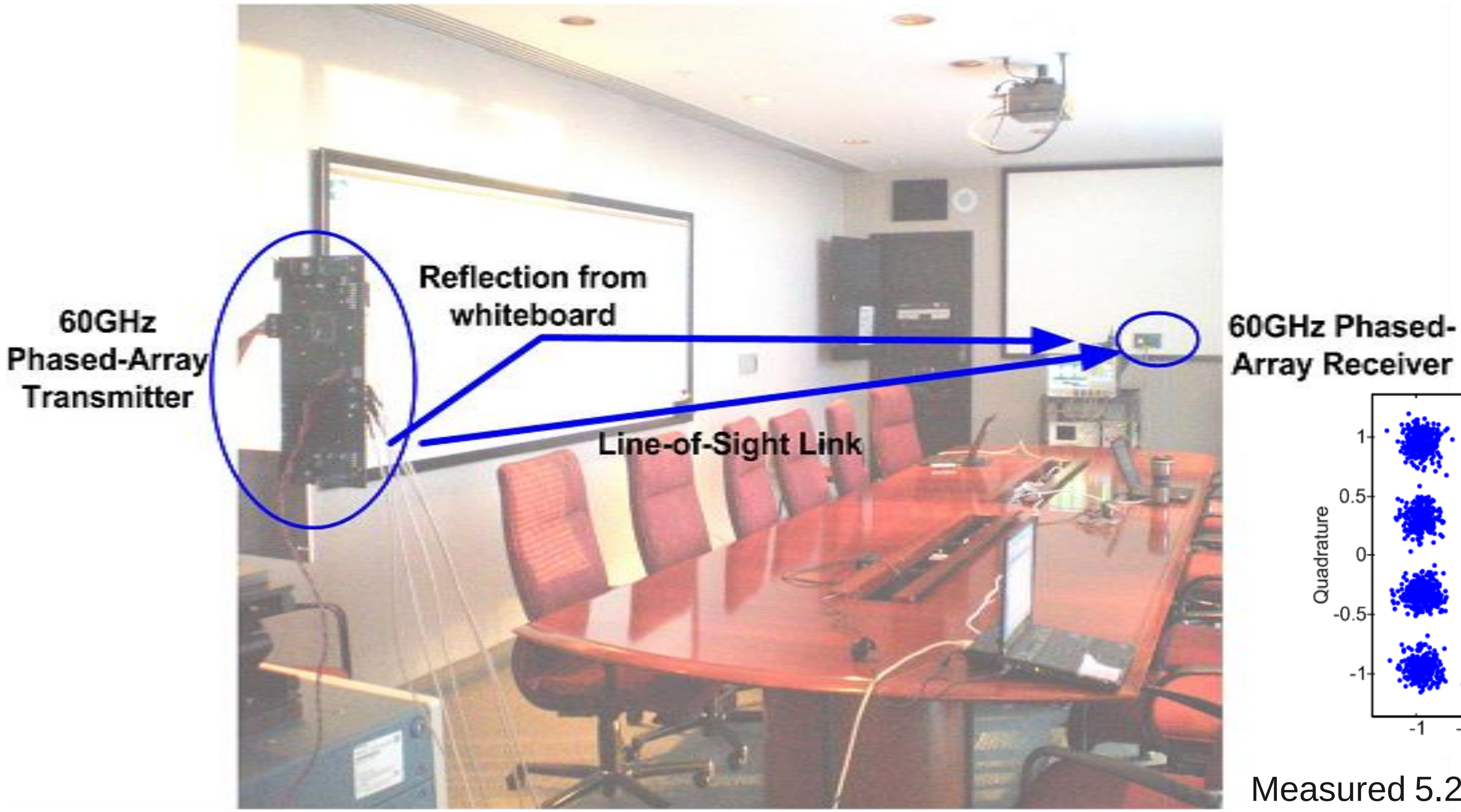
Measured in two angular dimensions

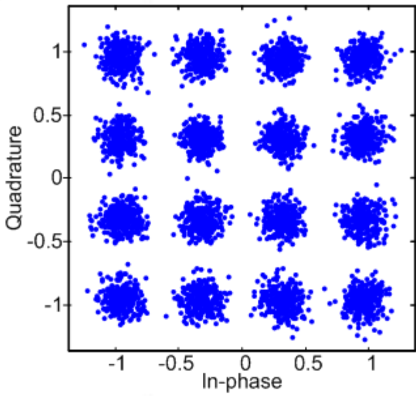


A. Valdes-Garcia, et al., "Single-Element and Phased-Array Transceiver Chipsets for 60-GHz Gb/s Communication", IEEE Communications Magazine, April 2011

