THz workshop, 2020 IEEE WCNC Conference

100-300GHz Wireless

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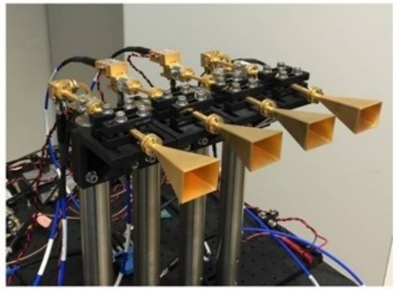
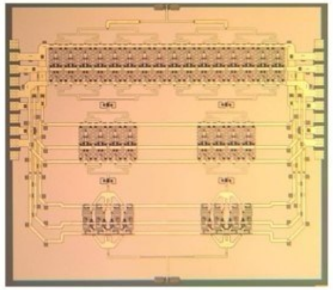
Wireless above 100GHz

Services

Systems



ICs



Devices

Wireless networks: exploding demand.

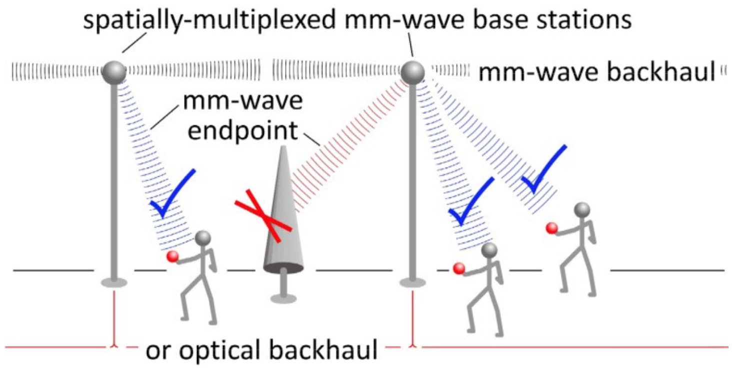
Immediate industry response: 5G.
28, 38, 57-71(WiGig), 71-86GHz
increased spectrum, extensive beamforming

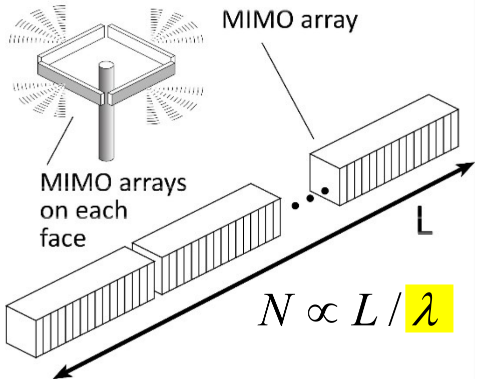
Next generation (6G ??): above 100GHz..
greatly increased spectrum, massive spatial multiplexing

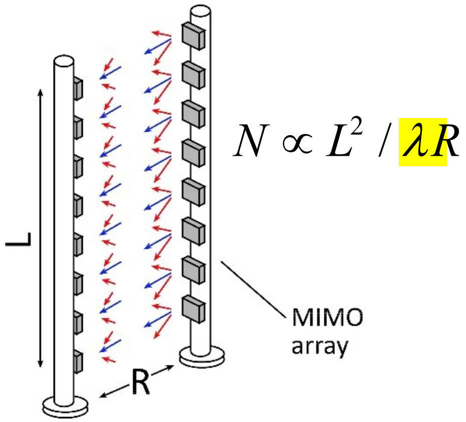
DOD applications: Imaging/sensing/radar, comms.

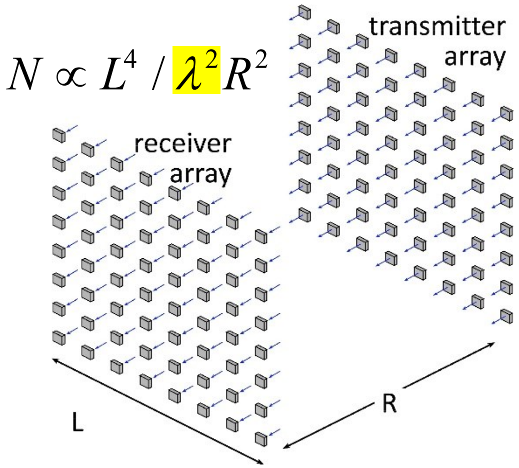
Benefits of Short Wavelengths

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

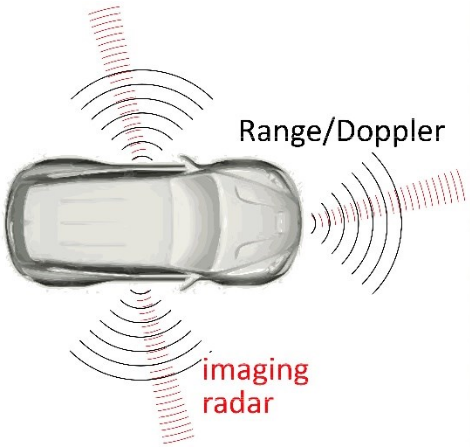


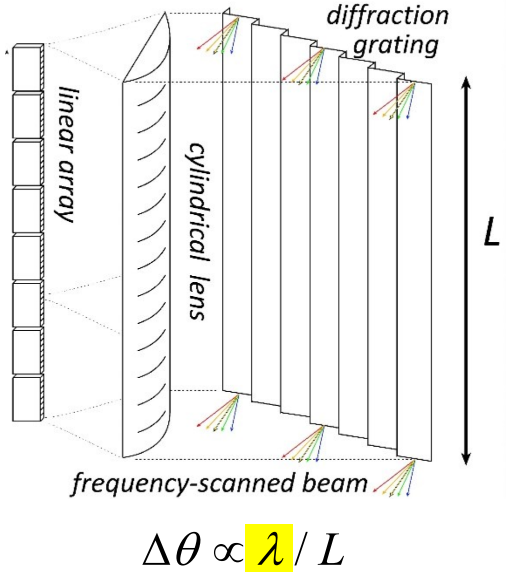






Imaging: very fine angular resolution

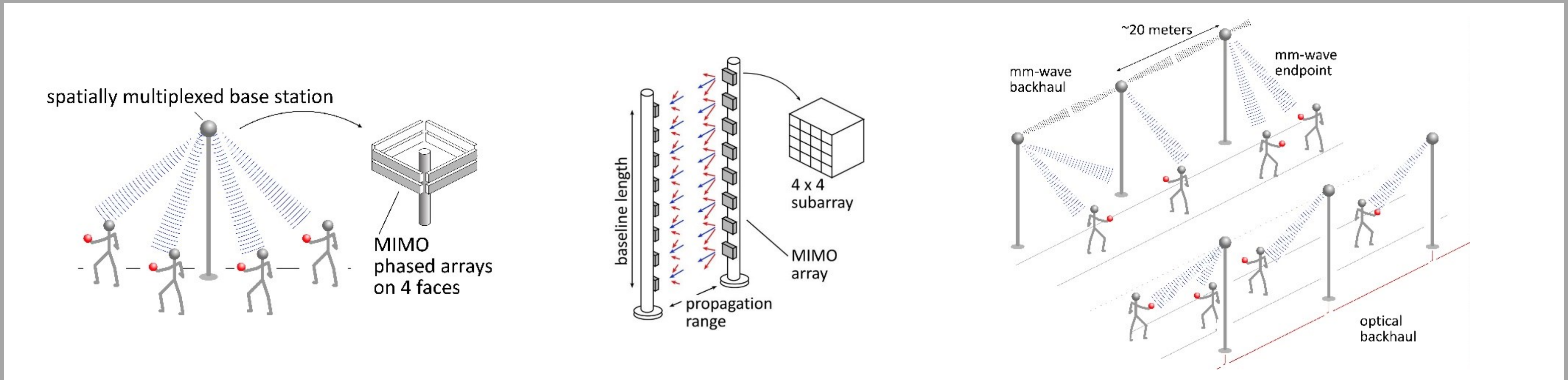




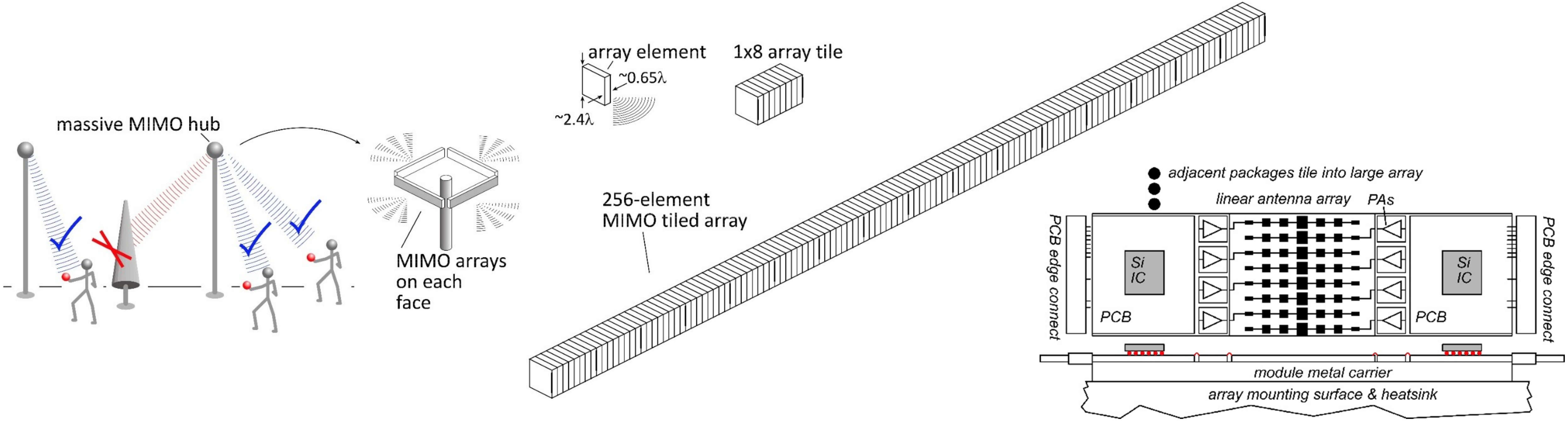
But:
High losses in foul or humid weather.
High λ^2/R^2 path losses.
ICs: poorer PAs & LNAs.
Beams easily blocked.

