Antennas for cellular base stations

— challenges, trends and constraints —

by Jan Hesselbarth, University of Stuttgart

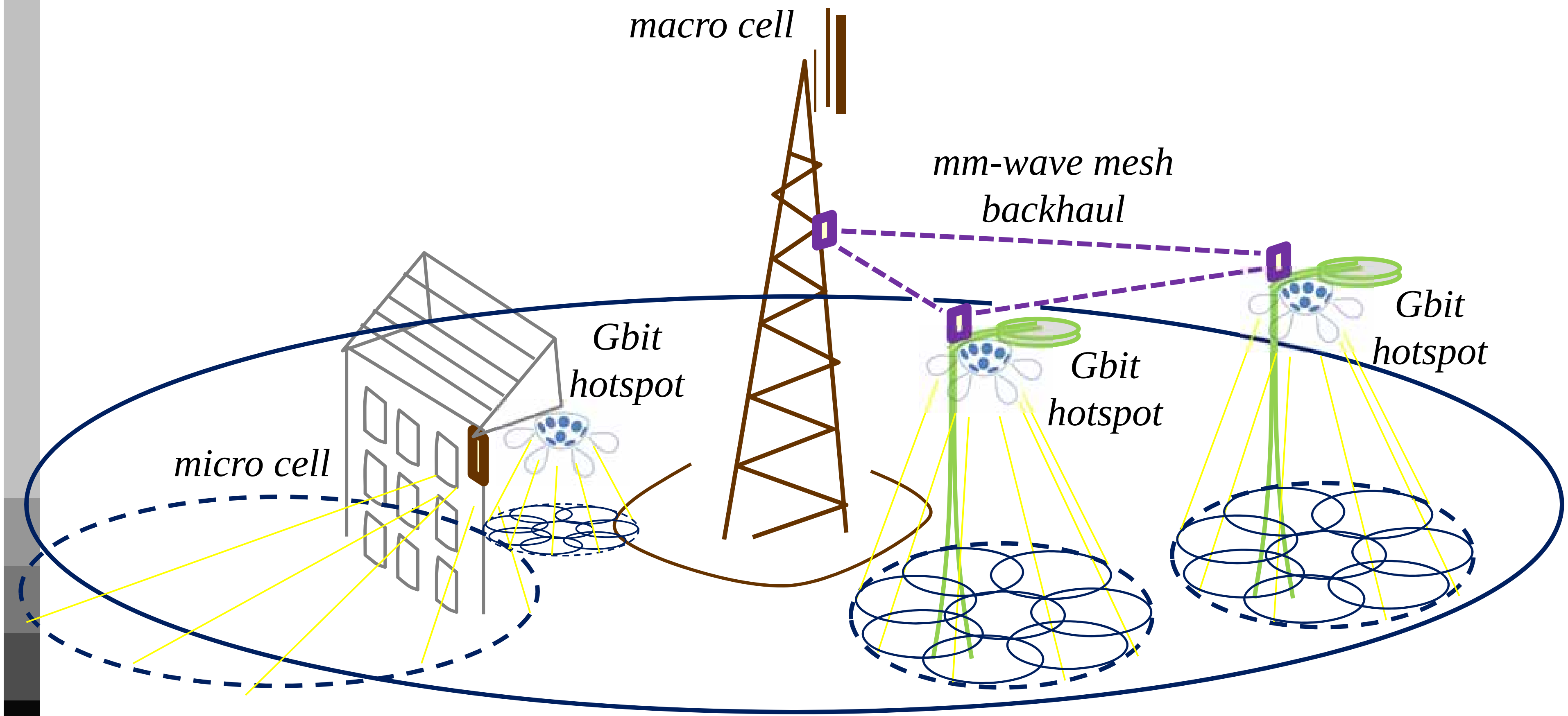
FP7–ARTISAN meeting, Belfast, January 30, 2014

outline:

- choice of frequency
- antenna radiator types and characteristics
- macro sector antennas
- antennas for in-buiding and in-cabin systems
- wireless backhaul
- what‘s next

Antennas to provide coverage, throughput, adaptivity

Different requirements for frequency, pattern, adaptivity, size, cost etc.



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Choice of frequency

Criteria for mobile cellular:

antenna size, path loss, diffraction, bandwidth, Doppler

low frequency cellular:

- low path loss / large cells
- strong diffraction
- small Doppler shift
- small bandwidth
- large antennas

→ for coverage and mobility
→ small throughput

(450 MHz) & 700 – 1000 MHz

high frequency cellular:

- high path loss / small cells
- weak diffraction
- large Doppler shift
- larger bandwidth
- smaller antennas

→ for increased throughput in rather small cells

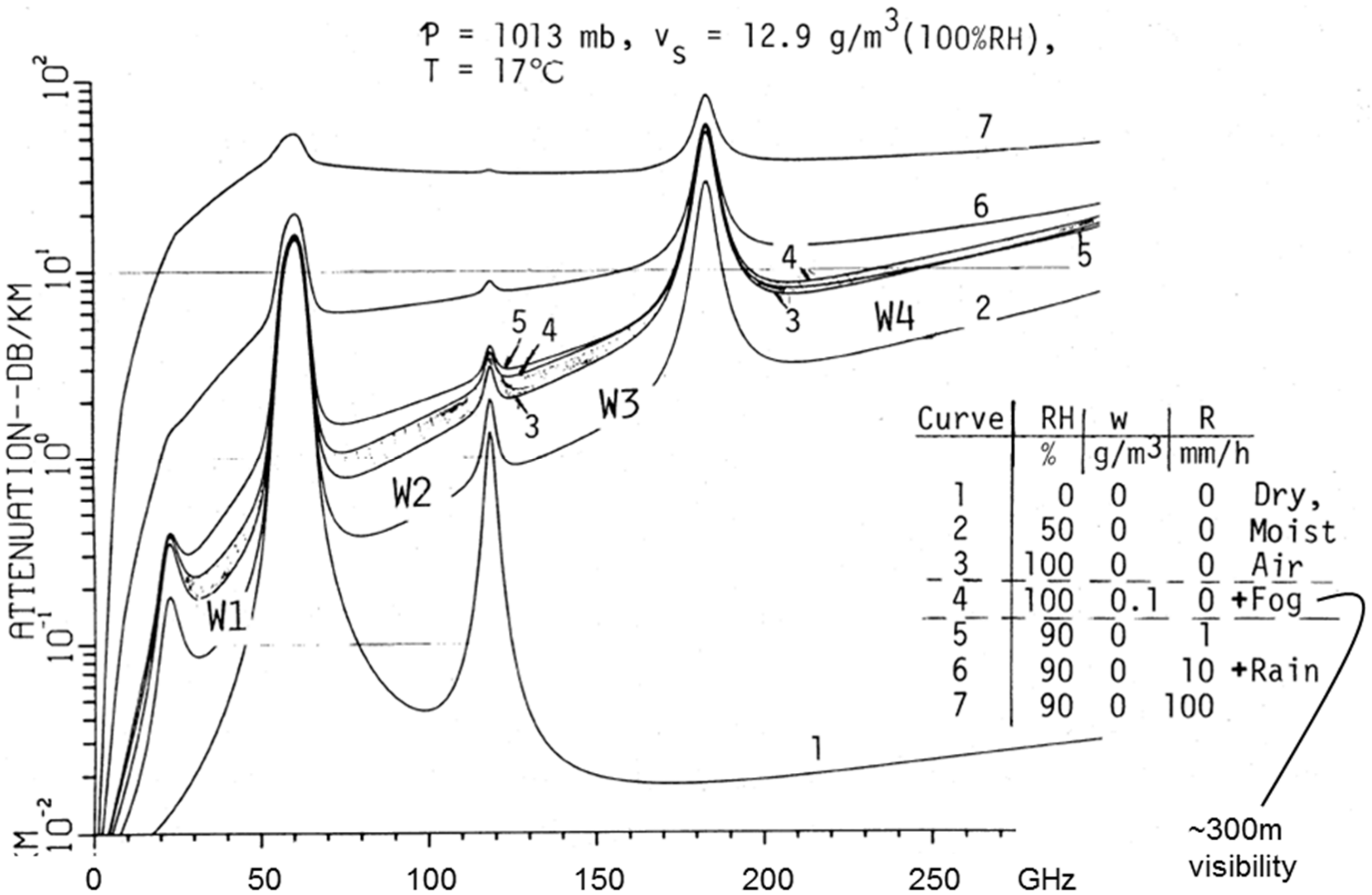
1700 – 2600 MHz

Example: „NMT“ network in Skandinavia at 450 MHz: 25 km cell radius, few users → congested in some cities as early as 1983

