2021 Joint EuCNC & 6G Summit, June 8-11, 2021 (online meeting)

100-300GHz Wireless Communications: Systems, Arrays, ICs, and Transistors

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***Muhannad Bakir**: Georgia Tech*
***Sundeep Rangan**: New York University*
***Amin Arbabian, Srabanti Chowdhury**: Stanford*
***Elad Alon, Ali Niknejad, Borivoje Nikolic** : University of California, Berkeley*
***Danijela Cabric, Tim Fisher**: University of California, Los Angeles*
***Andrew Kummel, Gabriel Rebeiz**: University of California, San Diego*
***Jim Buckwalter, Upamanyu Madhow, Umesh Mishra, Mark Rodwell, Susanne Stemmer**: University of California, Santa Barbara*
***Andreas Molisch**: University of Southern California*
***Kenneth O**: University of Texas, Dallas*

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

Collaborators (ComSenTer Wireless Team)

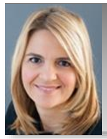
Systems


Sundeep Rangan
Networks, Applications, MIMO, Power


Upamanyu Madhow
UC Santa Barbara
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


Kenneth O
UT Dallas
140-300GHz
SiGe ICs


Muhannad Bakir
Georgia Tech
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
UC Berkeley
design automation equalizers


Tim Fisher
UCLA
advanced packaging materials


Andrew Kummel
UCSD
advanced packaging materials

Transistors


Umesh Mishra
UC Santa Barbara
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 Arabian
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

Sponsors

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LOCKHEED MARTIN
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ANALOG DEVICES
tsmc
SAMSUNG
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NSF
Micron
EMD PERFORMANCE MATERIALS
Raytheon Technologies
IBM
intel

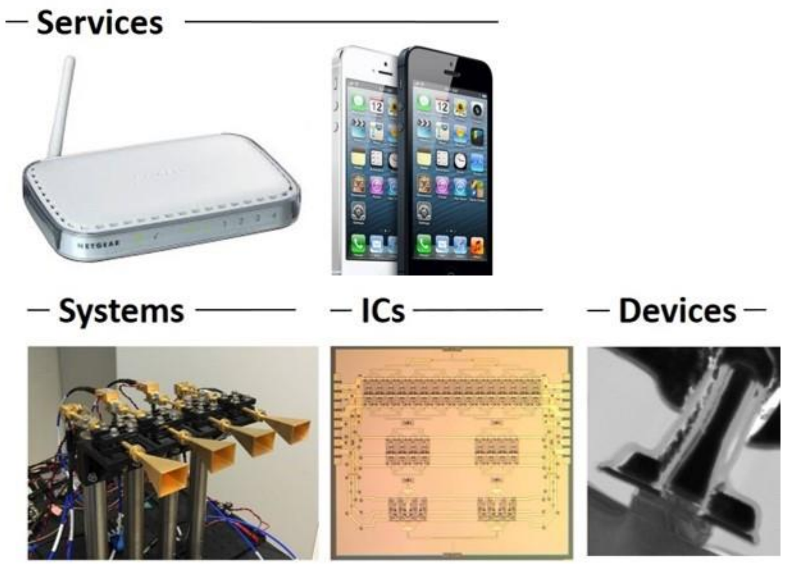
Beyond-5G Wireless

Wireless networks: exploding demand.

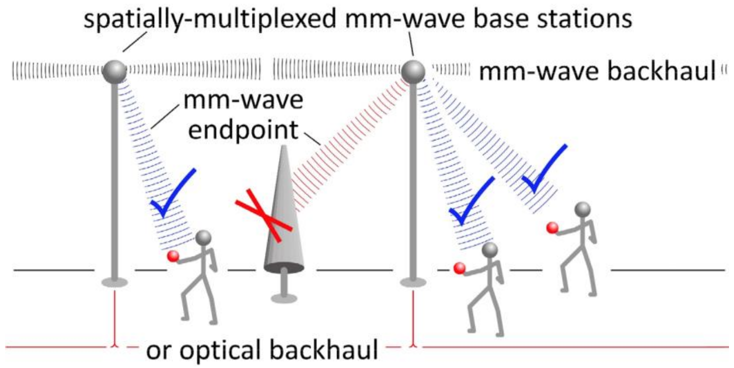
Immediate industry response: 5G.
~10-100GHz carriers.
increased spectrum, extensive beamforming

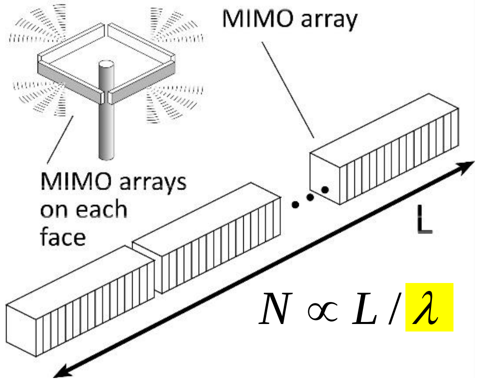
Next generation (6G ??): above 100GHz..
greatly increased spectrum, massive spatial multiplexing

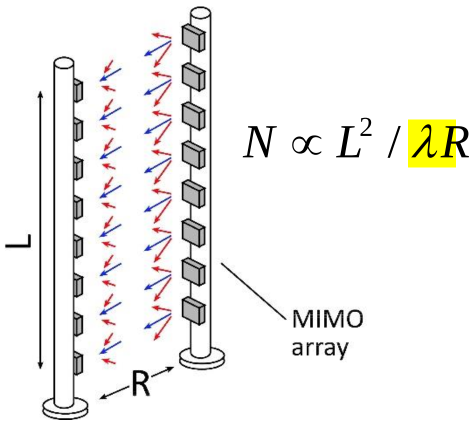
JUMP Centers: research commercialized in 15 years



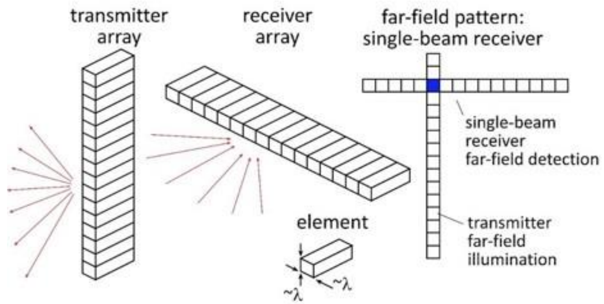
ComSenTer: 100-300GHz carriers, massive spatial multiplexing
→ Terabit hubs and backhaul links, high-resolution imaging radar





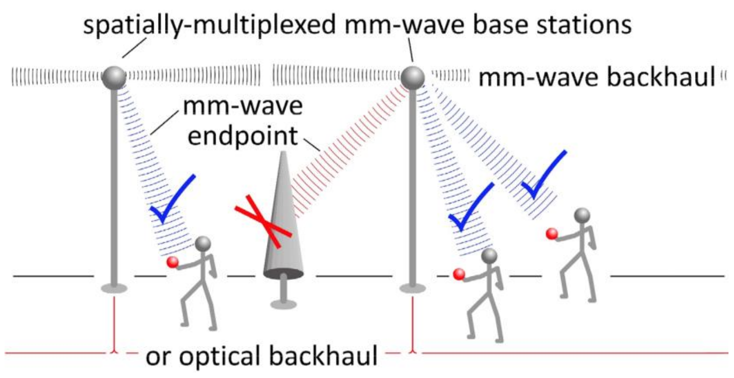


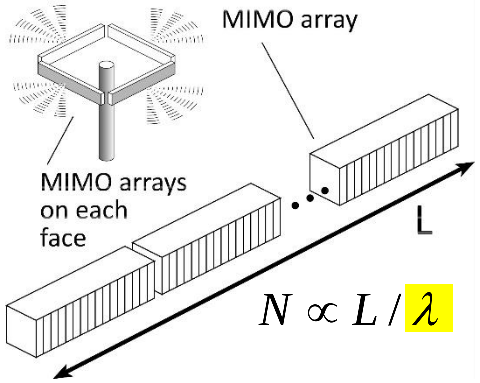
$\Delta\theta \propto \lambda / L$



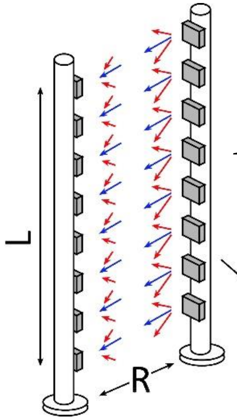
Benefits of Short Wavelengths

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

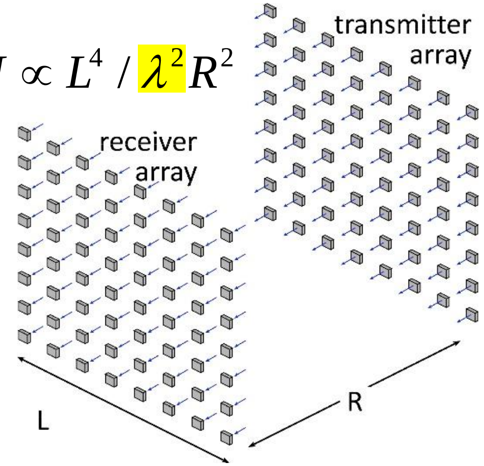




$N \propto L / \lambda$

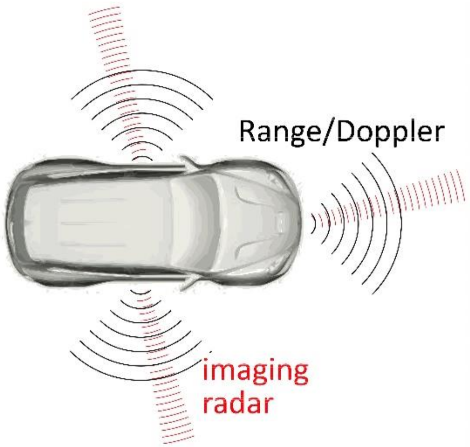


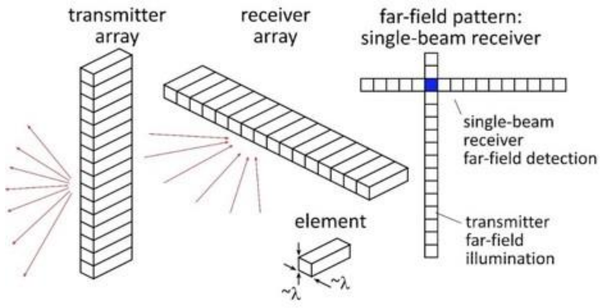
$N \propto L^2 / \lambda R$



$N \propto L^4 / \lambda^2 R^2$

Imaging: very fine angular resolution





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

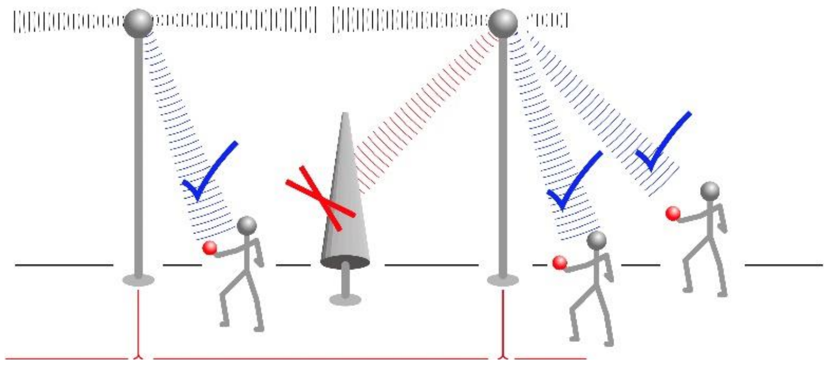
But:

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

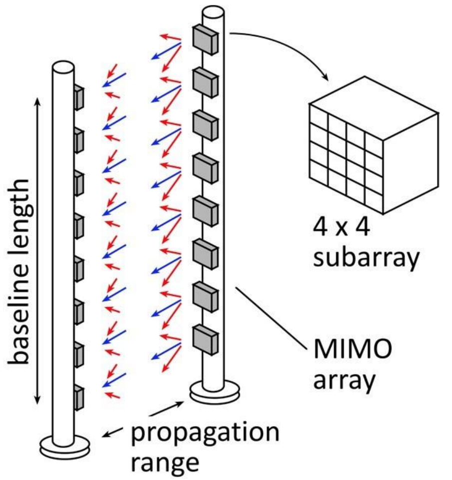
100-340GHz wireless:
terabit capacity,
short range,
highly intermittent