Link Demo over NLOS Channel

>5Gbps data link in all 4 60GHz channels



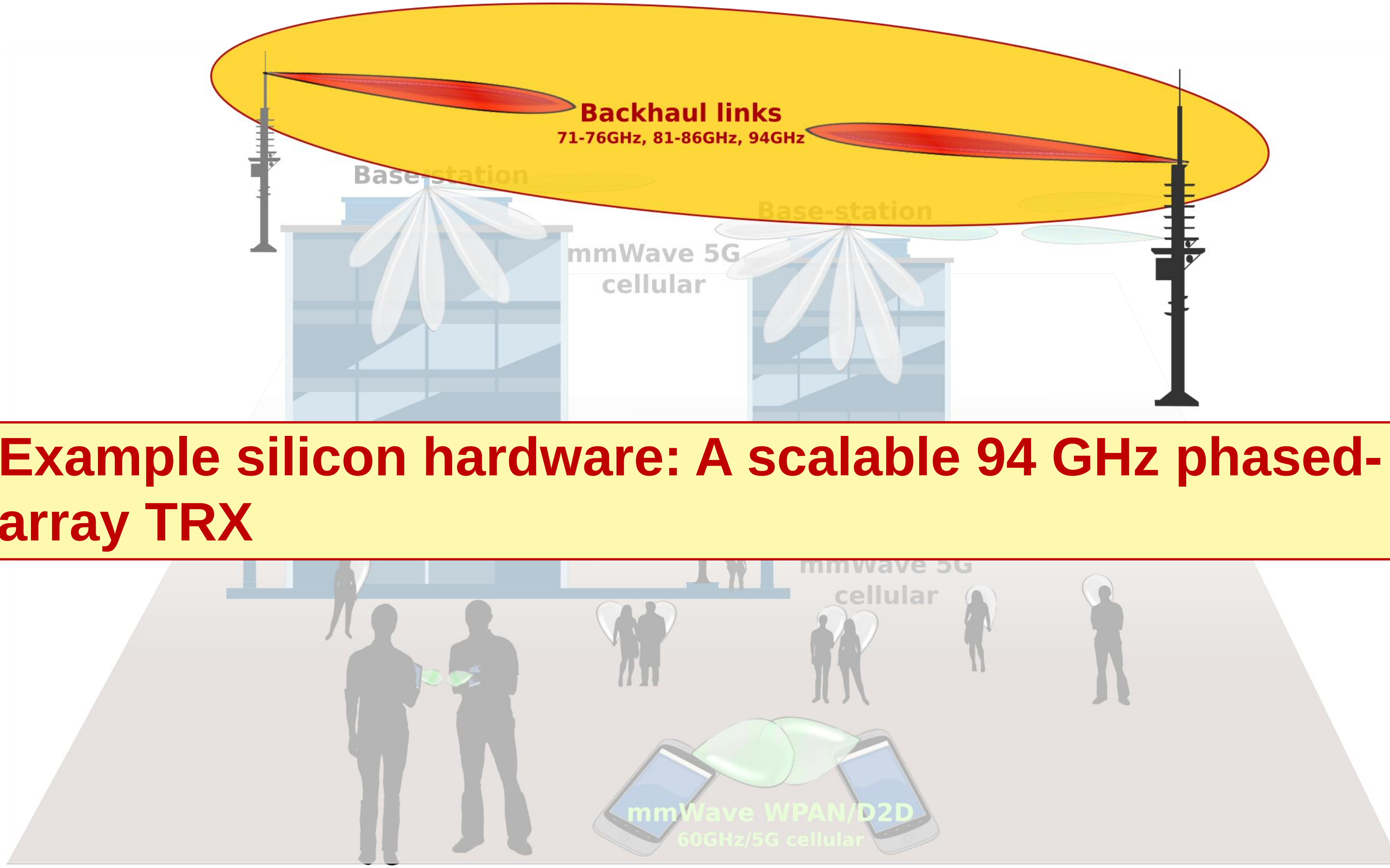


Measured 5.29Gb/s 16-QAM OFDM constellation for a 9m non-line-of-sight (NLOS) link for all 4 channels -- < -17dB EVM

A. Natarajan, et. al. “A Fully Integrated 16-Element Phased-Array Receiver in SiGe BiCMOS for 60-GHz Communications ”, IEEE JSSC, 2011

mmWave Backhaul Links

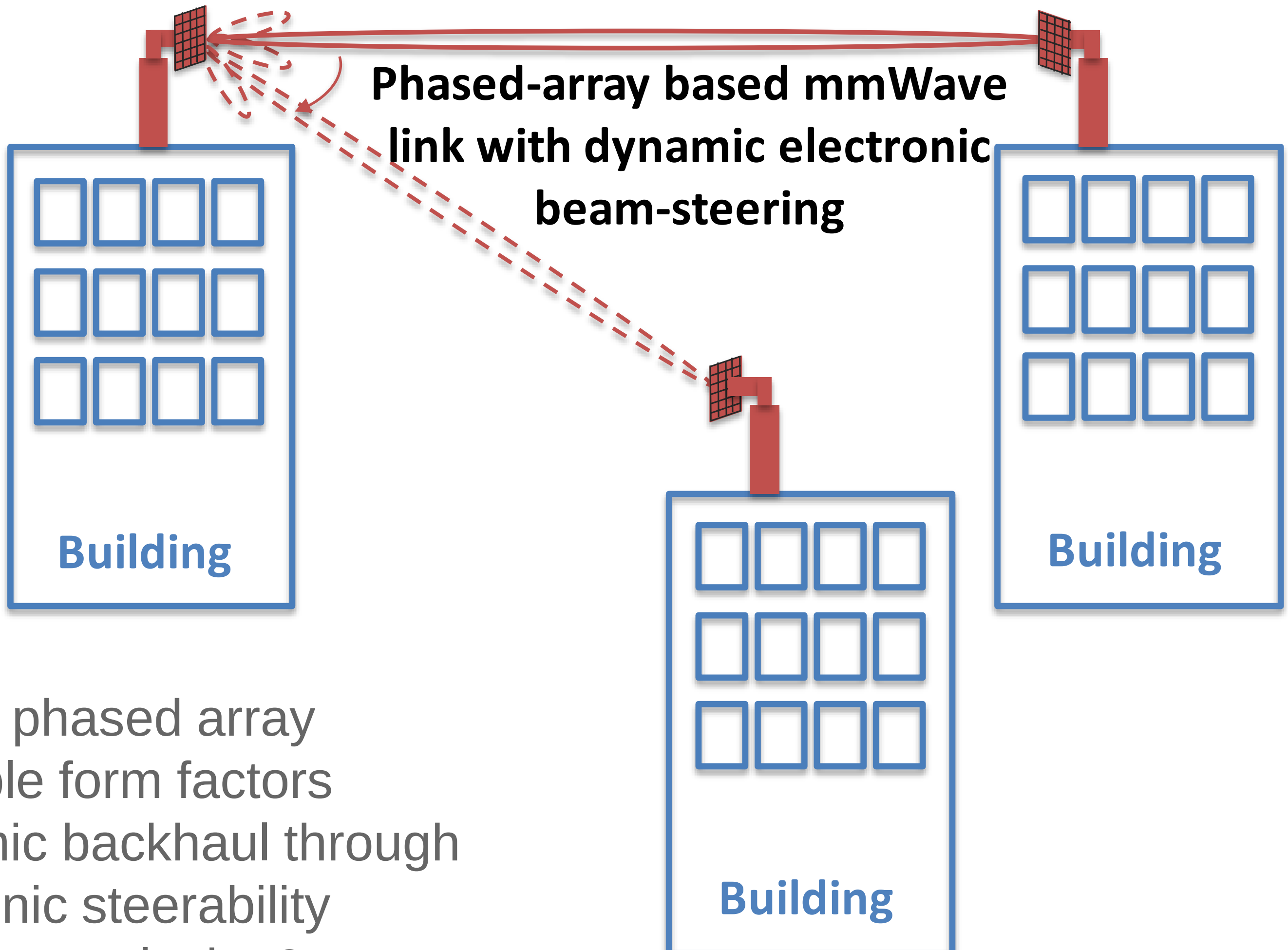
Packaged silicon hardware at IBM Watson labs