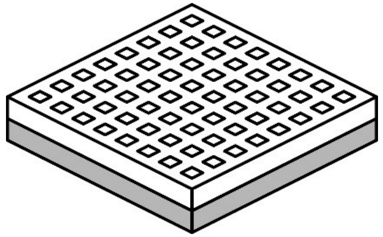
100-340GHz wireless:
terabit capacity,
short range,
highly intermittent

140-340 GHz: Applications



140GHz massive MIMO hub demo





Handset:
8 × 8 array
(9×9mm)

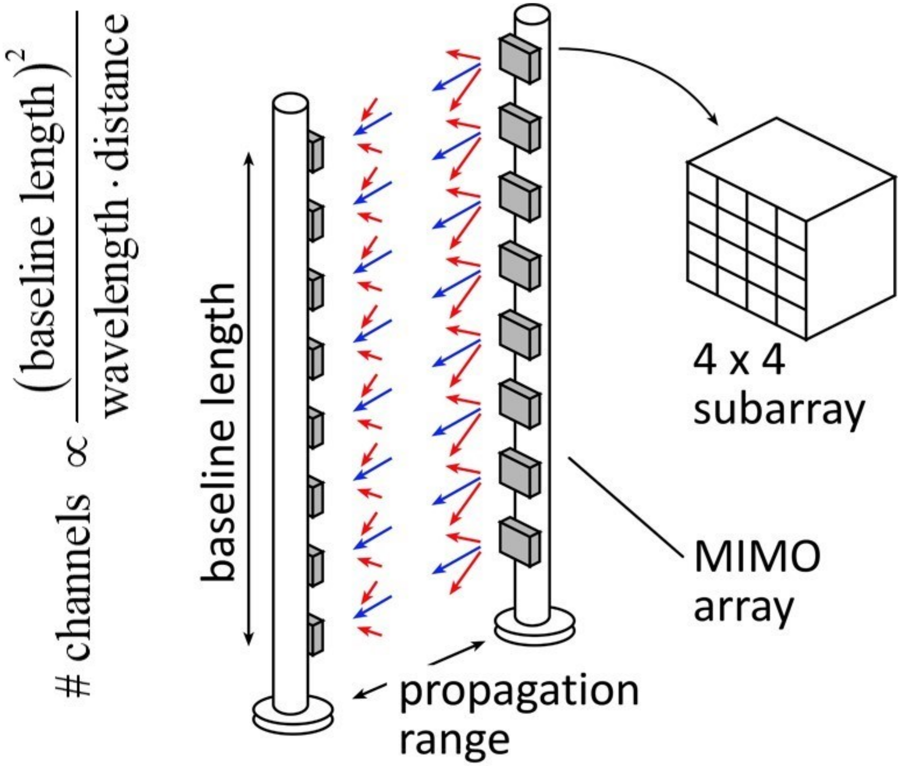
1 Tb/s spatially-multiplexed 140GHz base station

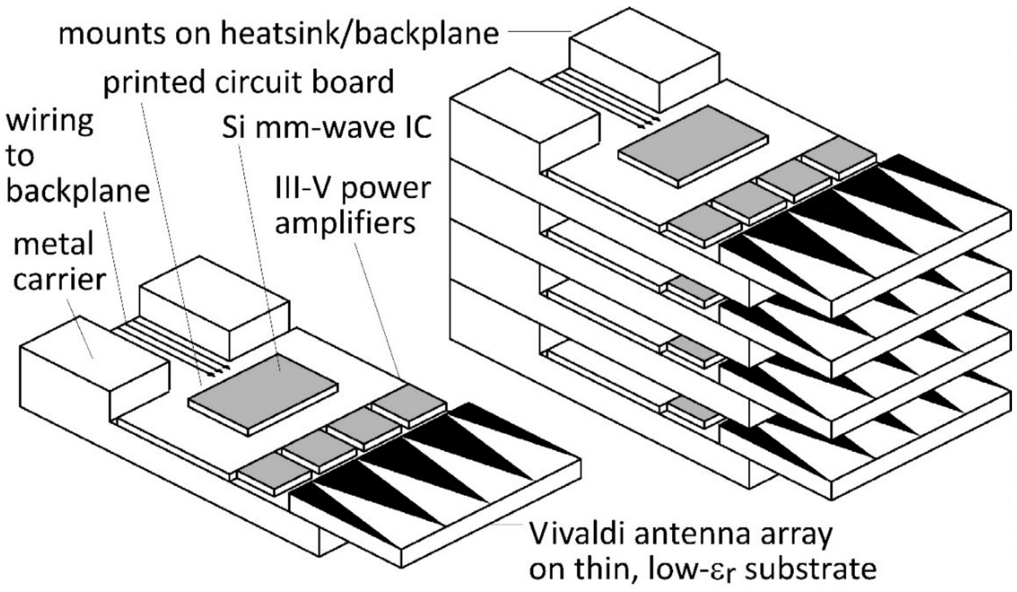
128 users/face, 4 faces. 21 dB_m PAs, F=8dB LNAs

1024 total users @ 1 user/beam, 1,10 Gb/s/beam;

225, 100 m range in 50mm/hr rain with 20dB total margins

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

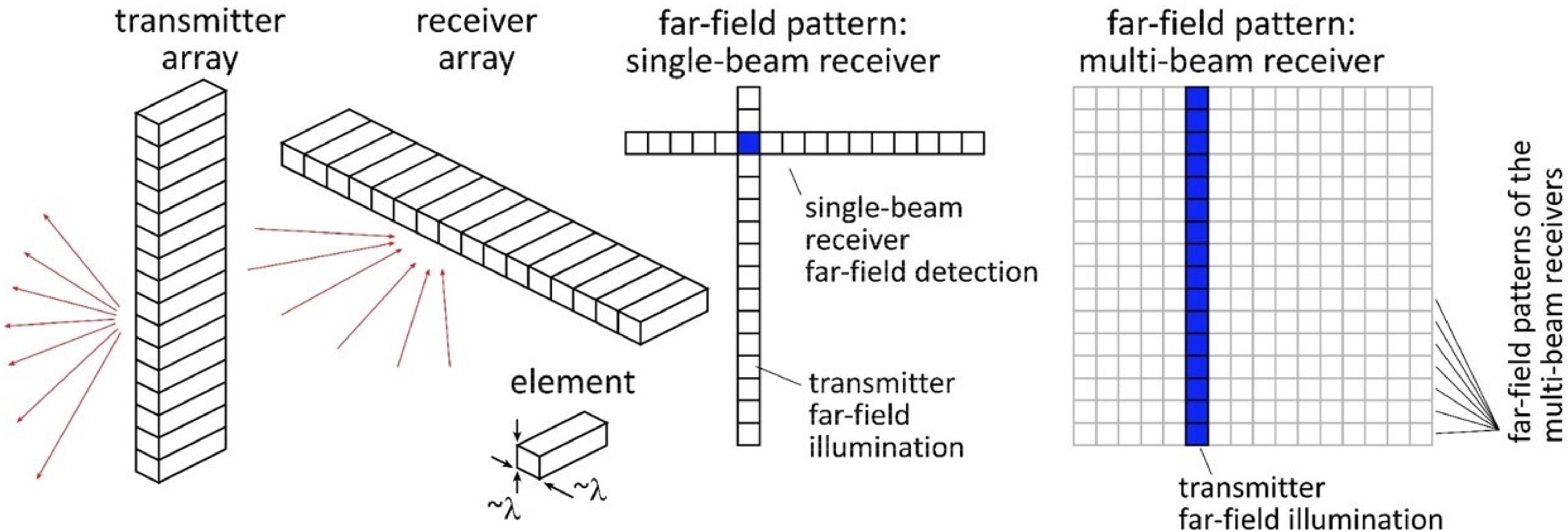
24 dB total margins:

packaging loss, obstruction, operating, design, aging

PAs: 24mW P_{out} (per élément)