Potential 100-300GHz Systems

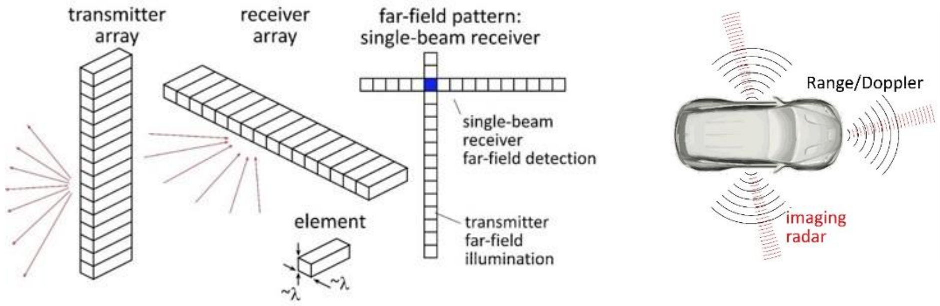
140GHz MIMO Hub

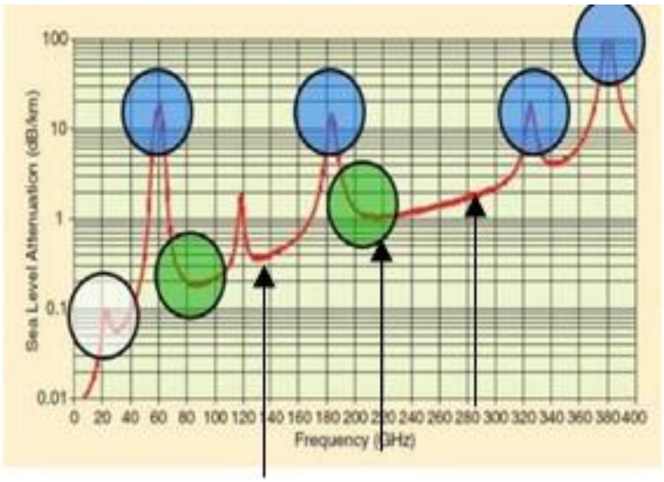


210 or 280GHz MIMO Backhaul

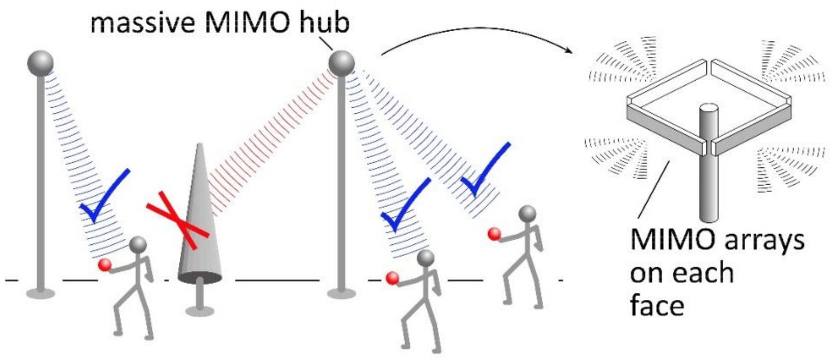


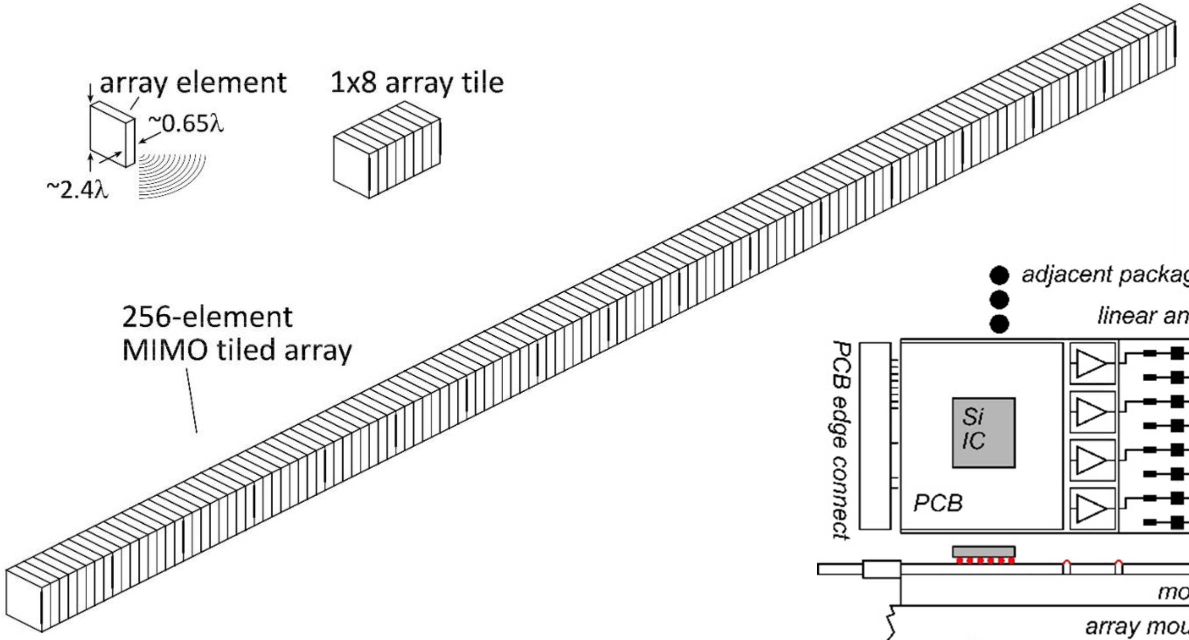
140 or 210GHz Imaging Radar

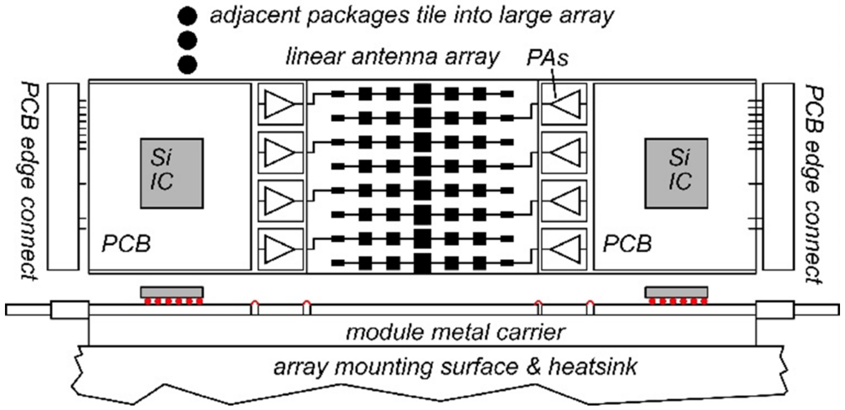


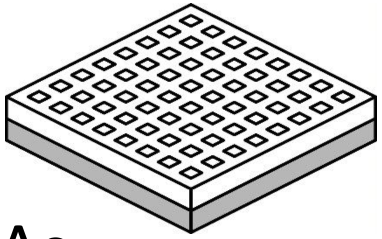


140GHz massive MIMO hub









Handset:
8 × 8 array
(9×9mm)

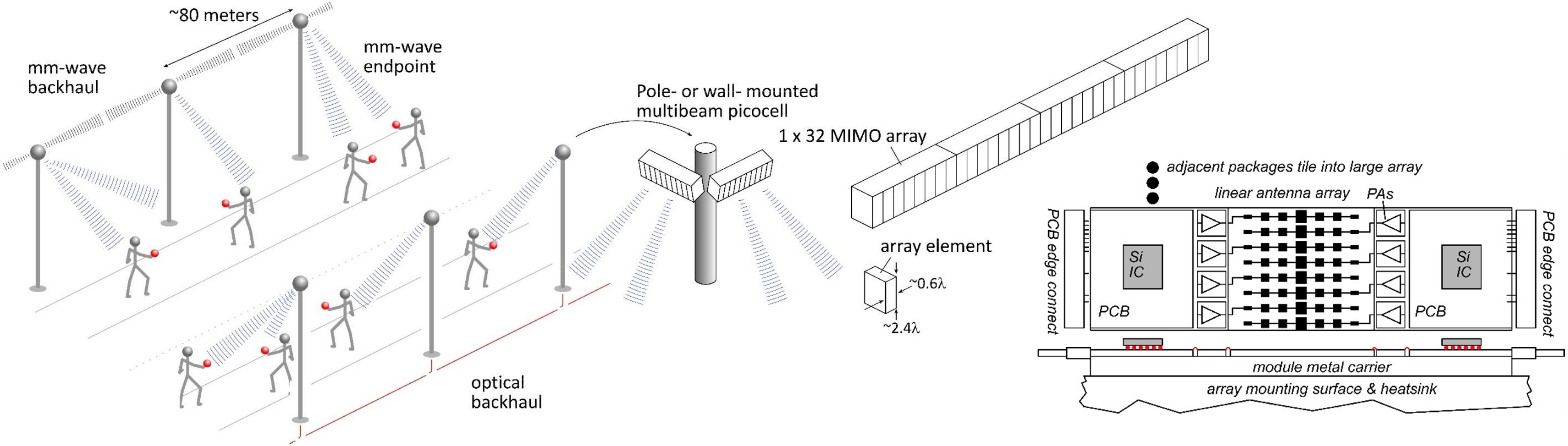
0.5-5 Tb/s spatially-multiplexed 140GHz base station

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

140GHz moderate-MIMO hub

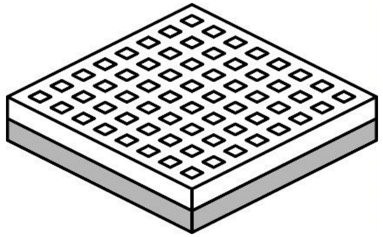


If demo uses 32-element array (four 1×8 modules):

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

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

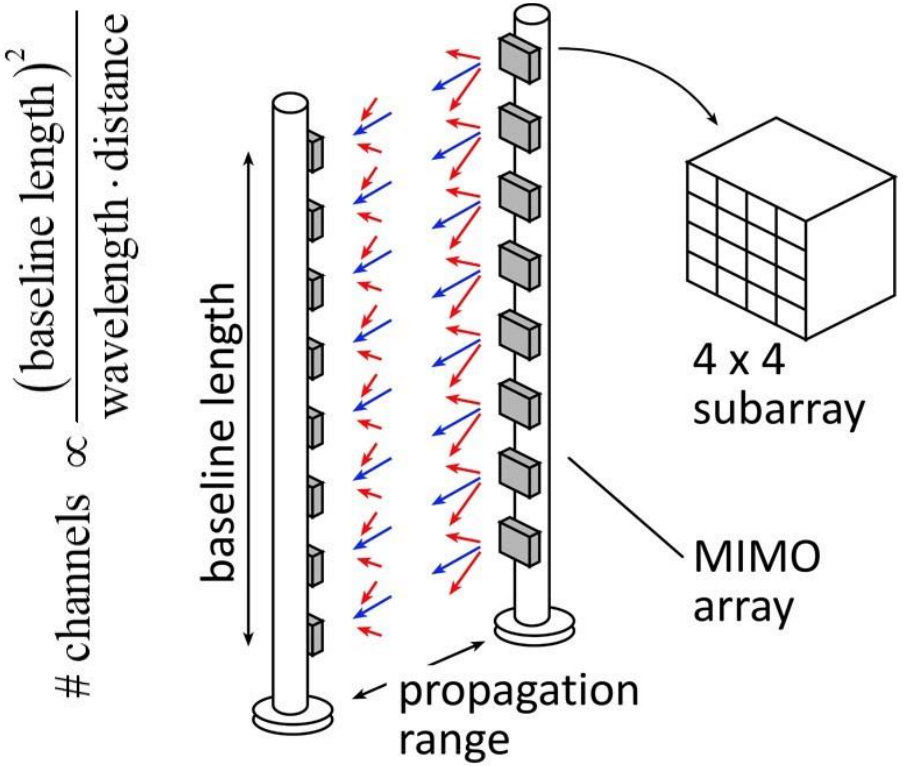
40, 70 m range in 50mm/hr rain with **17**dB total margins

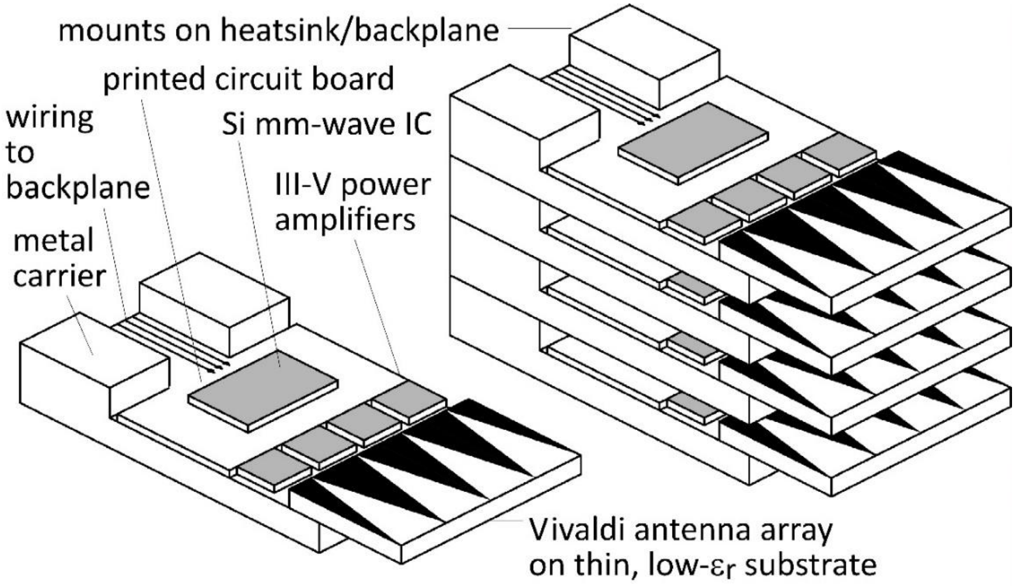


Handset:
8 × 8 array
(9×9mm)

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

210 GHz, 640 Gb/s MIMO Backhaul



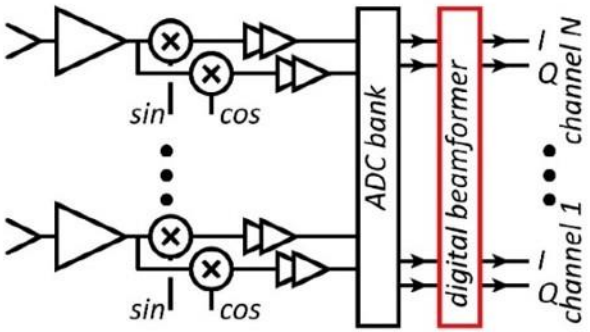


8-element MIMO array
3.1 m baseline.
80Gb/s/subarray→ 640Gb/s total
4 × 4 sub-arrays → 8 degree beamsteering

Key link parameters
500 meters range in 50 mm/hr rain; 23 dB/km
20 dB total margins:
packaging loss, obstruction, operating, design, aging
PAs: 18dBm =P_{1dB} (per element)
LNAs: 6dB noise figure

System Design

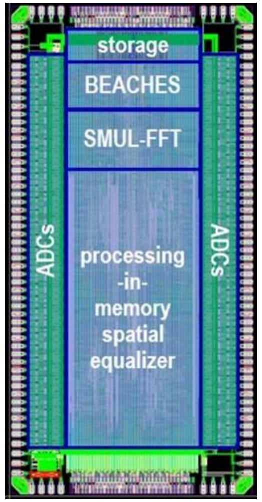
ADCs/DACs: only 3-4 bit ADC/DACs required
(Madhow, Studer, Rodwell)



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

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

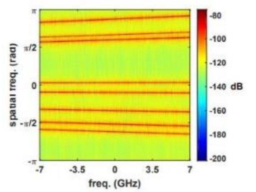
Efficient digital beamforming: beamspace algorithm=complexity ~N× log(N)
(Madhow, Studer)

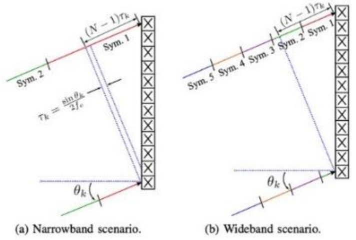


Efficient digital beamforming: low-resolution matrix
(Studer)

Efficient channel estimation : fast beamspace algorithm
(Studer)

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





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

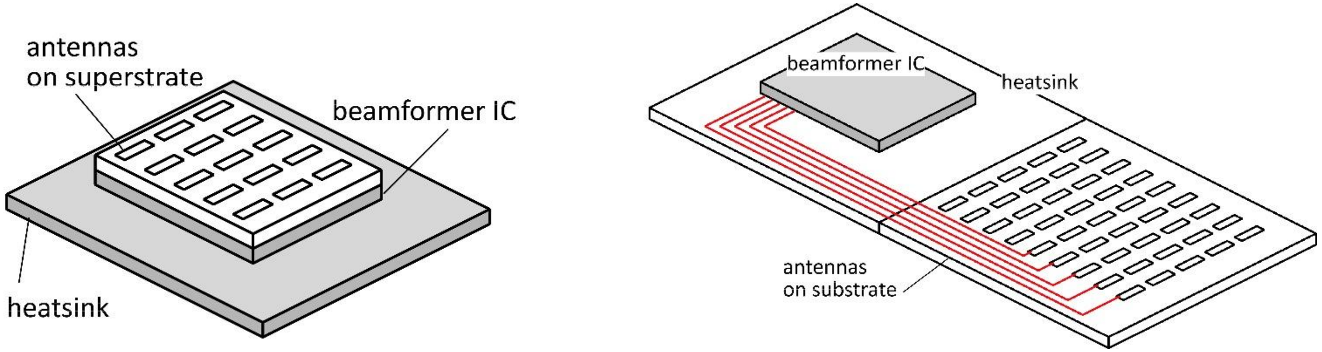
*can be addressed

There are THz transistors today; their bandwidth will increase

Challenge: reducing costs, increasing market size

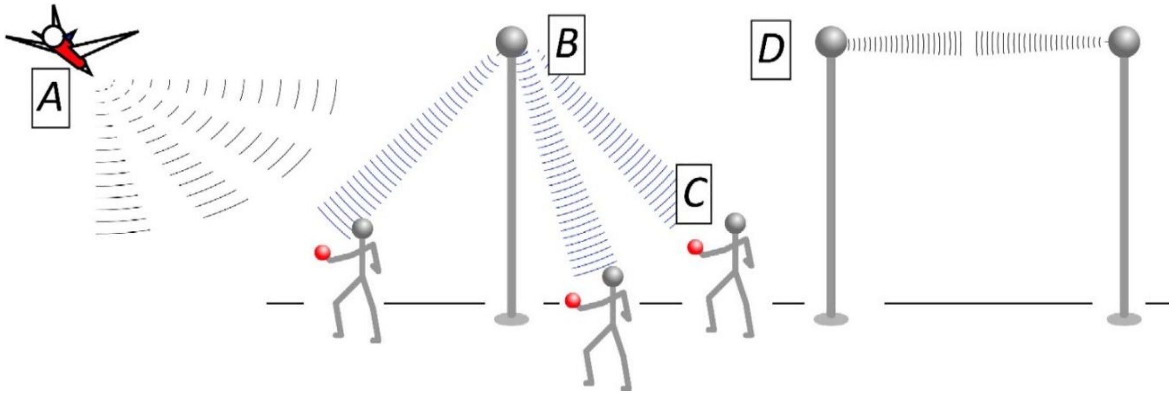
The mm-wave module design problem

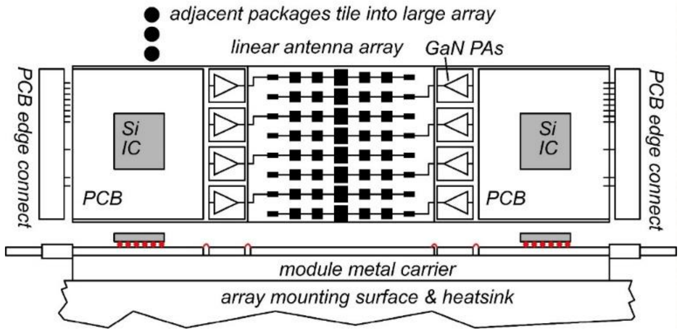
How to make the IC electronics fit ?
How to avoid catastrophic signal losses ?
How to remove the heat ?

