WSB:
100-300GHz systems:
Architectures and Applications

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Acknowledgement: This work was supported in part by the Semiconductor Research Corporation (SRC) and DARPA.

Acknowledgements

Systems


Sundeep Rangan
Networks, Applications, MIMO, Power


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MIMO algorithms
Imaging algorithms
Compressive imaging


Christoph Studer
Cornell
MIMO algorithms
VLSI MIMO
digital beamforming


Andreas Molisch
USC
100-300GHz propagation measurements


Danijela Cabric
UCLA
MIMO algorithms (funding via CONIX)

ICs


Ali Niknejad
UC Berkeley
mm-wave CMOS: hub
mm-wave arrays
mm-wave MIMO


James Buckwalter
UC Santa Barbara
efficient PAs
III-V arrays


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140-300GHz
SiGe ICs


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high-frequency packaging


Gabriel Rebeiz
UC San Diego
mm-wave CMOS: handset
mm-wave arrays


Alyosha Molnar
Cornell
N-path mixers
MIMO ADCs


Elad Alon
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design automation
equalizers


Tim Fisher
UCLA
advanced packaging materials


Andrew Kummel
UCSD
advanced packaging materials

Transistors


Umesh Mishra
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N-polar GaN HEMTs for 140, 210GHz


Huili (Grace) Xing
Cornell
AlN/GaN HEMTs for 140, 210GHz


Susanne Stemmer
UC Santa Barbara
transistors in novel materials


Debdeep Jena
Cornell
GaN HEMTs on Si


Srabanti Chowdhury
UC Davis
Diamond cooling for GaN

Massive MIMO demo.

Borivoje Nikolic
UC Berkeley
VLSI design automation
VLSI MIMO processors

Compressive imaging

Amin Arbabian
Stanford
140GHz radar chipsets and arrays

140/210/280GHz arrays for demos.

Mark Rodwell
UC Santa Barbara
THz HBTs for PAs
THz HEMTs for LNAs

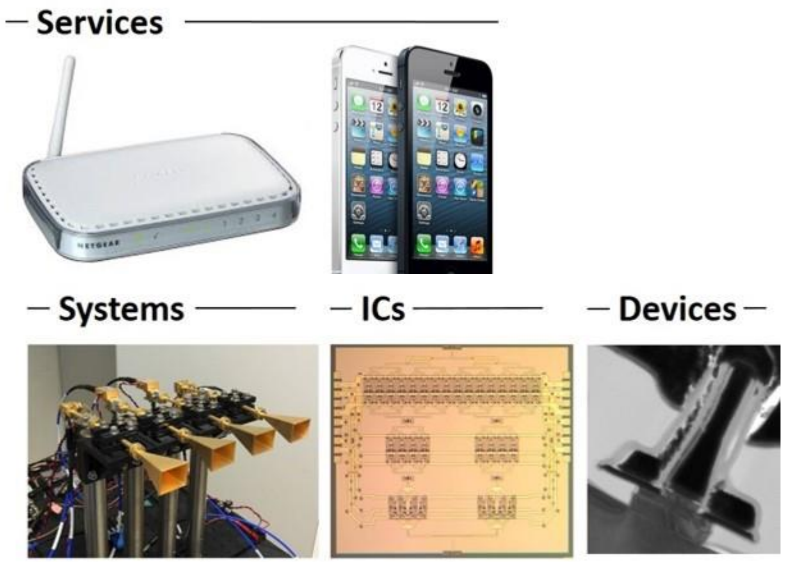
JUMP + nCORE Official Sponsors

100-300GHz Wireless

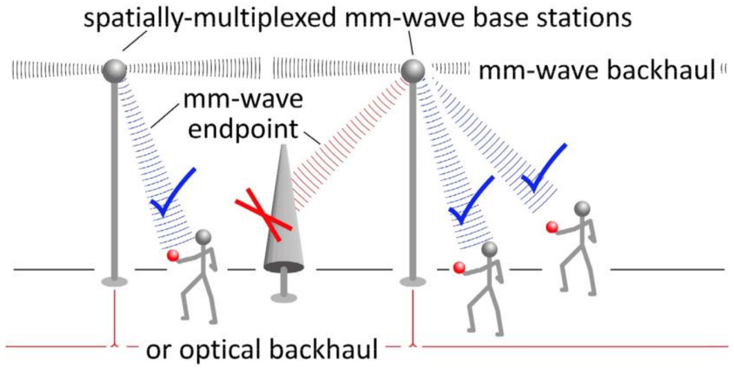
Wireless networks: exploding demand.

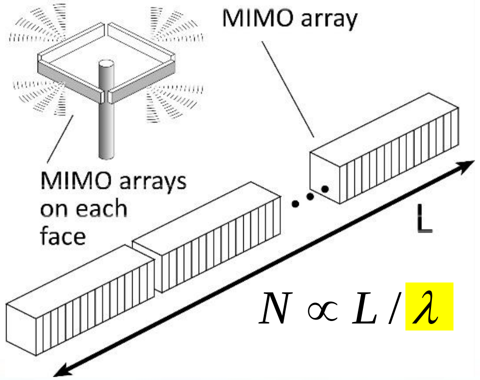
Immediate industry response: 5G.
- ~10~40 GHz ("5G")
- ~40~100GHz ("5.5G ?")
- increased spectrum, extensive beamforming

Next generation (6G ??): above 100GHz.. (?)
- greatly increased spectrum, massive spatial multiplexing

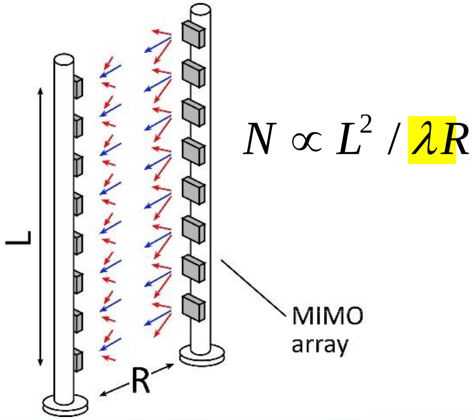


100-300GHz carriers, massive spatial multiplexing
→ Terabit hubs and backhaul links, high-resolution imaging radar

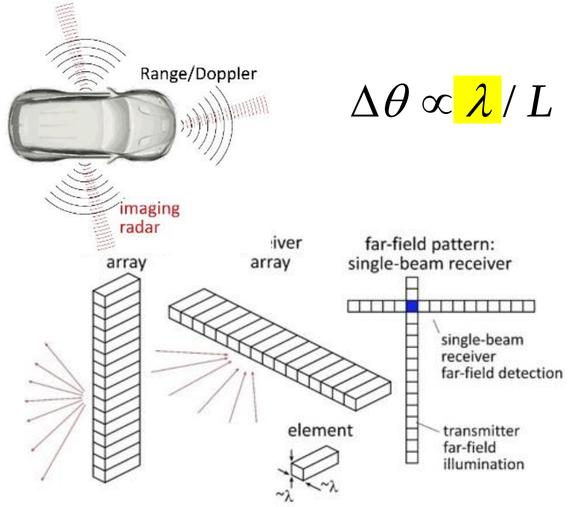




$N \propto L / \lambda$



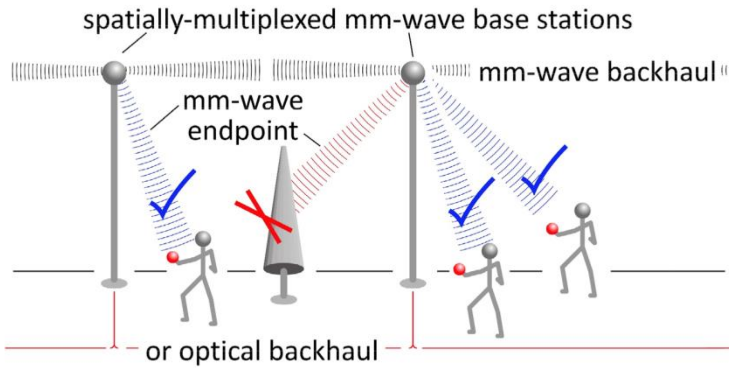
$N \propto L^2 / \lambda R$

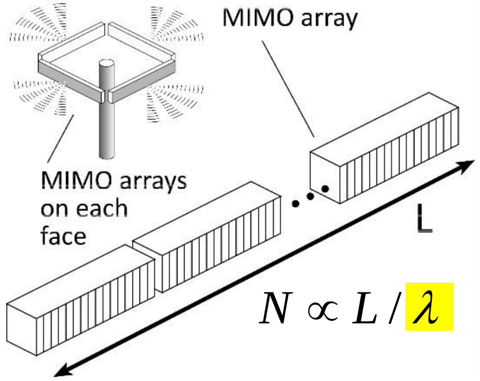


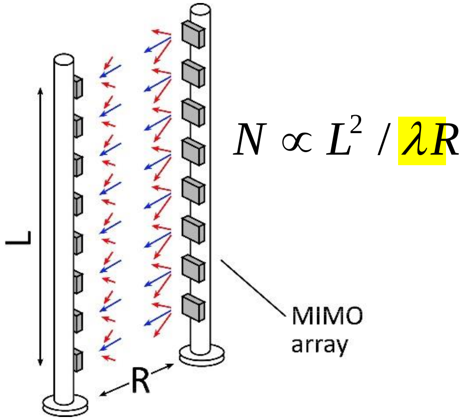
$\Delta\theta \propto \lambda / L$

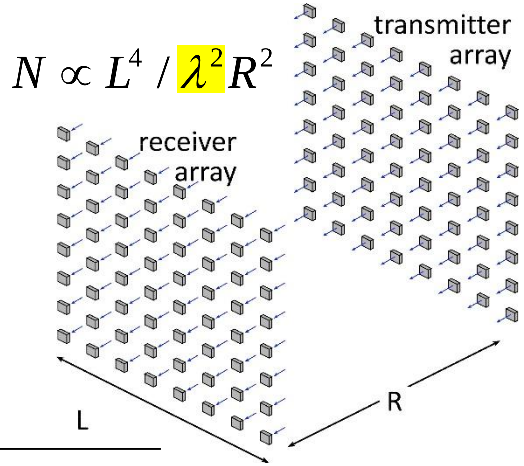
Benefits of Short Wavelengths

Communications: Massive spatial multiplexing, massive # of parallel channels. Also, more spectrum!

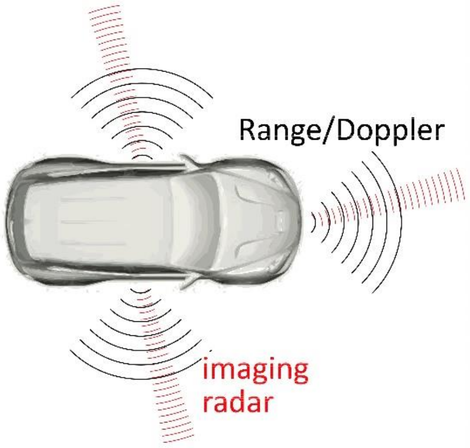


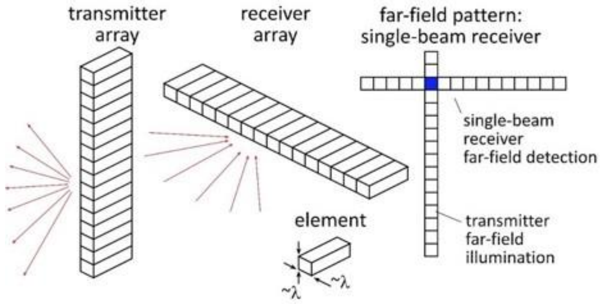






Imaging: very fine angular resolution





$$\Delta\theta \propto \lambda / L$$

But:

High losses in foul or humid weather.
High λ^2/R^2 path losses.
ICs: poorer PAs & LNAs.
Beams easily blocked.

100-340GHz wireless:
terabit capacity,
short range,
highly intermittent

Opportunities and Challenges

Wireless above 100 GHz:

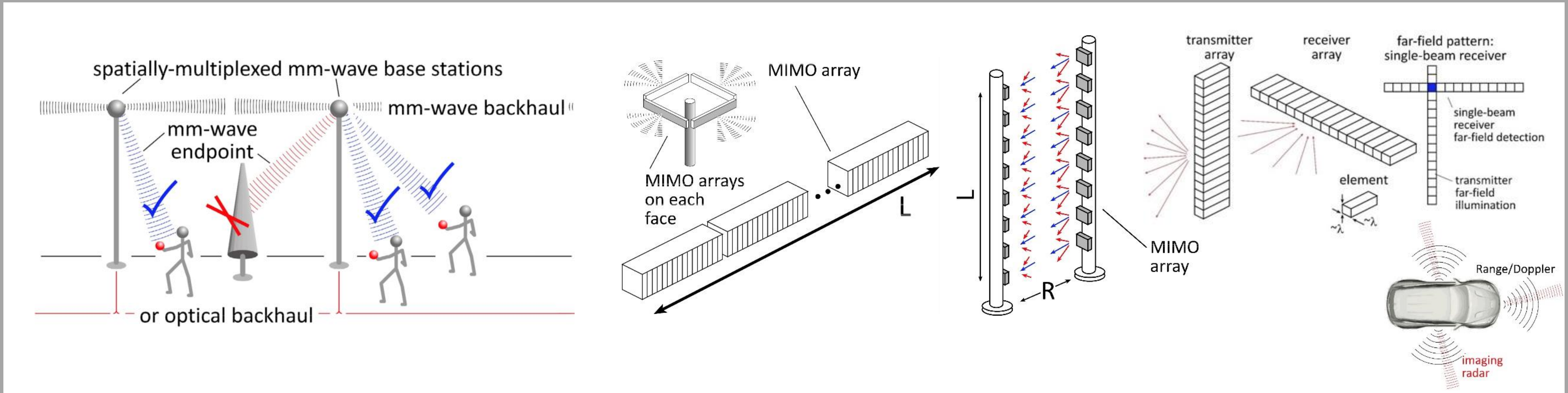
Massive capacities
large available bandwidths
massive spatial multiplexing in base stations and point-point links

Very short range: few 100 meters
short wavelength, high atmospheric losses. Easily-blocked beams.