Choice of frequency

Criteria for **wireless backhaul**:

path loss, bandwidth, atmospheric attenuation, licensing scheme



[H.J. Liebe, NTIA report 83-137]

Choice of frequency

Criteria for **wireless backhaul**:

path loss, bandwidth, atmospheric attenuation, licensing scheme

→ long-distance hops (>10 km) with raher low capacity at 6…20 GHz
. dish diameter ~ 1…2 m

→ medium-distance hops (3…10 km) with high capacity (~ 100 Mbps) at 28…44 GHz
. dish diameter ~ 0.6 m

→ shortest-distance hops (<1 km) with multi-GBps capacity at 60 GHz
. dish diameter ~ 0.3 m

→ short-distance hops (<2 km) with multi-GBps capacity at 71…86 GHz
. dish diameter ~ 0.3 m

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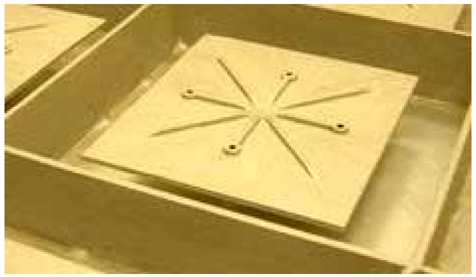
Antenna radiator types and characteristics

For most antennas with sectorial pattern (not: omnidirectional ones), a groundplane provides suppression of backward radiation and is used for mounting purposes.

Radiators with groundplane:

patch



dipole over ground

backed slot

… all similar in gain (5…9 dBi) and in beamwidth (90°…140°)

Antenna radiator types and characteristics

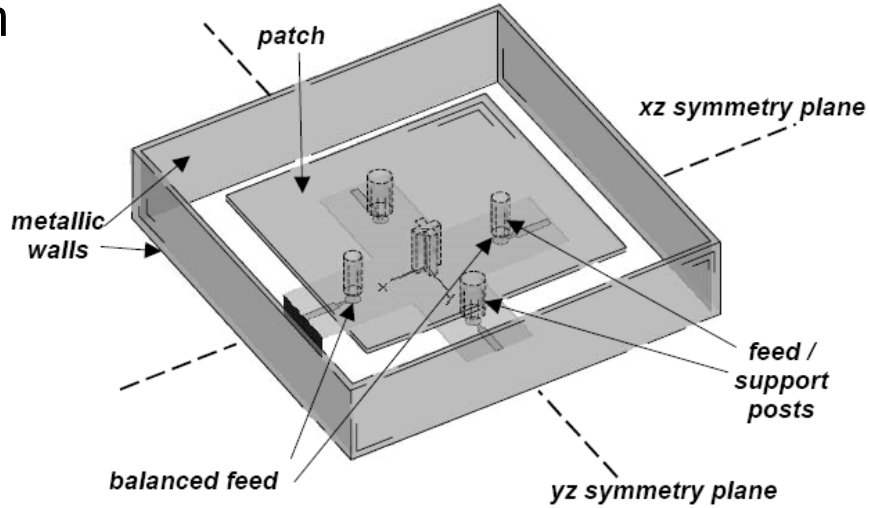
- **backed slot** antennas: severe problems with bandwidth
  → no relevant use

- **patch** antennas: reasonable bandwidth requires very thick dielectric or stacked patches;
  efficiency and cost and weight requirements lead to mechanically tricky air dielectric
  → limited use

example: thick air dielectric patch

(bandwidth ~8% @ $|S_{11}| < -10$dB)

[Alcatel - Lucent]

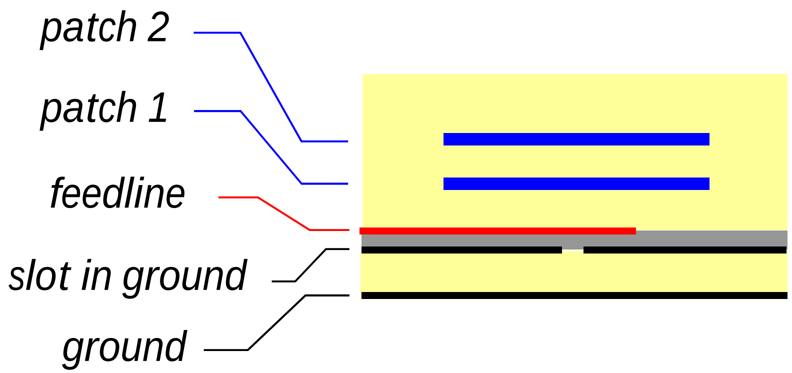


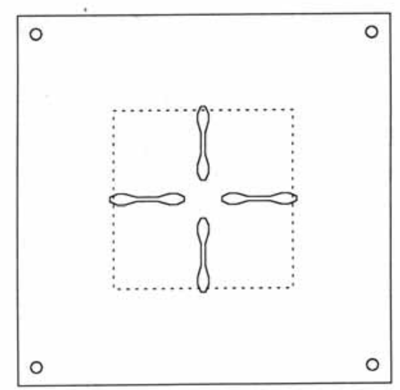
Antenna radiator types and characteristics

- **patch** antennas:

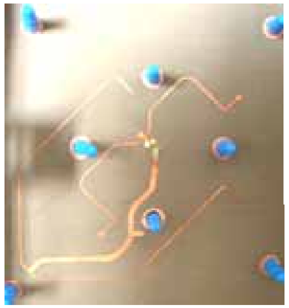
example: air dielectric stacked patch

(3 resonances — bandwidth
~19% @ $|S_{11}| < -10$ dB)

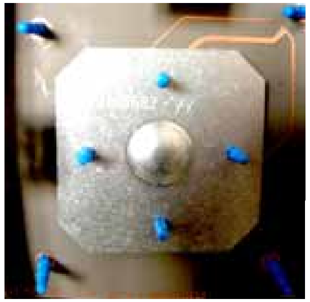




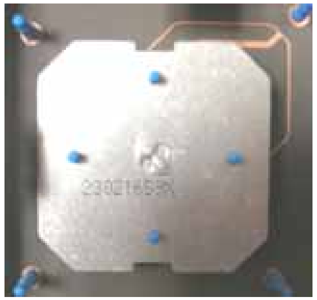
slot & patches



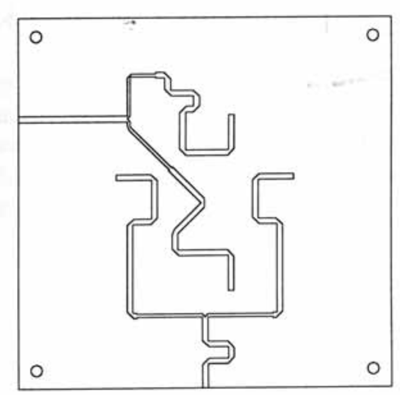
feed



patch 1



patch 2



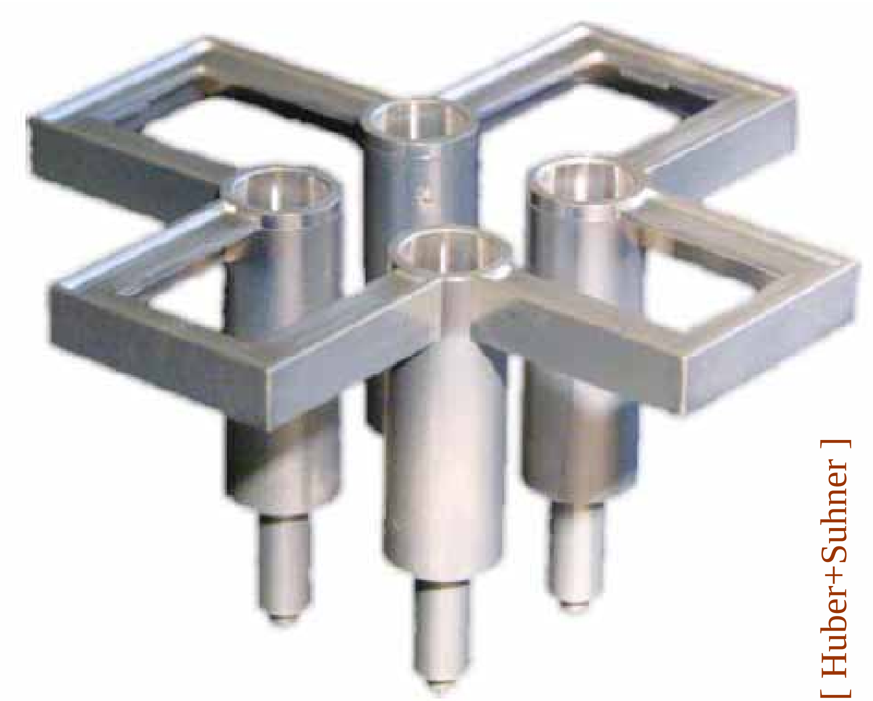
feed

[Huber+Suhner]