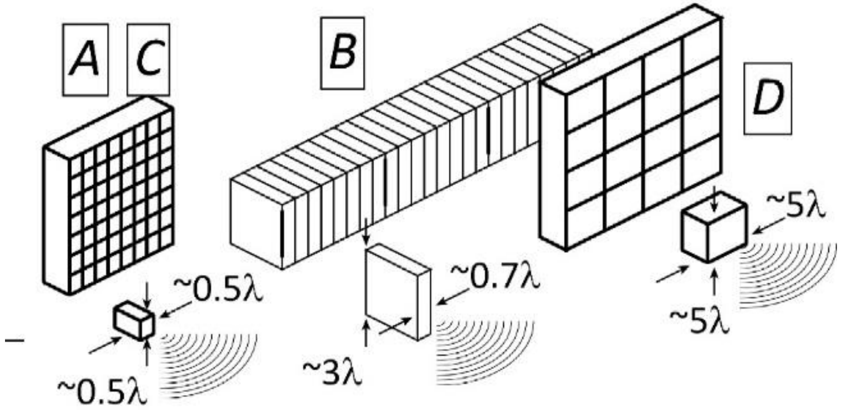


Not all systems steer in two planes...
...some steer in only one.

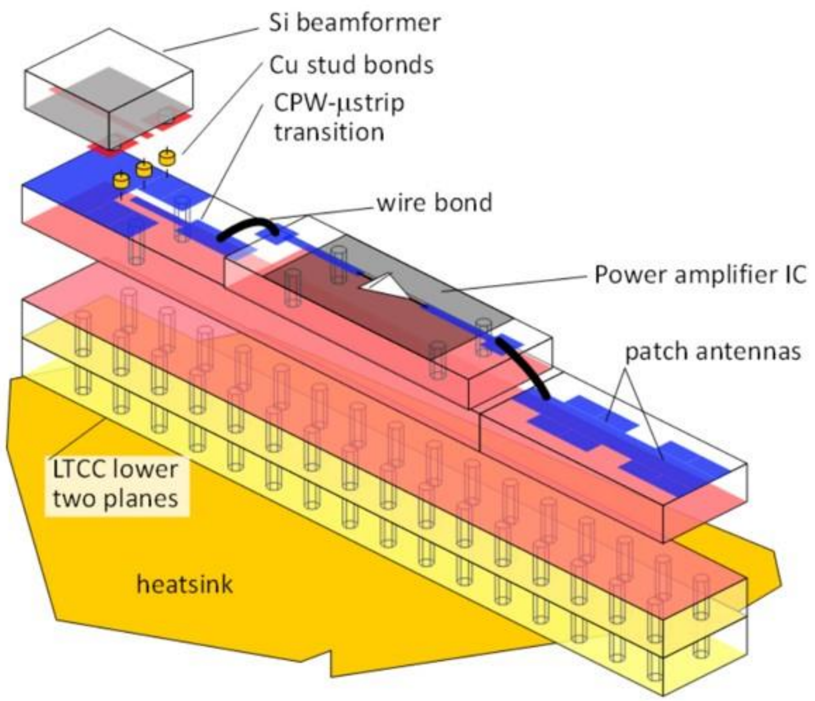
Not all systems steer over 180 degrees...
...some steer a smaller angular range



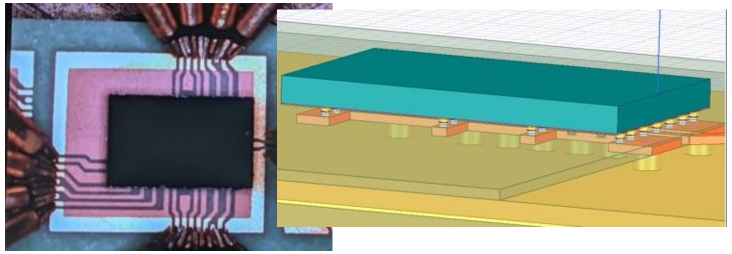




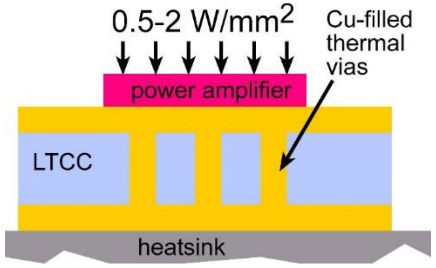
140GHz hub: packaging challenges



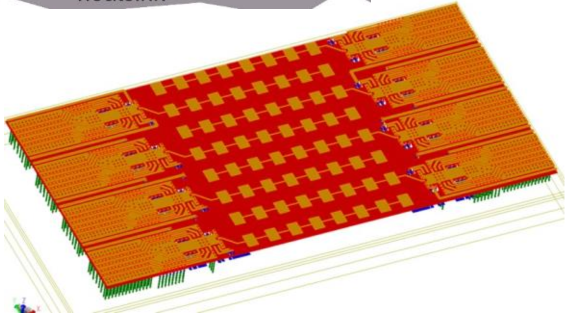
IC-package interconnects
Difficult at > 100 GHz



Removing heat
Thermal vias are marginal



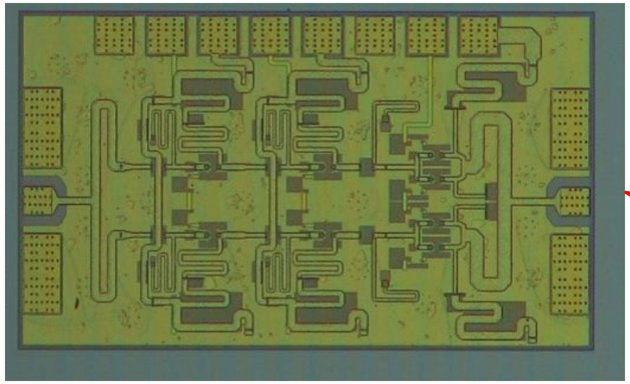
Interconnect density
Dense wiring for DC, LO, IF, control.
Hard to fit these all in.



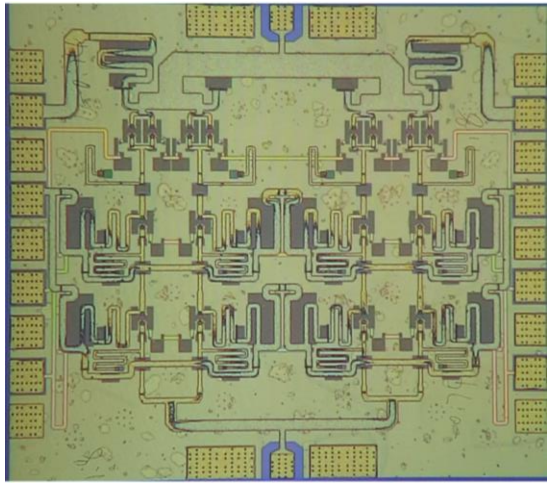
Economies of scale
Advanced packaging standards require sophisticated tools
High-volume orders only
Hard for small-volume orders (research, universities)
Packaging industry is moving offshore

140GHz hub: ICs & Antennas

110mW InP Power Amplifier
20.8% PAE

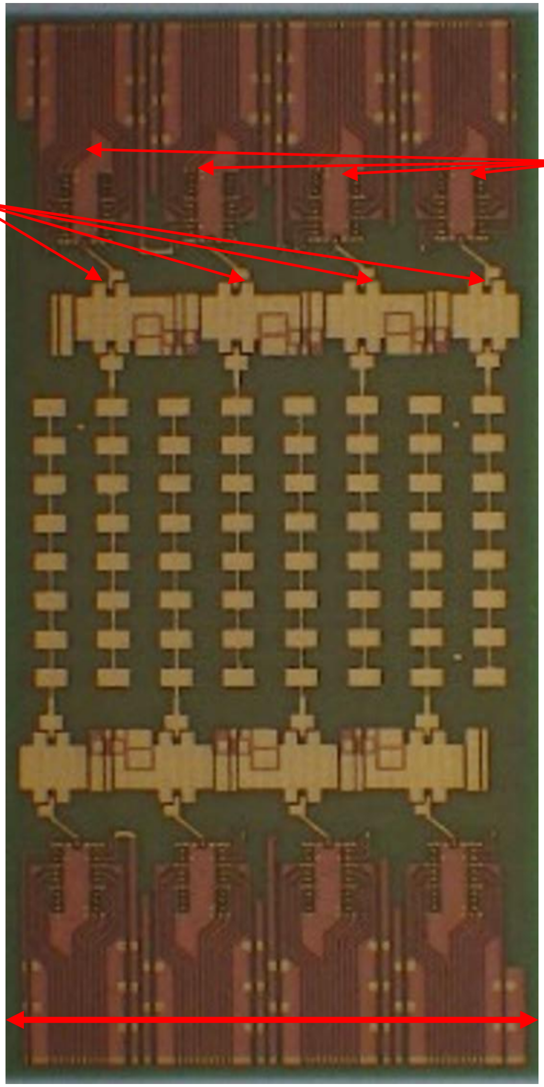


190mW InP Power Amplifier
16.7% PAE



Teledyne InP HBT

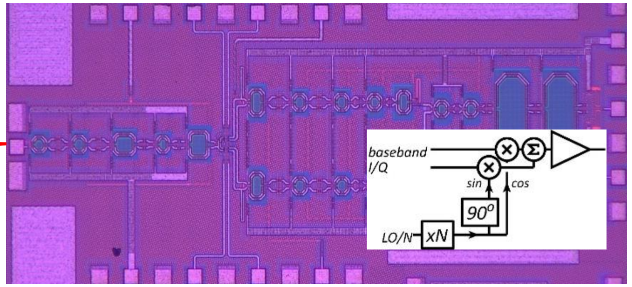
LTCC Array module



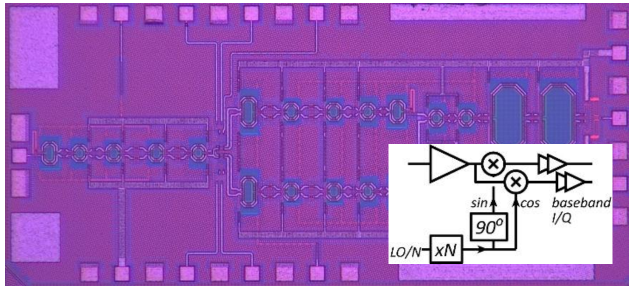
1 cm

Kyocera

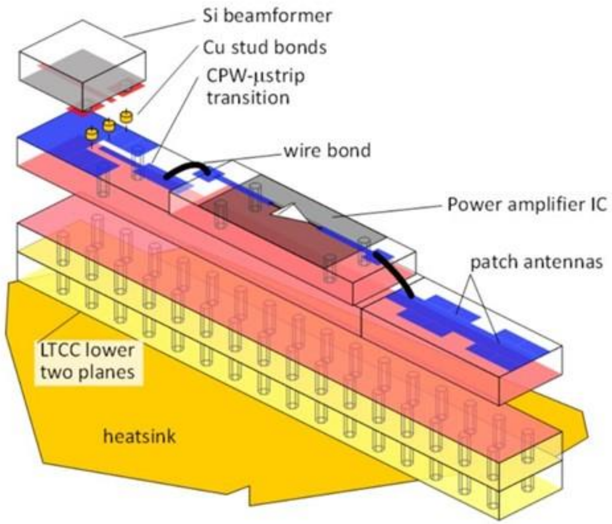
CMOS Transmitter IC
22nm SOI CMOS.



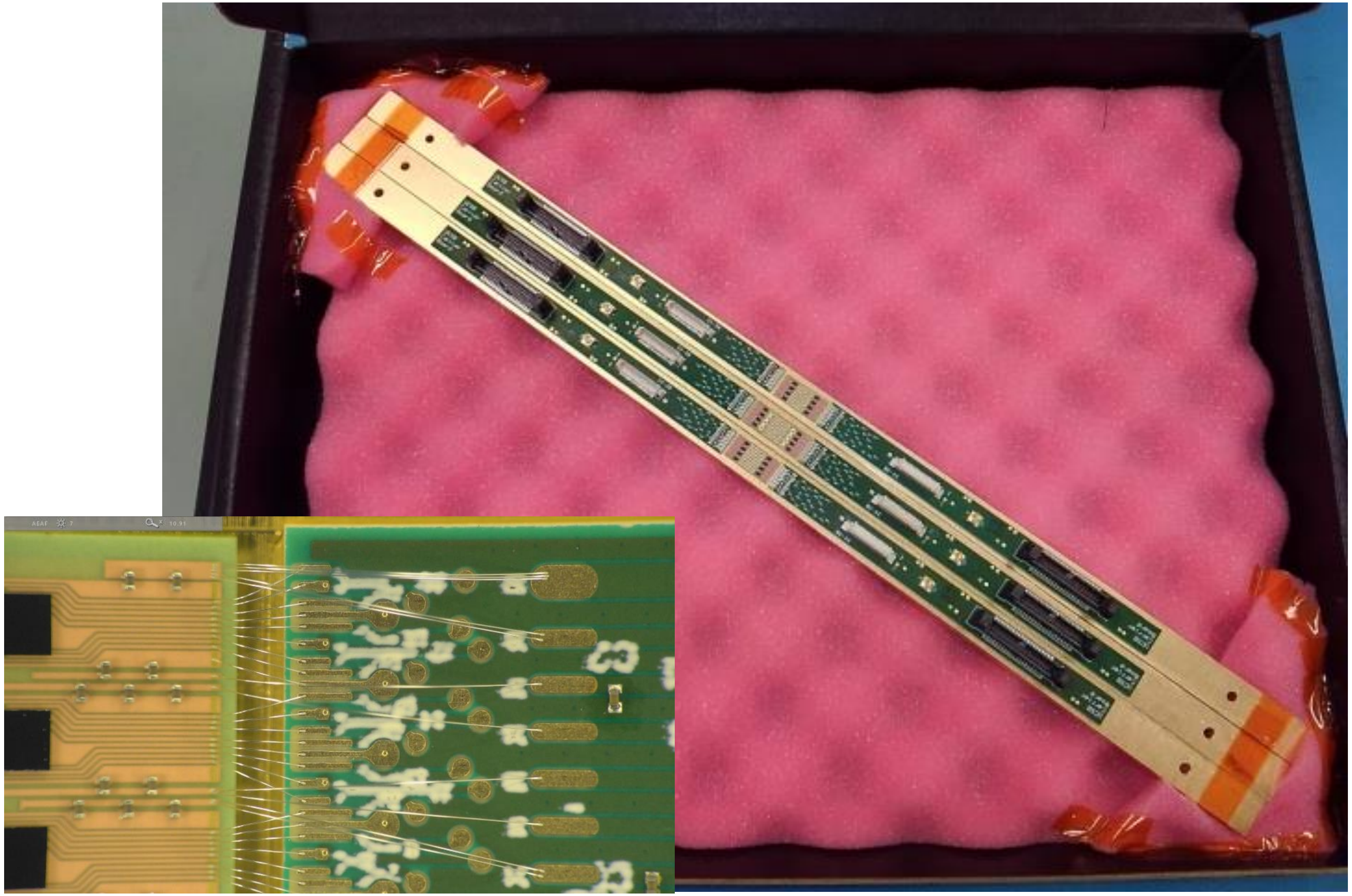
Receiver IC
22nm SOI CMOS.

