Sub-mm-Wave Technologies: Systems, ICs, THz Transistors

Mark Rodwell
University of California, Santa Barbara

Coauthors:

J. Rode, H.W. Chiang, T. Reed, S. Daneshgar, V. Jain, E. Lobisser, A. Baraskar, B. J. Thibeault, B. Mitchell, A. C. Gossard, ***UCSB***

Munkyo Seo, Jonathan Hacker, Adam Young, Zach Griffith, Richard Pierson, Miguel Urteaga, ***Teledyne Scientific Company***

rodwell@ece.ucsb.edu 805-893-3244

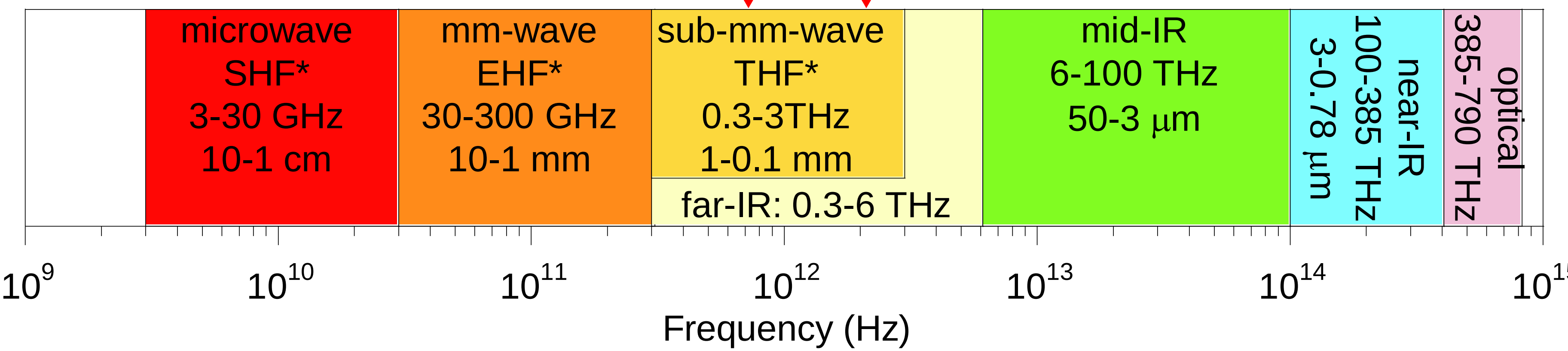
50-500 GHz Electronics: What Is It For ?

820 GHz transistor ICs today

2 THz clearly feasible

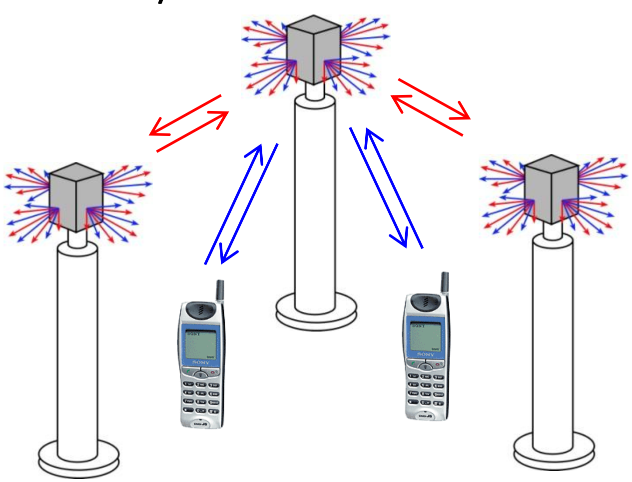
*ITU band designations

** IR bands as per ISO 20473

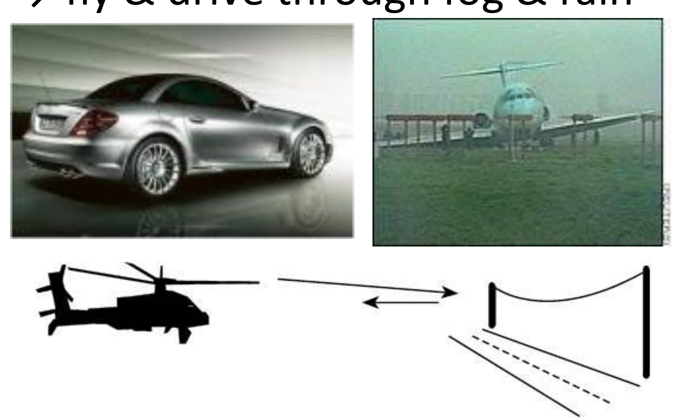


Applications

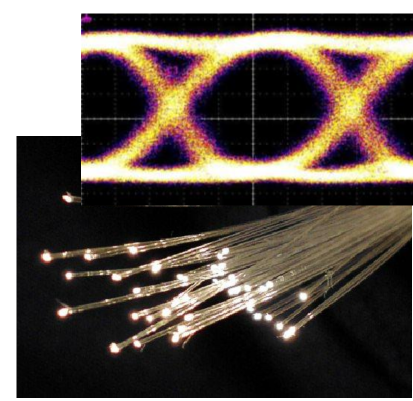
100+ Gb/s wireless networks



Video-resolution radar
→ fly & drive through fog & rain

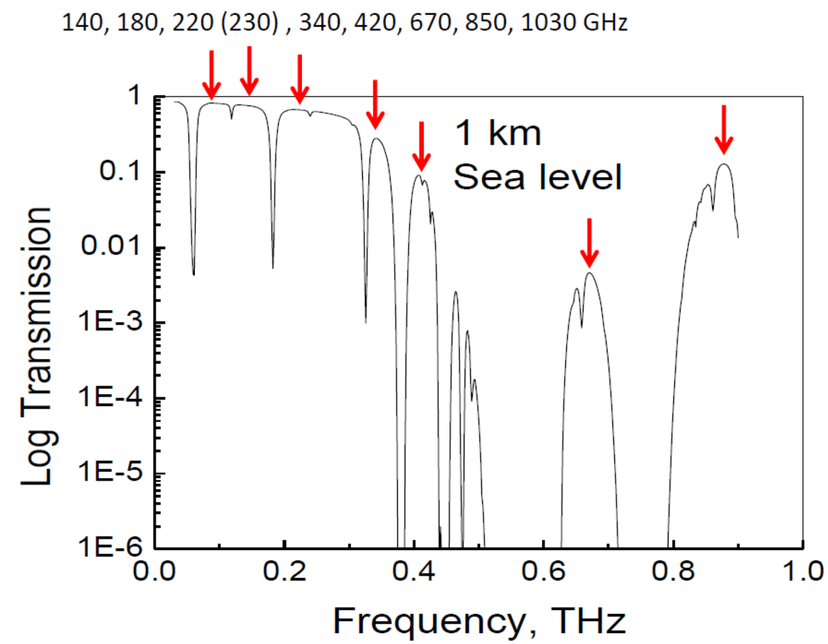


near-Terabit
optical fiber links



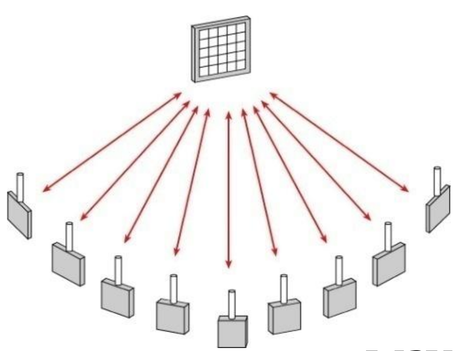
50-500 GHz Wireless Has High Capacity

very large bandwidths available

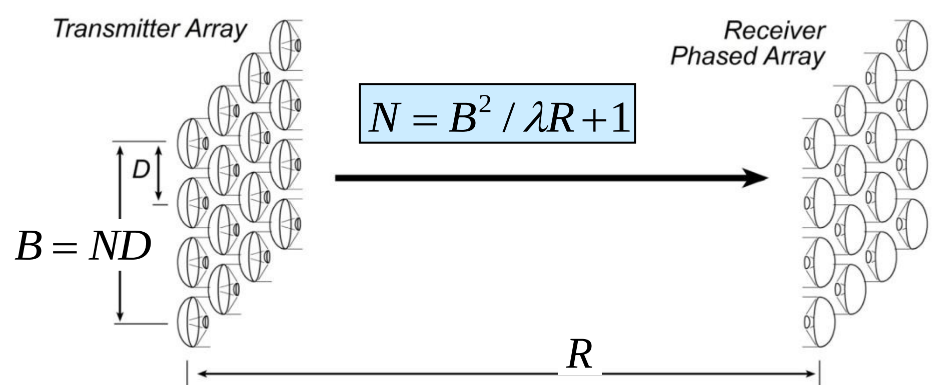


short wavelengths→ many parallel channels

Sheldon IMS 2009
Torkildson : IEEE Trans Wireless Comms. Dec. 2011.



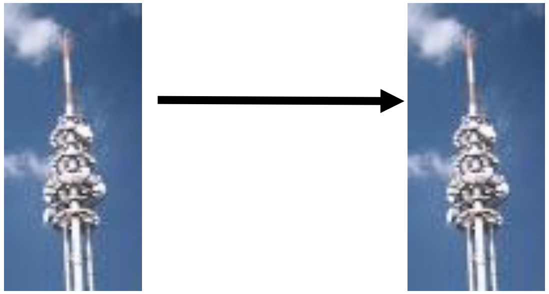
$$\text{angular resolution} \approx \frac{\text{wavelength}}{\text{array width}}$$



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

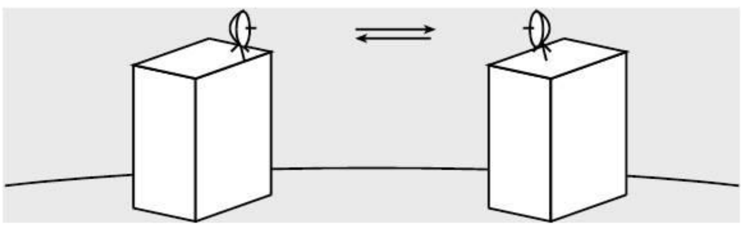
50-500 GHz Wireless Needs Phased Arrays

isotropic antenna → weak signal → short range



$$\left(\frac{P_{received}}{P_{transmitted}}\right) \propto \left(\frac{\lambda^2}{R^2}\right) e^{-\alpha R}$$

highly directional antenna → strong signal, but must be aimed

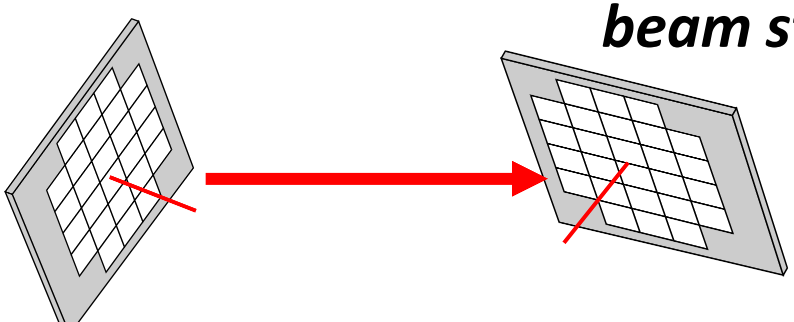


$$\left(\frac{P_{received}}{P_{transmitted}}\right) \propto D_t D_r \left(\frac{\lambda^2}{R^2}\right) e^{-\alpha R}$$

no good for mobile

must be precisely aimed → too expensive for telecom operators

beam steering arrays → strong signal, steerable

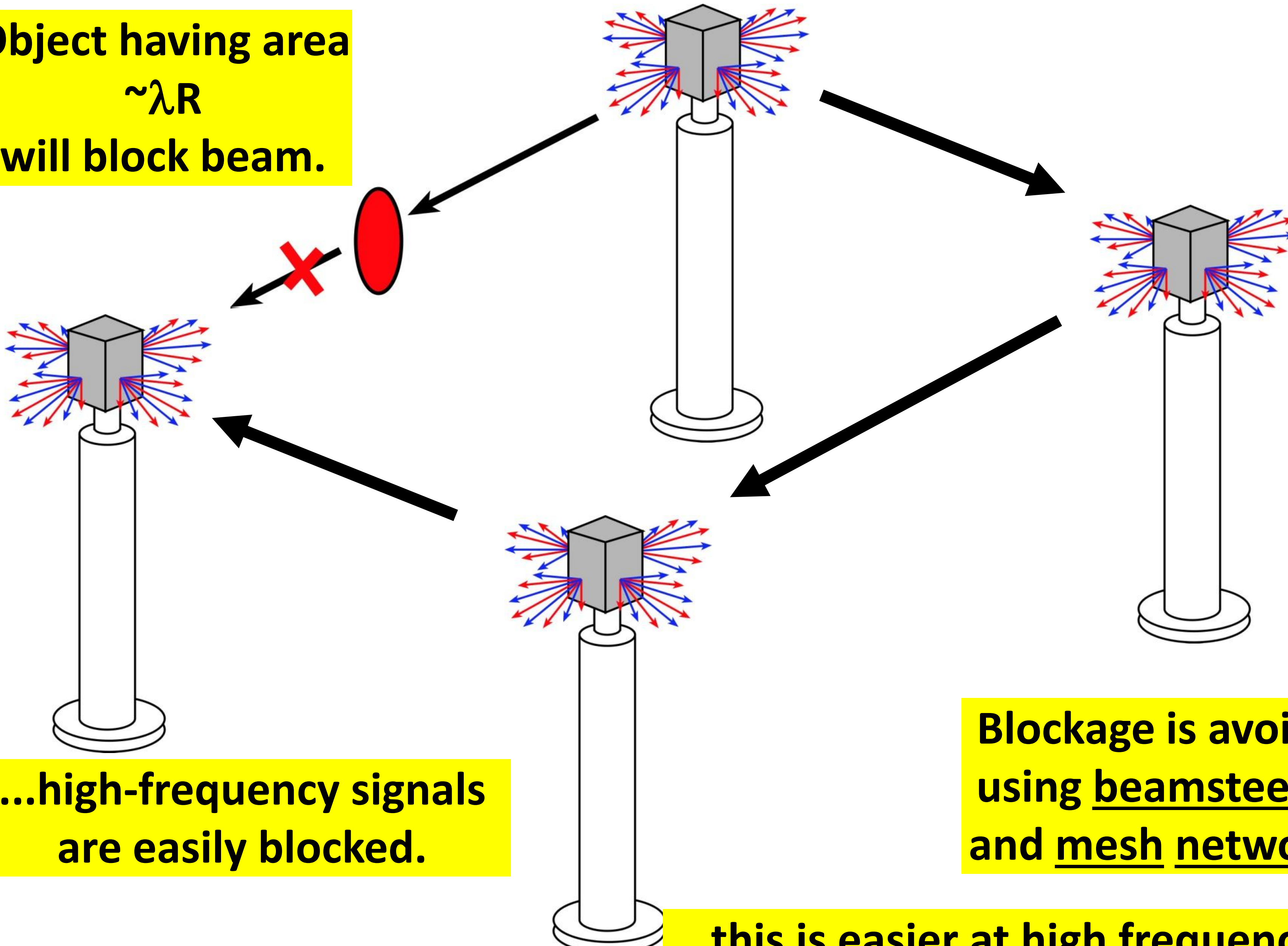


$$\frac{P_{received}}{P_{transmit}} \propto N_{receive} N_{transmit} \frac{\lambda^2}{R^2} e^{-\alpha R}$$

32-element array → 30 (45?) dB increased SNR

50-500 GHz Wireless Needs Mesh Networks

Object having area ~λR will block beam.



