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100-340GHz wireless communications and imaging

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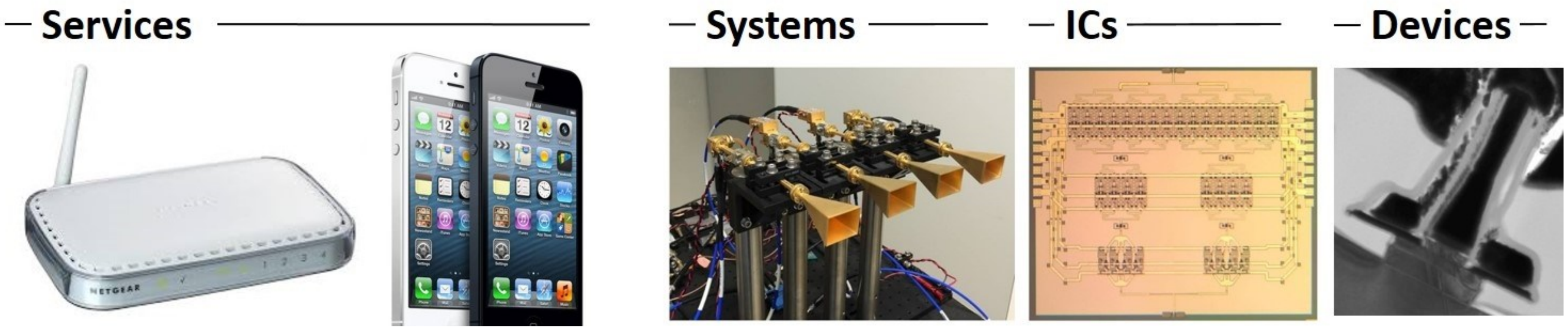
Why 100-340GHz wireless ?



Wireless networks: exploding demand.

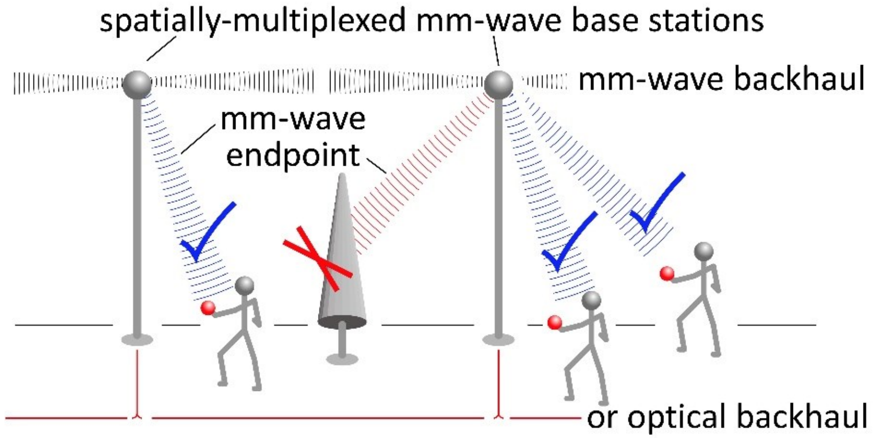
Immediate industry response: 5G.
28, 38, 57-71(WiGig), 71-86GHz
increased spectrum, extensive beamforming

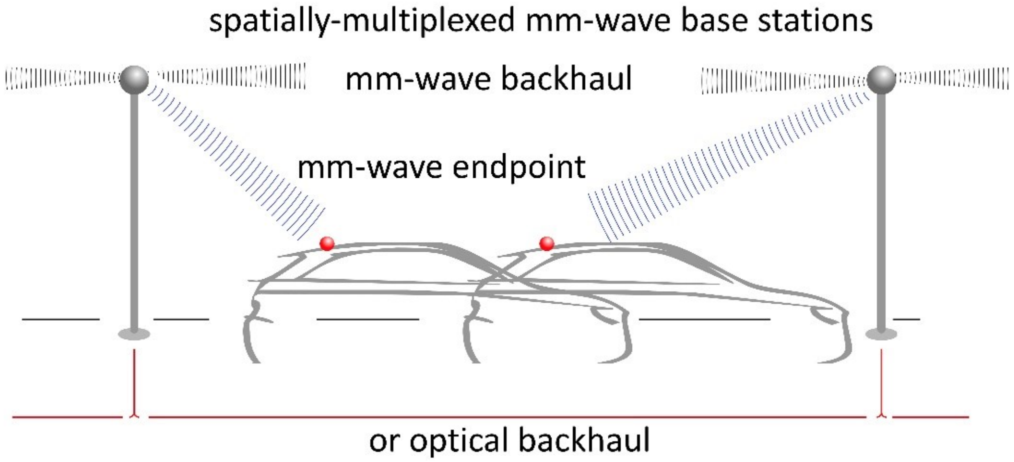
Next generation (6G ??): above 100GHz.
greatly increased spectrum, massive spectral multiplexing

Also TV-like imaging/sensing/radar: cars, airplanes, drones

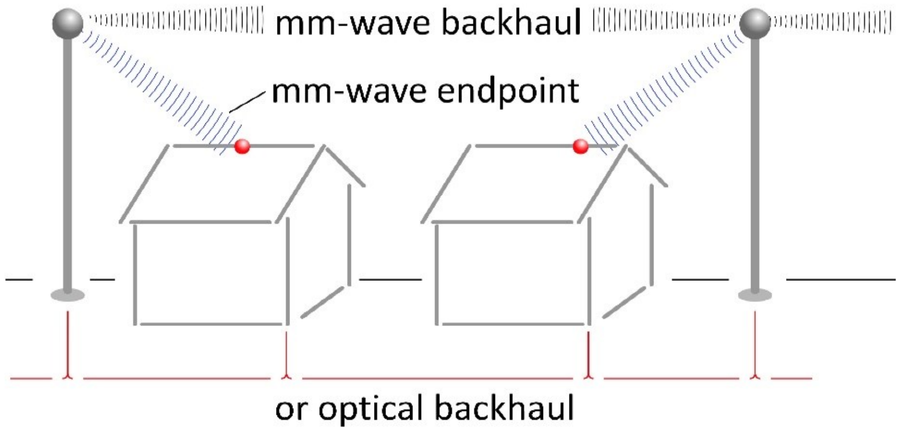
100-340GHz: high-capacity communications

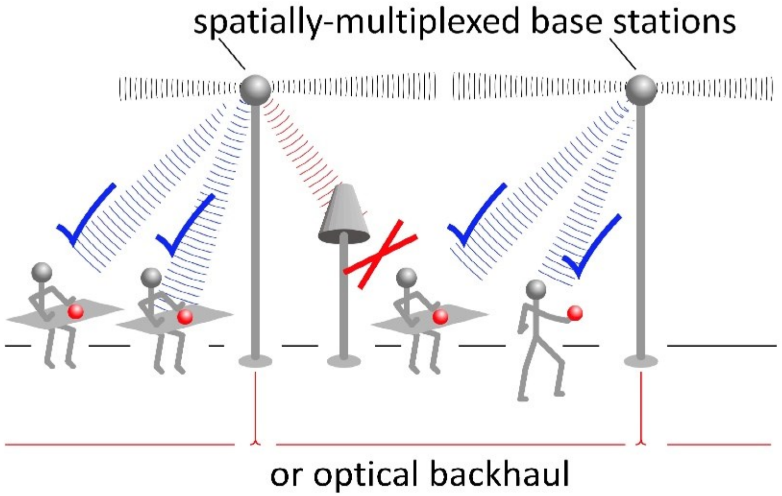
Gigabit mobile communication: Information anywhere, any time, without limits





Residential/office communication: Cellular/internet convergence: competition, low cost, broader deployment





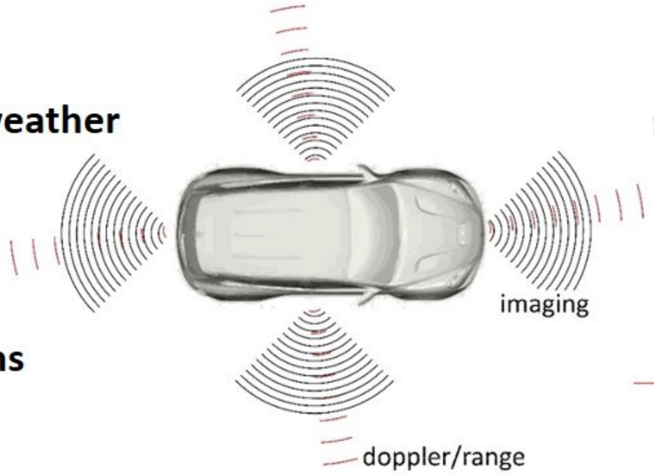
100-340GHz imaging: fog/clouds/smoke/dust

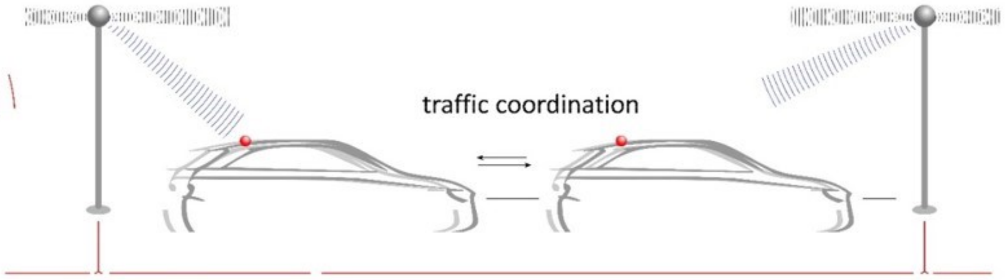
Automatic car, intelligent highway

340 GHz HDTV-resolution radar
drive safely in fog at 100 km/hr
self-driving: complements LIDAR, works in bad weather

Complements 70 GHz Doppler / ranging radar.
object near ? approaching ? Can't tell what.

Intelligent highway: coordinate traffic
anticipate & manage interactions, avoid collisions

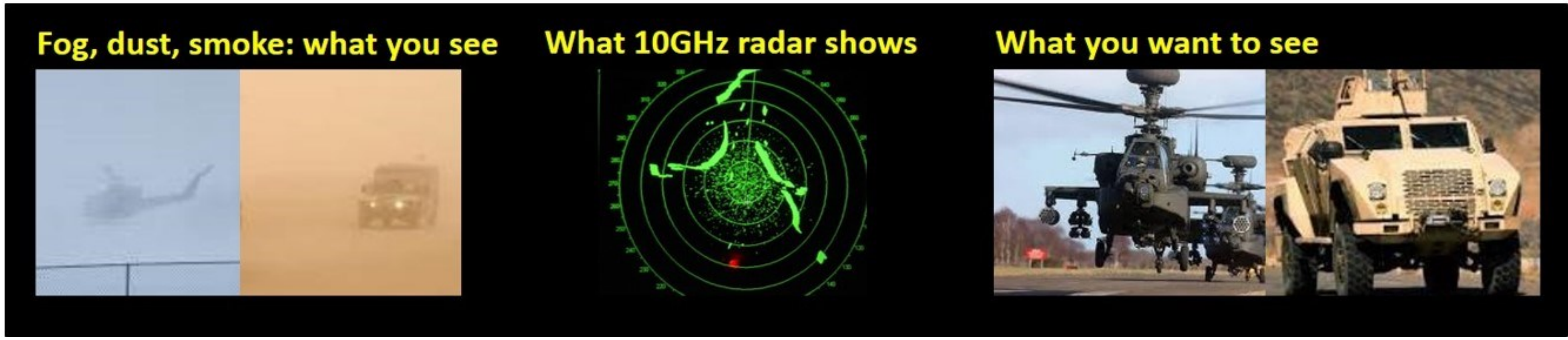




Sensing/imaging for national security

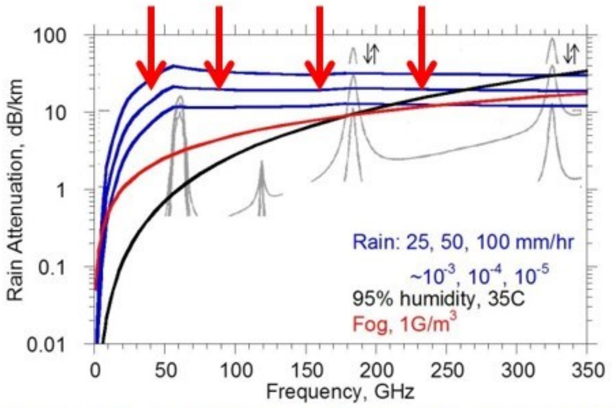
20/70/ 94 GHz radar: is something there ?
Long-range, low-resolution: can't tell what.

140-340GHz imaging radar: **what is it ?**
shorter range, TV-like resolution
small, light: jeep, helicopter, UAV.



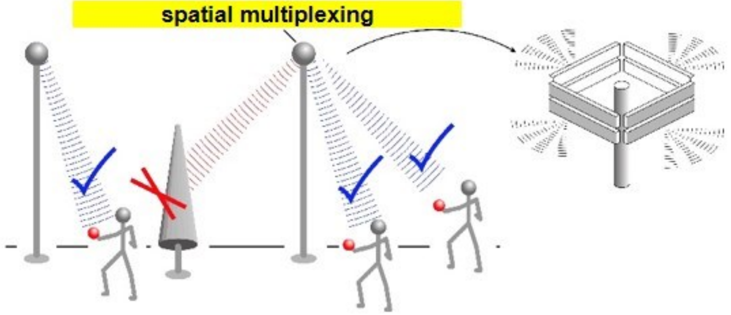
100-340GHz: benefits & challenges

Large available spectrum



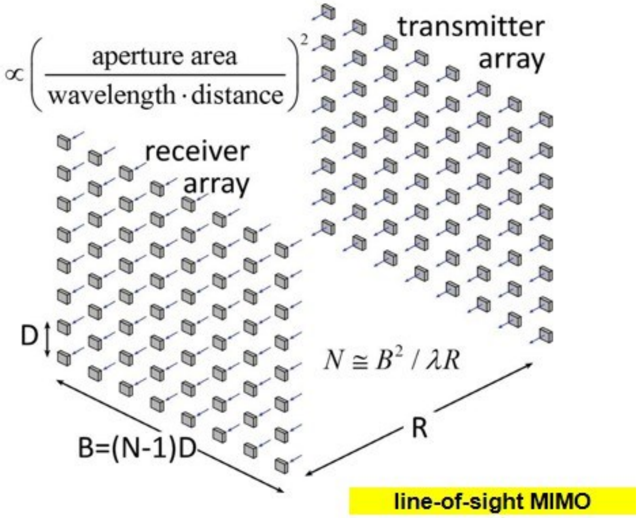
(note high attenuation in foul or humid weather)

Massive # parallel channels



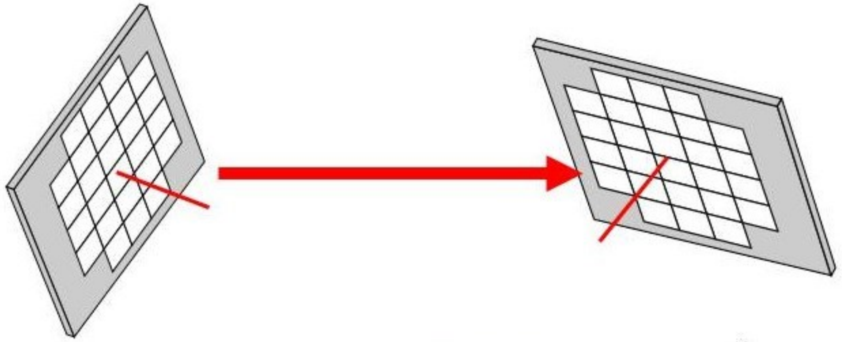
$$\text{angular resolution} = \frac{\text{wavelength}}{\text{array width}}$$

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



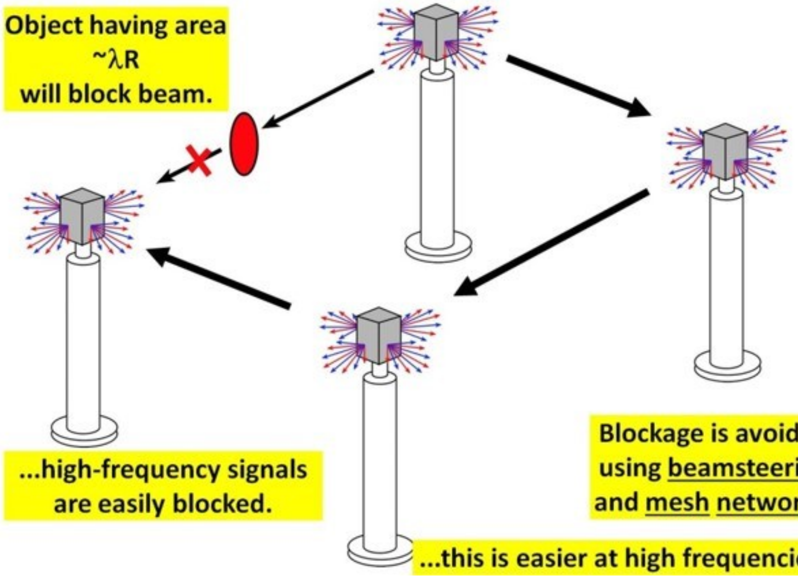
$$N \cong B^2 / \lambda R$$

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.

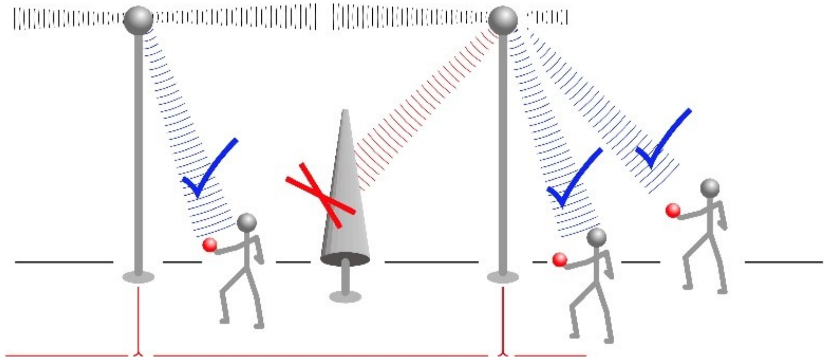
...high-frequency signals
are easily blocked.

Blockage is avoided
using beamsteering
and mesh networks.

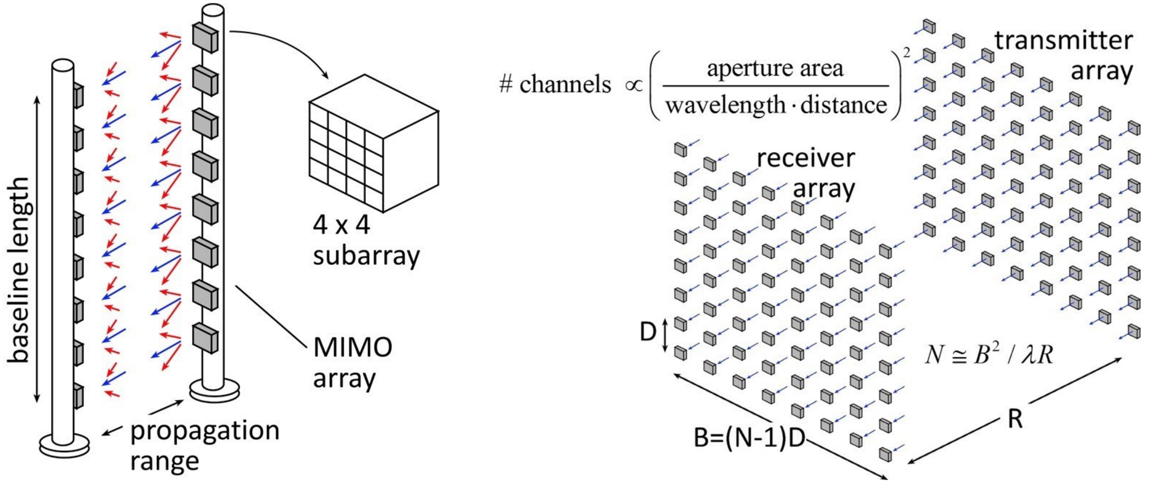
...this is easier at high frequencies.