IC Technology
All-CMOS for short ranges below 200 GHz.
SiGe, GaN, or III-V LNAs and PAs for longer-range links. Just like cell phones today
SiGe or III-V frequency extenders for 220GHz and beyond

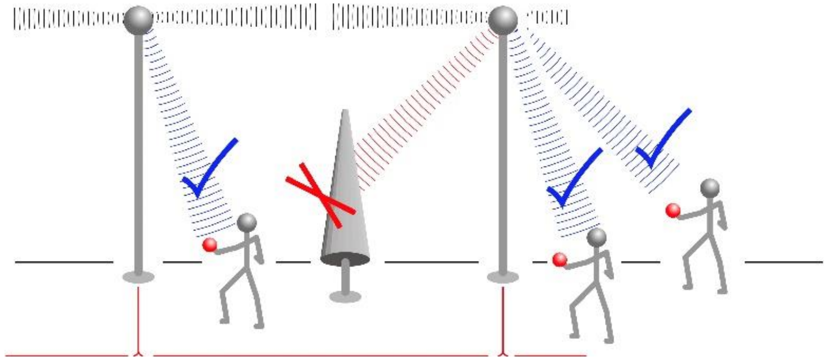
The challenges
digital beamformer computational complexity
packaging: fitting signal channels in very small areas
mesh networking to accommodate beam blockage
driving the technologies to low cost

Applications

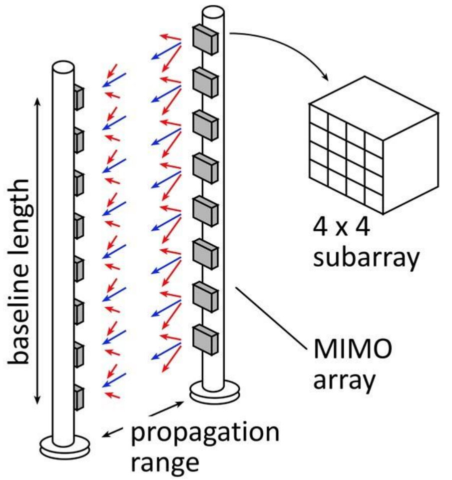


Potential 100-300GHz Systems

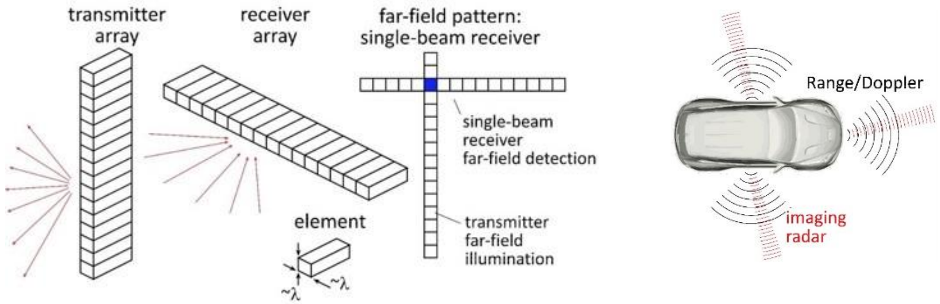
140GHz MIMO Hub

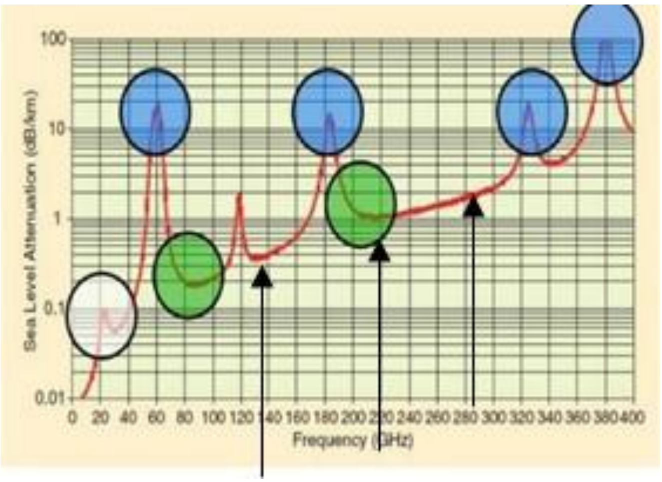


210 or 280GHz MIMO Backhaul

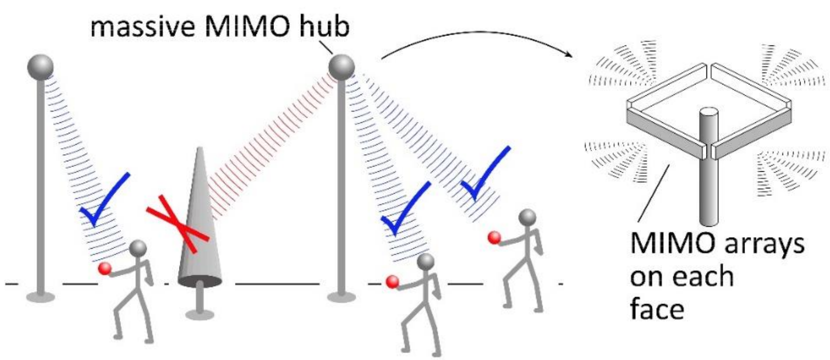


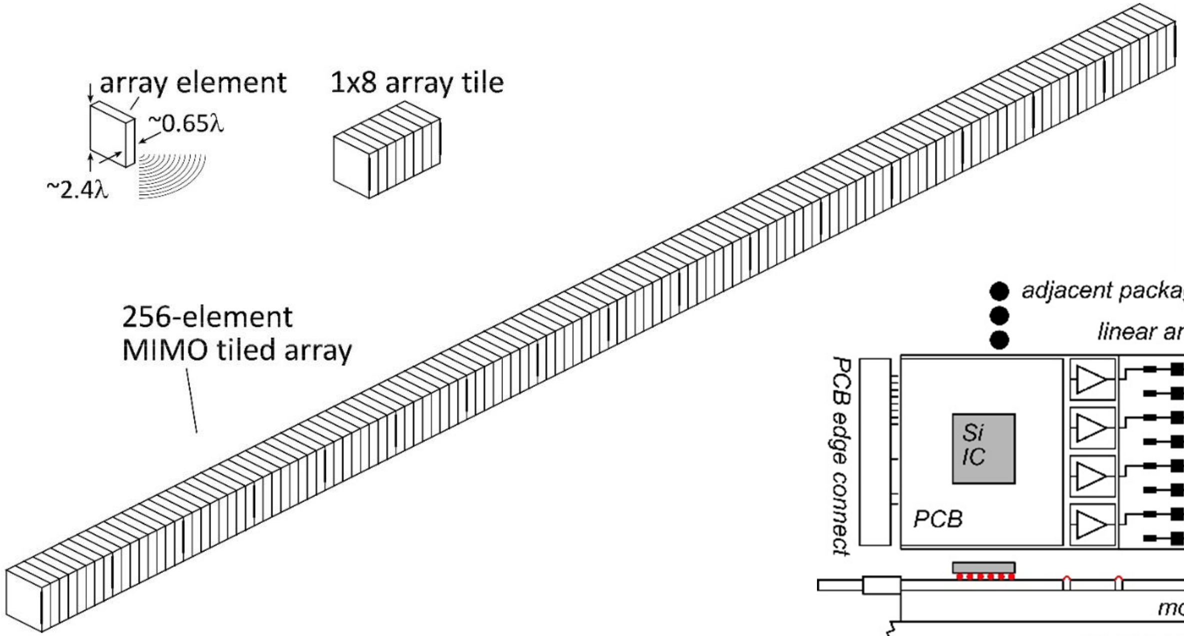
140 or 210GHz Imaging Radar

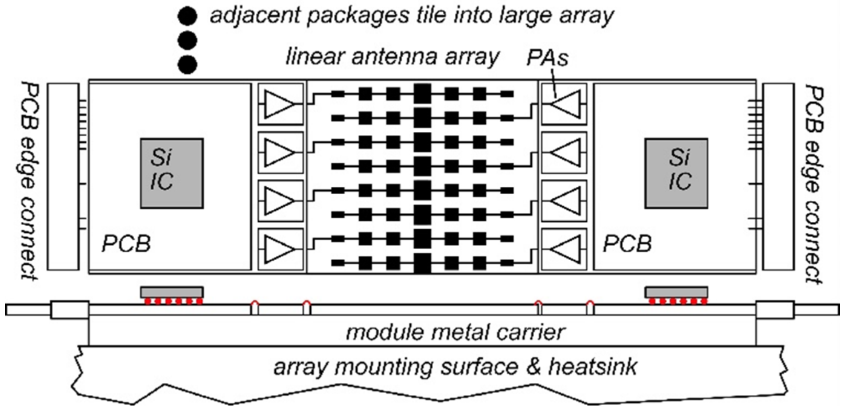




140GHz massive MIMO hub





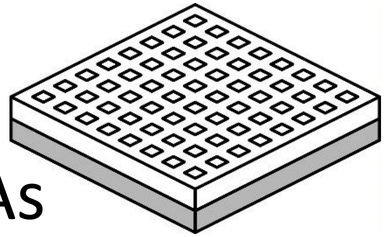


0.5-5 Tb/s spatially-multiplexed 140GHz base station

128 users/face, 4 faces. P_{1dB}=21 dB_m PAs, F=8dB LNAs

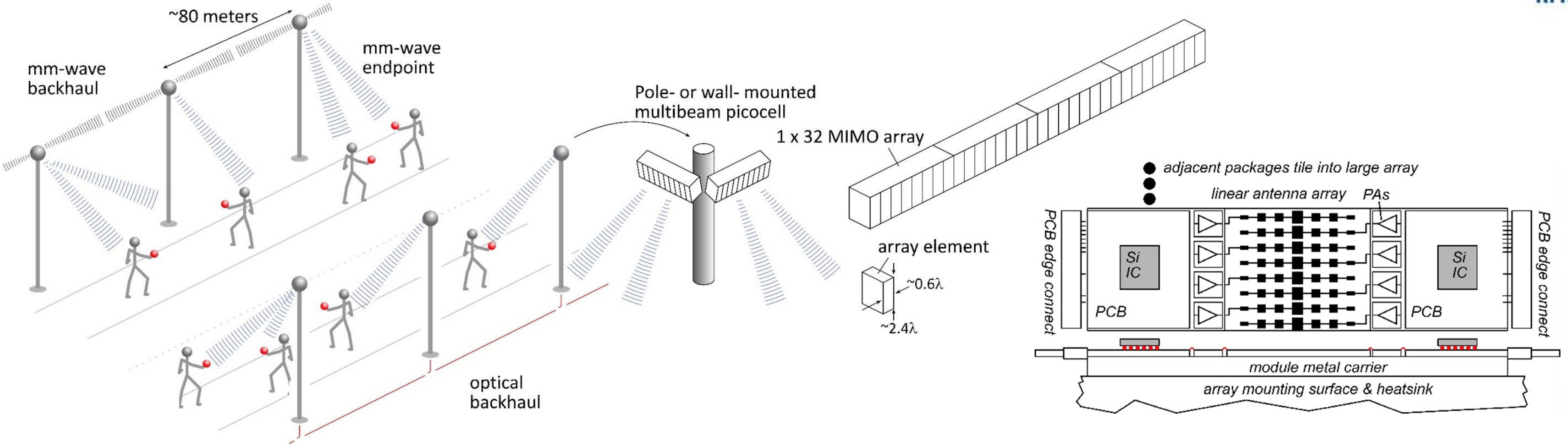
512 total users @ 1 user/beam, 1,10 Gb/s/beam;

230, 100 m range in 50mm/hr rain with **17**dB total margins



Handset:
8 × 8 array
(9×9mm)

140GHz moderate-MIMO hub

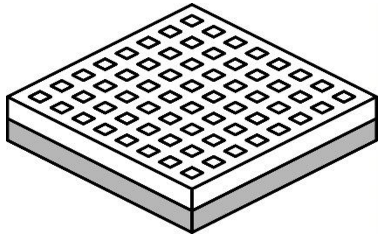


If demo uses 32-element array (four 1×8 modules):

16 users/array. P_{1dB}=21 dB_m PAs, F=8dB LNAs

1,10 Gb/s/beam→ 16, 160 Gb/s total capacity

70, 40 m range in 50mm/hr rain with **17**dB total margins



Handset:
8 × 8 array
(9×9mm)

Range varies as (# hub elements)$^{0.5}$ → (Service area/element) is constant

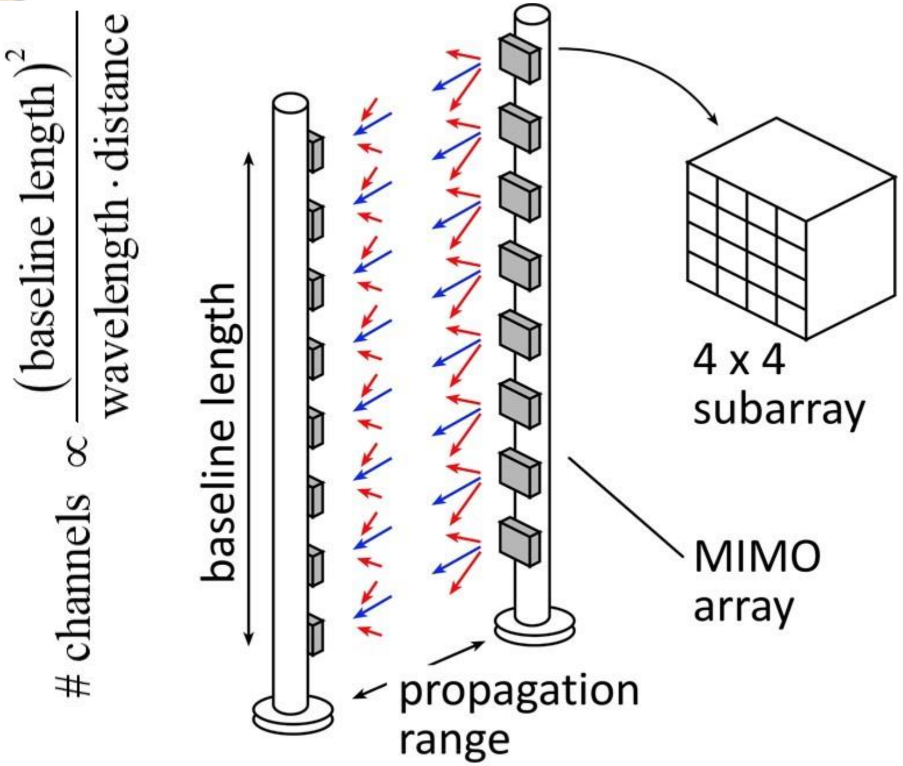
70 GHz spatially multiplexed base station

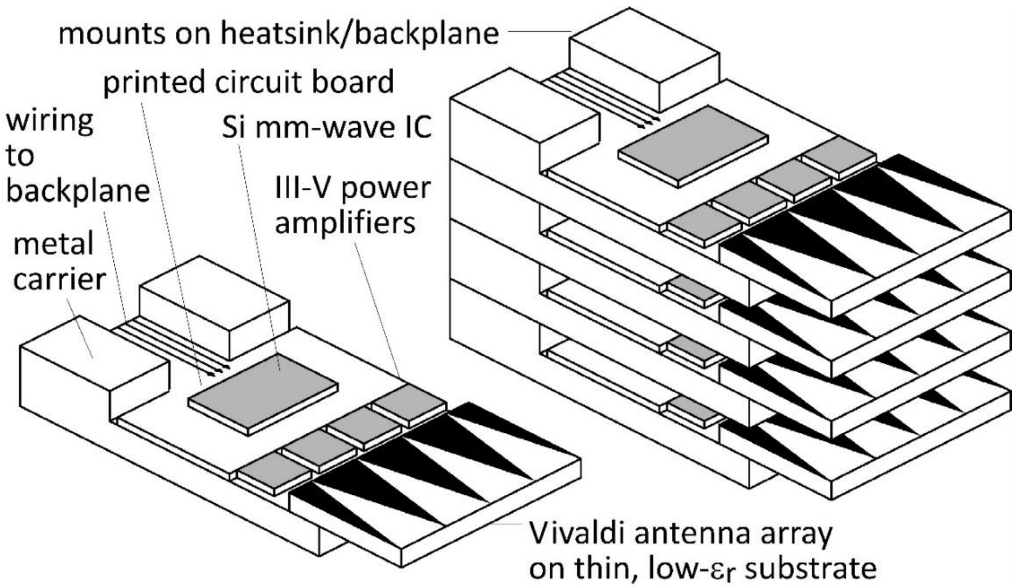
If we use instead a 70GHz carrier,
the range increases to **168 meters** (vs. **100 meters**)
but the handset becomes 16mm×16mm (vs. 8mm×8mm),
and the hub array becomes 20mm×524mm (vs. 10mm×262mm)

Or, use a 4×4 (8mm×8mm) handset array,
and the range becomes ..**100 meters**.