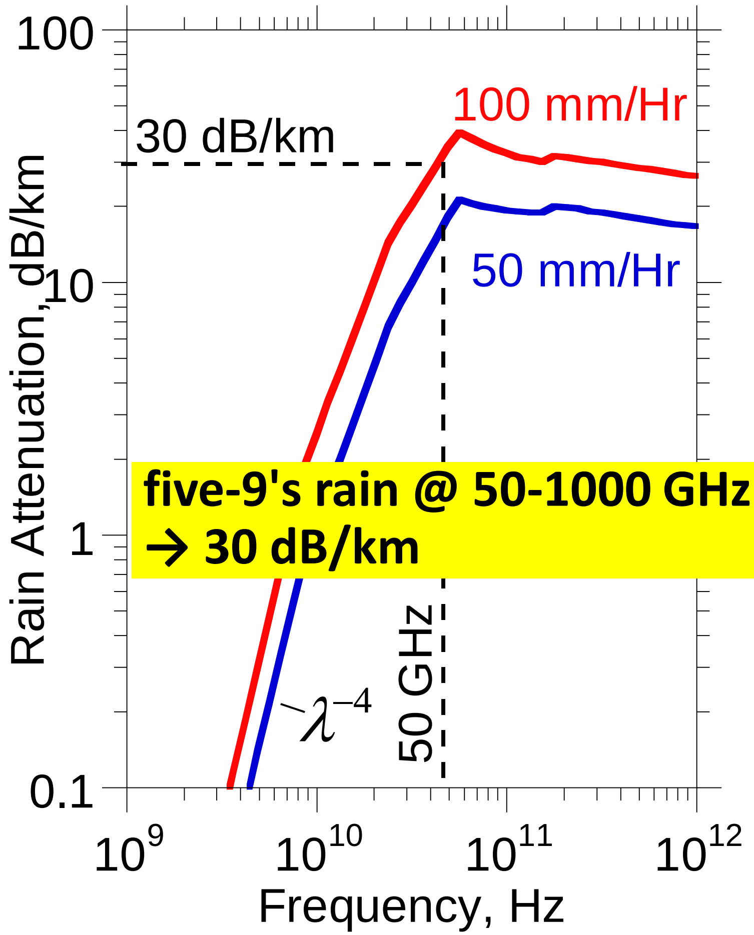
...high-frequency signals are easily blocked.

Blockage is avoided using beamsteering and mesh networks.

...this is easier at high frequencies.

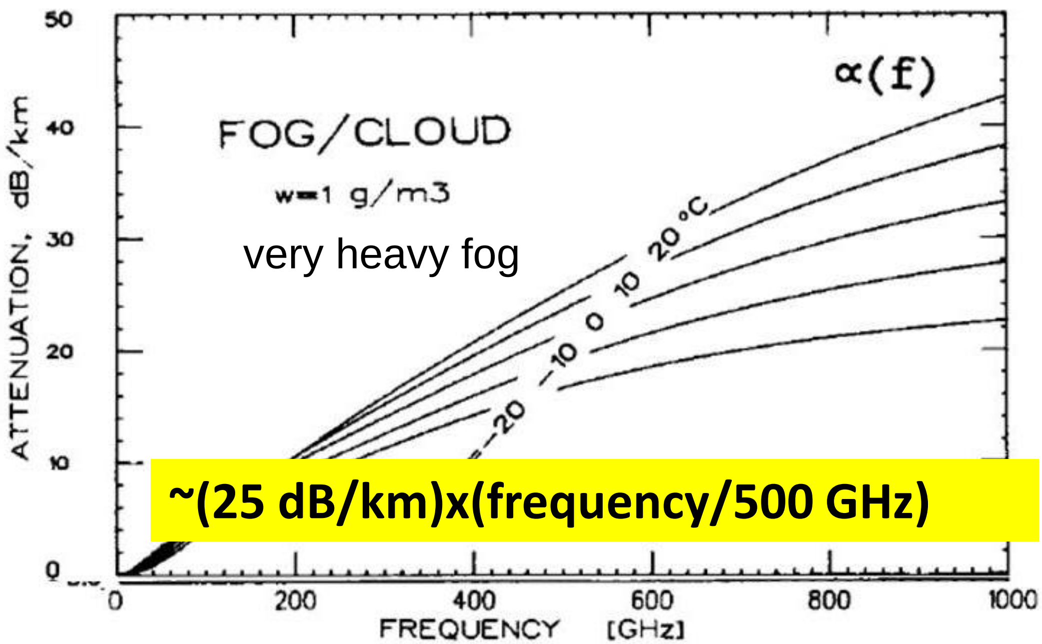
50-500 GHz Wireless Has High Attenuation

High Rain Attenuation



five-9's rain @ 50-1000 GHz:
→ 30 dB/km

High Fog Attenuation



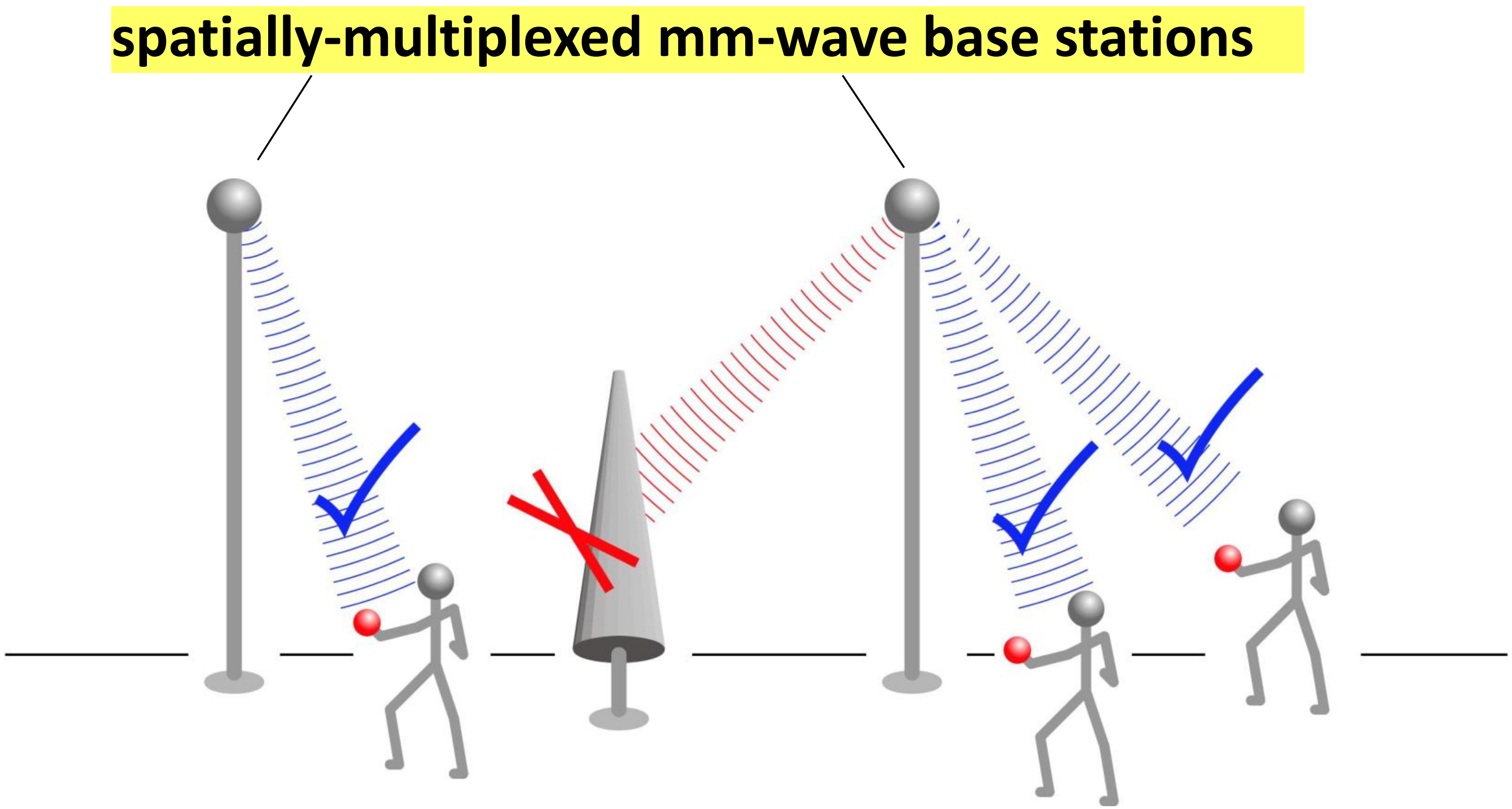
~(25 dB/km)x(frequency/500 GHz)

50-500 GHz links must tolerate ~30 dB/km attenuation

Olsen, Rogers, Hodge, IEEE Trans Antennas & Propagation Mar 1978 Liebe, Manabe, Hufford, IEEE Trans Antennas and Propagation, Dec. 1989

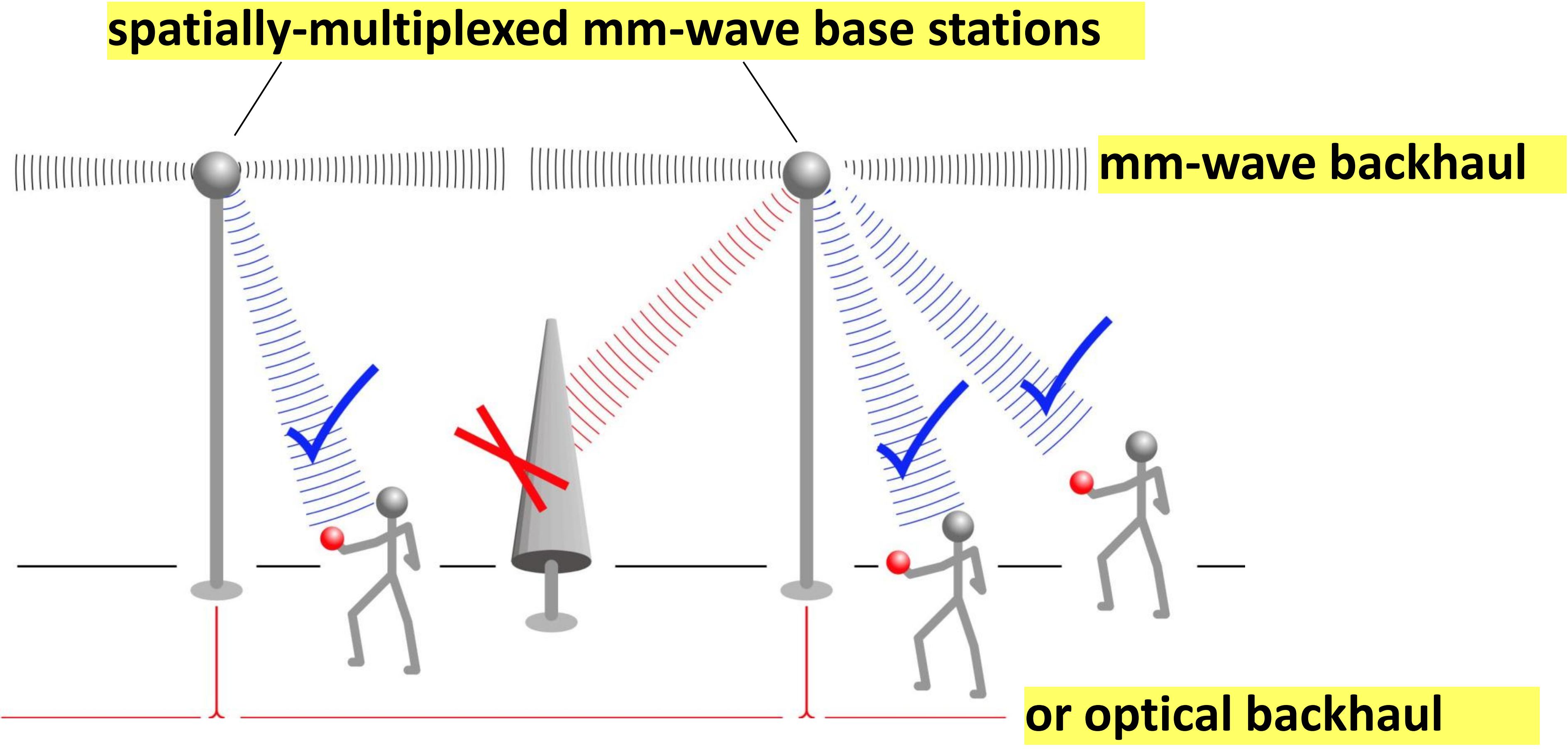
mm-Waves for Terabit Mobile Communications

Goal: ***1Gb/s per mobile user***



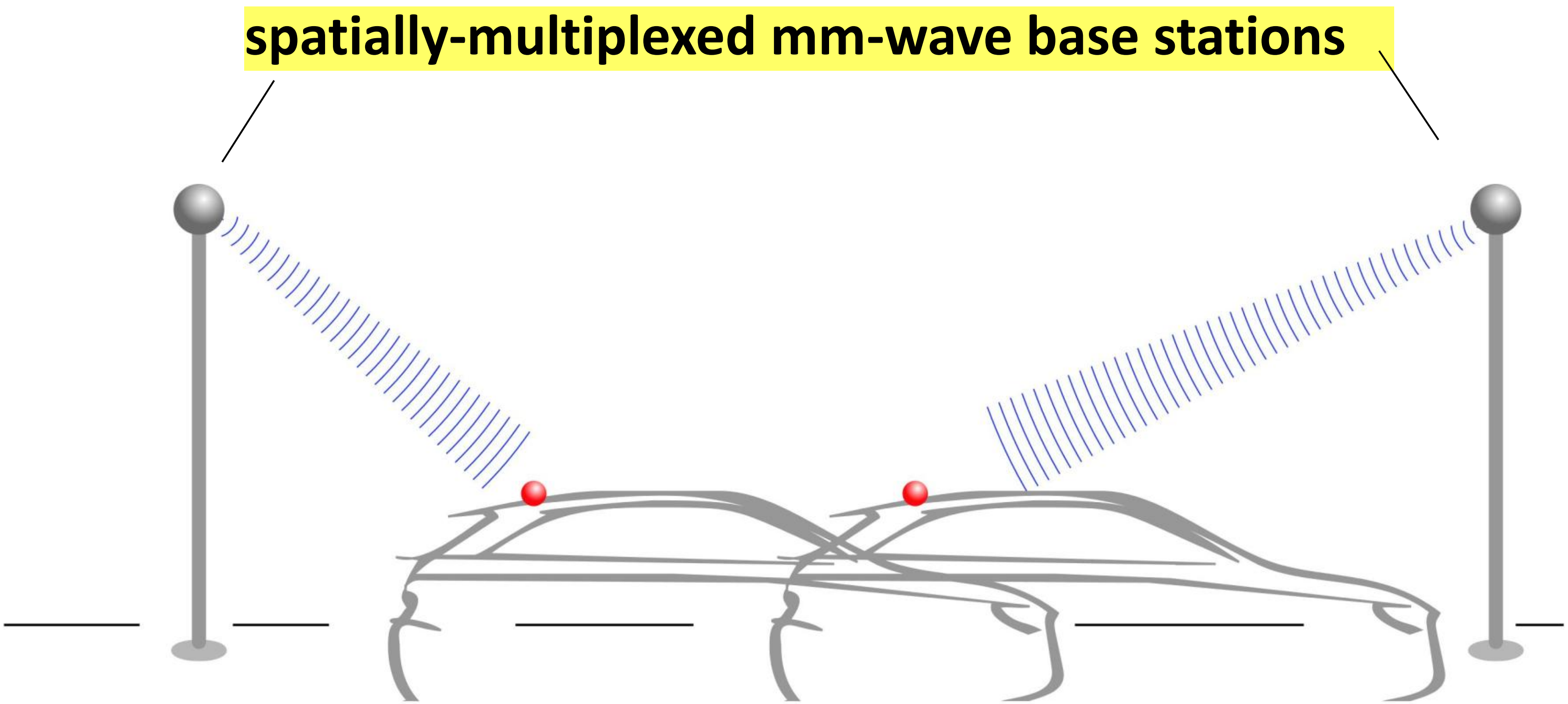
mm-Waves for Terabit Mobile Communications