140-340GHz: ComSenTer target applications

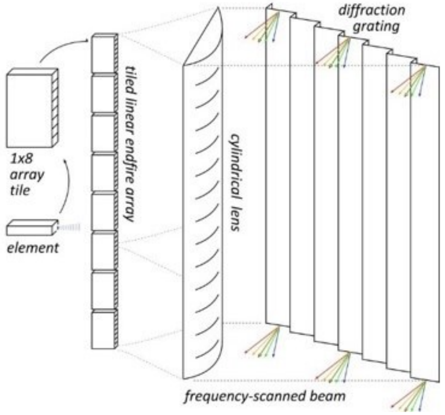
MIMO hub: 128 beams/face, 1/10Gb/s/user
140 GHz



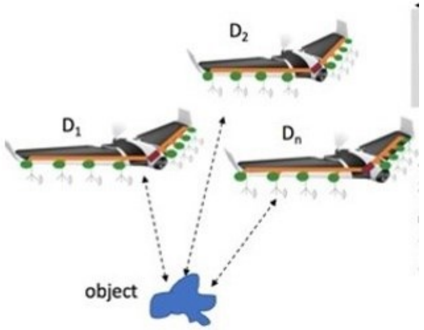
Point-point MIMO: 340GHz: Tb/s links
massive spatial multiplexing



220, 340GHz imaging: drive/fly in fog/rain/snow
300m, 512×64 image, 60Hz, 15dB SNR

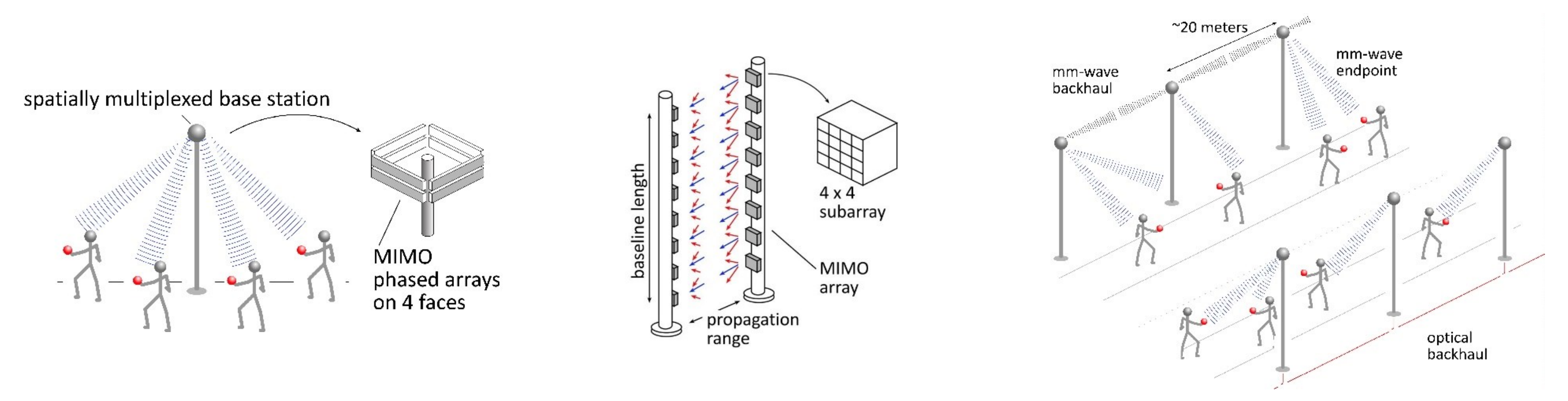


Ultra-compact imaging: drones
unlike visible: image through fog/smoke/rain

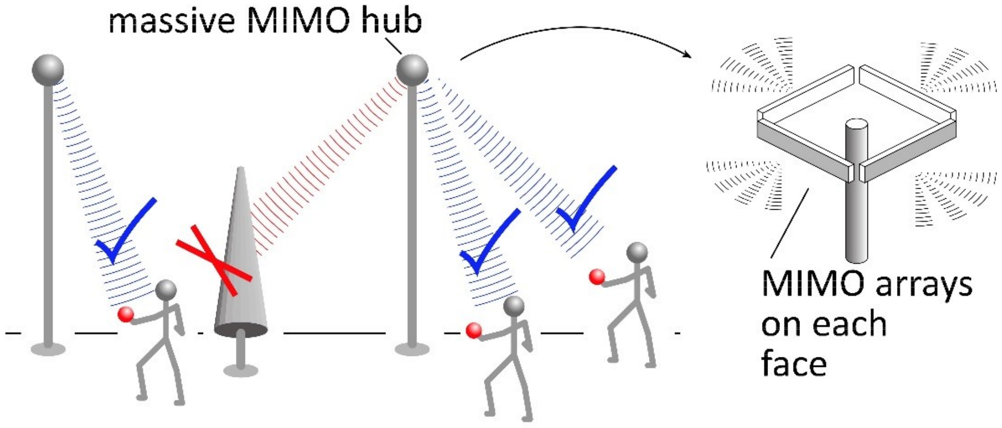


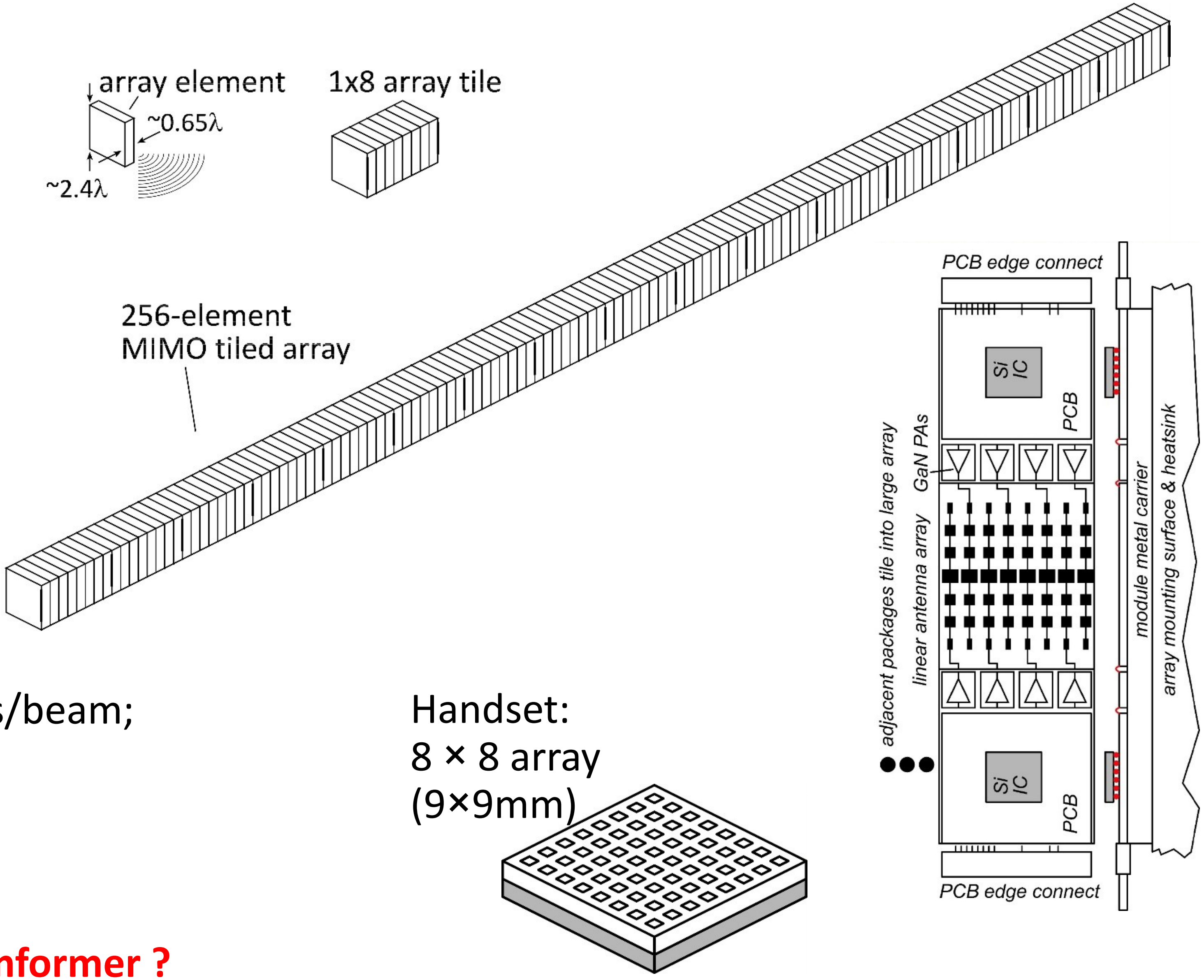
SRC® JUMP Joint University Microelectronics Program
ComSenTer COMMUNICATIONS SENSING TERAHERTZ

140-340 GHz: Applications



140 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;

225 m range

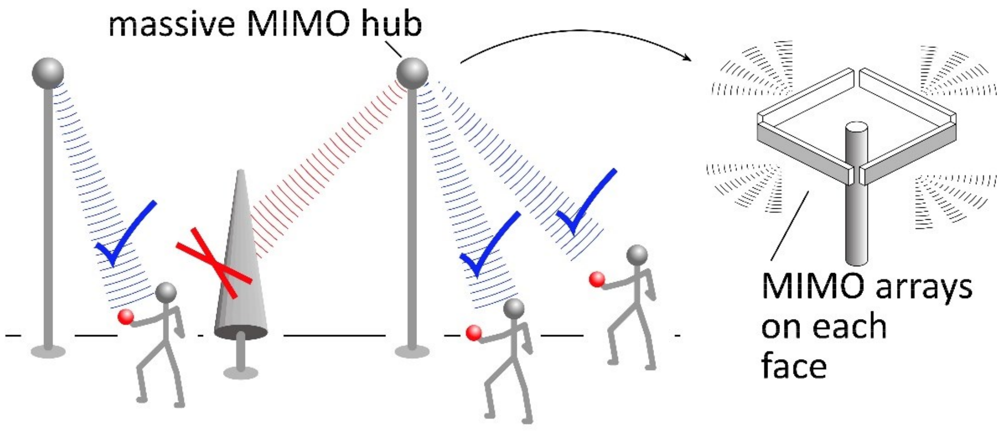
Handset:
8 × 8 array
(9×9mm)

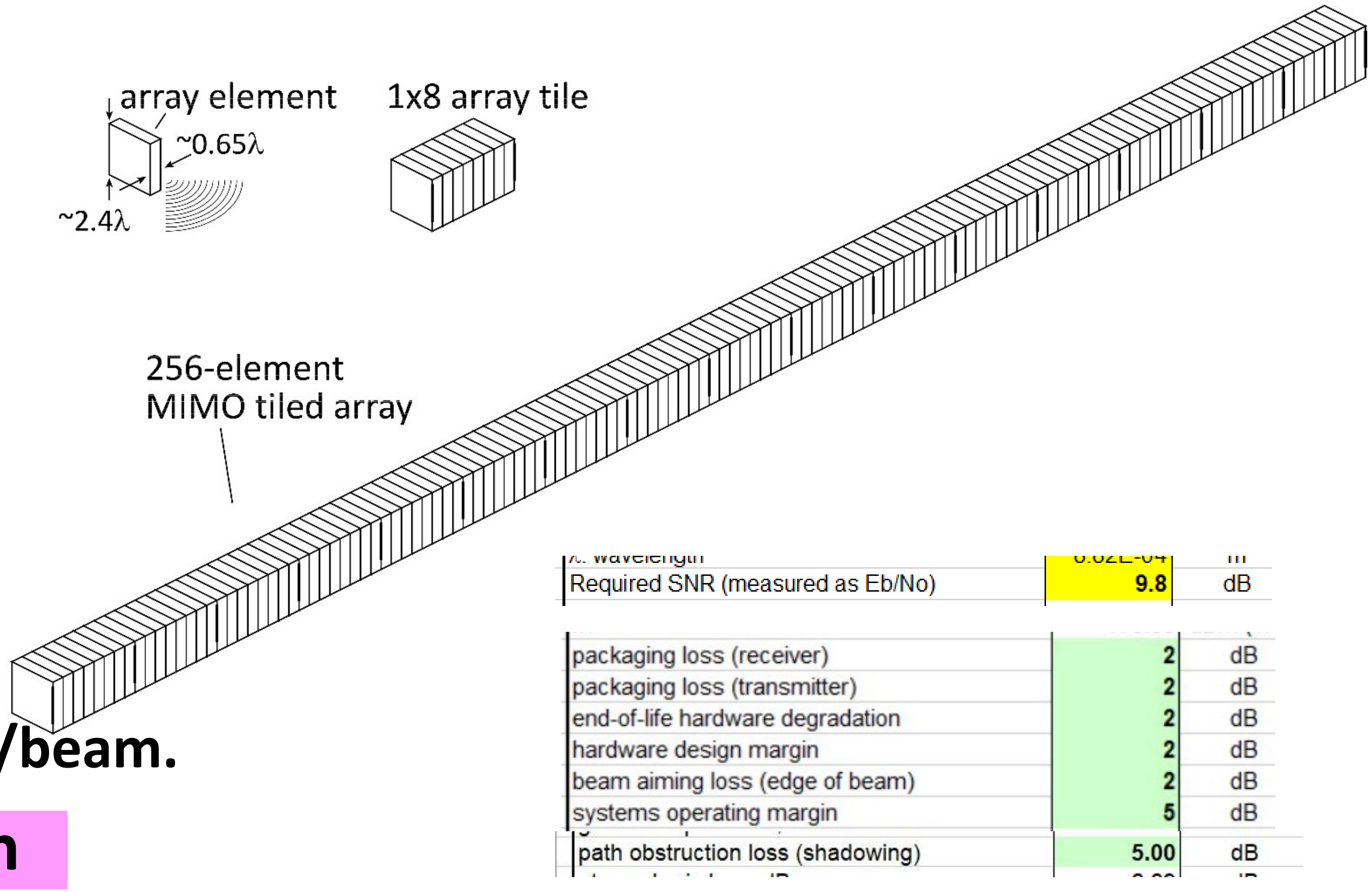
Link budget is feasible, but...

Required component dynamic range ?

Required complexity of back-end beamformer ?

140 GHz spatially multiplexed base station





Required SNR (measured as Eb/No)	9.8	dB
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
path obstruction loss (shadowing)	5.00	dB

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

225 meters range in 50 mm/hr rain

Realistic packaging loss, operating & design margins (20dB total)

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

LNAs: 3 dB noise figure

75 GHz spatially multiplexed base station

Suppose we instead use a 75GHz carrier:

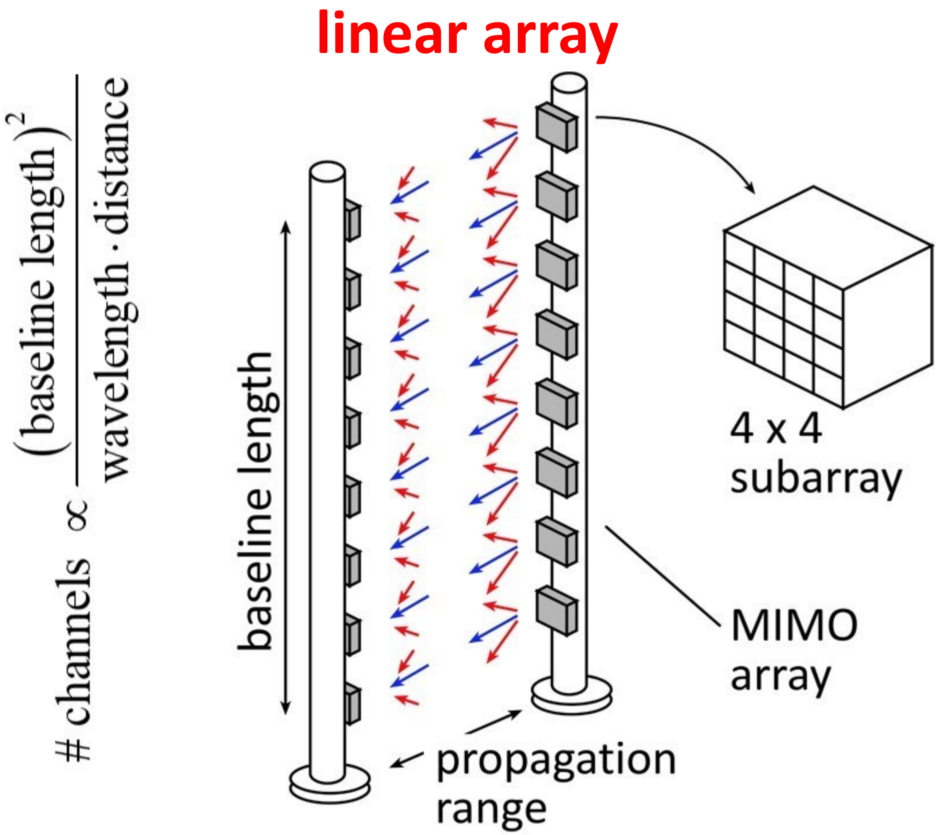
keep the handset the same size: 8mm×8mm (4×4)
keep the same # base station array elements
→ same Friss transmission losses
Also: same 4-9's foul-weather losses

Then:

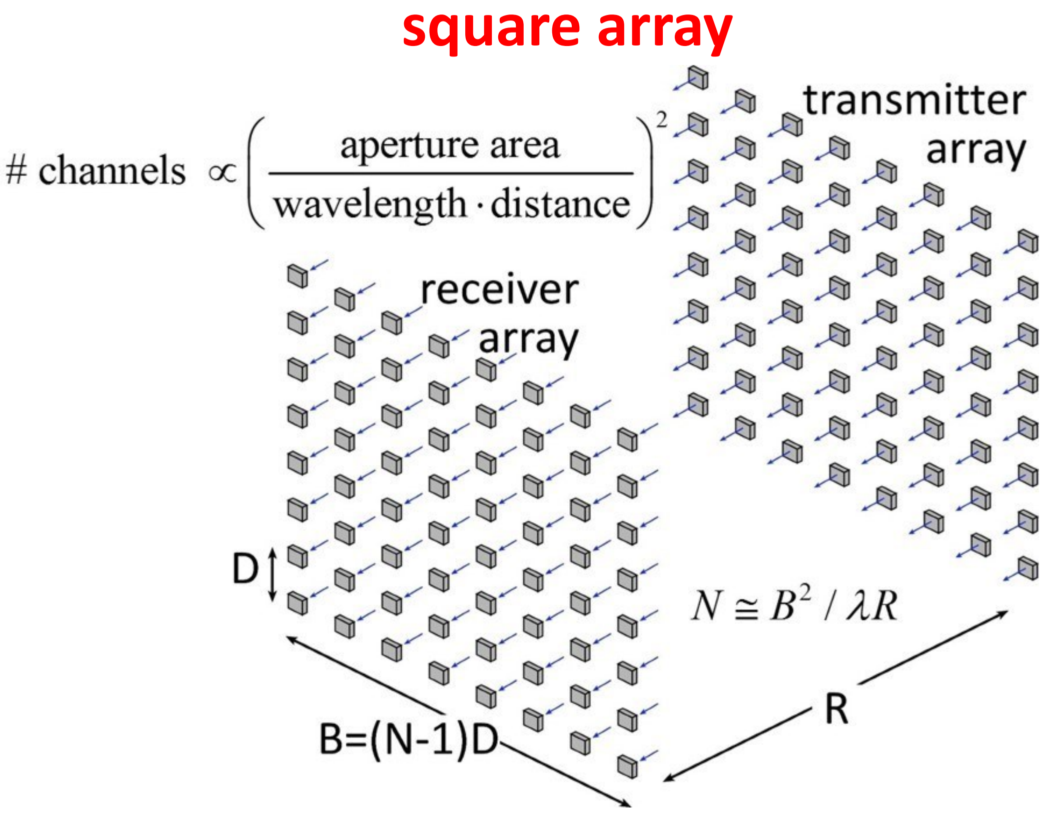
almost the same range (210 meters vs. 225 meters)
larger array dimensions 9mm×655mm (vs. 5mm×350mm)

but, today 75GHz ICs are easier than 140GHz ICs…

340 GHz (or even 650 GHz) backhaul



linear array



square array

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

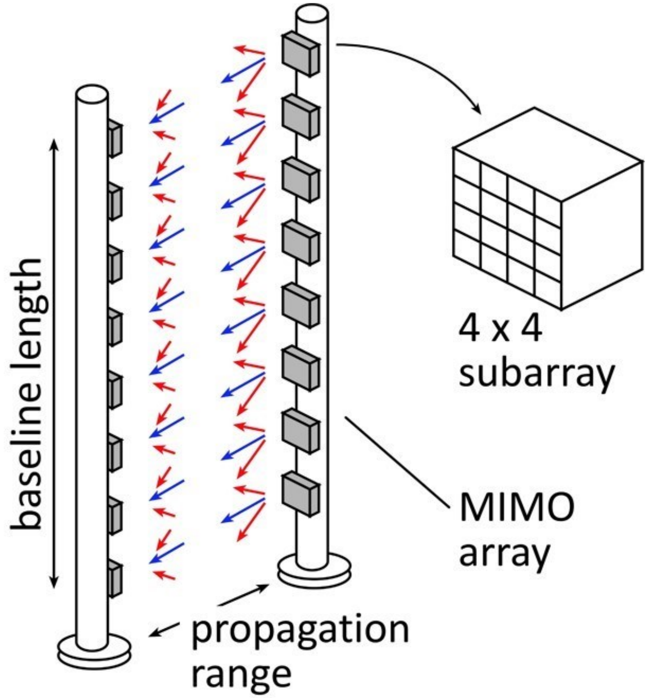
wireless @ optical speed; link network where fiber is too expensive to place.

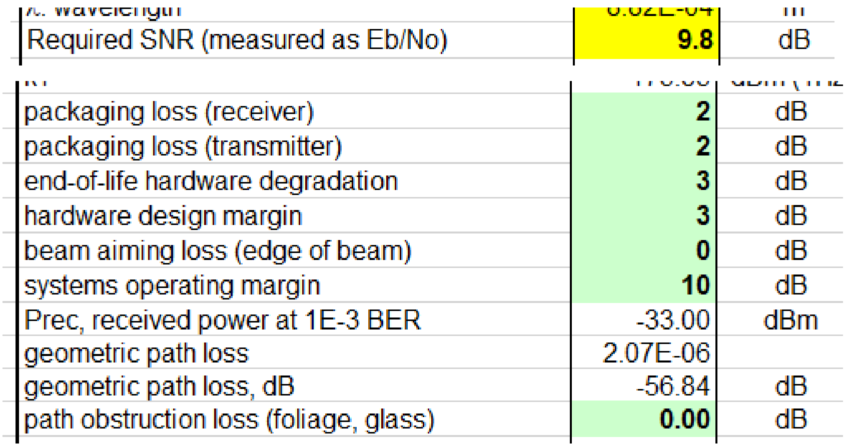
340 GHz: 640Gb/s @ 500 meters range; 1.6 meter linear array **(5Tb/s for 8×8 square array)**.