Same handset area (more handset elements)→ same link budget
Easier to obtain license for 140±2.5GHz than 75±2.5GHz

220 GHz, 640 Gb/s MIMO Backhaul





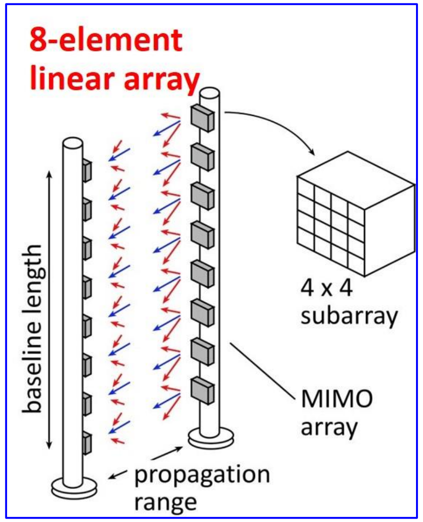
8-element MIMO array
3.1 m baseline.
80Gb/s/subarray→ 640Gb/s total
4 × 4 sub-arrays → 8 degree beamsteering

Key link parameters
500 meters range in 50 mm/hr rain; 23 dB/km
24 dB total margins:
packaging loss, obstruction, operating, design, aging
PAs: 24mW P_{out} (per element)
LNAs: 6dB noise figure

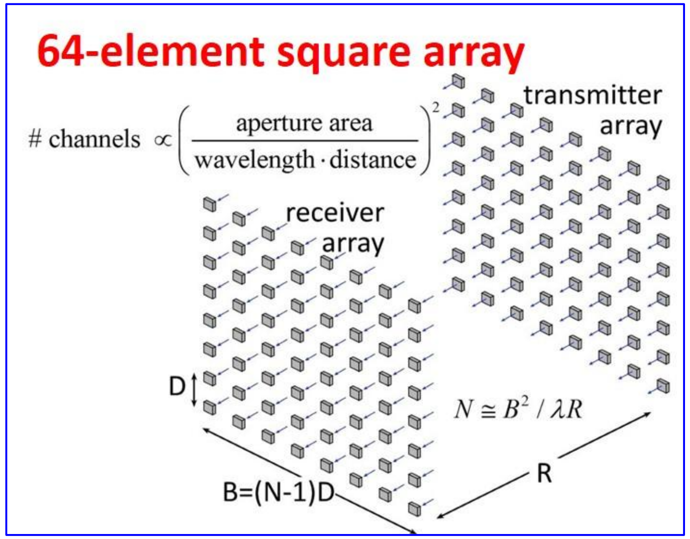
210 GHz, 5.1 Tb/s MIMO backhaul

500m range in 50mm/hr. rain.

8-element 640Gb/s linear array:
requires 14dB$_m$ transmit power/element (P_{out})
....3.2W total output power
requires 2.1m linear array



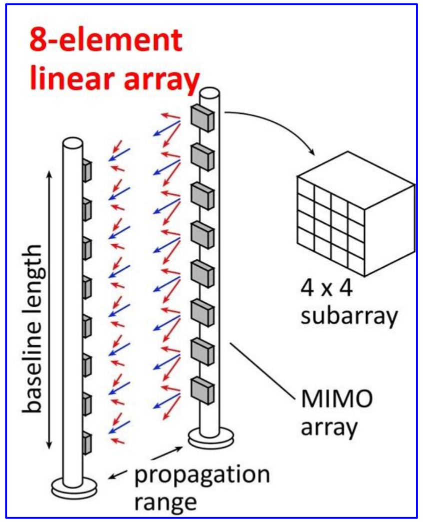
64-element 5Tb/s square array:
same link assumptions
requires 5dB$_m$ transmit power/element (P_{out})
....3.2W total output power
requires 2.1m square array



Complex system: can we make it cheaply ?

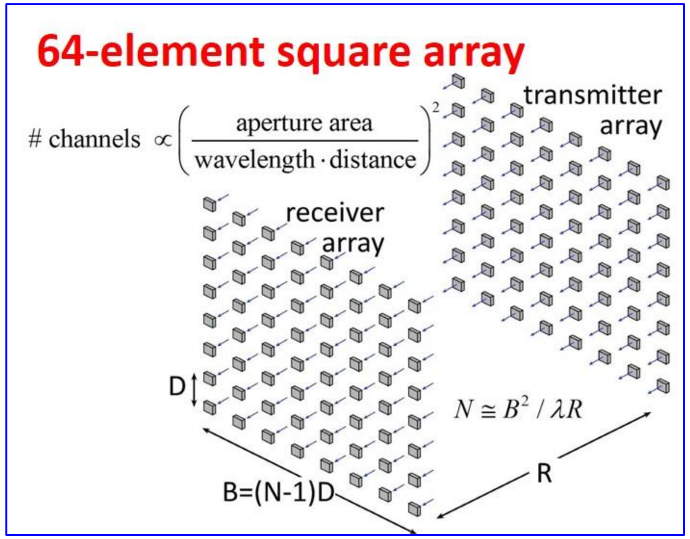
70 GHz, 640 Gb/s MIMO backhaul (16QAM)

Why not use a lower-frequency carrier, e.g. 70 GHz ?



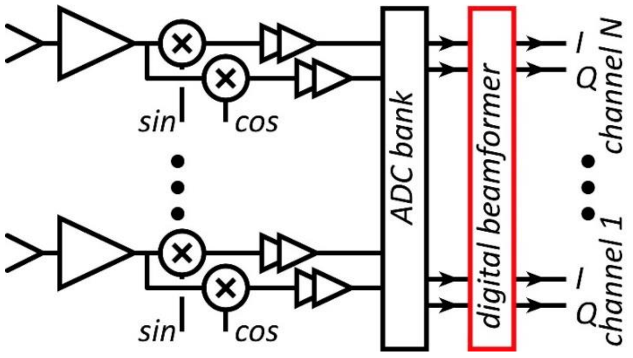
8-element 640Gb/s linear array:
requires 11dB$_m$ transmit power/element (P_{out})
....1.7W total output power
requires 5.5m linear array

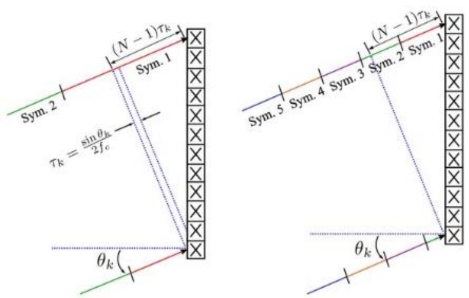
64-element 5Tb/s square array:
same link assumptions
requires 2dB$_m$ transmit power/element (P_{out})
....1.7W total output power
requires 5.5m square array



Similar RF power output, physically larger

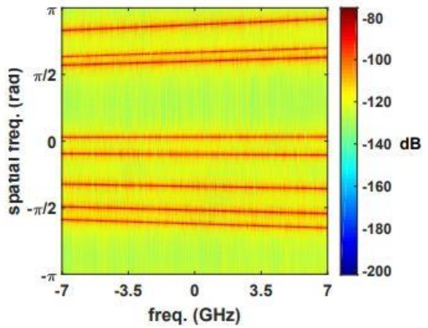
Systems



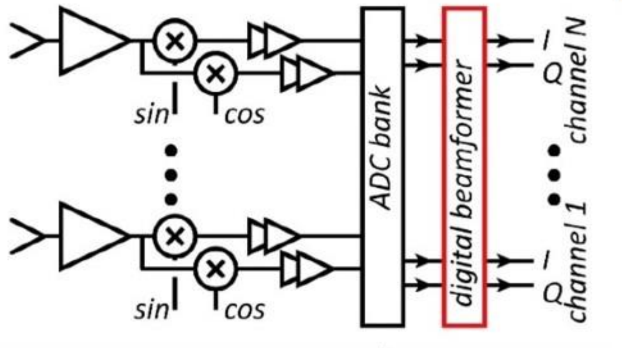


(a) Narrowband scenario.

(b) Wideband scenario.



System Design

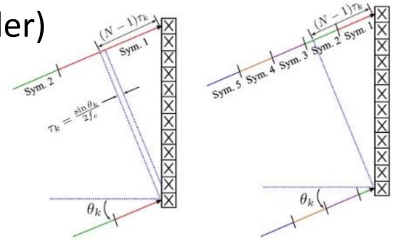


ADCs/DACs: only 3-4 bit ADC/DACs required (Madhow, Studer, Rodwell)

Linearity: Amplifier P_{1dB} need be only 3dB above average power (Madhow).

Phase noise: Requirements same as for SISO (Alon, Madhow, Niknejad, Rodwell)

Efficient digital beamforming: beamspace algorithm=complexity ~N× log(N) (Madhow, Studer)

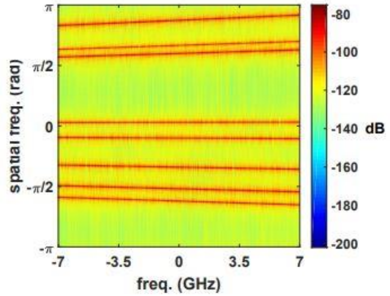


(a) Narrowband scenario. (b) Wideband scenario.

Efficient digital beamforming: low-resolution matrix (Studer)

Efficient channel estimation : fast beamspace algorithm (Studer)

Efficiently addressing true-time-delay problem: "rainbow" FFT algorithm (Madhow, Cabric, Studer)

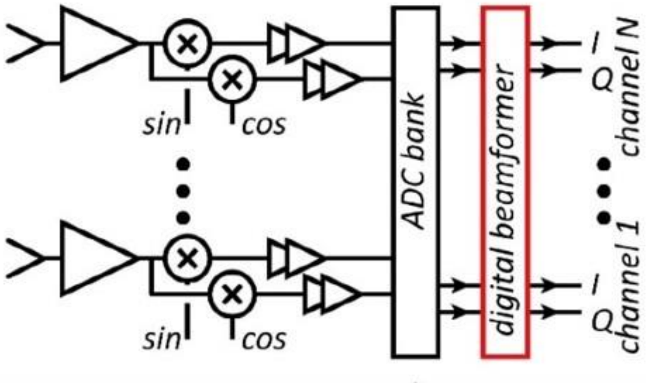


System Design

ADC resolution:

N ADC bits, M antennas, K signals: SNR=$6N+1.76+10\cdot\log_{10}(M/K)$

3 bits, $(M/K)=2\rightarrow$ SNR=23 dB. QPSK needs 9.8 dB.



Jammer tolerance:

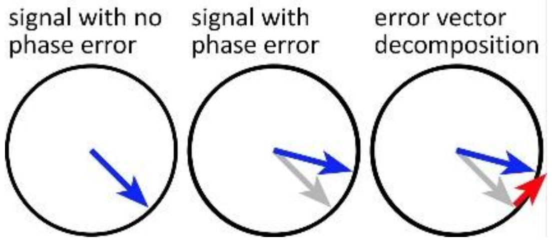
Increase ADC resolution by 1 bit→ $P_{jammer,max} = K\cdot P_{signal}$

Maximum jammer power = sum of all user's power.

Phase noise:

Phase error σ_ϕ : SNR= $-20\cdot\log_{10}(\sigma_\phi)+10\cdot\log_{10}(M/K)$, where $\sigma_\phi^2 = \int_{f_{low}}^{f_{symbol}/2} L(f)df$.

MIMO and SISO require similar $L(f)$.

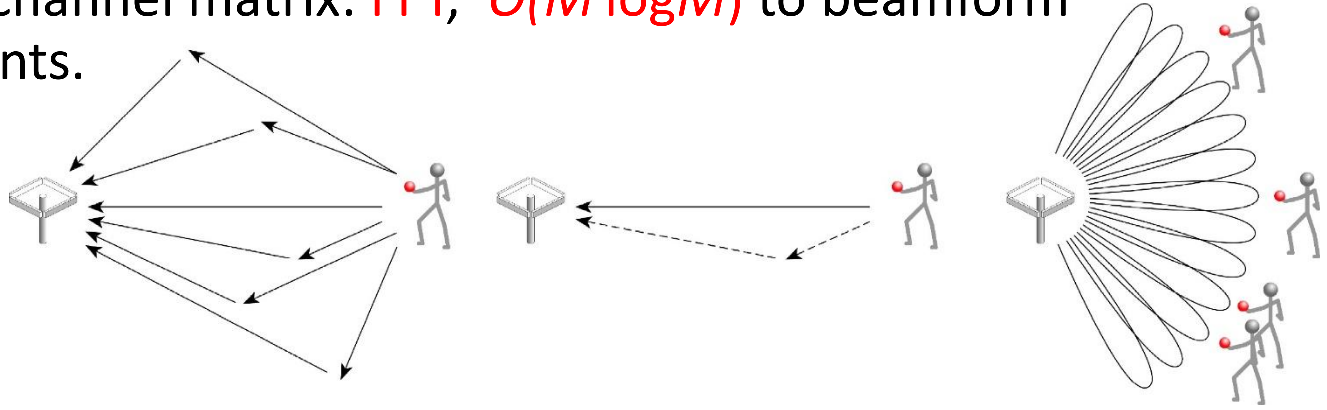


Beamspace:

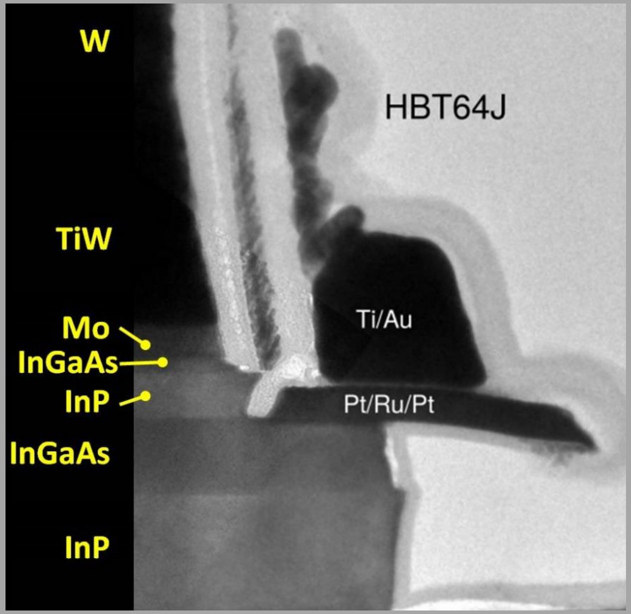
lower frequencies, many NLOS paths, complicated channel matrix: $O(M^3)$ to beamform