Goal: ***1Gb/s per mobile user***



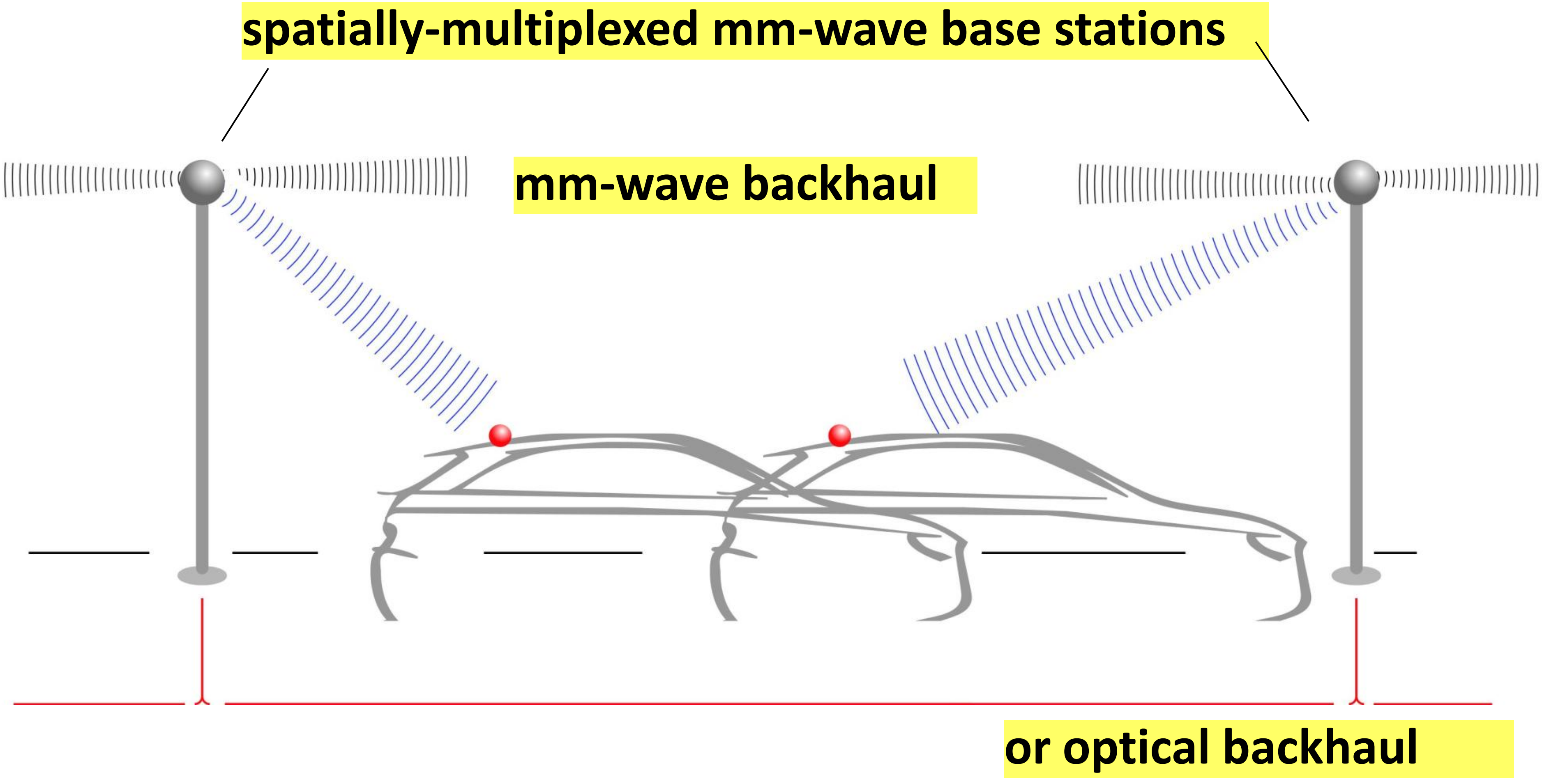
mm-Waves for Terabit Mobile Communications

Goal*:* ***1Gb/s per mobile user***

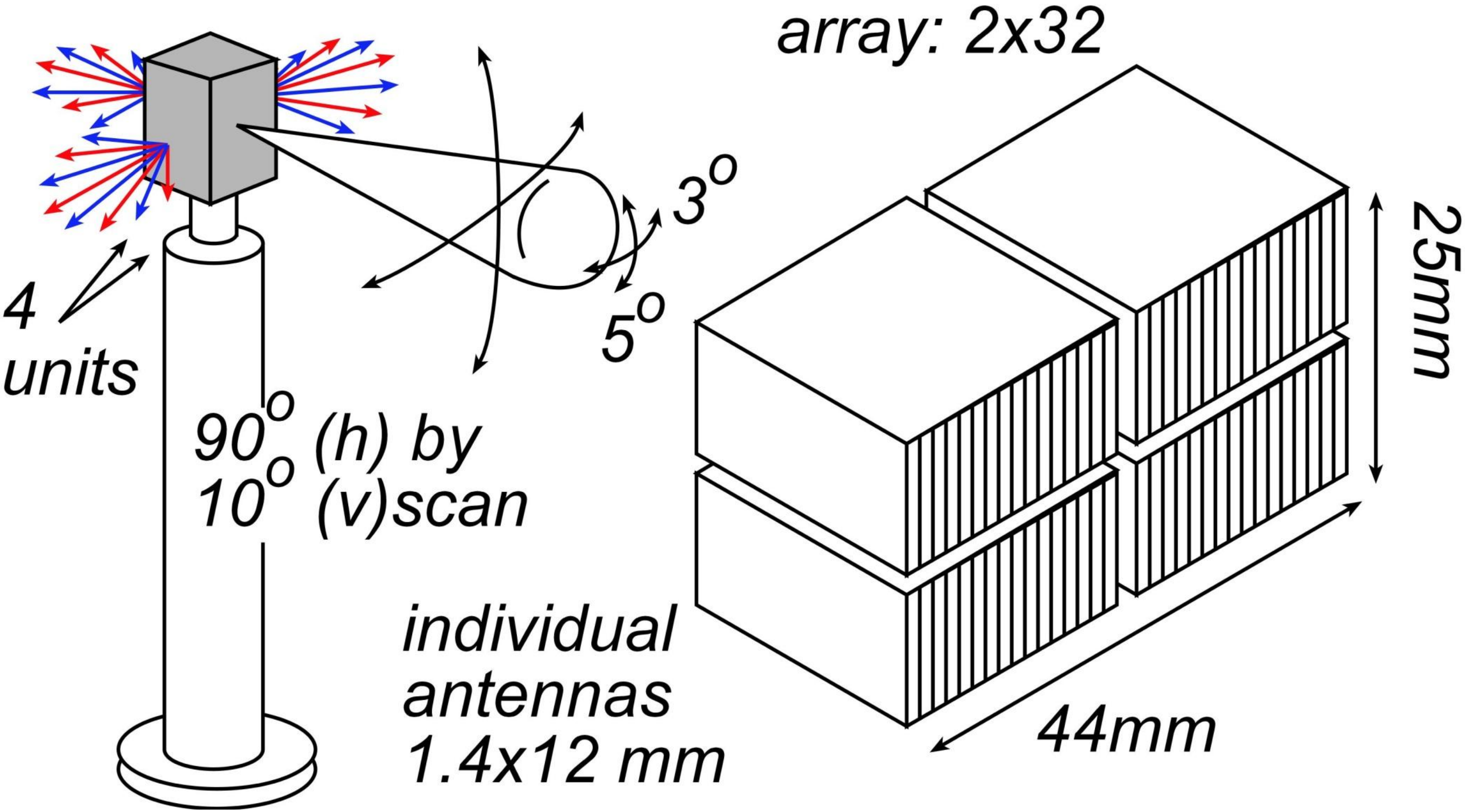


mm-Waves for Terabit Mobile Communications

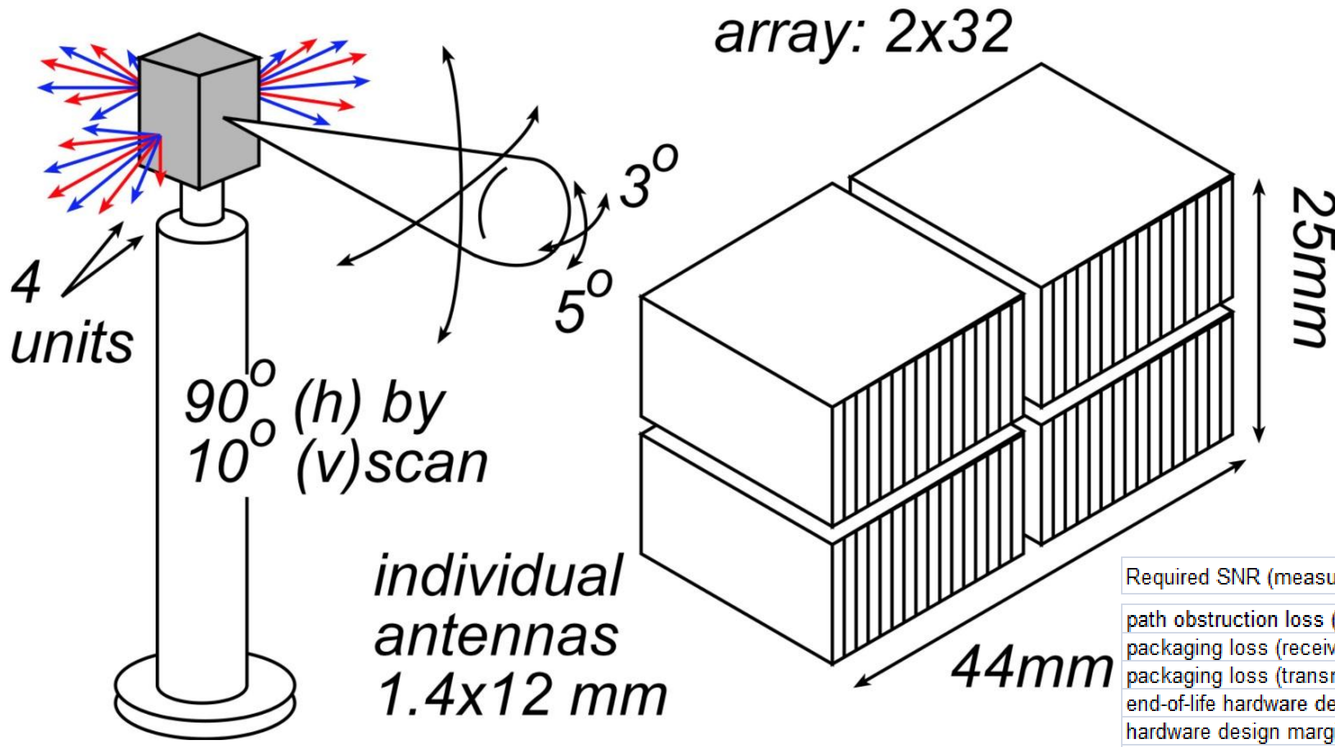
Goal: ***1Gb/s per mobile user***



140 GHz, 10 Gb/s Adaptive Picocell Backhaul



140 GHz, 10 Gb/s Adaptive Picocell Backhaul



Required SNR (measured as Eb/No)	6.8	dB
path obstruction loss (foliage, glass)	5.00	dB
packaging loss (receiver)	3	dB
packaging loss (transmitter)	3	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
PA backoff for OFDM	7.00E+00	dB

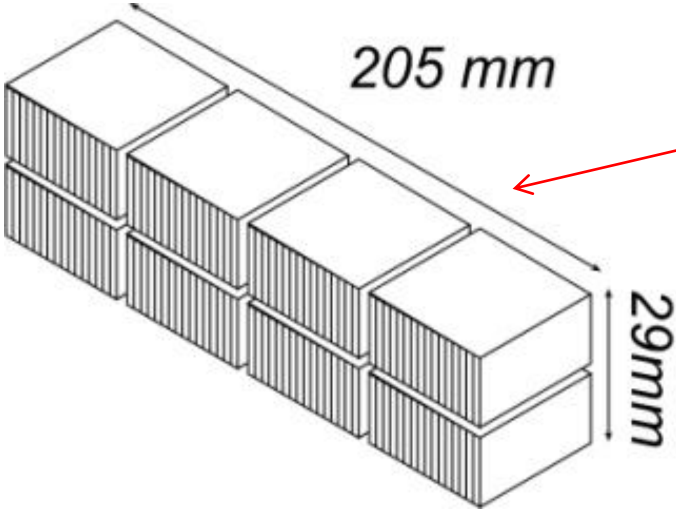
350 meters range in five-9's rain

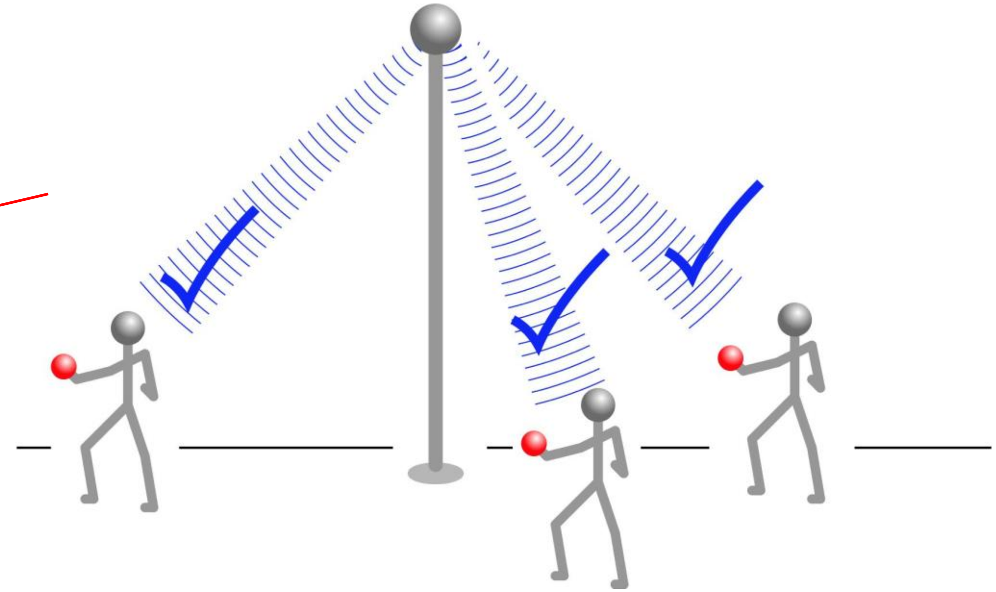
Realistic packaging loss, operating & design margins

PAs: 24 dBm P_{sat} (per element)→ GaN or InP

LNAs: 4 dB noise figure → InP HEMT

60 GHz, 1 Tb/s Spatially-Multiplexed Base Station





2x64 array on each of four faces.

Each face supports 128 users, 128 beams: 512 total users.

Each beam: 2Gb/s.