LNAs: 6dB noise figure

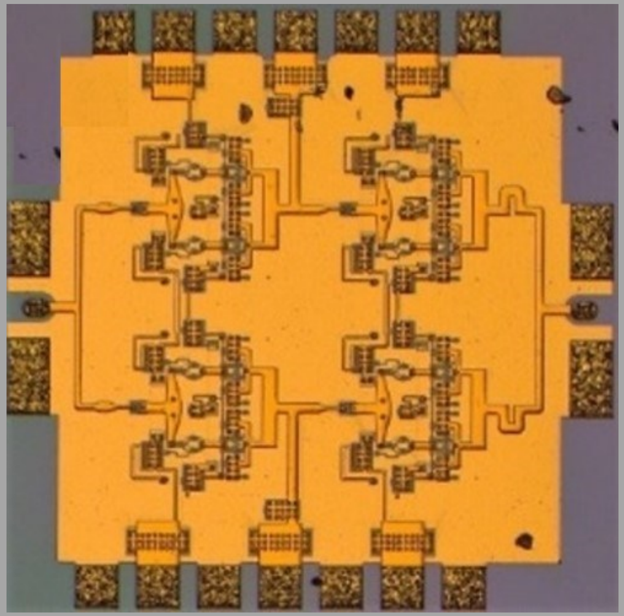
High-resolution imaging radar

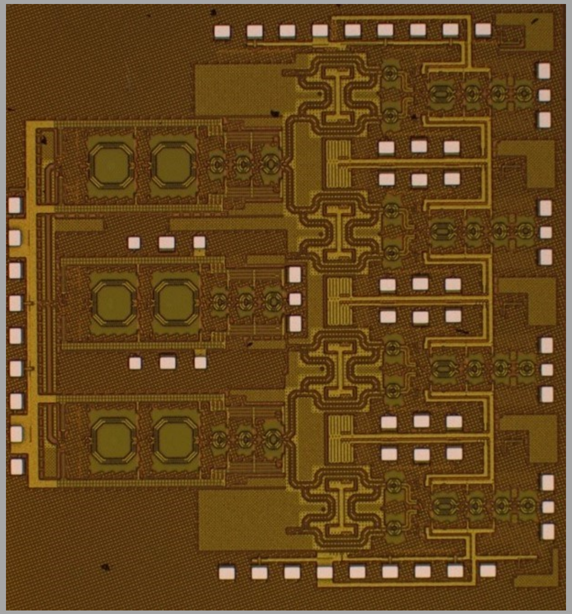


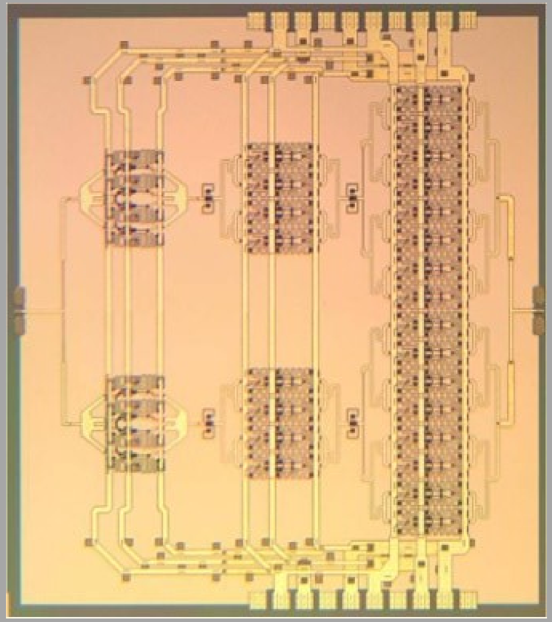
Goal: MIMO Imaging Radar

Carrier Frequencies: 140, 210GHz

ICs



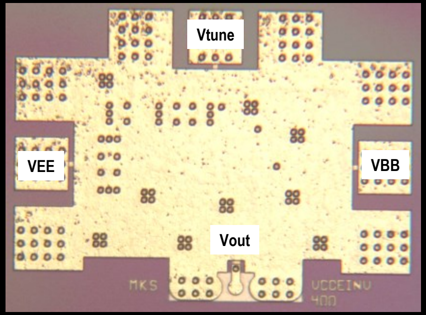




InP HBT to 670 GHz: DARPA TFAST and THz Programs

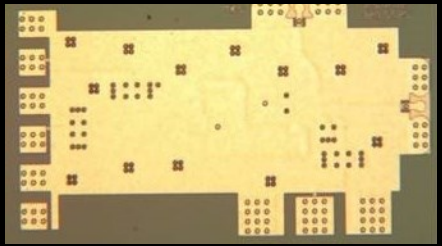
560 GHz fundamental VCO

M. Seo, TSC / UCSB



340 GHz dynamic frequency divider

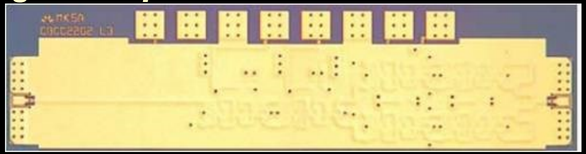
M. Seo, UCSB/TSC
IMS 2010



620 GHz, 20 dB gain amplifier

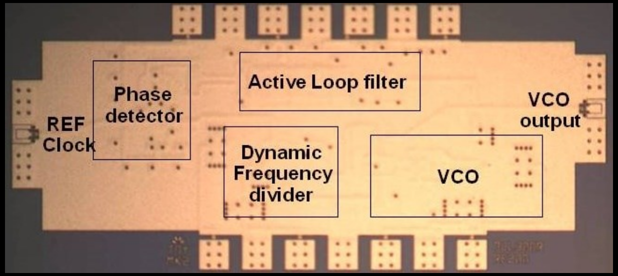
M Seo, TSC
IMS 2013

also: 670GHz amplifier
J. Hacker , TSC
IMS 2013 (not shown)



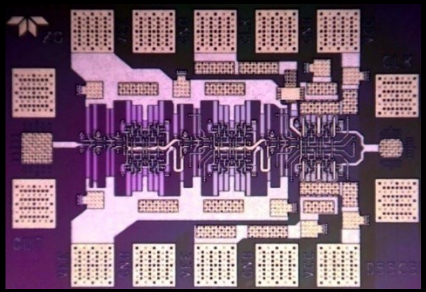
300 GHz fundamental PLL

M. Seo, TSC
IMS 2011



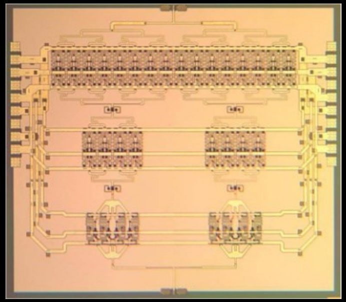
204 GHz static frequency divider (ECL master-slave latch)

Z. Griffith, TSC / UCSB
CSIC 2010



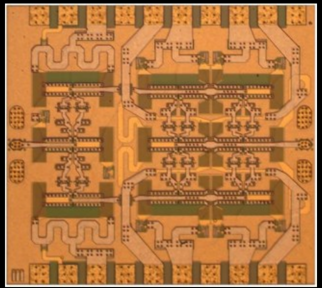
220 GHz 180 mW power amplifier

T. Reed, UCSB
CSICS 2013

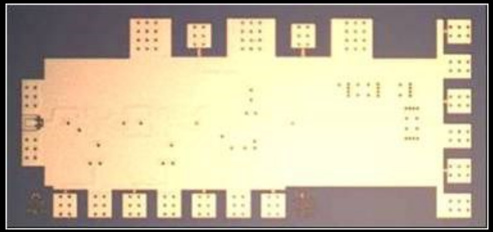


81 GHz 470 mW power amplifier

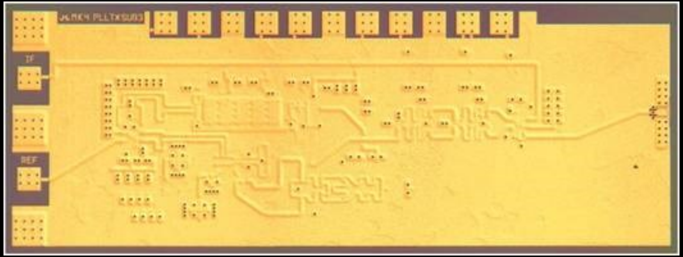
H-C Park UCSB
IMS 2014



Integrated 300/350GHz Receivers:
LNA/Mixer/VCO
M. Seo TSC



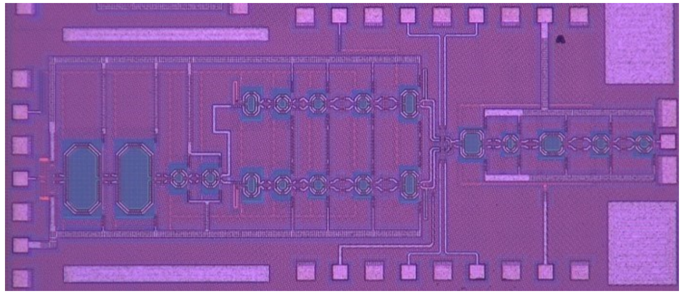
600 GHz Integrated Transmitter
PLL + Mixer
M. Seo TSC

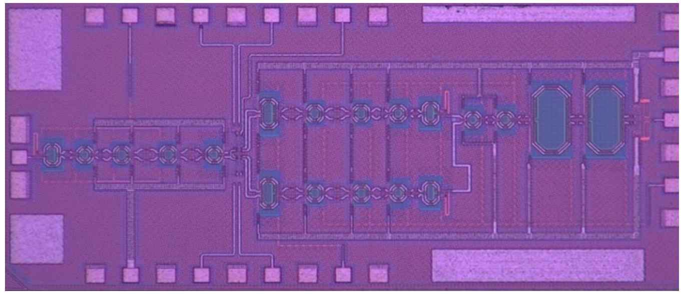


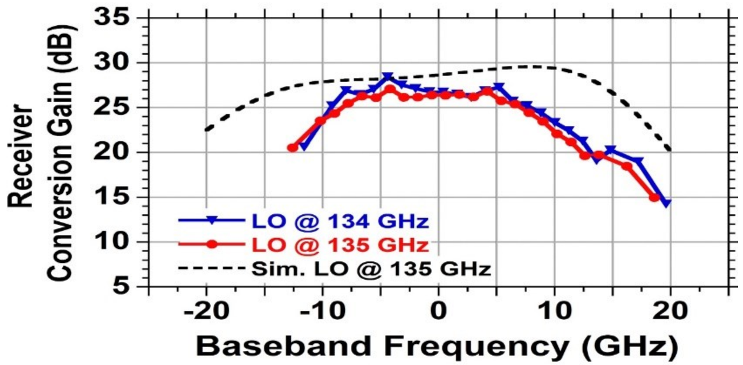
140GHz CMOS ICs

Hub ICs for MIMO Array

Farid (Rodwell) UCSB

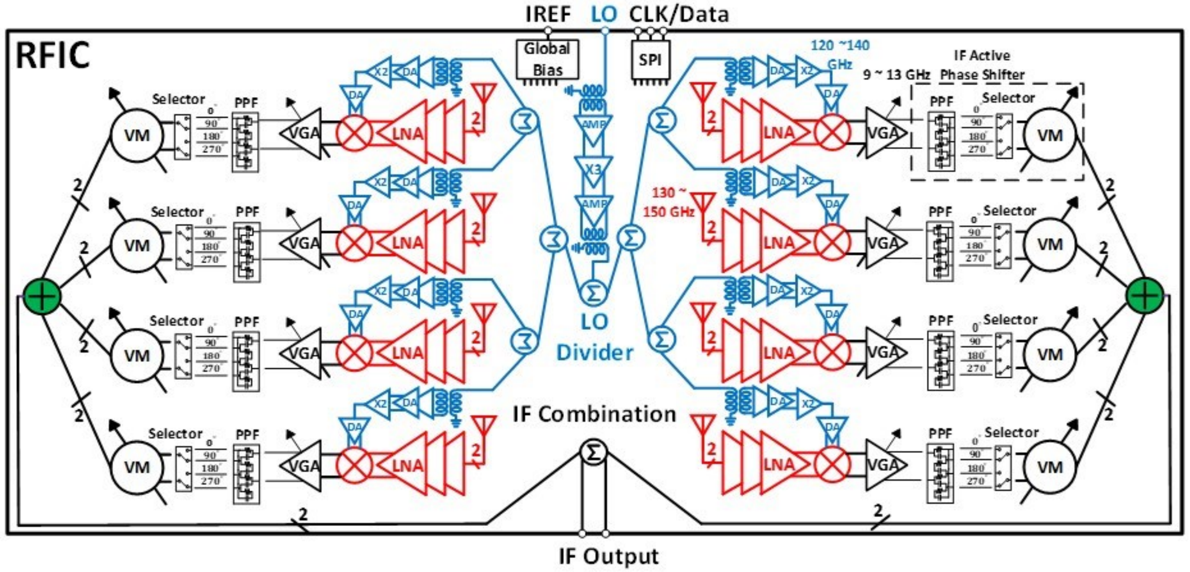


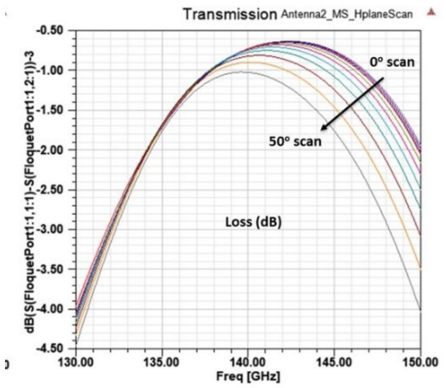


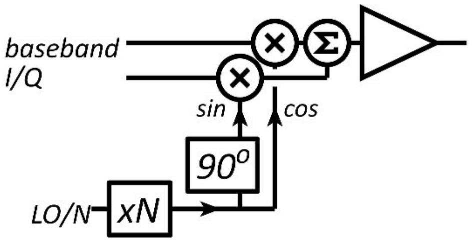


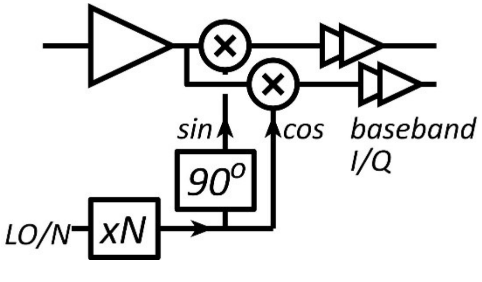
8-channel handset array ICs; transmitter and receiver