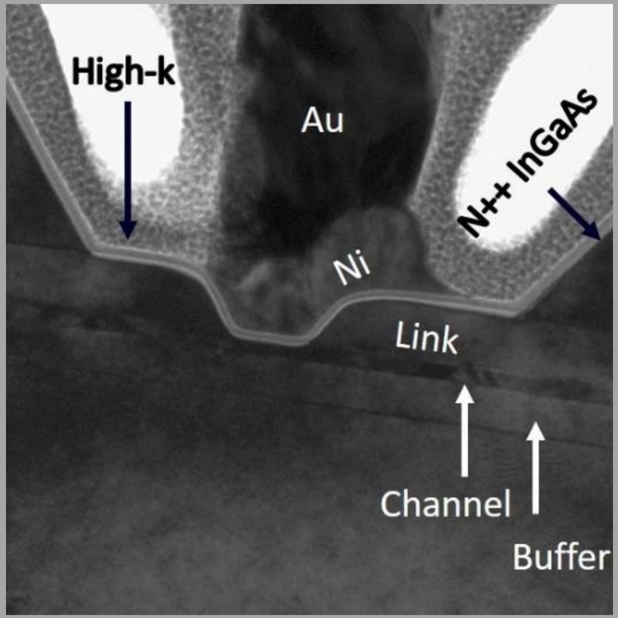
higher frequencies, few NLOS paths, simpler channel matrix: FFT, $O(M\cdot\log M)$ to beamform

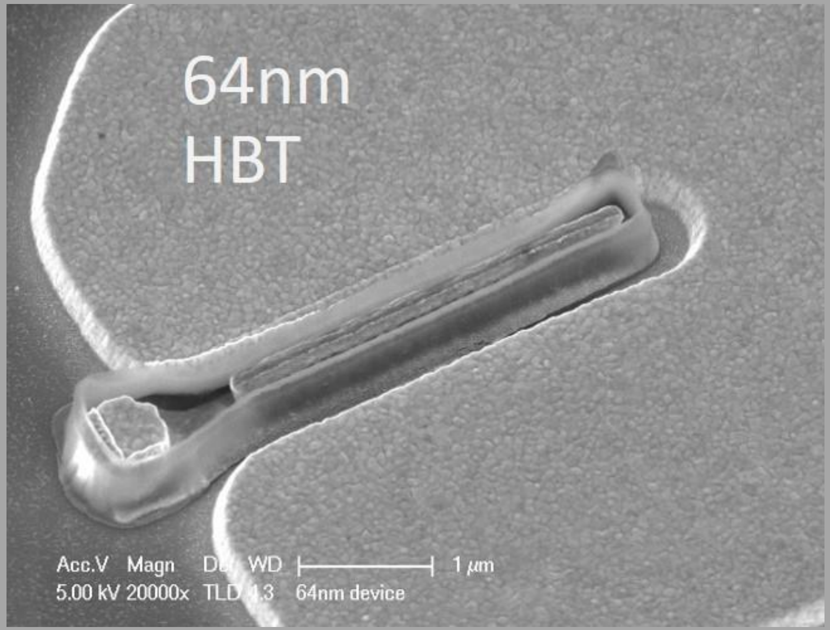
fewer bits in signal; fewer bits in FFT coefficients.



Transistors







100-1000 GHz Transistors and ICs

	f_{max} GHz	Good ICs to (GHz)	complexity	LNAs	PAS	increased bandwidth ?
CMOS	350	150/200	transceivers	good	weak: 10-30 mW	not easy
Production SiGe	300	200/250	transceivers	ok	OK: 20-100 mW	depends on $$
R&D SiGe	700	300/500	transceivers	good	OK: 20-100 mW	2-3THz
R&D InP HBT	1150	400/650	PA, converters	ok*	good: 100-200 mW	2-3THz
R&D InP HEMT	1500	500/1000	LNA	great	weak: 20-50 mW	2-3THz
R&D GaN	400	120/140	PAs	good	excellent: 0.1-1W	600GHz

ICs with useful performance, hero experiments

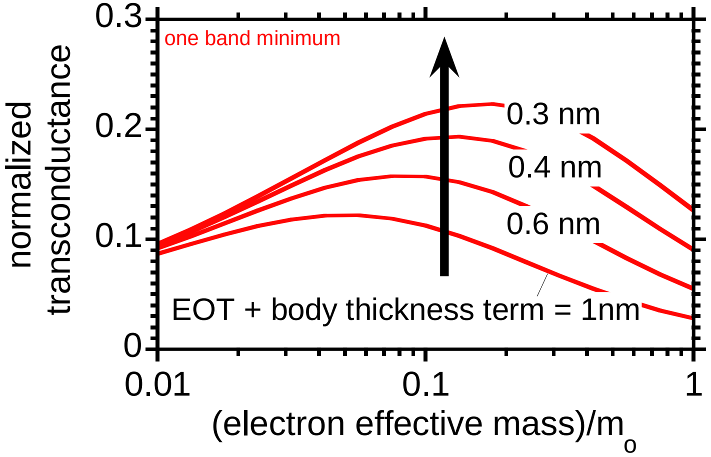
*can be addressed

There are THz transistors today; their bandwidth will increase

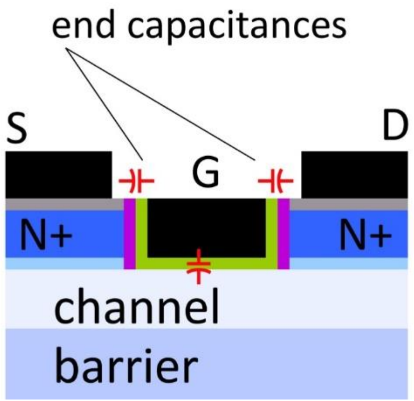
Challenge: reducing costs, increasing market size

mm-Wave CMOS won't scale much further

Gate dielectric can't be thinned
→ on-current, g_m can't increase



Shorter gates give no less capacitance
dominated by ends; ~1fF/μm total

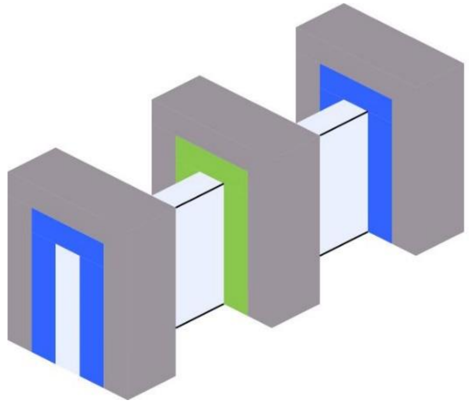


Maximum g_m, minimum C→ upper limit on f_τ.
about 350-400 GHz.

Tungsten via resistances reduce the gain

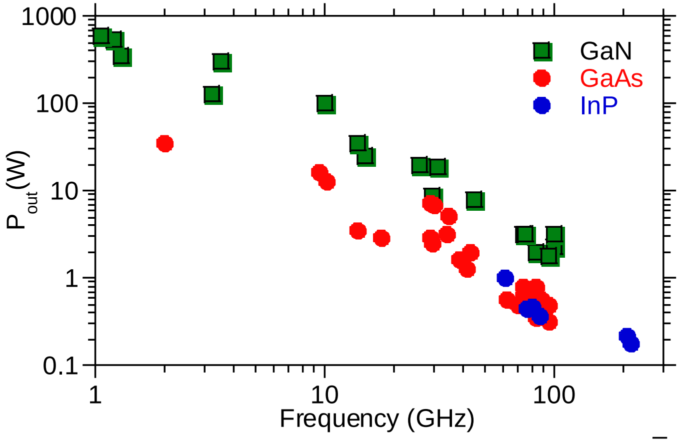
Inac et al, CSICS 2011

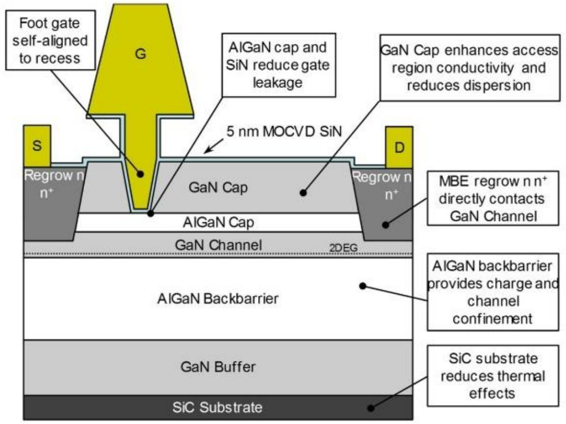
Present finFETs have yet larger end capacitances



mm-Wave Transistor Development

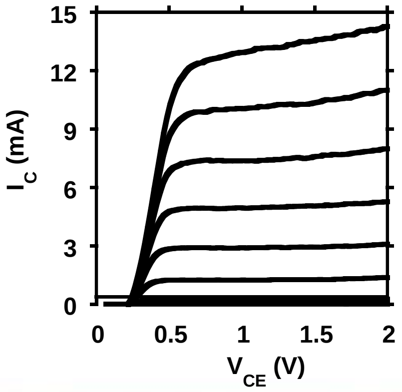
InGaN and GaN HEMTs:
High power from 100-340GHz
GaN: superior power density at all frequencies

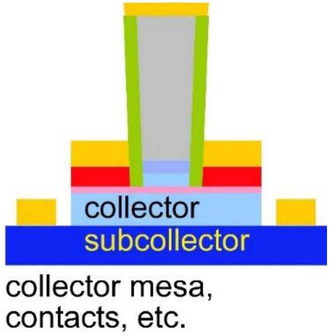




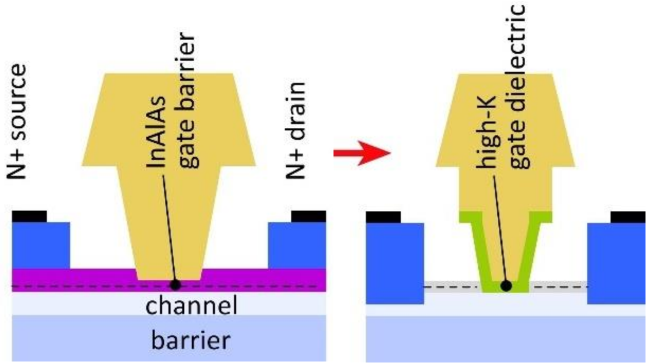
N-polar GaN: Mishra, UCSB

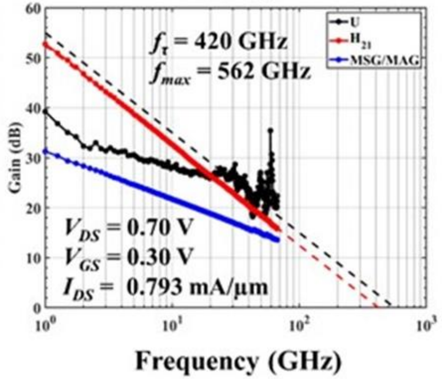
THz InP HBTs:
State-of-art: 1.1THz f_{max} @ 130nm node
Efficient 100-650GHz power
more f_{max}: more efficient, higher frequencies
base regrowth: better contacts→ higher f_{max}.
status: working DC devices; moving to THz



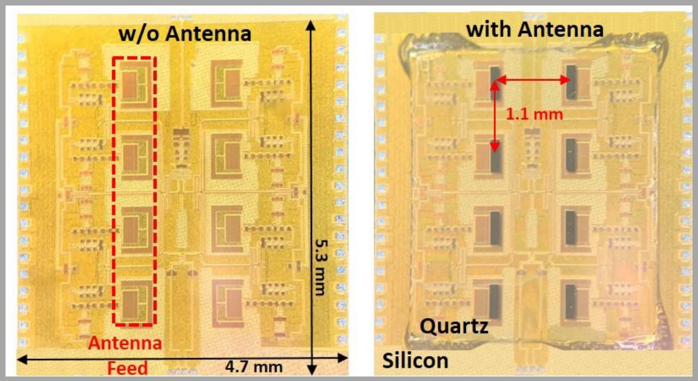


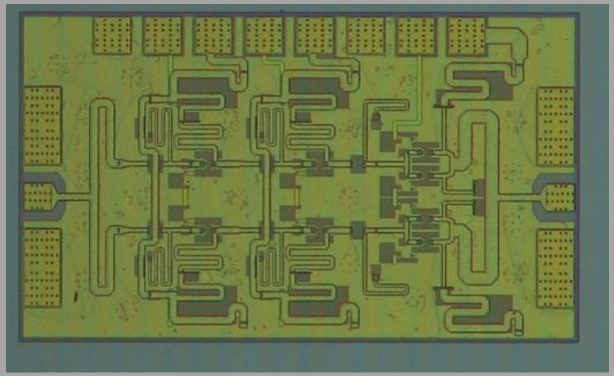
THz InP HEMTs:
State-of-art: 1.5THz f_{max} @ 32nm node
Sensitive 100-650GHz low-noise amplifiers
more f_τ: lower noise, higher frequencies
high-K gate dielectric → higher f_τ, f_{max}