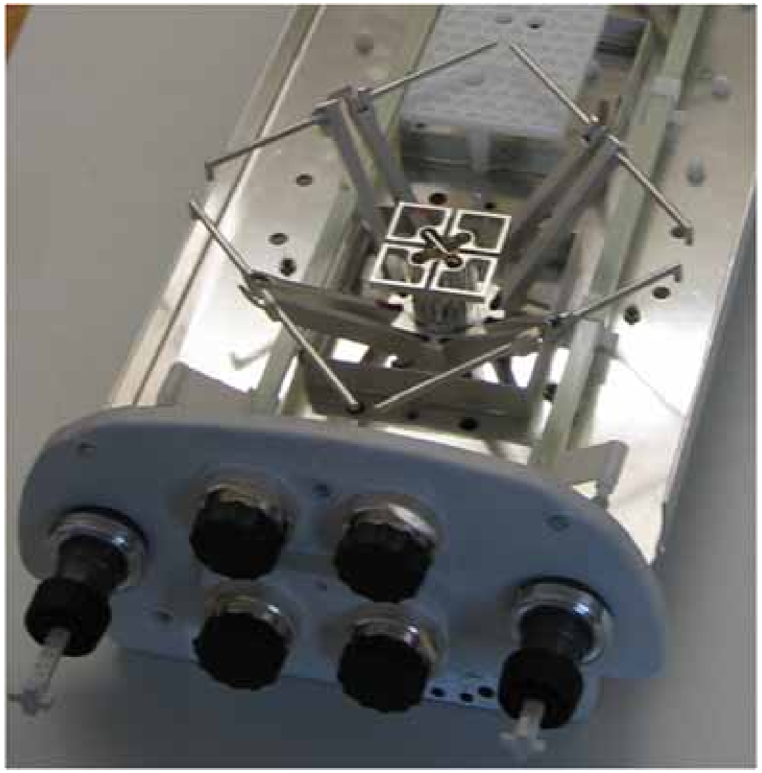
[J.-F. Zürcher, F.E. Gardiol, *Broadband Patch Antennas*, Artech 1995]

Antenna radiator types and characteristics

- **dipole-over-ground**: good radiator bandwdith, wideband balun needed, rather thick, various low-cost 3D technologies possible (punched sheet metal, circuit board arrangement, metalized molded plastic), many PIM-critical connections
→ widest use



[Huber+Suhner]



[Kathrein]

outline:

- choice of frequency
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- **macro sector antennas**
- antennas for in-buiding and in-cabin systems
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- what‘s next

Macro sector antennas

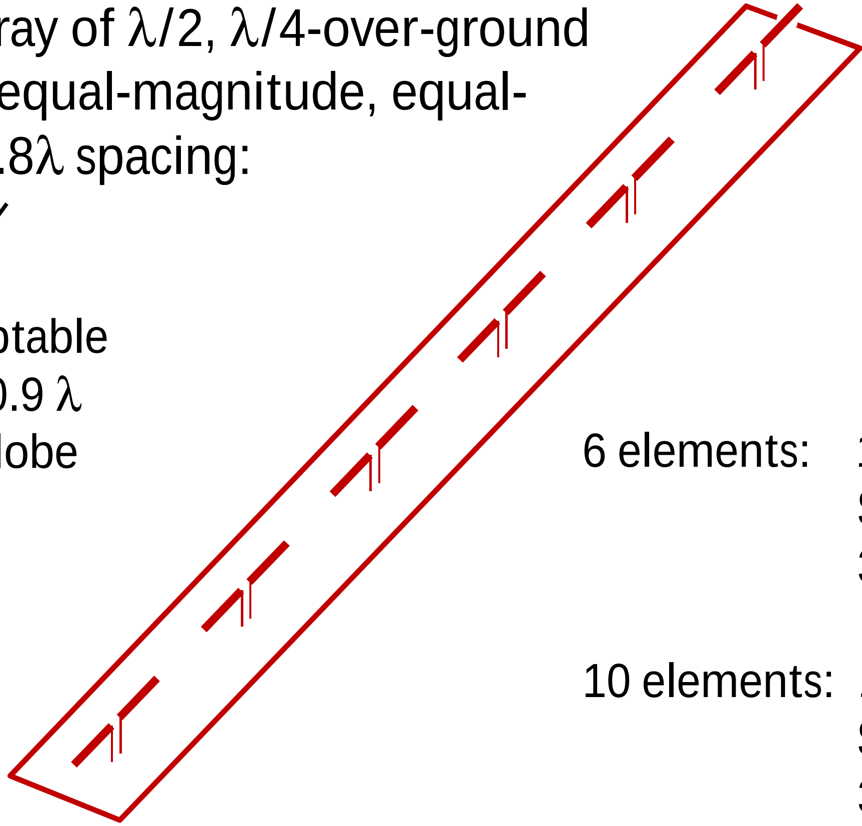
- a column of (almost-) in-phase radiators

wide horizonthal (azimuth) beam pattern (3dB BW ~ 60° … 120°)

focused vertical (elevation) beam pattern (3dB BW ~ 6°…12°)

linear array of λ/2, λ/4-over-ground dipoles; equal-magnitude, equal-phase, 0.8λ spacing:

maximum acceptable spacing is 0.8...0.9 λ because of sidelobe level

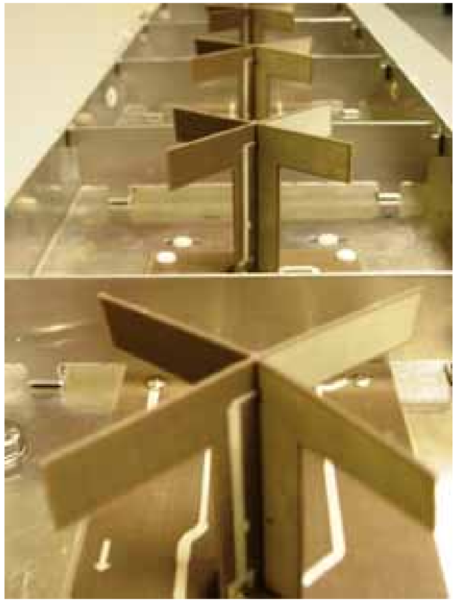


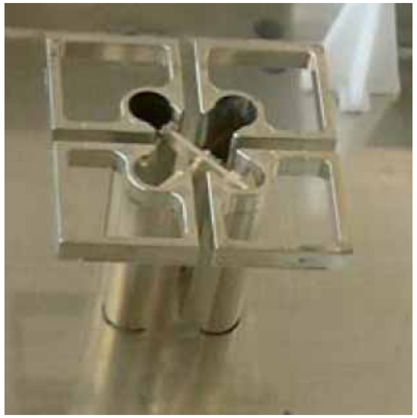
6 elements: 15.3 dBi, SLL -13.2 dB, 3dB BW 10.5°

