Radio and Wireless Week, January 14, 2018, Anaheim, CA

Wireless Above 100GHz

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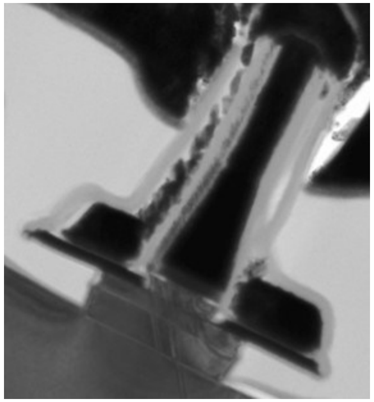
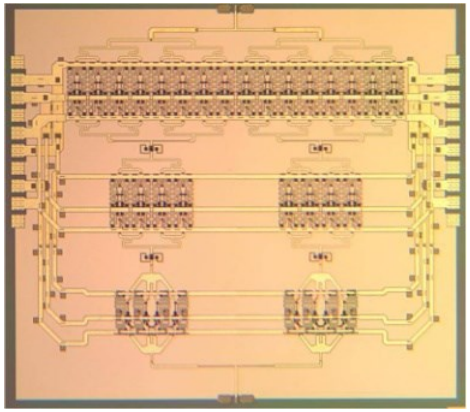
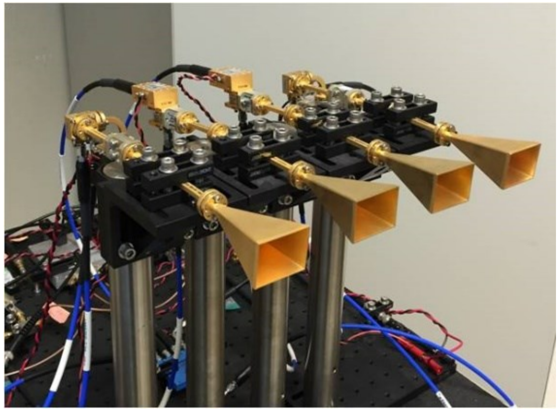
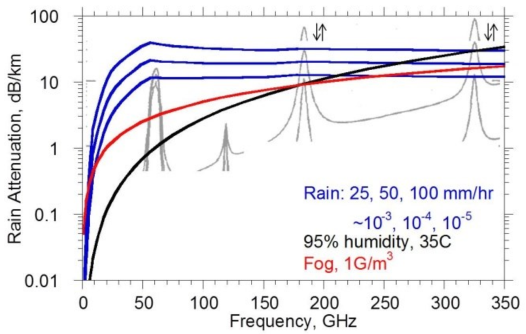
Why 100+ GHz wireless ?

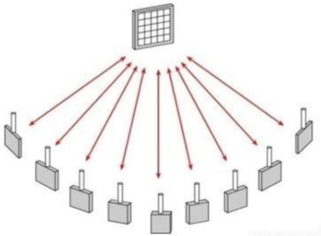




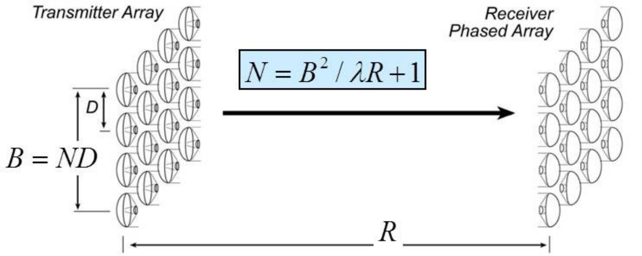


140-340 GHz properties





$$\text{angular resolution} \approx \frac{\text{wavelength}}{\text{array width}}$$



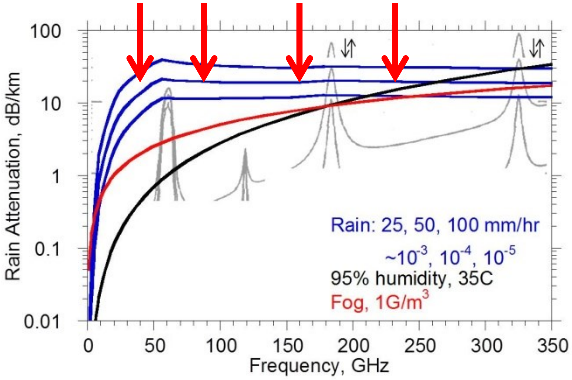
$$N = B^2 / \lambda R + 1$$

$$B = ND$$

$$\#\text{channels} \propto (\text{aperture area})^2 / (\text{wavelength} \cdot \text{distance})^2$$

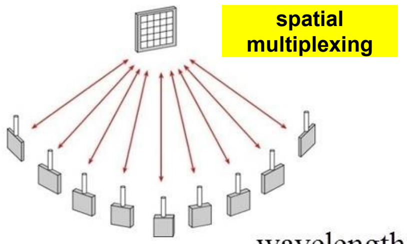
140-340 GHz: benefits & challenges

Large available spectrum

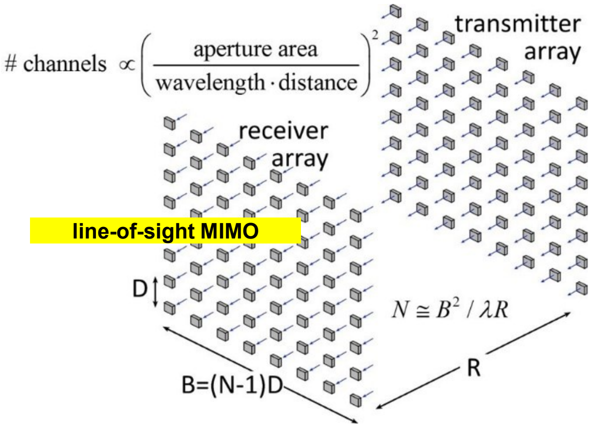


(note high attenuation in foul weather)

Massive # parallel channels



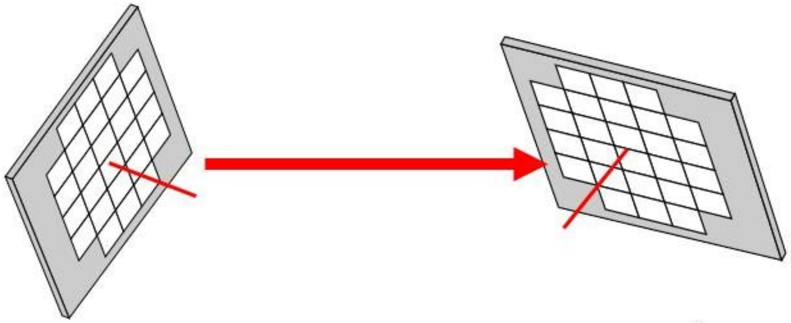
$$\text{angular resolution} \approx \frac{\text{wavelength}}{\text{array width}}$$



$$\#\,\text{channels} \propto \left(\frac{\text{aperture area}}{\text{wavelength} \cdot \text{distance}}\right)^2$$

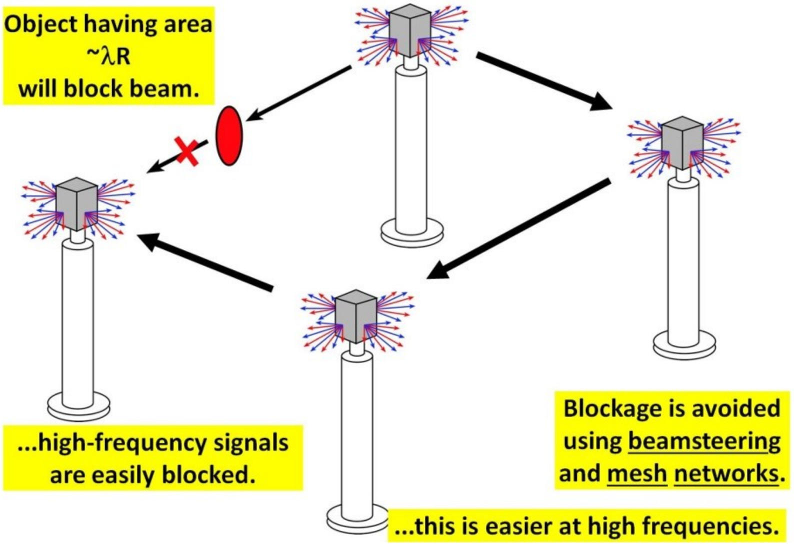
$$N \cong B^2 / \lambda R$$

Need phased arrays (overcome high attenuation)



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

Need mesh networks



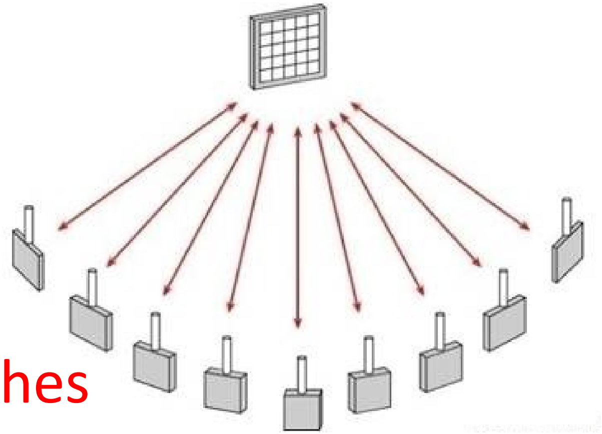
Object having area ~λR will block beam.

...high-frequency signals are easily blocked.

Blockage is avoided using beamsteering and mesh networks.

...this is easier at high frequencies.