650 GHz: 1.28Tb/s @ 500 meter range; 1.6 meter linear array.

Capacity doubles again if we use both polarizations.

340 GHz 640 Gb/s MIMO backhaul





Required SNR (measured as Eb/No)	9.8	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)	0	dB
systems operating margin	10	dB
Prec, received power at 1E-3 BER	-33.00	dBm
geometric path loss	2.07E-06	
geometric path loss, dB	-56.84	dB
path obstruction loss (foliage, glass)	0.00	dB

1.6m MIMO array: 8-elements, each 80 Gb/s QPSK; 640Gb/s total

4 × 4 sub-arrays → 8 degree beamsteering

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

Realistic packaging loss, operating & design margins

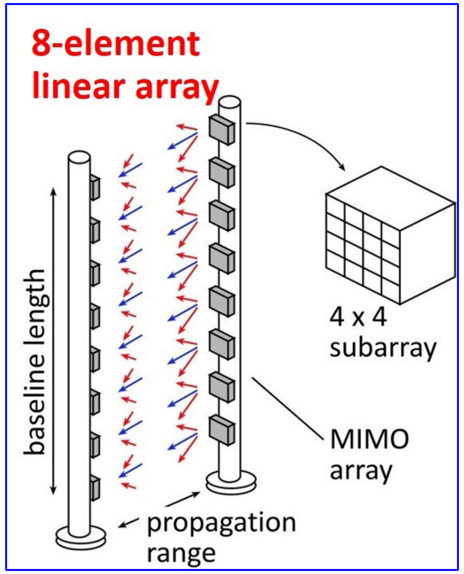
PAs: 82mW P_{out} (per element)

LNAs: 4 dB noise figure

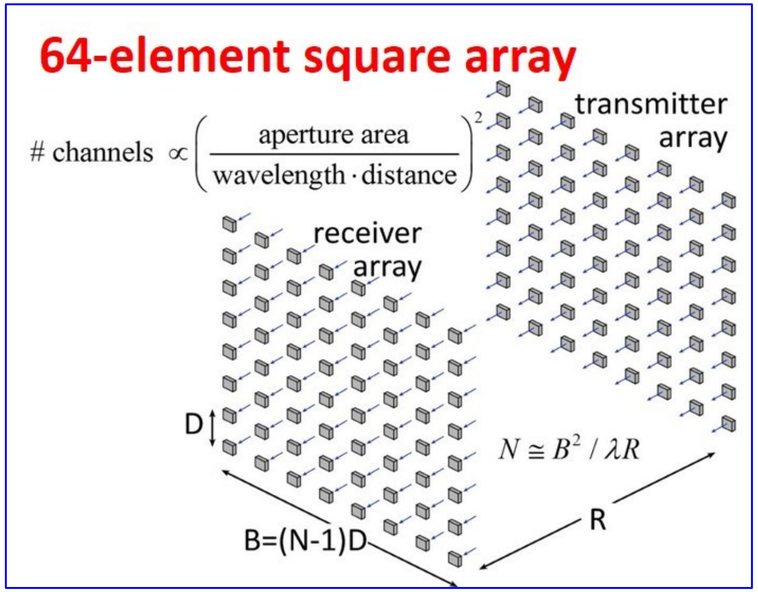
340 GHz 5 Tb/s MIMO backhaul

500m range in 50mm/hr. rain.

8-element 640Gb/s linear array:
requires 80mW power/element
requires 1.6m linear array



8-element 5Tb/s square array:
same link assumptions
requires 10mW power/element
...10W total radiated power
requires 1.6m square array



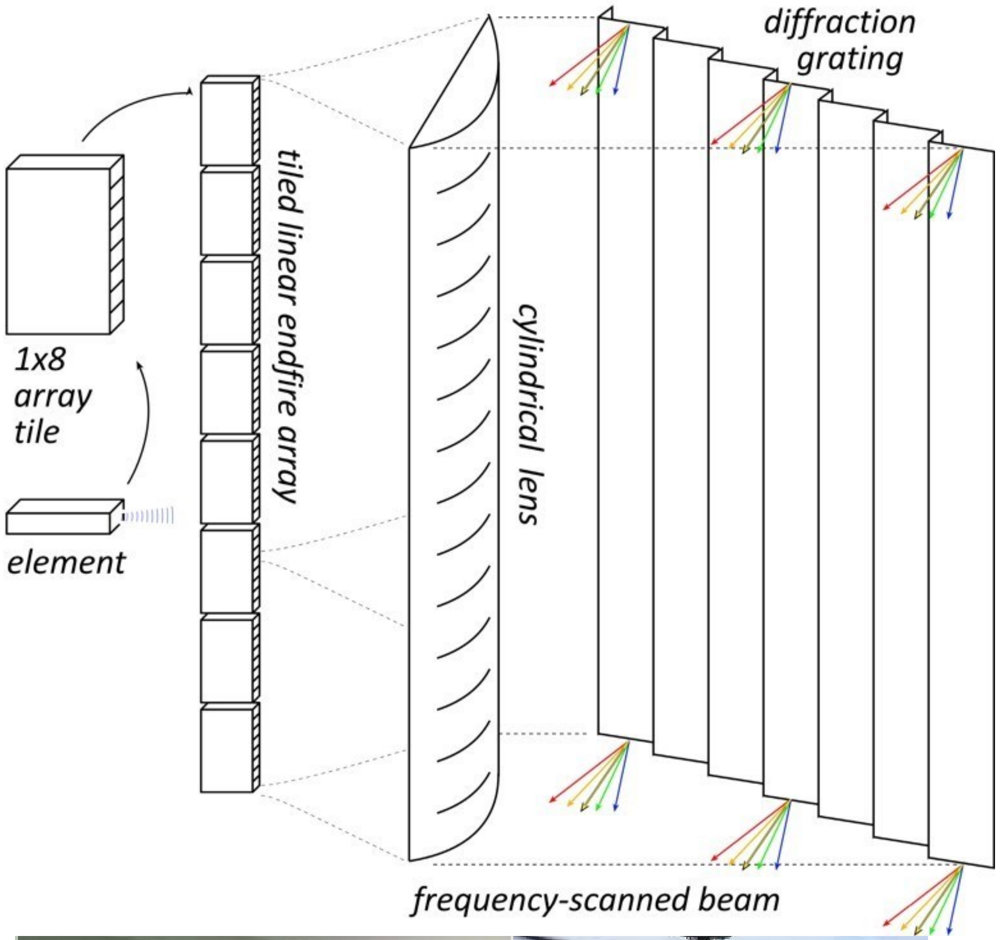
340 GHz frequency-scanned imaging car radar

Imaging for cars, aircraft
drive safely @ 65MPH in heavy fog
fly in heavy dust/fog/smoke

Short wavelengths:
HDTV-resolution imaging,
small: helicopter, drone, car

The challenge: complexity
standard array: # pixels = # RF channels
HDTV image: ~2×10^6 pixels.
Need 2×10^6 RF channels !

Hardware-efficient imaging
RF channels << # pixels
several techniques



340 GHz frequency-scanned imaging car radar

See a soccer ball at 300 meters in heavy fog
(10 seconds warning @ 100 km/hr.)
(5 dB SNR, 35 dB/km, 30cm diameter target, 10% reflectivity)

Image refresh rate: 60 Hz

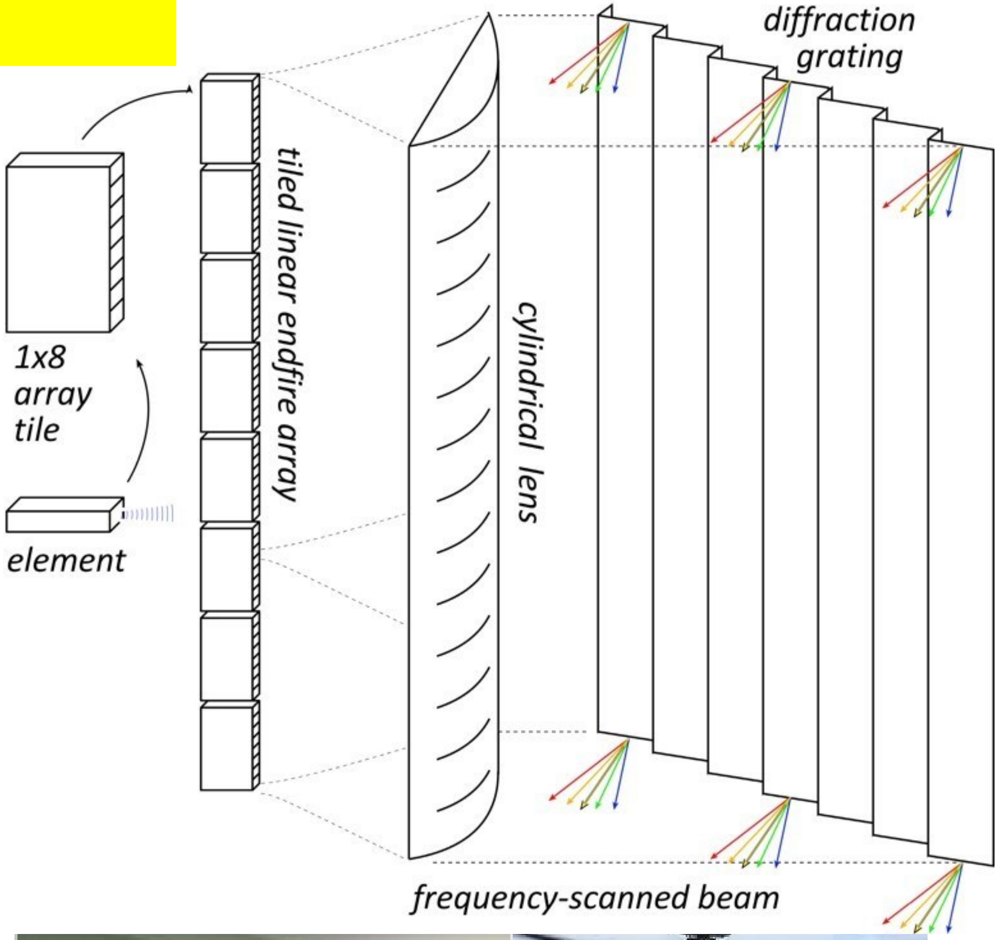
Resolution 64×512 pixels

Angular resolution: 0.14 degrees

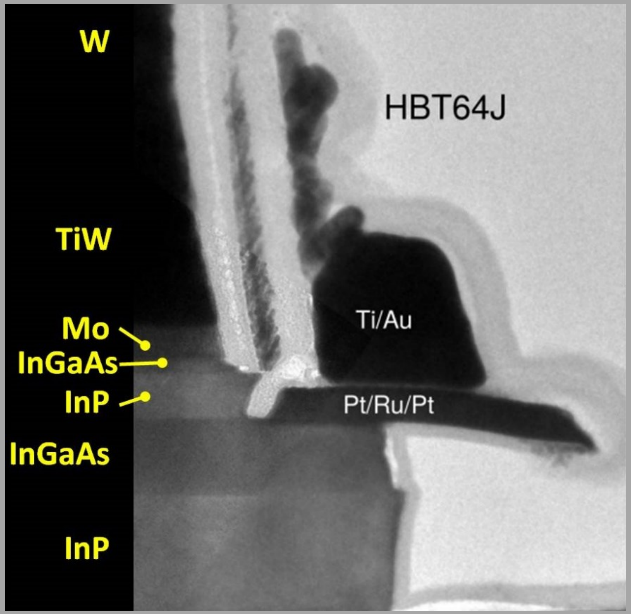
Angular field of view: 9 by 73 degrees

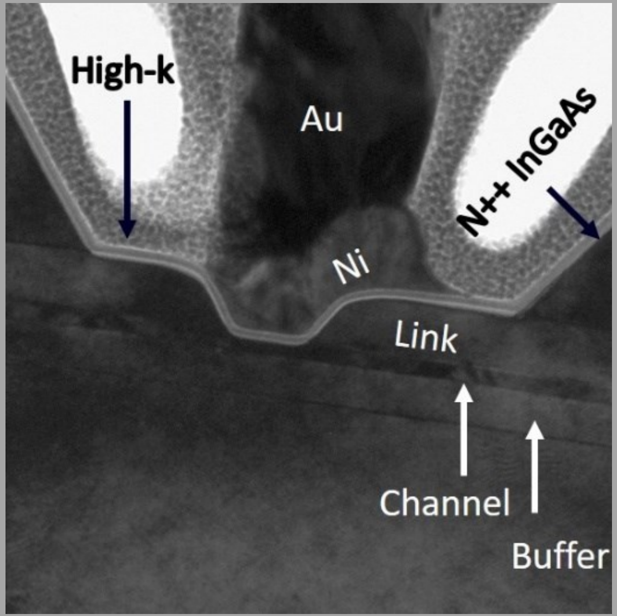
Aperture: 35 cm by 35 cm

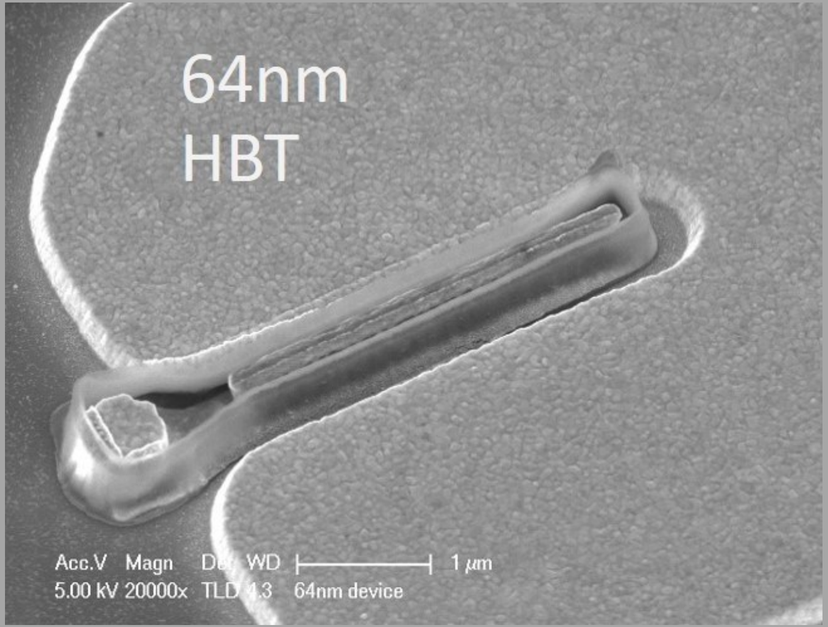
Component requirements:
44 mW peak power/element,
3% pulse duty factor
6 dB noise figure,
3 dB package losses (each: trx, rcvr)
5 dB manufacturing/aging margin



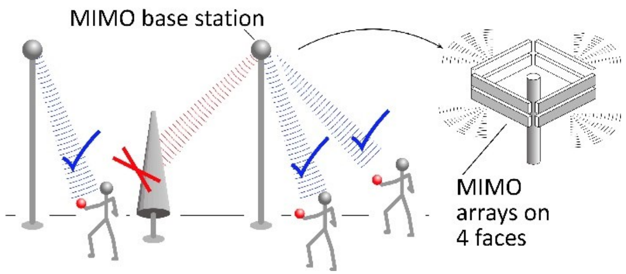
Transistors

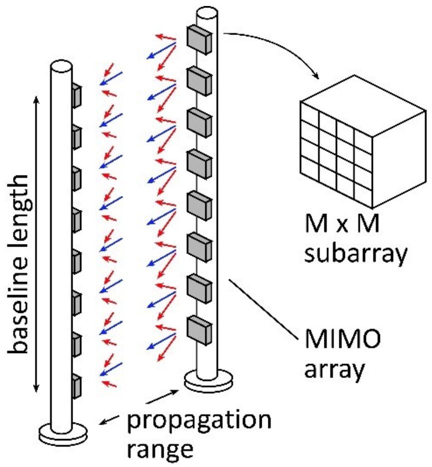


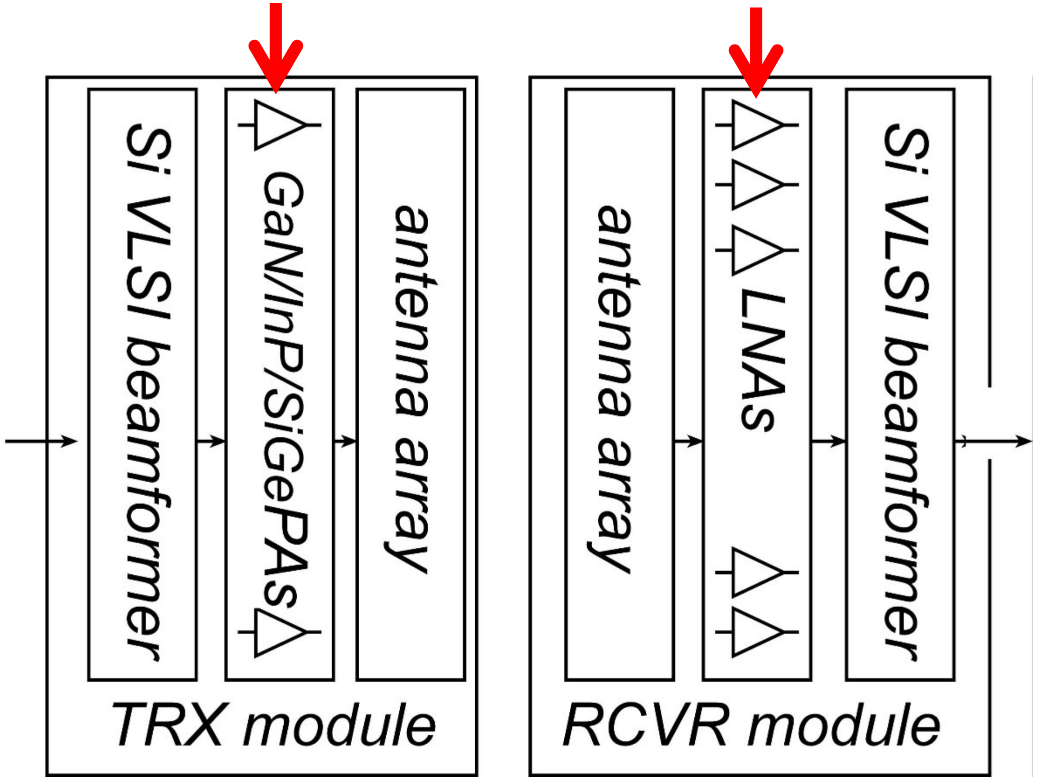




mm-Wave Wireless Transceiver Architecture







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

...similar to today's cell phones.