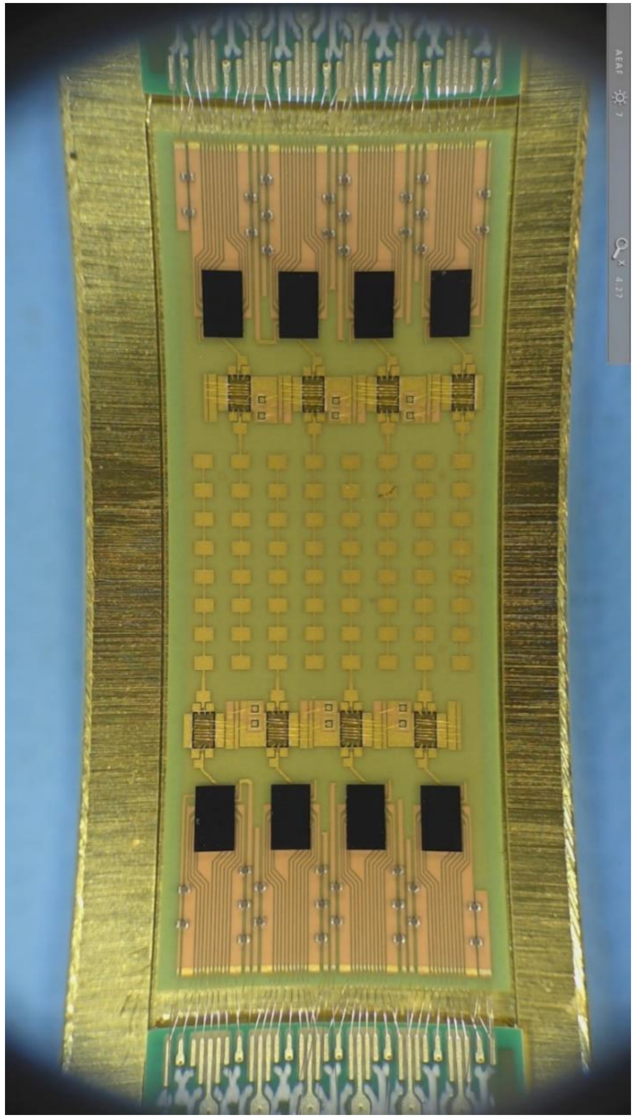


GlobalFoundries 22nm SOI CMOS



8-Channel 140GHz MIMO hub modules being tested.





ICs for 210GHz and 280GHz MIMO links

210GHz and 280GHz transceivers in development.

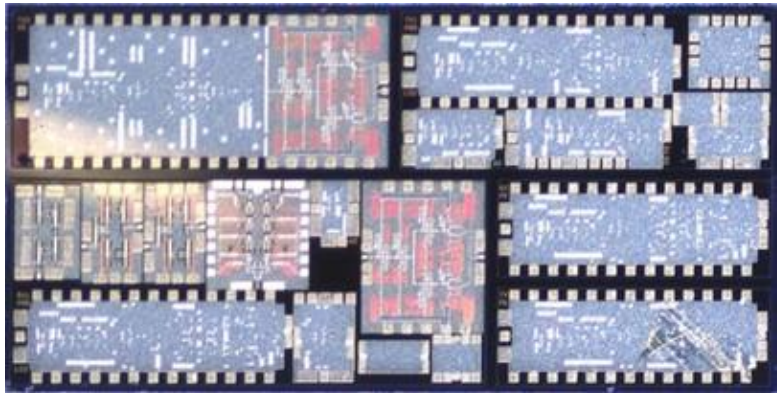
210GHz transmitter, receiver: M. Seo et al, 2021 IMS

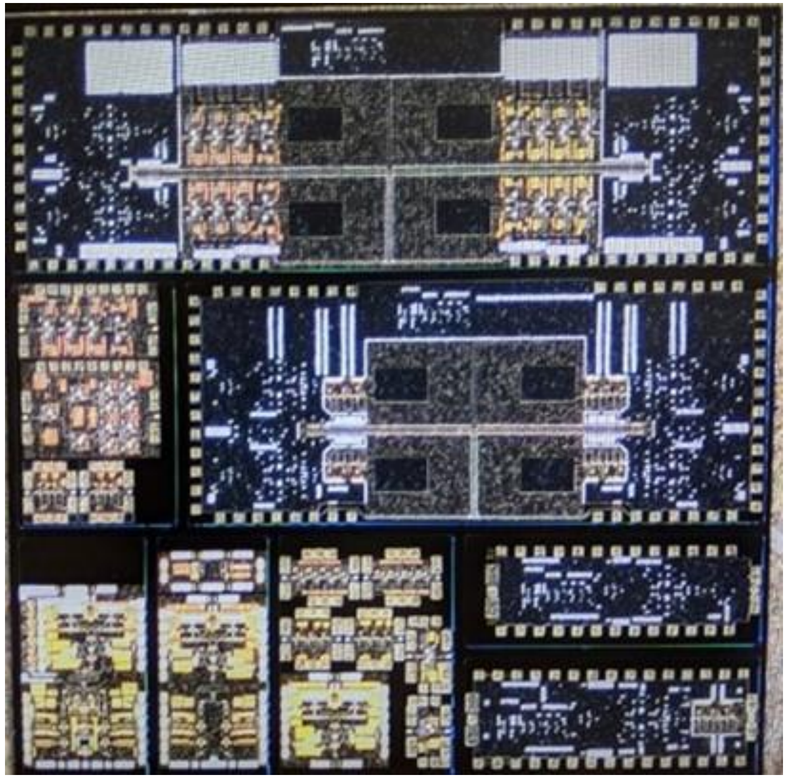
200GHz high-efficiency power amplifier: A. Ahmed et al, 2021 IMS

270GHz high-efficiency power amplifier: A. Ahmed et al, 2021 RFIC

4-channel 210GHz tranmistter and receiver arrays: to be tested

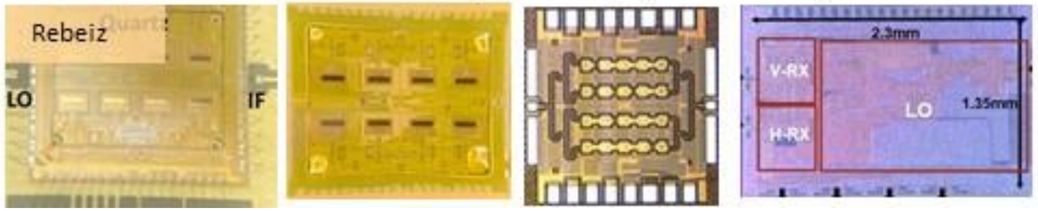
280GHz transmitter and receiver ICs: being designed.





A few key IC results

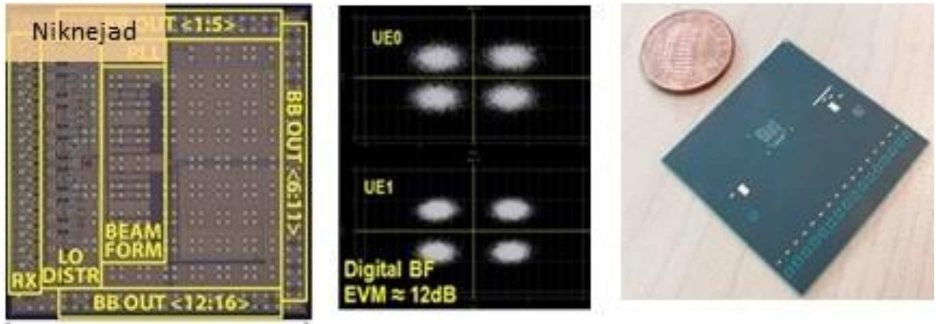
140GHz 8-element CMOS Tx, Rx arrays, record PA, 2-channel Rx



IMS2021, RFIC201, JSSC submission

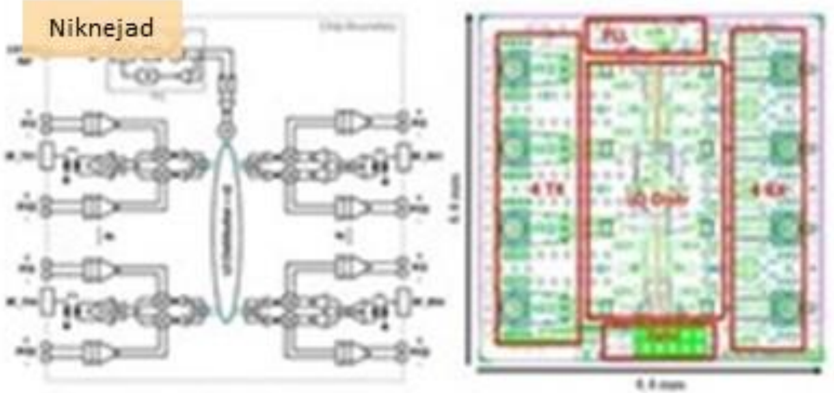
Beamspace digital beamformer

75GHz 16-channel CMOS MIMO receiver & module

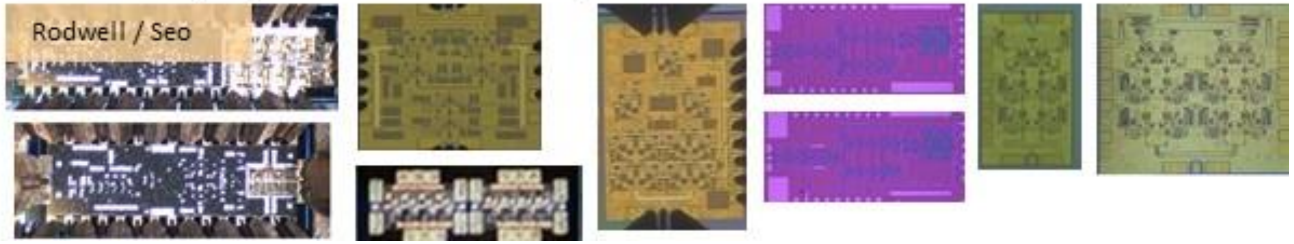


ISSCC2021

140GHz CMOS MIMO hub Tx/Rx arrays (coming soon)

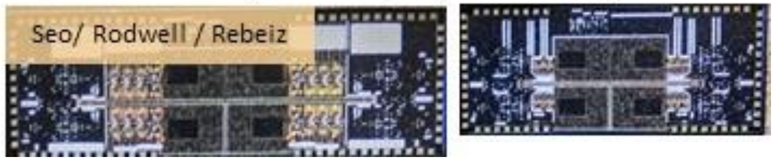


210GHz Tx, Rx, 210 & 270GHz PAs, LNAs. 140GHz hub ICs



IMS2021, RFIC2021, IMS2020, EuMIC2020, RFIC2019, EuMIC2021 submission

210GHz 2x2 Tx, Rx arrays (to be tested)



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

(backup files follow)

2021 Joint EuCNC & 6G Summit, June 8-11, 2021 (online meeting)

100-300GHz Wireless Communications: Systems, Arrays, ICs, and Transistors

Mark Rodwell,

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Muhannad Bakir*: Georgia Tech*
Sundeep Rangan*: New York University*
Amin Arbabian, Srabanti Chowdhury*: Stanford*
Elad Alon, Ali Niknejad, Borivoje Nikolic *: University of California, Berkeley*
Danijela Cabric, Tim Fisher*: University of California, Los Angeles*
Andrew Kummel, Gabriel Rebeiz*: University of California, San Diego*
Jim Buckwalter, Upamanyu Madhow, Umesh Mishra, Mark Rodwell, Susanne Stemmer*: University of California, Santa Barbara*
Andreas Molisch*: University of Southern California*
Kenneth O*: University of Texas, Dallas*

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

Collaborators (ComSenTer Wireless Team)

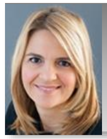
Systems


Sundeep Rangan
Networks, Applications, MIMO, Power


Upamanyu Madhow
UC Santa Barbara
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


Kenneth O
UT Dallas
140-300GHz
SiGe ICs


Muhannad Bakir
Georgia Tech
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
UC Berkeley
design automation
equalizers


Tim Fisher
UCLA
advanced packaging materials


Andrew Kummel
UCSD
advanced packaging materials

Transistors


Umesh Mishra
UC Santa Barbara
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 Arabian
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

Sponsors

DARPA
NORTHROP GRUMMAN
LOCKHEED MARTIN
NIST
arm
ANALOG DEVICES
tsmc
SAMSUNG
SK hynix
NSF
Micron
EMD PERFORMANCE MATERIALS
Raytheon Technologies
IBM
intel

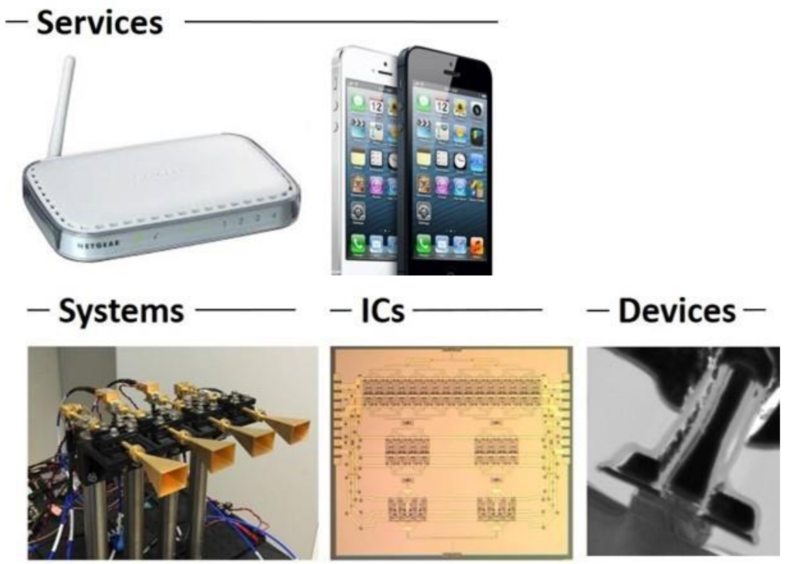
Beyond-5G Wireless

Wireless networks: exploding demand.