Spatial Multiplexing: massive capacity RF networks



multiple independent beams

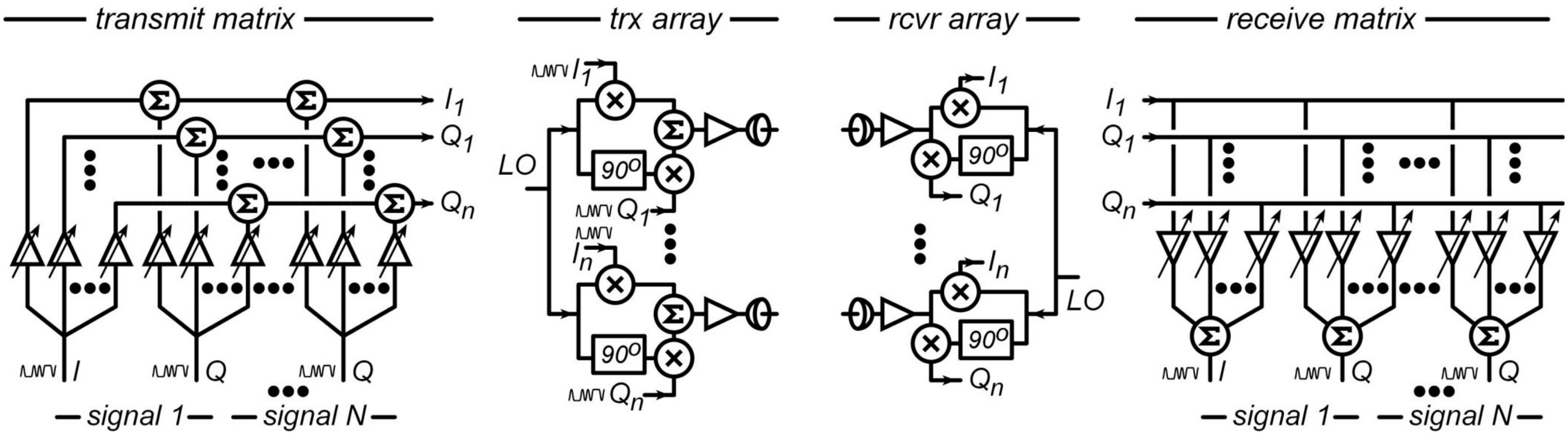
each carrying different data

each independently aimed

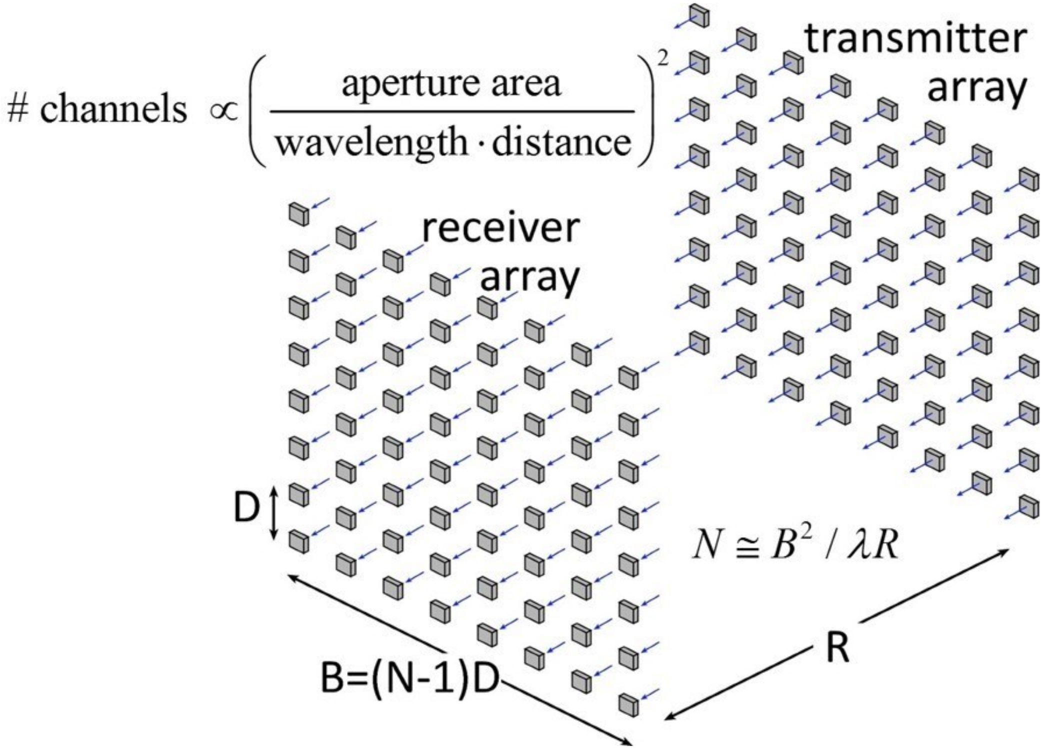
beams = # array elements

small: 1000 elements @220 GHz=3 square inches

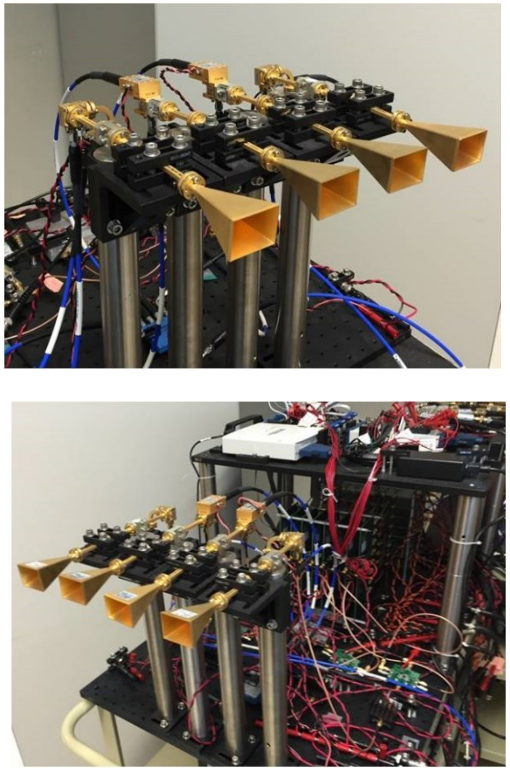
Hardware: multi-beam phased array ICs



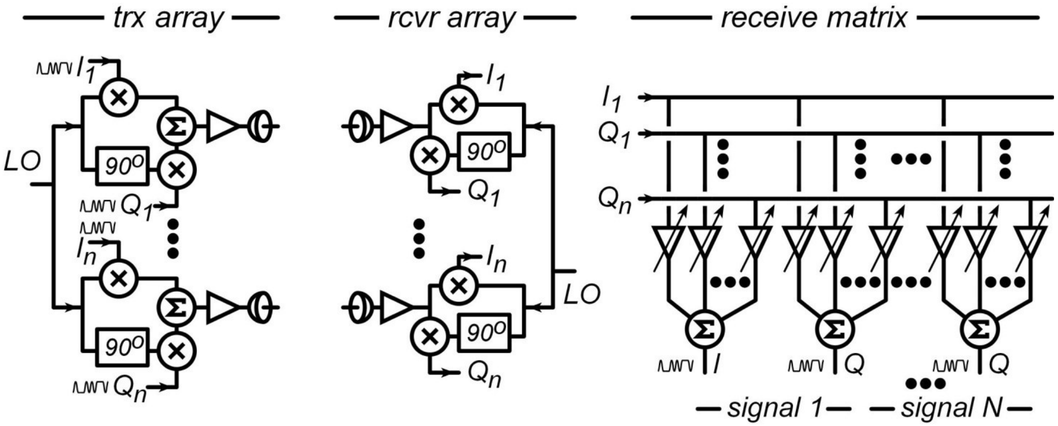
mm-Wave LOS MIMO: multi-channel for high capacity



$$\#\ \text{channels} \propto \left(\frac{\text{aperture area}}{\text{wavelength}\cdot\text{distance}}\right)^2$$



Massive capacity wireless; physically small



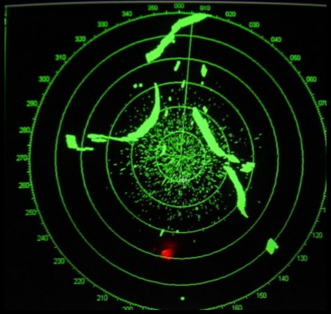
Torklinson : 2006 Allerton Conference
Sheldon : 2010 IEEE APS-URSI
Torklinson : 2011 IEEE Trans Wireless Comm.
2012 IEEE Marconi prize paper award

140-340GHz imaging: TV-like resolution

mm-waves → high resolution from small antenna apertures

What you see in fog

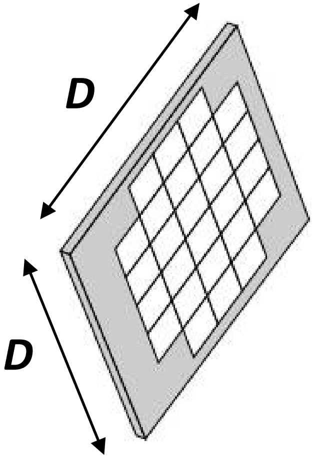
What 10GHz radar shows



What you want to see

goal: ~0.2° resolution, 10^3-10^6 pixels

NxN phased array

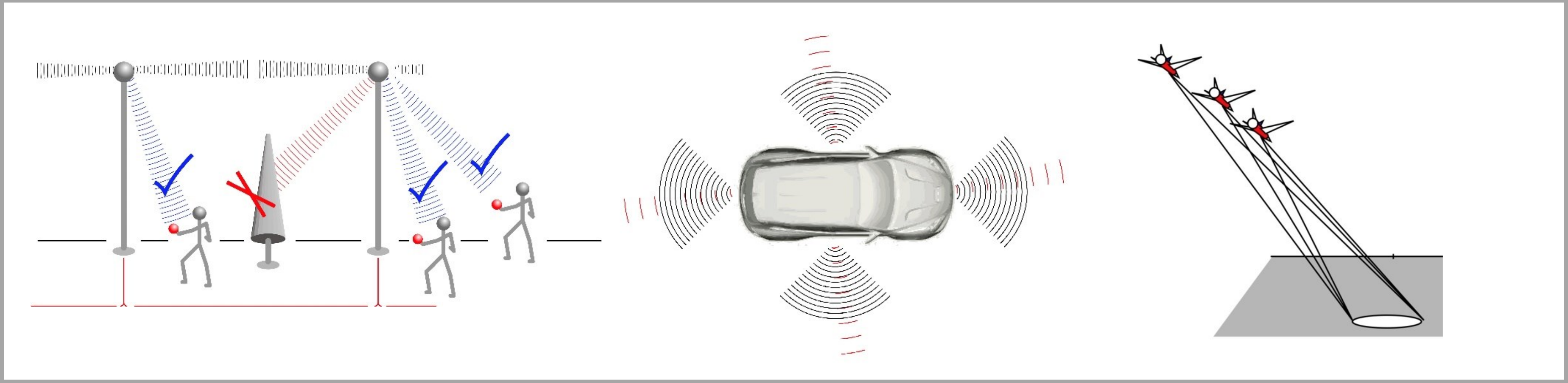


angular resolution = λ /D (radians)

340 GHz, 35 cm/14 inch aperture → 0.14 degree resolution

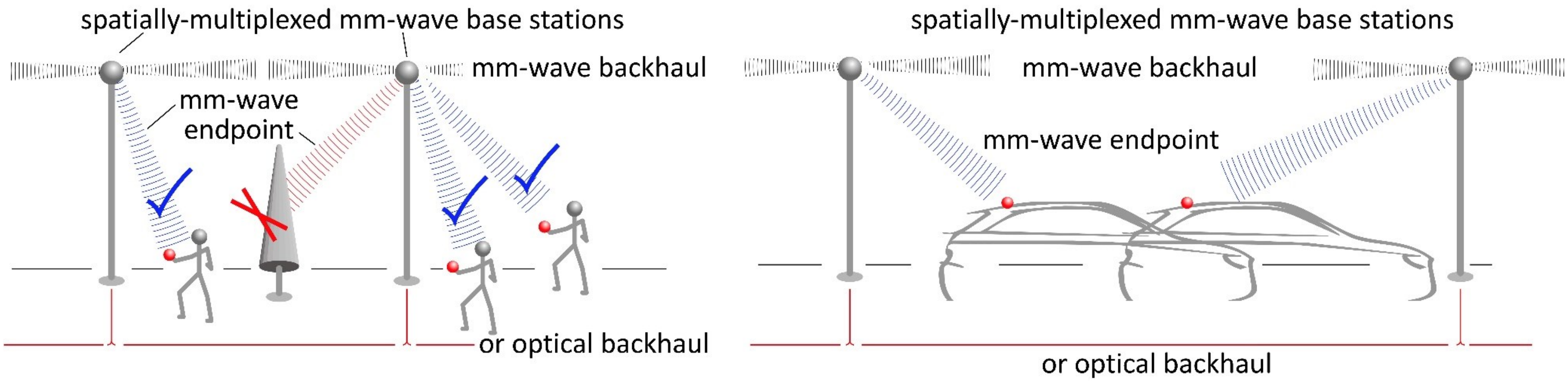
HDTV-like resolution, yet fits in car, plane, or UAV

140-340 GHz applications



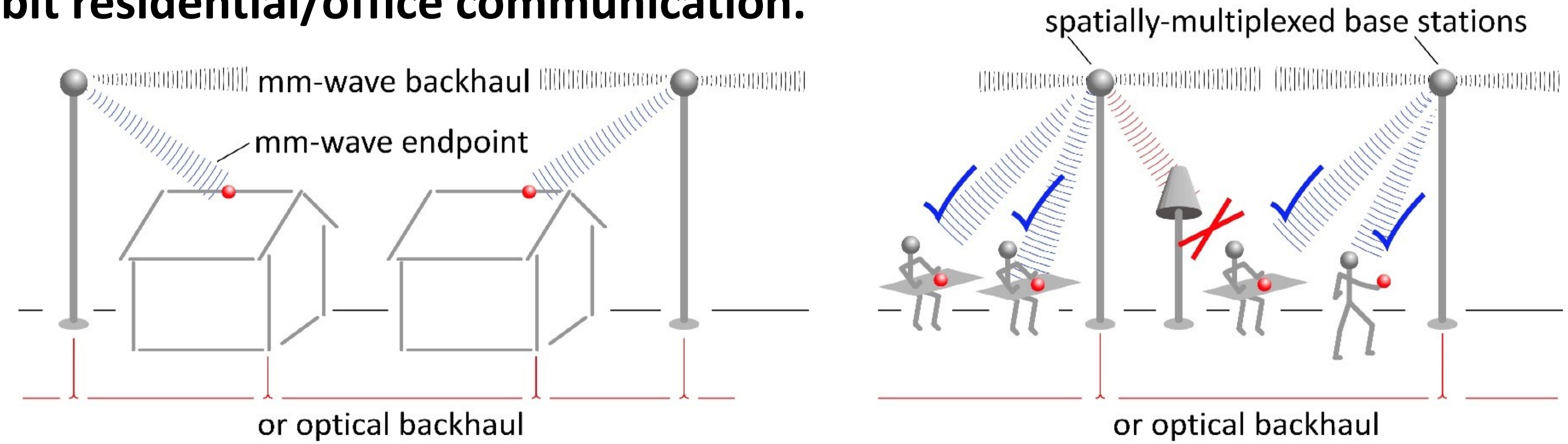
140-340GHz: high-capacity communications

Gigabit mobile communication.



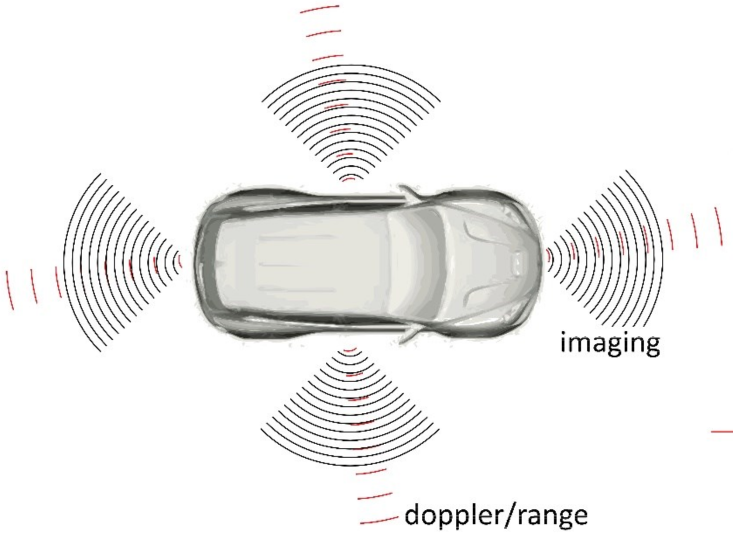
Mobile information Access

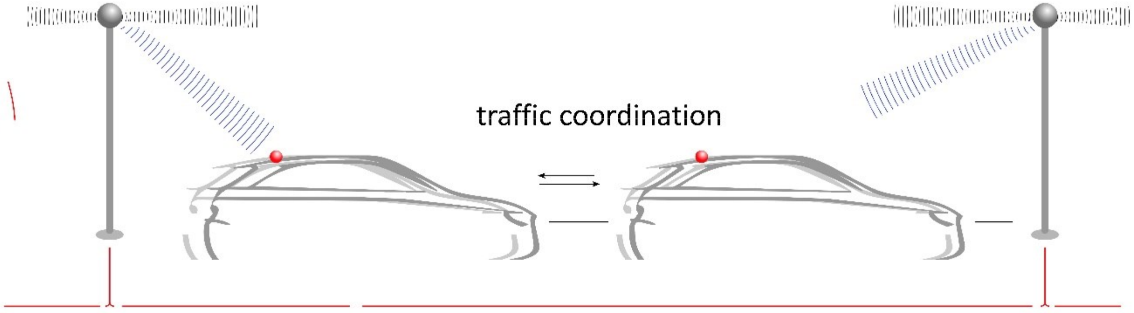
Gigabit residential/office communication.



Cellular/internet convergence

140-340GHz: automotive applications





340 GHz HDTV-resolution sub-mm-wave imaging radar: see through fog and rain.

assist driver: drive safely in fog at 100 km/hr

self-driving: complements LIDAR, but works in bad weather.

60 GHz Doppler / ranging radar.

object near ? approaching ? Avoid collision.