10 elements: 17.5 dBi, SLL -13.3 dB, 3dB BW 6.3°

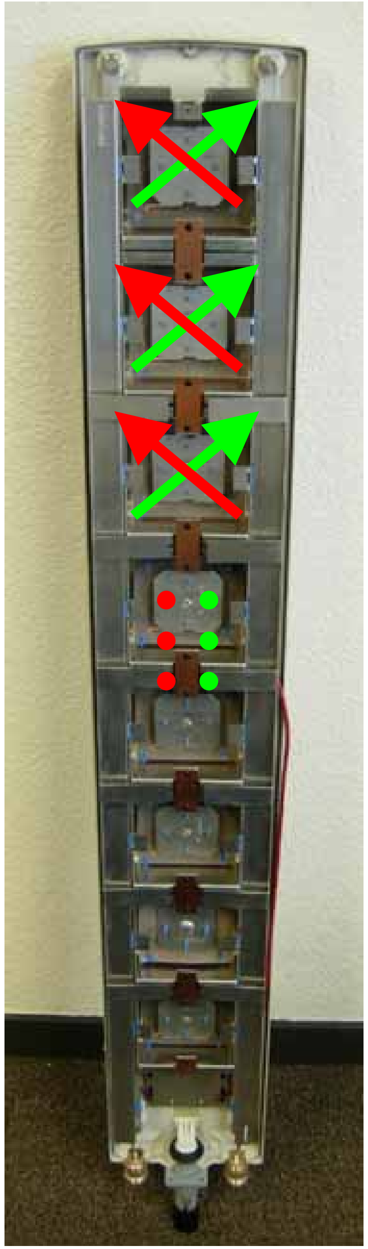
Macro sector antennas

- single (V) polarization rarely used
- standard is dual (+45°/–45°) polarization
  for diversity receive
- „broadband“ antennas cover about 20% bandwidth


[Jaybeam]

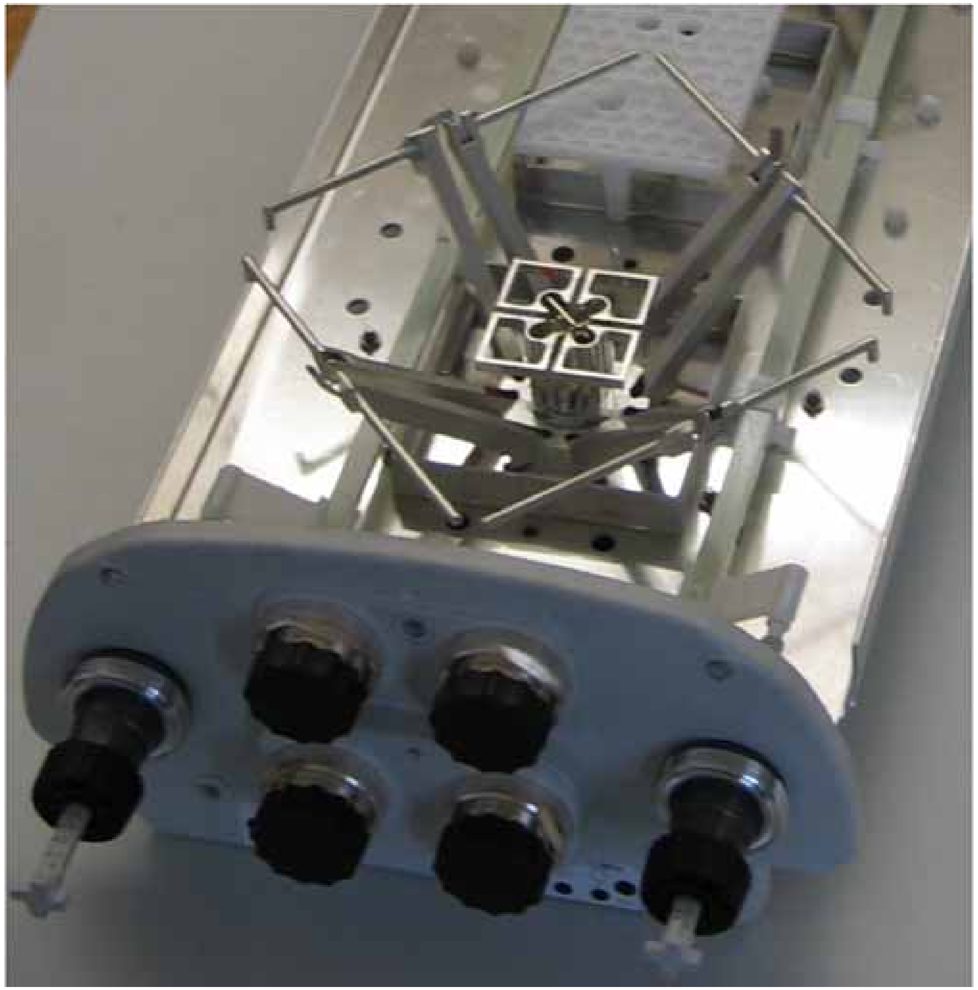

[Kathrein]


[Huber+Suhner]



Macro sector antennas

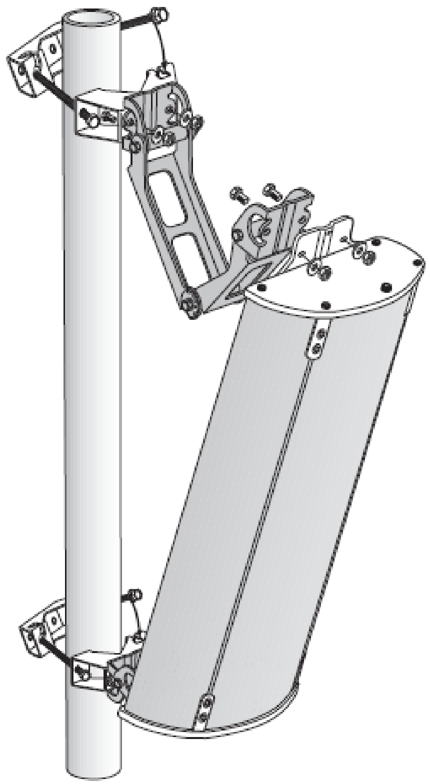
- „multi-band“ antennas have separate radiator columns with separate feeds



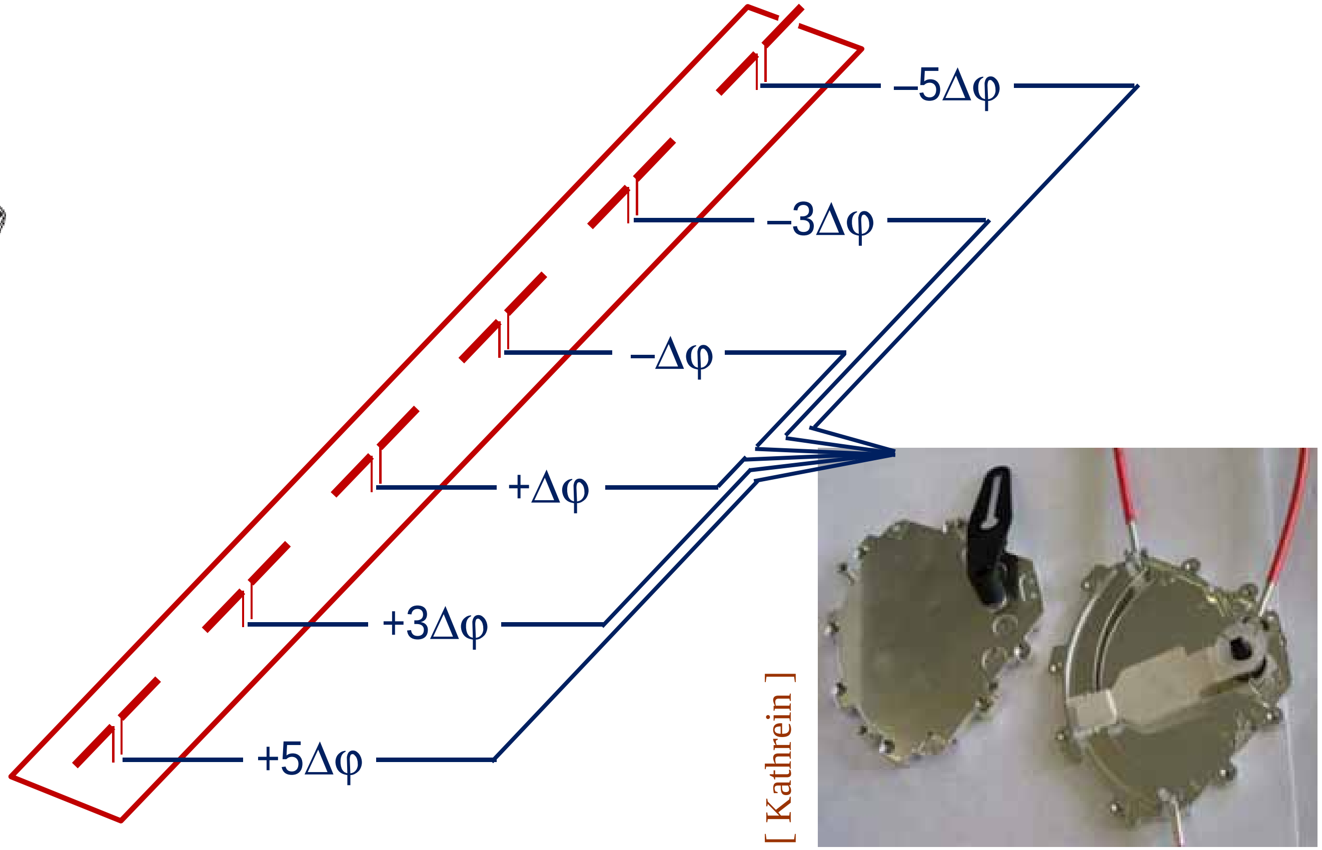
[Kathrein]