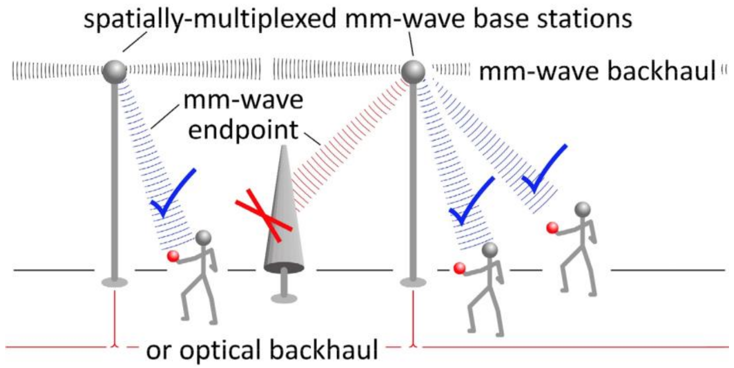
Immediate industry response: 5G.
~10-100GHz carriers.
increased spectrum, extensive beamforming

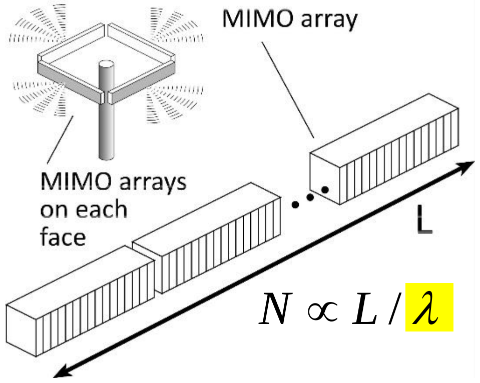
Next generation (6G ??): above 100GHz..
greatly increased spectrum, massive spatial multiplexing

JUMP Centers: research commercialized in 15 years

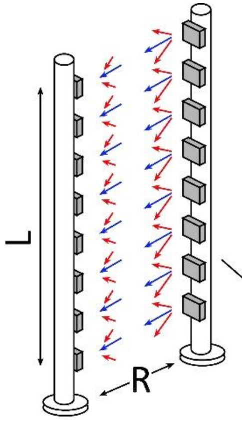


ComSenTer: 100-300GHz carriers, massive spatial multiplexing
→ Terabit hubs and backhaul links, high-resolution imaging radar



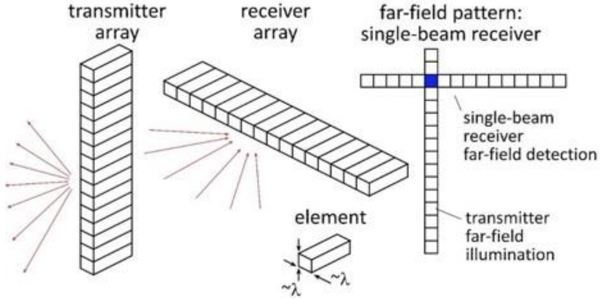


$N \propto L / \lambda$



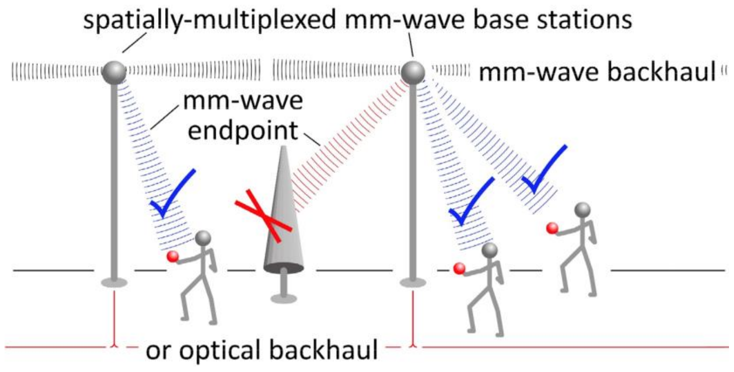
$N \propto L^2 / \lambda R$

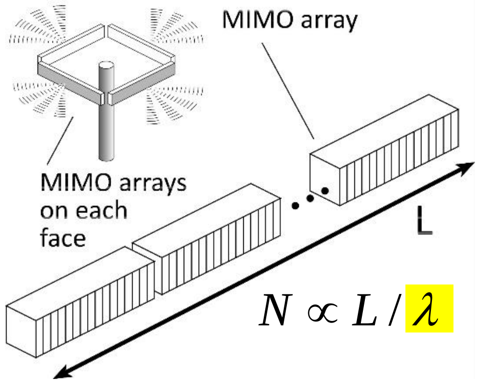
$\Delta\theta \propto \lambda / L$



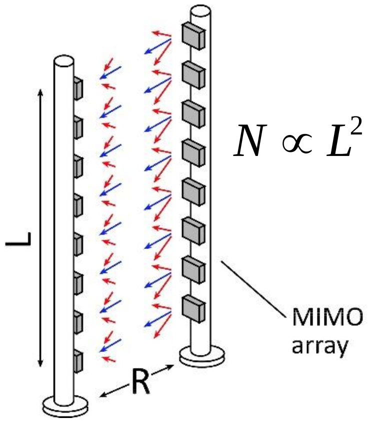
Benefits of Short Wavelengths

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

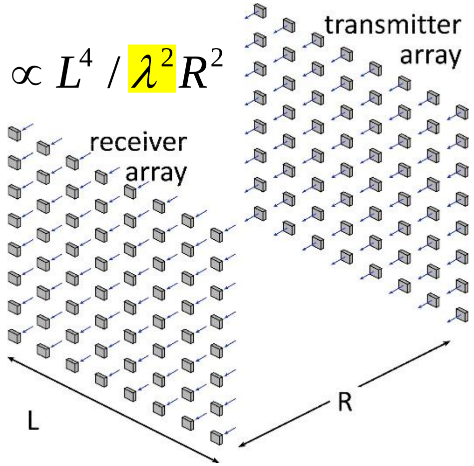




$N \propto L / \lambda$

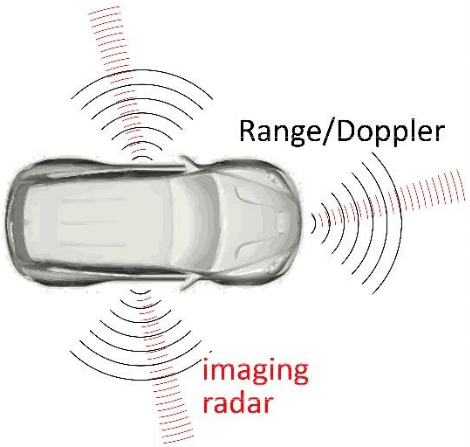


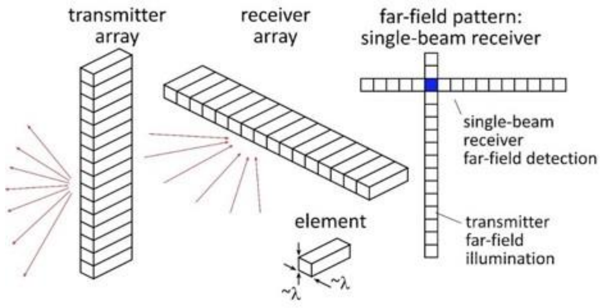
$N \propto L^2 / \lambda R$



$N \propto L^4 / \lambda^2 R^2$

Imaging: very fine angular resolution





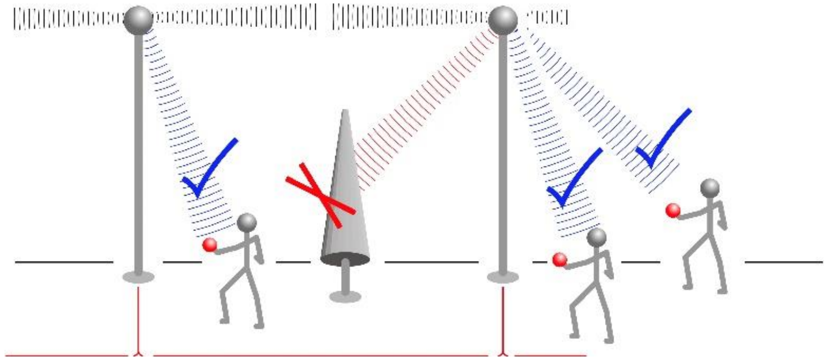
$\Delta\theta \propto \lambda / L$

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

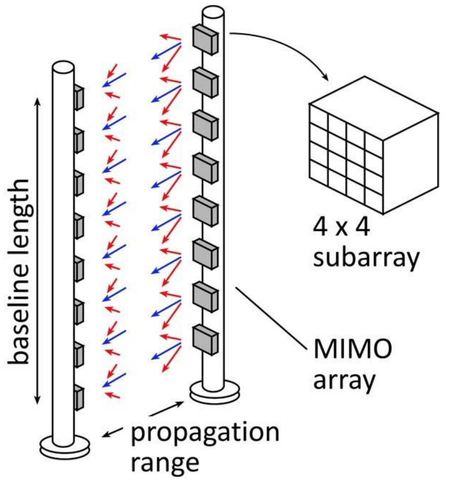
100-340GHz wireless:
terabit capacity,
short range,
highly intermittent

Potential 100-300GHz Systems

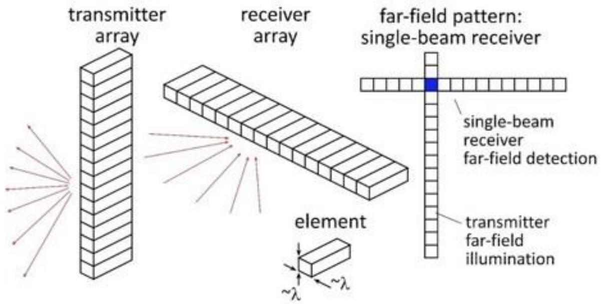
140GHz MIMO Hub

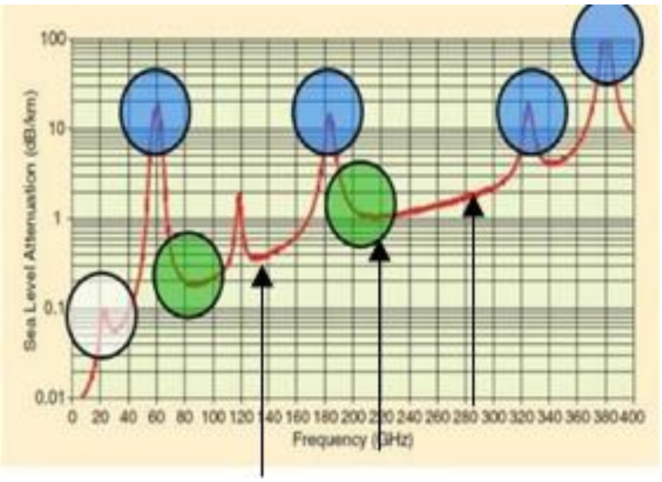


210 or 280GHz MIMO Backhaul

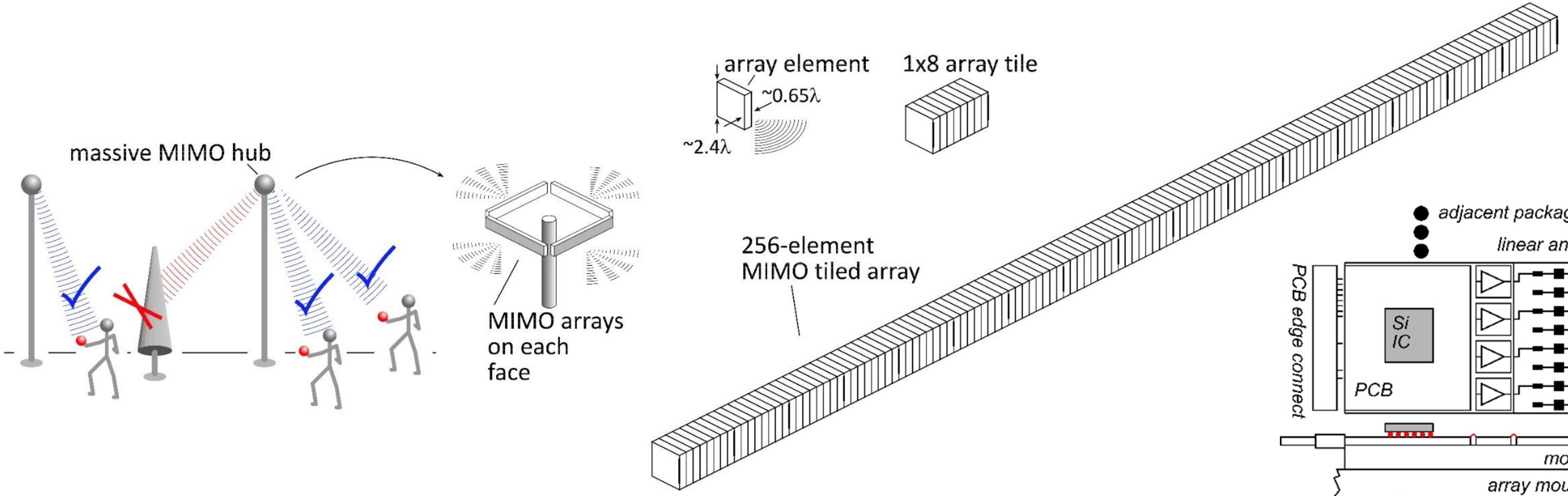


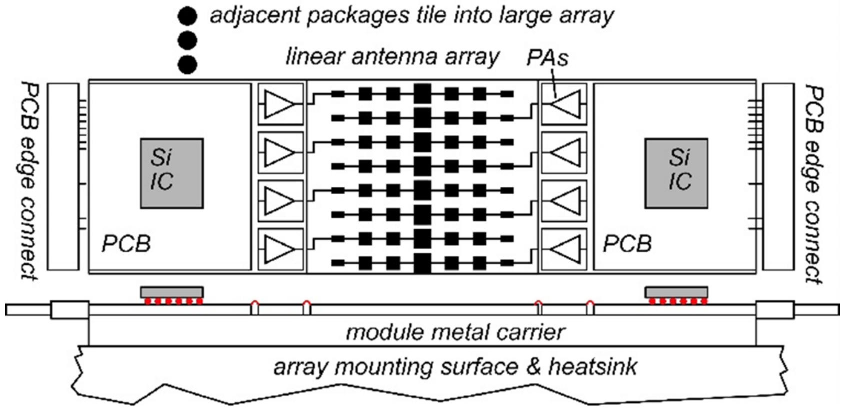
140 or 210GHz Imaging Radar

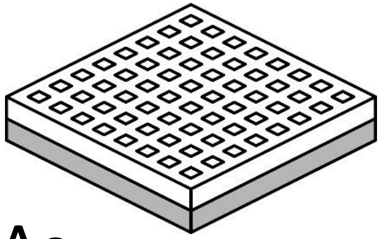




140GHz massive MIMO hub







Handset:
8 × 8 array
(9×9mm)

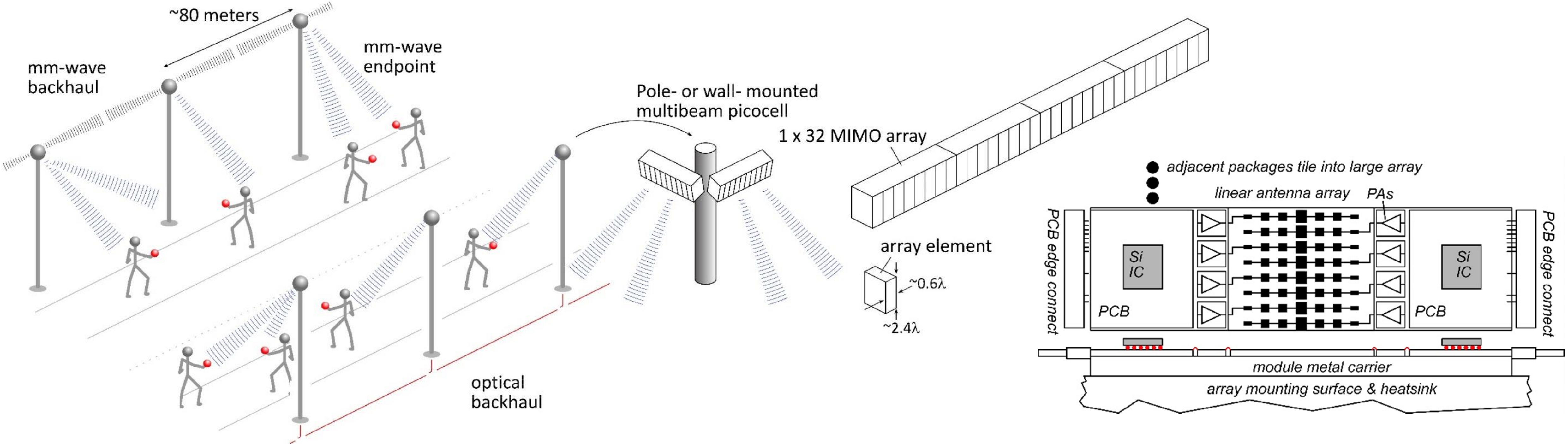
0.5-5 Tb/s spatially-multiplexed 140GHz base station

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

140GHz moderate-MIMO hub

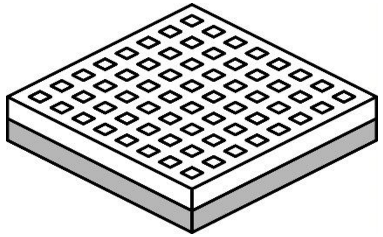


If demo uses 32-element array (four 1×8 modules):