Intelligent highway: coordinate traffic

anticipate & manage interactions, avoid collisions

140-340 GHz: sensing and imaging radar

Fog, dust, smoke: what you see

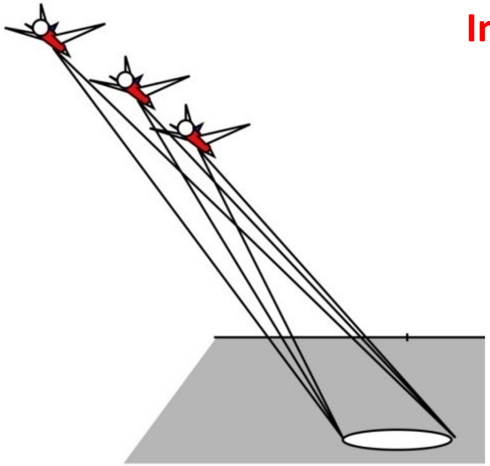
What 10GHz radar shows

What you want to see

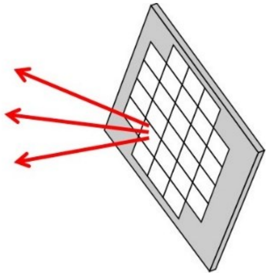
Radar: See threats through fog/smoke/dust, *when you can't see in the optical*.

30/70/ 94 GHz early-warning radar: threat detection = something is there
Longer range→ lower resolution: something's there, can't tell what.

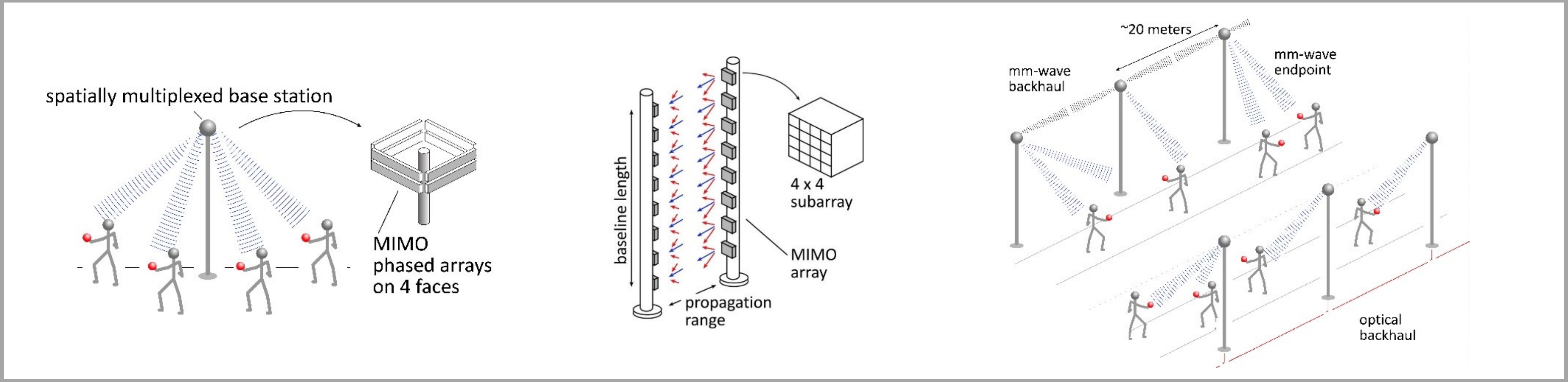
140-340GHz imaging radar: threat identification= what is it ?
Shorter range (500m in fog), TV-like resolution. Small and light.



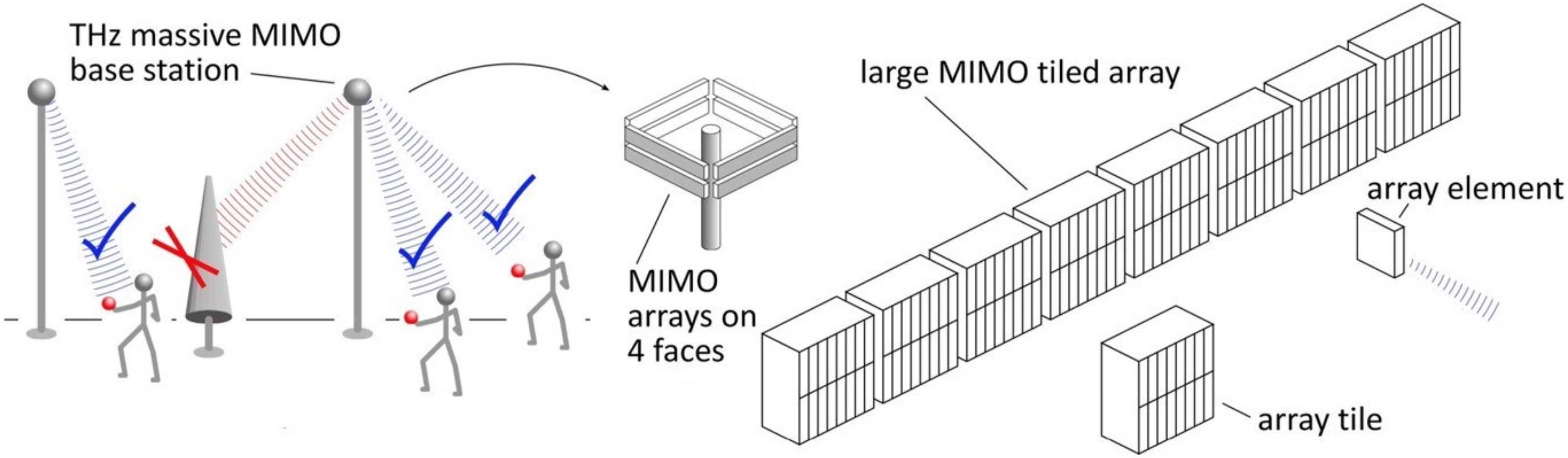
Imaging for UAVs, drones, small planes.
small, light aperture, high resolution.
sub-mm-wave SAR: see through fog, optical-like resolution, kilometers range
mm-wave PAR: imaging/ranging/Doppler



140-340 GHz: Possible Systems



140/220 GHz spatially multiplexed base station



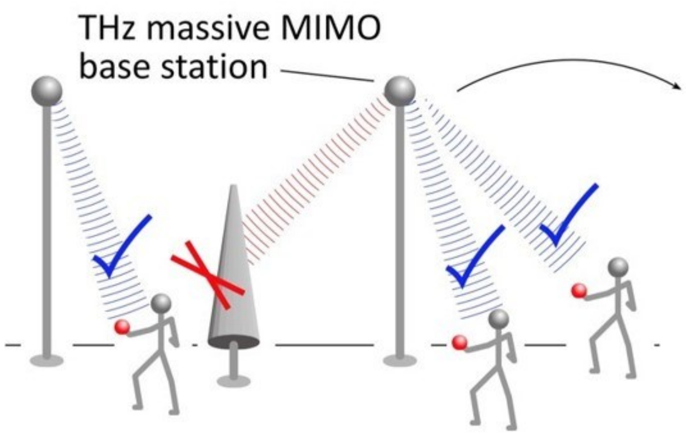
1 Tb/s spatially-multiplexed base station

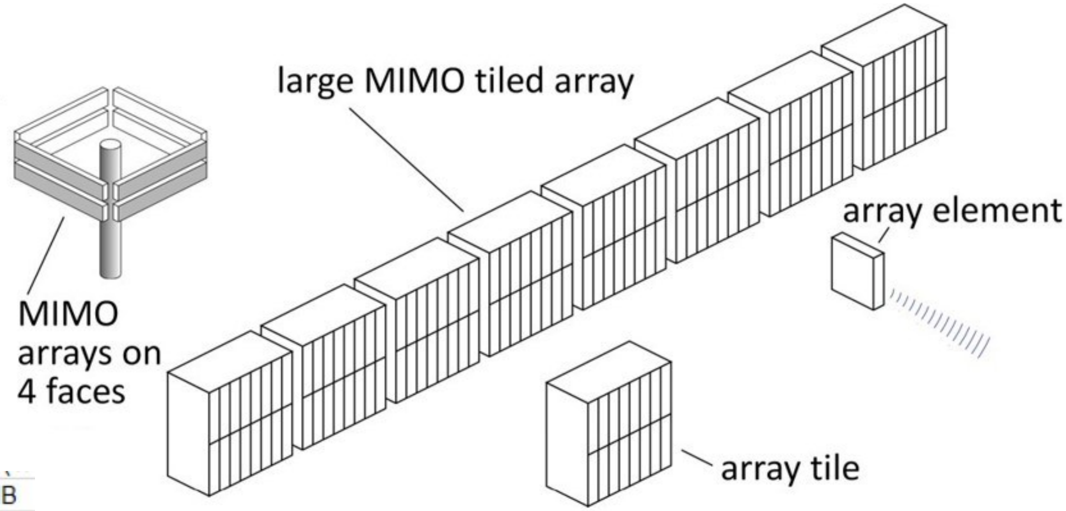
256 users/face, 4 faces
1024 total users @ 1 user/beam, 1 Gb/s/beam;
200 m range

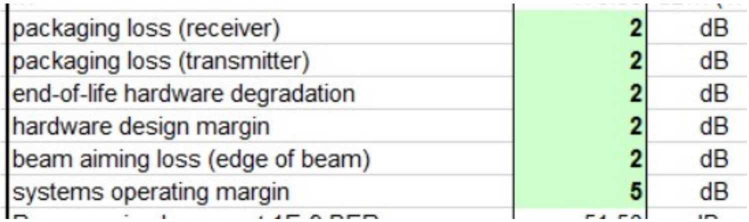
Link budget is feasible, but...

Required component dynamic range ?
Required complexity of back-end beamformer ?

140 GHz spatially multiplexed base station







packaging loss (receiver)	2	dB
packaging loss (transmitter)	2	dB
end-of-life hardware degradation	2	dB
hardware design margin	2	dB
beam aiming loss (edge of beam)	2	dB
systems operating margin	5	dB

Each face supports 256 beams @ 1Gb/s/beam.

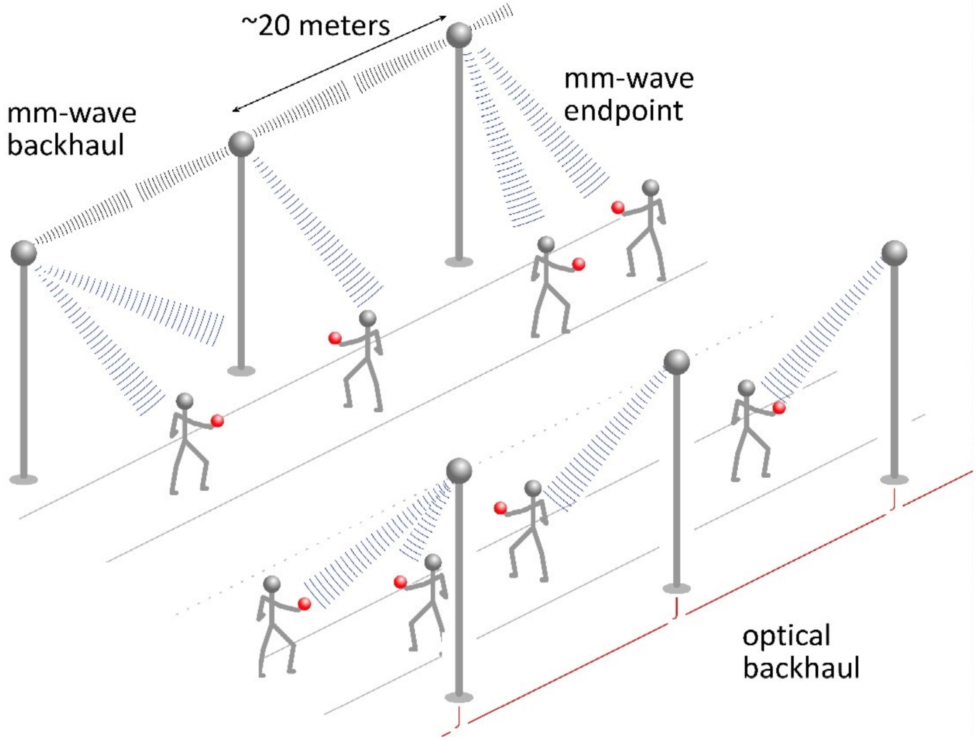
100 meters range in 50 mm/hr rain

Realistic packaging loss, operating & design margins

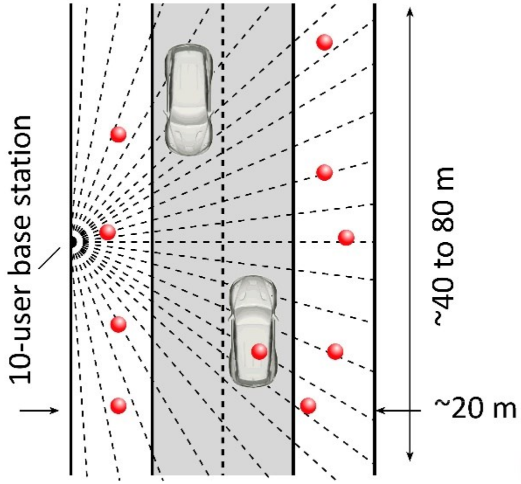
PAs: 16 dBm P_{out} (per element)