100-1000 GHz transistors and ICs

	f_{max} GHz	Good ICs to (GHz)	complexity	LNAs	PAS	increased bandwidth ?
CMOS	350	150/200	multichannel transceivers	ok	poor: 1-5 mW	not looking good
Production SiGe	300	200/250	multichannel transceivers	good	OK: 20-100 mW	depends on $$
R&D SiGe	700	300/500	multichannel transceivers	good	OK: 20-100 mW	2-3THz
R&D InP HBT	1150	400/650	PA, frequency converters	poor	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

CNT, 2D, plasmonics etc. : no evidence or theory suggesting that these are useful or superior for 100-2000GHz

ICs with useful performance, hero experiments

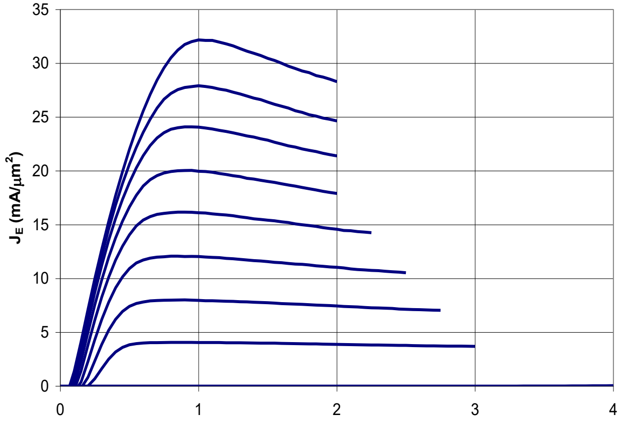
THz transistors exist today; further R&D will further extend their bandwidth

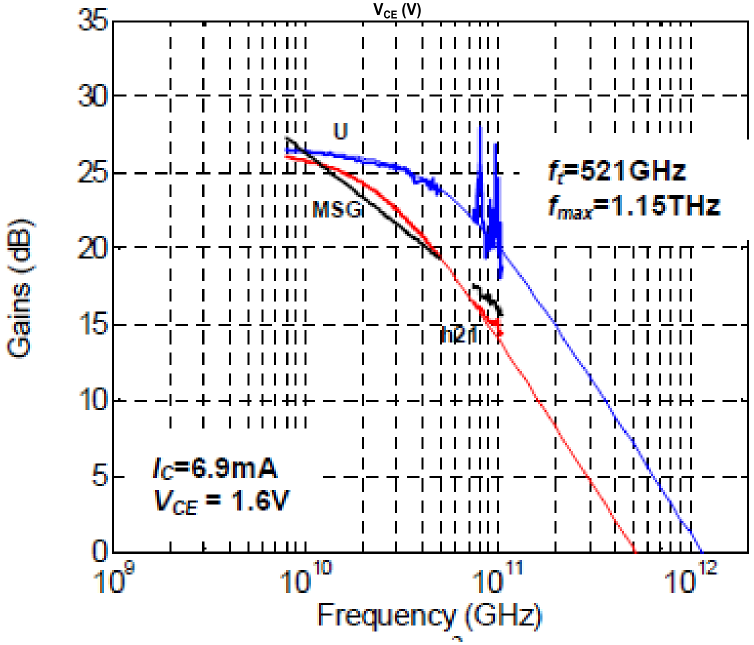
The challenge: driving the (reduced cost→ larger market→ reduced cost) cycle

130nm / 1.1THz InP HBT Technology

1.1THz f_{max} HBT,
3.5 V breakdown

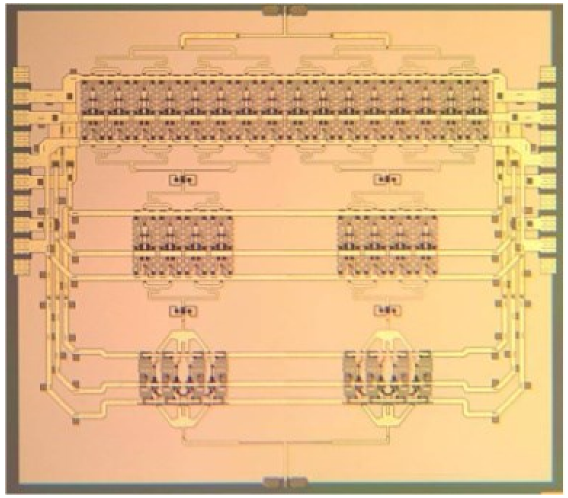
Teledyne/UCSB: M. Urteaga et al: 2011 DRC





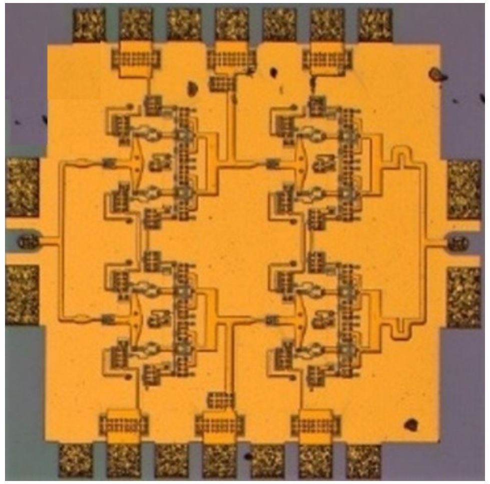
220 GHz, 0.18W
power amplifier

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



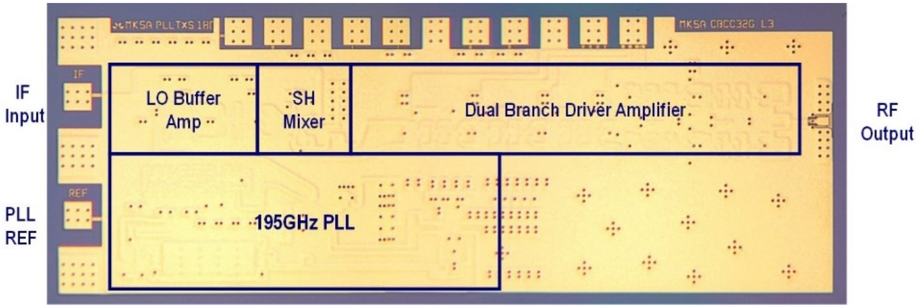
325 GHz, 16mW
power amplifier

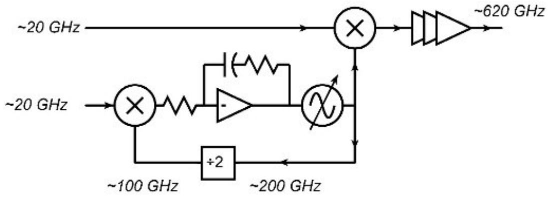
UCSB/Teledyne:
A. Ahmed, 2018 EuMIC Symp.



Integrated ~600GHz transmitter

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



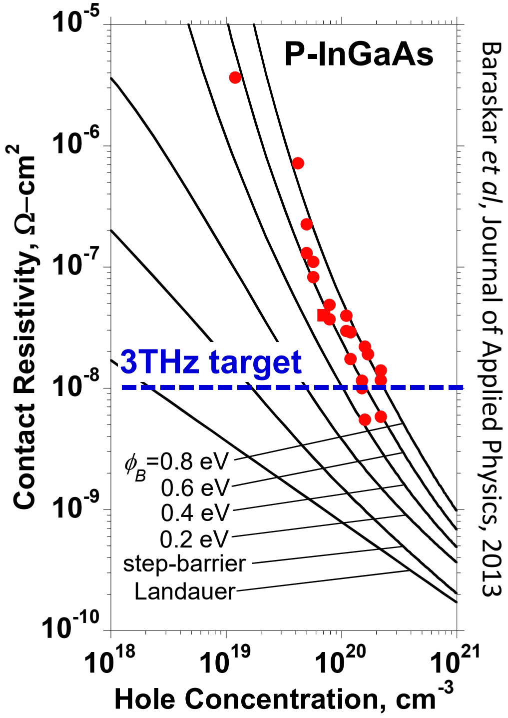


Challenges at the 64nm/2THz & 32nm/3THz Nodes

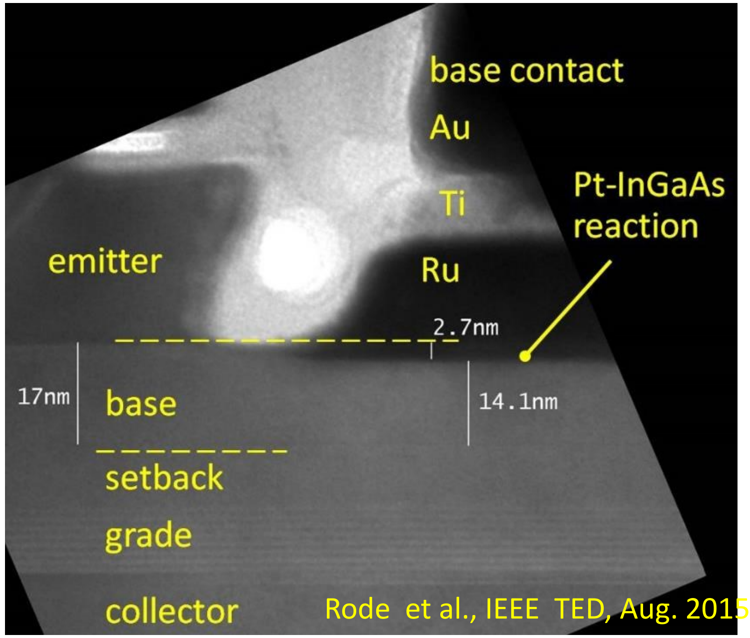
Need high base contact doping
$>10^{20}/\text{cm}^3$ for good contacts
high Auger recombination
very low β.

Need moderate contact penetration
Pd or Pt contacts
react with 3++ nm of base
penetrate surface contaminants
too deep for thin base

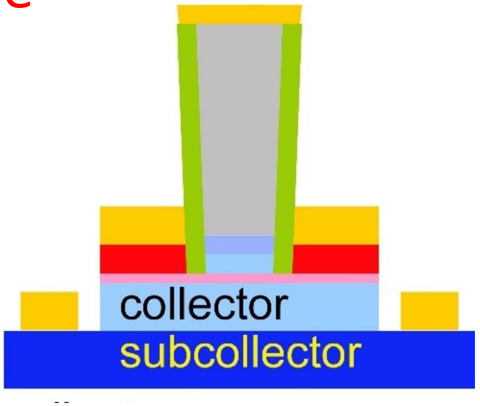
Solution: base regrowth:
thin, moderately-doped intrinsic base
thick, heavily-doped extrinsic base

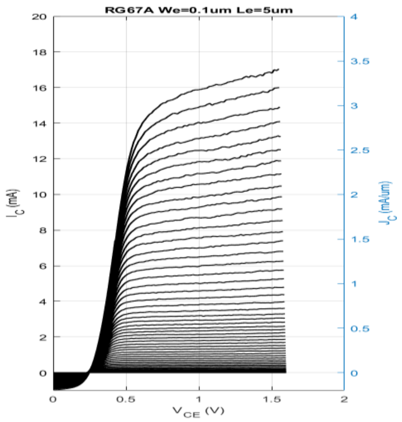


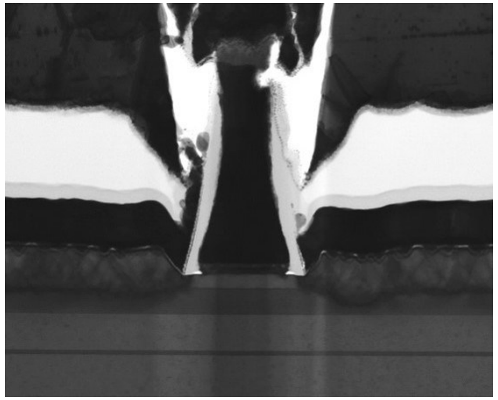
Baraskar *et al*, Journal of Applied Physics, 2013



Rode et al., IEEE TED, Aug. 2015



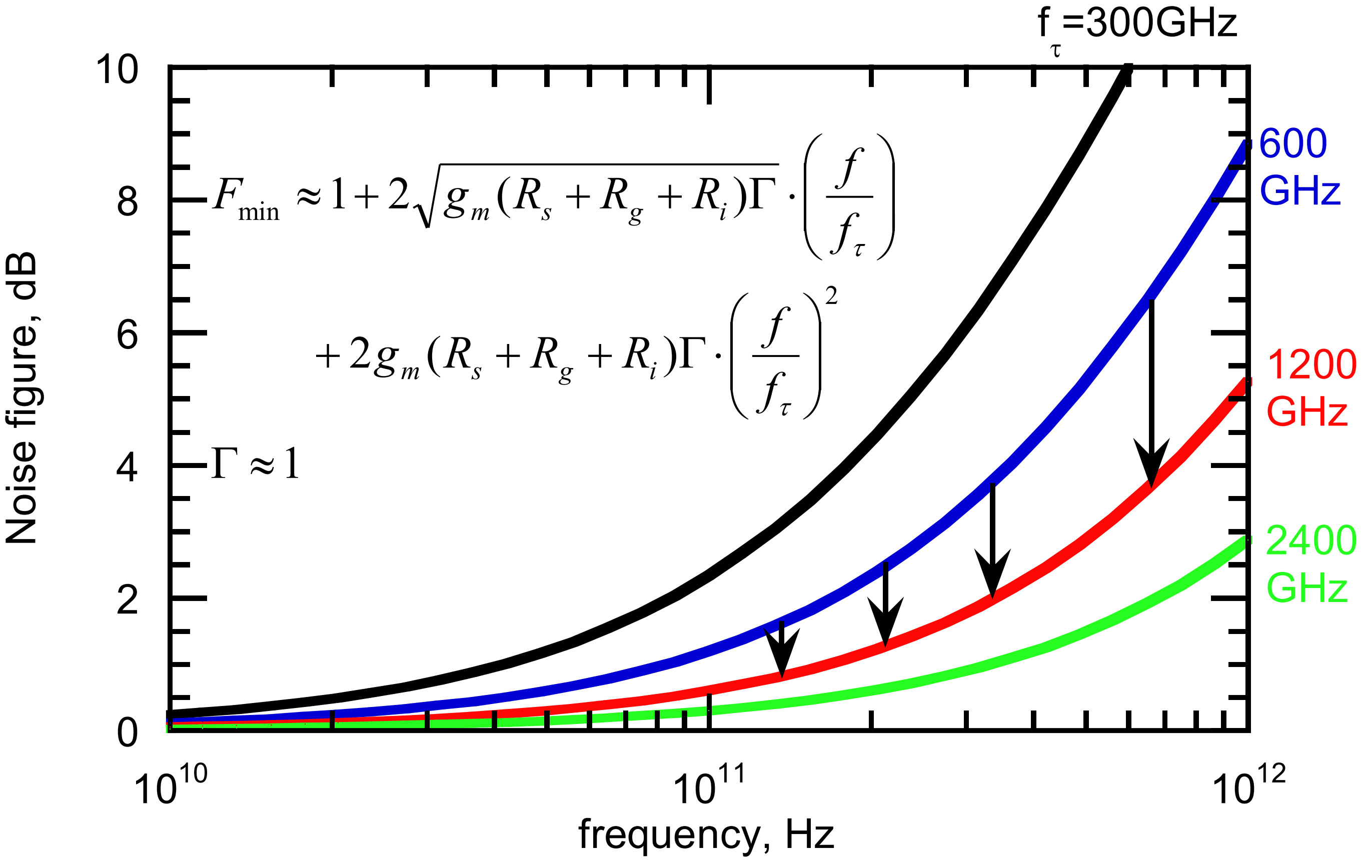


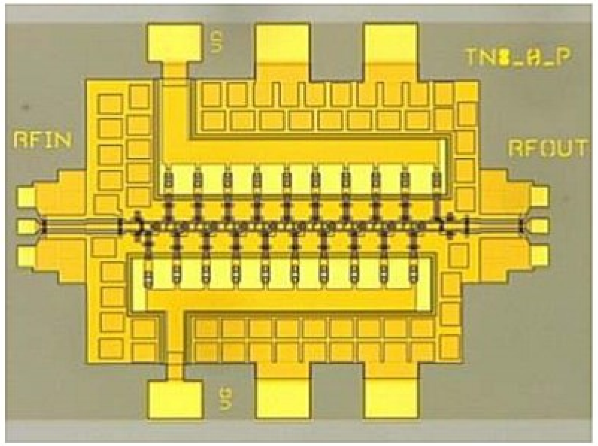


FETs (HEMTs): key for low noise

2:1 to 4:1 increase in f_τ :
improved noise
less required transmit power
smaller PAs, less DC power

or higher-frequency systems





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)**

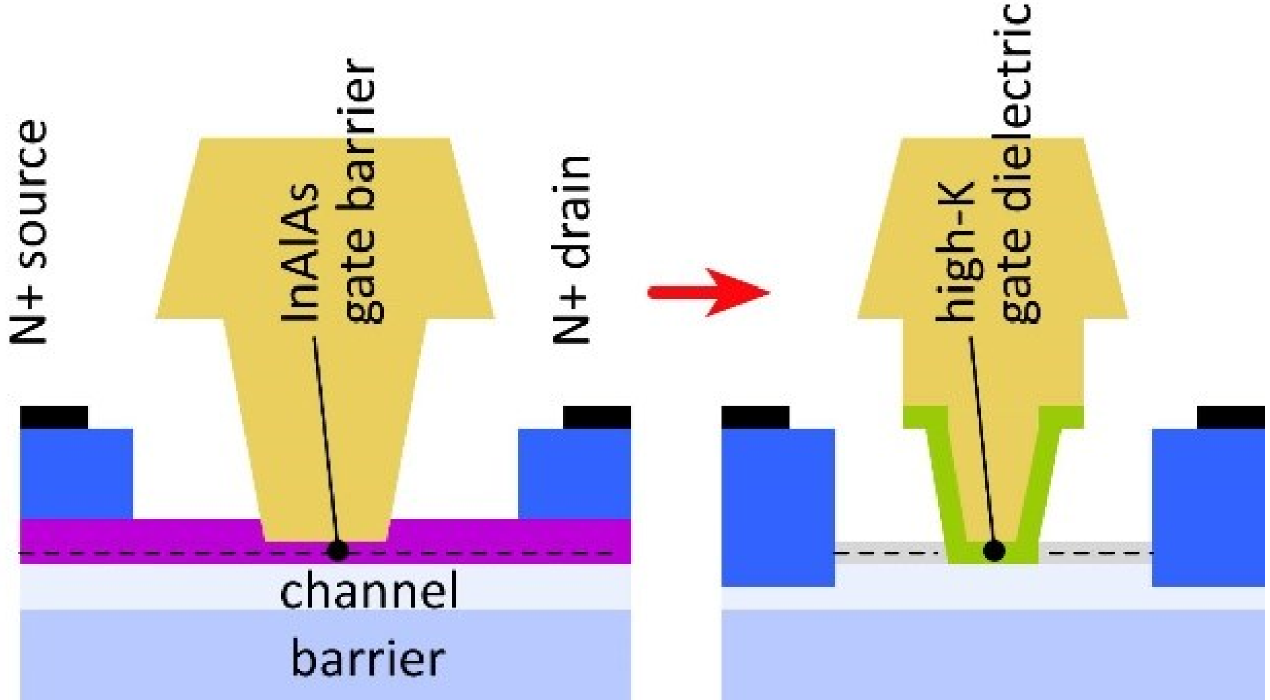
Towards faster HEMTs: MOS-HEMTs

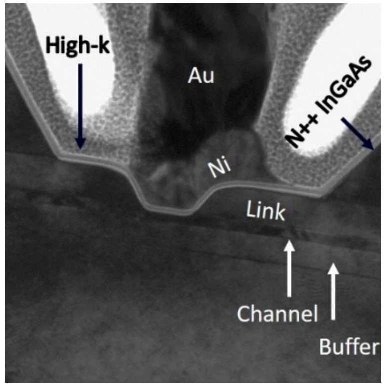
1st demonstration: Fraunhofer IAF

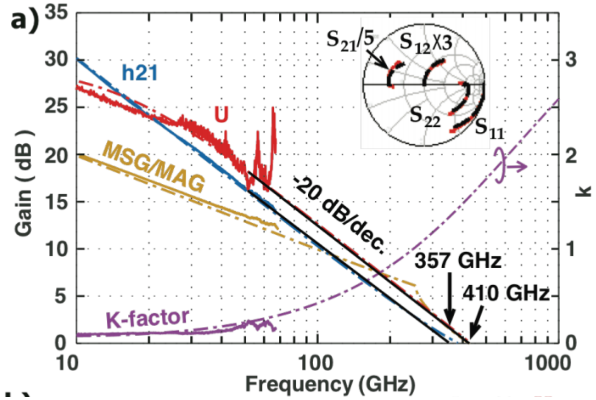
Scaling limit: gate insulator thickness
HEMT: InAlAs barrier: tunneling, thermionic leakage
solution: replace InAlAs with high-K dielectric
2nm ZrO_2 (ε_r=25): adequately low leakage

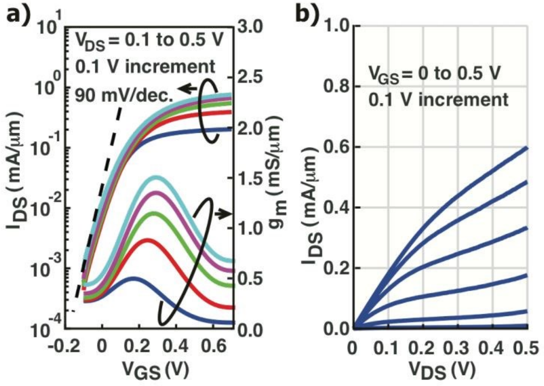
Scaling limit: source access resistance
HEMT: InAlAs barrier is under N+ source/drain
solution: regrowth, place N+ layer <u>on</u> InAs channel

Target ~10nm node
~0.3nm EOT, 3nm thick channel
1.2 to 1.5 THz f_τ.