200 meters range in 50 mm/hr rain

Realistic packaging loss, operating & design margins

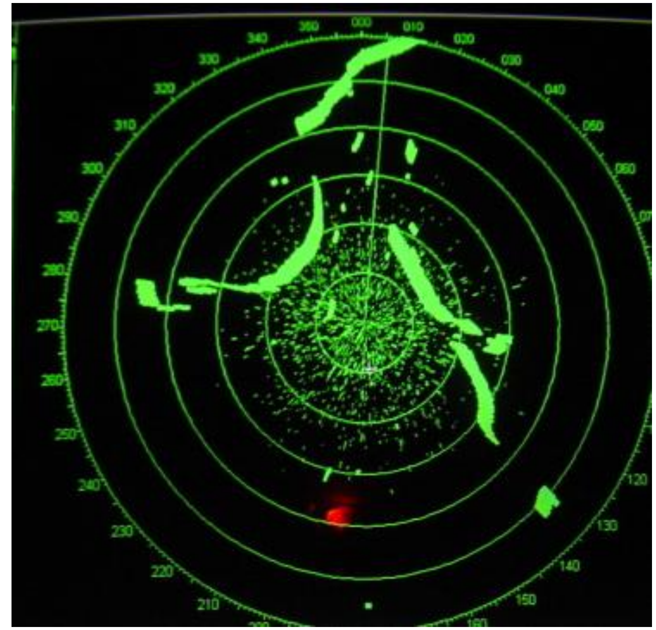
PAs: 20 dBm P_{out} , 26 dBm P_{sat} (per element)

LNAs: 3 dB noise figure

400 GHz frequency-scanned imaging radar

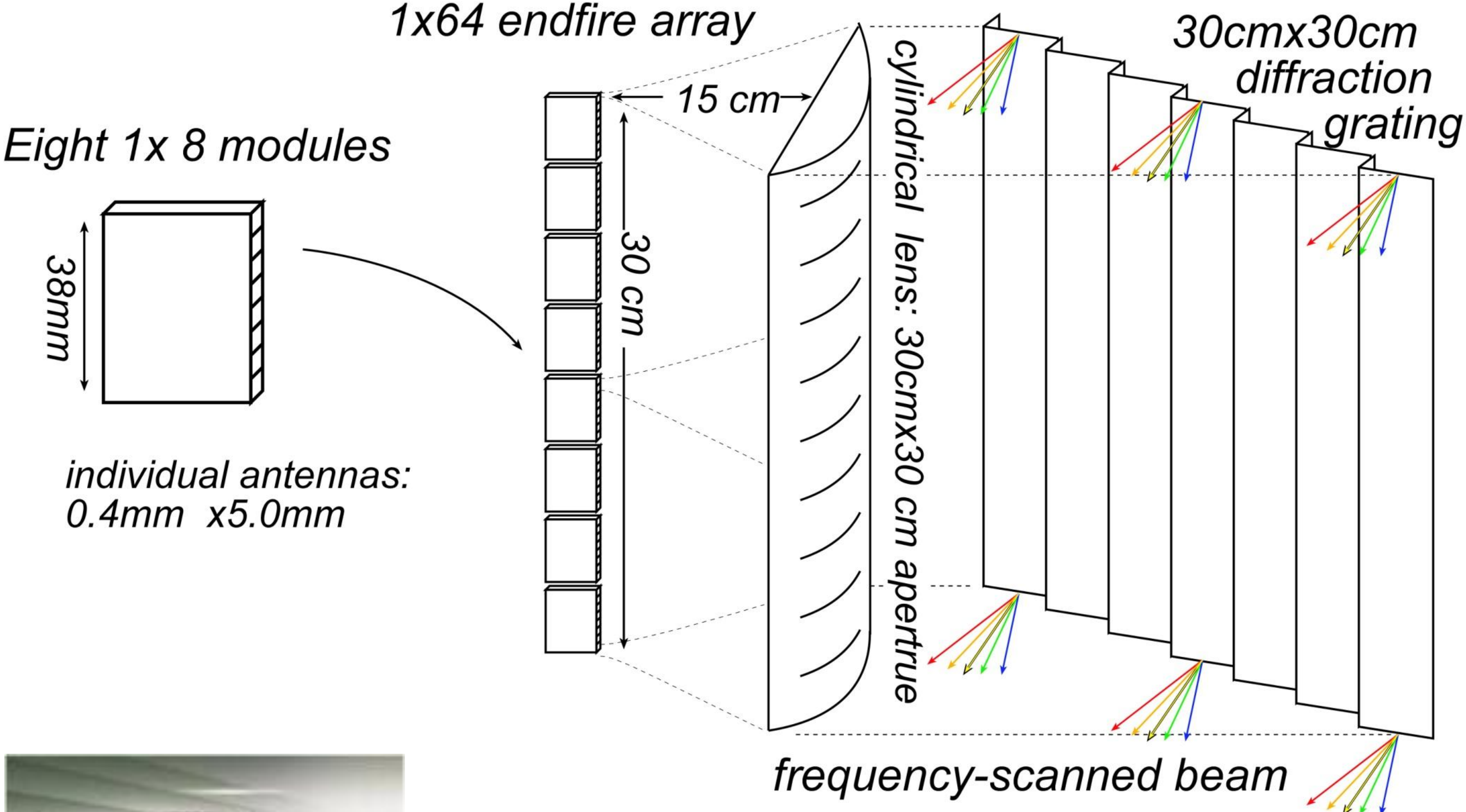
What your eyes see-- in fog

What you see with X-band radar



What you would like to see

400 GHz frequency-scanned imaging car radar



400 GHz frequency-scanned imaging car radar

Range: see a basketball at 300 meters (10 seconds warning) in heavy fog
(10 dB SNR, 25 dB/km, 30cm diameter target, 10% reflectivity, 100 km/Hr)

Image refresh rate: 60 Hz

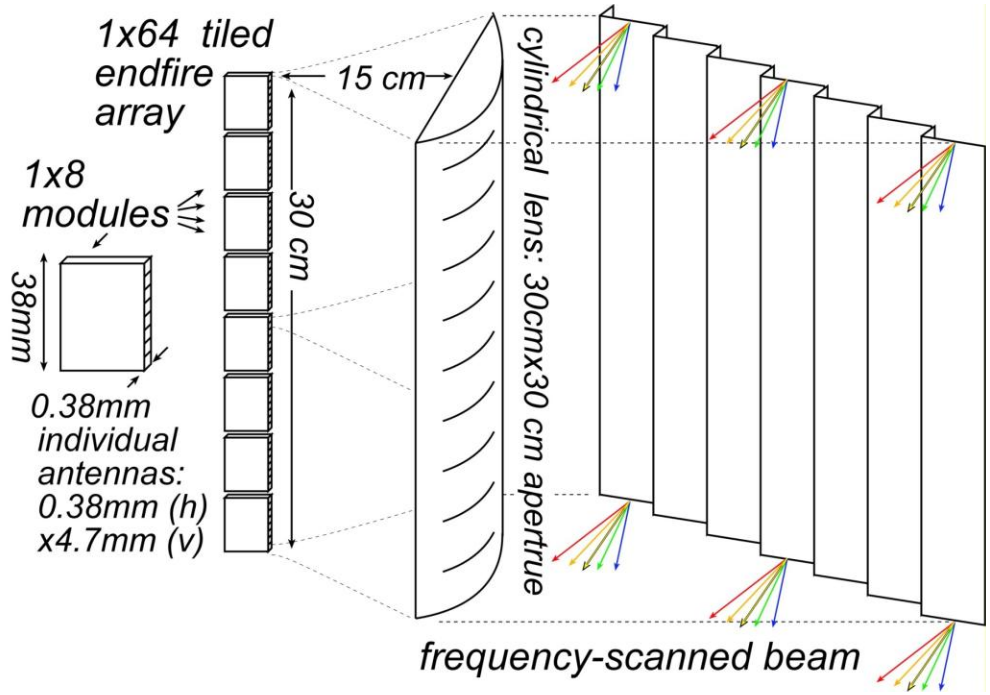
Resolution 64×512 pixels

Angular resolution: 0.14 degrees

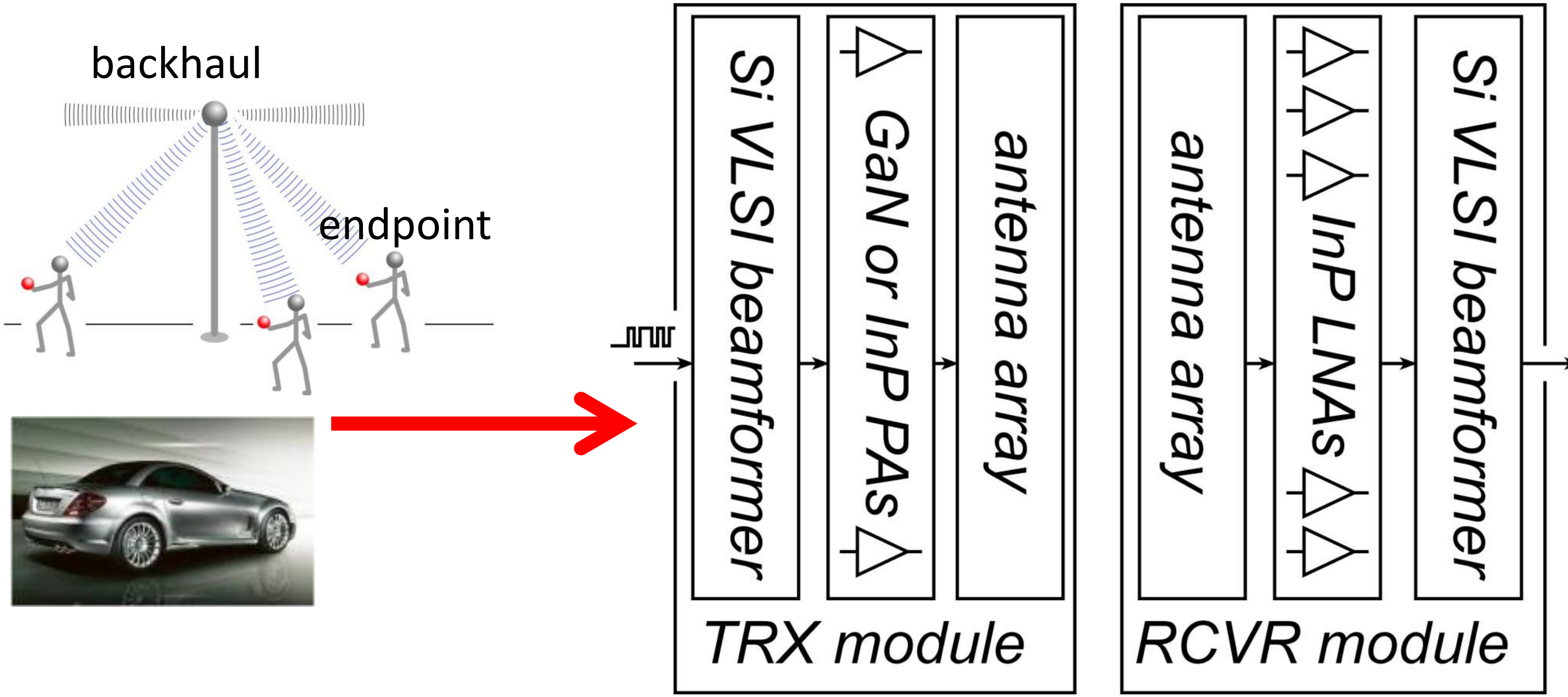
Angular field of view: 9 by 73 degrees

Aperture: 35 cm by 35 cm

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



50-500 GHz Wireless Transceiver Architecture

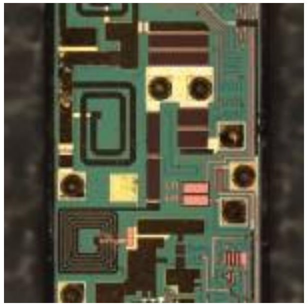


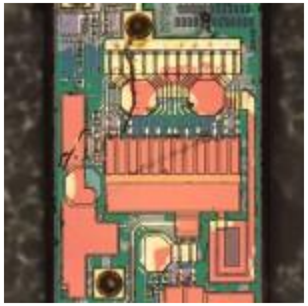
III-V LNAs, III-V PAs → power, efficiency, noise
Si CMOS beamformer→ integration scale

...similar to today's cell phones.

High antenna array gain → large array area
→ far to large for monolithic integration

III-V PAs and LNAs in today's wireless systems...

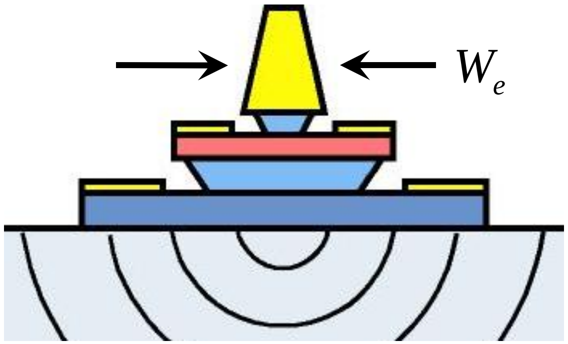




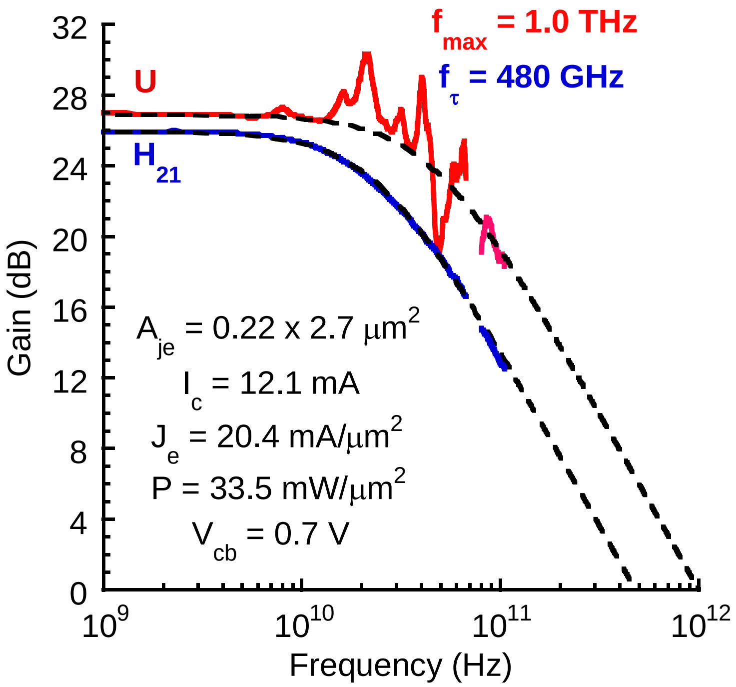
http://www.chipworks.com/blog/recentteardowns/2012/10/02/apple-iphone-5-the-rf/

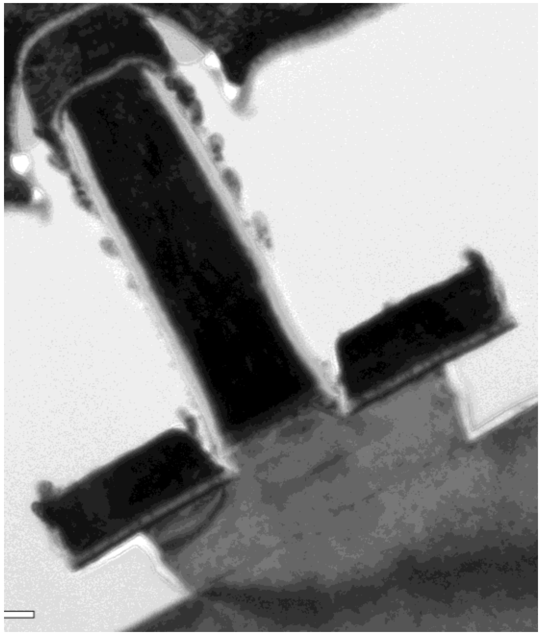
Transistors for 50-500 GHz systems

THz InP Heterojunction Bipolar Transistors



HBT parameter	change
emitter & collector junction widths	decrease 4:1
current density (mA/μm²)	increase 4:1
current density (mA/μm)	constant
collector depletion thickness	decrease 2:1
base thickness	decrease 1.4:1
emitter & base contact resistivities	decrease 4:1