LNAs: 3 dB noise figure

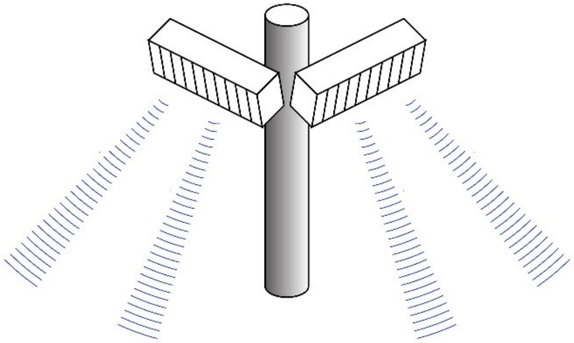
140/220 GHz femtocells

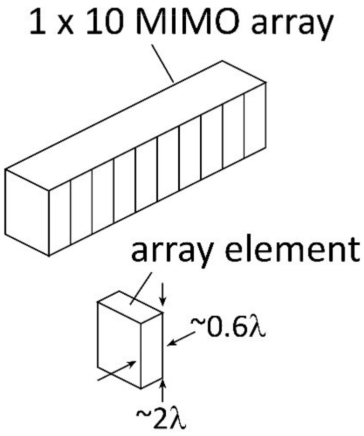


pedestrians on sidewalks, cars on street



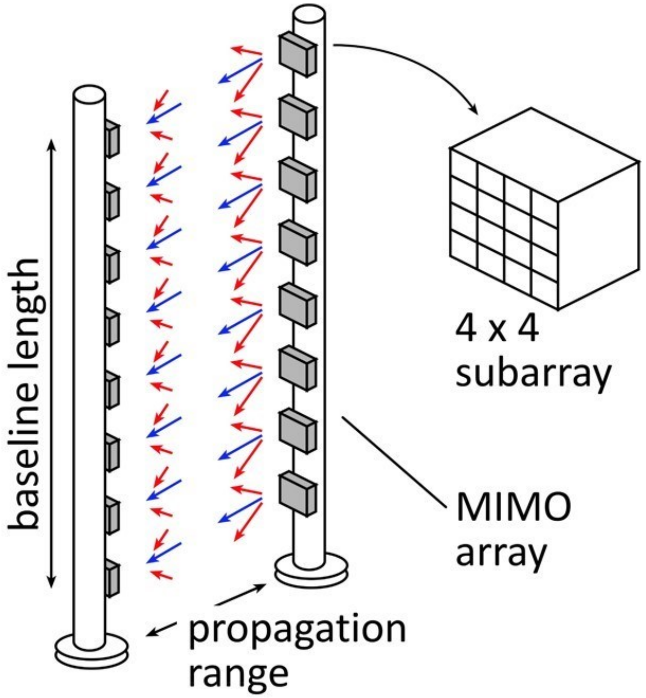
Pole- or wall- mounted multibeam picocell



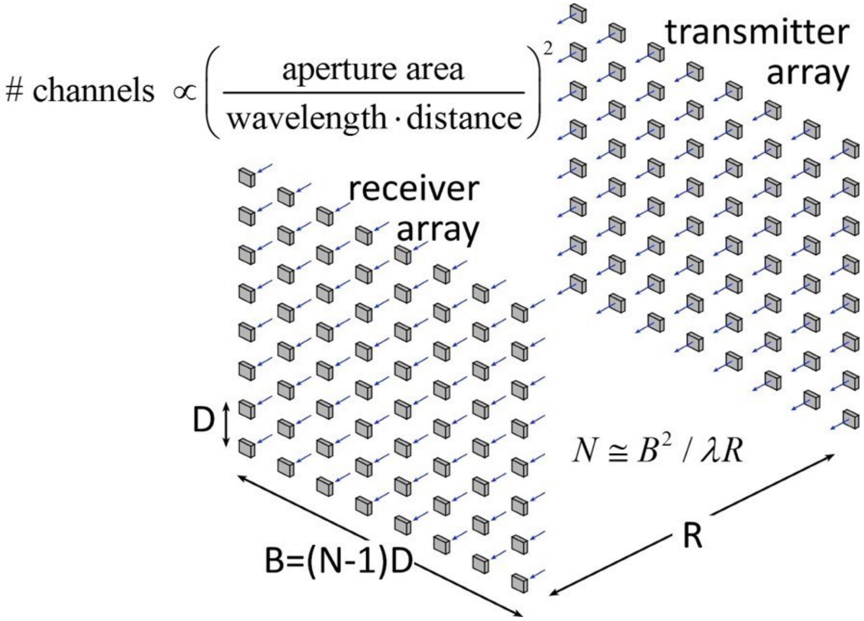


340 GHz or 650 GHz backhaul

linear array



square array



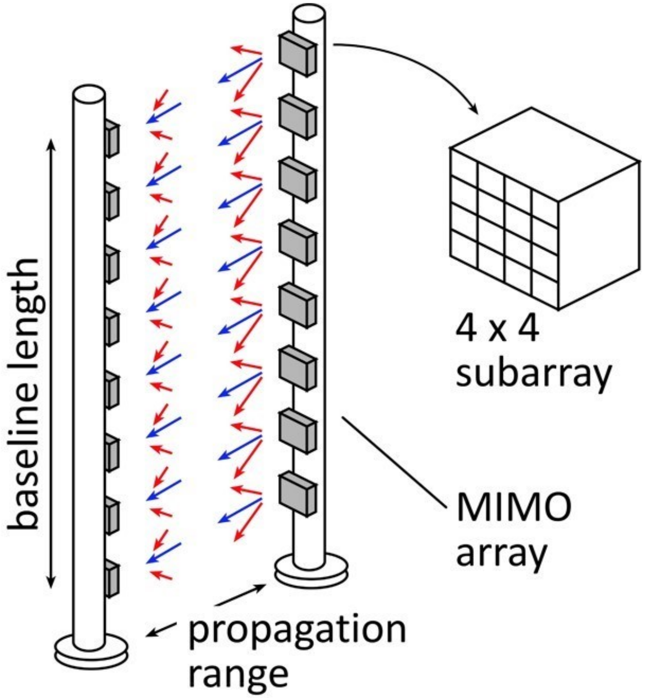
Sub-mm-wave line-of-sight MIMO network backbone

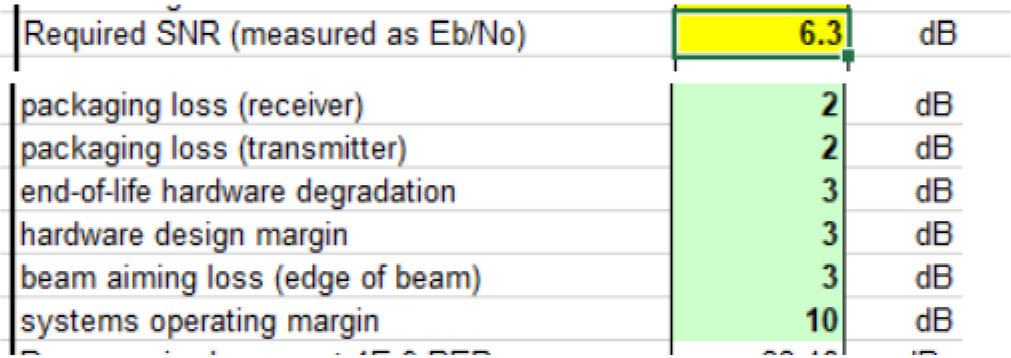
wireless @ optical speed; backhaul when you can't run fiber

340 GHz: 640Gb/s @ 240 meters; 1.2 meter, 8-element array

650 GHz: 1.28Tb/s @ 240 meter; 1.2 meter, 16-element array

340 GHz 640 Gb/s MIMO backhaul





Required SNR (measured as Eb/No)	6.3	dB
packaging loss (receiver)	2	dB
packaging loss (transmitter)	2	dB
end-of-life hardware degradation	3	dB
hardware design margin	3	dB
beam aiming loss (edge of beam)	3	dB
systems operating margin	10	dB

1.2m MIMO array: 8-elements, each 80 Gb/s QPSK; 640Gb/s total
4 × 4 sub-arrays → 8 degree beamsteering

250 meters range in 50 mm/hr rain; 29 dB/km

Realistic packaging loss, operating & design margins

PAs: 10 dBm P_{out} (per element)

LNAs: 4 dB noise figure

340 GHz frequency-scanned imaging car radar

Range: see a soccer ball at 300 meters (10 seconds warning) in heavy fog
(15 dB SNR, 35 dB/km, 30cm diameter target, 10% reflectivity, 100 km/Hr)

Image refresh rate: 60 Hz

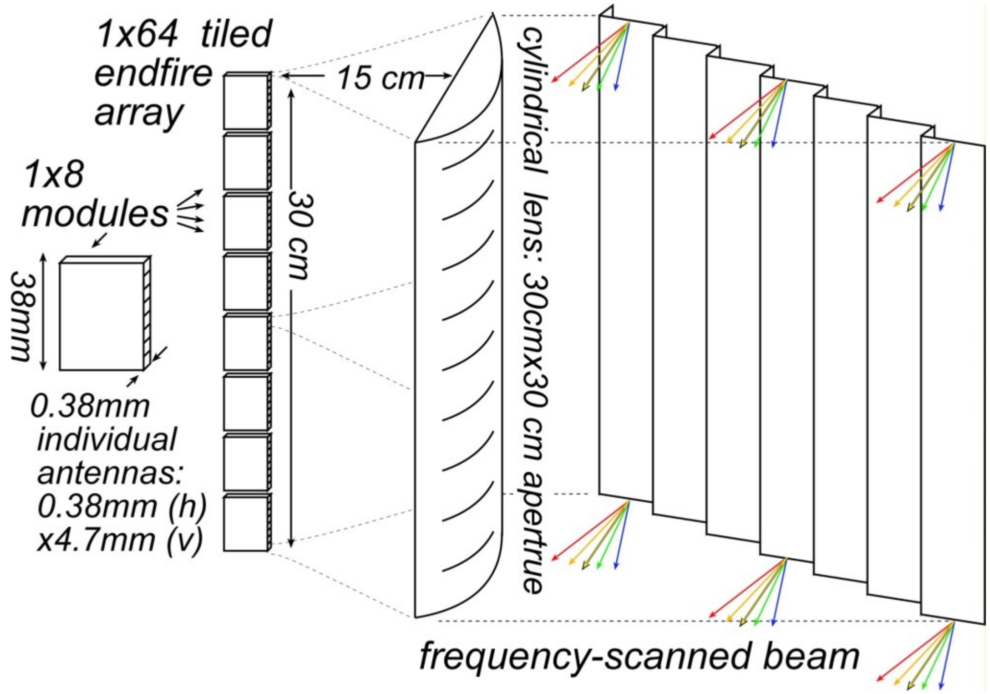
Resolution 64×512 pixels

Angular resolution: 0.14 degrees

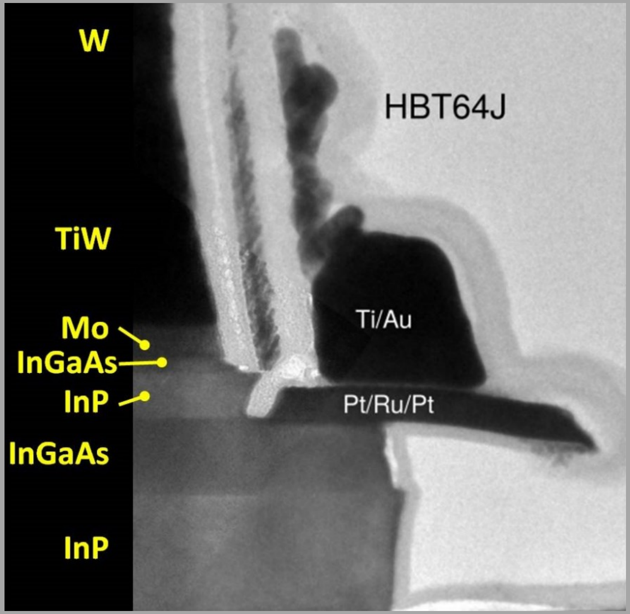
Angular field of view: 9 by 73 degrees

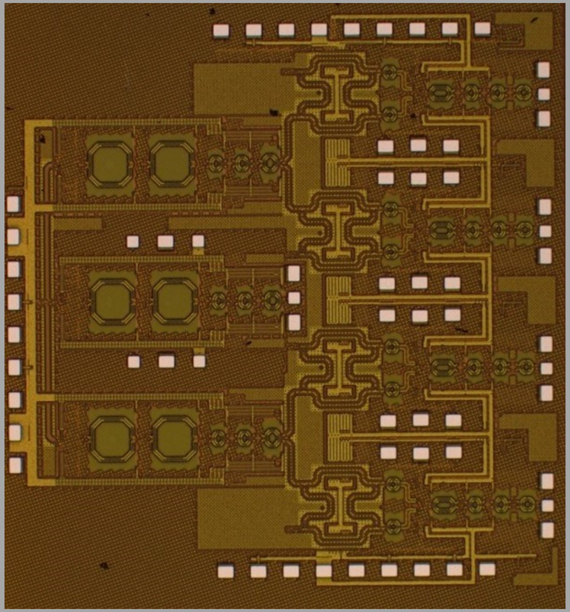
Aperture: 35 cm by 35 cm

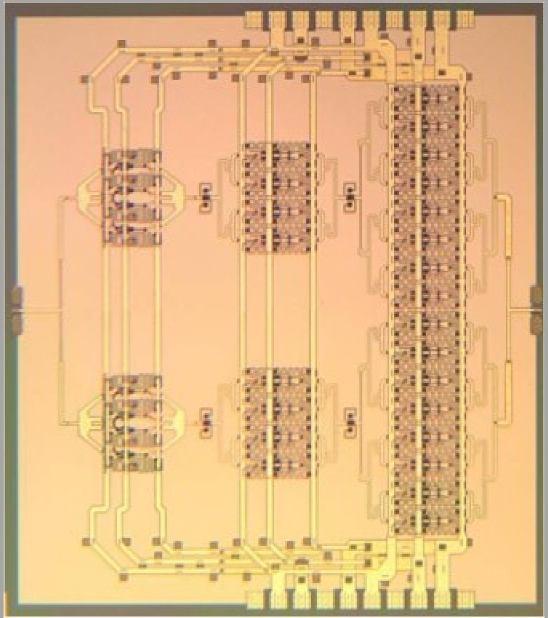
Component requirements:
35 mW peak power/element,
3% pulse duty factor
6 dB noise figure,
5 dB package losses
5 dB manufacturing/aging margin



Transistors & ICs







IC Technologies for 100 + GHz systems

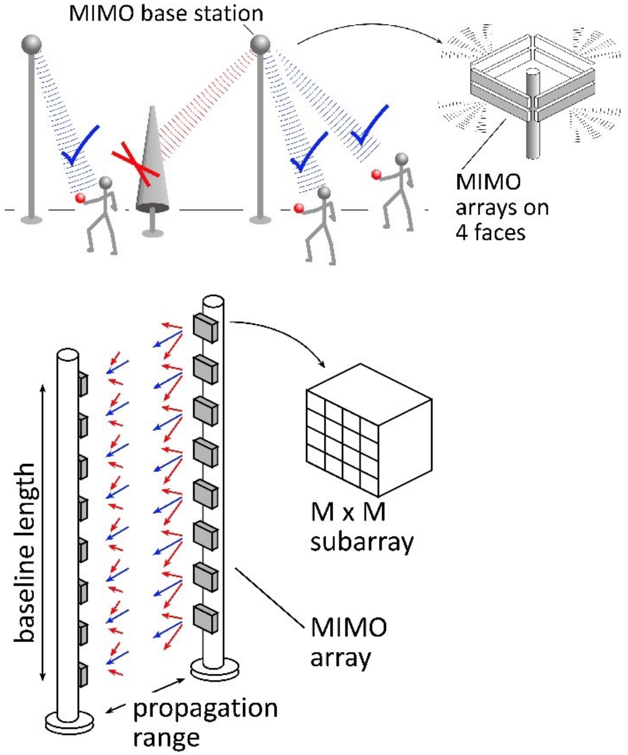
Si VLSI CMOS, SiGe HBT
Baseband signal processing at any carrier frequency
high-frequency interfaces to ~220 GHz
low power, high noise → long range needs large arrays.