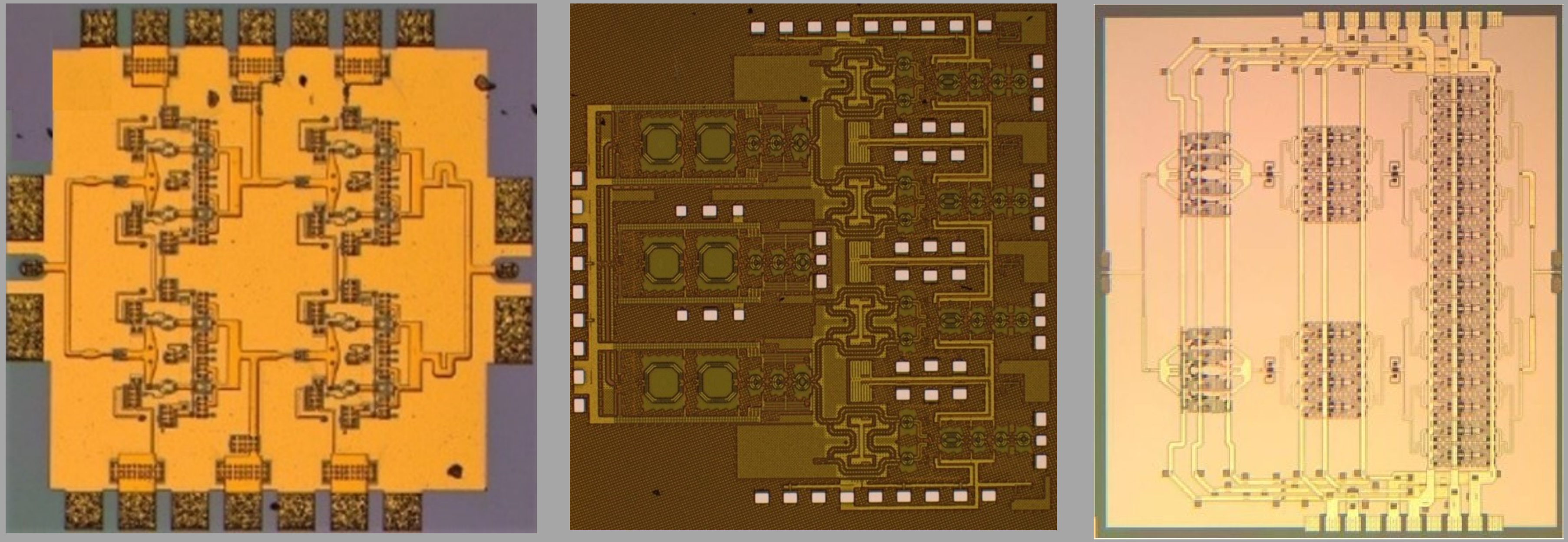






Jun Wu, UCSB, IEEE EDL, 2018

ICs



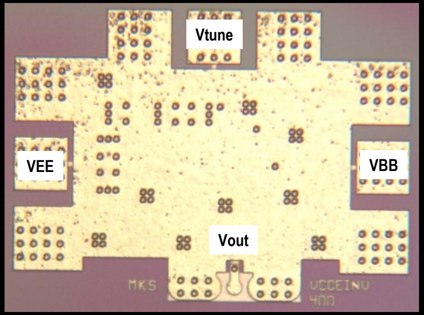
130nm / 1.1 THz InP HBT ICs to 670 GHz

TELEDYNE SCIENTIFIC COMPANY
A Teledyne Technologies Company

UCSB

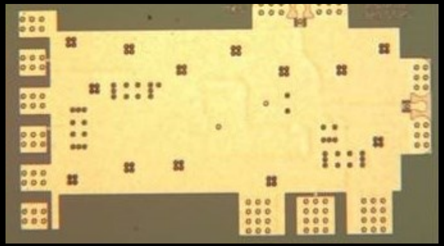
614 GHz fundamental VCO

M. Seo, TSC / UCSB



340 GHz dynamic frequency divider

M. Seo, UCSB/TSC
IMS 2010



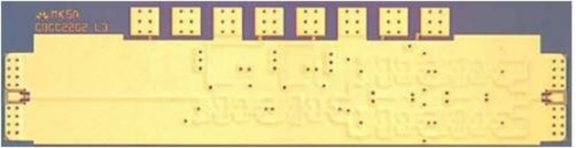
530 GHz dynamic frequency divider

M. Seo, TSC
IEICE letter 2015

620 GHz, 20 dB gain amplifier

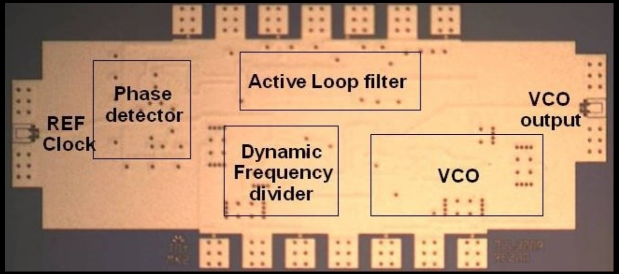
M Seo, TSC
IMS 2013

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



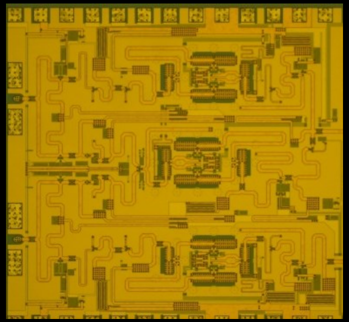
300 GHz fundamental PLL

M. Seo, TSC
IMS 2011



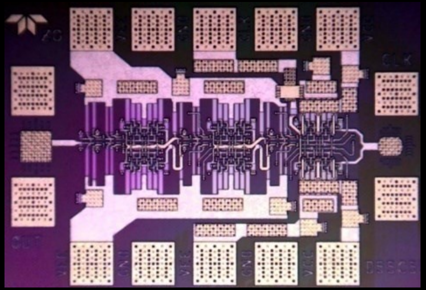
94 GHz ultra low power phased-array pixel

S-K. Kim, UCSB
IEEE JSSC 2017



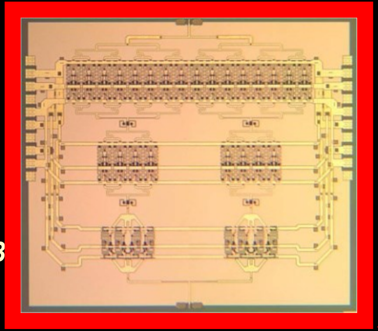
204 GHz static frequency divider (ECL master-slave latch)

Z. Griffith, TSC / UCSB
CSIC 2010



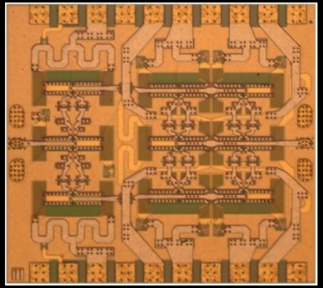
220 GHz 180 mW power amplifier

T. Reed, UCSB
CSICS 2013

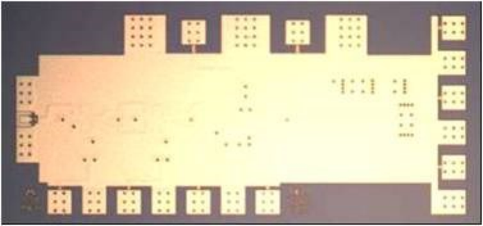


81 GHz 470 mW power amplifier

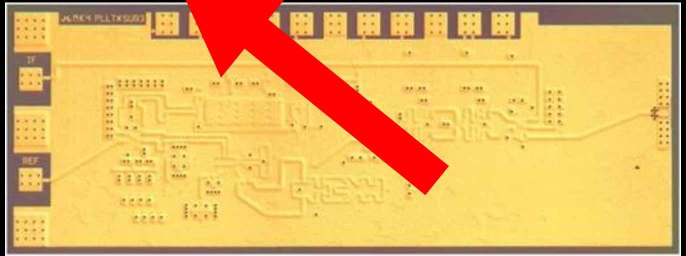
H-C Park UCSB
IMS 2014



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

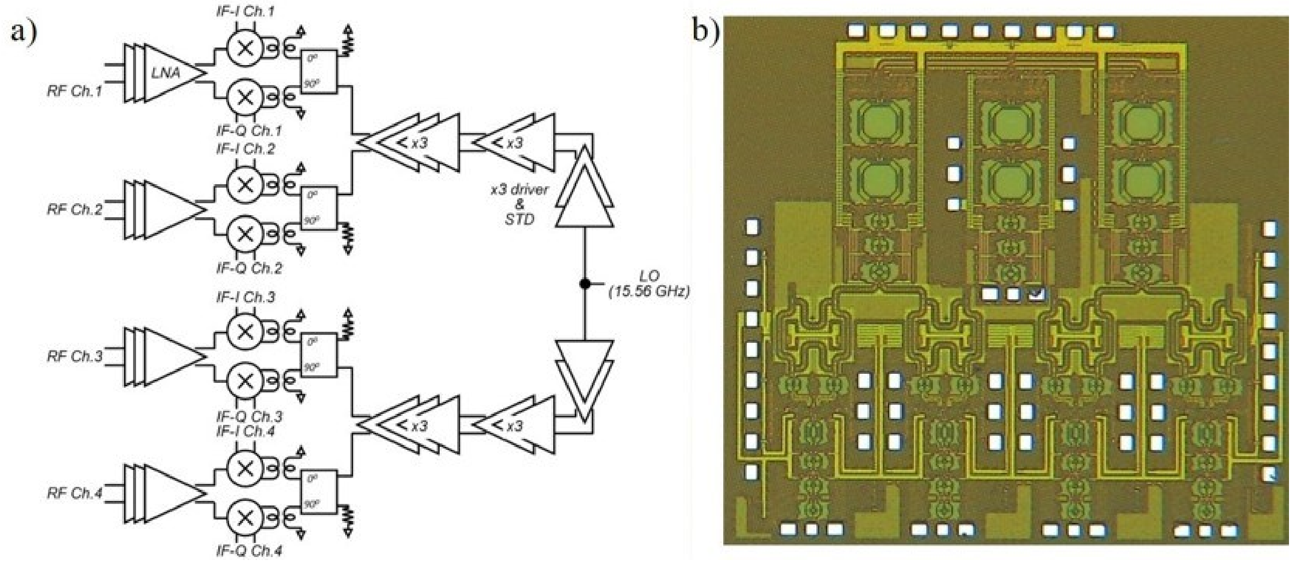


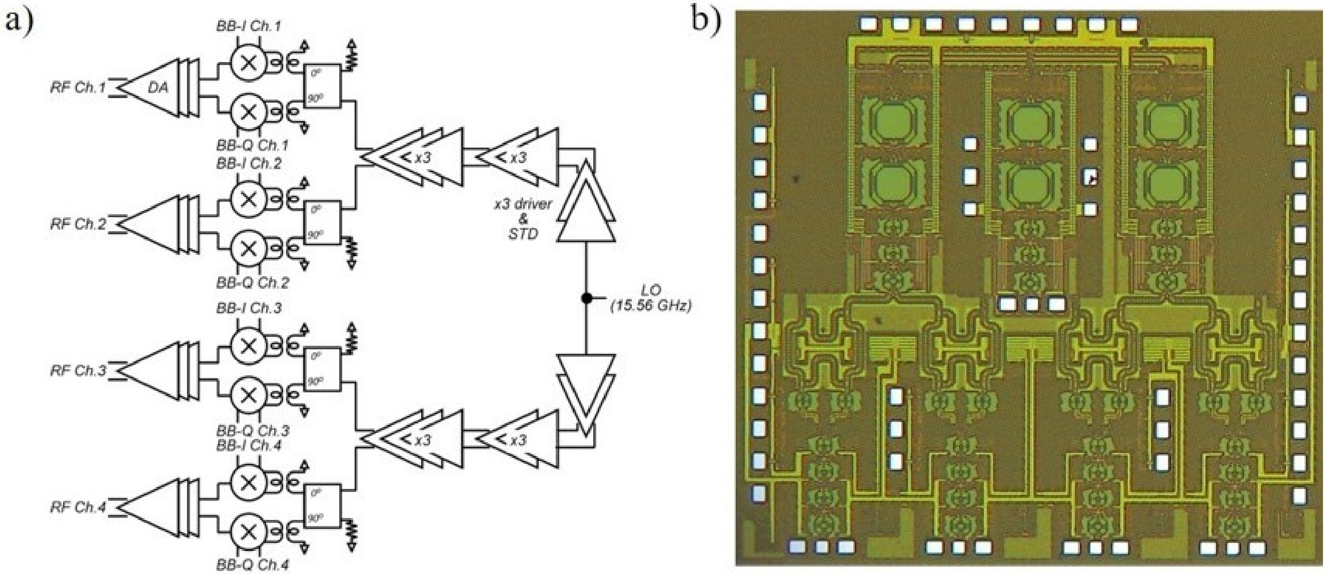
600 GHz Integrated Transmitter
PLL + Mixer
M. Seo TSC

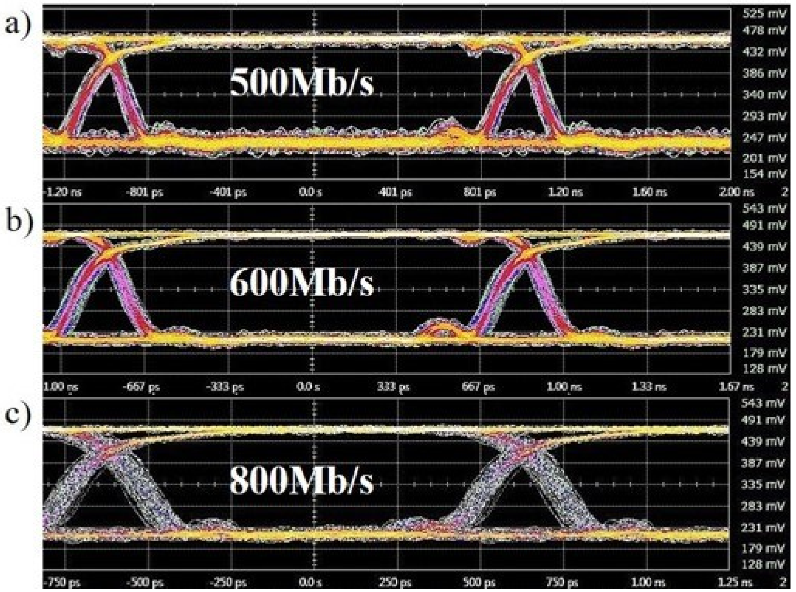


140GHz MIMO transceiver front-end ICs

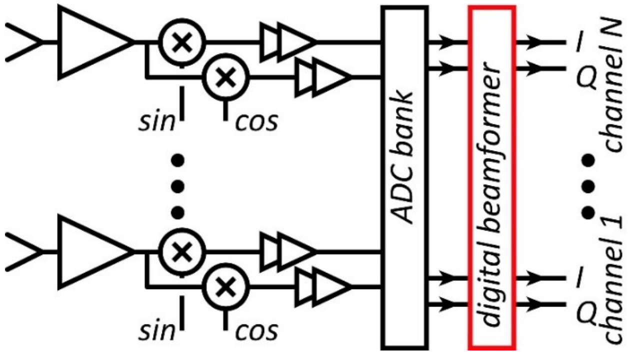
S. Lee, A. Simseck, UCSB, 2018 BCICTS, to be presented

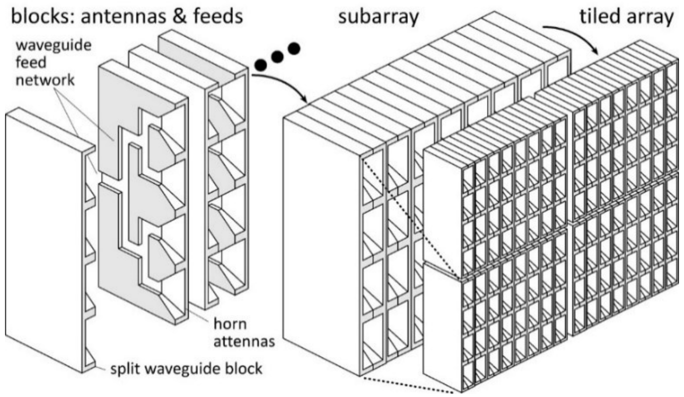




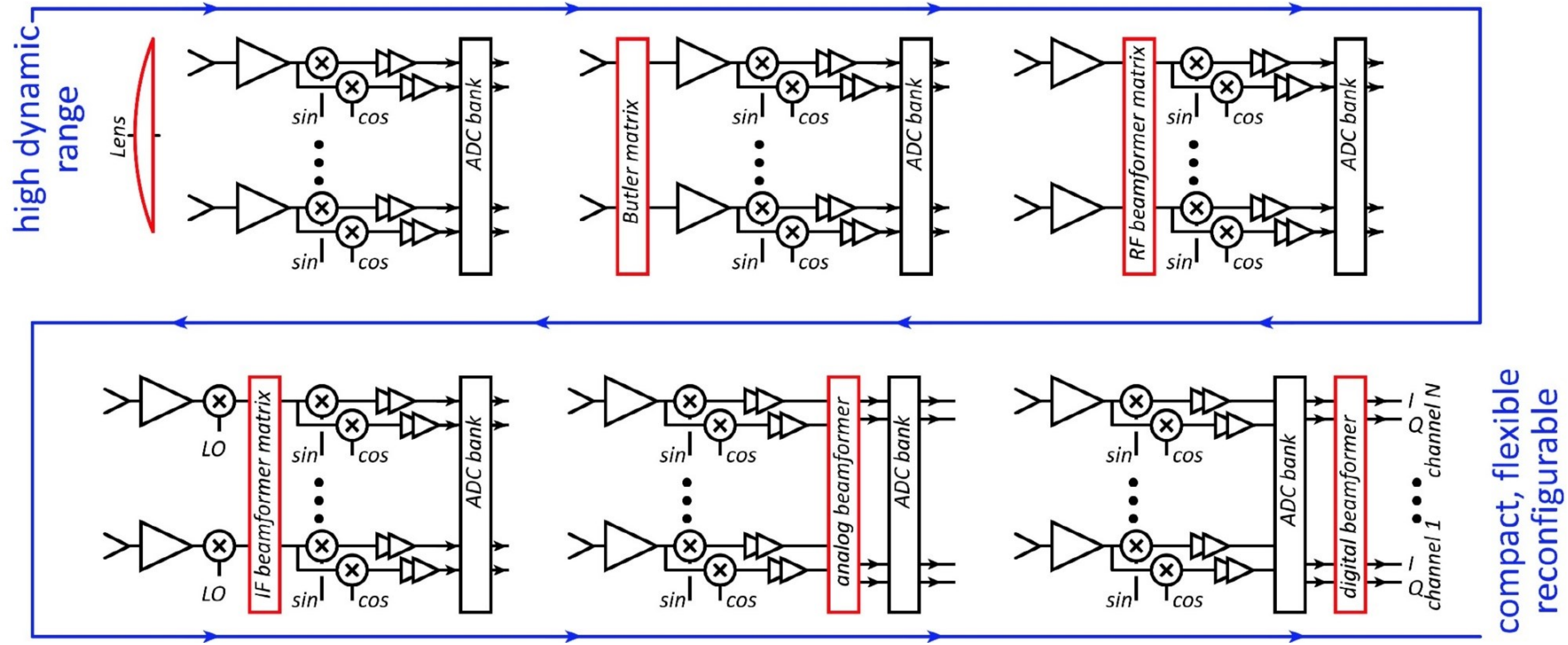


Systems & Packages





Beamforming for massive spatial multiplexing



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

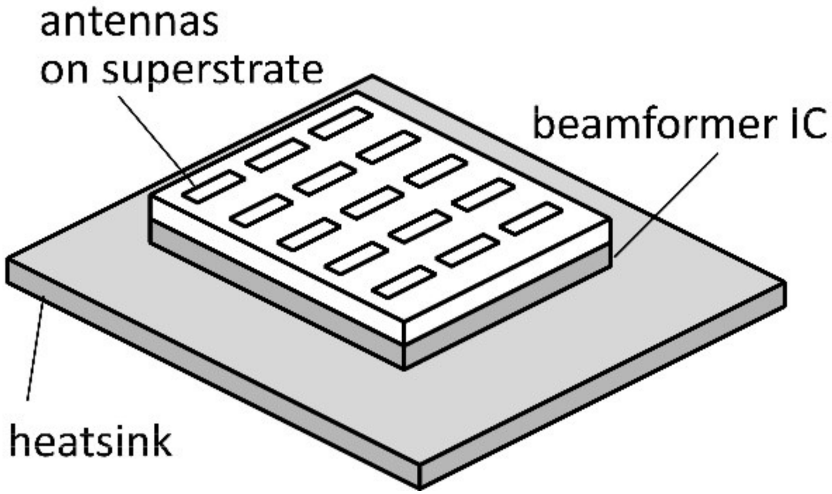
Pure RF beamforming: (focal plane, Butler matrixes, RF beamforming)
Established approach in DOD systems (high dynamic range). Issues of array tiling.

The mm-wave module design problem

How to make the IC electronics fit ?

$\lambda_0/2$ spacing= 1mm @ 150GHz

How to fit large power amplifier die ?



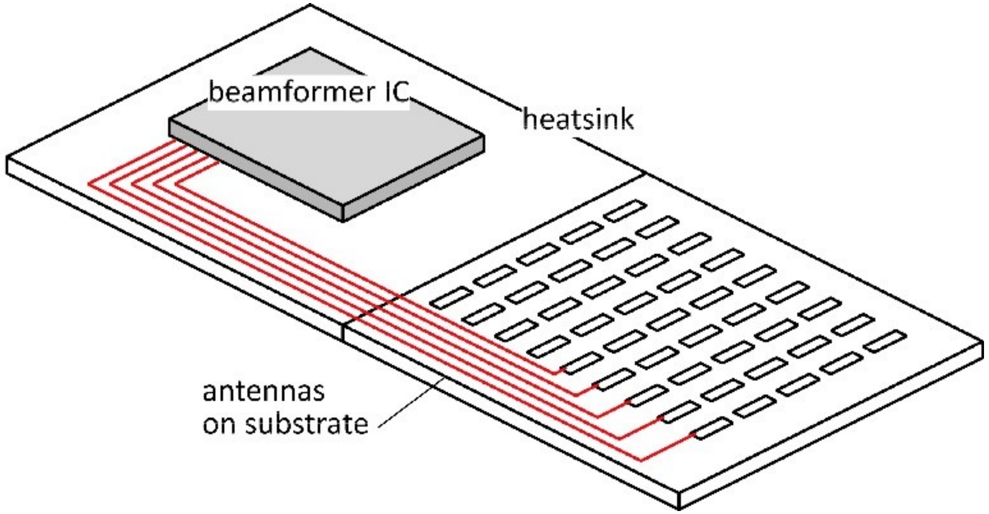
Catastrophic losses ?

Wire bonds, flip-chip bonds

If large apertures, losses on any long interconnects

How to remove the heat ?