„Adaptivity“ for macro sector antennas

- **adaptive downtilt** adapts the max cell radius and/or cell edge coverage



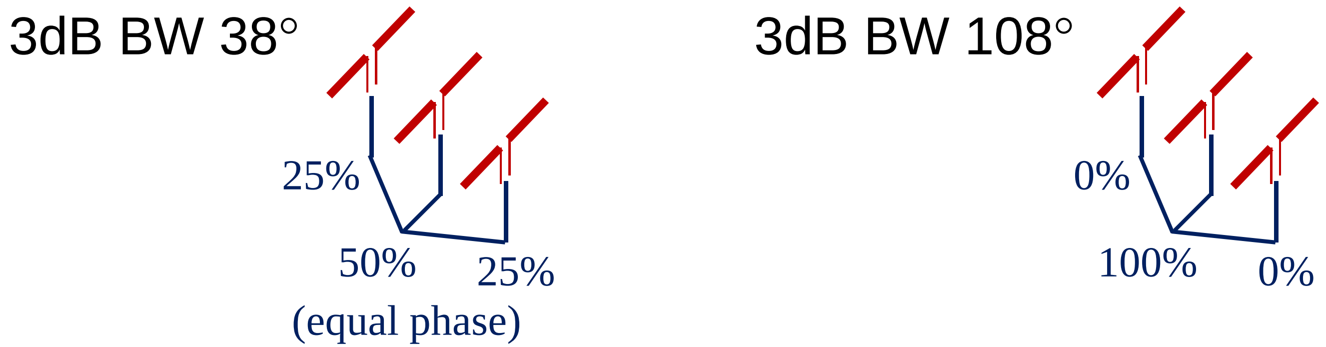
mechanical downtilt
(can be motorized)



electrical (i.e., motorized) downtilt

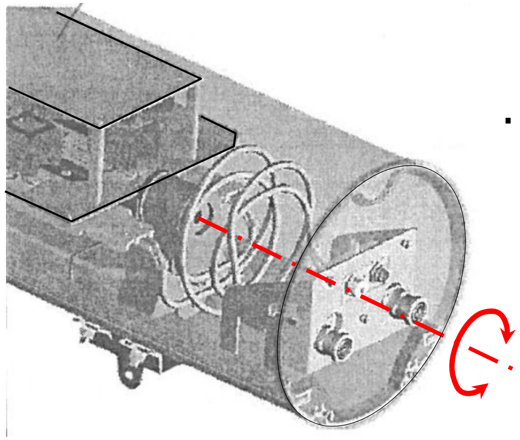
„Adaptivity“ for macro sector antennas

- **adaptive beamwidth** adapts cell sector width (e.g., 3dB BW 35°…105°)



… using a motorized differential phase shifter and a 90° hybrid

- **adaptive pan** (azimuth beam steering by, e.g., ±30°)

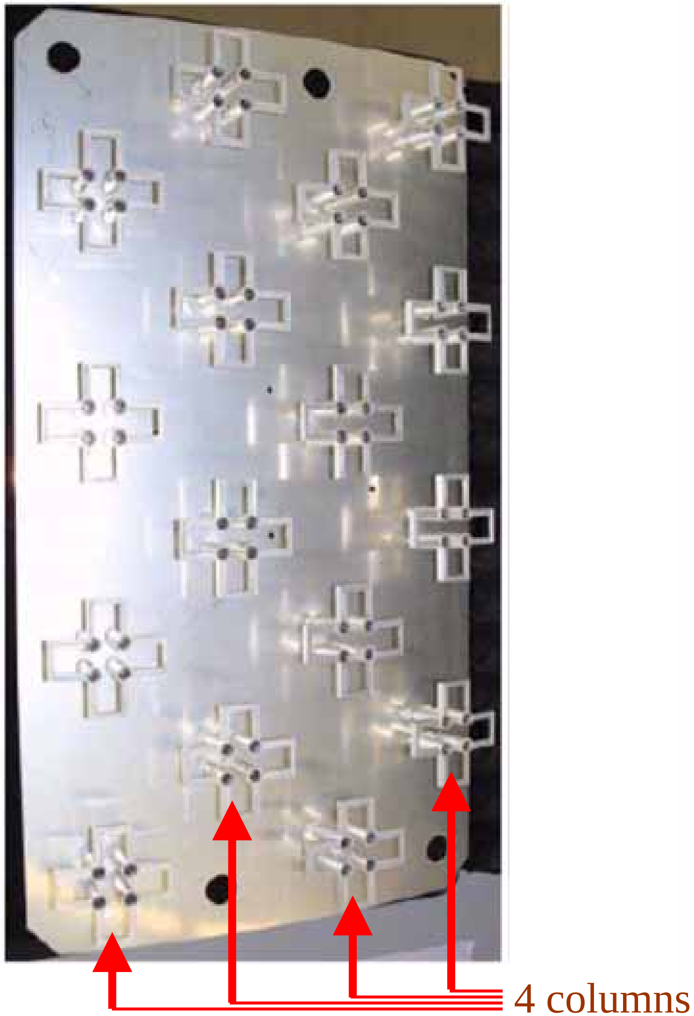


… motorized rotation of the complete radiator column inside the radome antenna box

[Andrew / CommScope]

„Adaptivity“ for macro sector antennas

- **beam steering / switching** using multi-column antennas



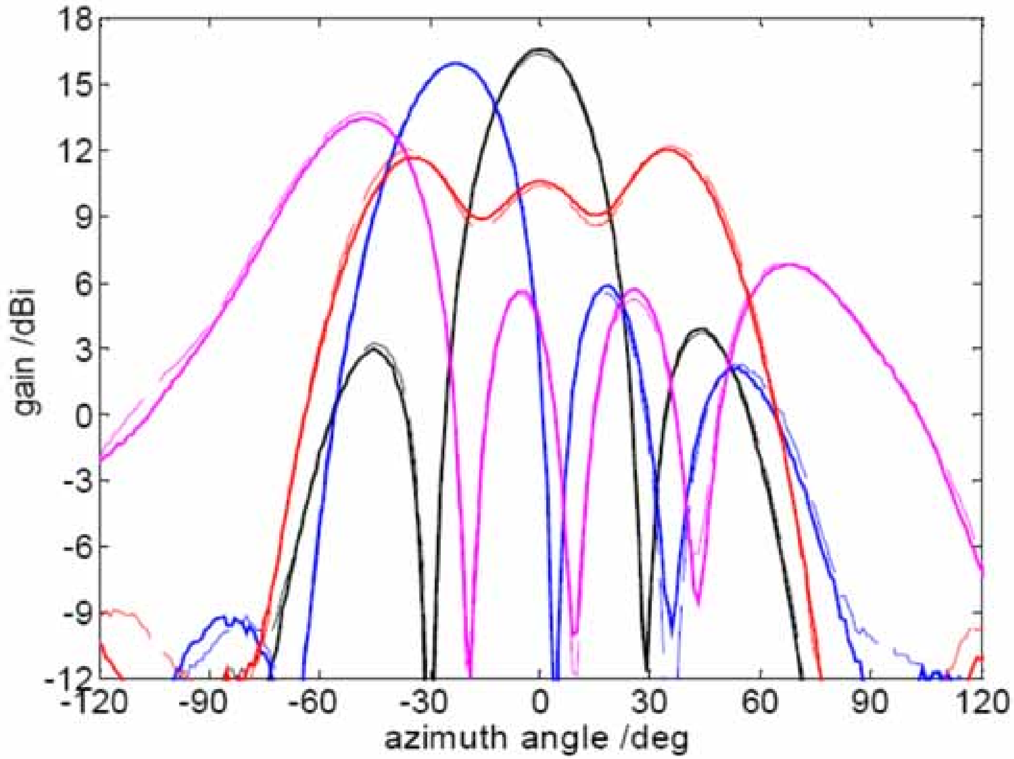


Fig. 8: Gain of the 4x4 array in +45° slant polarization (solid) and –45° polarization (dashed) for inphase feed (black), 0°/75°/150°/225° feed (blue), 0°/150°/300°/450° feed (magenta), 0°/120°/120°/0° feed (red), respectively, at 2 GHz. Equal power.