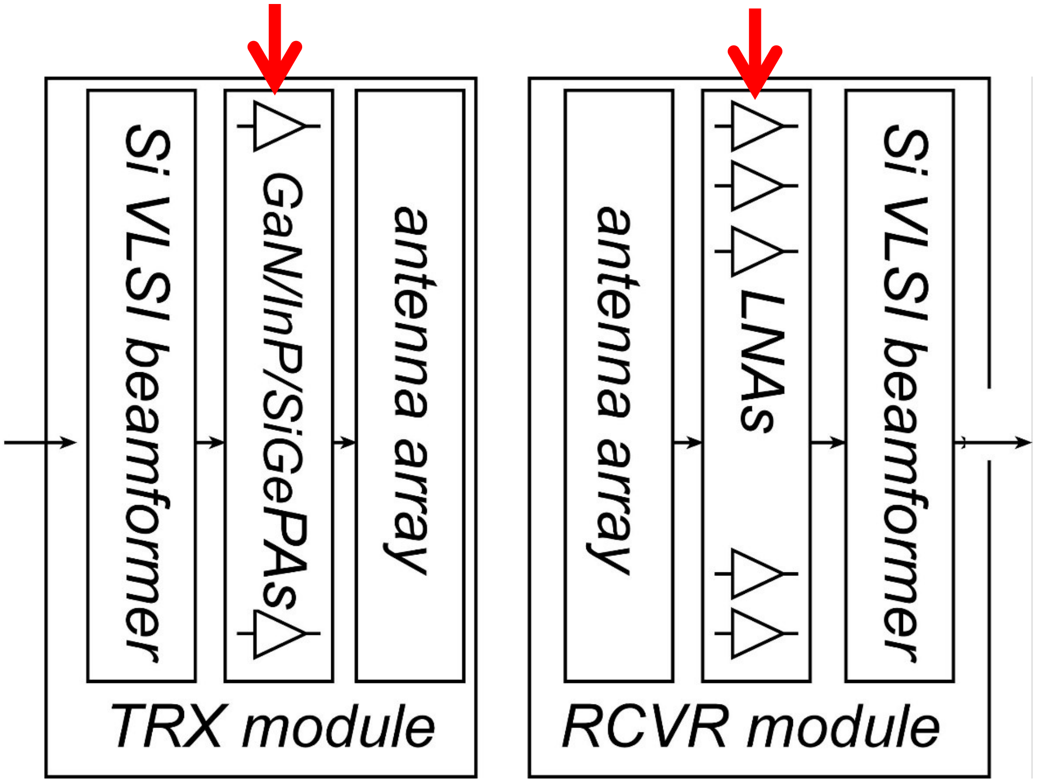
GaN
High-power amplifiers for long-range links
Several Watts @94 GHz, likely will evolved to Watts at 220 GHz

InP HBT
up/downconvert to 340, 650 GHz from 220 GHz Si VLSI
medium-power amplifiers at 140, 220 GHz.

InP MOS-HEMT
Lowest-noise amplifiers at any frequency
low receiver noise→ less transmit power→ less system power

mm-Wave Wireless Transceiver Architecture





custom PAs, LNAs → power, efficiency, noise
Si CMOS beamformer→ integration scale

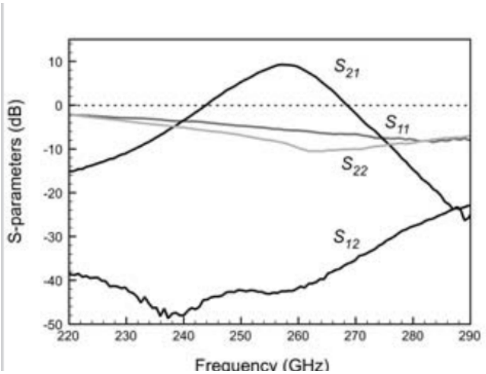
...similar to today's cell phones.

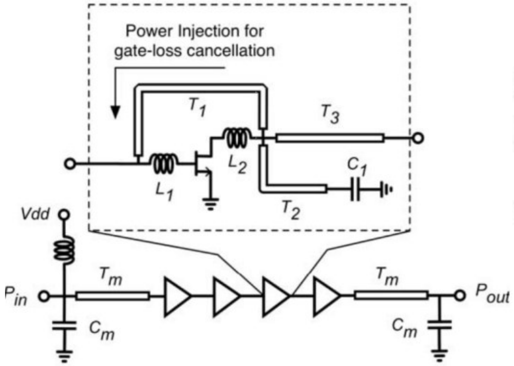
mm-wave CMOS (examples)

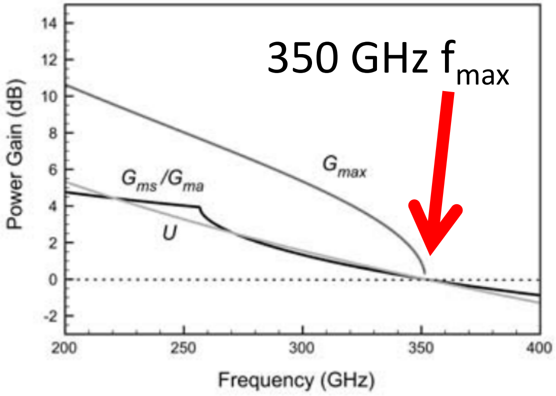
260 GHz amplifier, Feedback-enhanced-gain:

65nm bulk CMOS, 2.3 dB gain per stage (350GHz f_{max})

Momeni ISSCC, March 2013





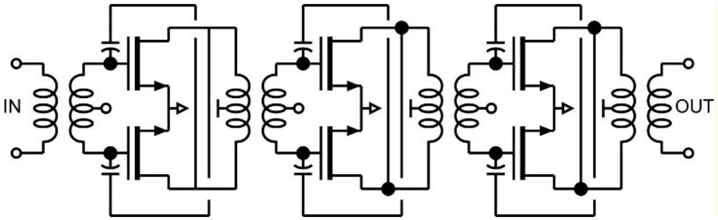


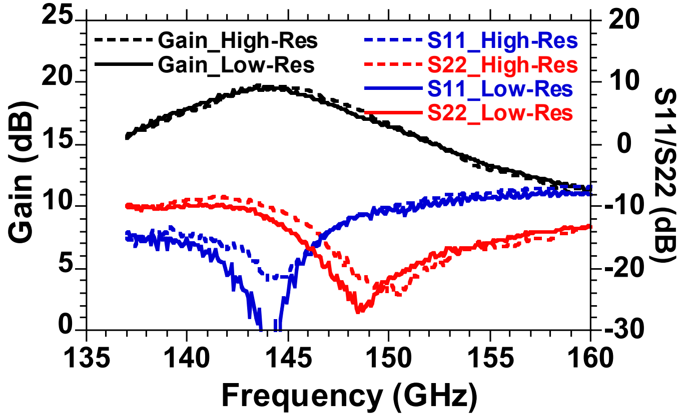
350 GHz f_{max}

145 GHz amplifier, conventional neutralized design:

45 nm SOI CMOS, 6.3 dB gain per stage

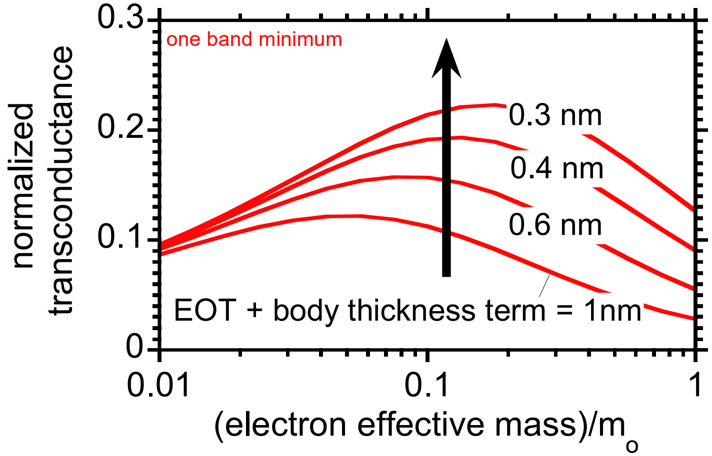
Kim et al. (UCSB), unpublished



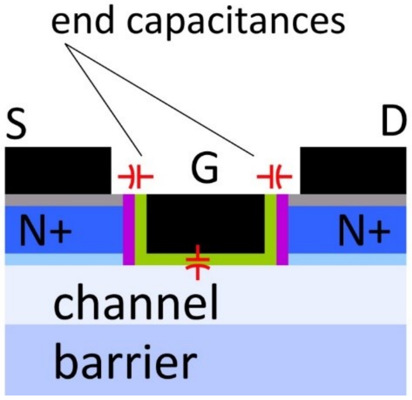


mm-Wave CMOS won't scale much further

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

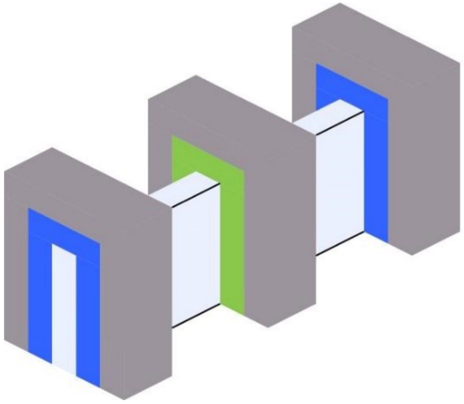


Maximum g_m, minimum C→ upper limit on f_τ.
about 350-400 GHz.

Tungsten via resistances reduce the gain

Inac et al, CSICS 2011

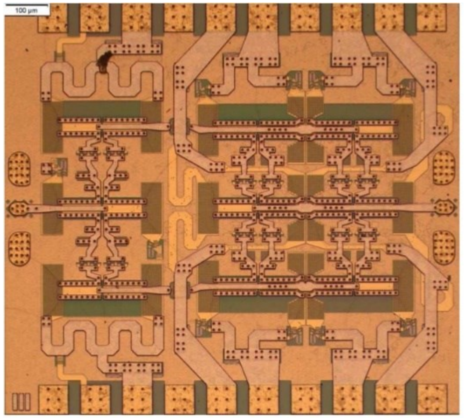
Present finFETs have yet larger end capacitances