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

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

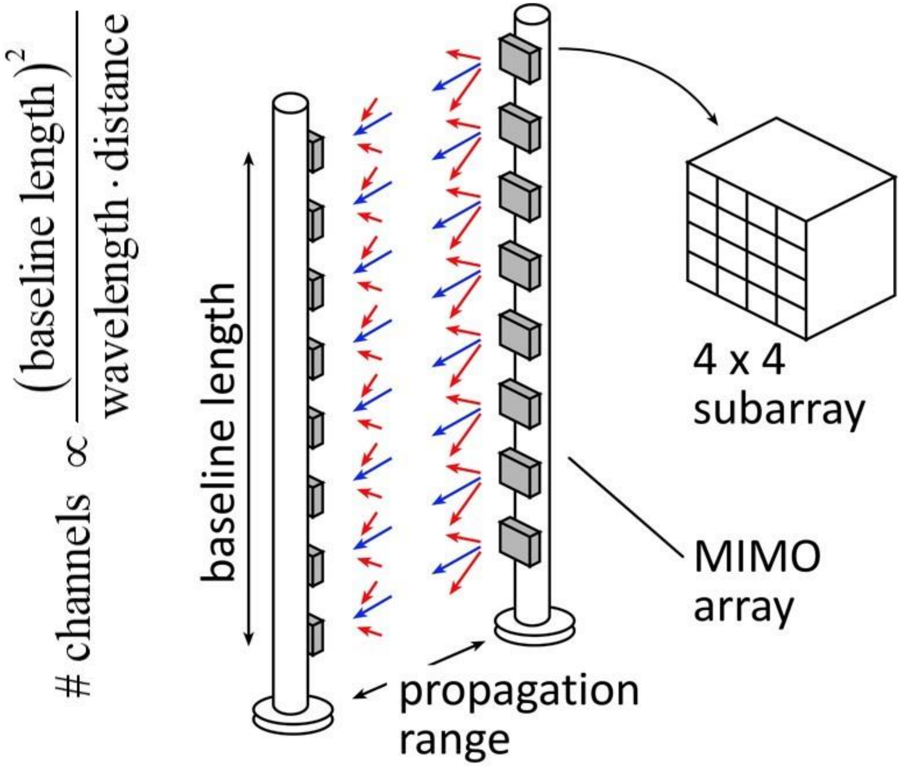
40, 70 m range in 50mm/hr rain with **17**dB total margins

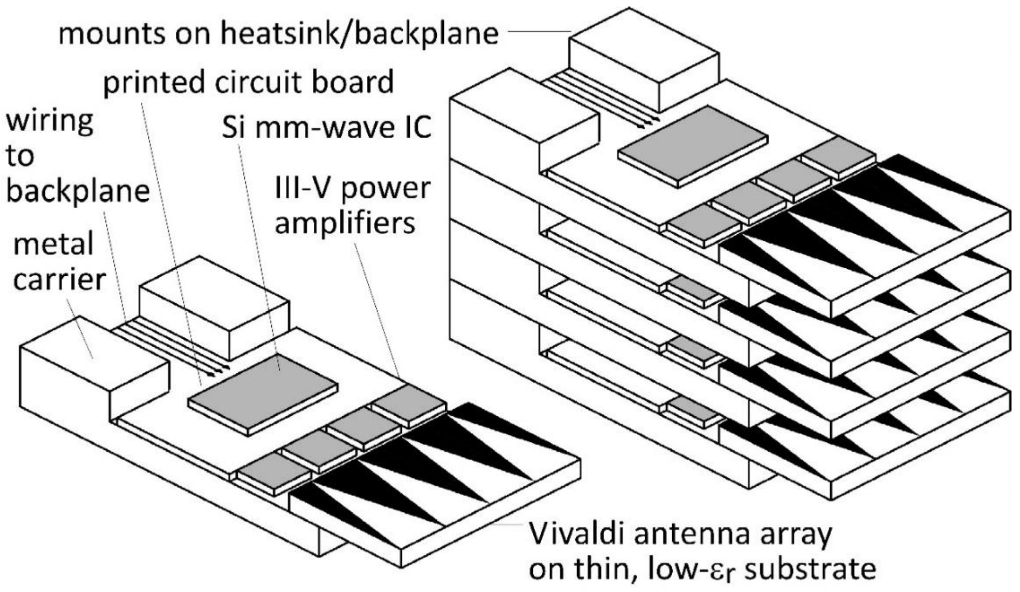


Handset:
8 × 8 array
(9×9mm)

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

210 GHz, 640 Gb/s MIMO Backhaul

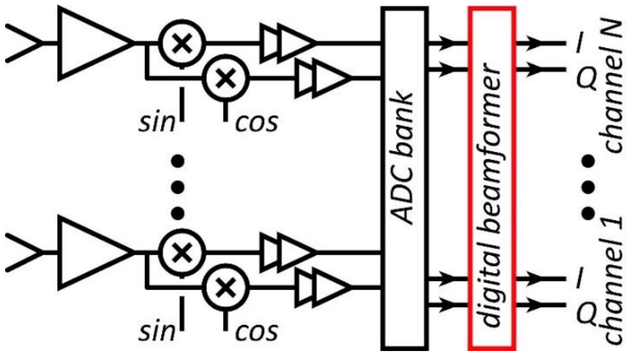


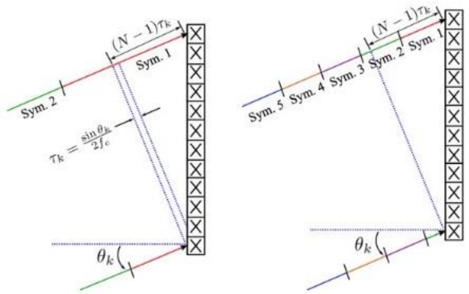


8-element MIMO array
3.1 m baseline.
80Gb/s/subarray→ 640Gb/s total
4 × 4 sub-arrays → 8 degree beamsteering

Key link parameters
500 meters range in 50 mm/hr rain; 23 dB/km
20 dB total margins:
packaging loss, obstruction, operating, design, aging
PAs: 18dBm $=P_{1dB}$ (per element)
LNAs: 6dB noise figure

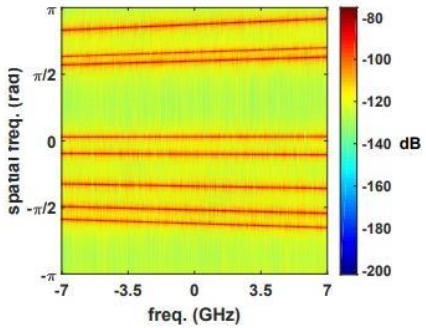
Systems



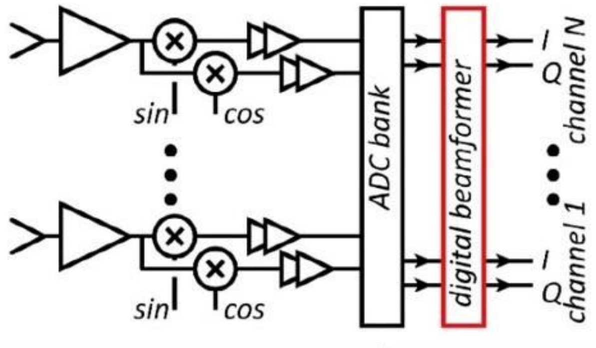


(a) Narrowband scenario.

(b) Wideband scenario.



System Design

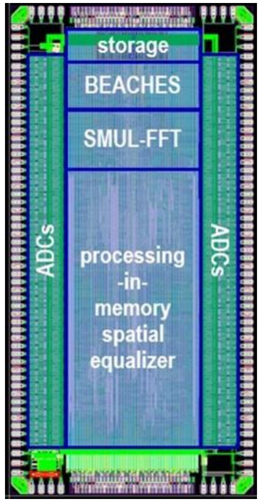


ADCs/DACs: only 3-4 bit ADC/DACs required
(Madhow, Studer, Rodwell)

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

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

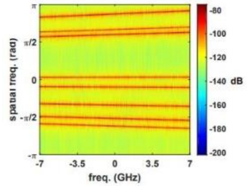
Efficient digital beamforming: beamspace algorithm=complexity ~N× log(N)
(Madhow, Studer)

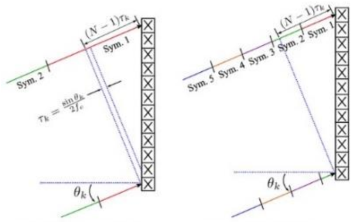


Efficient digital beamforming: low-resolution matrix
(Studer)

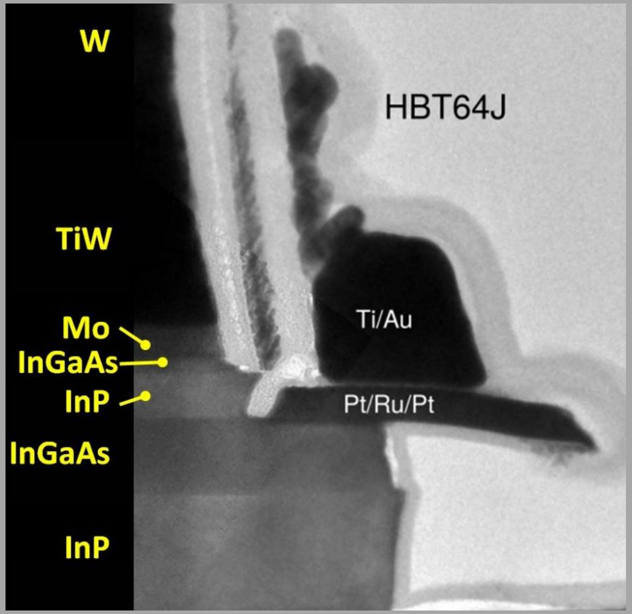
Efficient channel estimation : fast beamspace algorithm
(Studer)

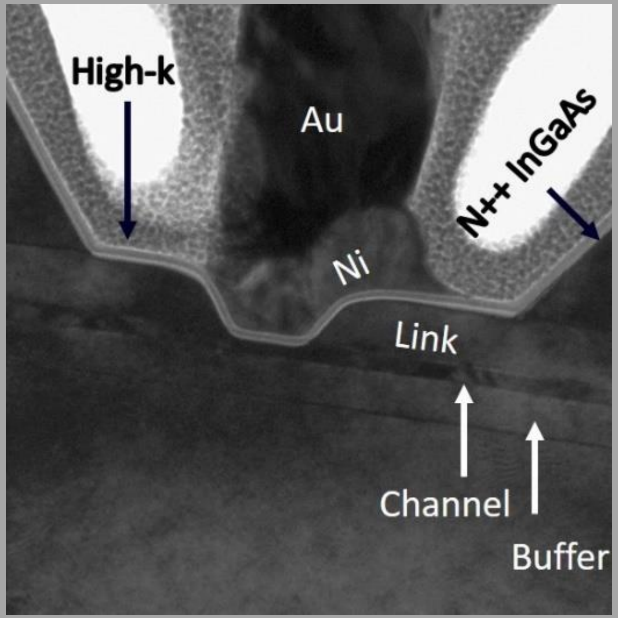
Efficiently addressing true-time-delay problem: "rainbow" FFT algorithm
(Madhow, Cabric, Studer)

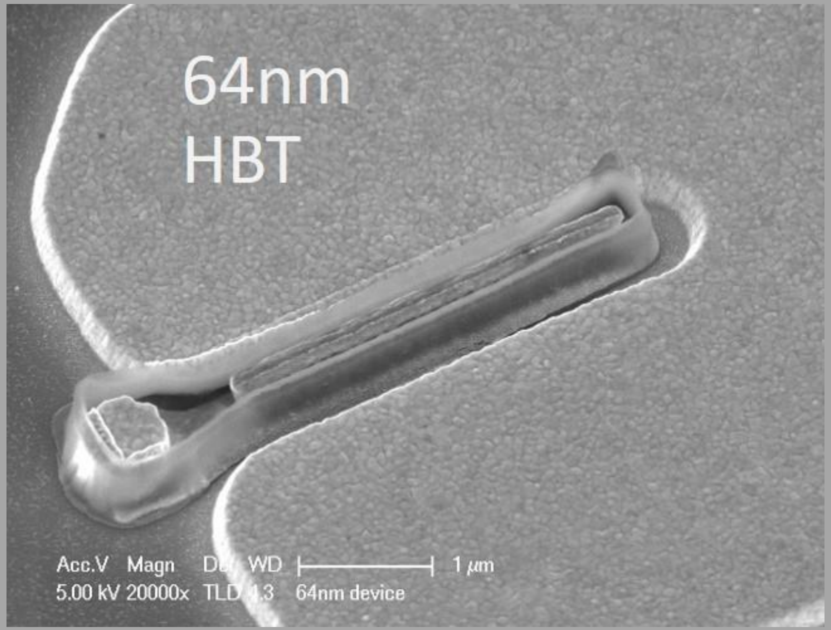



(a) Narrowband scenario.
(b) Wideband scenario.

Transistors







100-1000 GHz Transistors and ICs

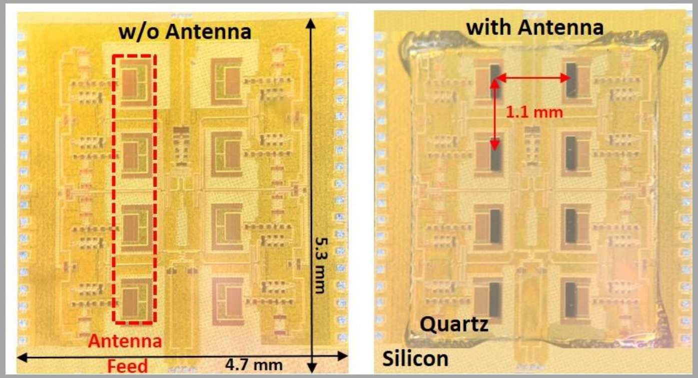
	f_{max} GHz	Good ICs to (GHz)	complexity	LNAs	PAS	increased bandwidth ?
CMOS	350	150/200	transceivers	good	weak: 10-30 mW	not easy
Production SiGe	300	200/250	transceivers	ok	OK: 20-100 mW	depends on $$
R&D SiGe	700	300/500	transceivers	good	OK: 20-100 mW	2-3THz
R&D InP HBT	1150	400/650	PA, converters	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

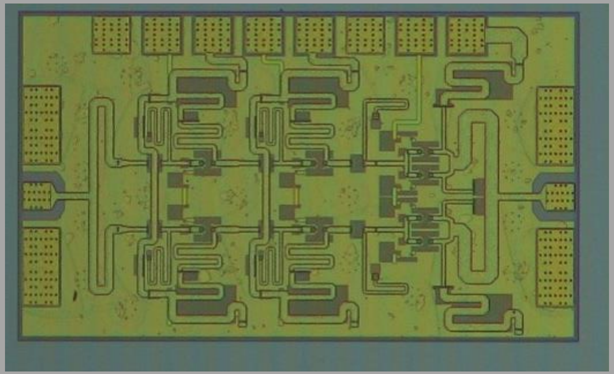
ICs with useful performance, hero experiments
*can be addressed

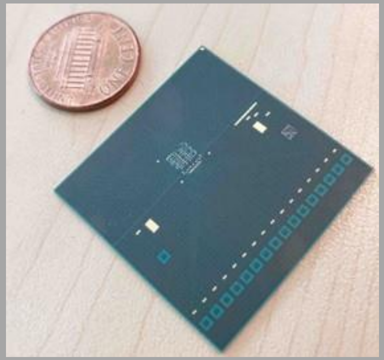
There are THz transistors today; their bandwidth will increase

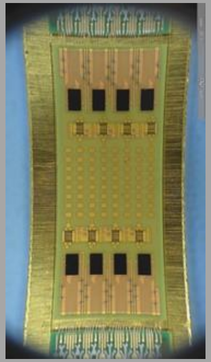
Challenge: reducing costs, increasing market size