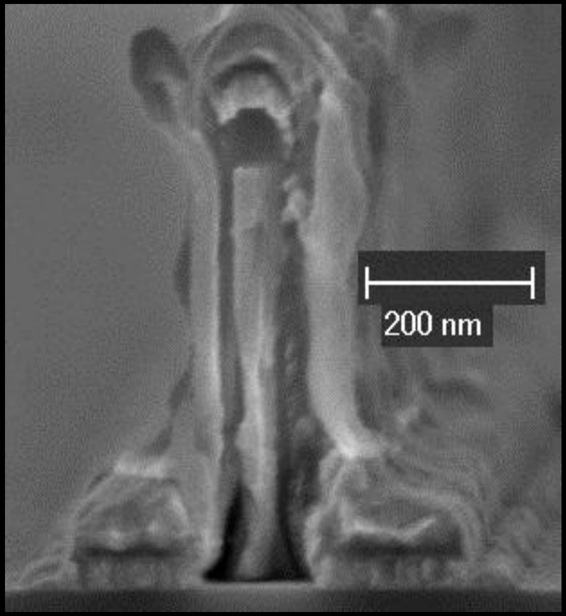


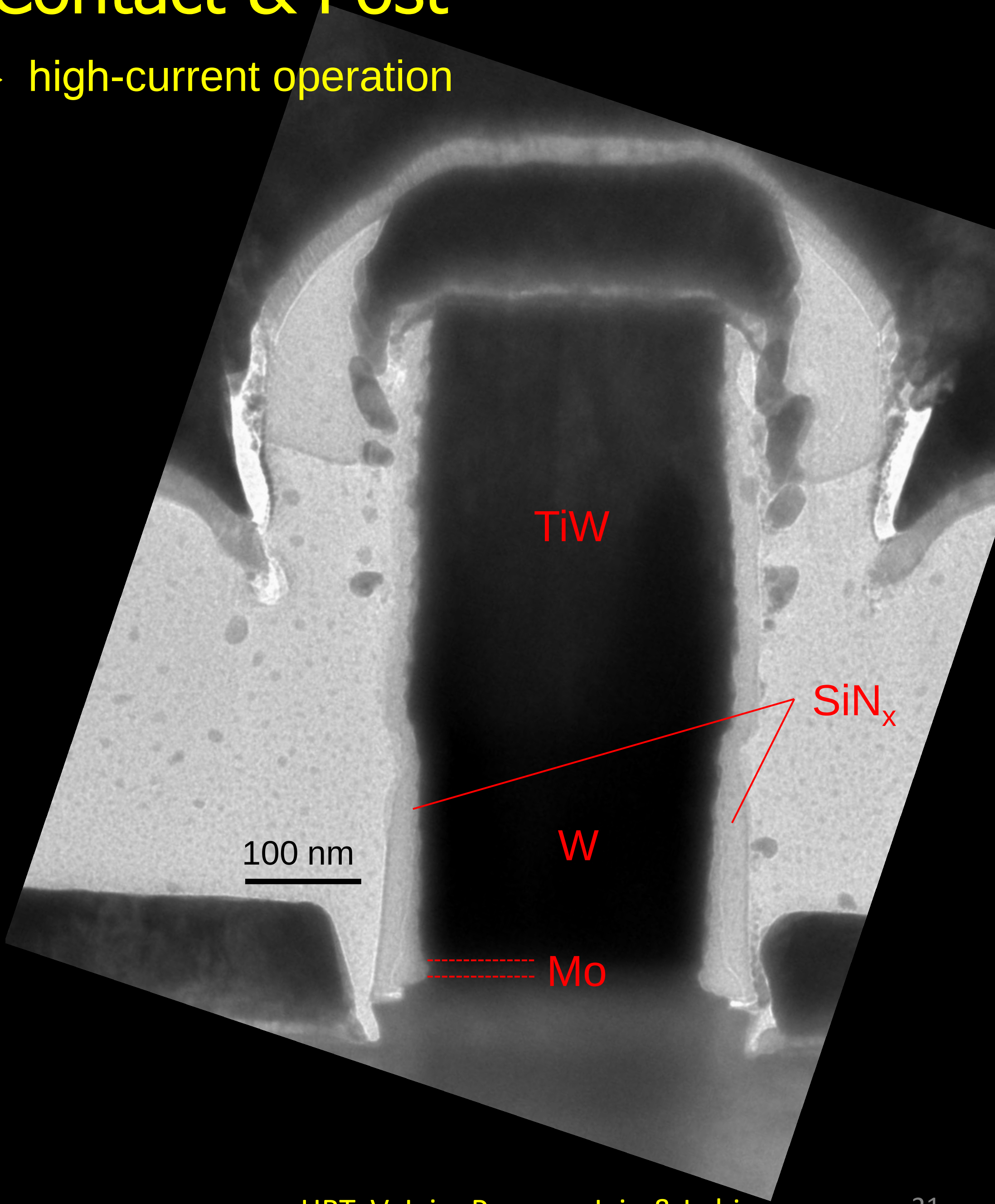
***Challenges*:**
Narrow junctions
low-resistivity contacts.
high current densities

Sub-200-nm Emitter Contact & Post

Refractory contact, refractory post→ high-current operation

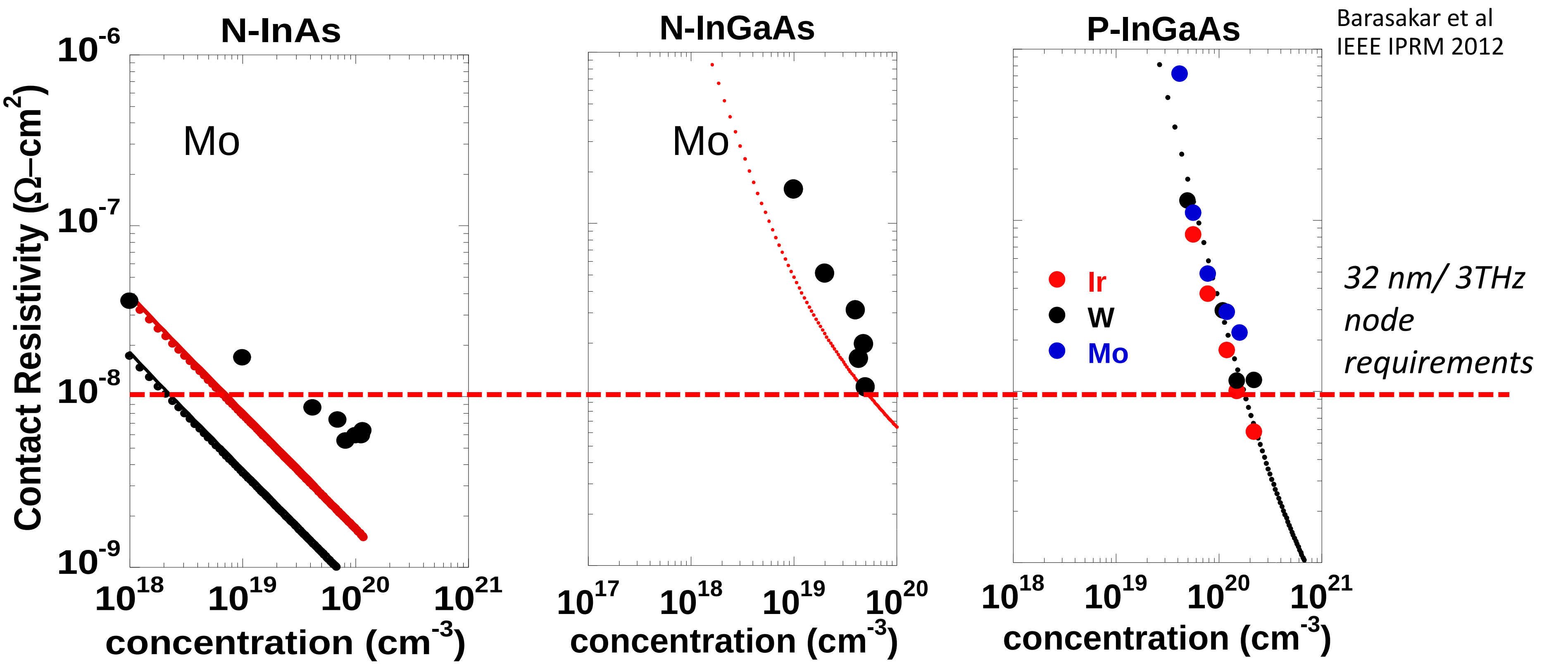
Fabrication: blanket sputter, dry-etch





HBT: V. Jain. Process: Jain & Lobisser

Ultra Low-Resistivity Refractory Contacts

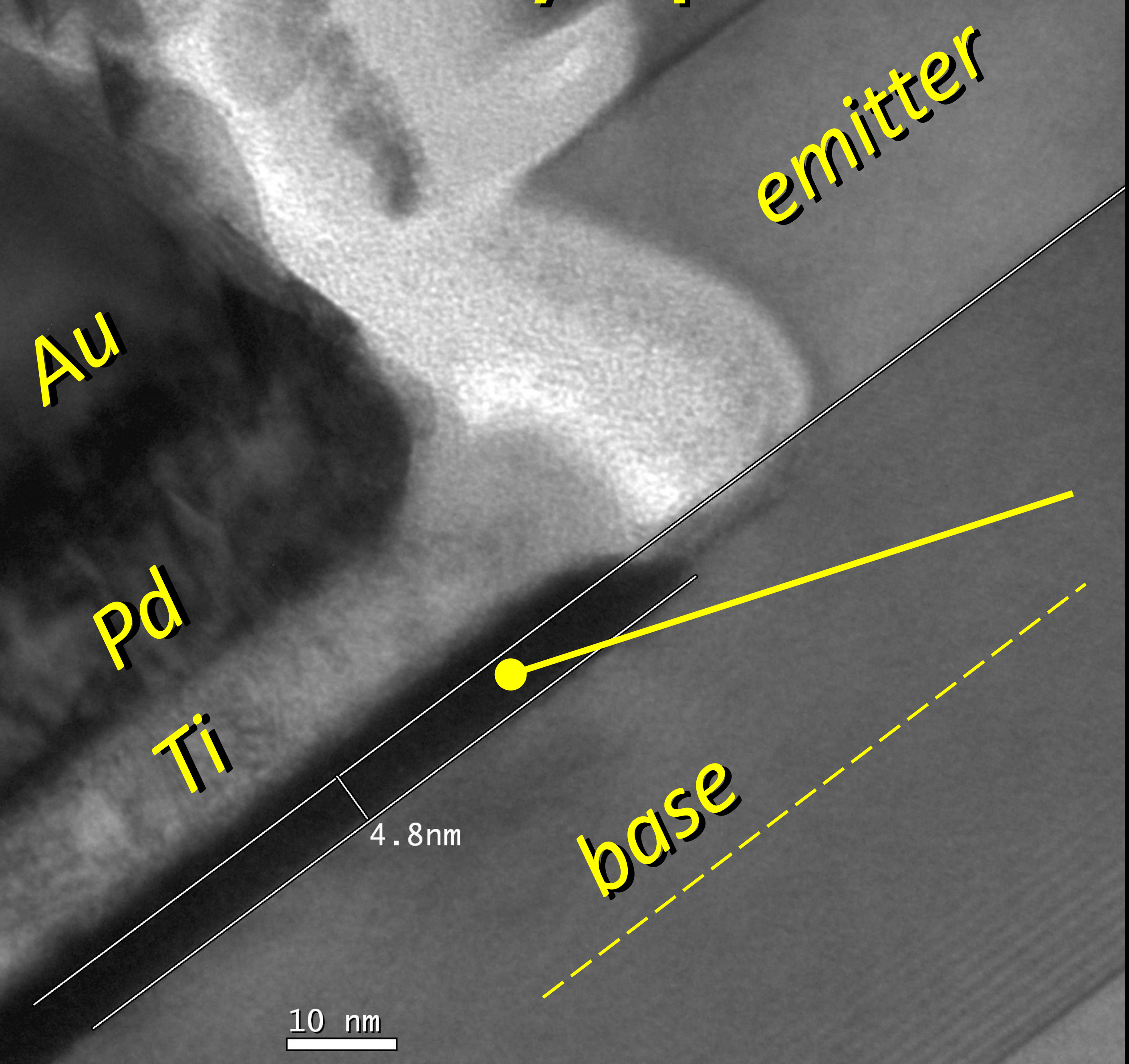


Refractory: robust under high-current operation

Low penetration depth, ~ 1 nm

Contact performance sufficient for 32 nm /2.8 THz node.

Needed: Greatly Improved Ohmic Contacts



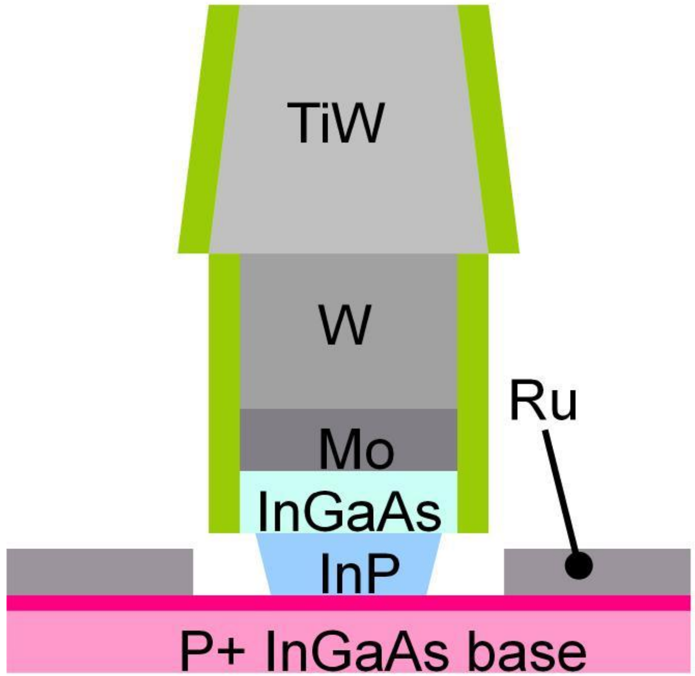
Pt/Ti/Pd/Au

~5 nm
Pt contact
penetration

(into 25 nm base)