(Rebeiz group), UCSD



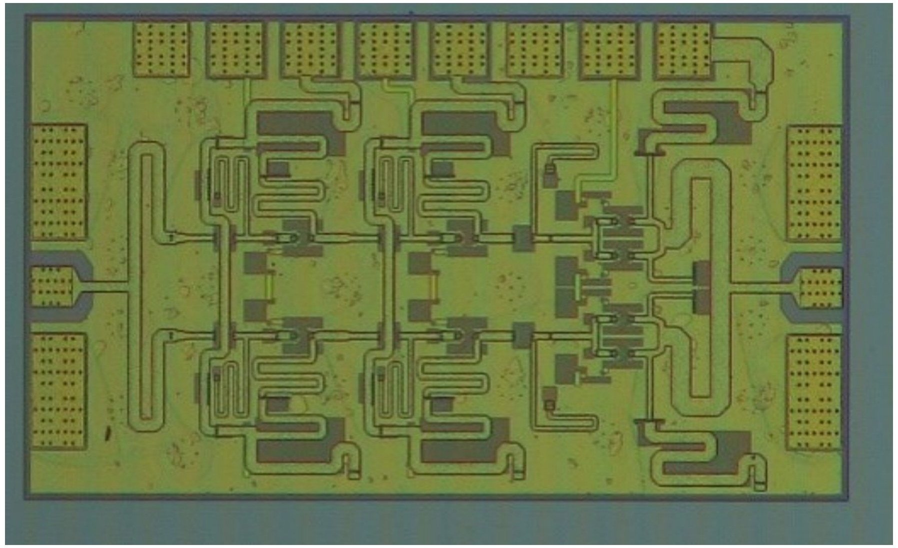




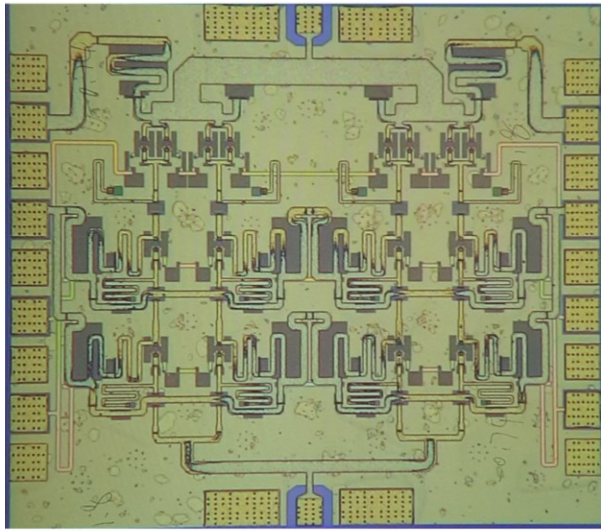


Progress in IC Design: 140GHz InP PAs

110mW power amplifier, 20.8% PAE
A. Ahmed, IMS 2020

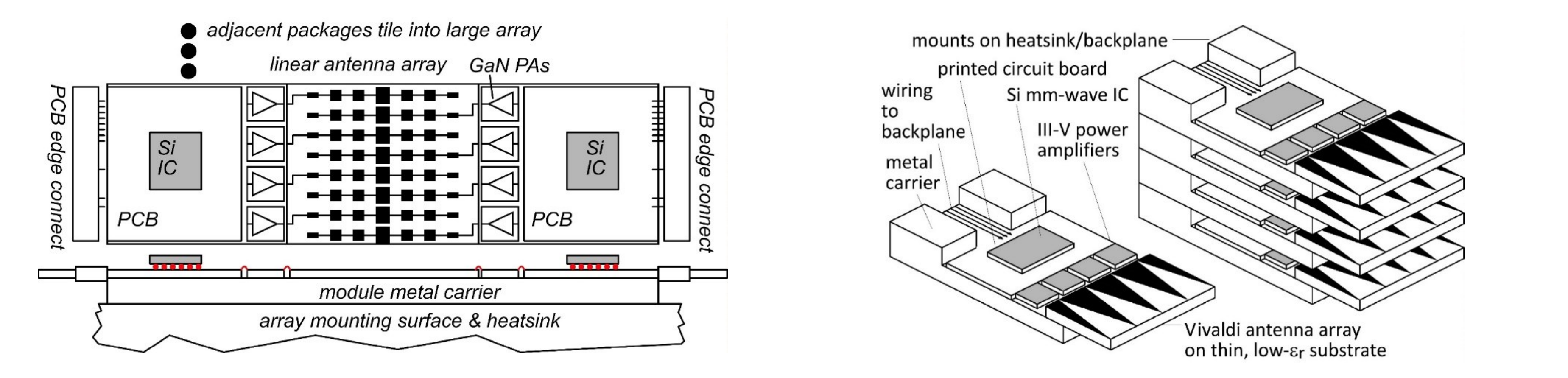


190mW power amplifier
A. Ahmed, submitted.



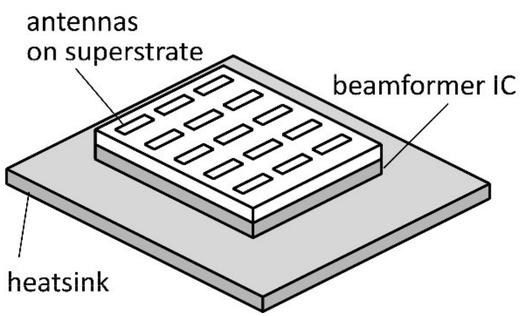
Also: **"A 130-GHz Power Amplifier in a 250-nm InP Process with 32% PAE"**
Kang Ning (Buckwalter group) 2020 RFIC symposium

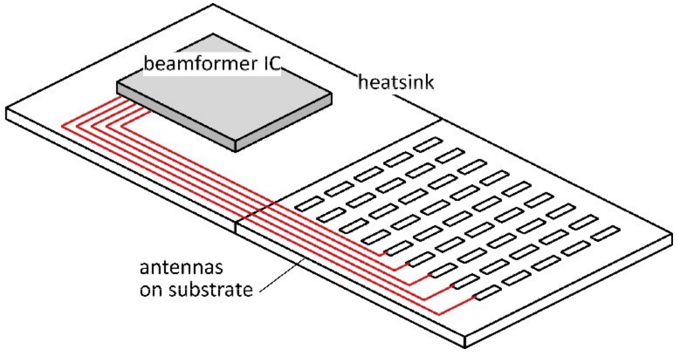
Packages / array modules



The mm-wave module design problem

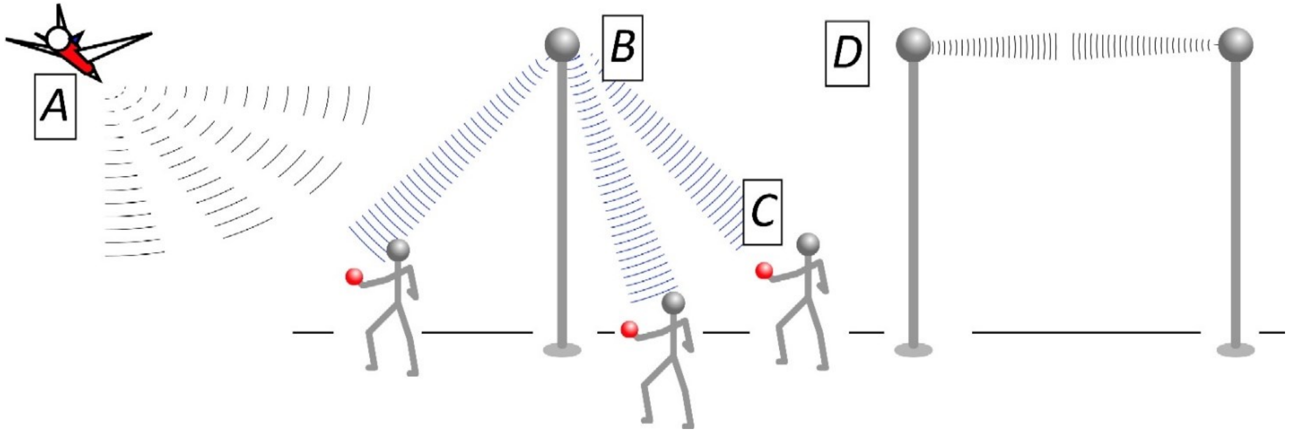
How to make the IC electronics fit ?
How to avoid catastrophic signal losses ?
How to remove the heat ?

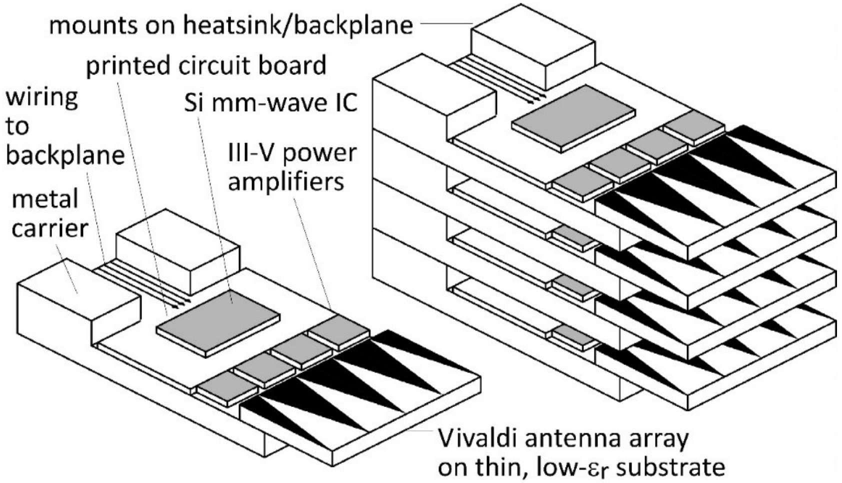


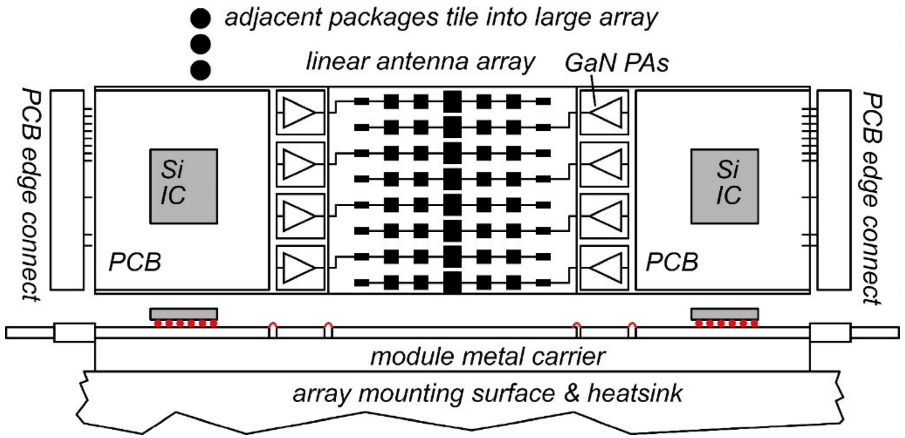


Not all systems steer in two planes...
...some steer in only one.