III-V high-power transmitters, low-noise receivers

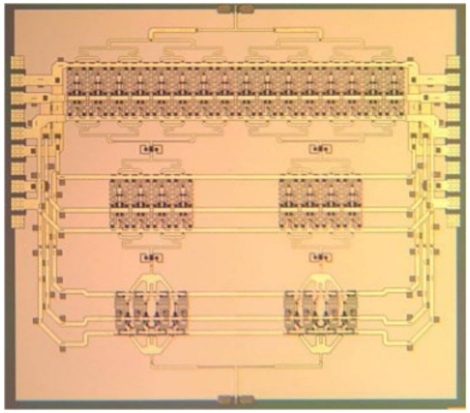
Cell phones & WiFi:
GaAs PAs, LNAs

mm-wave links need
high transmit power,
low receiver noise



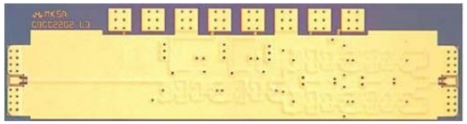
0.47 W @86GHz

H Park, UCSB, IMS 2014



0.18 W @220GHz

T Reed, UCSB, CSICS 2013

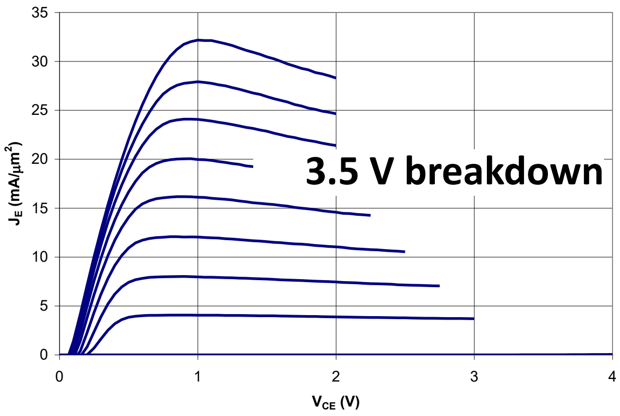


1.9mW @585GHz

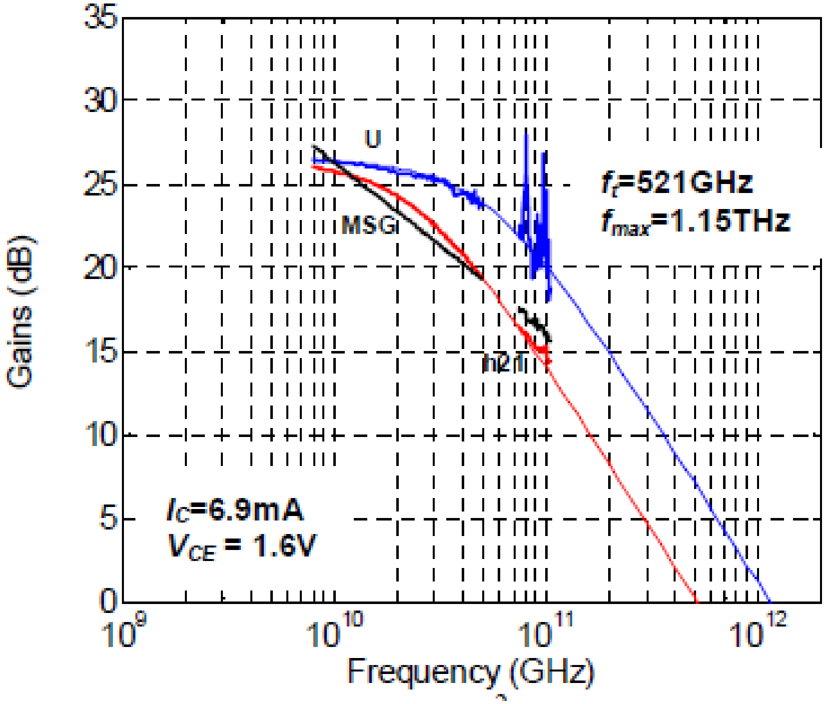
M Seo, TSC, IMS 2013

130nm / 1.1THz InP HBT Technology

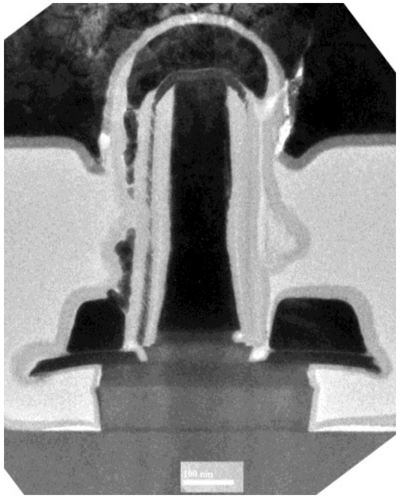
Teledyne: M. Urteaga *et al*: 2011 DRC

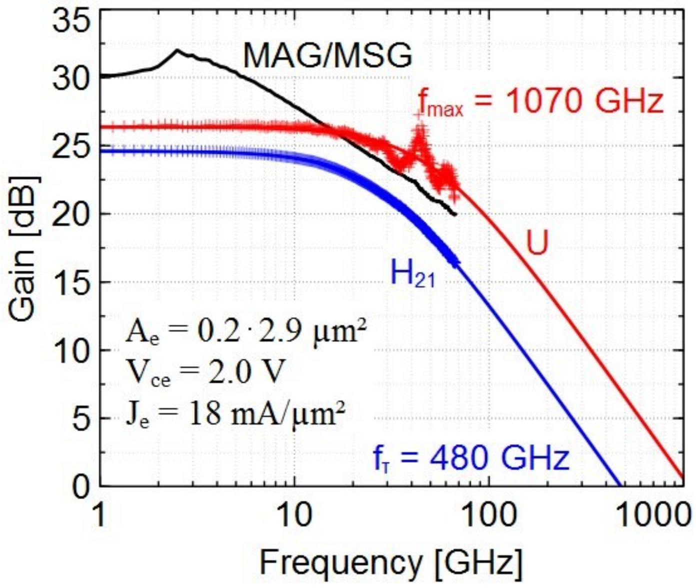


3.5 V breakdown



Rode (UCSB), IEEE TED, 2015

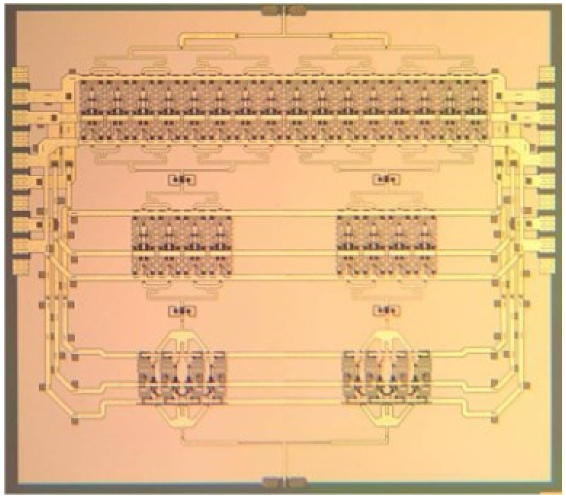




130nm / 1.1THz InP HBT: IC Examples

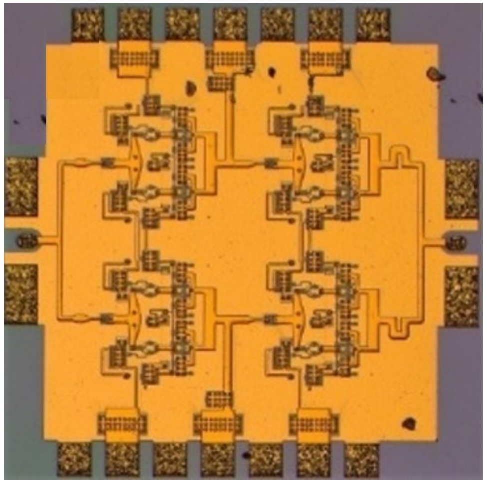
220 GHz 0.18W power amplifier

UCSB/Teledyne: T. Reed *et al*: 2013 CSICS



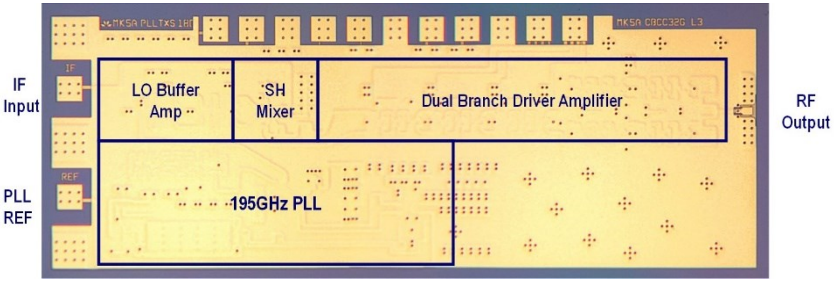
325 GHz power amplifier

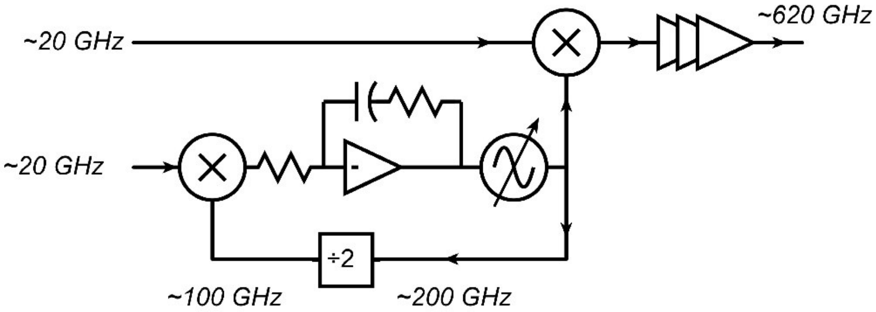
UCSB/Teledyne: (being tested)



Integrated ~600GHz transmitter

Teledyne: M. Urteaga *et al*: 2017 IEEE Proceedings





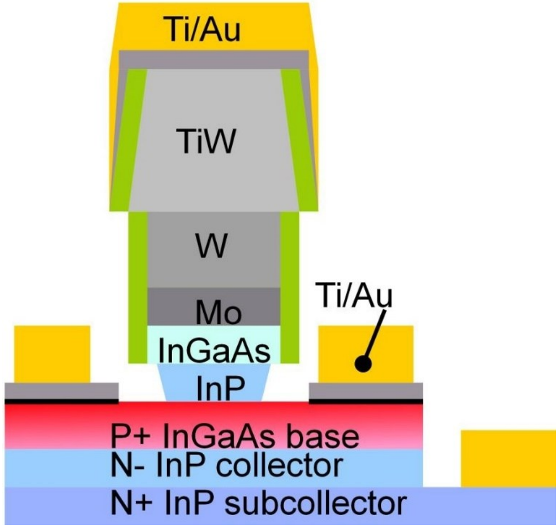
InP HBT: Towards the 2 THz / 64nm Node

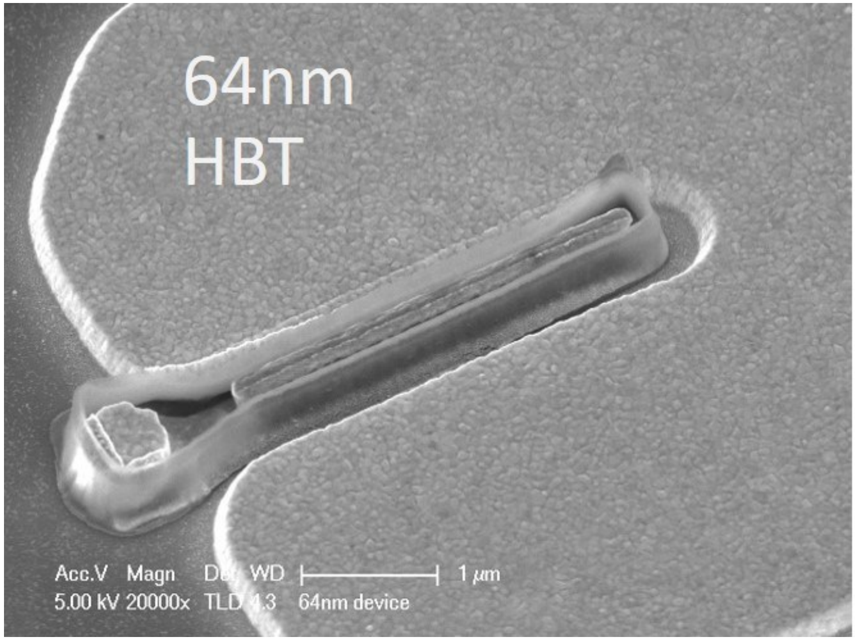
Narrow junctions.

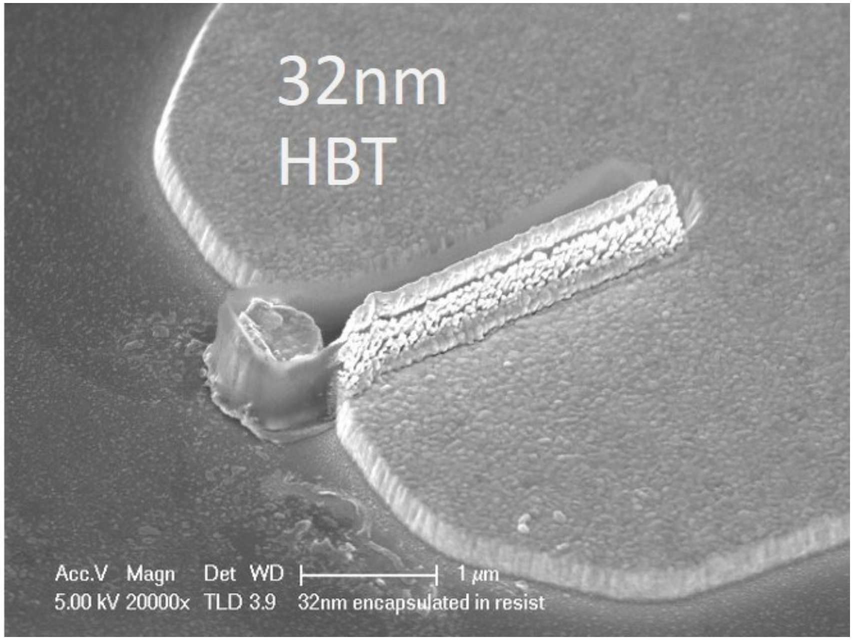
Thin semiconductor layers

High current density

Ultra low resistivity contacts

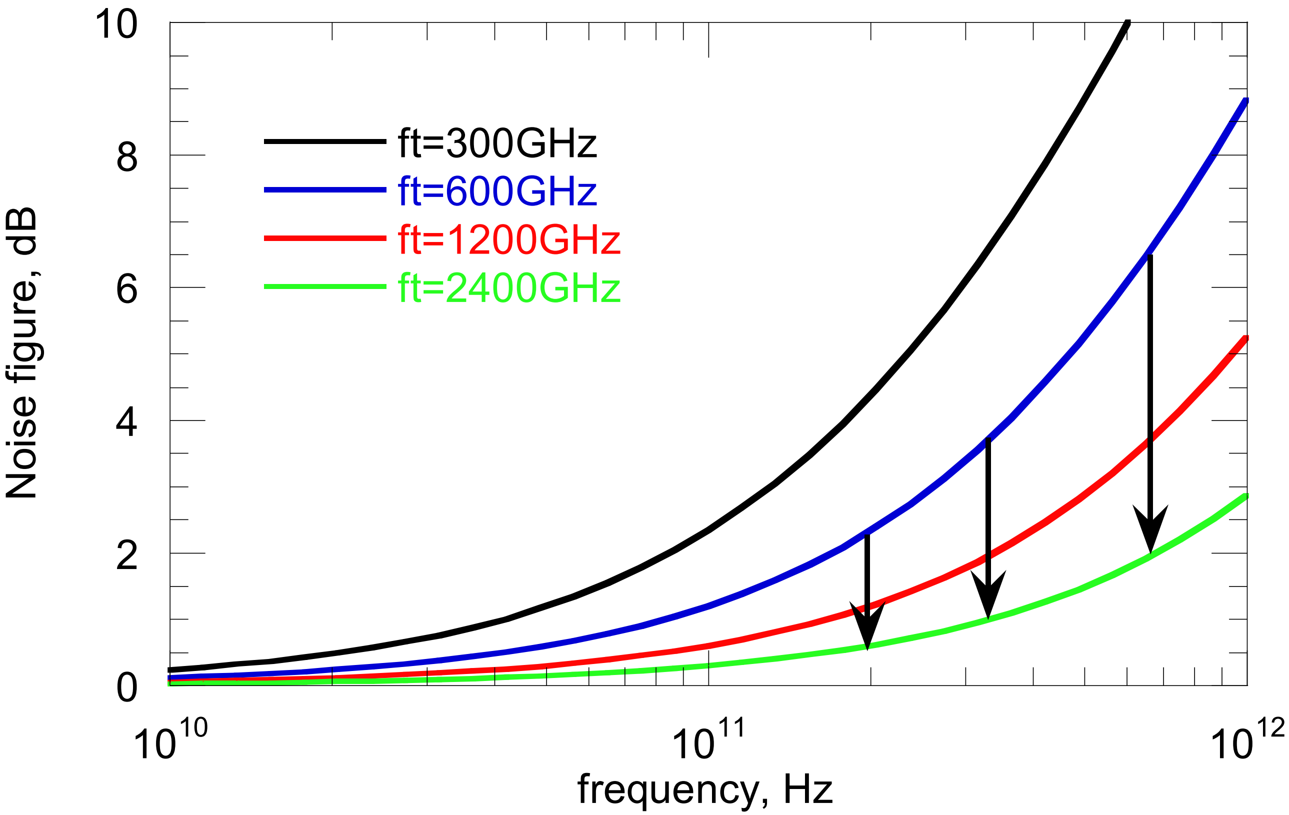






Yihao Fang, UCSB, unpublished

HEMTs: key for low noise



$$F_{\min} \approx 1 + 2\sqrt{g_m (R_s + R_g + R_i)\Gamma} \cdot \left(\frac{f}{f_\tau}\right)$$

$$+ 2 g_m (R_s + R_g + R_i)\Gamma \cdot \left(\frac{f}{f_\tau}\right)^2$$

$$\Gamma \approx 1$$

Hand-derived modified Fukui Expression, fits CAD simulation extremely well.