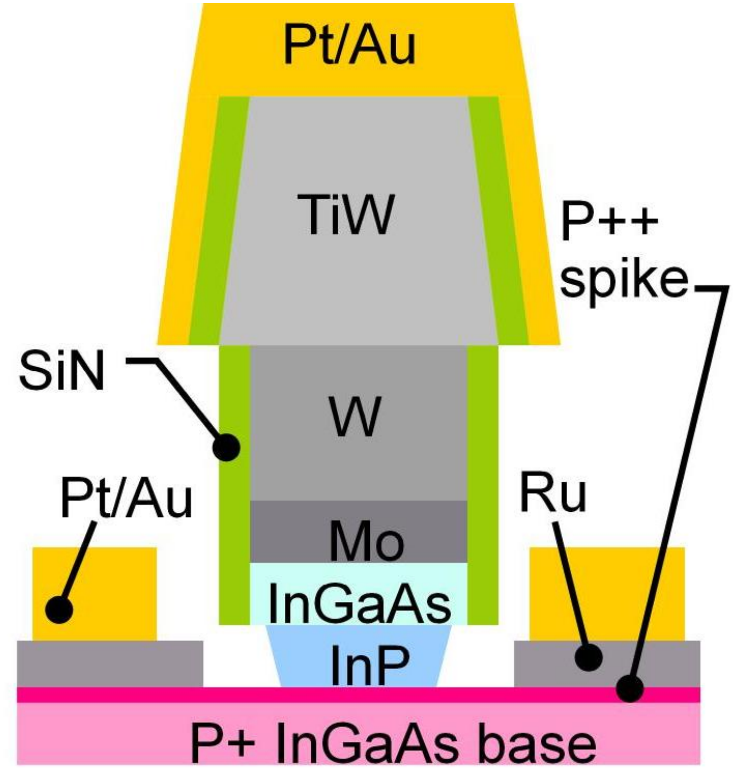
Refractory Base Process (1)

Blanket liftoff; refractory base metal



low contact resistivity
low penetration depth

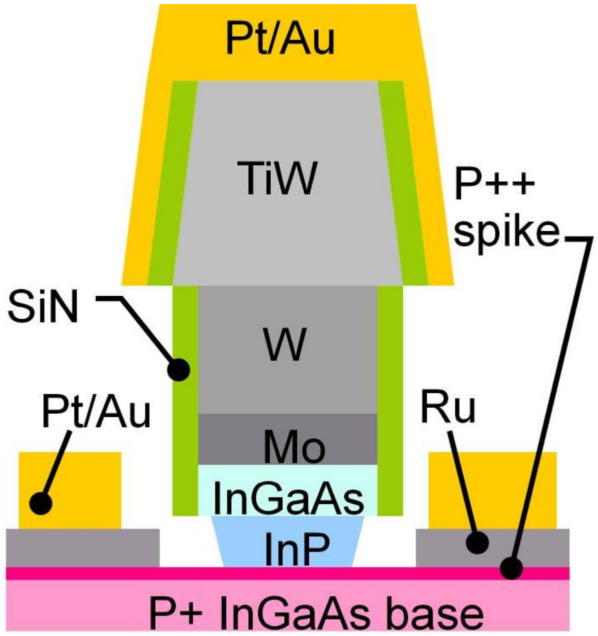
Patterned liftoff; Thick Ti/Au

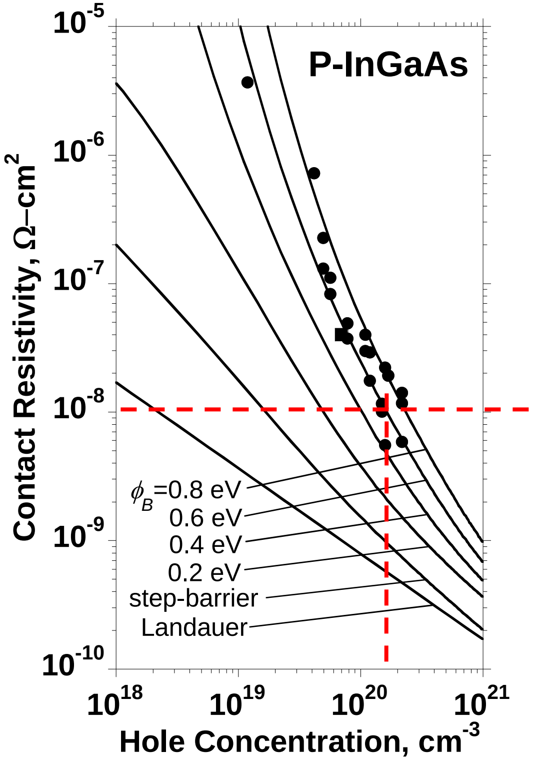


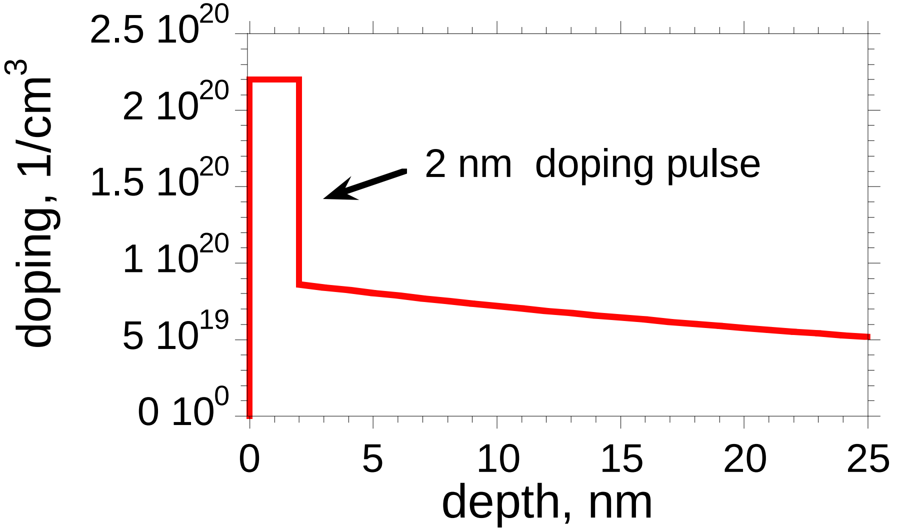
low bulk access resistivity

base surface not exposed to photoresist chemistry: no contamination
low contact resistivity, shallow contacts
low penetration depth allows thin base, pulsed-doped base contacts

Refractory Base Process (2)





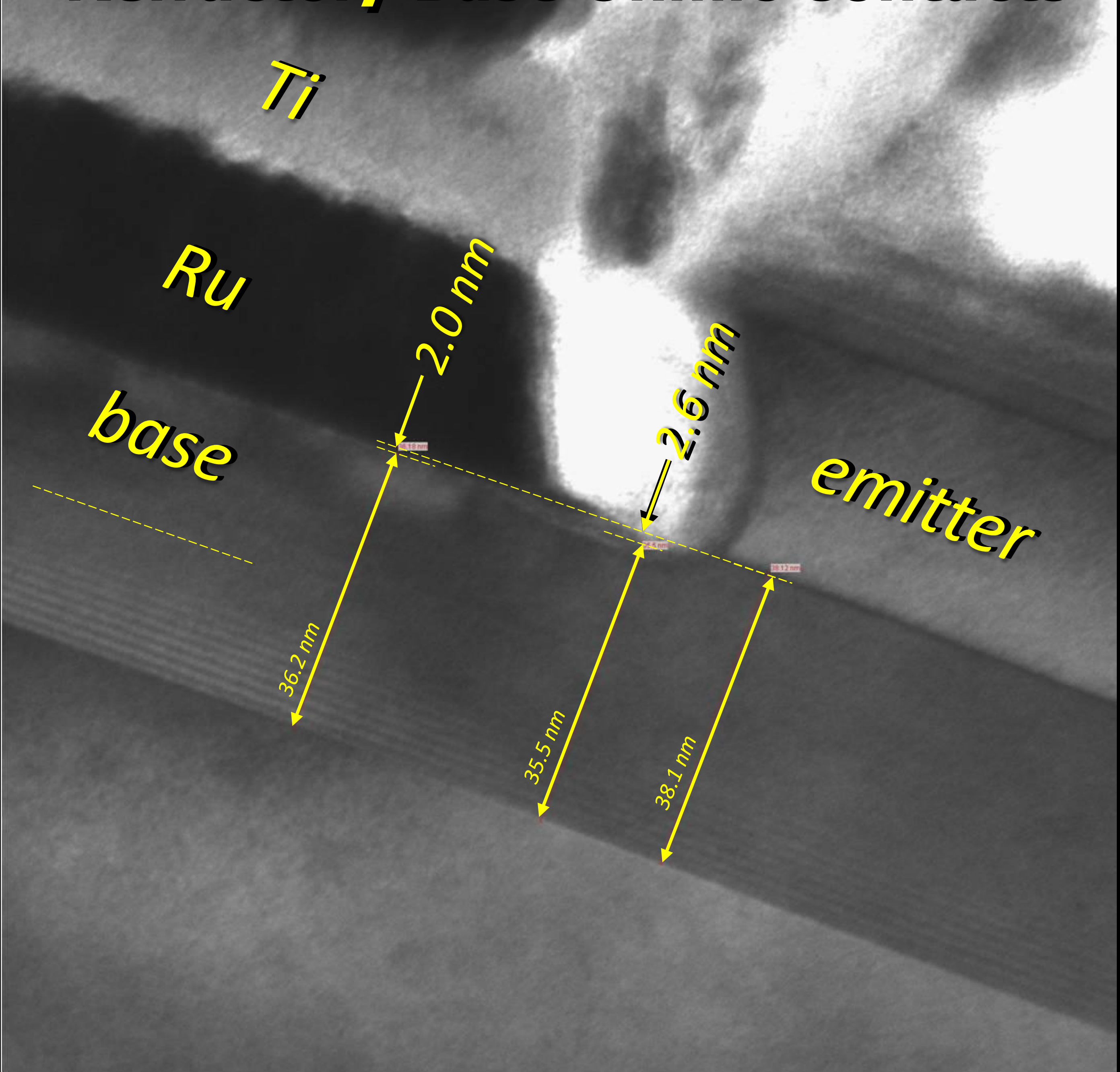


Increased surface doping:
reduced contact resistivity,
but increased Auger recombination.

→ Surface doping spike at most 2-5 thick.

Refractory contacts do not penetrate;
compatible with pulse doping.

Refractory Base Ohmic Contacts



Ru / Ti / Au

<2 nm
Ru contact
penetration

(surface removal
during cleaning)

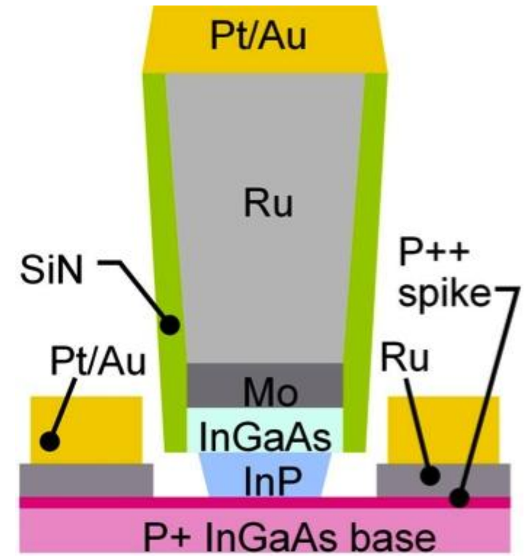
3-4 THz Bipolar Transistors are Feasible.

4 THz HBTs realized by:

Extremely low resistivity contacts

Extreme current densities

Processes scaled to 16 nm junctions



Scaling Node	64	32	16	nm
Emitter Width	64	32	16	nm
Resistivity	2	1	0.5	$\Omega\text{-}\mu m^2$
Base Thickness	18	15	13	nm
Contact width	60	30	15	nm
Contact ρ	2.5	1.25	0.63	$\Omega\text{-}\mu m^2$
Collector Width	180	90	45	nm
Thickness	53	37.5	26	nm
Current Density	36	72	140	$mA/\mu m^2$
f_τ	1.0	1.4	2.0	THz
f_{max}	2.0	2.8	4.0	THz

Impact:
efficient power amplifiers
and complex signal processing
from 100-1000 GHz.

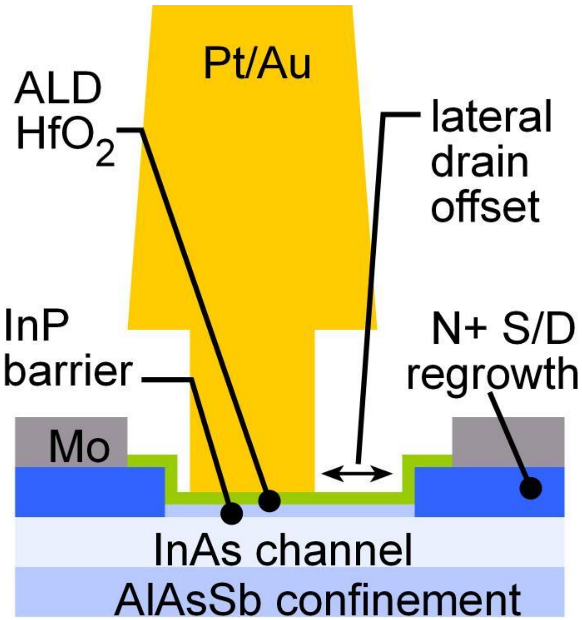
2-3 THz Field-Effect Transistors are Feasible.

3 THz FETs realized by:

Regrown low-resistivity source/drain

Very thin channels, high-K dielectrics

Gates scaled to 9 nm junctions



gate length	36	18	9	nm
EOT	0.8	0.4	0.2	nm
well thickness	5.6	2.8	1.4	nm
effective mass	0.05	0.08	0.08	times m_0
# bands	1	1	1	--
S/D resistivity	150	74	37	Ω-µm
extrinisic g_m	2.5	4.2	6.4	mS/µm
on-current	0.55	0.8	1.1	mA/µm
f_τ	0.70	1.2	2.0	THz
f_{max}	0.81	1.4	2.7	THz

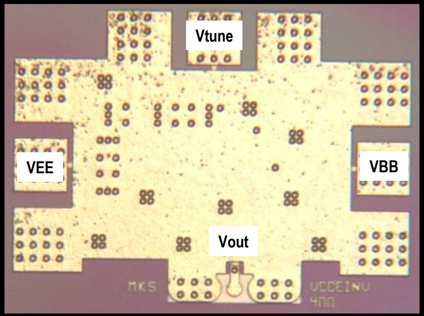
Impact:
Sensitive, low-noise receivers from 100-1000 GHz.

3 dB less noise →
need 3 dB less transmit power.