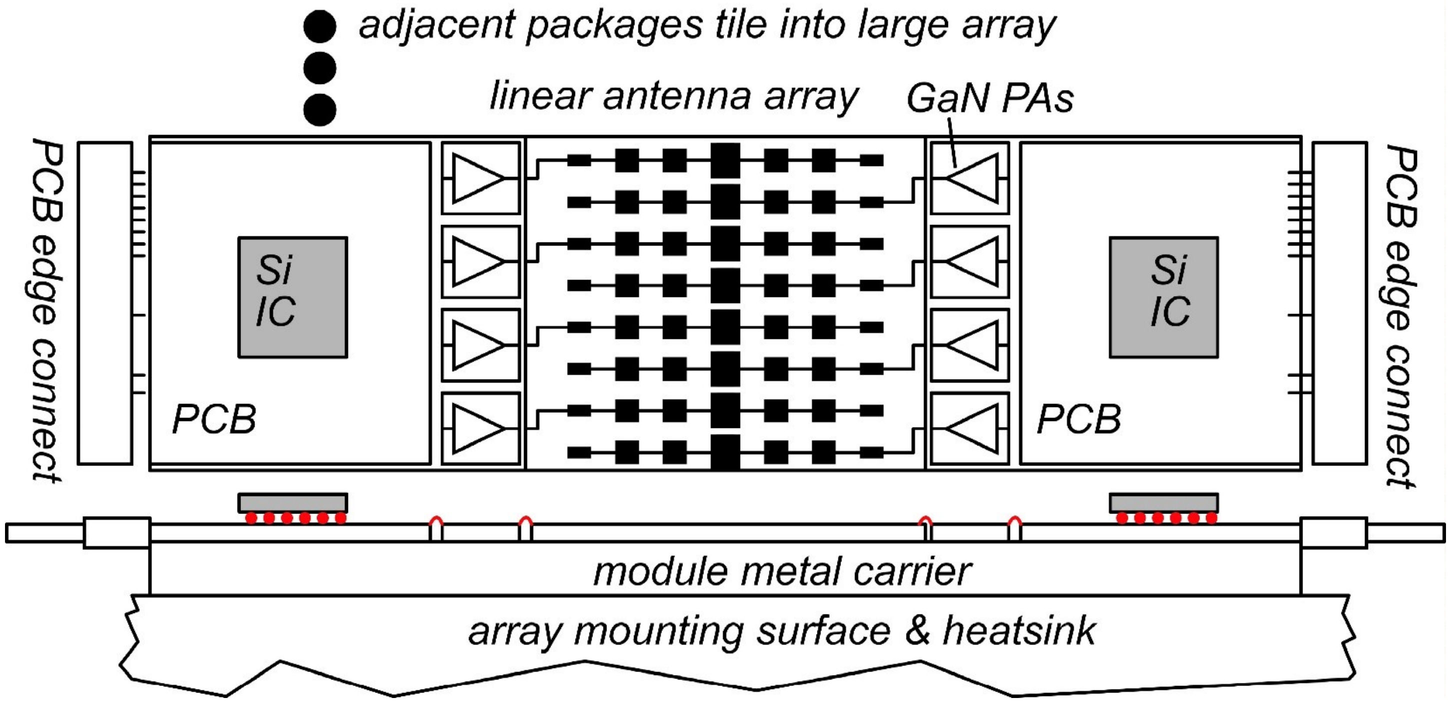
Not all systems steer over 180 degrees...
...some steer a smaller angular range

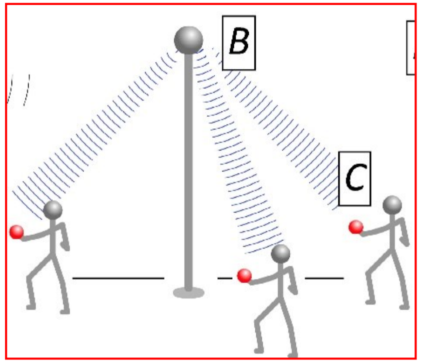






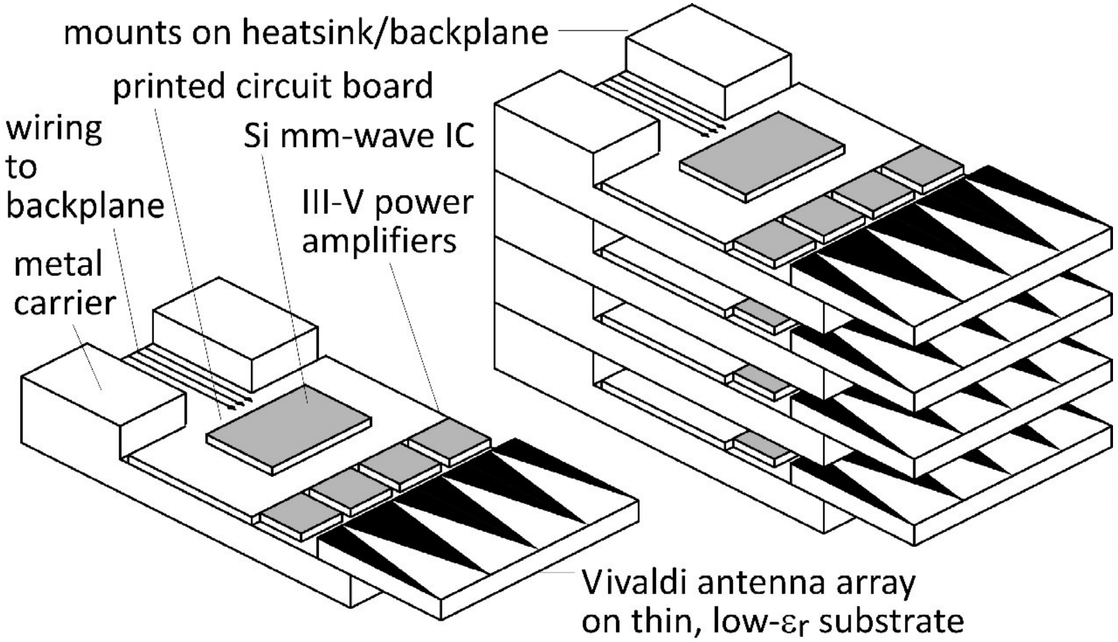
Concept: Tile for linear arrays

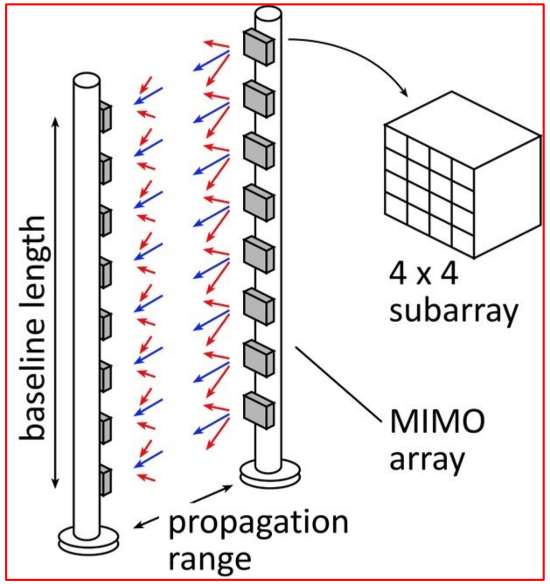




Terrestrial system: horizontal steering only→ linear array.
Space at edges of linear array: room for III-V PAs, LNAs.
Alternating-sides feed: 2mm pitch→ room for large GaN PAs.
Mounting directly on metal carrier→ heatsinking.

Concept: module for small angular scanning

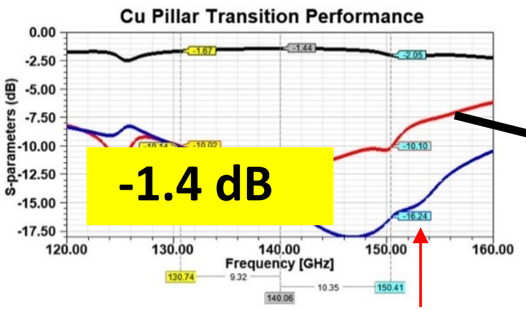


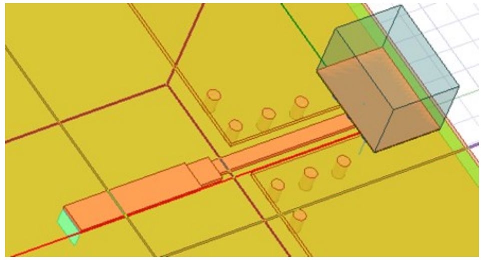


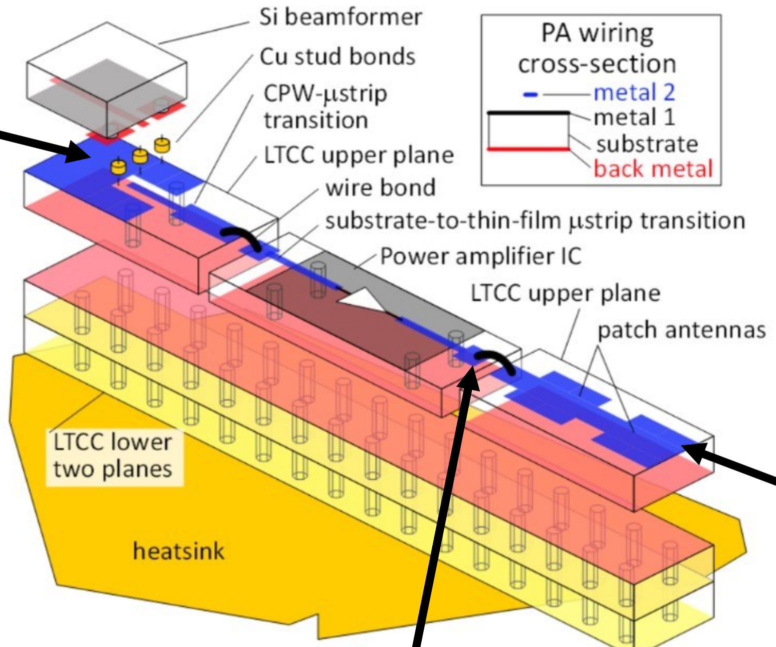
Terrestrial system: horizontal + vertical steering → rectangular array.
Limited angular steering range (installation)→ spacing >> $\lambda/2$
Endfire / edge-card geometry: room for III-V PAs, LNAs.
Mounting directly on metal carrier→ heatsinking.