Example silicon hardware: A scalable 94 GHz phased-array TRX

Dynamic Phased Array Backhaul

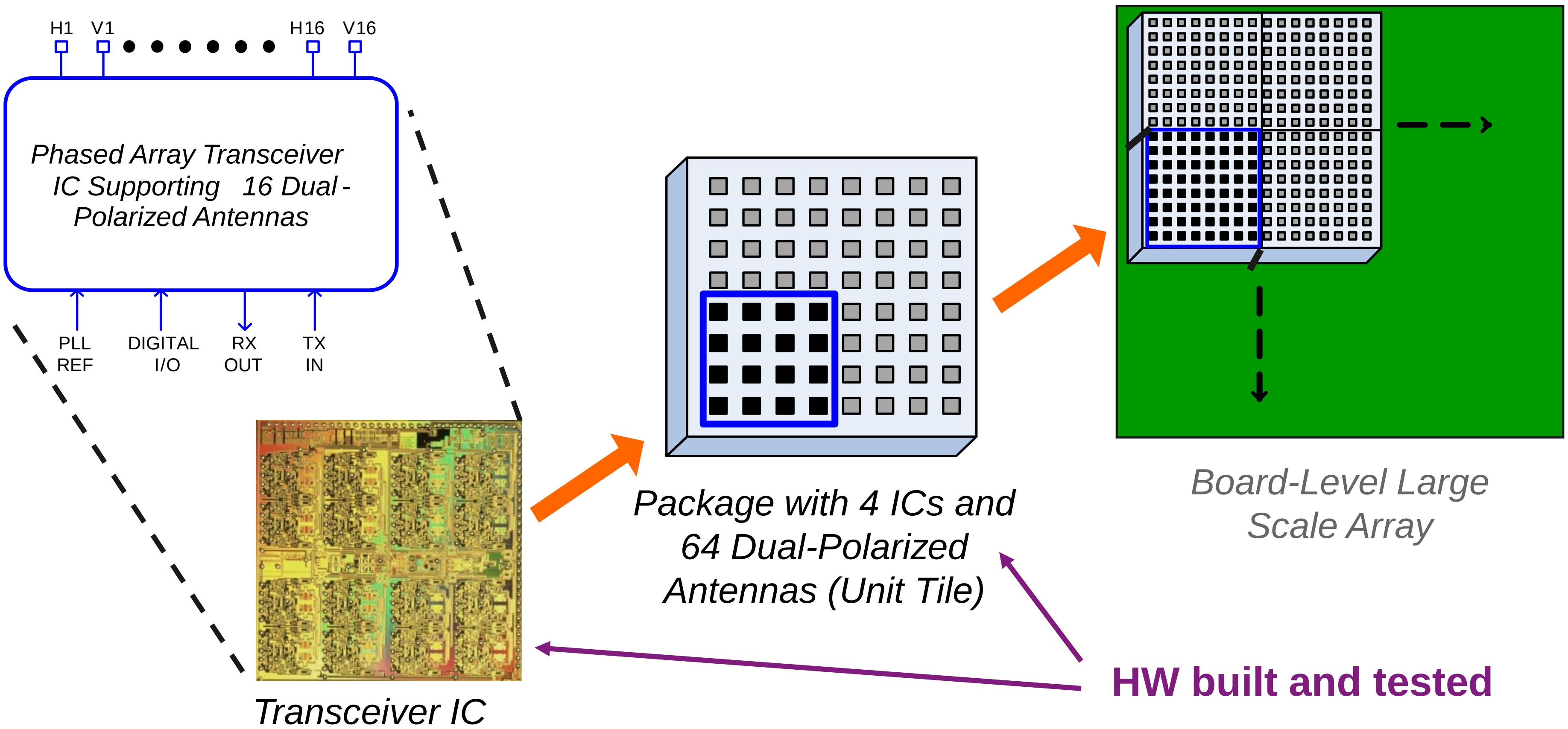
Reconfigurable and dynamic



- Scalable phased array
  - Scalable form factors
  - Dynamic backhaul through electronic steerability
  - Higher complexity & power

X. Gu, et al., "W-band Scalable Phased Arrays for Imaging and Communications", IEEE Communication Magazine, April 2015

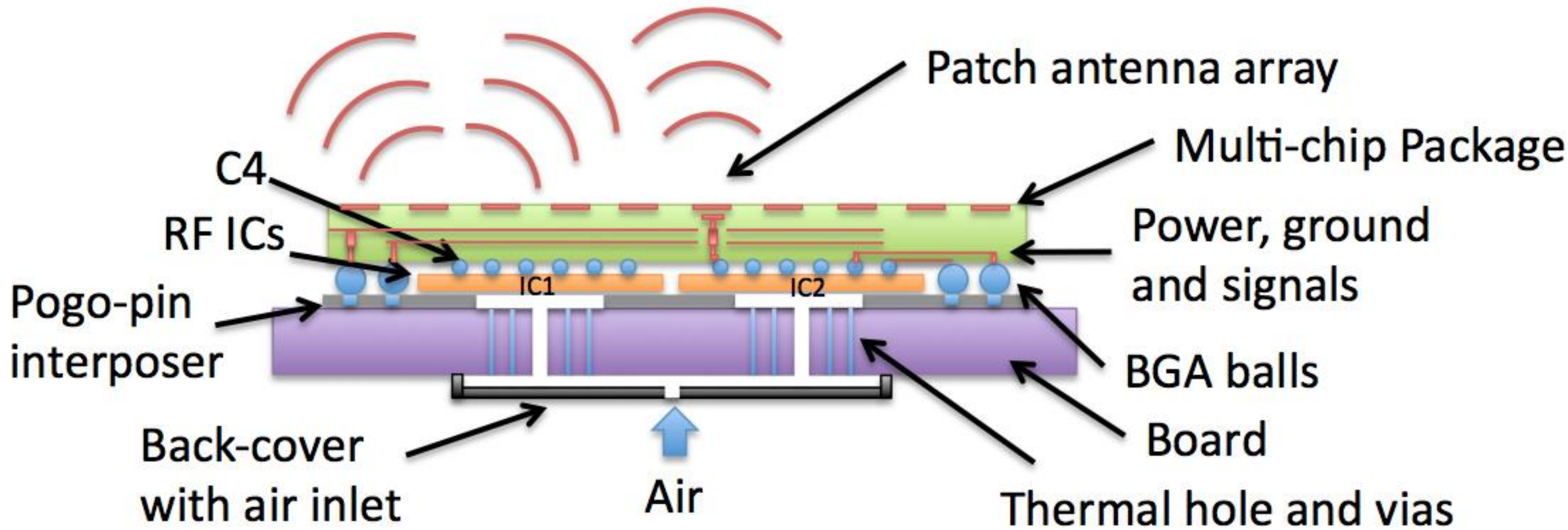
Scalable Phased Array Concept

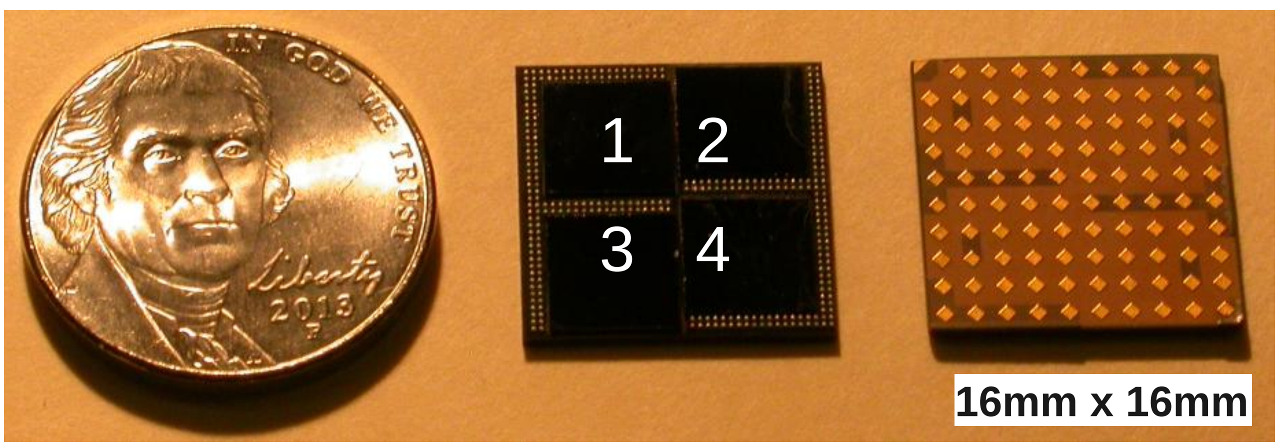


By tiling packages adjacent to one another on a PCB, **phased arrays of large aperture** can be created.