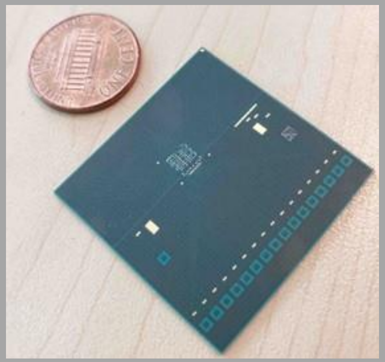


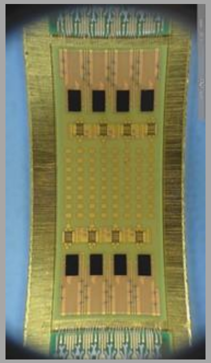


ICs and Packages:
140 GHz



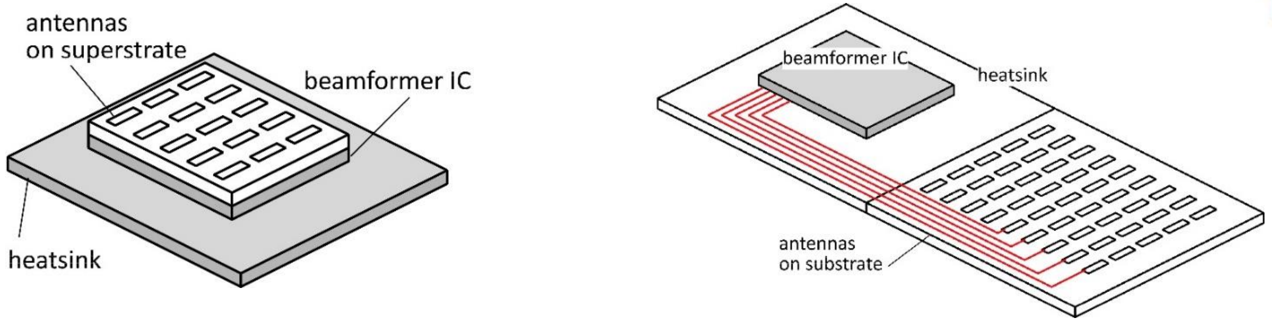






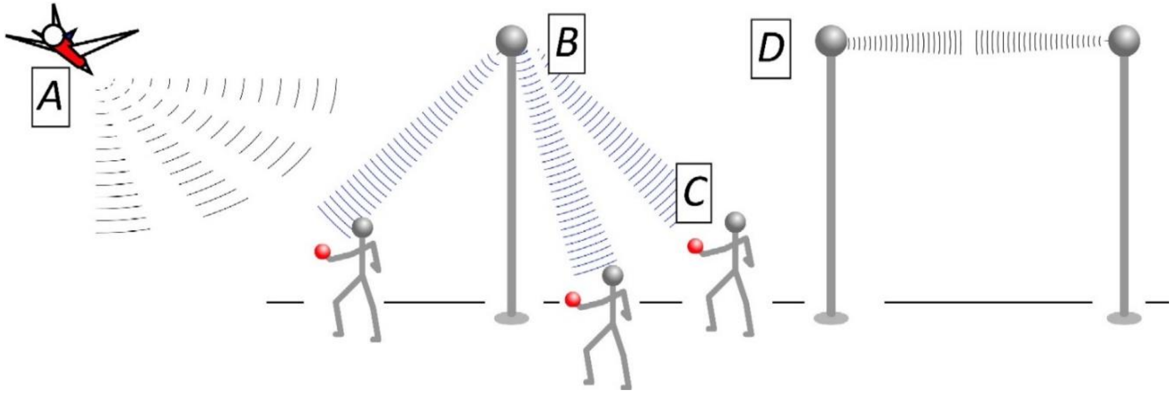
The mm-wave module design problem

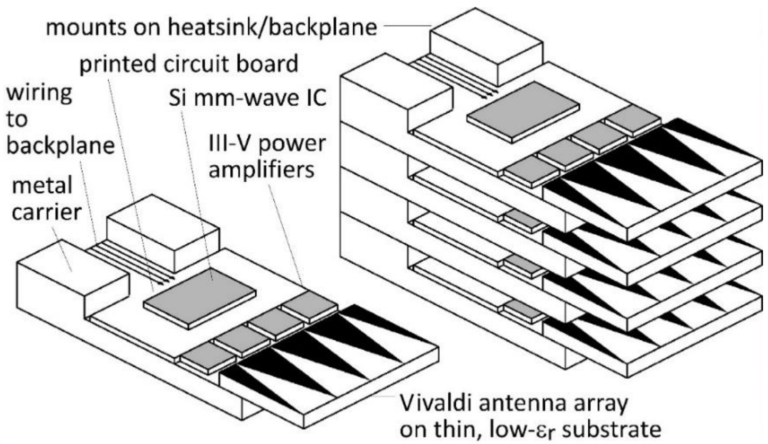
How to make the IC electronics fit ?
How to avoid catastrophic signal losses ?
How to remove the heat ?

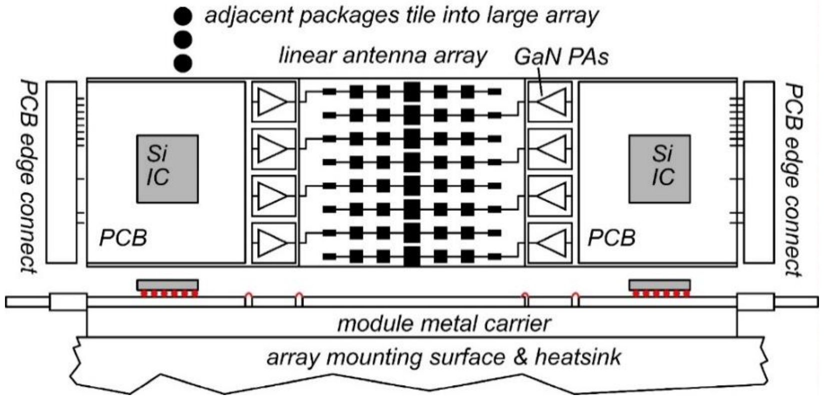


Not all systems steer in two planes...
...some steer in only one.

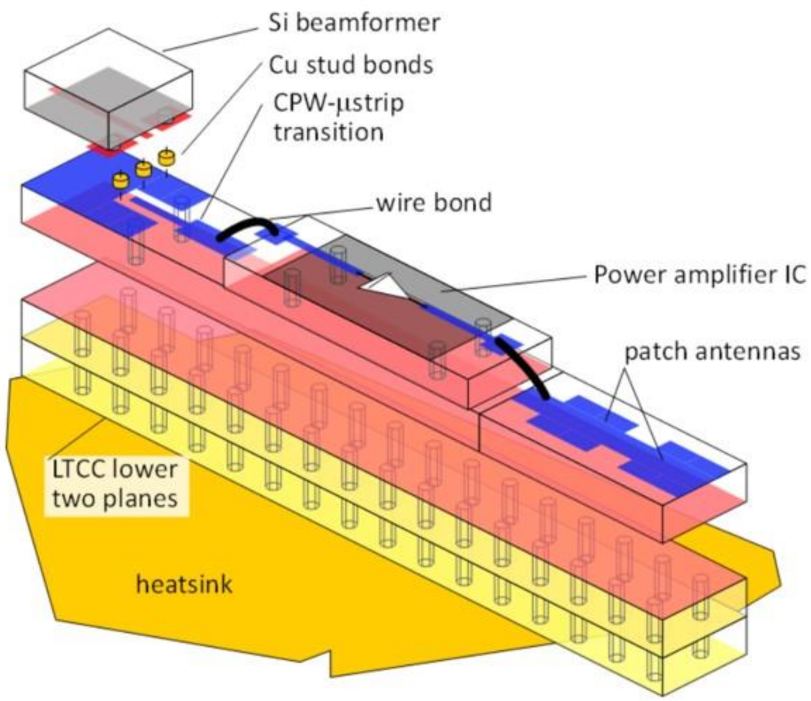
Not all systems steer over 180 degrees...
...some steer a smaller angular range



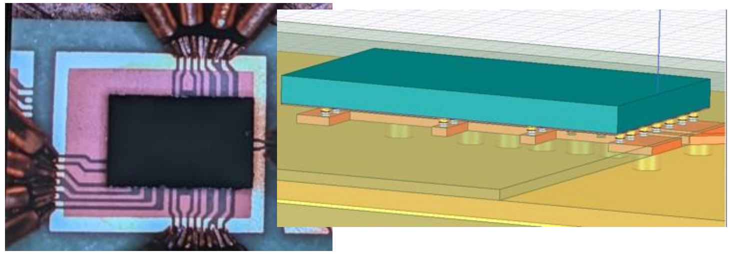




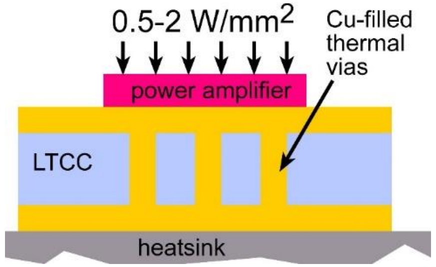
140GHz hub: packaging challenges



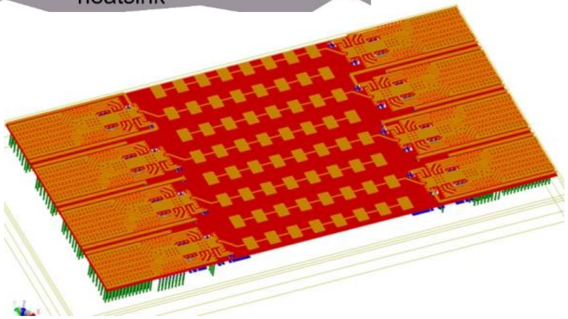
IC-package interconnects
Difficult at > 100 GHz



Removing heat
Thermal vias are marginal



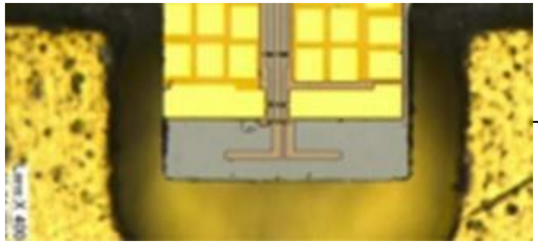
Interconnect density
Dense wiring for DC, LO, IF, control.
Hard to fit these all in.



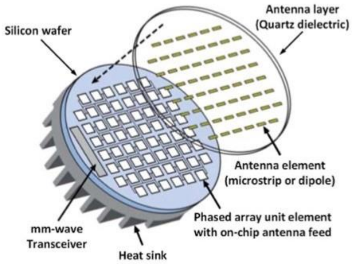
Economies of scale
Advanced packaging standards require sophisticated tools
High-volume orders only
Hard for small-volume orders (research, universities)
Packaging industry is moving offshore

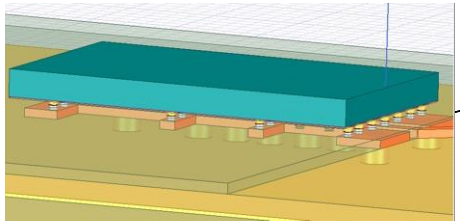
100-300GHz IC-package connections

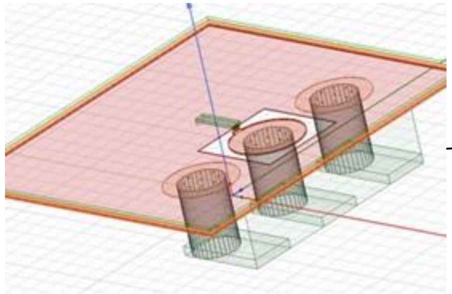
Deal, IEEE Trans THz, Sept 2011

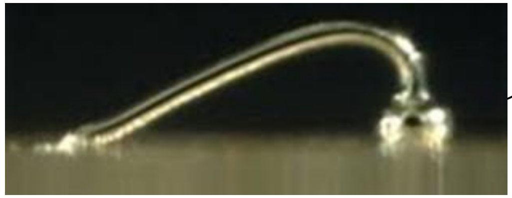


G. Rebeiz





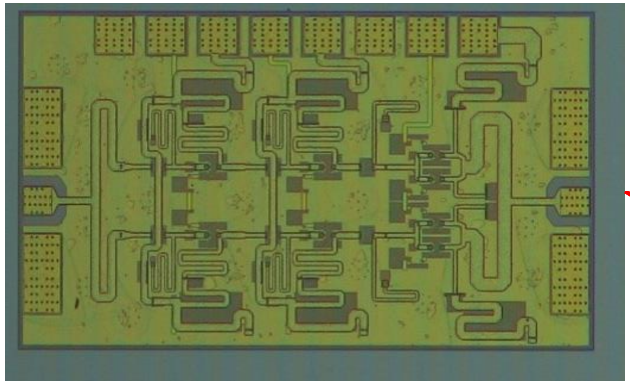




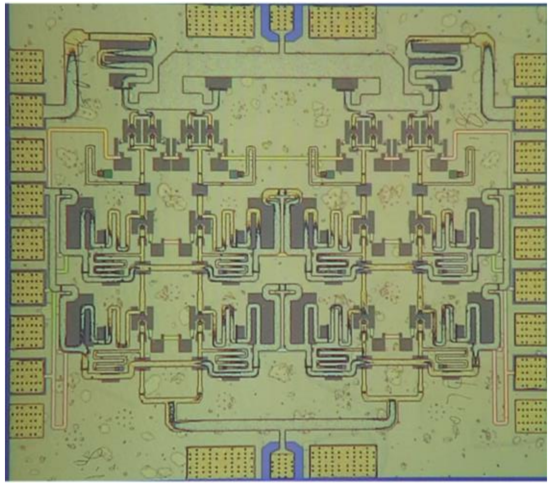
type	Frequency	technology	cost	heatsinking
micromachined waveguide interface	1000 GHz	Research. Cheap one day ?	**high** ✗	good
ribbon, mesh bond	200 GHz	Handcrafted.	**high** ✗	good
patch antennas on superstrate	1000 GHz	Straightforward	low	good
Cu stud flip-chip	>200 GHz	Industry standard	low	ok, **marginal for PA** ✗
hot vias	200 GHz	Development	low ?	good
(ball) wirebonds	**100 GHz** ✗	Industry standard	low	good

140GHz CMOS+InP MIMO hub array tile

110mW InP Power Amplifier
20.8% PAE

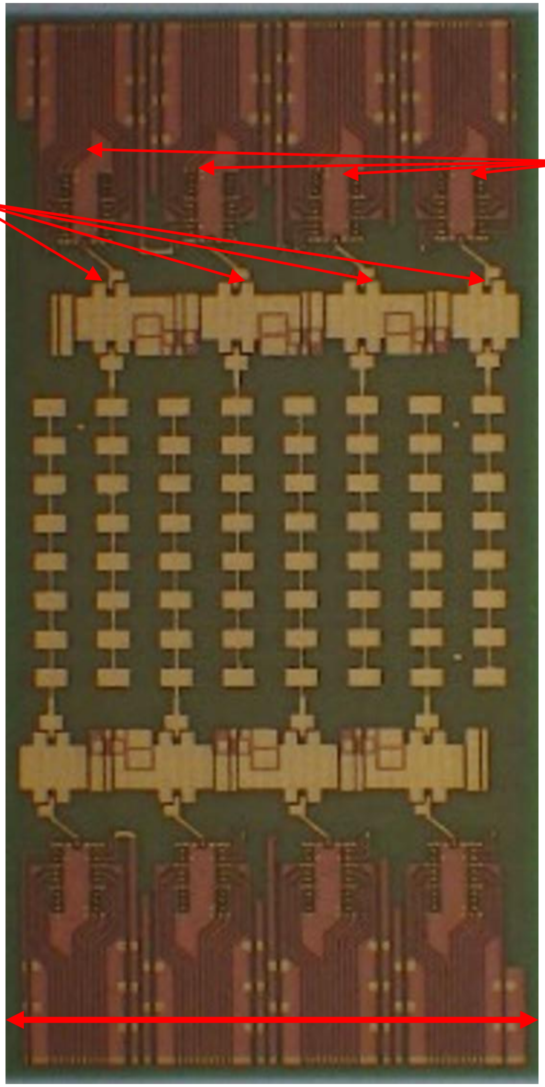


190mW InP Power Amplifier
16.7% PAE



Teledyne InP HBT

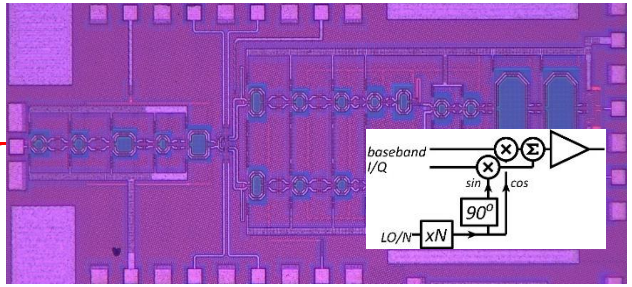
LTCC Array module



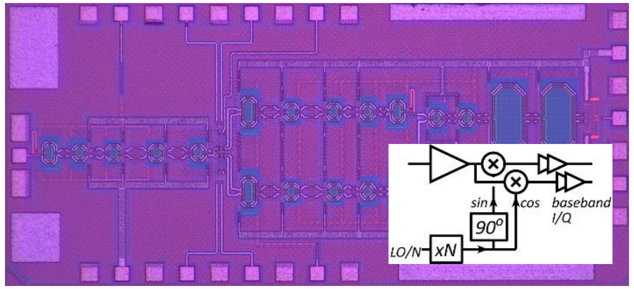
1 cm

Kyocera

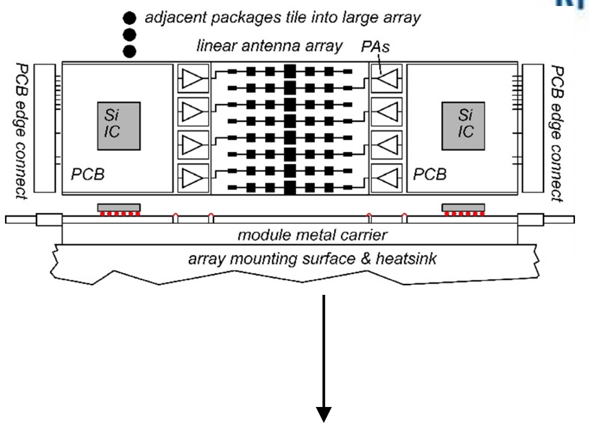
CMOS Transmitter IC
22nm SOI CMOS.