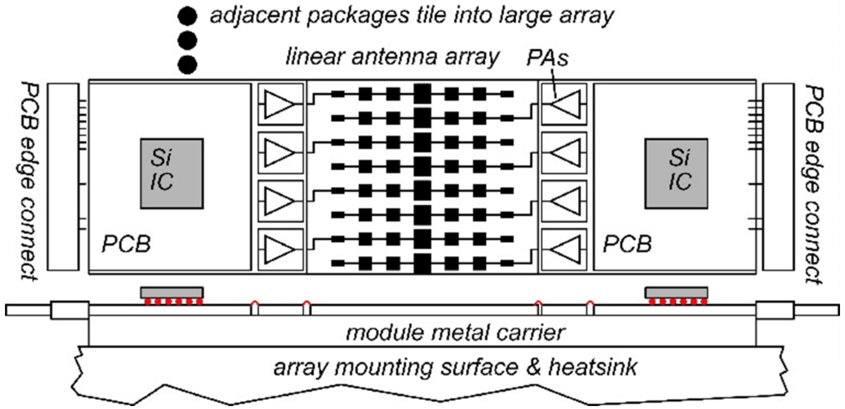
If Vivaldi's are replaced with dipoles, element spacing can be reduced to $\lambda/2$.
→ potential for wider angular scanning

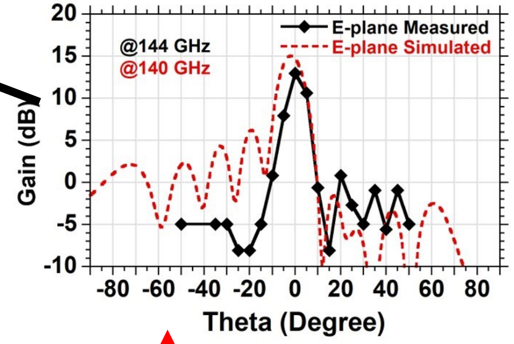
140GHz array module design

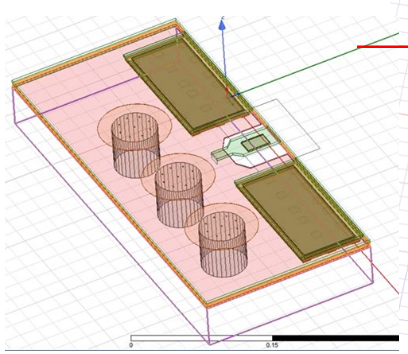


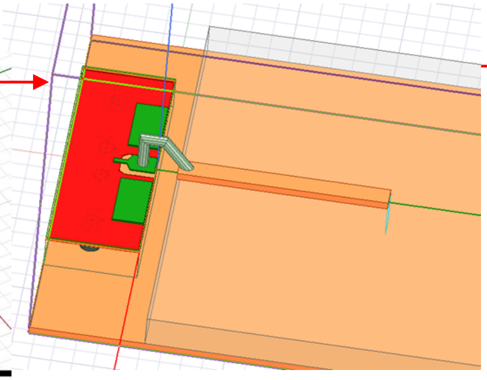


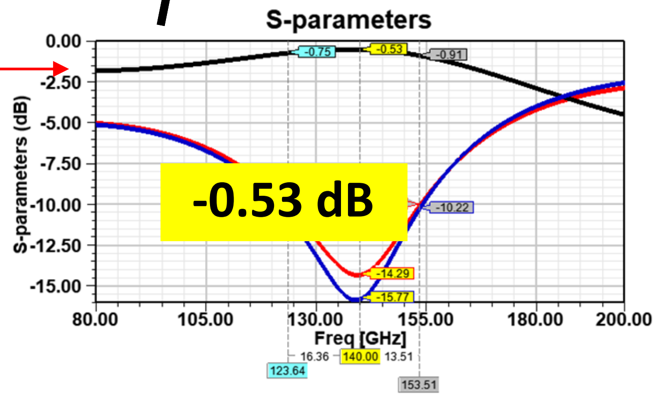


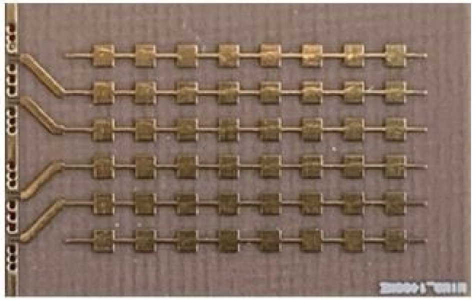


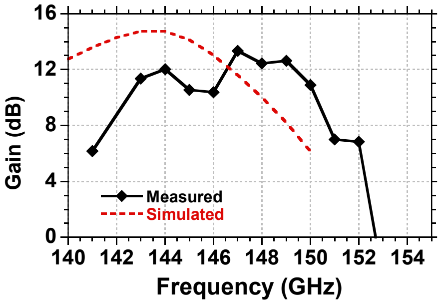






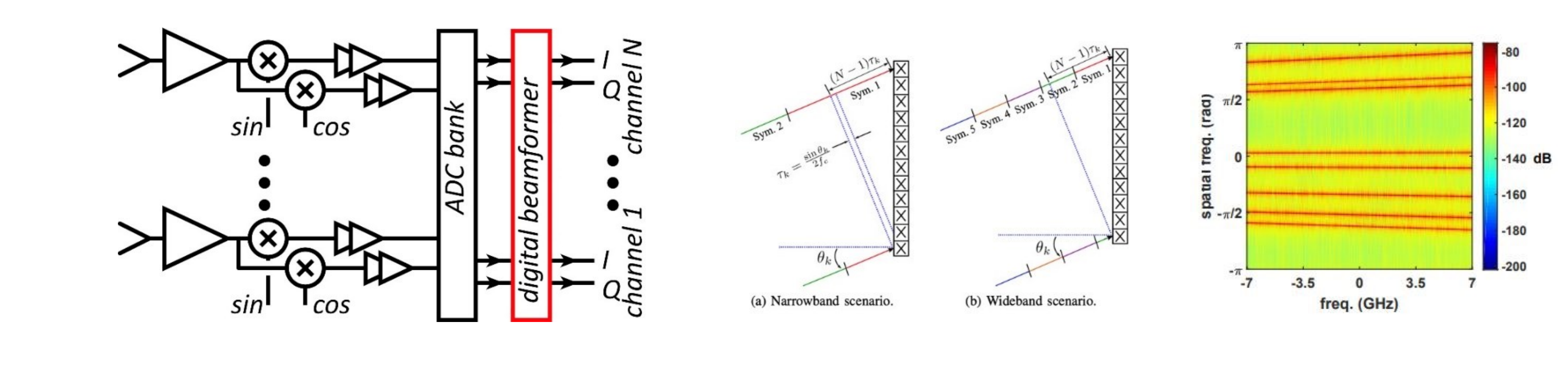




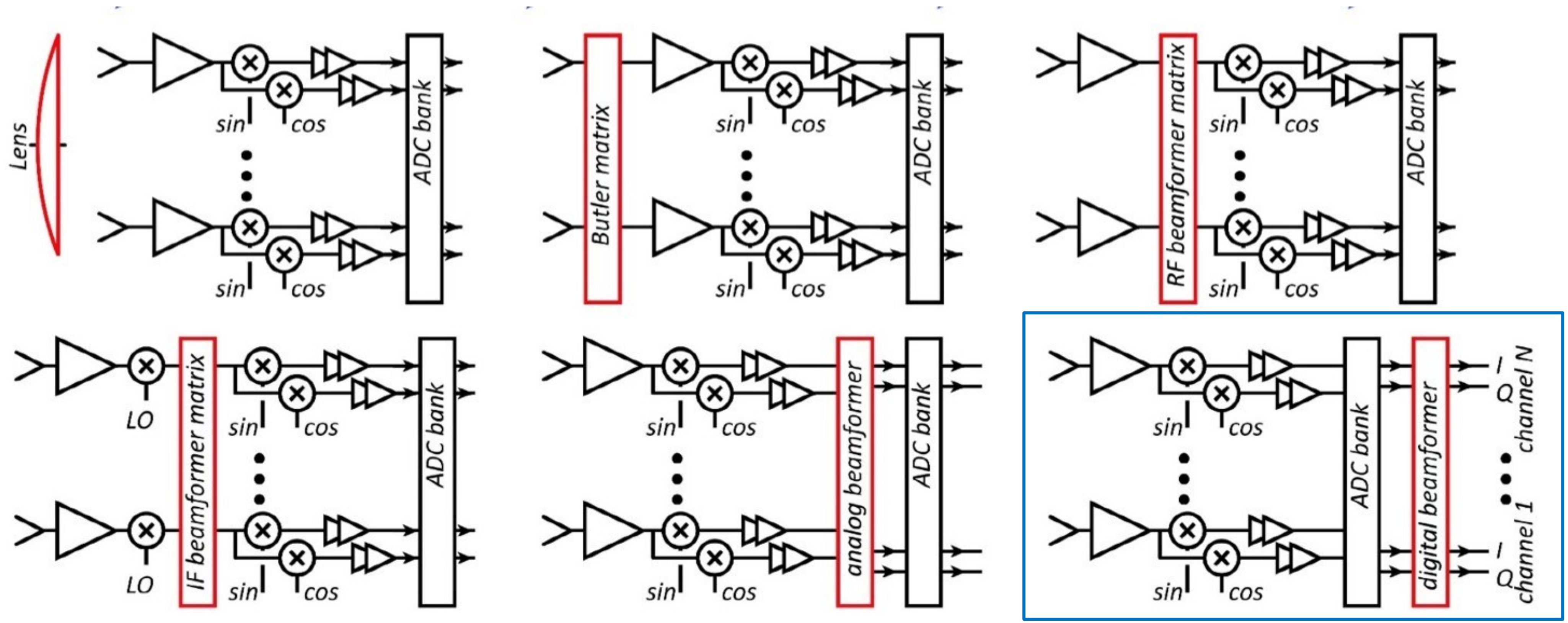


Simulations good: working with Kyocera. June tapeout ?

Systems


sin
cos
ADC bank
digital beamformer
I
Q
channel N
channel 1
Sym. 1
Sym. 2
Sym. 3
Sym. 4
Sym. 5
(a) Narrowband scenario.
(b) Wideband scenario.
spatial freq. (rad)
freq. (GHz)
-7
-3.5
0
3.5
7
-80
-100
-120
-140
-160
-180
-200
dB

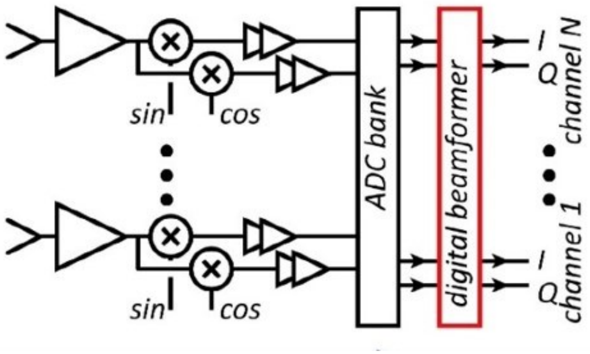
Beamforming for massive spatial multiplexing



Pure digital beamforming:
dynamic range & phase noise requirements: appear to be manageable ✓✓✓
Digital back-end processing requirements (die area, DC power): being investigated ?

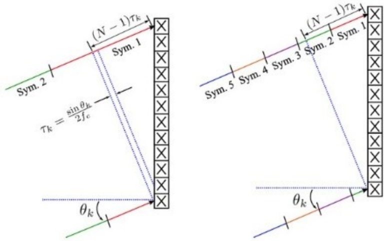
Analog, hybrid beamforming:
Do not appear to significantly improve dynamic range in massive MIMO.