A. Valdes Garcia, *et al.*, “A Fully-Integrated Dual-Polarization 16-Element W-band Phased-Array Transceiver in SiGe BiCMOS” IEEE RFIC 2013

Compact Packages with 4 Transceiver ICs and 64 Dual-Polarized Antennas





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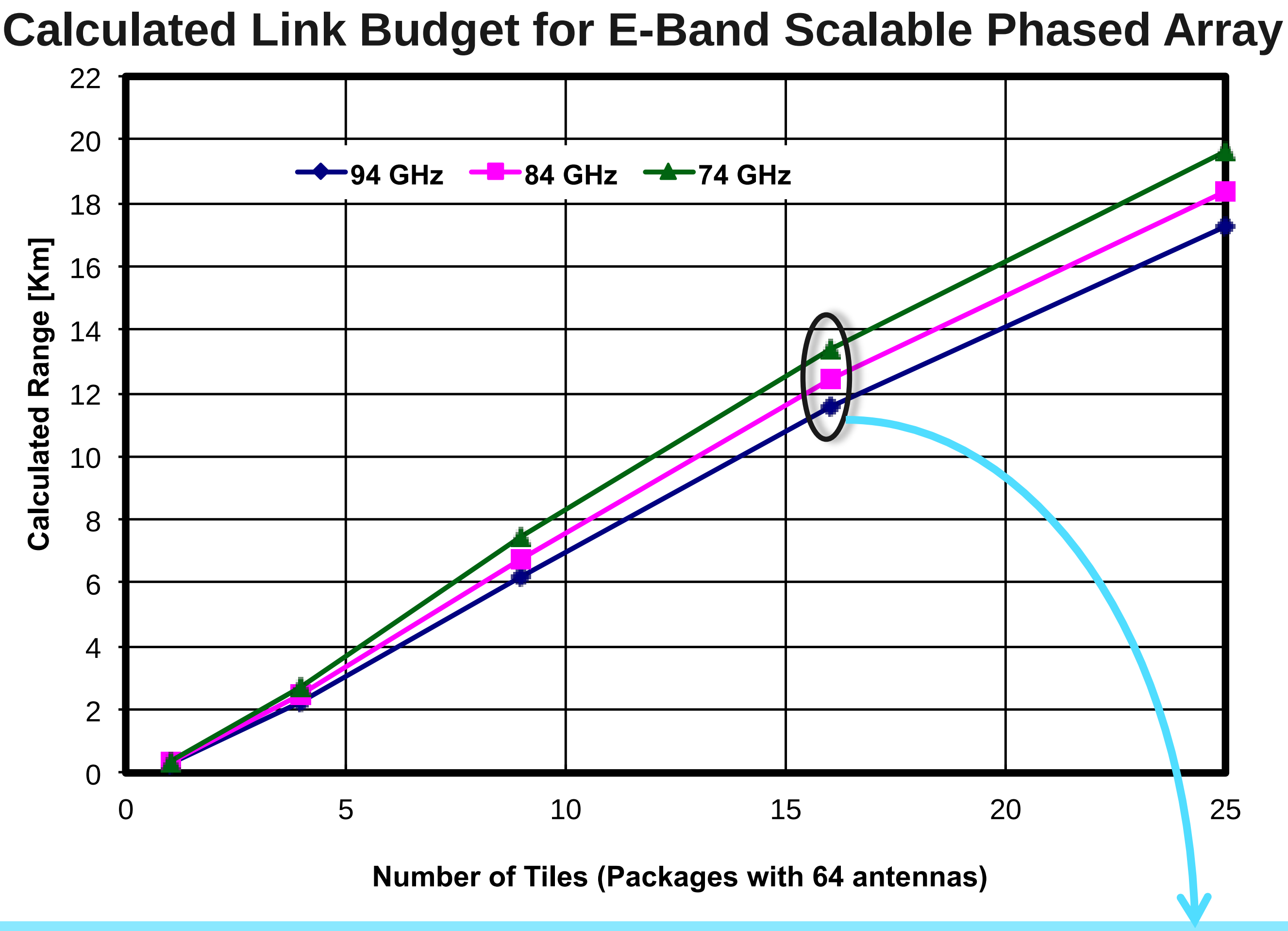
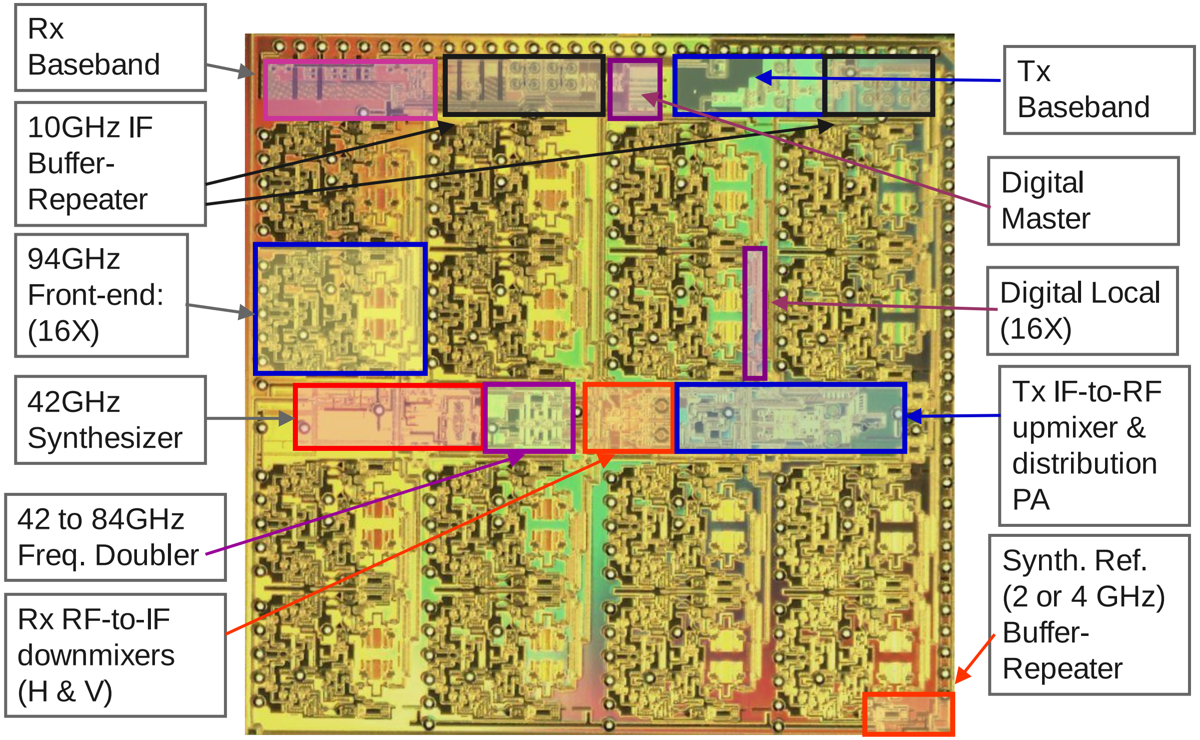
Can Achieve 10+km Range Using Silicon



Example take-away: 1024 elements are required for a 10km link

X. Gu, et al., "W-band Scalable Phased Arrays for Imaging and Communications", IEEE Communication Magazine, April 2015

Single IC Integrates the 94GHz 16-Element Dual-Polarized Phased-Array Transceiver