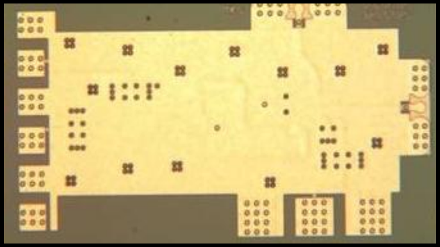
InP HBT Integrated Circuits: 600 GHz & Beyond

TELEDYNE SCIENTIFIC COMPANY
A Teledyne Technologies Company
UCSB

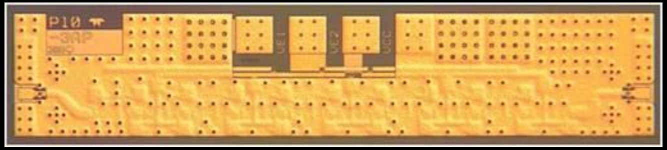
614 GHz fundamental VCO
M. Seo, TSC / UCSB



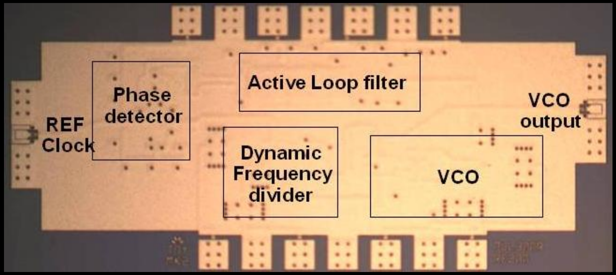
340 GHz dynamic frequency divider
M. Seo, UCSB/TSC
IMS 2010



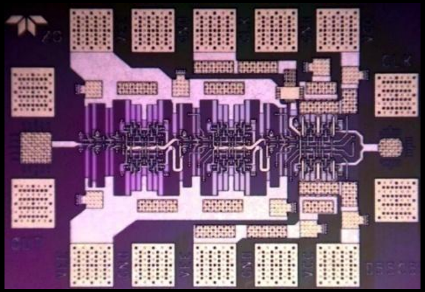
585-600 GHz amplifier, > 34 dB gain, 2.8 dBm output
M. Seo, TSC
IMS 2013



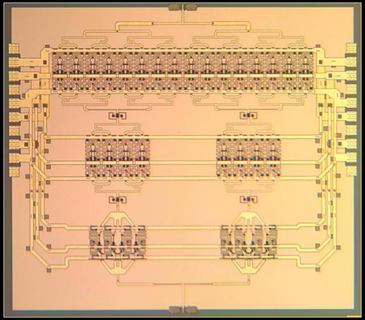
300 GHz fundamental PLL
M. Seo, TSC
IMS 2011



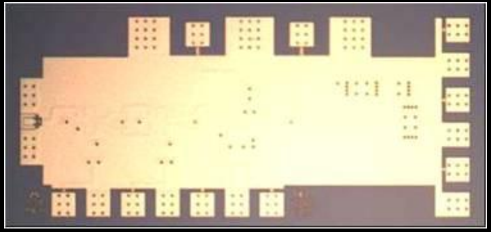
204 GHz static frequency divider (ECL master-slave latch)
Z. Griffith, TSC
CSIC 2010



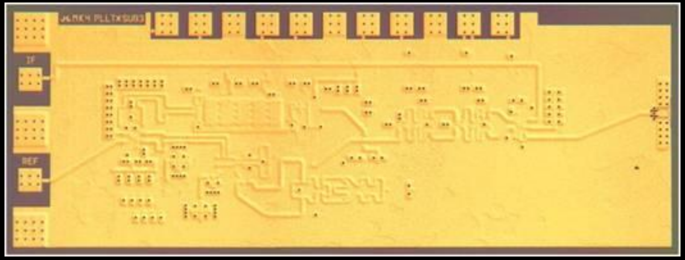
220 GHz 180 mW power amplifier
T. Reed, UCSB
Z. Griffith, Teledyne
CSICS 2013



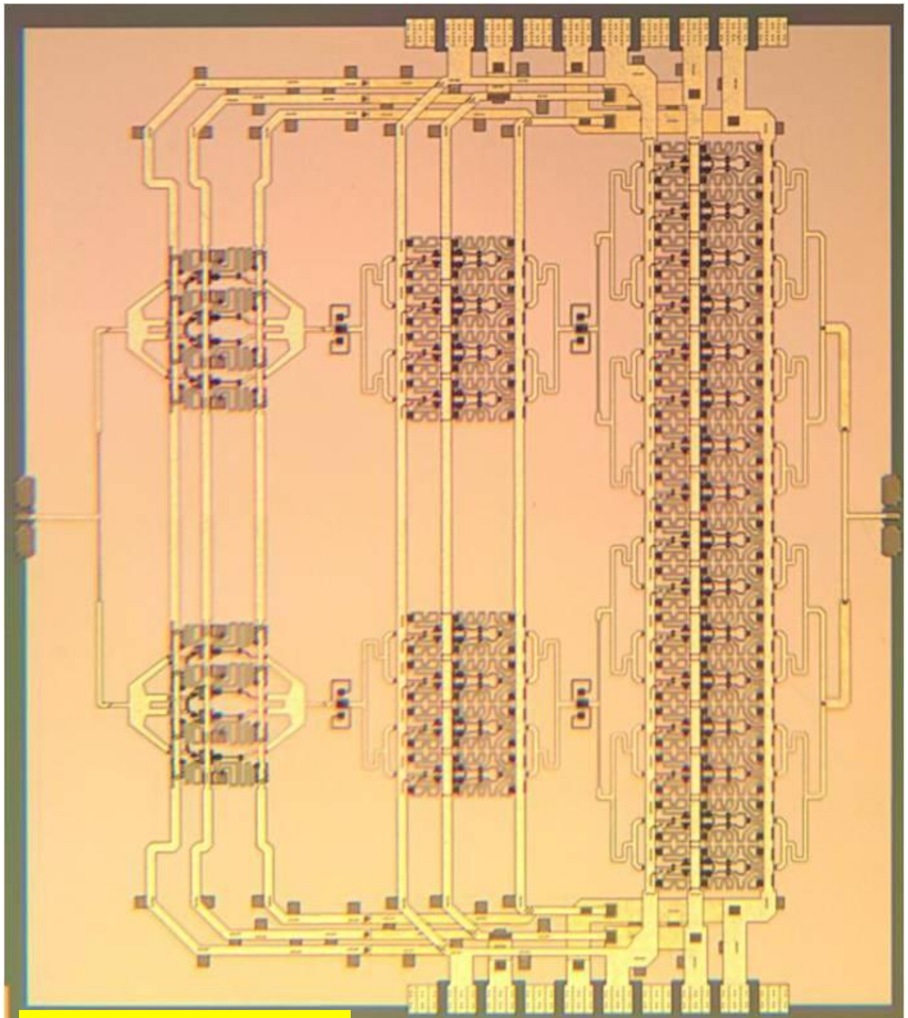
Integrated 300/350GHz Receivers:
LNA/Mixer/VCO
M. Seo TSC



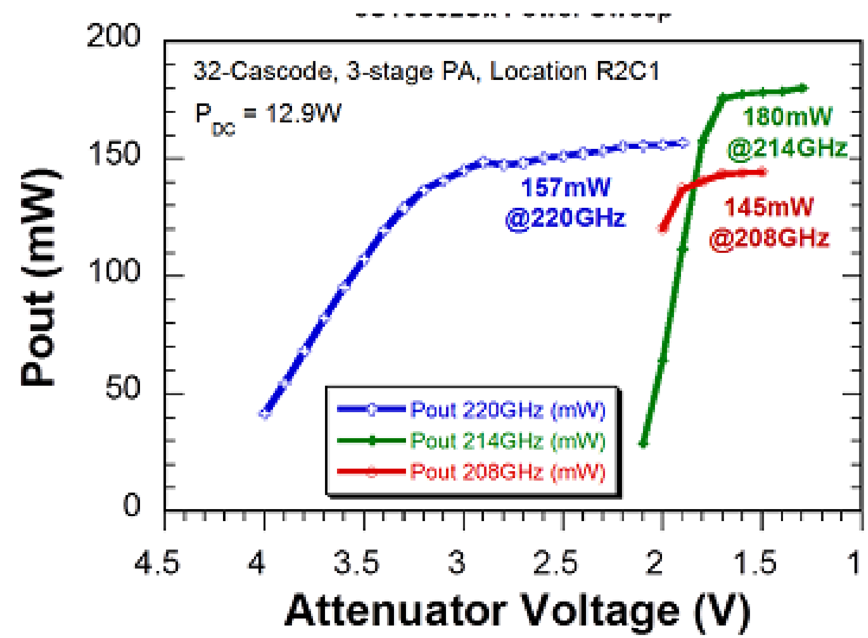
600 GHz Integrated Transmitter
PLL + Mixer
M. Seo TSC

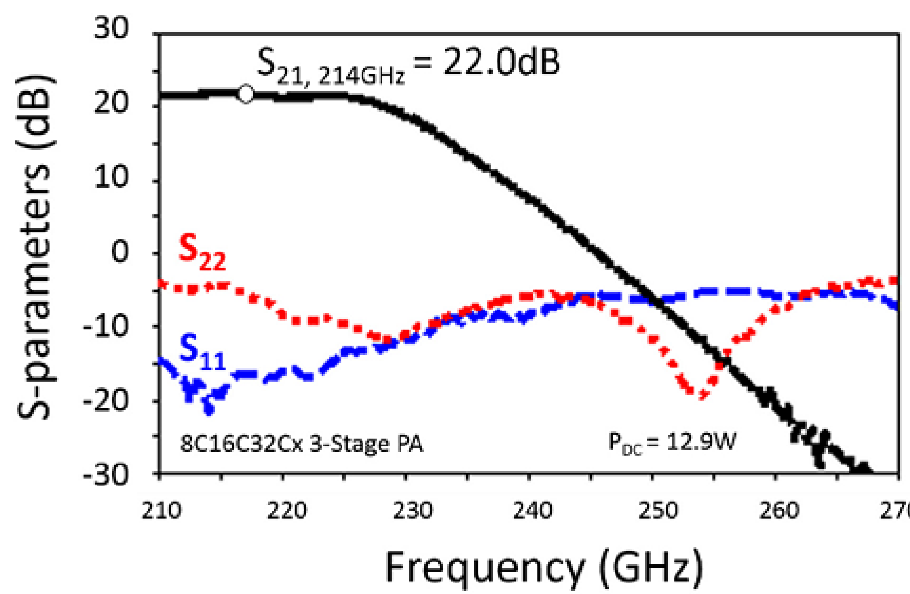


220 GHz 180mW Power Amplifier (330 mW design)



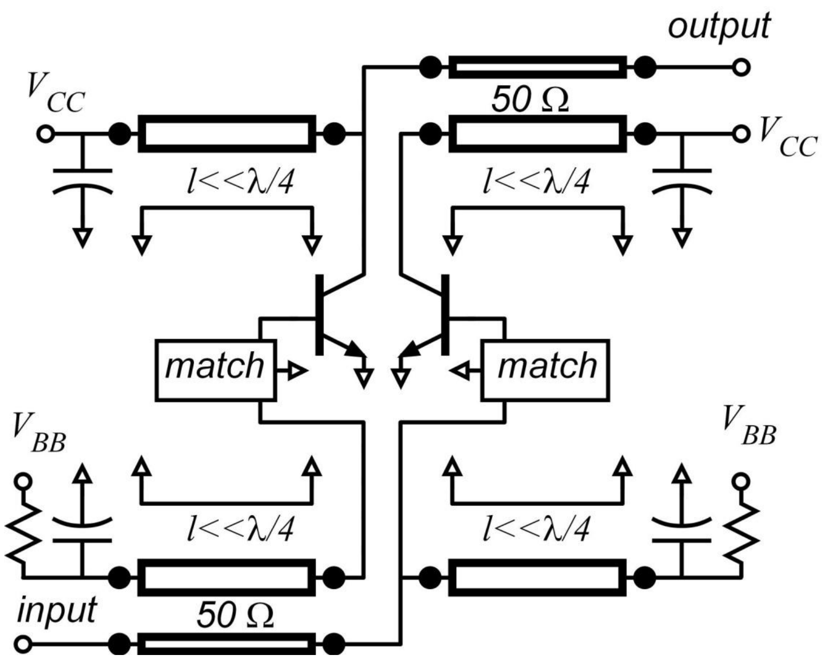
2.3 mm x 2.5 mm

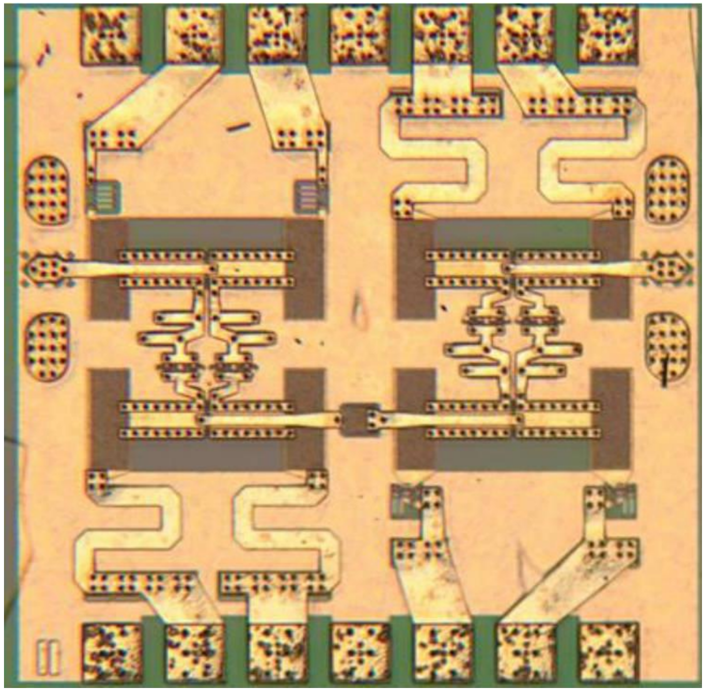


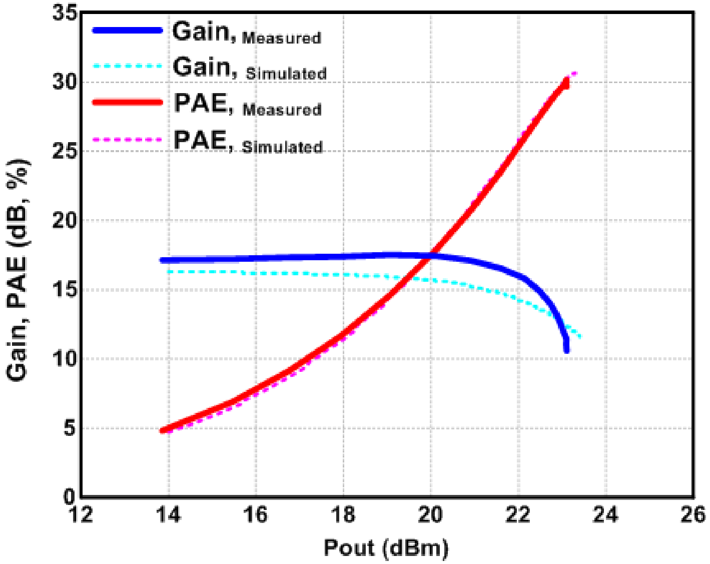


T. Reed, UCSB
Z. Griffith, Teledyne
Teledyne 250 nm InP HBT

PAs using **Sub-λ/4** Baluns for Series-Combining







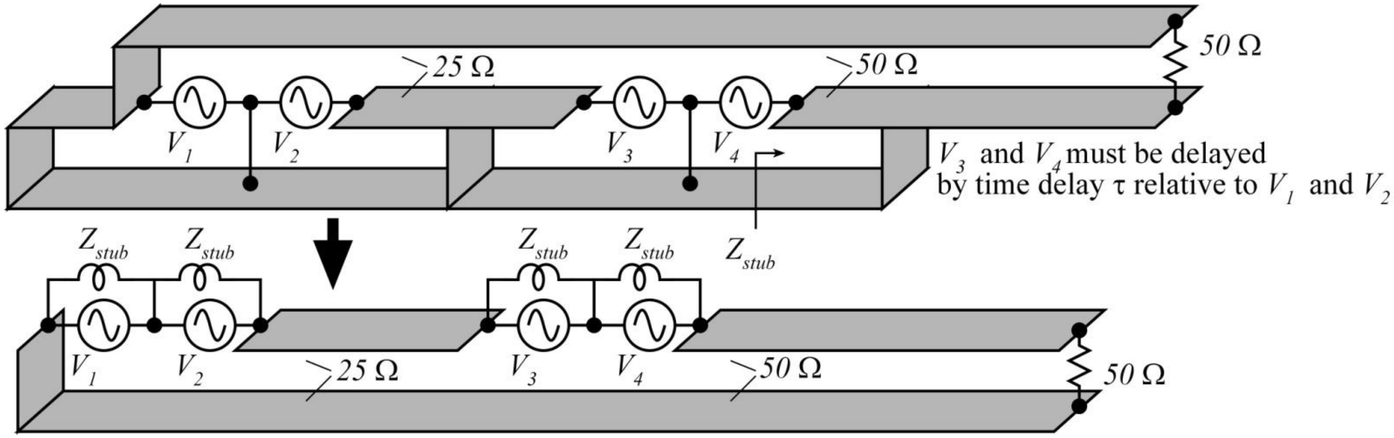
80-90 GHz Power Amplifier

17.5dB Gain, >200mW P_{SAT}, >30% PAE

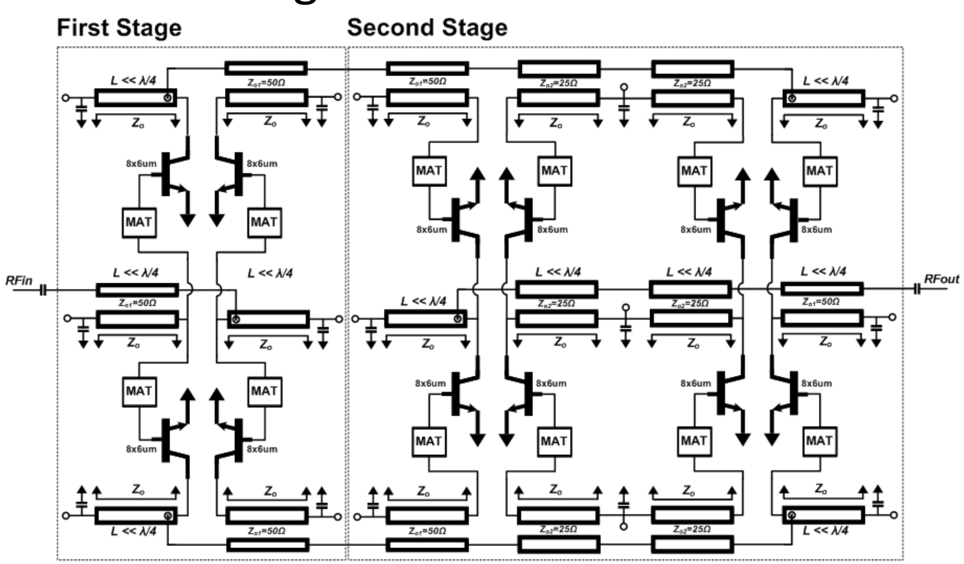
Power per unit IC die area*
=307 mW/mm² (pad area included)
=497 mW/mm² (if pad area not included)