Progress in System Design



Digital beamforming

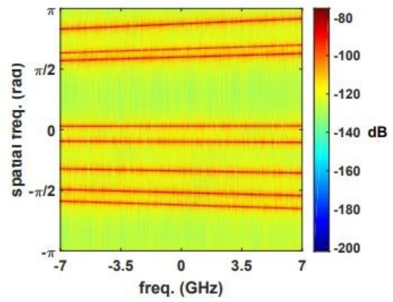
- ✓**ADCs/DACs**: only 3-4 bit ADC/DACs required (Madhow, Studer, Rodwell)
- ✓**Linearity**: Amplifier P_{1dB} need be only 3dB above average power (Madhow).
- ✓**Phase noise**: Requirements same as for SISO (Alon, Madhow, Niknejad, Rodwell)
- **Efficient digital beamforming**: beamspace algorithm=complexity ~N× log(N) (Madhow)
- **Efficient digital beamforming**: low-resolution matrix (Studer)
- **Efficient channel estimation** : fast beamspace algorithm (Studer)
- **Efficiently addressing true-time-delay problem**: "rainbow" FFT algorithm (Madhow)
- ✓**Array-to-backplane interconnect power**: low-power analog baseband 50Ω links (Rodwell)



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

In progress...

- **Propagation models and measurements**: (Molisch)
- **Blockage probability, mesh networks, network protocols**: (Rangan, Cabric)
- **MIMO system power analysis**: (Rangan, Cabric, Buckwalter)



JUMP Progress: All-Digital Beamformer

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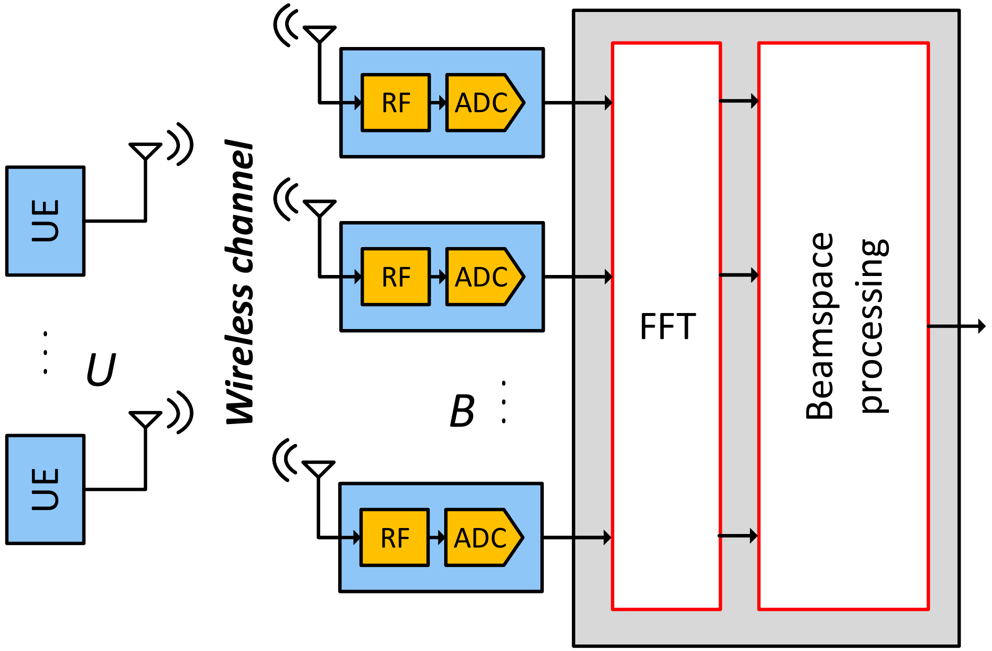
- mmWave/THz channels are sparse in beamspace domain
- Exploiting sparsity can significantly reduce baseband complexity
- Challenge: requires fast Fourier transforms (FFTs) at baseband sampling rates



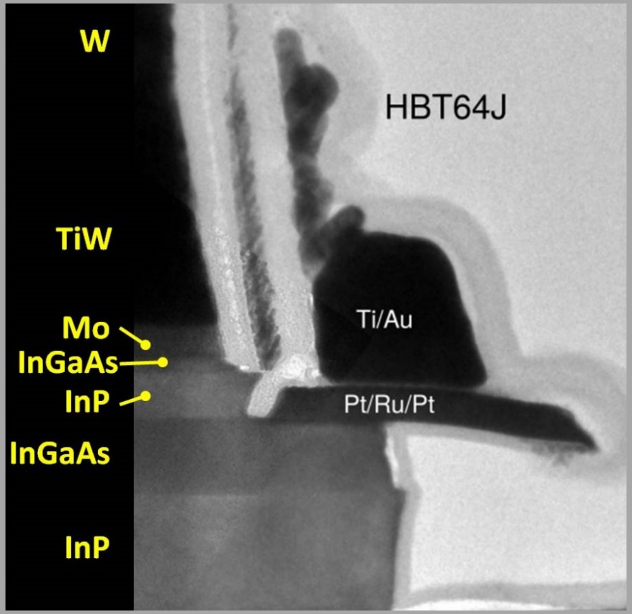
- Implementation examples
  - 1 GHz bandwidth
  - 10b FFTs generated with Spiral
- Specialized FFTs (radix-4, higher streaming width, etc.) will further reduce area and power!

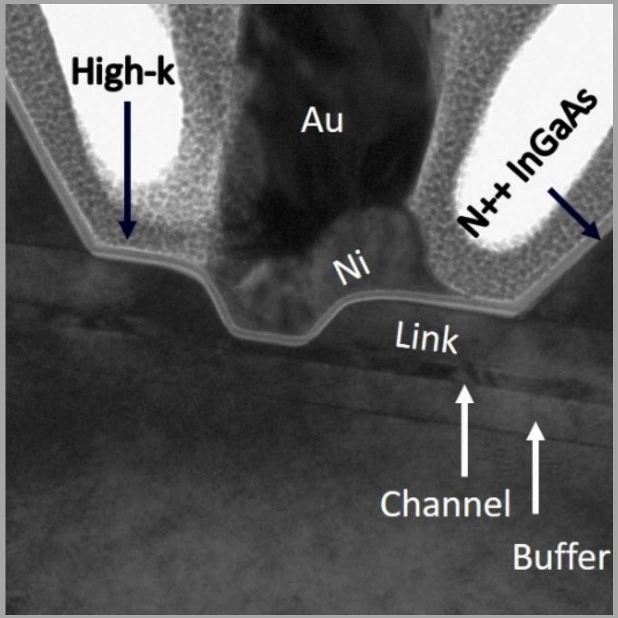
BS antennas	Area	Power
64	9mm^2	2W
128	32mm^2	7W
256	122mm^2	26W

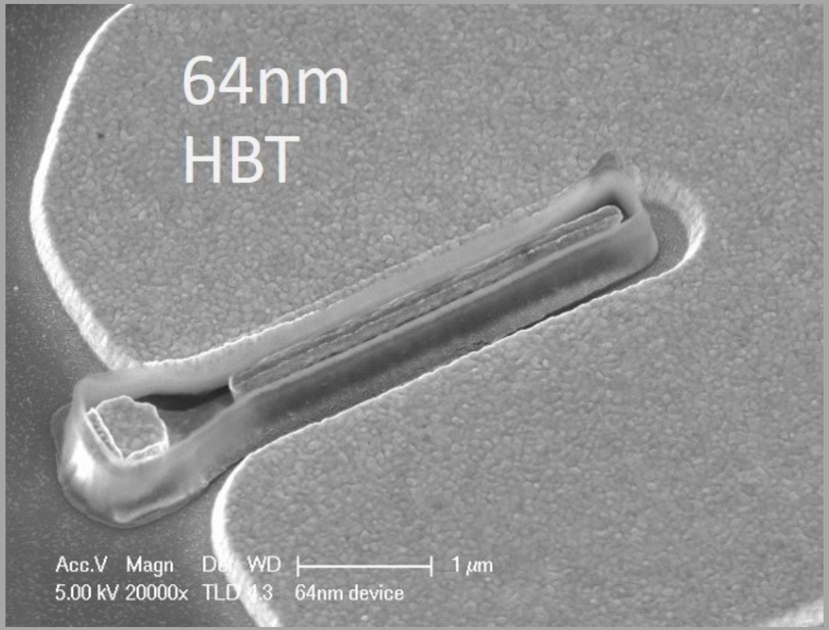
Synthesis results for 28nm CMOS

Christoph Studer, Cornell

Transistors



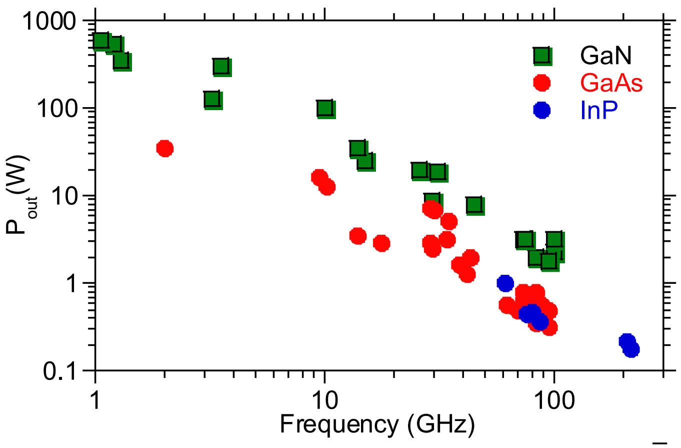


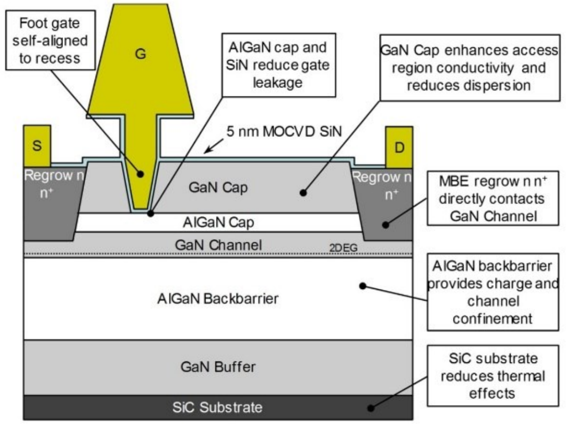


Progress in mm-Wave Transistors

InGaN and GaN HEMTs:

High power from 100-340GHz
GaN: superior power density at all frequencies
UCSB/Mishra: InGaN for increased mobility
Cornell/Xing: AlN/GaN/AlN

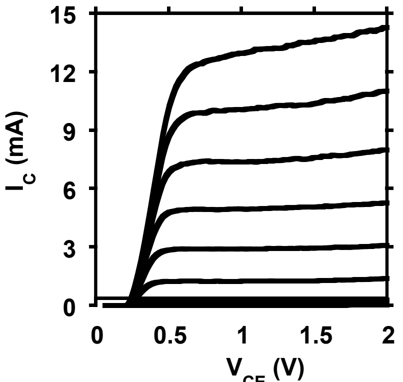


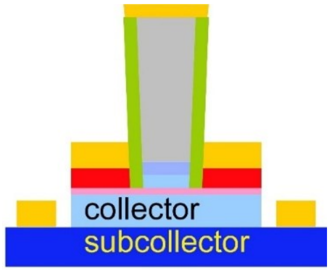


N-polar GaN: Mishra, UCSB

THz InP HBTs:

SOA today: 130nm node, 1.1 THz f_{max}, 3.5 V breakdown
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

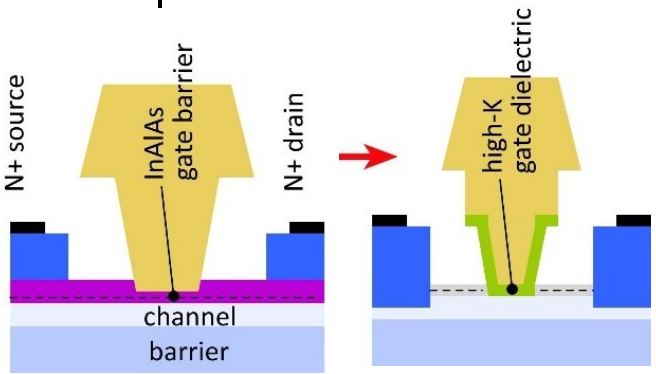


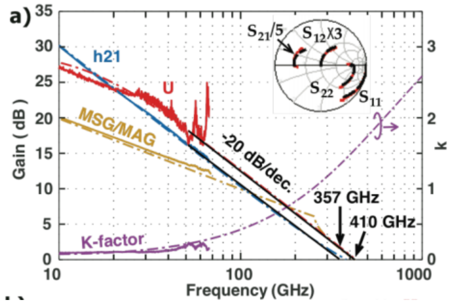


collector mesa, contacts, etc.