6.6mm x 6.7mm

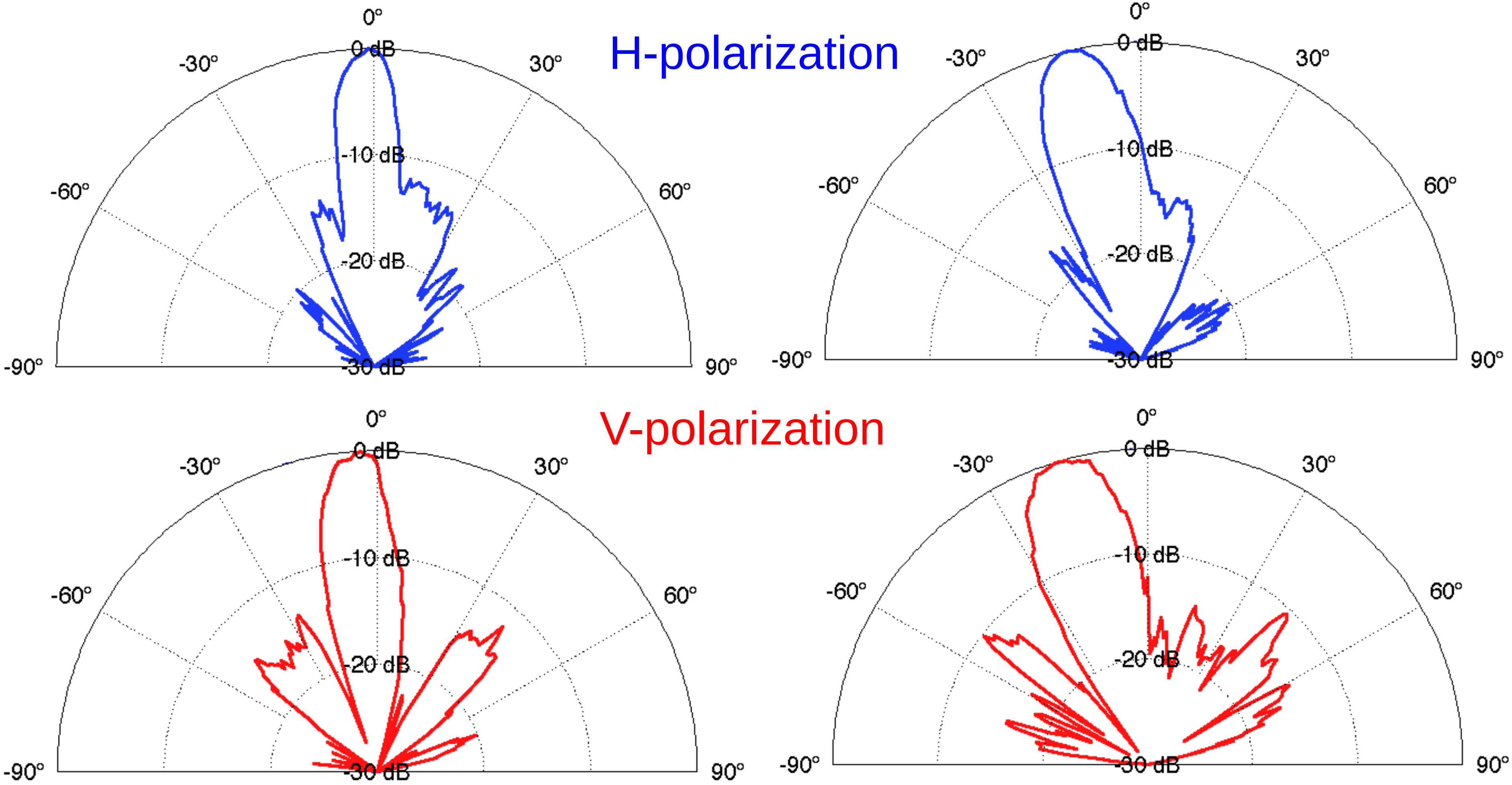
RX-mode RF front-end NF	8.2 dB
TX-mode IC Saturated Output Per Element	>2 dBm
Phase Shifter Range/Resolution	360°/ 11.25°
RX-mode power consumption: 32 inputs for simultaneous H & V	3.4 W
TX-mode power consumption	2.9 W

Data are taken at 94GHz and 25C.

- This IC integrates 5.1K+ BJTs and 1.5M+ FETs representing the highest level of monolithic integration at W-band frequencies

A. Valdes Garcia, *et al.*, “A Fully-Integrated Dual-Polarization 16-Element W-band Phased-Array Transceiver in SiGe BiCMOS” IEEE RFIC 2013