2:1 to 4:1 increase in f_τ → improved noise

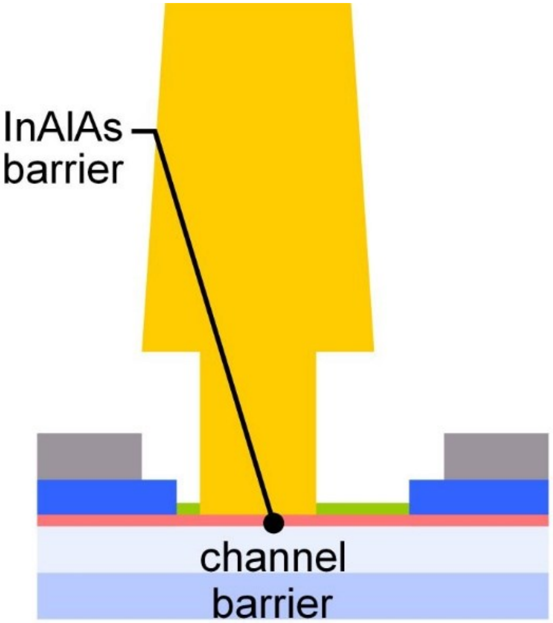
→ less required transmit power→ easier PAs, less DC power

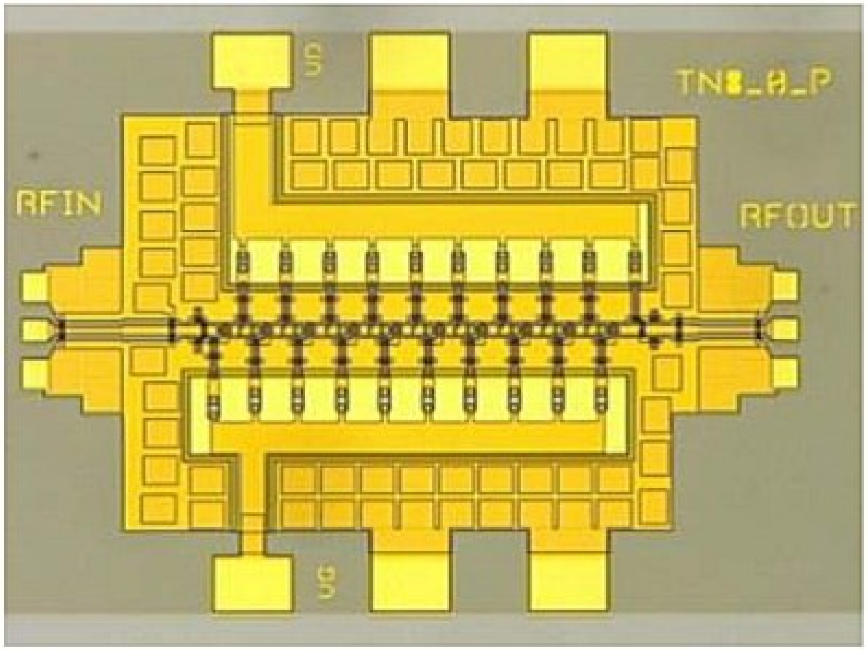
or enable higher-frequency systems

HEMTs: State of the art

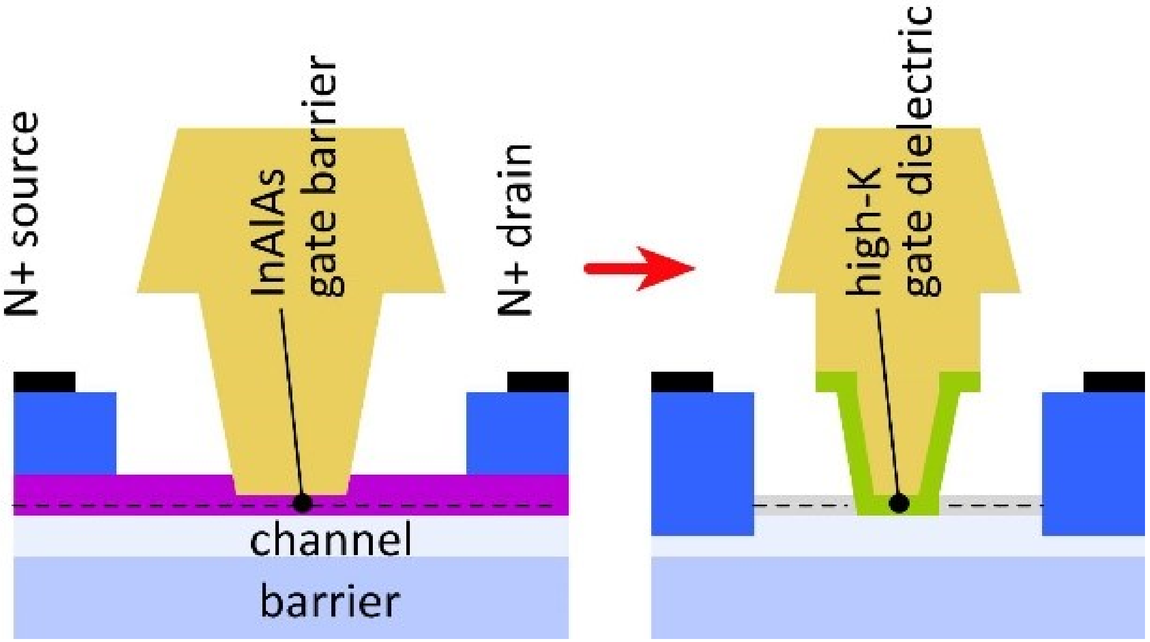
First Demonstration of Amplification at 1 THz Using 25-nm InP High Electron Mobility Transistor Process

Xiaobing Mei, et al, IEEE EDL, April 2015 **(Northrop-Grumman)**





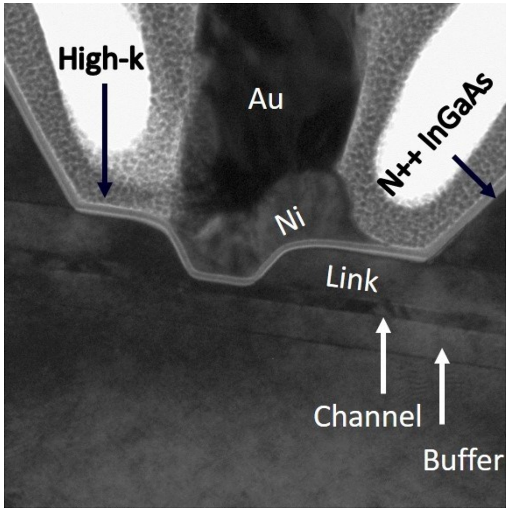
Towards faster HEMTs



Gate barrier:
Key scaling limit

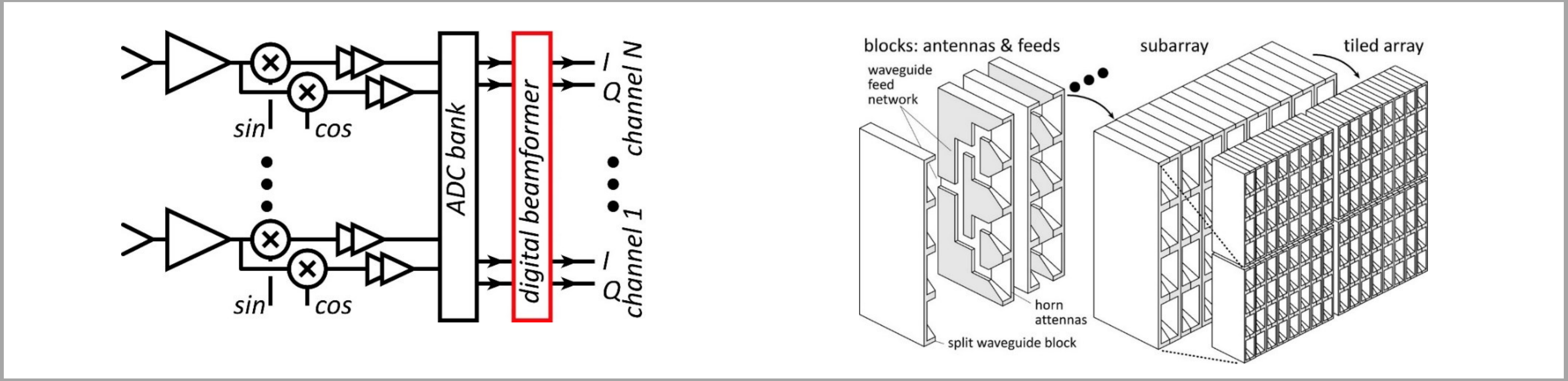
Solution
replace InAlAs barrier
with high-K dielectric

Target ~10nm node
~0.5nm EOT, ~1.5 THz f_τ.