ICs and Packages



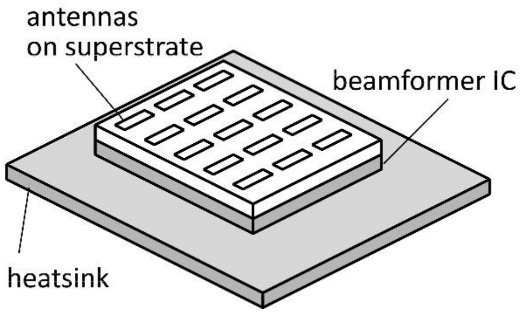


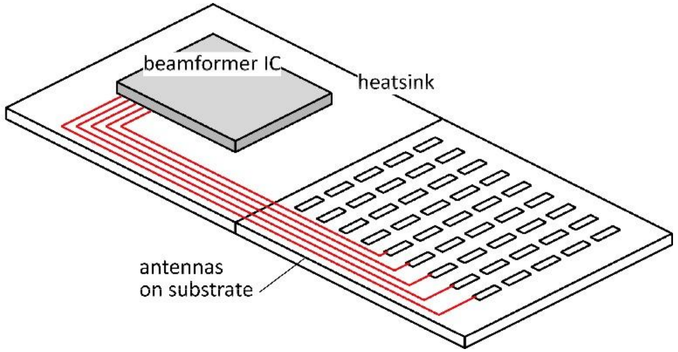




The mm-wave module design problem

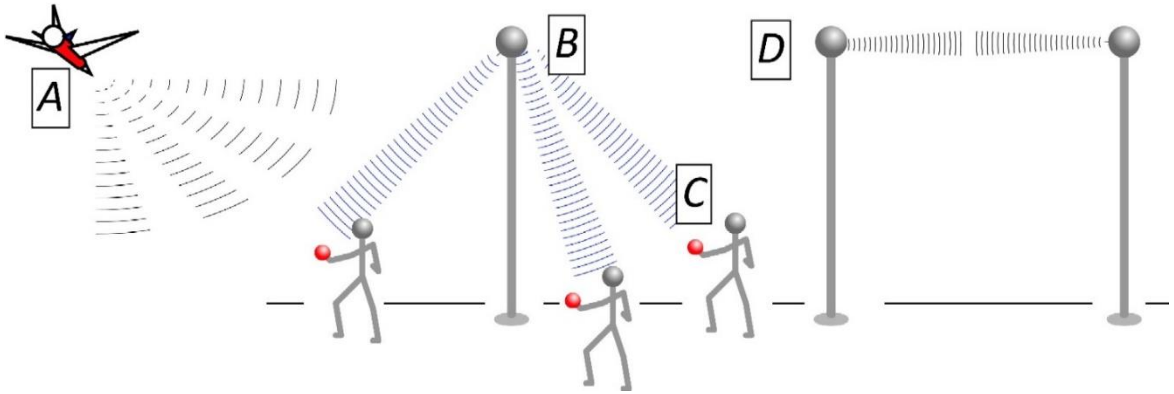
How to make the IC electronics fit ?
How to avoid catastrophic signal losses ?
How to remove the heat ?

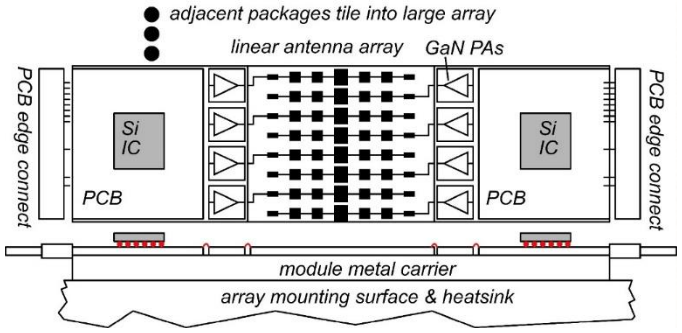


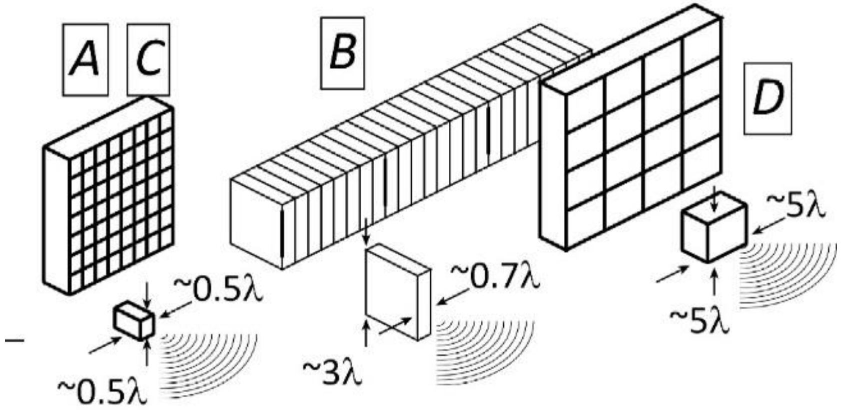


Not all systems steer in two planes...
...some steer in only one.

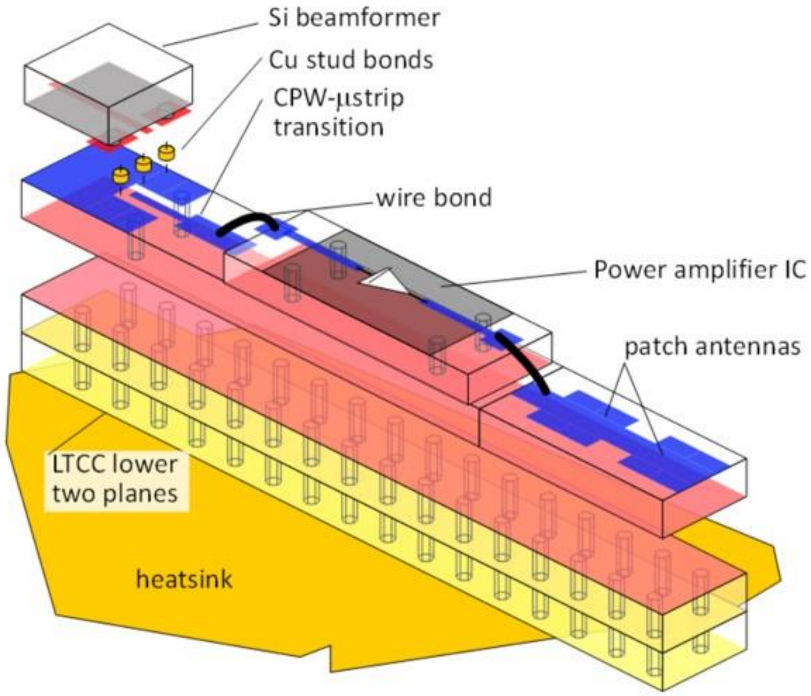
Not all systems steer over 180 degrees...
...some steer a smaller angular range

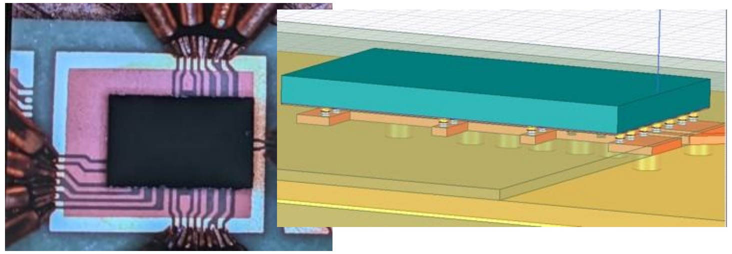




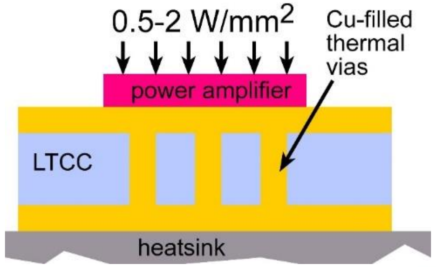


140GHz hub: packaging challenges

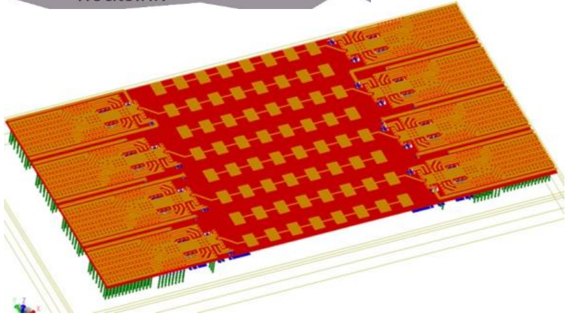




IC-package interconnects
Difficult at > 100 GHz



Removing heat
Thermal vias are marginal

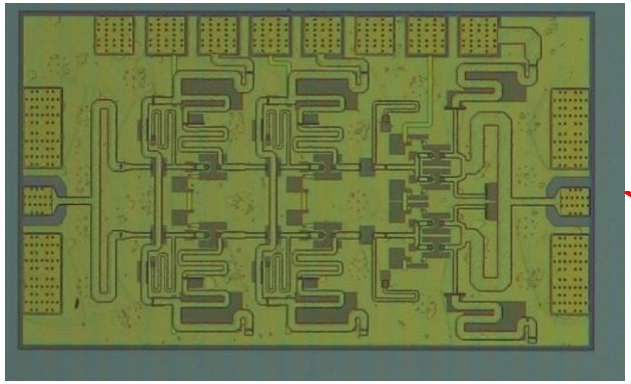


Interconnect density
Dense wiring for DC, LO, IF, control.
Hard to fit these all in.

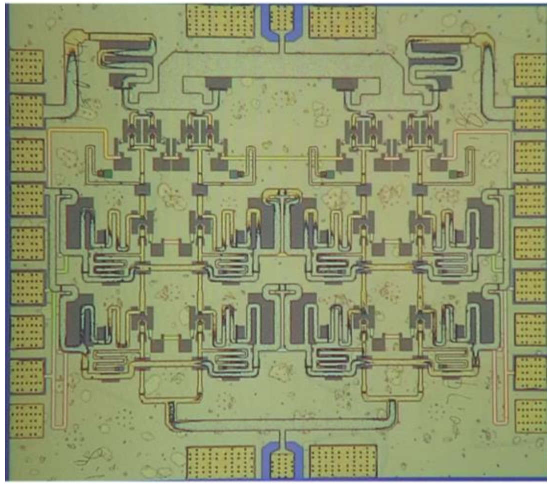
Economies of scale
Advanced packaging standards require sophisticated tools
High-volume orders only
Hard for small-volume orders (research, universities)
Packaging industry is moving offshore

140GHz hub: ICs & Antennas

110mW InP Power Amplifier
20.8% PAE

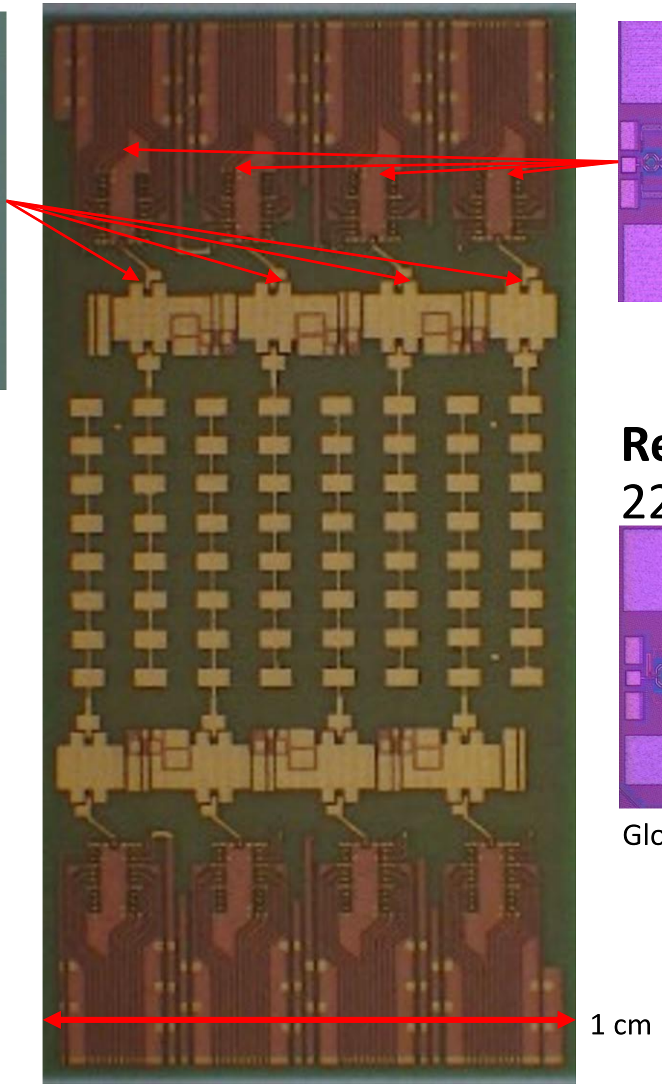


190mW InP Power Amplifier
16.7% PAE



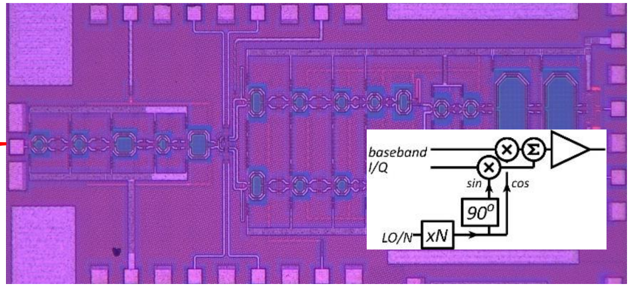
Teledyne InP HBT

LTCC Array module

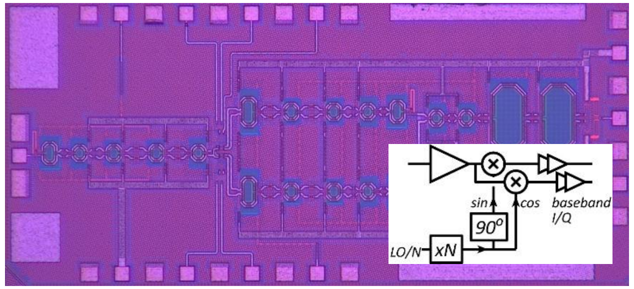


Kyocera

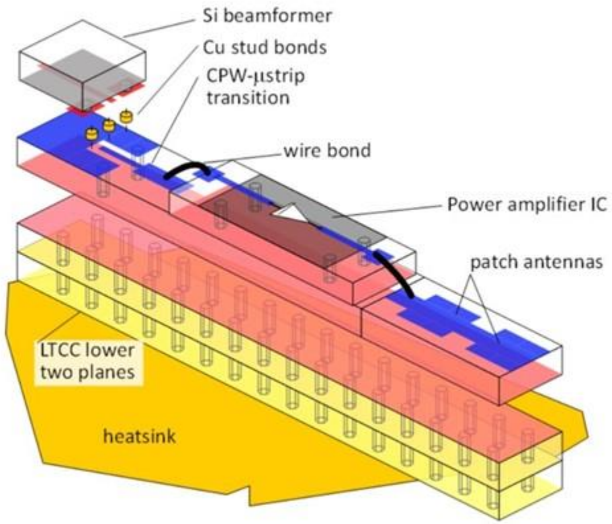
CMOS Transmitter IC
22nm SOI CMOS.