Measurements Show 64-Element Beamforming in Silicon



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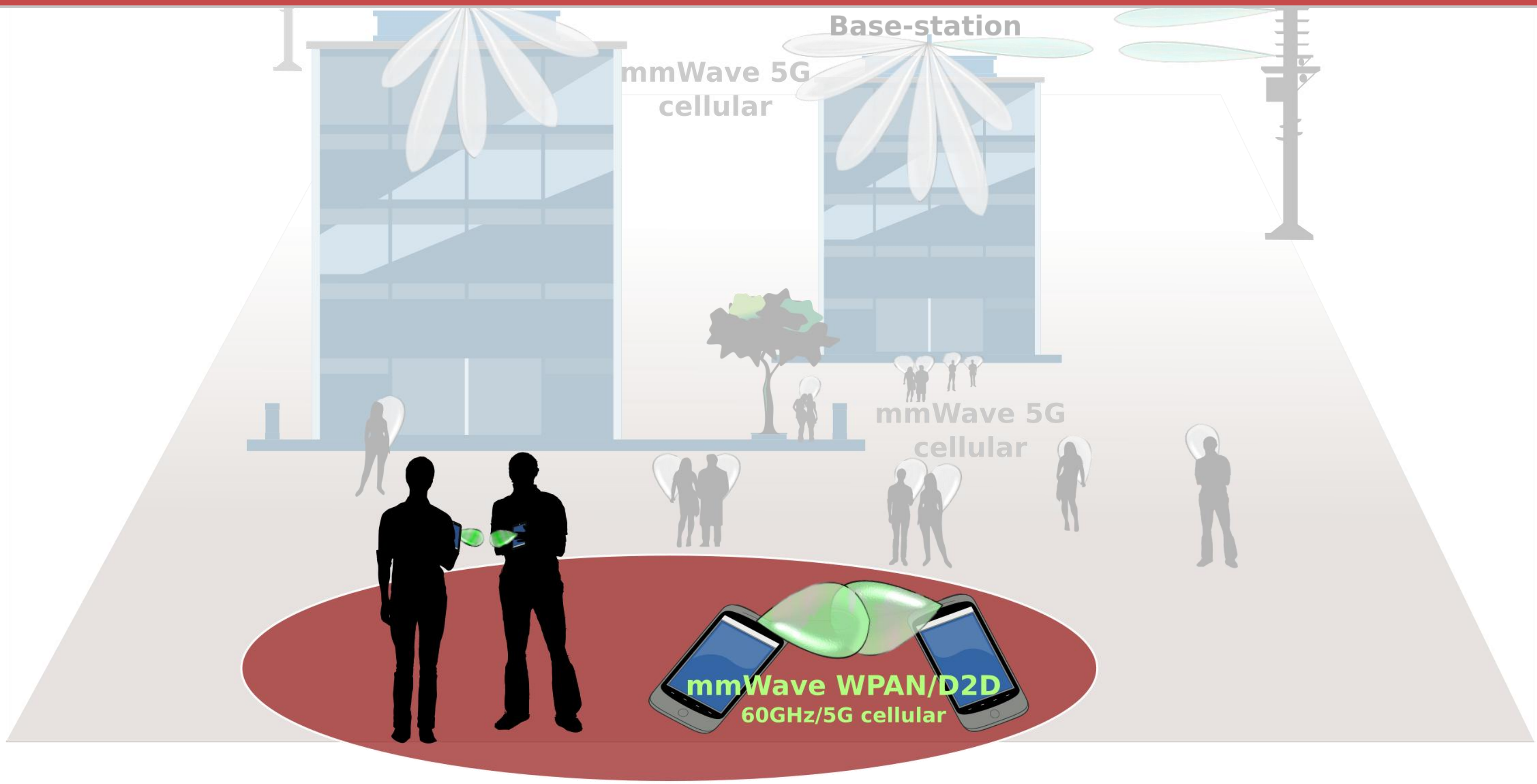
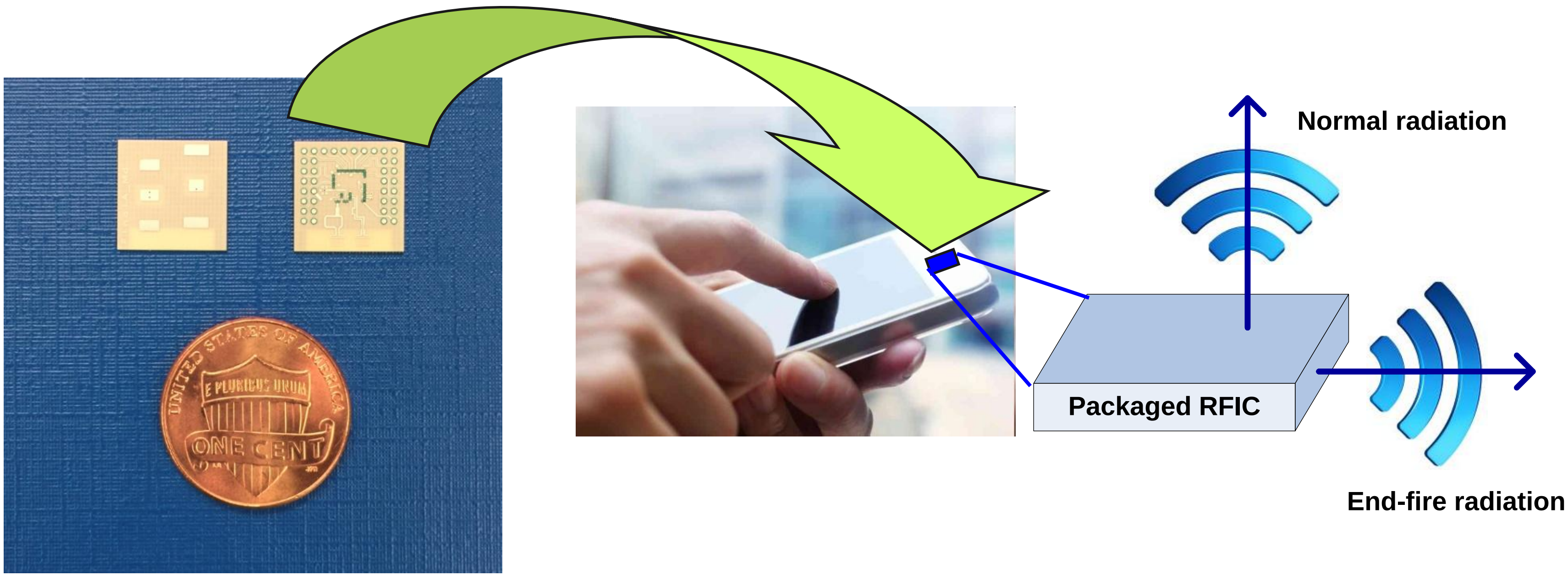
WPAN / Device to Device (D2D)
Packaged silicon hardware at IBM Watson labs

Example silicon hardware: A 60GHz switched beam single-element TRX

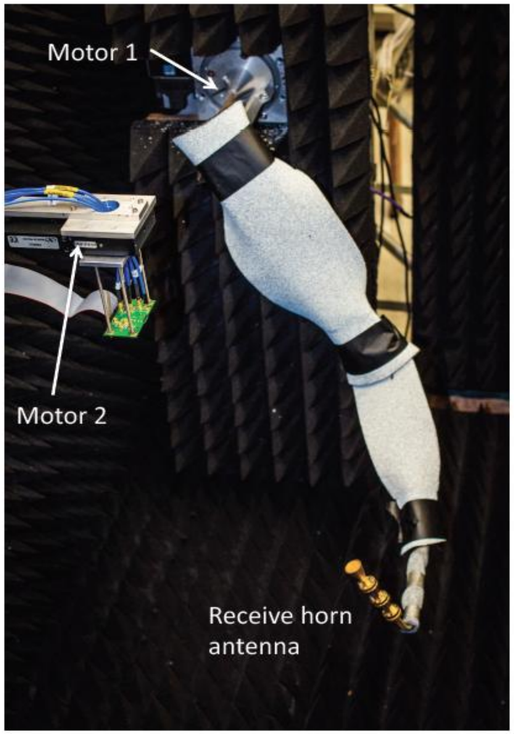


Antenna Diversity is Critical for Portable Devices



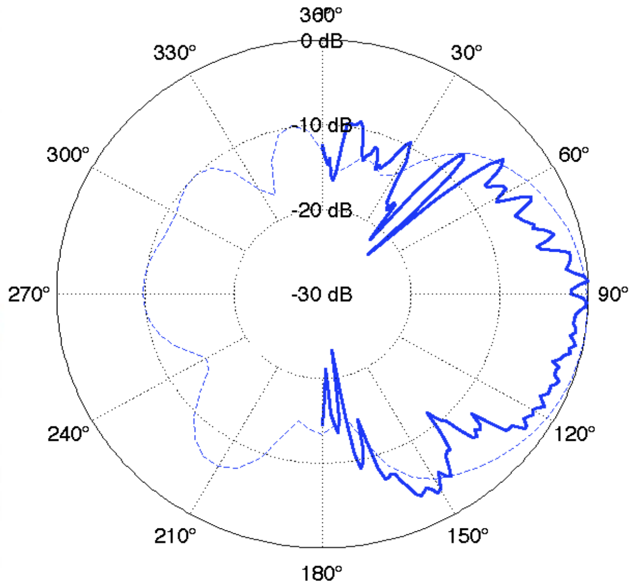
- Compact switched-beam transceiver concept: support for end-fire and normal radiation
- 3mm x 3mm CMOS IC, 11mm x 11mm package
- Low-power (<250mW) with15dBm EIRP

Measured Radiation Patterns for TX antennas (Gain in dBi)