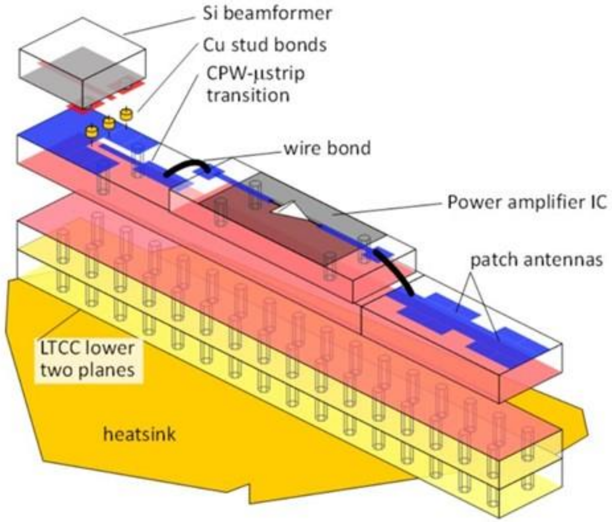


Receiver IC
22nm SOI CMOS.



GlobalFoundries 22nm SOI CMOS



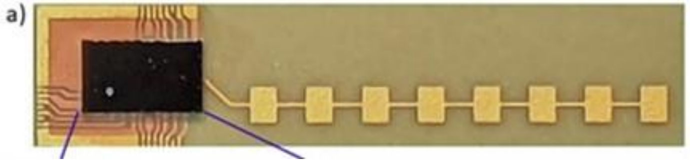


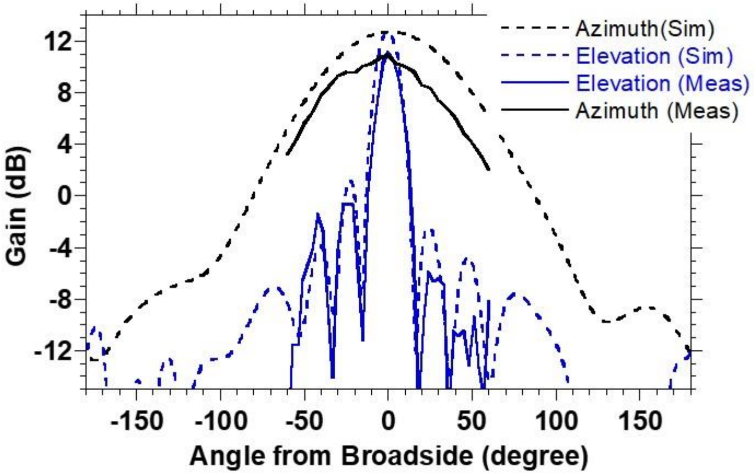
140GHz transmitter channel

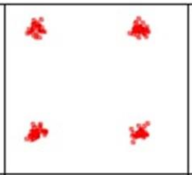
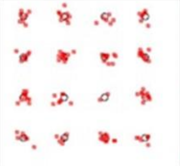
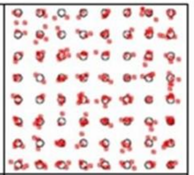
Farid, 2021 IMS, RFIC

CMOS-only TX channel

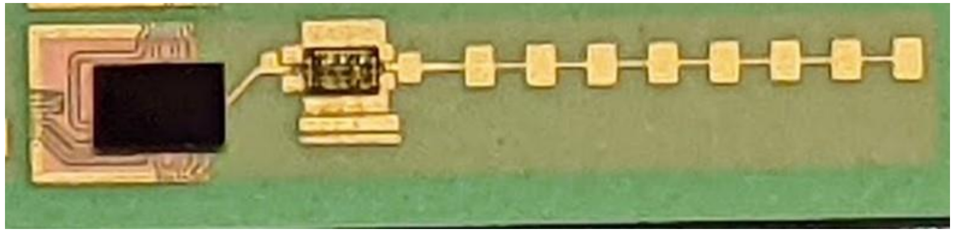
a)

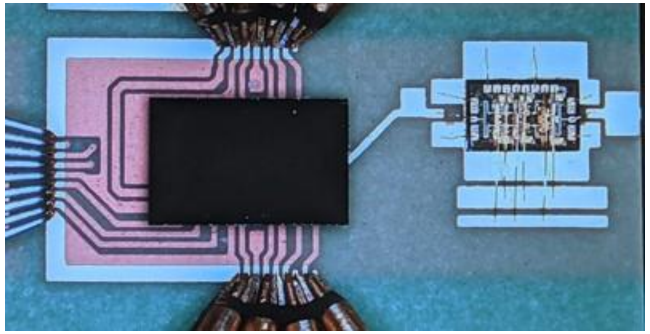


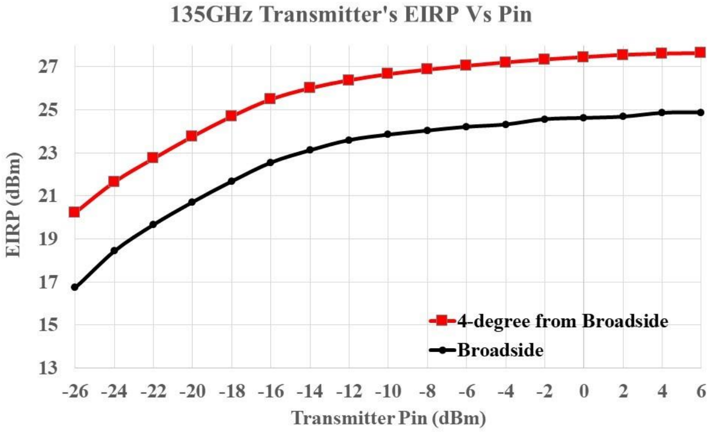


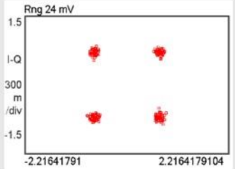
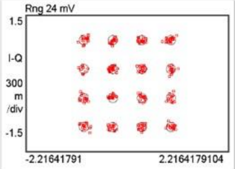
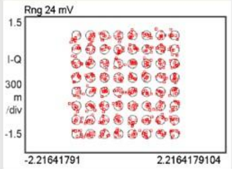
			
rate	4 Gbaud	4 Gbaud	2 Gbaud
power	3dB backoff	6dB backoff	8dB backoff
EVM (RMS)	7.9%	9.2%	7.4%

CMOS+InP TX channel

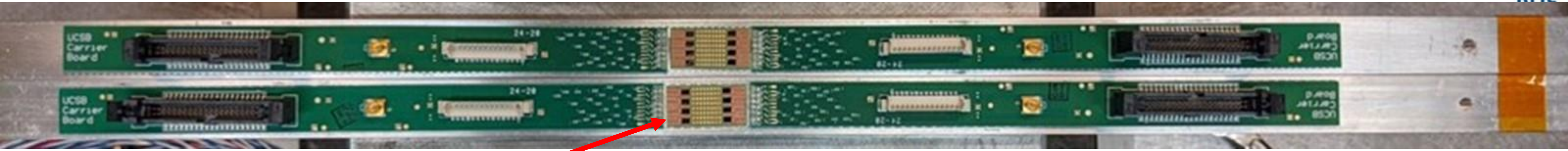


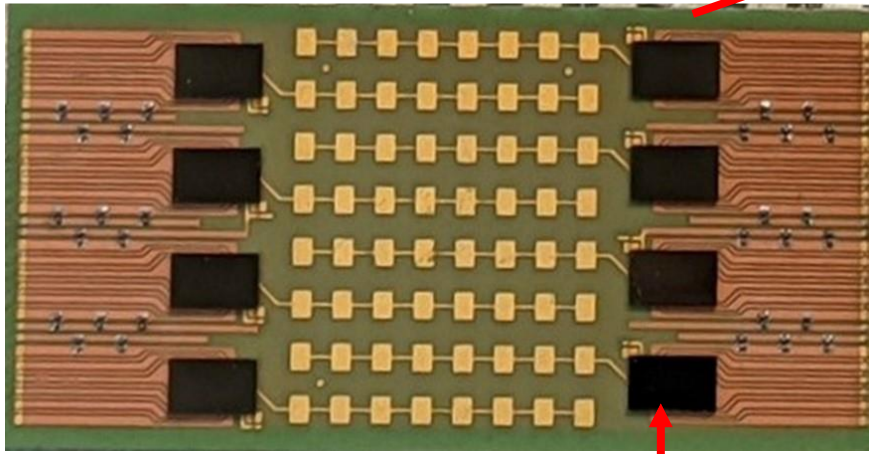


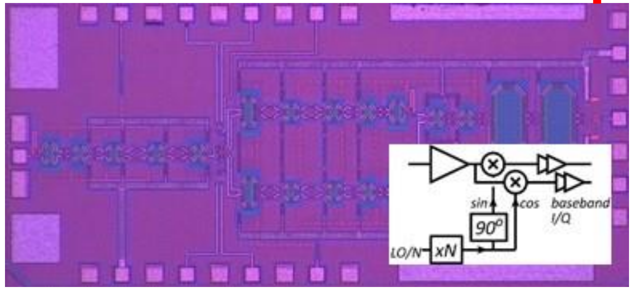


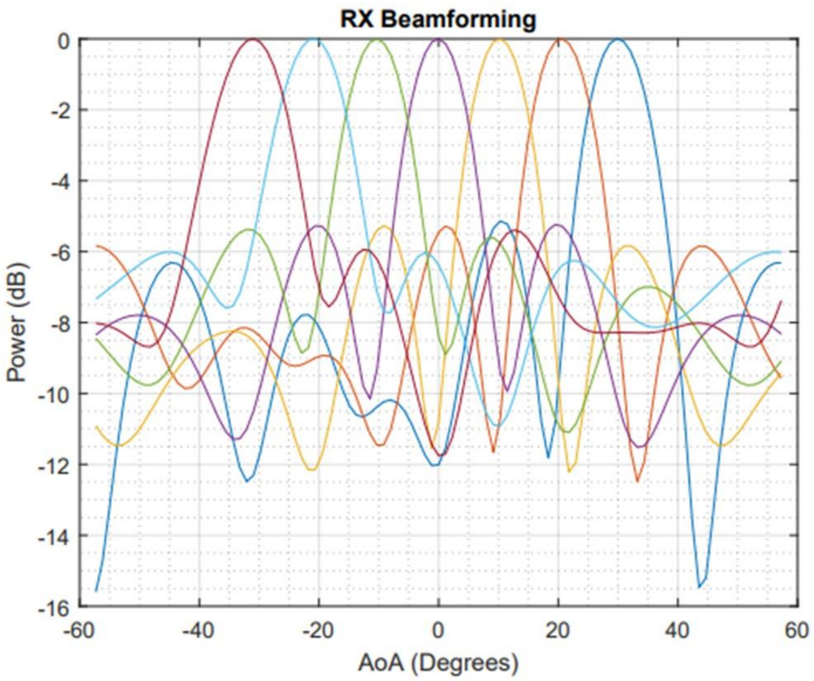
EIRP =19dBm/ 6dB-BO from Psat		
QPSK (5G Baud)	16QAM (5G Baud)	64QAM (5G Baud)
		
7.69% (RMS)	8.4% (RMS)	8.5% (RMS)