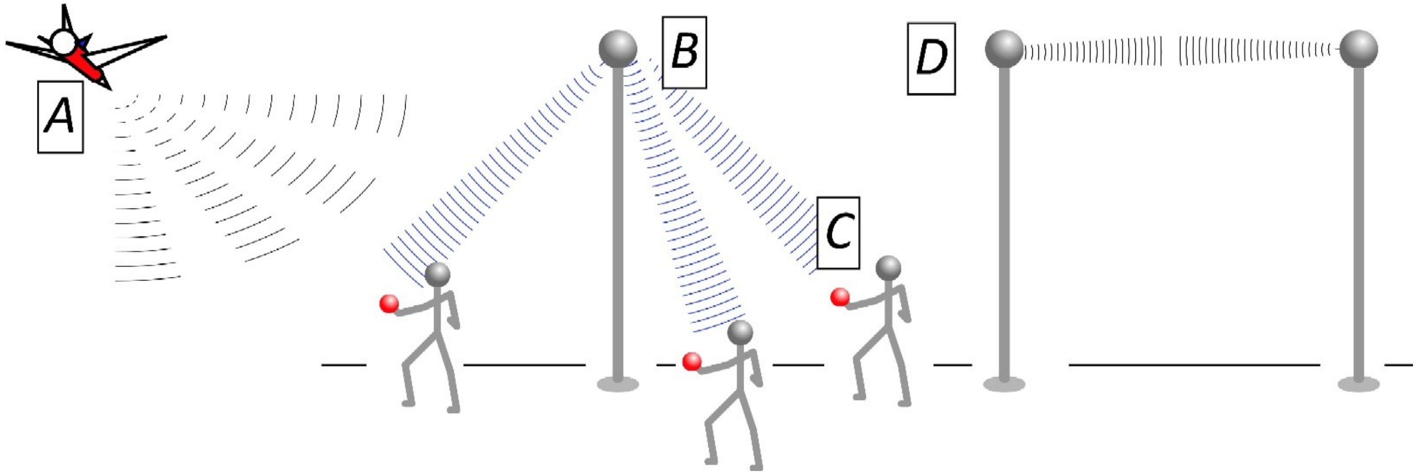
High power densities



mm-wave/sub-mm-wave packaging

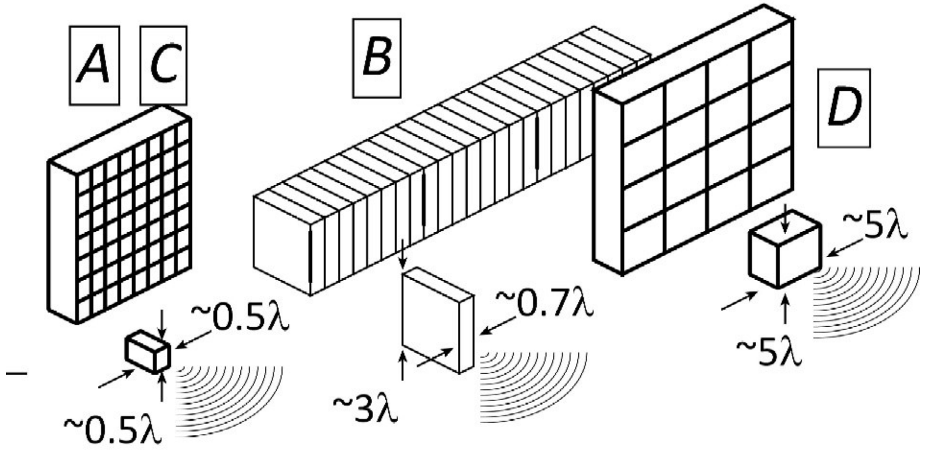
Not all systems steer in two planes...
...some steer in only one.

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

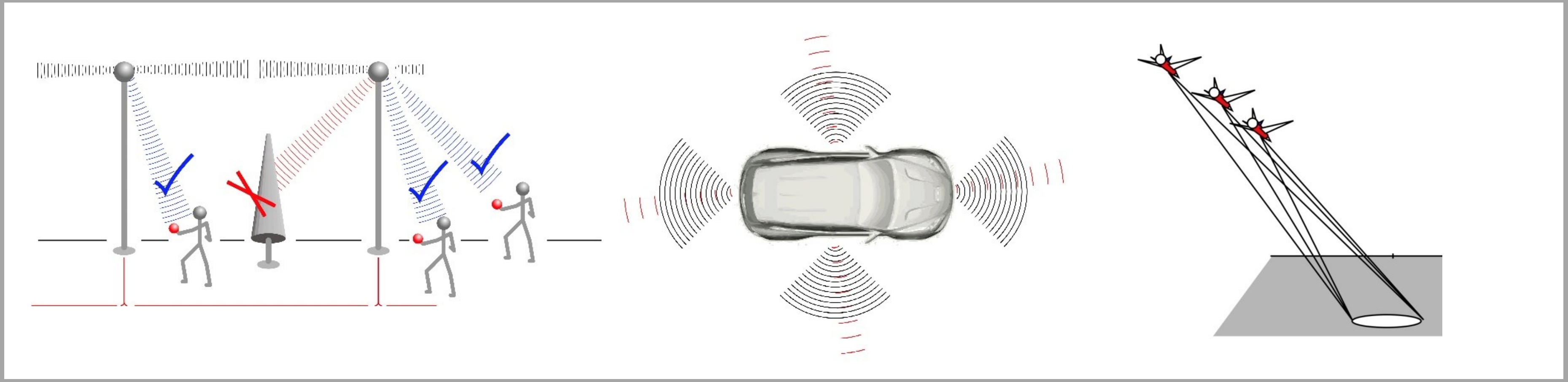


Arrays can often be linear (1D), instead of rectangular (2D)
Element spacing can often be greater than λ/2.

→ Array packaging then greatly simplified.



Wireless above 100GHz



Wireless above 100 GHz

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

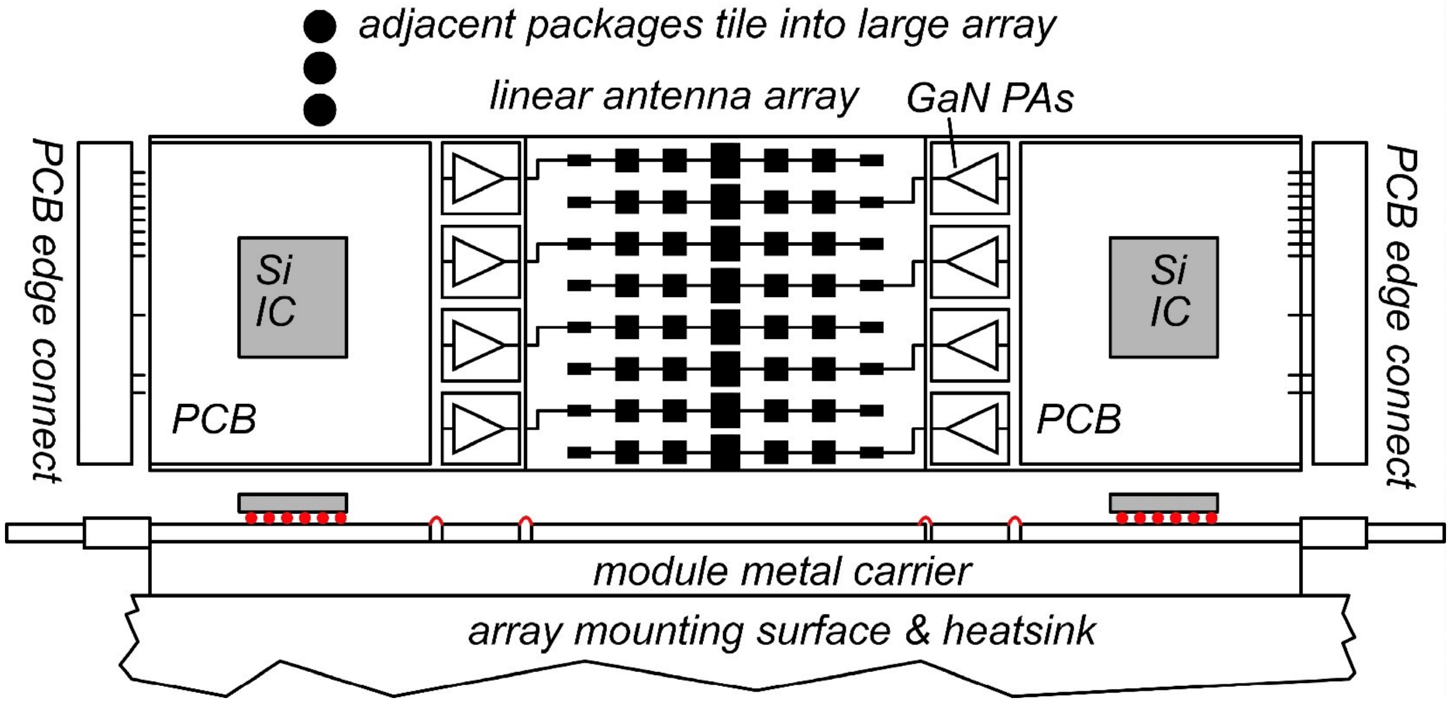
Very short range: few 100 meters
short wavelength, high atmospheric losses. Easily-blocked beams.

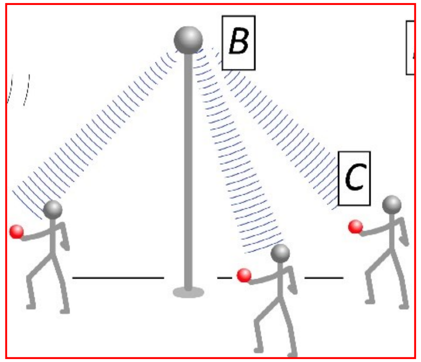
IC Technology
All-silicon for short ranges below 250 GHz.
III-V LNAs and PAs for longer-range links. Just like cell phones today
III-V frequency extenders for 340GHz and beyond

The challenges
spatial multiplexing: computational complexity, ~~dynamic range~~
packaging: fitting signal channels in very small areas

In case of questions

Concept: Tile for linear arrays



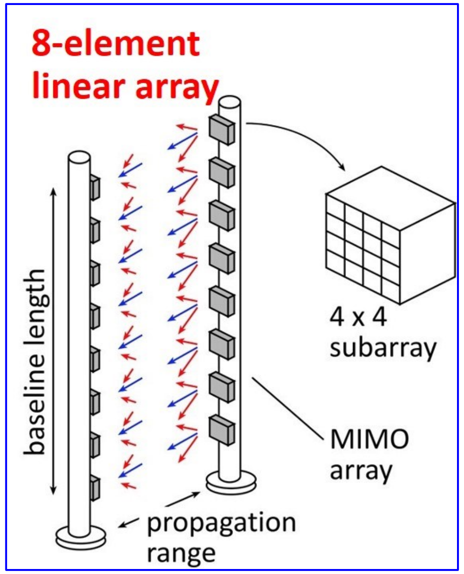


Terrestrial system: horizontal steering only→ linear array.
Space at edges of linear array: room for III-V PAs, LNAs.
Alternating-sides feed: 2mm pitch→ room for large GaN PAs.
Mounting directly on metal carrier→ heatsinking.

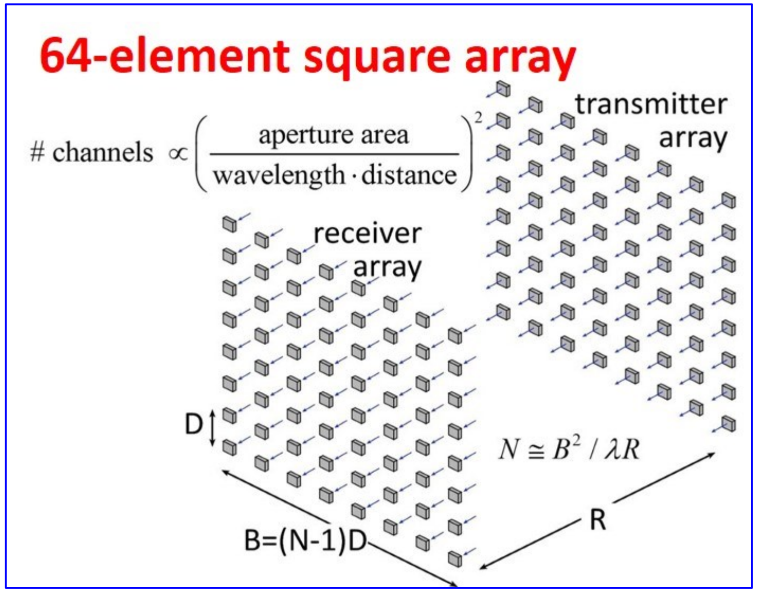
140 GHz, 640 Gb/s MIMO backhaul

Why not use a lower-frequency carrier, e.g. 140 GHz ?

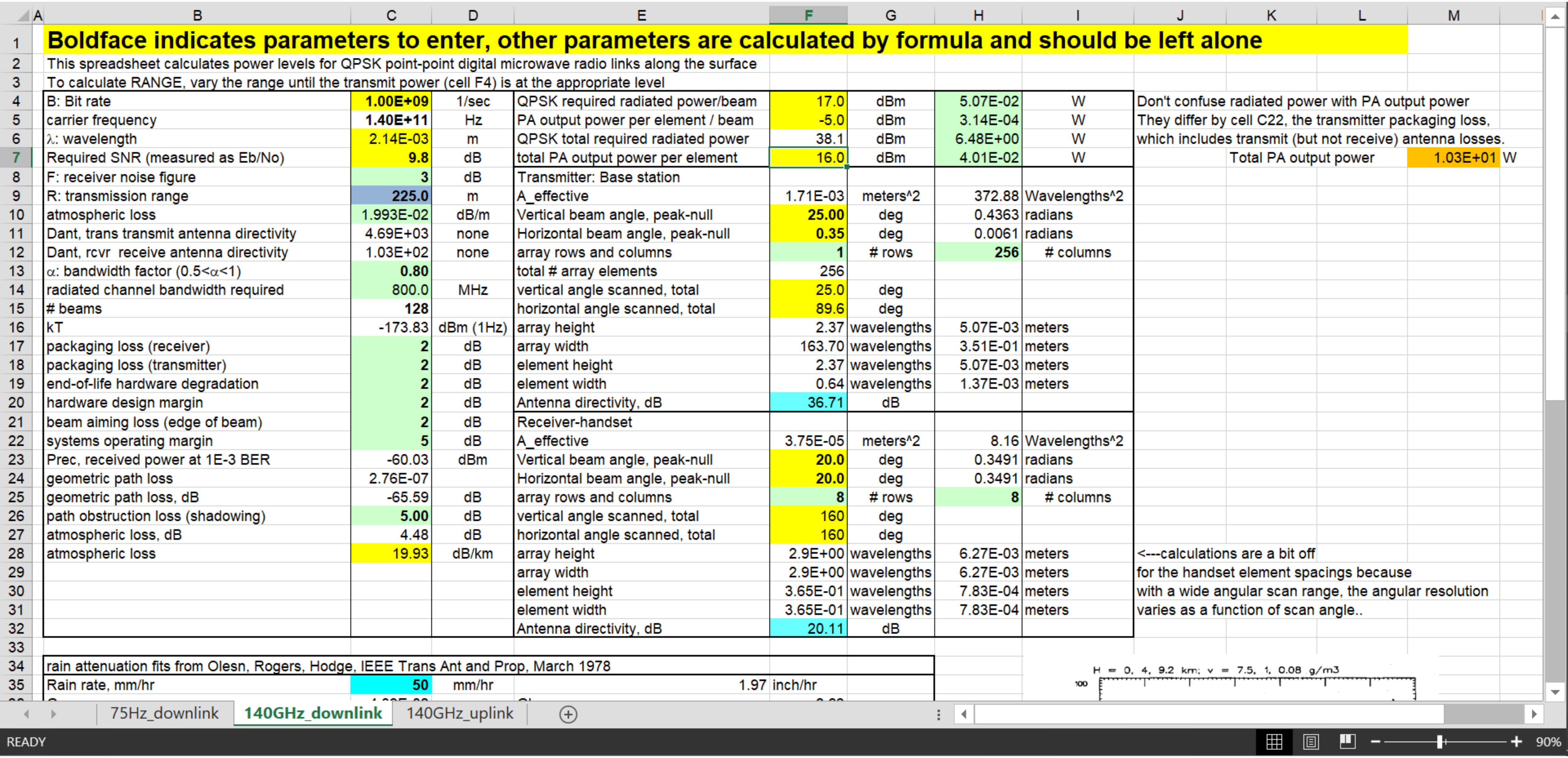
8-element 640Gb/s linear array:
same link assumptions
requires 2mW (vs. 80mW) power/element
requires 2.6m (vs. 1.6m) linear array



8-element 5Tb/s square array:
same link assumptions
requires 0.25mW (vs. 10mW) power/element
requires 2.6m (vs. 1.6m) square array

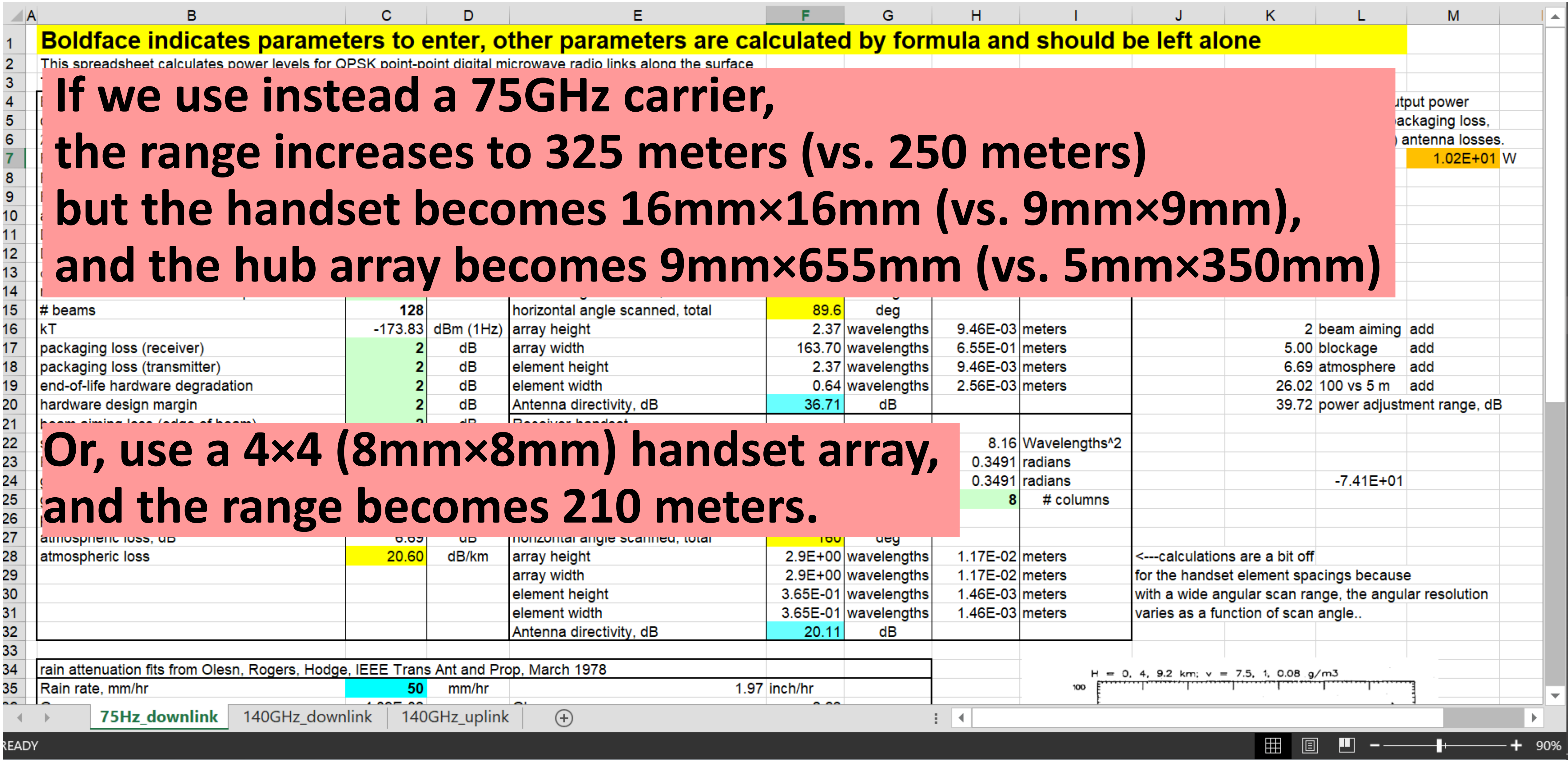


140 GHz spatially multiplexed base station



	B	C	D	E	F	G	H	I	J	K	L	M	
1	**Boldface indicates parameters to enter, other parameters are calculated by formula and should be left alone**												
2	This spreadsheet calculates power levels for QPSK point-point digital microwave radio links along the surface												
3	To calculate RANGE, vary the range until the transmit power (cell F4) is at the appropriate level												
4	B: Bit rate	**1.00E+09**	1/sec	QPSK required radiated power/beam	17.0	dBm	5.07E-02	W	Don't confuse radiated power with PA output power				
5	carrier frequency	**1.40E+11**	Hz	PA output power per element / beam	-5.0	dBm	3.14E-04	W	They differ by cell C22, the transmitter packaging loss,				
6	λ: wavelength	2.14E-03	m	QPSK total required radiated power	38.1	dBm	6.48E+00	W	which includes transmit (but not receive) antenna losses.				
7	Required SNR (measured as Eb/No)	**9.8**	dB	total PA output power per element	16.0	dBm	4.01E-02	W		Total PA output power		1.03E+01	W
8	F: receiver noise figure	**3**	dB	Transmitter: Base station									
9	R: transmission range	**225.0**	m	A_effective	1.71E-03	meters^2	372.88	Wavelengths^2					
10	atmospheric loss	1.993E-02	dB/m	Vertical beam angle, peak-null	**25.00**	deg	0.4363	radians					
11	Dant, trans transmit antenna directivity	4.69E+03	none	Horizontal beam angle, peak-null	**0.35**	deg	0.0061	radians					
12	Dant, rcvr receive antenna directivity	1.03E+02	none	array rows and columns	**1**	# rows	**256**	# columns					
13	α: bandwidth factor (0.5<α<1)	**0.80**		total # array elements	256								
14	radiated channel bandwidth required	800.0	MHz	vertical angle scanned, total	25.0	deg							
15	# beams	**128**		horizontal angle scanned, total	89.6	deg							
16	kT	-173.83	dBm (1Hz)	array height	2.37	wavelengths	5.07E-03	meters					
17	packaging loss (receiver)	**2**	dB	array width	163.70	wavelengths	3.51E-01	meters					
18	packaging loss (transmitter)	**2**	dB	element height	2.37	wavelengths	5.07E-03	meters					
19	end-of-life hardware degradation	**2**	dB	element width	0.64	wavelengths	1.37E-03	meters					
20	hardware design margin	**2**	dB	Antenna directivity, dB	36.71	dB							
21	beam aiming loss (edge of beam)	**2**	dB	Receiver-handset									
22	systems operating margin	**5**	dB	A_effective	3.75E-05	meters^2	8.16	Wavelengths^2					
23	Prec, received power at 1E-3 BER	-60.03	dBm	Vertical beam angle, peak-null	**20.0**	deg	0.3491	radians					
24	geometric path loss	2.76E-07		Horizontal beam angle, peak-null	**20.0**	deg	0.3491	radians					
25	geometric path loss, dB	-65.59	dB	array rows and columns	**8**	# rows	**8**	# columns					
26	path obstruction loss (shadowing)	**5.00**	dB	vertical angle scanned, total	160	deg							
27	atmospheric loss, dB	4.48	dB	horizontal angle scanned, total	160	deg							
28	atmospheric loss	19.93	dB/km	array height	2.9E+00	wavelengths	6.27E-03	meters	<---calculations are a bit off				
29				array width	2.9E+00	wavelengths	6.27E-03	meters	for the handset element spacings because				
30				element height	3.65E-01	wavelengths	7.83E-04	meters	with a wide angular scan range, the angular resolution				
31				element width	3.65E-01	wavelengths	7.83E-04	meters	varies as a function of scan angle..				
32				Antenna directivity, dB	20.11	dB							
33													
34	rain attenuation fits from Olesn, Rogers, Hodge, IEEE Trans Ant and Prop, March 1978												
35	Rain rate, mm/hr	**50**	mm/hr		1.97	inch/hr							

75 GHz spatially multiplexed base station



If we use instead a 75GHz carrier,
the range increases to 325 meters (vs. 250 meters)
but the handset becomes 16mm×16mm (vs. 9mm×9mm),
and the hub array becomes 9mm×655mm (vs. 5mm×350mm)

Or, use a 4×4 (8mm×8mm) handset array,
and the range becomes 210 meters.