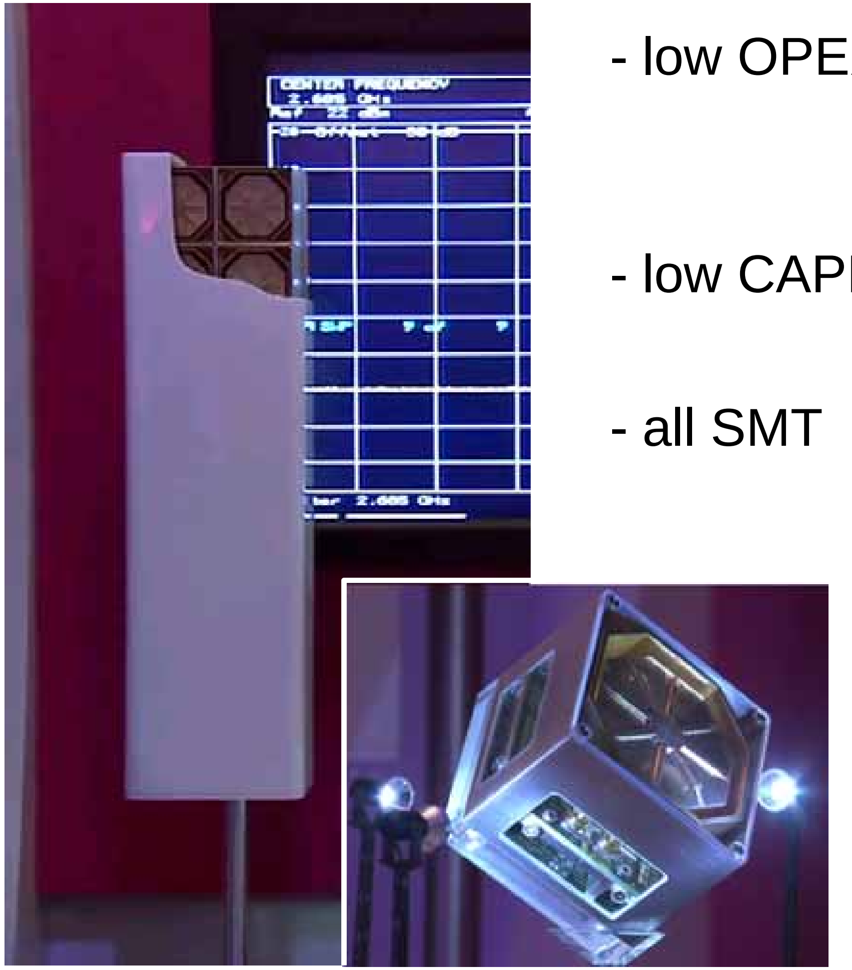
[Huber+Suhner]

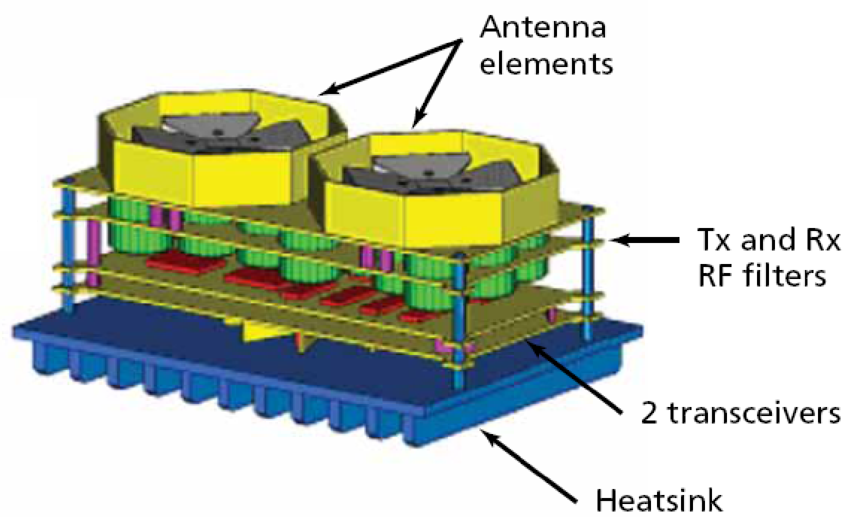
„Adaptivity“ for macro sector antennas

- **multi-radio array**:

LightRadio — the antenna-integrated base-station

- scalable and flexible
- low OPEX: . small real estate
  . reliable (graceful degradation)
  . green (passive cooling)
- low CAPEX: . distributed power amp
  . no RF cabling
- all SMT

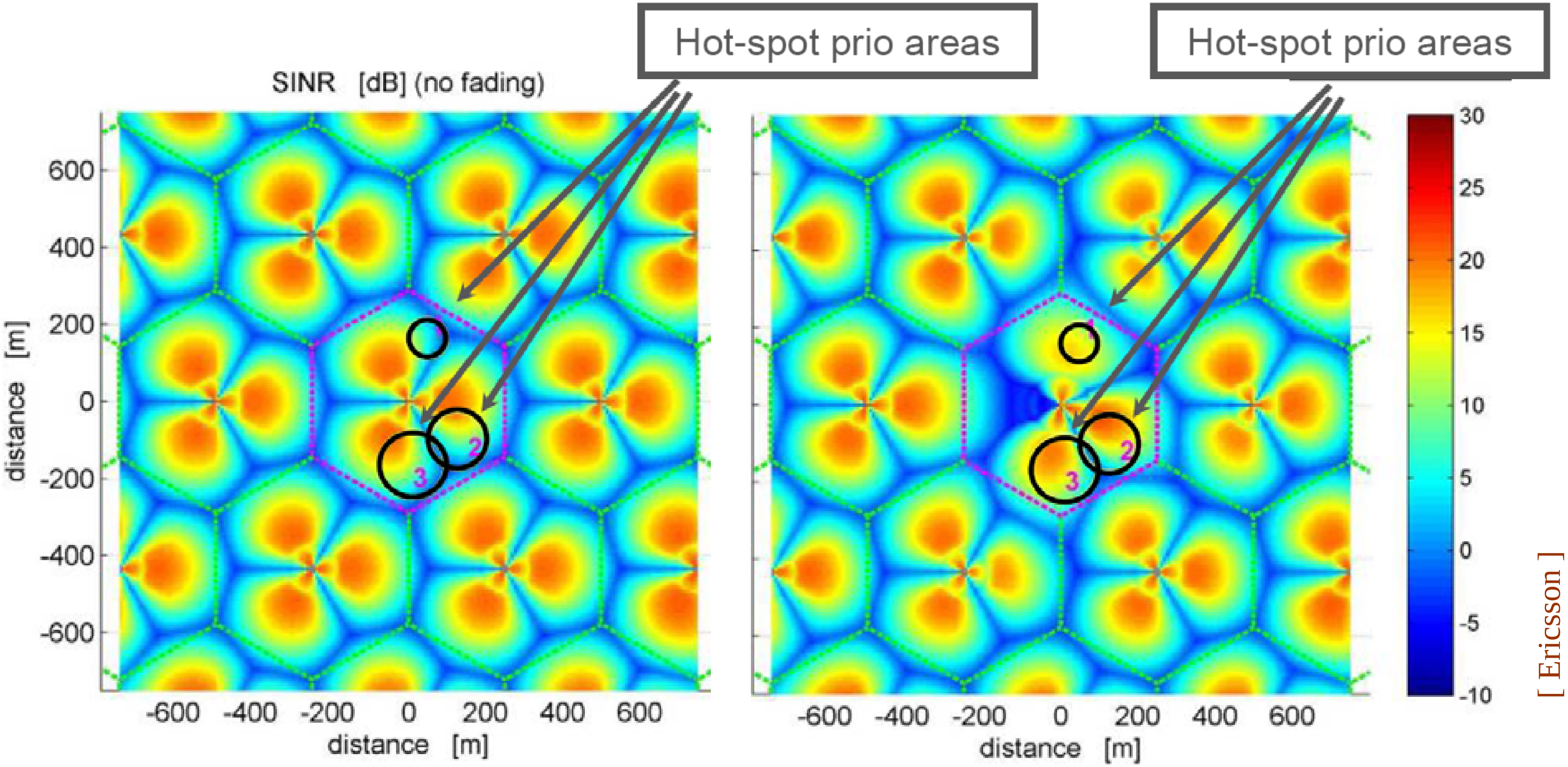




[Alcatel - Lucent]