140GHz MIMO Receiver Array Tile

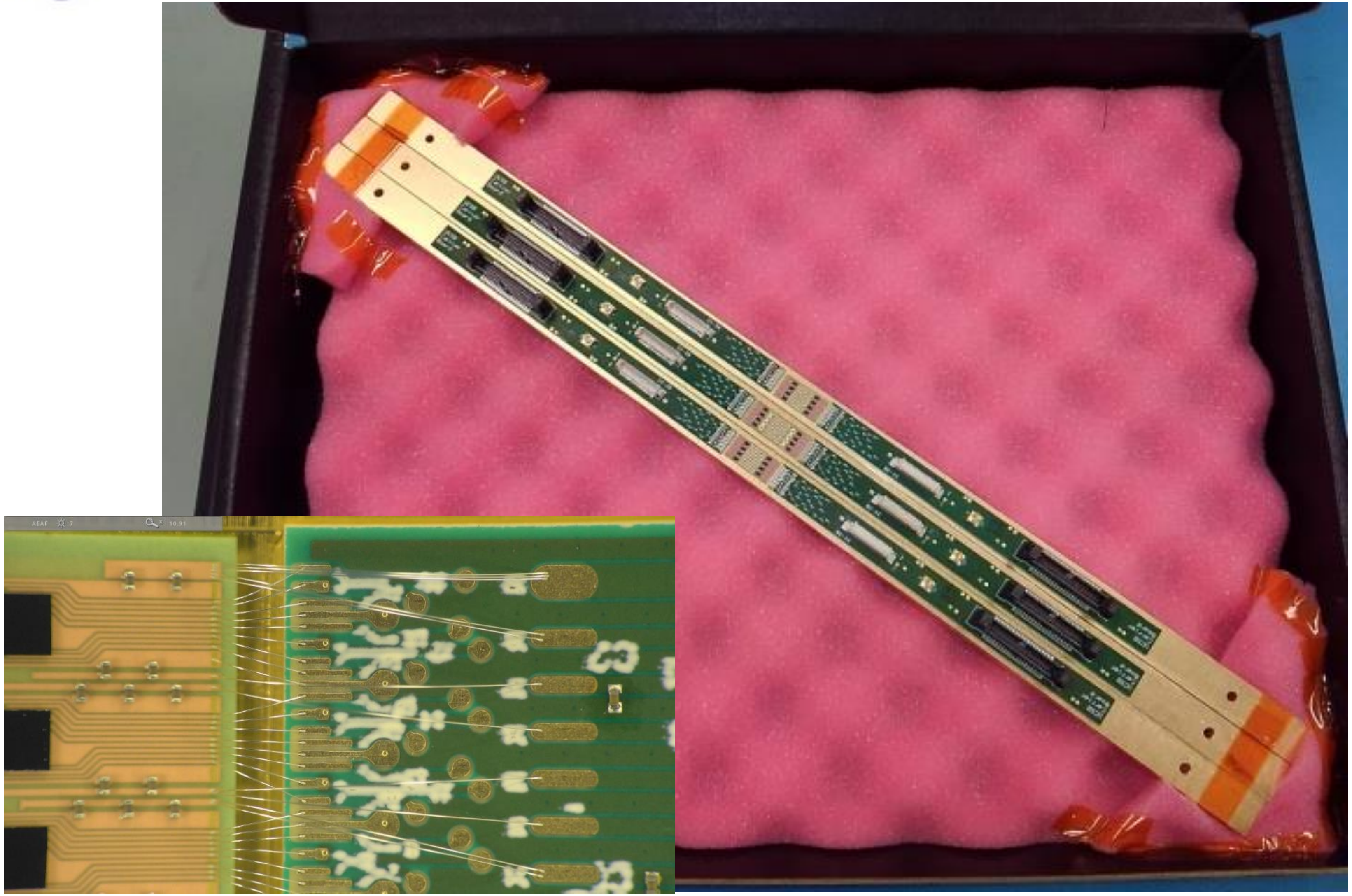


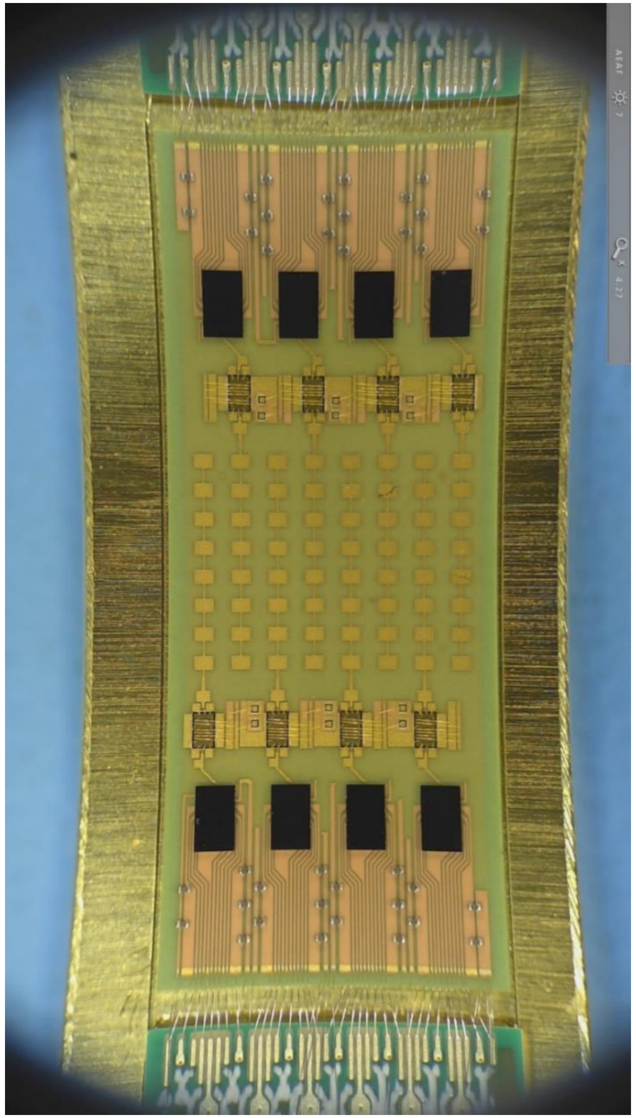




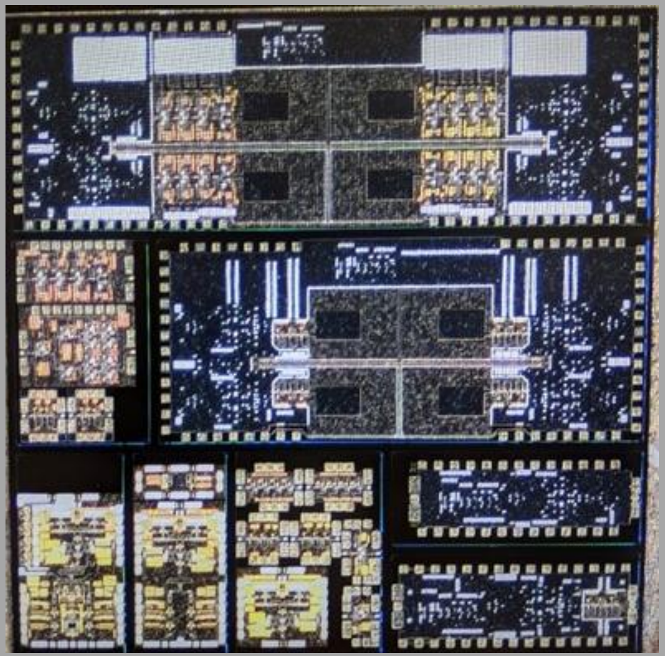


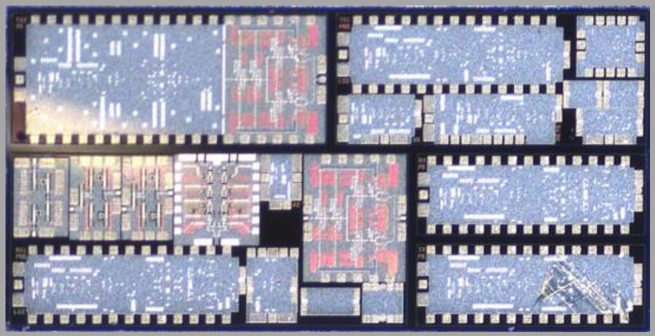
8-Channel 140GHz MIMO hub modules being tested.



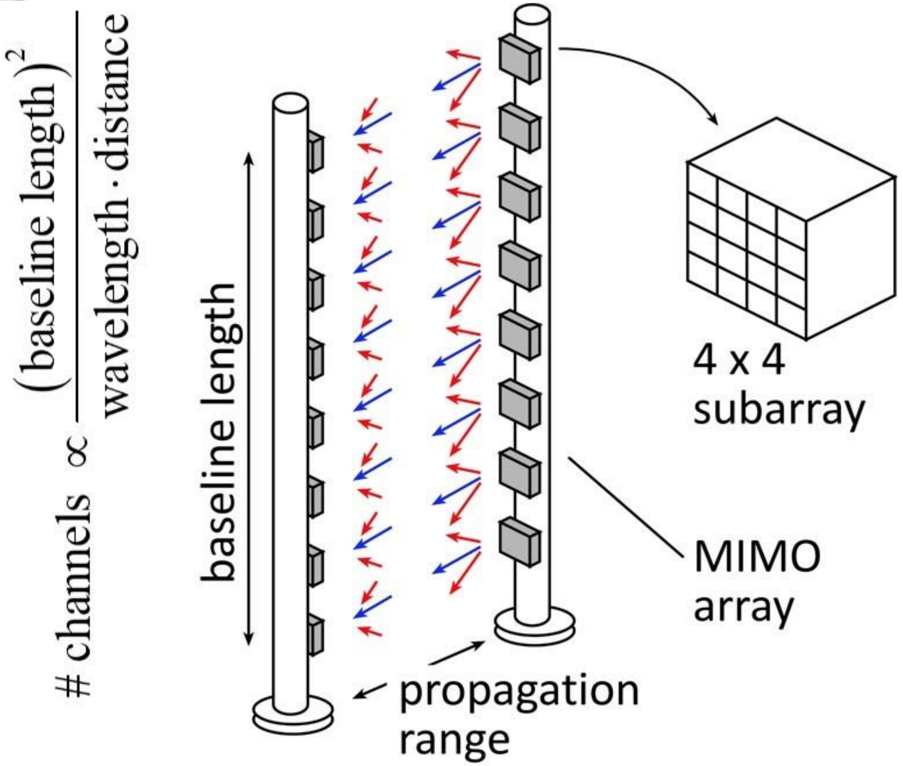


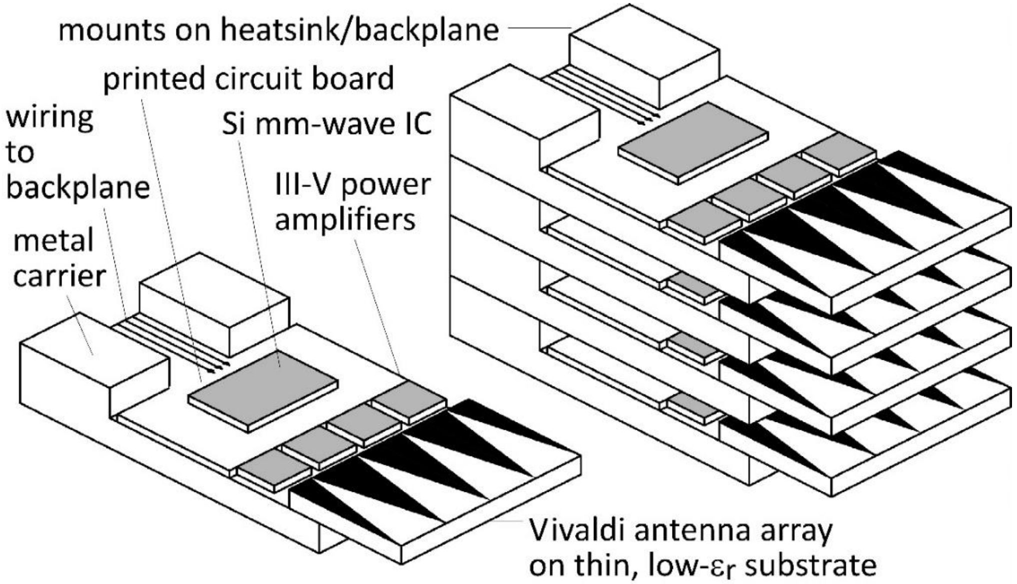
ICs and Packages: 210 & 280 GHz





210 GHz MIMO backhaul demo





8-element MIMO array

3.1 m baseline for 500m link.

80Gb/s/subarray→ 640Gb/s total

4 × 4 sub-arrays → 8 degree beamsteering

Key link parameters

500 meters range in 50 mm/hr rain; 23 dB/km

20 dB total margins:

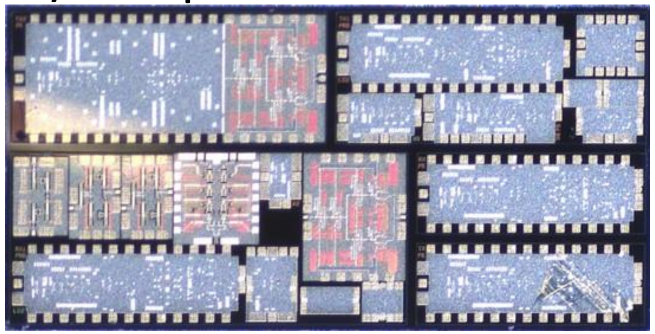
packaging loss, obstruction, operating, design, aging

PAs: 63mW $=P_{1dB}$ (per element)

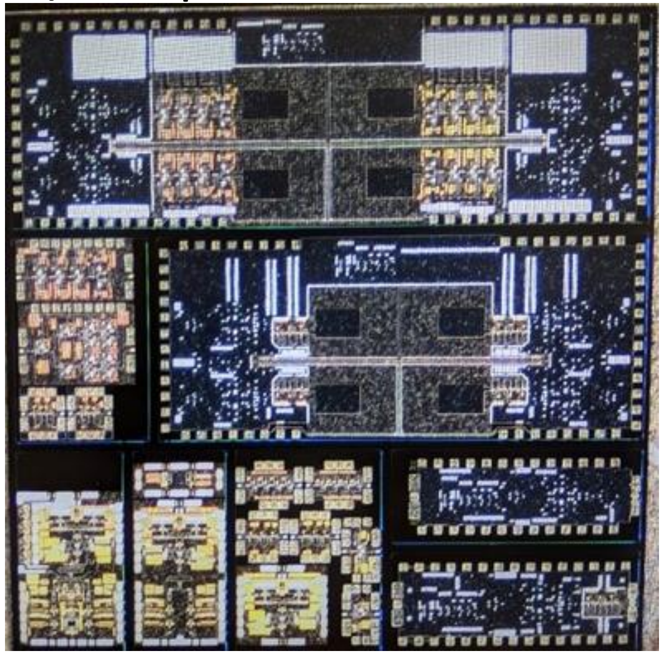
LNAs: 6dB noise figure

ICs for 210GHz and 280GHz MIMO links

2/2020 tapeout

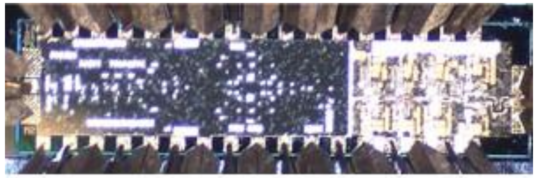


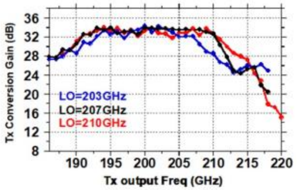
5/2020 tapeout

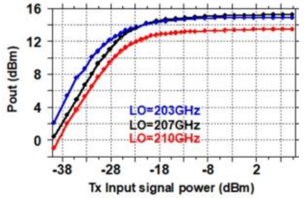


Technology:
Teledyne 250nm InP HBT.

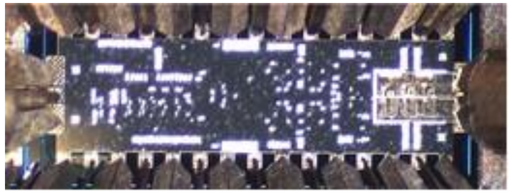
210 GHz TX: measured 15.8 dBm Psat, 20GHz BW, 33dB gain

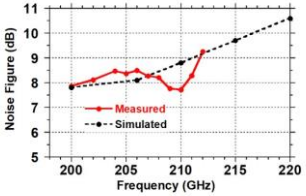


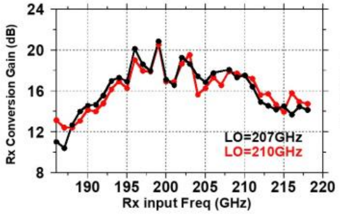


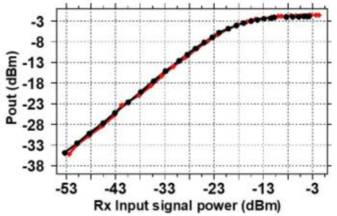


210 GHz RX: measured 27dB gain, 25GHz BW, 8-8.5dB NF.

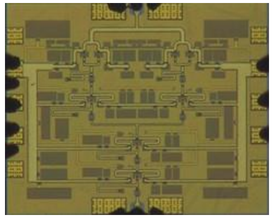


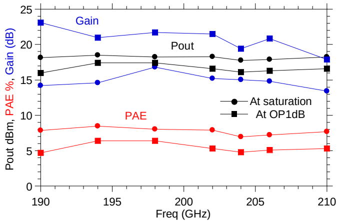




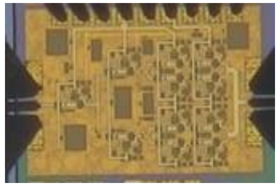


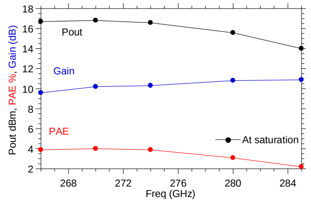
200 GHz PA: measured 17.7-18.5 dBm Psat, 6.9-8.5% PAE.