Boldface indicates parameters to enter, other parameters are calculated by formula and should be left alone

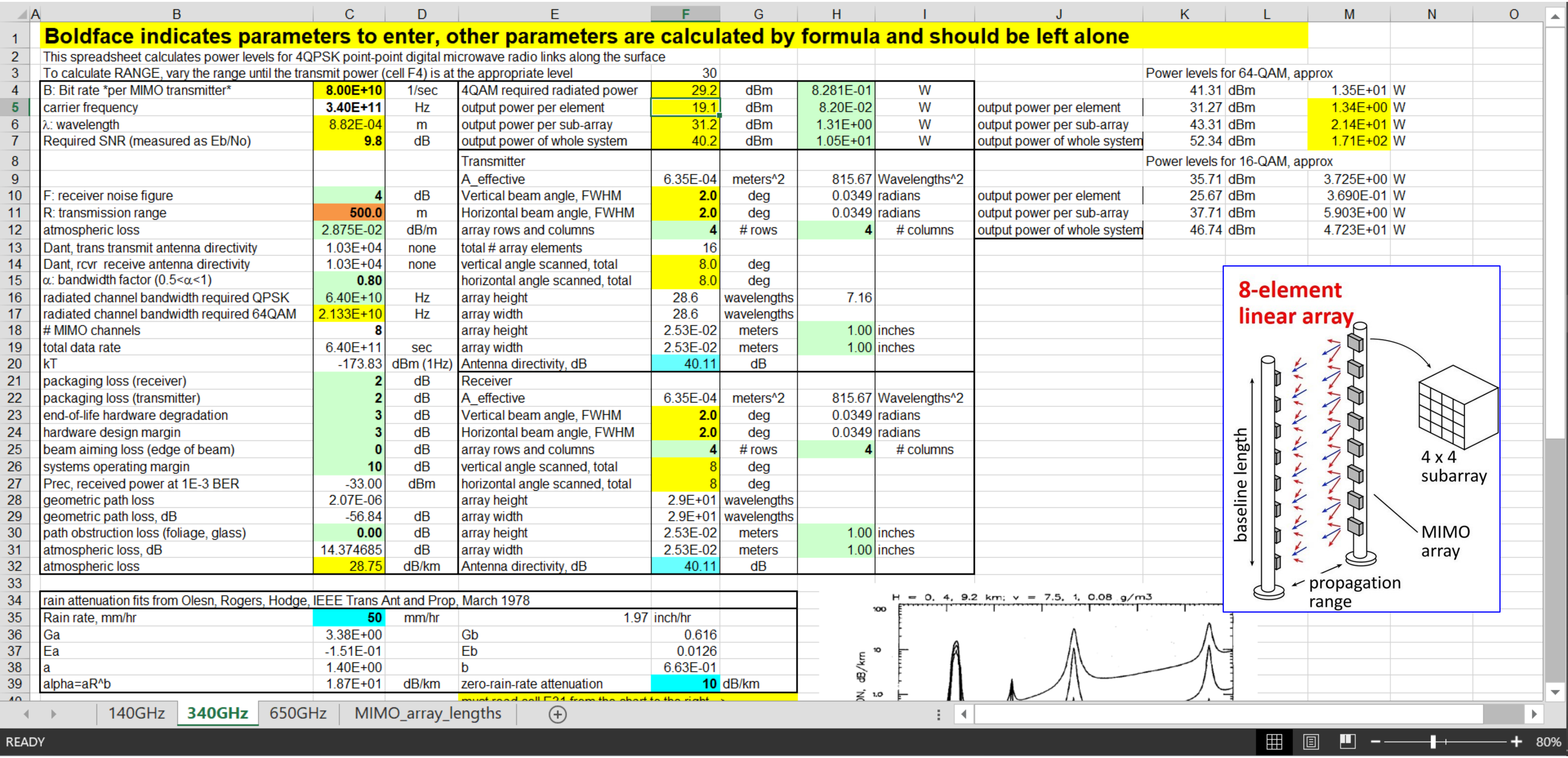
This spreadsheet calculates power levels for QPSK point-point digital microwave radio links along the surface

	B	C	D	E	F	G	H	I	K	L	M
4											utput power
5											ackaging loss,
6											antenna losses.
7											1.02E+01 W
15	# beams	**128**		horizontal angle scanned, total	89.6	deg					
16	kT	-173.83	dBm (1Hz)	array height	2.37	wavelengths	9.46E-03	meters	2	beam aiming	add
17	packaging loss (receiver)	**2**	dB	array width	163.70	wavelengths	6.55E-01	meters	5.00	blockage	add
18	packaging loss (transmitter)	**2**	dB	element height	2.37	wavelengths	9.46E-03	meters	6.69	atmosphere	add
19	end-of-life hardware degradation	**2**	dB	element width	0.64	wavelengths	2.56E-03	meters	26.02	100 vs 5 m	add
20	hardware design margin	**2**	dB	Antenna directivity, dB	36.71	dB			39.72	power adjustment range, dB	
22							8.16	Wavelengths^2			
23							0.3491	radians			
24							0.3491	radians		-7.41E+01	
25							**8**	# columns			
28	atmospheric loss	20.60	dB/km	array height	2.9E+00	wavelengths	1.17E-02	meters	<---calculations are a bit off		
29				array width	2.9E+00	wavelengths	1.17E-02	meters	for the handset element spacings because		
30				element height	3.65E-01	wavelengths	1.46E-03	meters	with a wide angular scan range, the angular resolution		
31				element width	3.65E-01	wavelengths	1.46E-03	meters	varies as a function of scan angle..		
32				Antenna directivity, dB	20.11	dB					

rain attenuation fits from Olesn, Rogers, Hodge, IEEE Trans Ant and Prop, March 1978

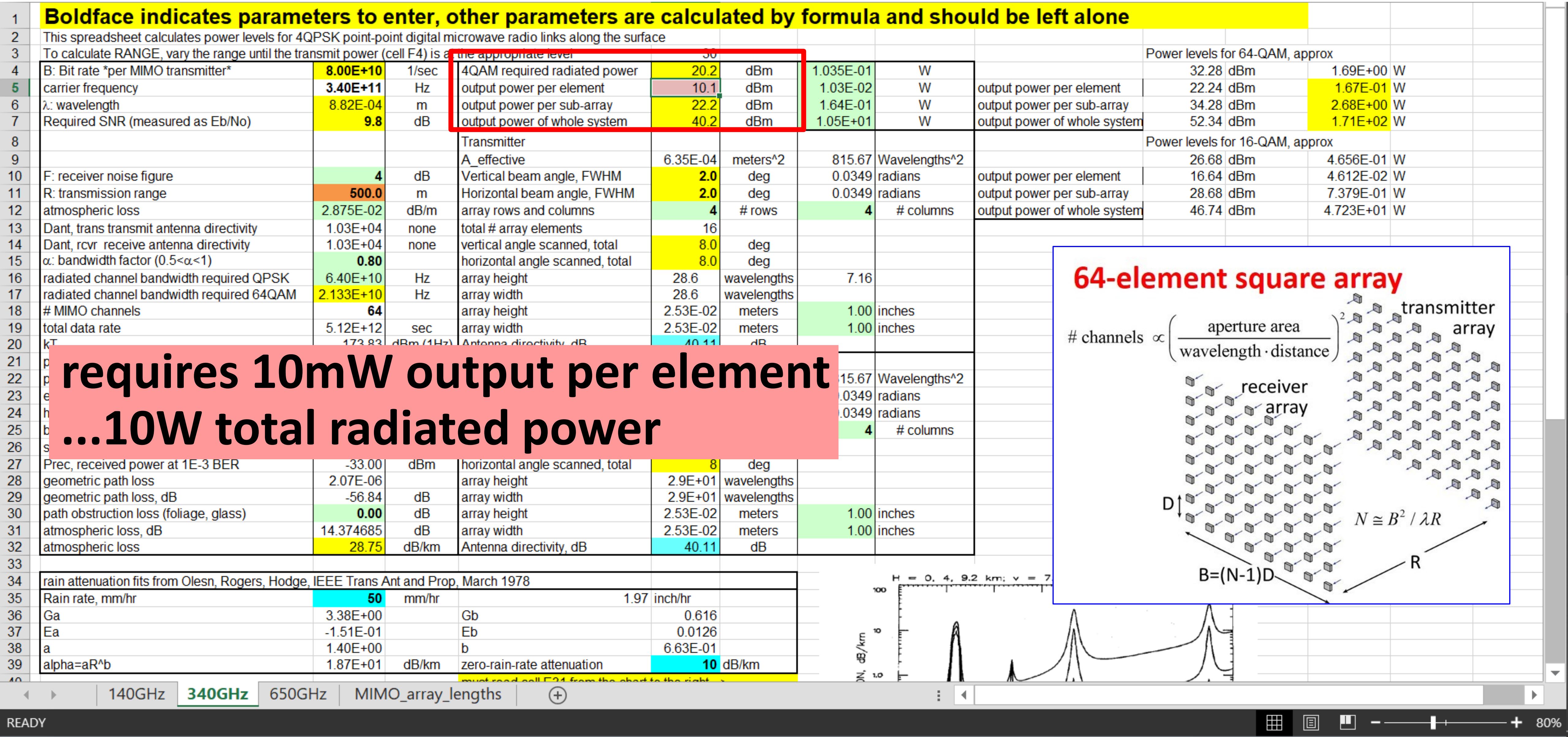
	B	C	D	E	F	G
35	Rain rate, mm/hr	**50**	mm/hr		1.97	inch/hr

340 GHz 640 Gb/s MIMO backhaul



	B	C	D	E	F	G	H	I	J	K	L	M	N
1	**Boldface indicates parameters to enter, other parameters are calculated by formula and should be left alone**												
2	This spreadsheet calculates power levels for 4QPSK point-point digital microwave radio links along the surface												
3	To calculate RANGE, vary the range until the transmit power (cell F4) is at the appropriate level				30					Power levels for 64-QAM, approx			
4	B: Bit rate *per MIMO transmitter*	**8.00E+10**	1/sec	4QAM required radiated power	29.2	dBm	8.281E-01	W		41.31	dBm	1.35E+01	W
5	carrier frequency	**3.40E+11**	Hz	output power per element	19.1	dBm	8.20E-02	W	output power per element	31.27	dBm	1.34E+00	W
6	λ: wavelength	8.82E-04	m	output power per sub-array	31.2	dBm	1.31E+00	W	output power per sub-array	43.31	dBm	2.14E+01	W
7	Required SNR (measured as Eb/No)	**9.8**	dB	output power of whole system	40.2	dBm	1.05E+01	W	output power of whole system	52.34	dBm	1.71E+02	W
8				Transmitter						Power levels for 16-QAM, approx			
9				A_effective	6.35E-04	meters^2	815.67	Wavelengths^2		35.71	dBm	3.725E+00	W
10	F: receiver noise figure	**4**	dB	Vertical beam angle, FWHM	**2.0**	deg	0.0349	radians	output power per element	25.67	dBm	3.690E-01	W
11	R: transmission range	**500.0**	m	Horizontal beam angle, FWHM	**2.0**	deg	0.0349	radians	output power per sub-array	37.71	dBm	5.903E+00	W
12	atmospheric loss	2.875E-02	dB/m	array rows and columns	**4**	# rows	**4**	# columns	output power of whole system	46.74	dBm	4.723E+01	W
13	Dant, trans transmit antenna directivity	1.03E+04	none	total # array elements	16								
14	Dant, rcvr receive antenna directivity	1.03E+04	none	vertical angle scanned, total	8.0	deg							
15	α: bandwidth factor (0.5<α<1)	**0.80**		horizontal angle scanned, total	8.0	deg							
16	radiated channel bandwidth required QPSK	6.40E+10	Hz	array height	28.6	wavelengths	7.16						
17	radiated channel bandwidth required 64QAM	2.133E+10	Hz	array width	28.6	wavelengths							
18	# MIMO channels	**8**		array height	2.53E-02	meters	1.00	inches					
19	total data rate	6.40E+11	sec	array width	2.53E-02	meters	1.00	inches					
20	kT	-173.83	dBm (1Hz)	Antenna directivity, dB	40.11	dB							
21	packaging loss (receiver)	**2**	dB	Receiver									
22	packaging loss (transmitter)	**2**	dB	A_effective	6.35E-04	meters^2	815.67	Wavelengths^2					
23	end-of-life hardware degradation	**3**	dB	Vertical beam angle, FWHM	**2.0**	deg	0.0349	radians					
24	hardware design margin	**3**	dB	Horizontal beam angle, FWHM	**2.0**	deg	0.0349	radians					
25	beam aiming loss (edge of beam)	**0**	dB	array rows and columns	**4**	# rows	**4**	# columns					
26	systems operating margin	**10**	dB	vertical angle scanned, total	8	deg							
27	Prec, received power at 1E-3 BER	-33.00	dBm	horizontal angle scanned, total	8	deg							
28	geometric path loss	2.07E-06		array height	2.9E+01	wavelengths							
29	geometric path loss, dB	-56.84	dB	array width	2.9E+01	wavelengths							
30	path obstruction loss (foliage, glass)	**0.00**	dB	array height	2.53E-02	meters	1.00	inches					
31	atmospheric loss, dB	14.374685	dB	array width	2.53E-02	meters	1.00	inches					
32	atmospheric loss	28.75	dB/km	Antenna directivity, dB	40.11	dB							
33													
34	rain attenuation fits from Olesn, Rogers, Hodge, IEEE Trans Ant and Prop, March 1978												
35	Rain rate, mm/hr	**50**	mm/hr		1.97	inch/hr							
36	Ga	3.38E+00		Gb	0.616								
37	Ea	-1.51E-01		Eb	0.0126								
38	a	1.40E+00		b	6.63E-01								
39	alpha=aR^b	1.87E+01	dB/km	zero-rain-rate attenuation	**10**	dB/km							

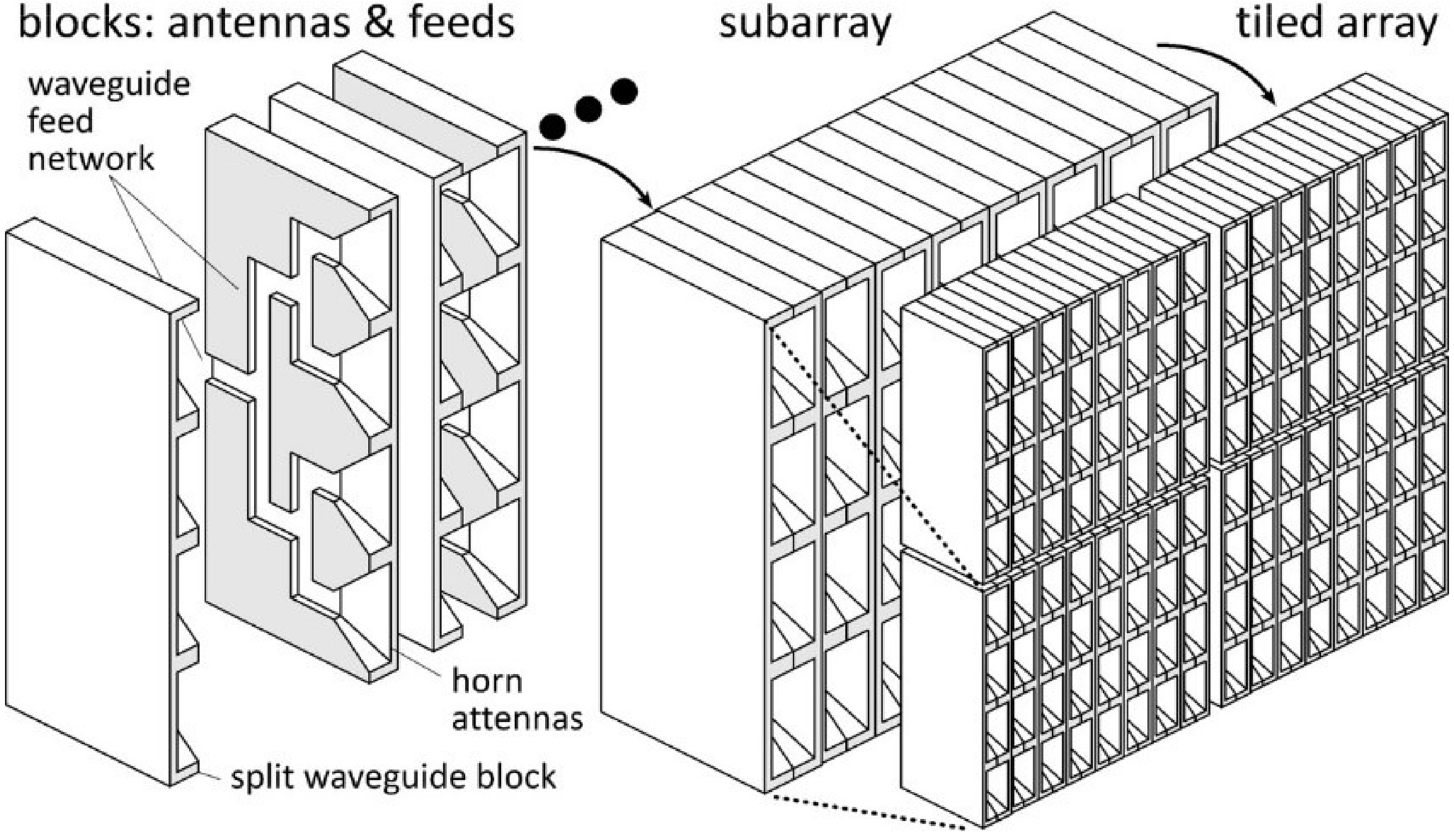
340 GHz 5 Tb/s MIMO backhaul



1	**Boldface indicates parameters to enter, other parameters are calculated by formula and should be left alone**												
2	This spreadsheet calculates power levels for 4QPSK point-point digital microwave radio links along the surface												
3	To calculate RANGE, vary the range until the transmit power (cell F4) is a the appropriate level				30					Power levels for 64-QAM, approx			
4	B: Bit rate *per MIMO transmitter*	**8.00E+10**	1/sec	4QAM required radiated power	20.2	dBm	1.035E-01	W		32.28	dBm	1.69E+00	W
5	carrier frequency	**3.40E+11**	Hz	output power per element	10.1	dBm	1.03E-02	W	output power per element	22.24	dBm	1.67E-01	W
6	λ: wavelength	8.82E-04	m	output power per sub-array	22.2	dBm	1.64E-01	W	output power per sub-array	34.28	dBm	2.68E+00	W
7	Required SNR (measured as Eb/No)	**9.8**	dB	output power of whole system	40.2	dBm	1.05E+01	W	output power of whole system	52.34	dBm	1.71E+02	W
8				Transmitter						Power levels for 16-QAM, approx			
9				A_effective	6.35E-04	meters^2	815.67	Wavelengths^2		26.68	dBm	4.656E-01	W
10	F: receiver noise figure	**4**	dB	Vertical beam angle, FWHM	**2.0**	deg	0.0349	radians	output power per element	16.64	dBm	4.612E-02	W
11	R: transmission range	**500.0**	m	Horizontal beam angle, FWHM	**2.0**	deg	0.0349	radians	output power per sub-array	28.68	dBm	7.379E-01	W
12	atmospheric loss	2.875E-02	dB/m	array rows and columns	**4**	# rows	**4**	# columns	output power of whole system	46.74	dBm	4.723E+01	W
13	Dant, trans transmit antenna directivity	1.03E+04	none	total # array elements	16								
14	Dant, rcvr receive antenna directivity	1.03E+04	none	vertical angle scanned, total	8.0	deg							
15	α: bandwidth factor (0.5<α<1)	**0.80**		horizontal angle scanned, total	8.0	deg							
16	radiated channel bandwidth required QPSK	6.40E+10	Hz	array height	28.6	wavelengths	7.16						
17	radiated channel bandwidth required 64QAM	2.133E+10	Hz	array width	28.6	wavelengths							
18	# MIMO channels	**64**		array height	2.53E-02	meters	1.00	inches					
19	total data rate	5.12E+12	sec	array width	2.53E-02	meters	1.00	inches					
20	kT	173.83	dBm (1Hz)	Antenna directivity, dB	40.11	dB							
21	p												
22	p						15.67	Wavelengths^2					
23	e						.0349	radians					
24	h						.0349	radians					
25	b						**4**	# columns					
26	s												
27	Prec, received power at 1E-3 BER	-33.00	dBm	horizontal angle scanned, total	8	deg							
28	geometric path loss	2.07E-06		array height	2.9E+01	wavelengths							
29	geometric path loss, dB	-56.84	dB	array width	2.9E+01	wavelengths							
30	path obstruction loss (foliage, glass)	**0.00**	dB	array height	2.53E-02	meters	1.00	inches					
31	atmospheric loss, dB	14.374685	dB	array width	2.53E-02	meters	1.00	inches					
32	atmospheric loss	28.75	dB/km	Antenna directivity, dB	40.11	dB							
33													
34	rain attenuation fits from Olesn, Rogers, Hodge, IEEE Trans Ant and Prop, March 1978												
35	Rain rate, mm/hr	**50**	mm/hr		1.97	inch/hr							
36	Ga	3.38E+00		Gb	0.616								
37	Ea	-1.51E-01		Eb	0.0126								
38	a	1.40E+00		b	6.63E-01								
39	alpha=aR^b	1.87E+01	dB/km	zero-rain-rate attenuation	**10**	dB/km							