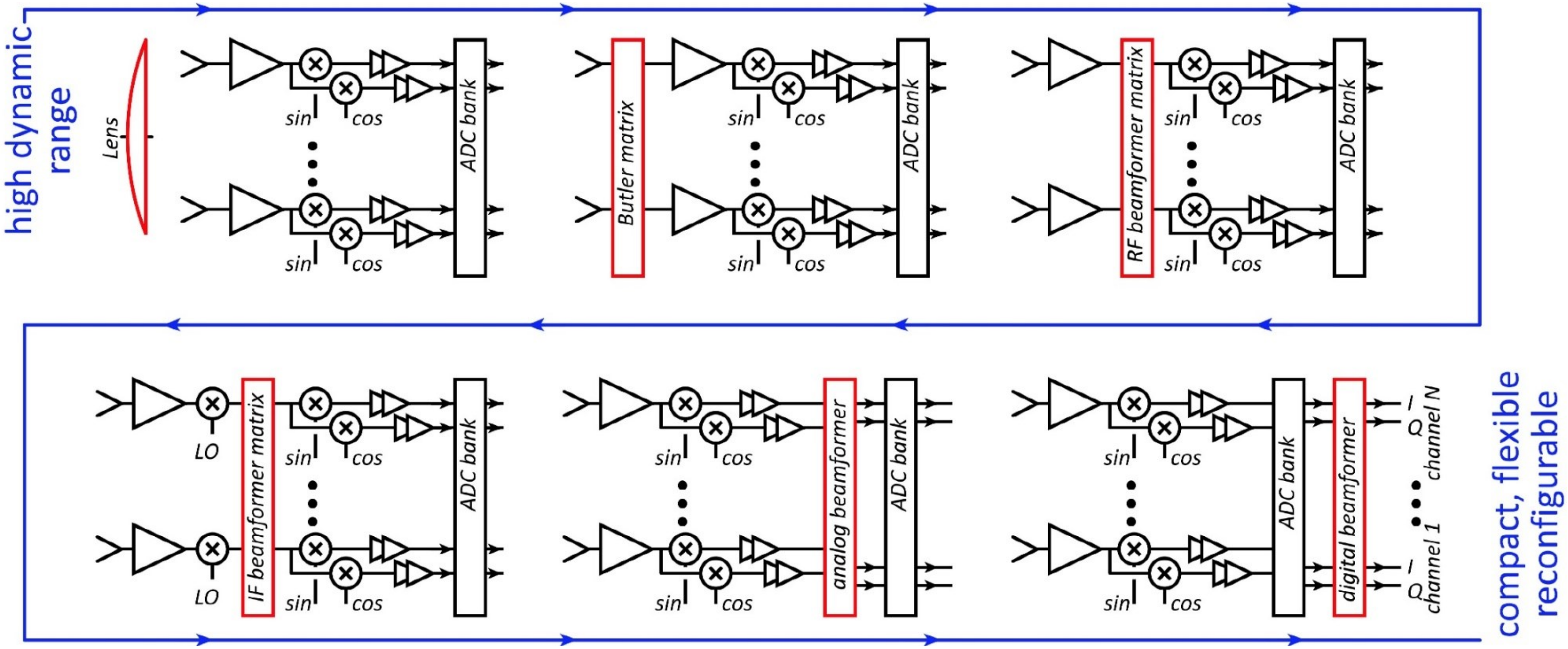


Jun Wu, UCSB, unpublished

Systems & Packages



Beamforming for massive spatial multiplexing

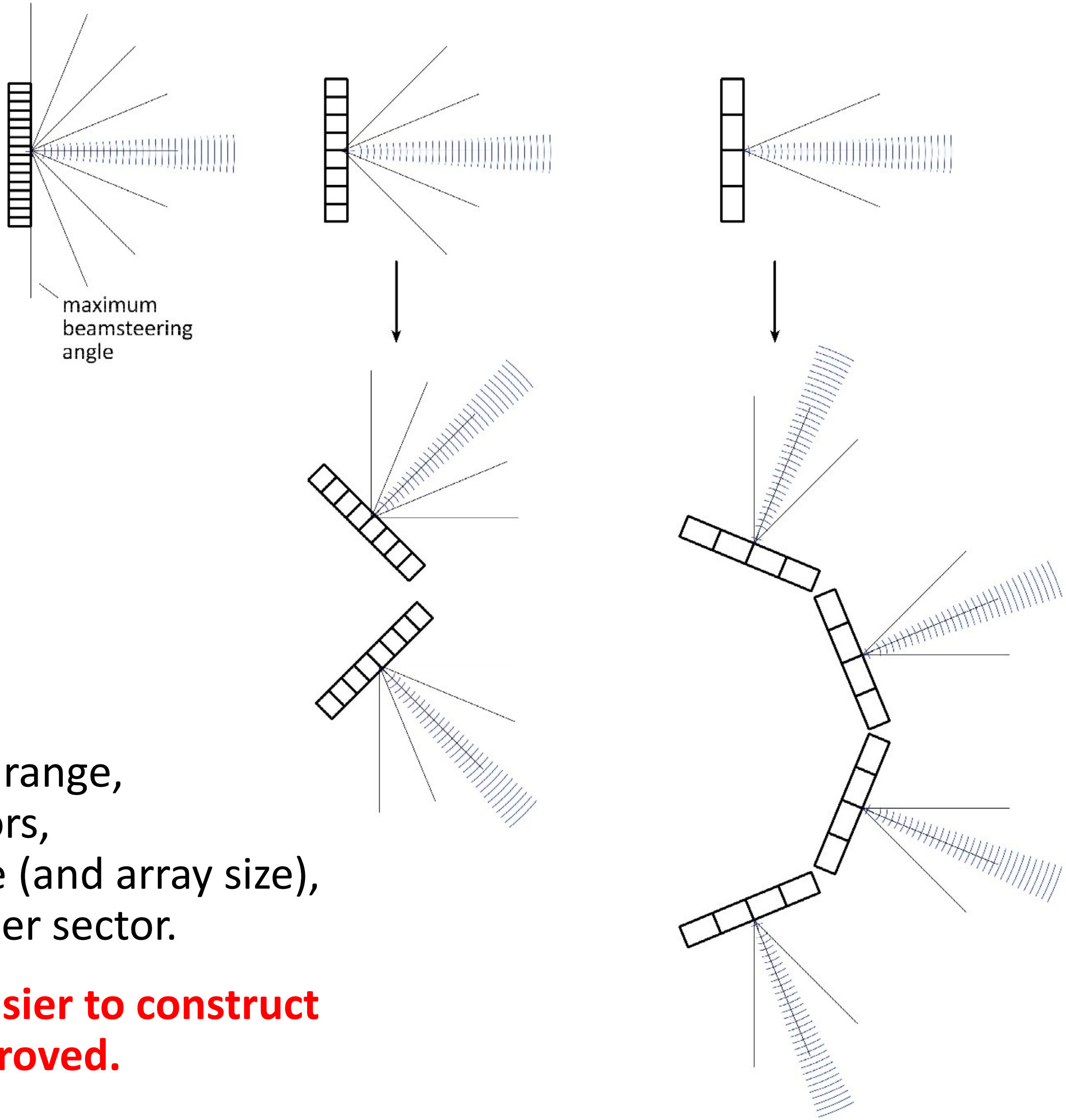


Pure digital beamforming:
massive dynamic range throughout signal chain
massive computational complexity

Pure RF beamforming: (focal plane, Butler matrixes, RF beamforming)
Physically complex. Component precision. Lack of adaptation.

Likely best approach is tiled
Butler or RF beamforming in the tile. Analog or digital in overall array

Sectoral phased arrays for size, dynamic range



At a given beamwidth
and a given angular steering range,
as we increase the # of sectors,
we increase the element size (and array size),
and reduce the # of beams per sector.

mm-wave arrays become easier to construct
Dynamic range is vastly improved.

The mm-wave module design problem

How to make the IC electronics fit ?

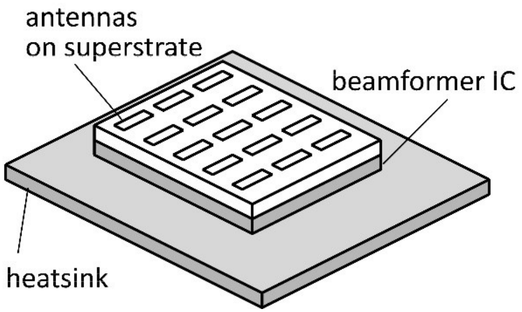
100+ GHz arrays: $\lambda_0/2$ element spacing is very small.
Antennas on or above IC → IC channel spacing = antenna spacing
→ ***limited IC area to place circuits***

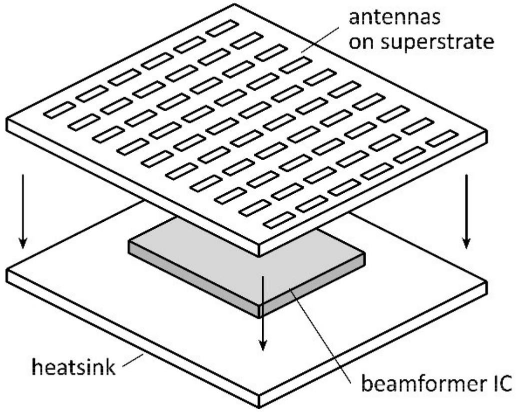
How to avoid catastrophic signal distribution losses ?

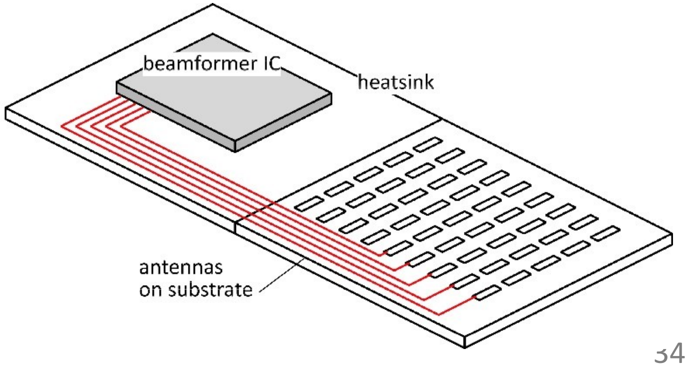
long-range, high-gain arrays: array size can be large.
ICs beside array → very long wires between beam former and antenna
→ ***potential for very high signal distribution losses***

How to remove the heat ?

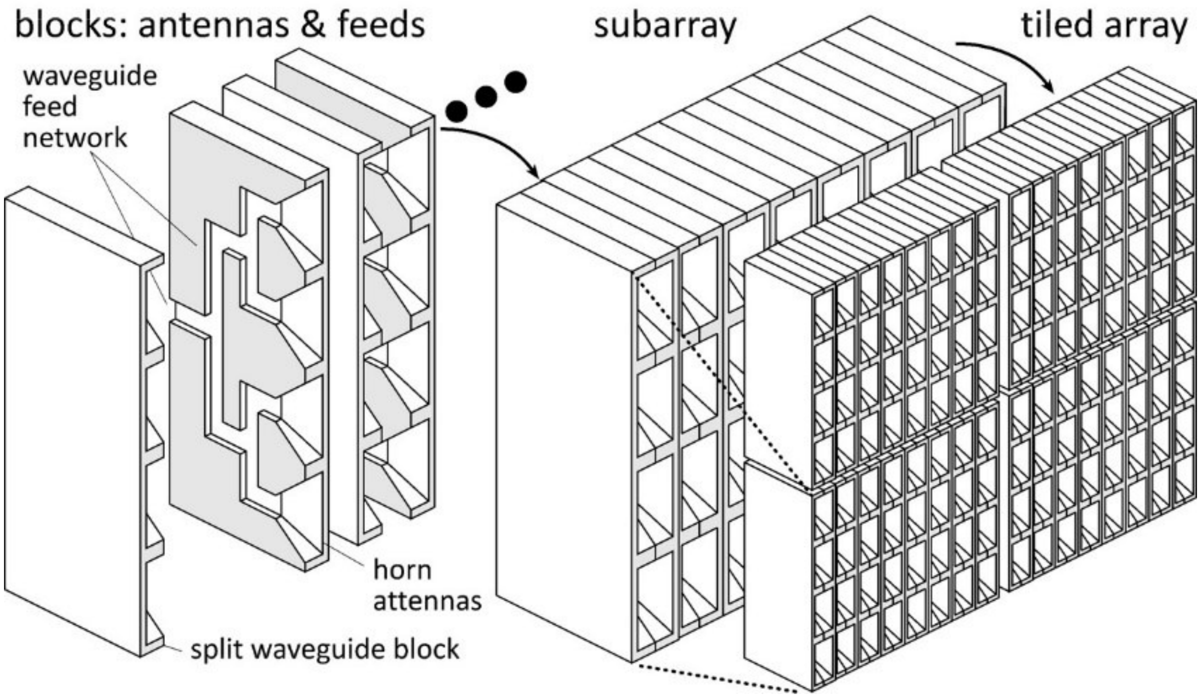
100+ GHz arrays: element spacing is very small.
If antenna spacing = IC channel spacing, then power density is very large







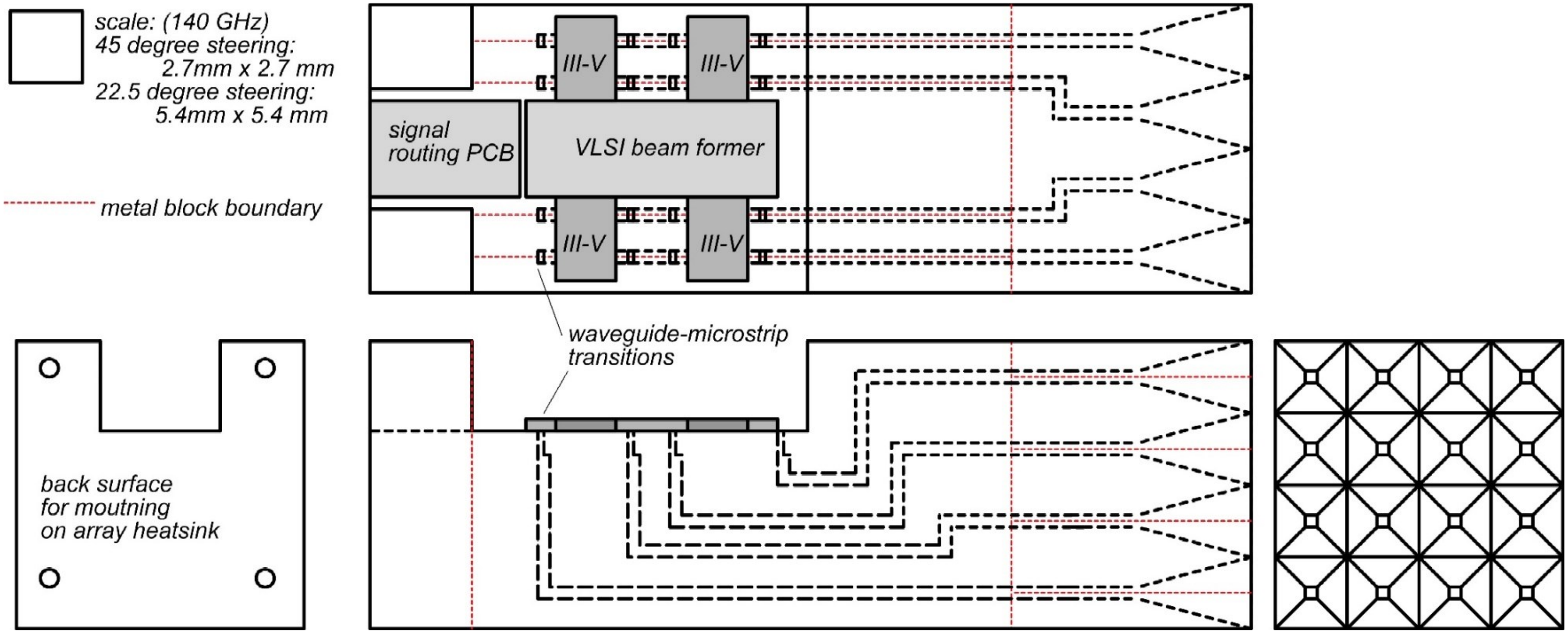
background: split-block waveguides



Waveguides are manufactured (milled or die cast) from a set of pieces

Precision pins aid alignment

Concept: Tile for mm-wave arrays



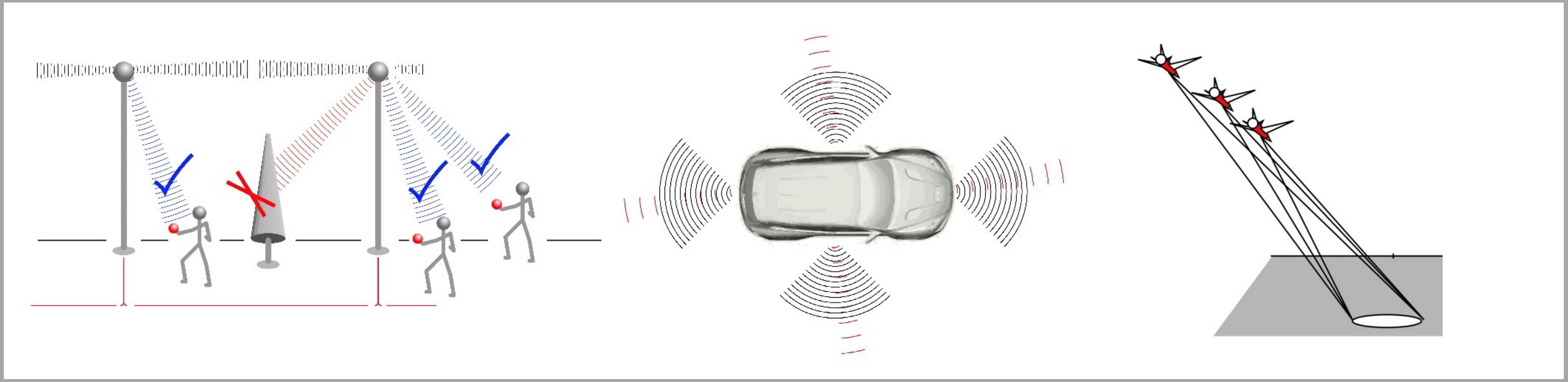
Split-block assembly.   Modules tile into larger array

IC area can be much larger than antenna area→ electronics can fit

Low-loss waveguide feeds, efficient waveguide horn antennas

Efficient heat-sinking: permits W-level GaN, InP, SiGe PAs for long range

Wireless Above 100 GHz



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, dynamic range
packaging: fitting signal channels in very small areas

(backup slides follow)

Talk is 30 min plus 10 min for questions…

25-30 slides