„Adaptivity“ for macro sector antennas

- **application** of adaptivity: priorization of hot-spot areas



before …. *after* priorization: CDF(SINR) @ 50% : +6.5 dB

Additional aspects: weight, modularity

- **weight**: arrays and antennas with active electronics quickly become heavy

  . metalized plastics instead of metal
  . carbon structures for frames and support
  . sandwich structures for maximum stability

[Huber+Suhner]

- **modularity**: antennas with active electronics must be modular
  (repair / parts replacement without taken down from tower)

Additional aspects: passive intermodulation — PIM

- **PIM**: in channelized FDD systems, odd-order IM of two transmit signals can mask a weak receive signal

  example: GSM 1900 (US): UL @ 1850–1910 & DL @ 1930–1990

  $TX_1 = 1940\,\text{MHz}$, $TX_2 = 1980\,\text{MHz}$ → $IM_{2TX1-TX2} = 1900\,\text{MHz}$

given the receive sensitity, acceptable PIM level must be very small

standard test uses two signals of +43 dBm
measured PIM is at -100…-120 dBm, that is, up to -160 dBc !!!

typical specified PIM level of a base station antenna is „<–150 dBc“

PIM measurement & calibration equipment is tricky & expensive

Additional aspects: PIM

Any electrical non-linearity can (Murphy‘s law: will) cause PIM:

. micro-flashes
  - loose metal-to-metal or oxide-to-metal joints
    → avoid cracks in solder joints or cold solder joints
    → avoid loosened screws, bolts and connectors
    → clean production – avoid metal dust in the device

. non-linear material
  - even some polymers produce PIM
    → PTFE, PE do not
  - corroded metal: e.g., CuO is a known semiconductor
    → completely (!) plated metal with Sn, Ag, Au
  - magnetic material, stainless steel, Co, Ni …
    → avoid galvanic finish (and even PCB) with Ni adhesion layer
    → use special galvanic processes
    → low-PIM PCB
  - loose metallic building roof installations
    → place antennas at roof edges

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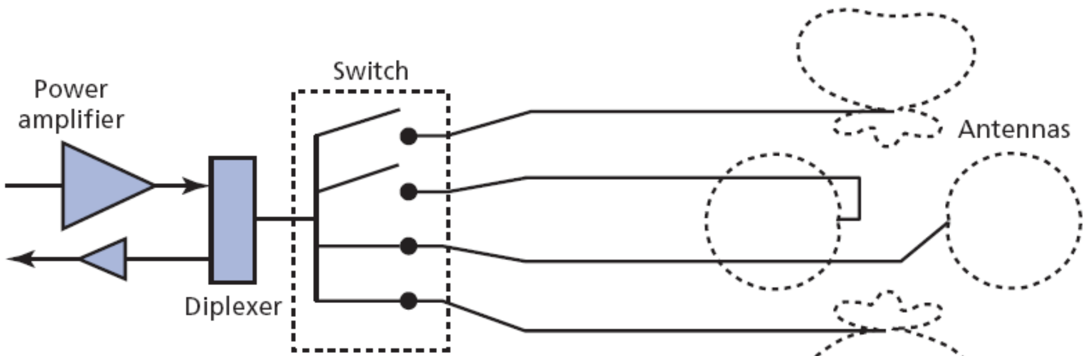
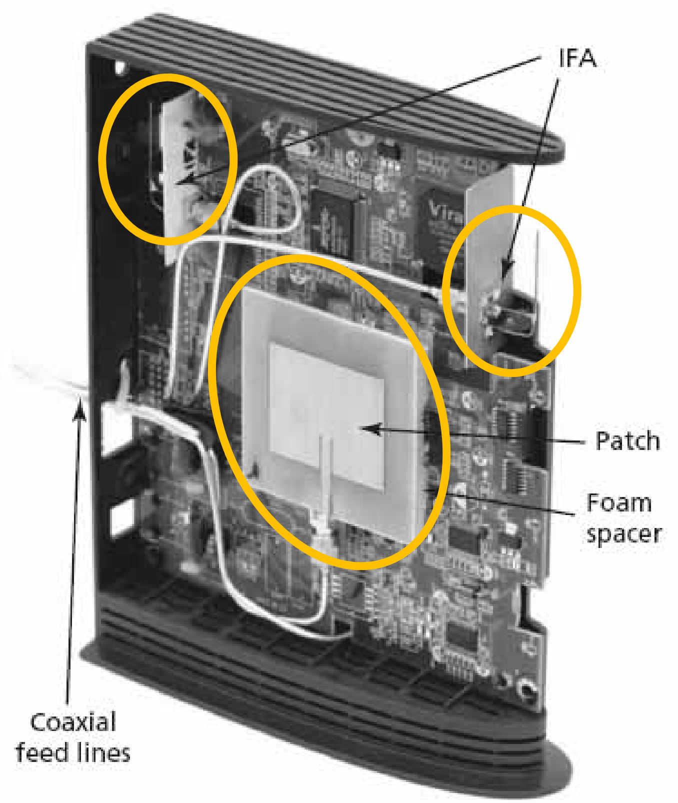
Antennas for in-building and in-cabin systems

Femto-cells

- signalling / overlapping cells (e.g.: indoors versus outdoors) require dynamically (e.g., switched) optimized coverage using multiple antennas
- antennas must be cheap;
- high efficiency / low PIM are not required





[Alcatel - Lucent]

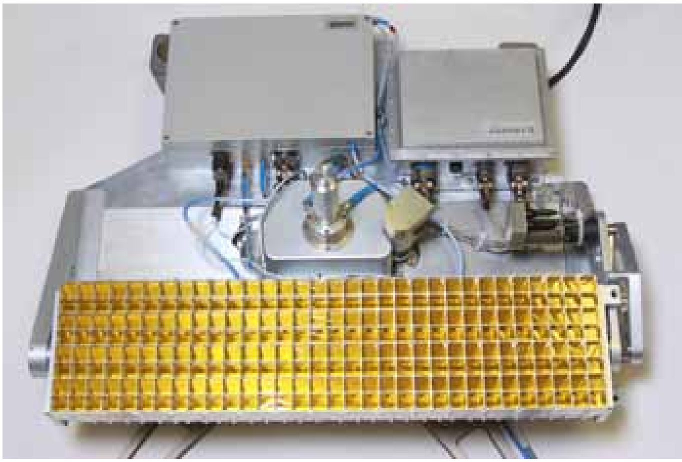
Antennas for in-building and in-cabin systems

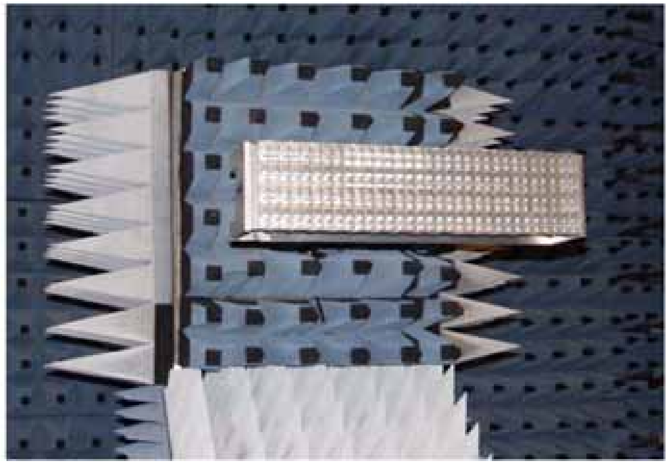
in-cabin WiFi (also: GSM1800) does not benefit from directive antennas

several hotspots will guarantee complete coverage

alternative: leaky cable „antenna“

backhaul (aircraft-to-satellite):
Ku band (UL: 13.75-14.5 GHz,
DL: 10.7-12.75 GHz)





[Motorola] [Kontron] [SITA OnAir] [Gore] [row44] [Tecom] [Qest]