requires 10mW output per element
...10W total radiated power

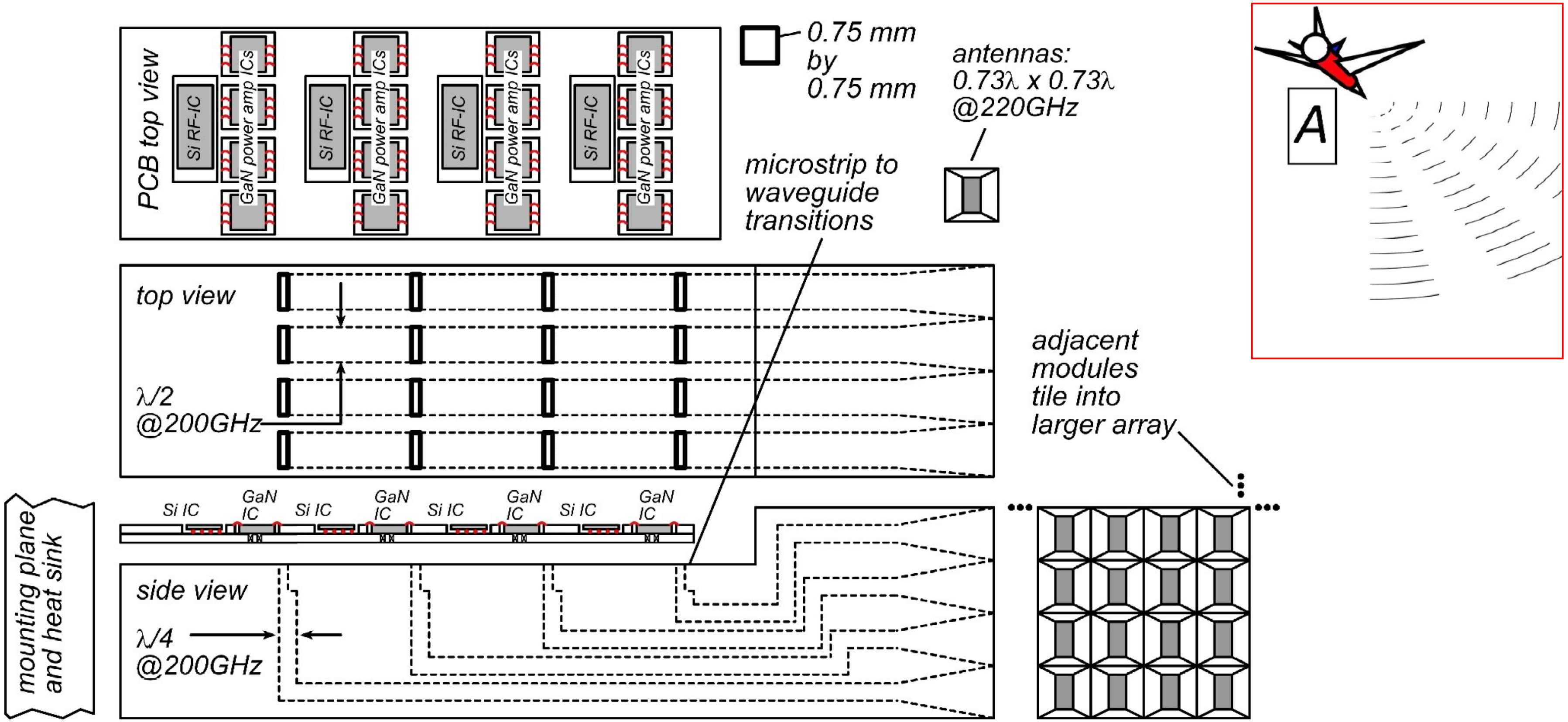
Background: split-block waveguides



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

Precision pins aid alignment

Concept: Tile for mm-wave arrays



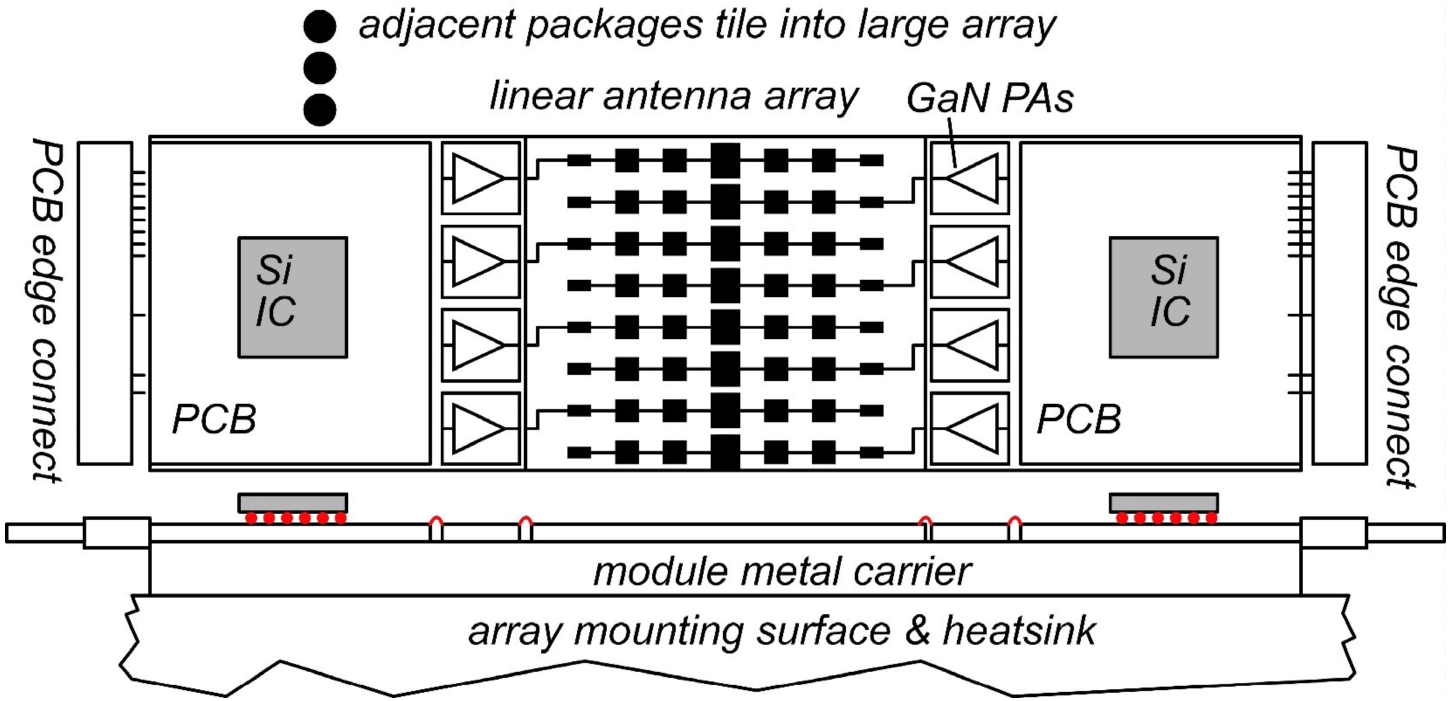
Split-block assembly. Modules tile into larger array

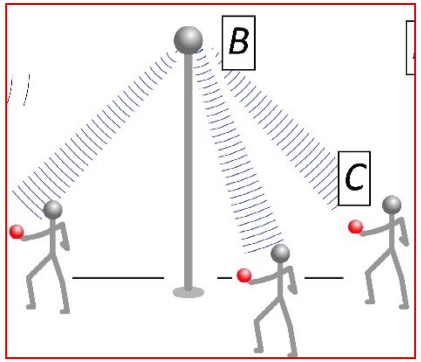
IC area can be much larger than antenna area→ electronics can fit

Low-loss waveguide feeds, efficient waveguide horn antennas

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

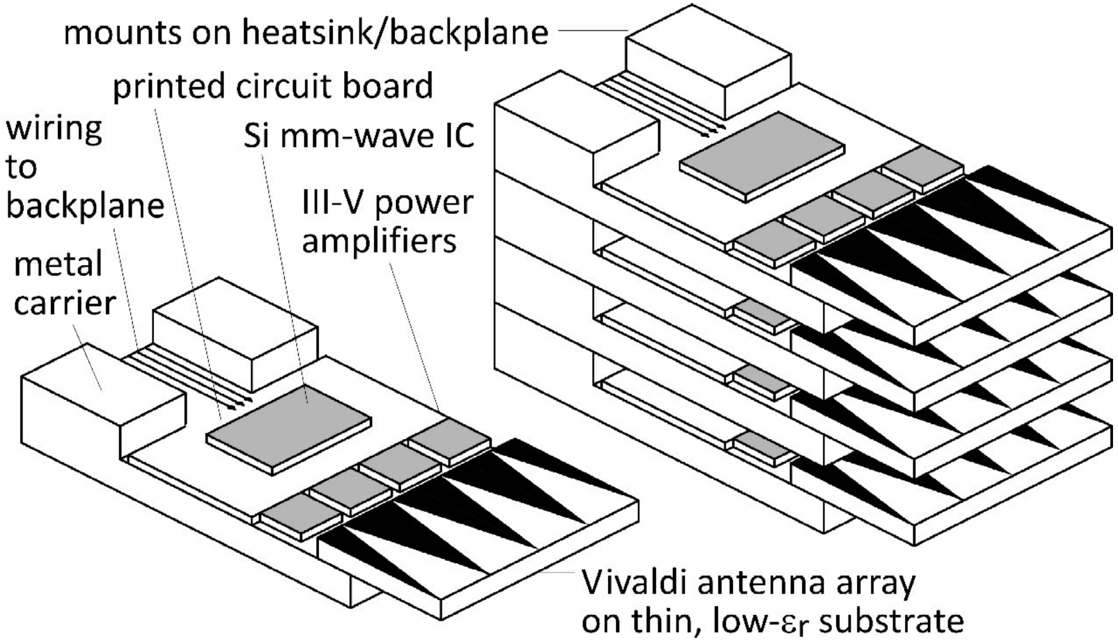
Concept: Tile for linear arrays

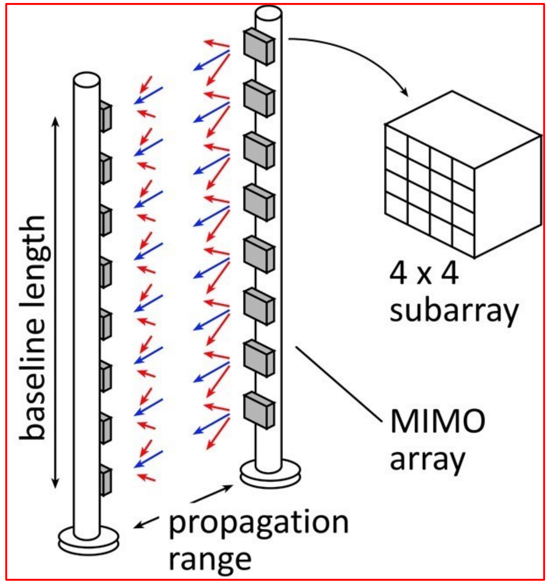




Terrestrial system: horizontal steering only→ linear array.
Space at edges of linear array: room for III-V PAs, LNAs.
Alternating-sides feed: 2mm pitch→ room for large GaN PAs.
Mounting directly on metal carrier→ heatsinking.

Concept: module for small angular scanning

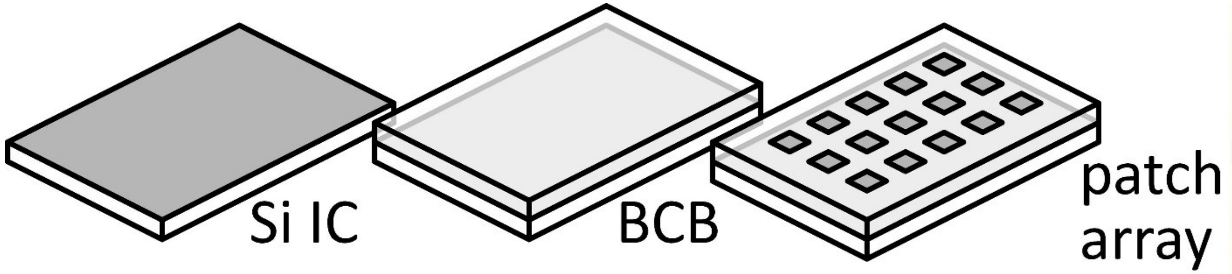


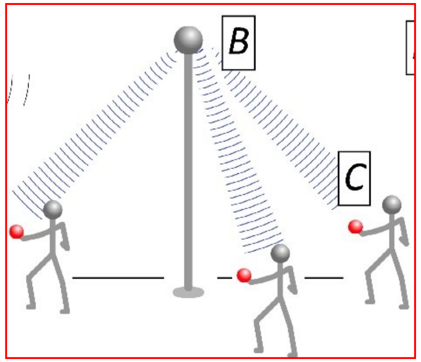


Terrestrial system: horizontal + vertical steering → rectangular array.
Limited angular steering range (installation)→ spacing >> $\lambda/2$
Endfire / edge-card geometry: room for III-V PAs, LNAs.
Mounting directly on metal carrier→ heatsinking.

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

Concept: module for handset





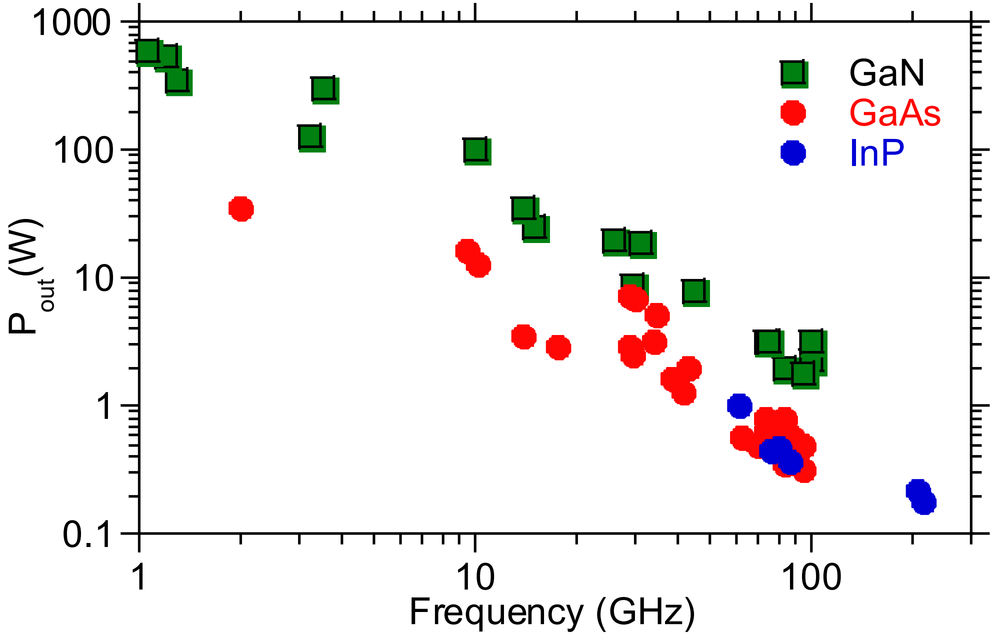
Handset transceiver performance: less challenging.
    No external III-V PAs, LNAs

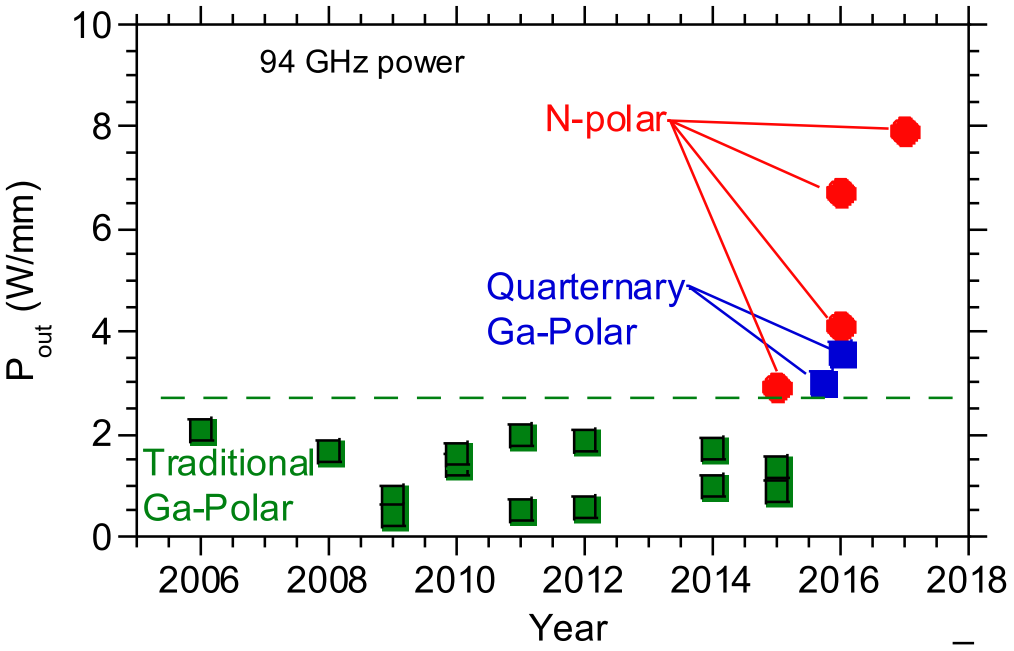
Handset transceiver is simpler: single-beam, not spatially multiplexed
    Smaller die area→ array pixel fits in $\lambda/2 \times \lambda/2$

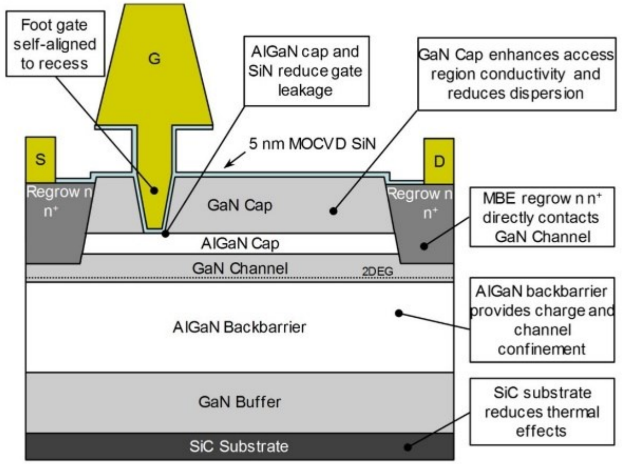
Vertical integration of antenna on low-ε_r superstrate.
    fused Silica (Rebeiz)
    possibly also: spin-cast BCB or polyimide, post-process.

Gallium Nitride Power Technologies

GaN is the leading high-frequency power technology







N-polar GaN: Mishra