800 mW 1.3mm^2 Design Using 4:1 Baluns

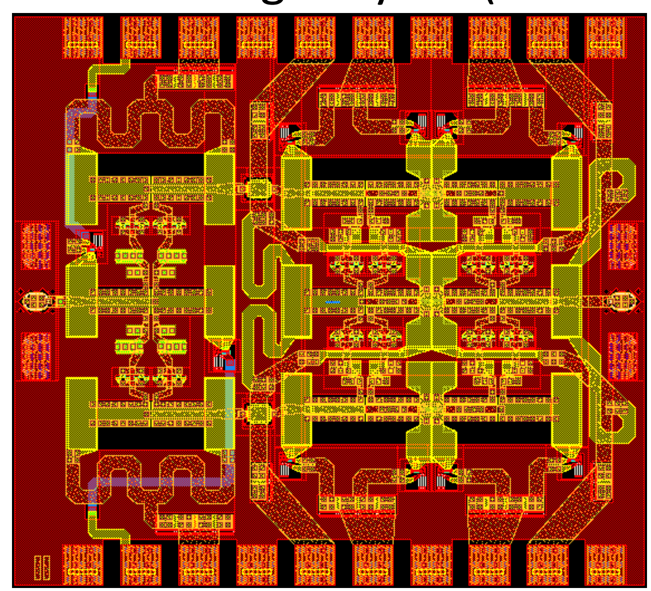
Baluns for 4:1 series-connected power-combining



4:1 Two-Stage Schematic



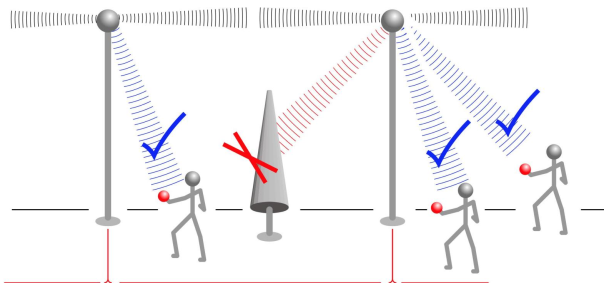
4:1 Two-Stage Layout (1.2x1.1mm^2)

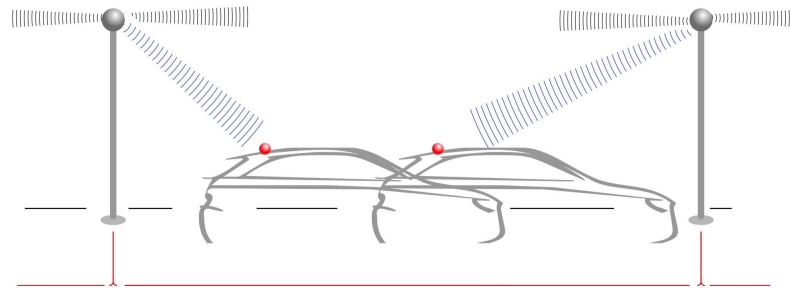


Small-signal data looks good. Need driver amp for P_{sat} testing.

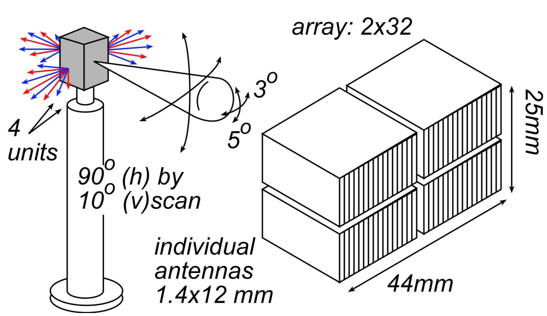
50-500 GHz Wireless Electronics

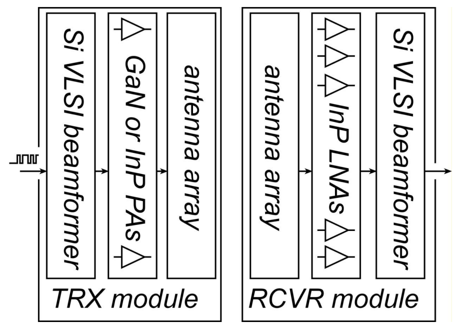
Mobile communication @ 2Gb/s per user, 1 Tb/s per base station





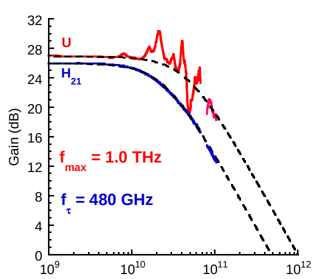
Requires: large arrays, complex signal processing, high P_{out}, low F_{min}

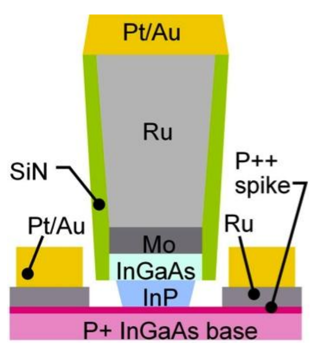


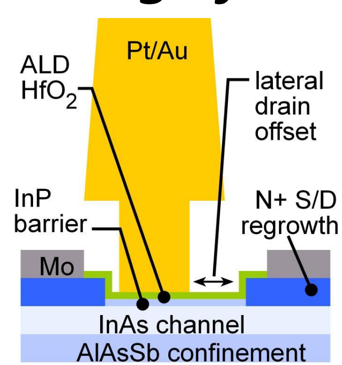


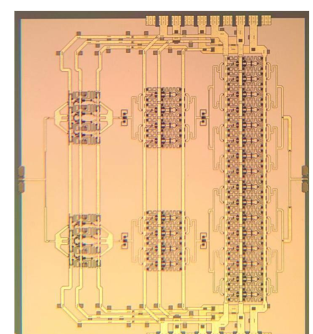
VLSI beamformers
VLSI equalizers
III-V LNAs & PAs

III-V Transistors will perform well enough for 1.5-2 THz systems.



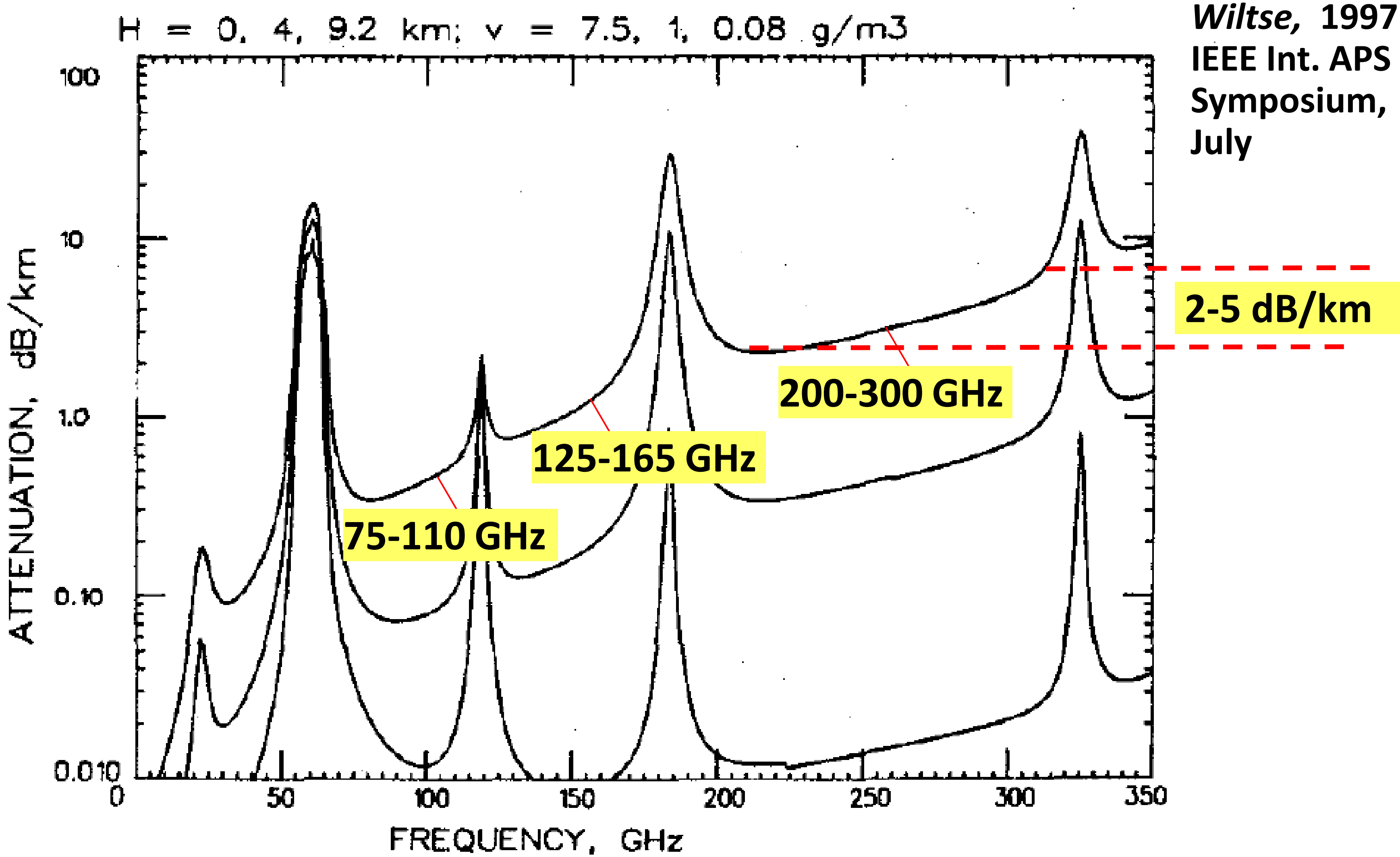






(backup slides follow)

50-500 GHz Wireless Has Low Attenuation ?



***Wiltse,* 1997**
IEEE Int. APS Symposium, July

Low attenuation on a sunny day

mm/sub-mm-waves: Not my usual presentation

My typical THz electronics presentation:
THz transistor design & fabrication, mm/sub-mm-wave IC design

Today a different emphasis:

50+ GHz systems: potential high-volume applications

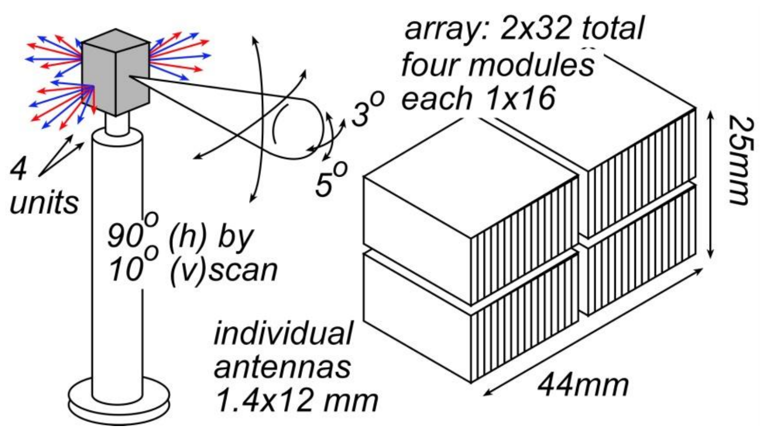
Link analysis→ what performance do we need ?

What will the hardware look like ?

What components, packages, devices should we develop ?

(wrap up with a quick summary of THz transistor & IC results)

Effects of array size, Transmitter PAE, Receiver F_{min}



200 mW phase shifters in TRX & RCVR, 0.1 W LNAs

Large arrays:
more directivity, more complex ICs

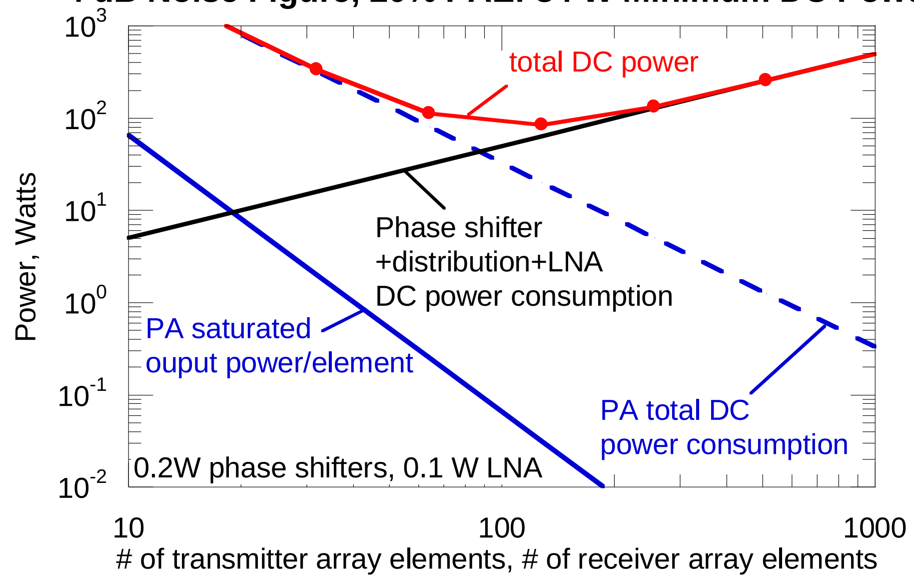
Small arrays:
less directivity, less complex ICs

→ ***Proper array size minimizes DC power***

Low transmitter PAE
& high receiver noise
are partially offset using arrays,

but DC power, system complexity still suffer

4 dB Noise Figure, 20% PAE: 84 W Minimum DC Power



10 dB Noise Figure, 5%PAE: 208 W Minimum DC Power