THz InP HBTs:

SOA today: 1.5 THz f_{max}, ~1.1 V breakdown
Sensitive 100-650GHz low-noise amplifiers
more f_τ: lower noise, higher frequencies
high-K gate dielectric → higher f_τ.
status: process modules





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 250 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
spatial multiplexing: computational complexity
packaging: fitting signal channels in very small areas

(backup files follow)

Progress in System Design

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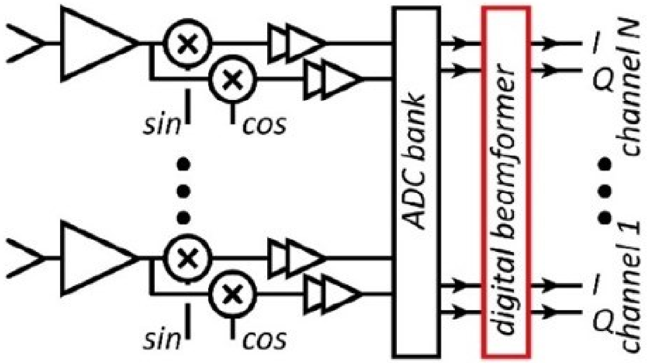


ADC resolution:

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

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

Jammer tolerance:

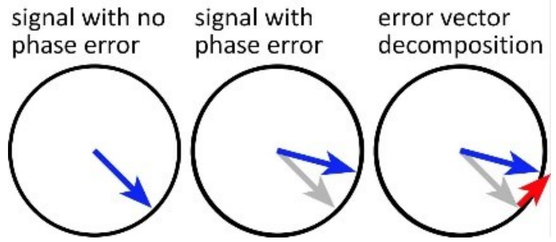
Increase ADC resolution by 1 bit $\rightarrow$ $P_{\text{jammer,max}} = K\cdot P_{\text{signal}}$

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

Phase noise:

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

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

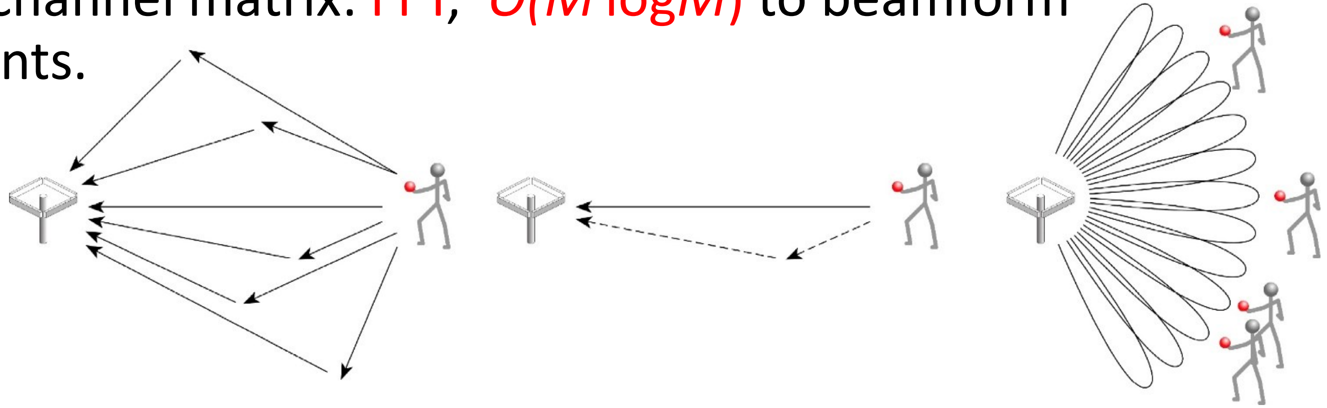


Beamspace:

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.



The mm-wave module design problem

How to make the IC electronics fit ?

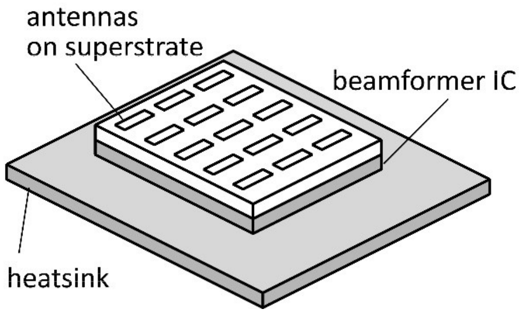
100+ GHz arrays: $\lambda_0/2$ element spacing is very small.
Antennas on or above IC → IC channel spacing = antenna spacing
→ ***limited IC area to place circuits***

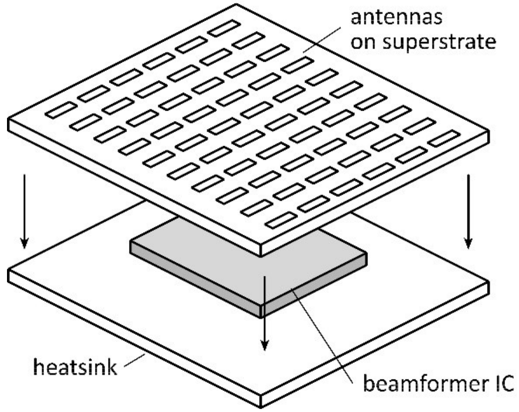
How to avoid catastrophic signal distribution losses ?

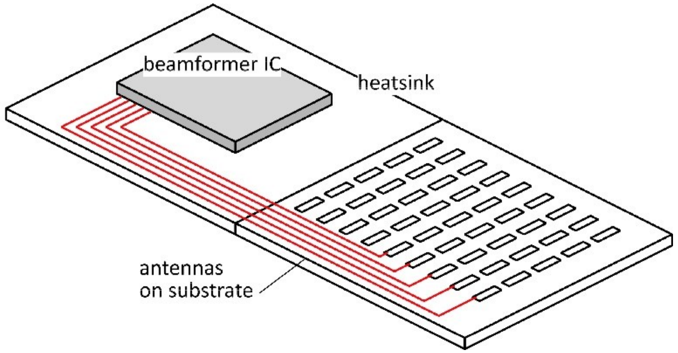
long-range, high-gain arrays: array size can be large.
ICs beside array → very long wires between beam former and antenna
→ ***potential for very high signal distribution losses***

How to remove the heat ?

100+ GHz arrays: element spacing is very small.
If antenna spacing = IC channel spacing, then power density is very large







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Center for Converged Communications & Sensing at THz.

Duration:
5-years; 1/2018-12/2022.

Funding:
about $32 million total.

Team:
21 Professors,
~65 Ph.D. students

Sponsors:
SRC, DARPA

Focus:
wireless systems,
10-15 years out,
100-340GHz

JUMP 100-340 GHz: challenges & solutions

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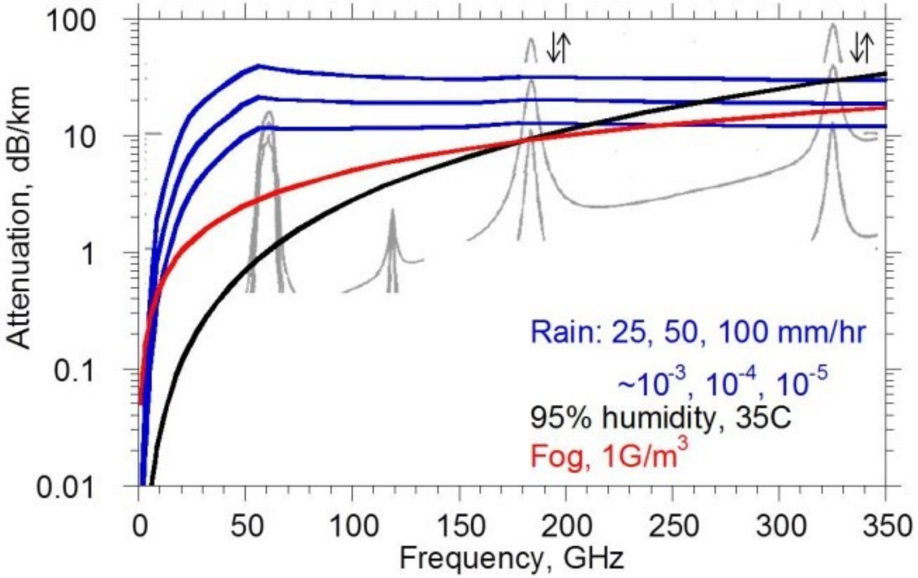
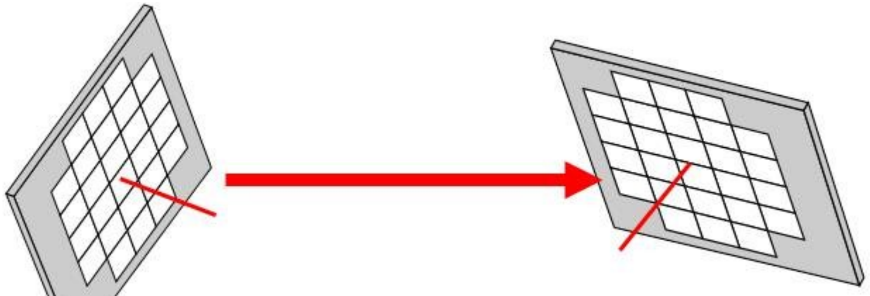
High attenuation in foul or humid weather



Need mesh networks

Need large arrays



$$\frac{P_{received}}{P_{transmit}} \propto N_{receive} N_{transmit} \frac{\lambda^2}{R^2} e^{-\alpha R}$$