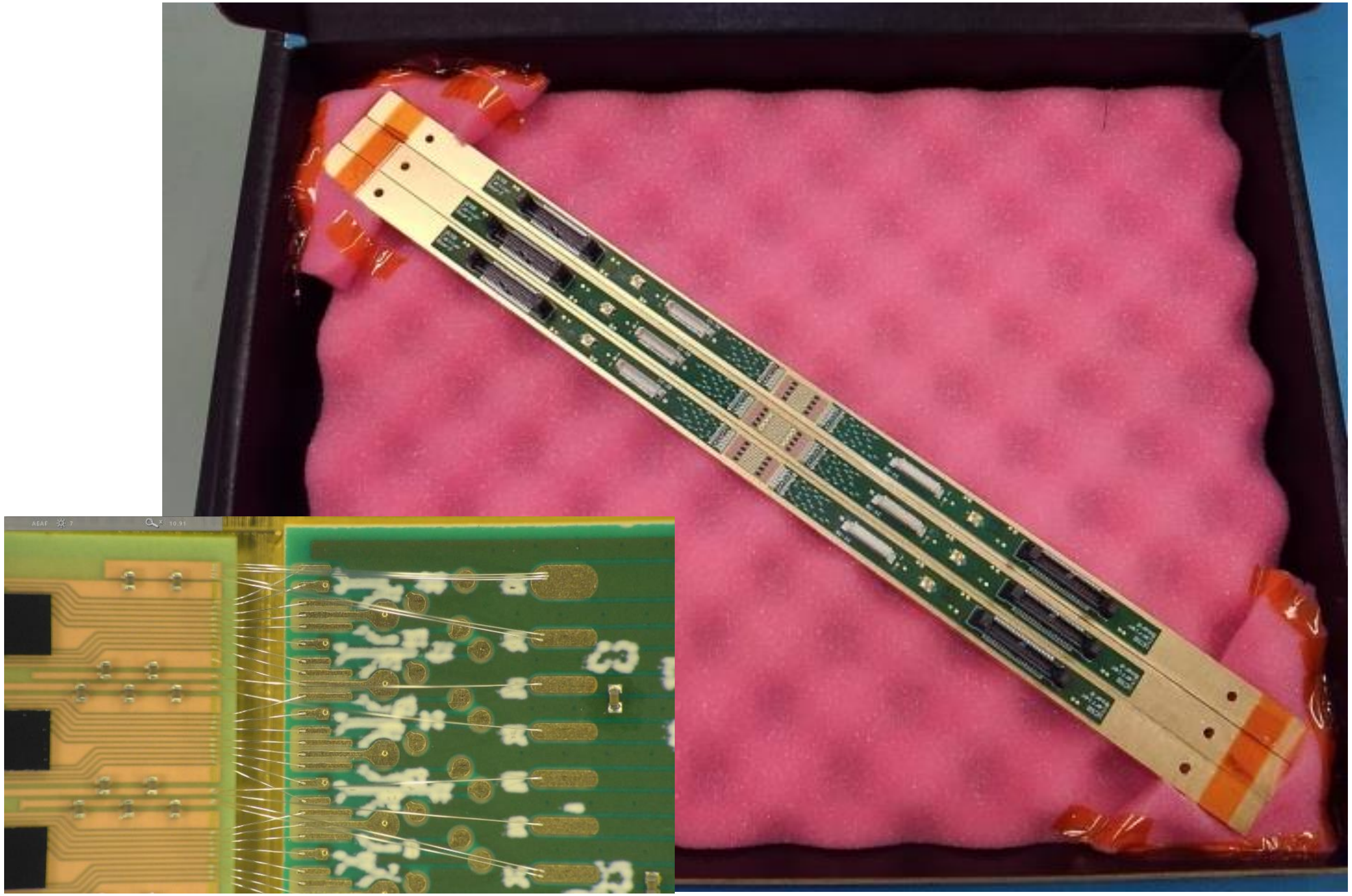
Receiver IC
22nm SOI CMOS.

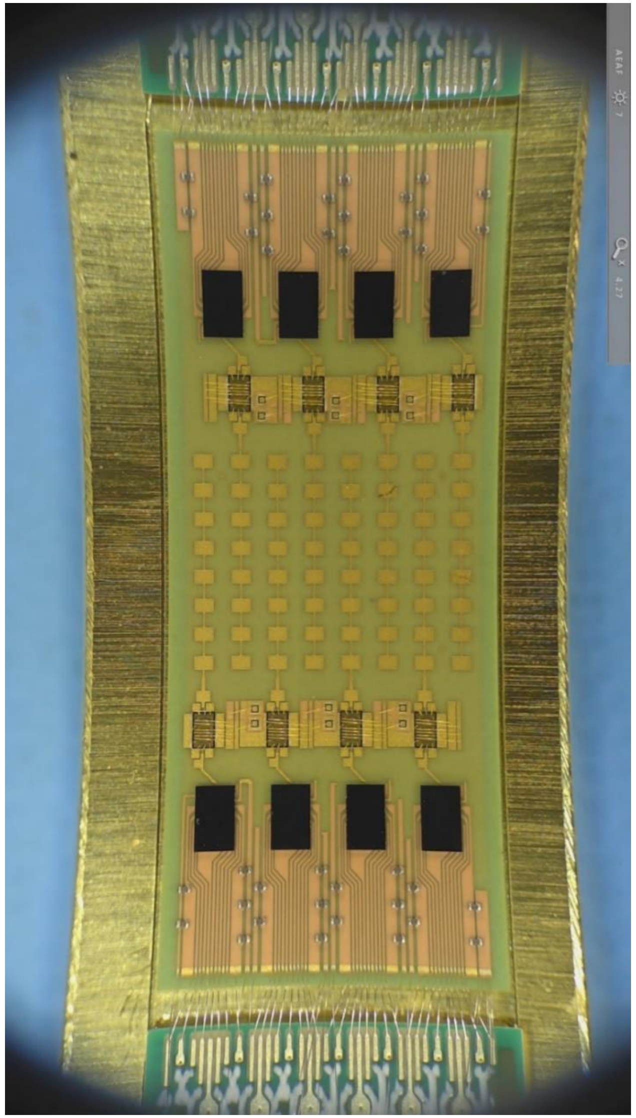


GlobalFoundries 22nm SOI CMOS



8-Channel 140GHz MIMO hub modules being tested.





ICs for 210GHz and 280GHz MIMO links

210GHz and 280GHz transceivers in development.

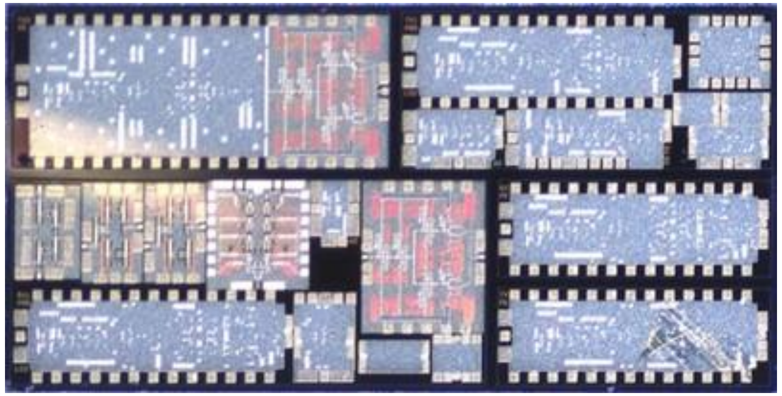
210GHz transmitter, receiver: M. Seo et al, 2021 IMS

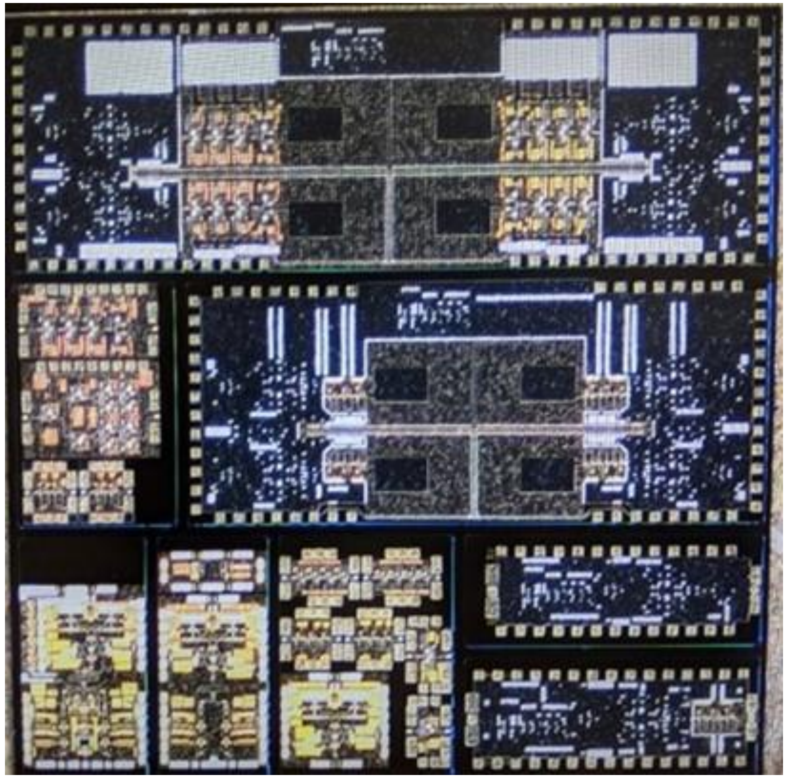
200GHz high-efficiency power amplifier: A. Ahmed et al, 2021 IMS

270GHz high-efficiency power amplifier: A. Ahmed et al, 2021 RFIC

4-channel 210GHz tranmistter and receiver arrays: to be tested

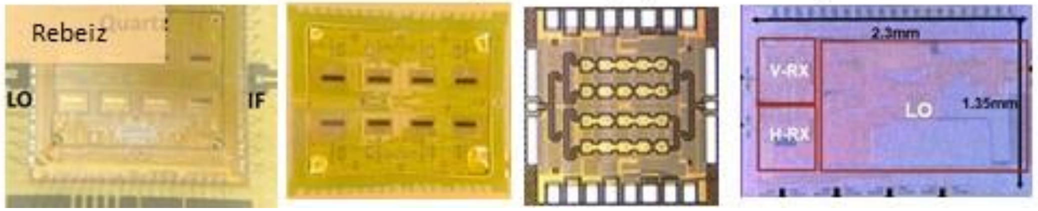
280GHz transmitter and receiver ICs: being designed.





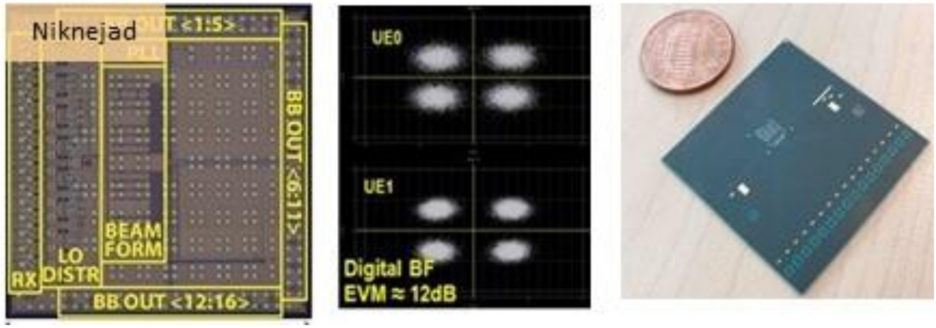
A few key IC results

140GHz 8-element CMOS Tx, Rx arrays, record PA, 2-channel Rx

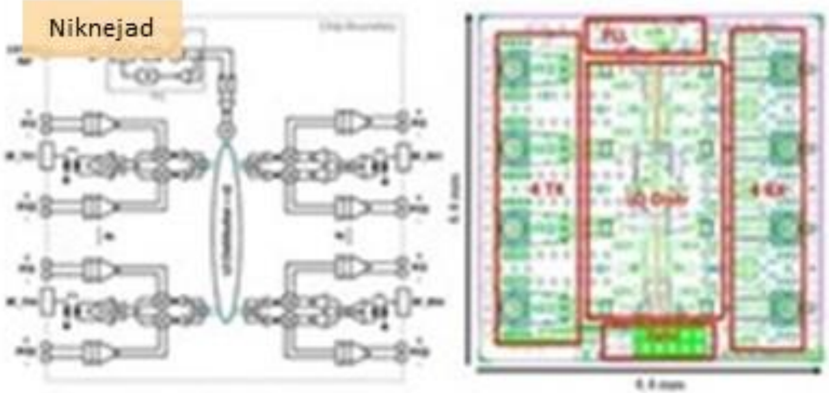


Beamspace digital beamformer

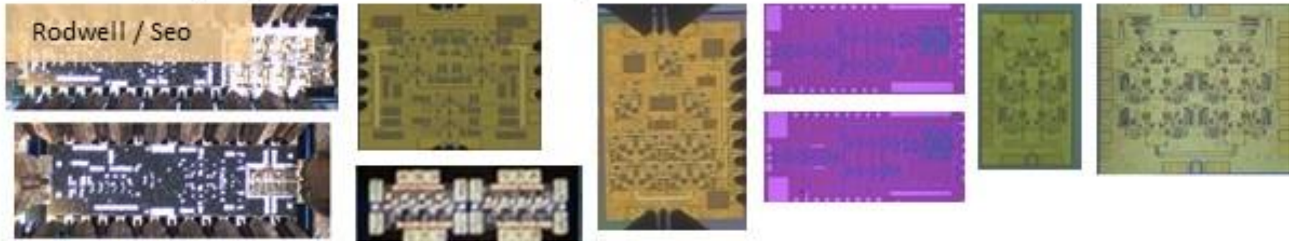
75GHz 16-channel CMOS MIMO receiver & module



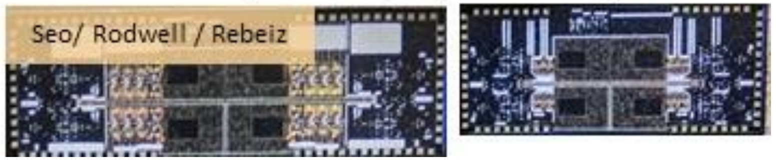
140GHz CMOS MIMO hub Tx/Rx arrays (coming soon)



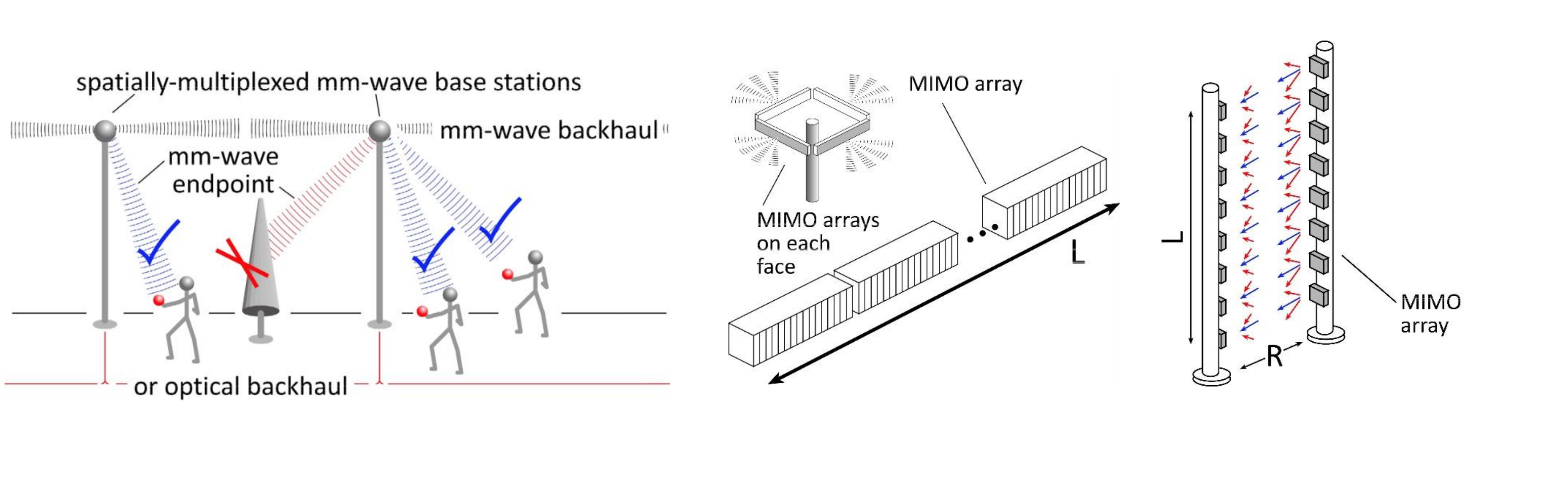
210GHz Tx, Rx, 210 & 270GHz PAs, LNAs. 140GHz hub ICs



210GHz 2x2 Tx, Rx arrays (to be tested)



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-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