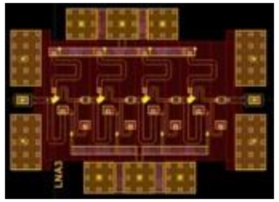


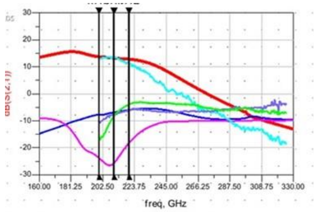
270 GHz PA: measured 16.7 dBm Psat, 4% PAE.



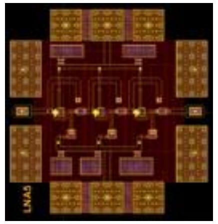


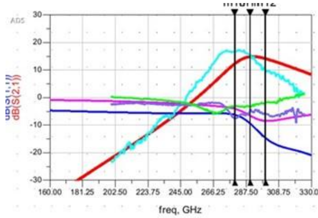
210 GHz LNA: measured 13dB gain, NF TBD.





280 GHz LNA: measured 12dB gain, NF TBD.

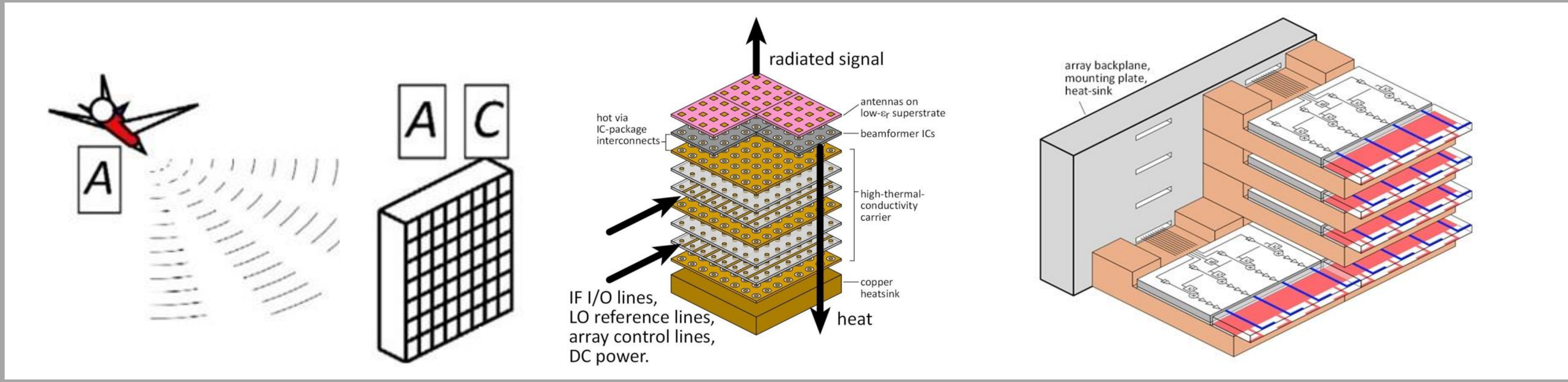




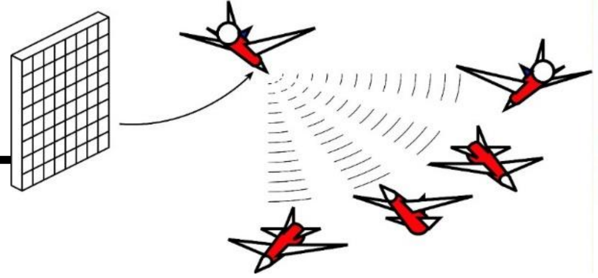
Acknowledgements & Publications:
200GHz PA: A. Ahmed et al, 2021 IMS
270GHz PA: A. Ahmed et al, 2021 RFIC symposium
210GHz TX, RX: M. Seo et al, 2021 IMS

Ongoing efforts:
210GHz single-channel TX, RX modules
2x2 arrays (with antenna superstrate: Rebiez, UCSD)

2D arrays


A
A
C
radiated signal
antennas on
low-ε_r superstrate
hot via
IC-package
interconnects
beamformer ICs
high-thermal-
conductivity
carrier
copper
heatsink
IF I/O lines,
LO reference lines,
array control lines,
DC power.
heat
array backplane,
mounting plate,
heat-sink

The 100-300GHz 2D Array Challenge



System architecture:

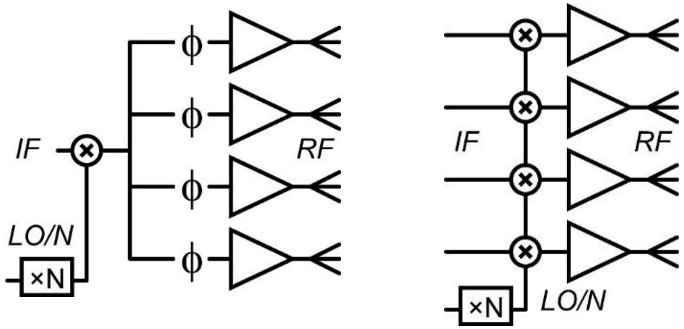
Single-beam: simpler RF front-end, simpler baseband
MIMO: complex digital baseband, flexible, many beams

Arrays can be made from either **tiles** or **trays**

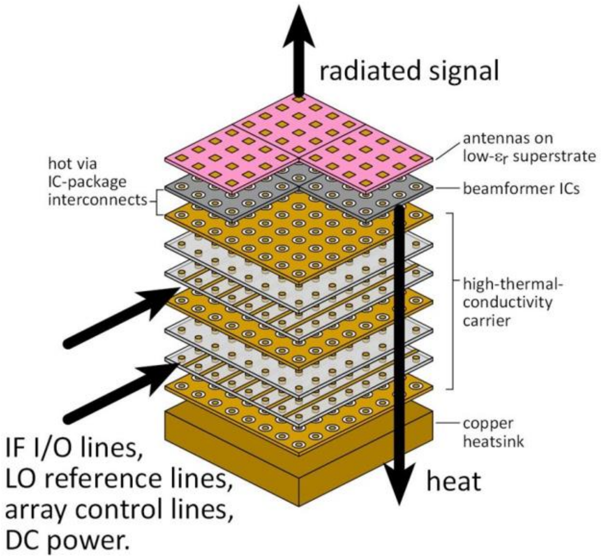
Arrays must be vast: 100-1,000-10,000 elements

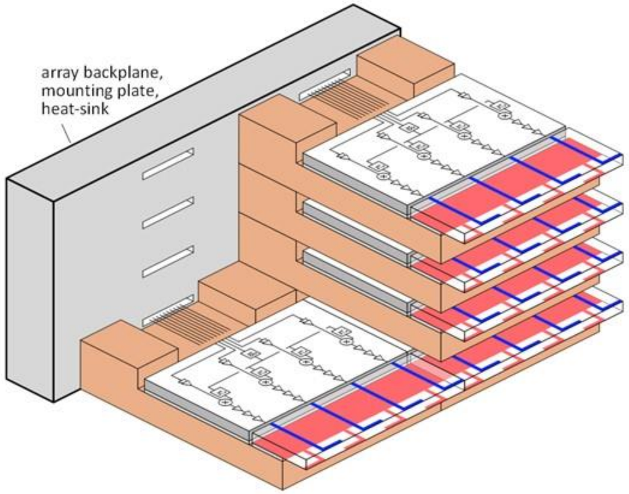
Arrays must be dense: packaging challenges

Many DC/IF/LO lines, plus antenna interface.
Fitting IC functions into available area.
Removing the heat.



f	100	150	200	250	300	GHz
λ	3	2	1.5	1.2	1	mm
$\lambda/2$	1.5	1	0.75	0.6	0.5	mm
0.6λ	1.8	1.2	0.9	0.72	0.6	mm





100-300GHz array frequency scaling

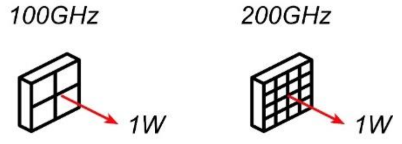
$$P_{received} = \frac{A_t A_r}{\lambda^2 R^2} e^{-\alpha R} \cdot P_{trans} \longrightarrow \#\text{beams} \cdot (\text{bit rate per beam}) \cdot kTF \cdot \text{SNR} = \frac{A_t A_r}{\lambda^2 R^2} e^{-\alpha R} \cdot P_{trans}$$

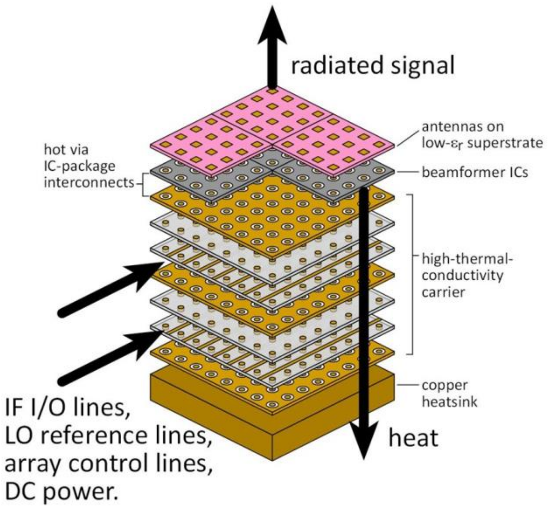
(Worst-case atmospheric loss: ~constant over 50-300GHz)

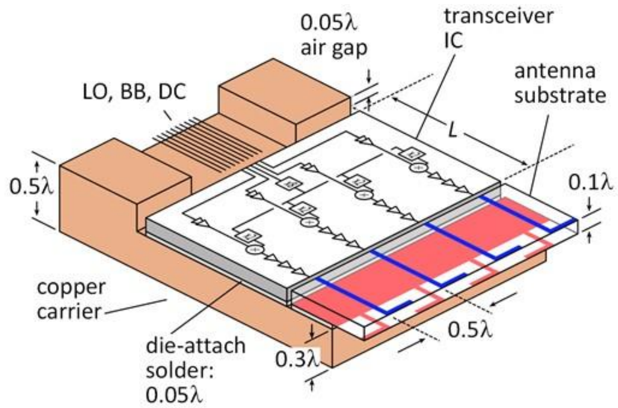
Proposed scaling law	change
carrier frequency	increase 2:1
aperture area	keep constant
total transmit power	keep constant

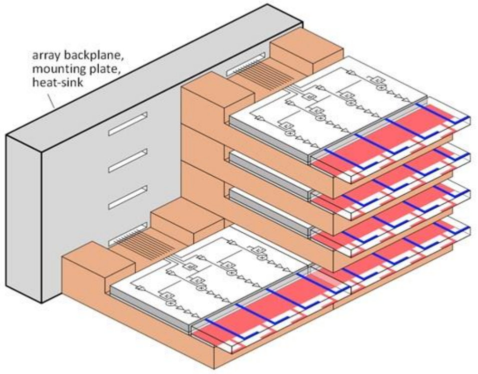
→

Implication	change
capacity (# beams·bit rate per beam)	increases 4:1
number elements	increases 4:1
RF power per cm^2 aperture area	stays constant
RF power per element	decreases 4:1
IC area/element (tiled array)	decreases 4:1
IC area/element (trayed array)	decreases 2:1
IC power/area (tiled array)	stays constant
IC power/area (trayed array)	decreases 2:1

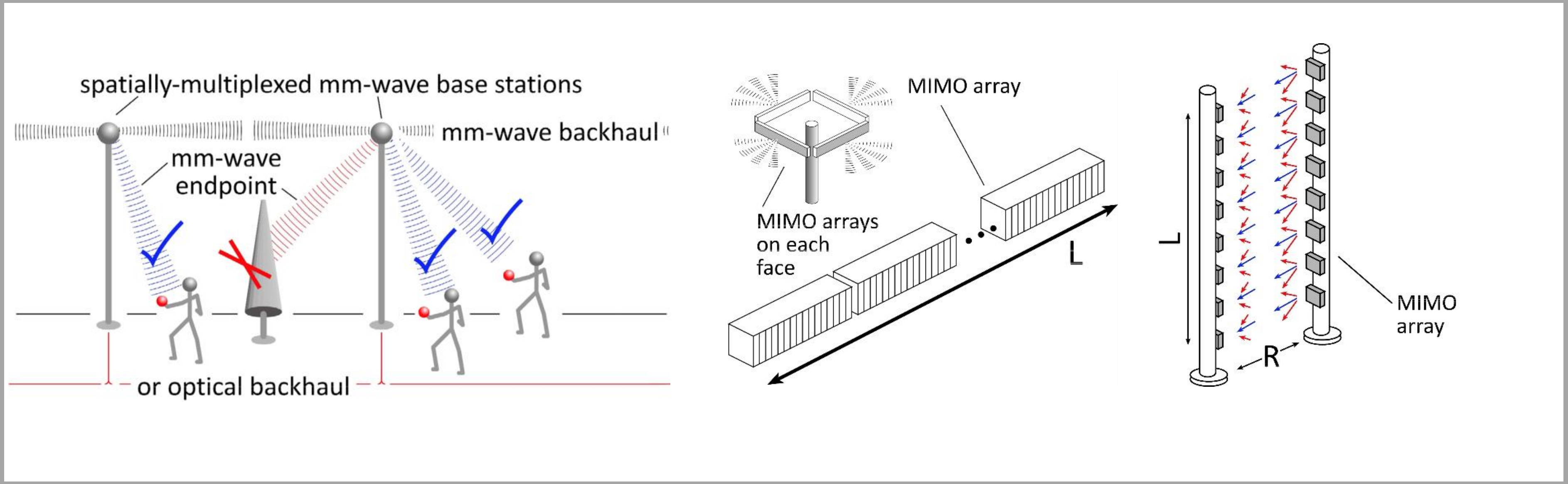








100-300GHz Wireless



Wireless above 100 GHz

Massive capacities
large available bandwidths
massive spatial multiplexing in base stations and point-point links

Very short range: few 100 meters
short wavelength, high atmospheric losses. Easily-blocked beams.

IC Technology
All-silicon for short ranges below 200 GHz.
III-V LNAs and PAs for longer-range links. Just like cell phones today
III-V frequency extenders for 340GHz and beyond

The challenges
computational complexity
packaging: fitting signal channels in very small areas
mesh networking to accommodate beam blockage
driving the technologies to low cost

(backup files follow)