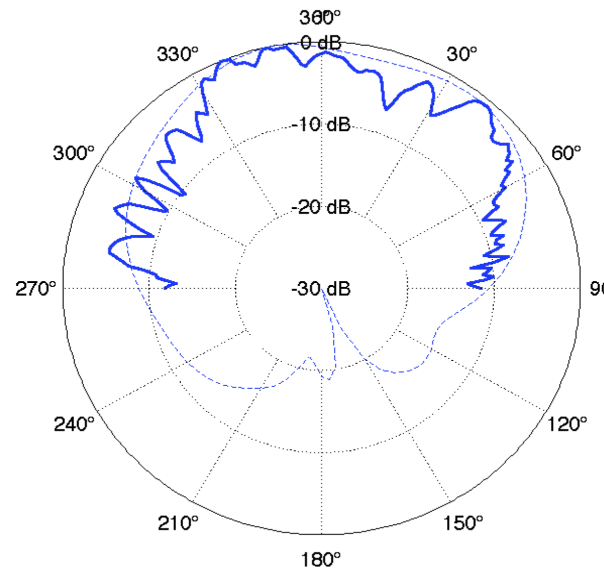


Antenna chamber setup

Measurement Simulation



Yagi antenna
(End-fire direction)

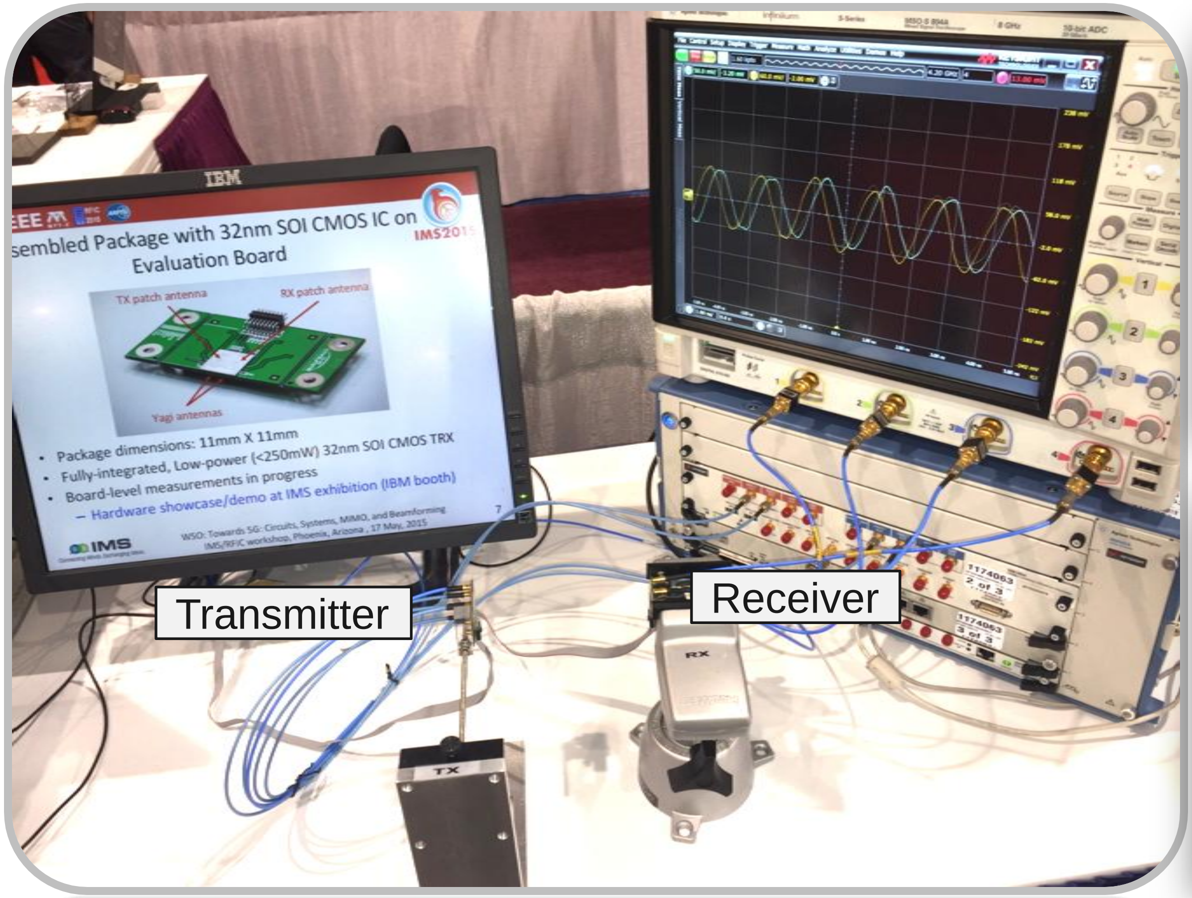


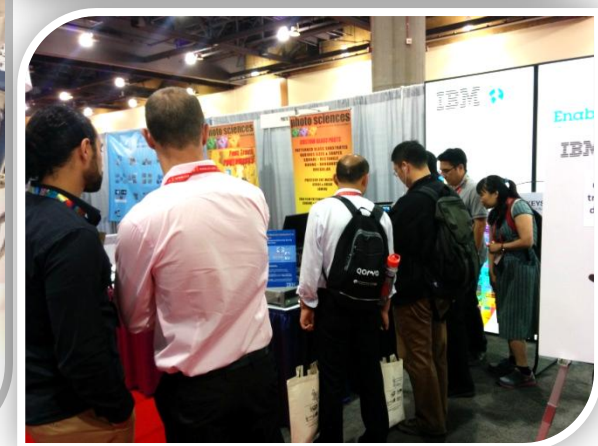
Patch antenna
(normal direction)

- Antennas cover ~270 degrees to provide maximum diversity

X. Gu et al., “A Multilayer Organic Package with Four Integrated 60GHz Antennas Enabling Broadside and End-Fire Radiation for Portable Communication Devices”, IEEE ECTC 2015

Link Demonstration of 60GHz TRX at International Microwave Symposium Exhibition 2015





Demo overview and broad angle antenna coverage:
https://www.dropbox.com/s/hepkxqyw97586xp/ims%20demo%201.mov?dl=0

Penetration through wood and metal for possible imaging applications:
https://www.dropbox.com/s/qlmqsmis3dif00x/ims%20demo%202.mov?dl=0

Penetration through plastic, wood, human body for cellular applications:
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mmWave Production Test Challenges

Mechanical test challenges

- Fragile probes & connectors
- Losses necessitate equipment proximity

Electrical test challenges

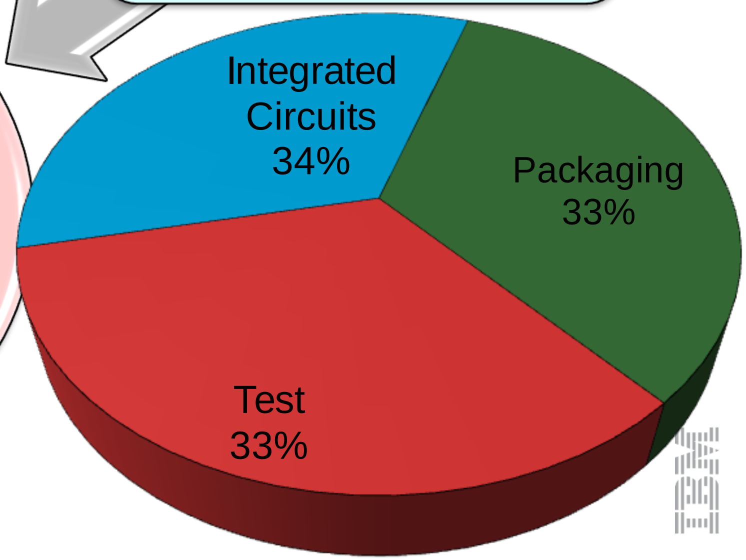
- Noise & phase measurement
- High signal path loss
- Narrowband equipment
- Calibrate, calibrate, calibrate

Other test challenges

- Tests take time
- Tests requires unique setups
- Equipments are expensive

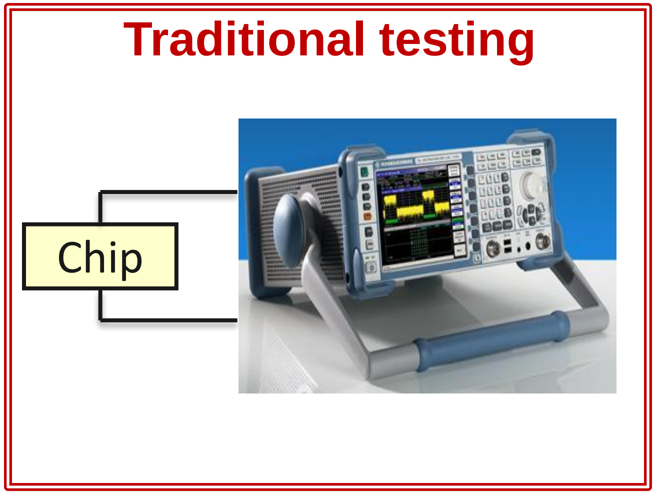
High test cost

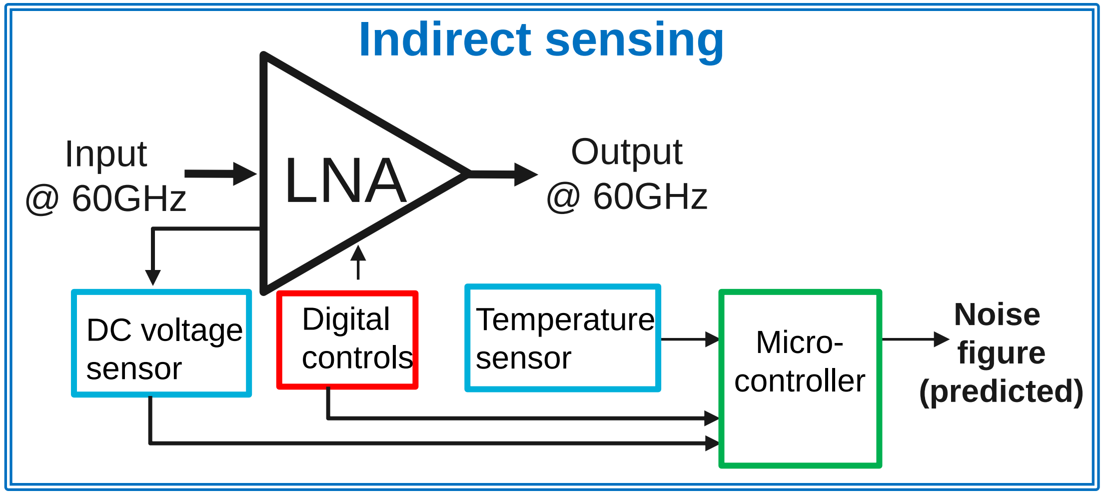
Time + Money

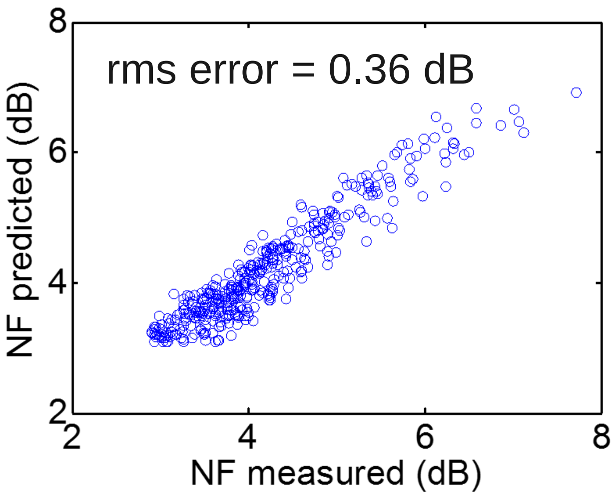


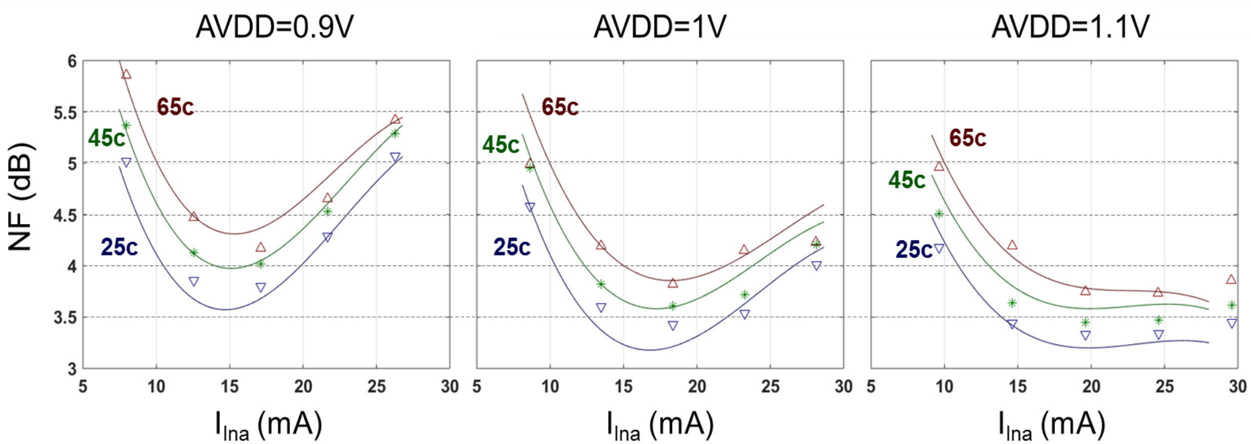
DFT: Indirect Measurements at mmWave

Indirect sensing: Estimate the performance of interest by using other performance metrics that are straightforward to measure









IBM, CMU collaborative project under DARPA HEALICs
For details, see J.-O. Plouchart, et al., RFIC, 2015
Also, for indirect phase noise sensing, see B. Sadhu, et al., JSSC, 2013

Conclusions

- Silicon based mmWave is ready for 5G
  - Cellular, backhaul, D2D
- Antenna and packaging need special attention
  - Co-design is critical
- Testing is expensive – use on-chip test

‘Ultimately though, we should expect mmWave systems to become as inexpensive and ubiquitous as 2.4- and 5-GHz WLAN systems are today. Some of the early companies developing products in the mmWave space will succeed and become profitable, and some will fail. But the end result will be “millimeter-waves for the masses.”’ -- Advanced Millimeter Wave Technologies: Antenna, Packaging and Circuits, Wiley Press, 2009

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