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Wireless backhaul

LTE-tower macro cell backhaul is > 500 MBps gross: optical fiber or mm-wave

small cell backhaul can be anything „small", including in-band or copper wire

- wired acces (optical, copper) is preferred if existent (of non-existent, it is often too time-consuming and/or too expensive to be built)
- in-band backhaul is a waste of precious (0.7 GHz – 3 GHz) frequency
- microwave (6 GHz – 20 GHz) allows long distance (~ 20 km) but needs large dishes and has problems with datarates > 100 MBps
- Ka-band (28 GHz – 44 GHz) is preferred for macro cell but urban areas may run out of capacity
- 60 GHz (59 GHz – 64 GHz) becomes the best solution for dense deployments of small cells and fast/ non-permanent installations
- E-band (71 GHz – 86 GHz) becomes the best and only solution for carrier-grade wireless backhaul with >> 1 GBps speed

The parabolic dish

macro cell & small cell backhaul

- useful formulas:

farfield distance:

$$\text{farfield distance} \approx \frac{2\left(\text{aperture diameter}\right)^2}{\lambda}$$

Friis:

$$D \approx G = \eta_{aperture\_efficiency} \frac{4\pi}{\lambda^2} \cdot \text{physical area}$$

aperture effiiciency:

$$\eta_{aperture\_efficiency} = \frac{\text{maximum effective area}}{\text{physical area}}$$

Kraus:

$$D \approx G = \frac{41253}{\theta^2_{3dB\_beamwidth}\Big|_{\text{deg}}}$$

Tai & Pereira:

$$D \approx G = \frac{36408}{\theta^2_{3dB\_beamwidth}\Big|_{\text{deg}}}$$

The parabolic dish

macro cell & small cell backhaul

- some typical E-band Cassegrain dishes:

diameter [mm]	datasheet values gain [dBi]	datasheet values HPBW	maximum directivity [dBi] 60 GHz	maximum directivity [dBi] 90 GHz	aperture efficiency 60 GHz	aperture efficiency 90 GHz	directivity from HPBW Kraus [dBi]	directivity from HPBW Tai & Pereira [dBi]
200	39.9	1.3°	42.0	45.6	62%	27%	43.9	43.3
300	43.5	0.9°	45.5	49.1	63%	28%	47.1	46.5
450	46.6	0.6°	49.0	52.6	58%	25%	50.6	50.0

[Elva-1]

- narrow beamwidth requires very accurate alignment and structural stability

- radome loss ranges from nothing at a few GHz to 0.7 dB at E-band

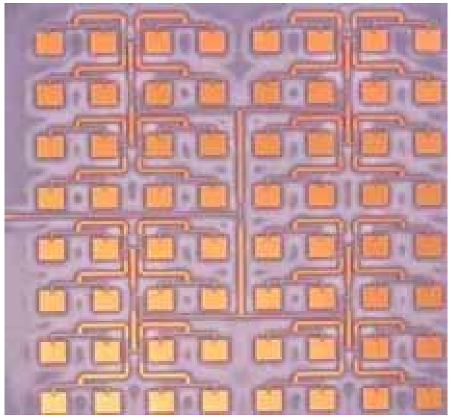
Planar array versus parabolic dish

Can a planar array replace the parabolic dish ?

- con: the parabolic mirror is a 3D structure and „looks like an antenna“
- pro: the parabolic mirror is dual polarized and has very low loss

A large planar array (32 x 32 or 64 x 64 elements)

- is flat and square and has larger aperture efficiency (> 90%) than a dish
- loss of the array is in the feed network
- most arrays are single (linearly) polarized

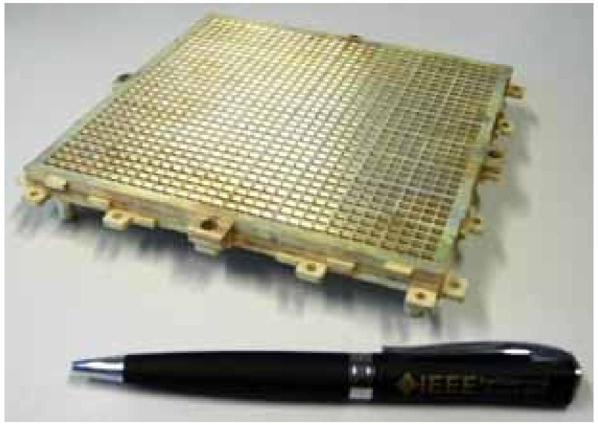


1% efficiency (~ 20 dB loss) of a 32x32 patch array with microstrip feed network at 60 GHz.

[M. Al Henawy, M. Schneider, “Planar antenna arrays at 60 GHz realized on a new thermoplastic polymer substrate,” Proc. EuCAP 2010]

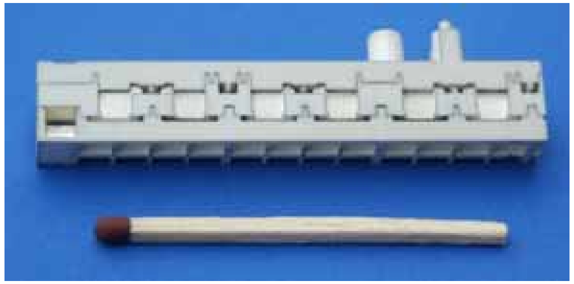
Planar array versus parabolic dish

Can a planar array replace the parabolic dish ?



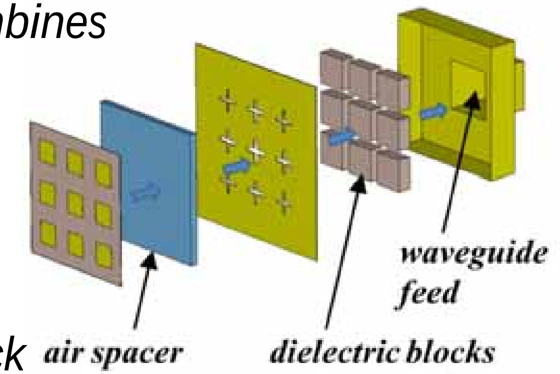
~70% efficiency (1.5 dB loss) of a 32x32 open-ended waveguide array with ridge waveguide feed network at 60 GHz.

[Huber+Suhner]



A suspended-substrate slot-coupled square patch array with waveguide feed – two feeder trees for two orthogonal linear polarization – combines all advantages

freq-scaled array building block



Beam steering for mm-wave wireless backhaul

- small-angle electronic beam steering for ease of alignment

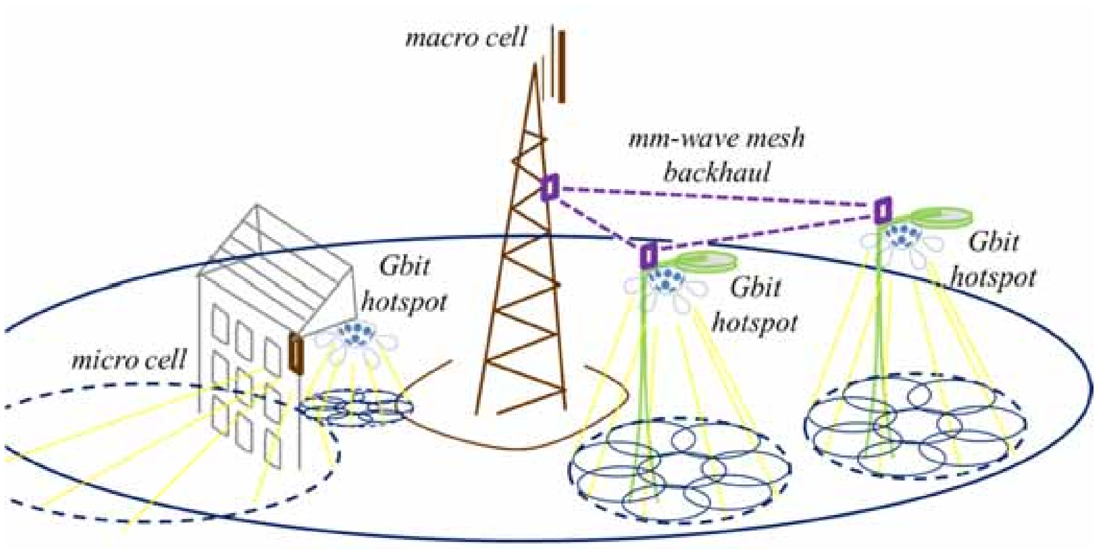
  alignment at installation is very expensive (mostly labor costs)

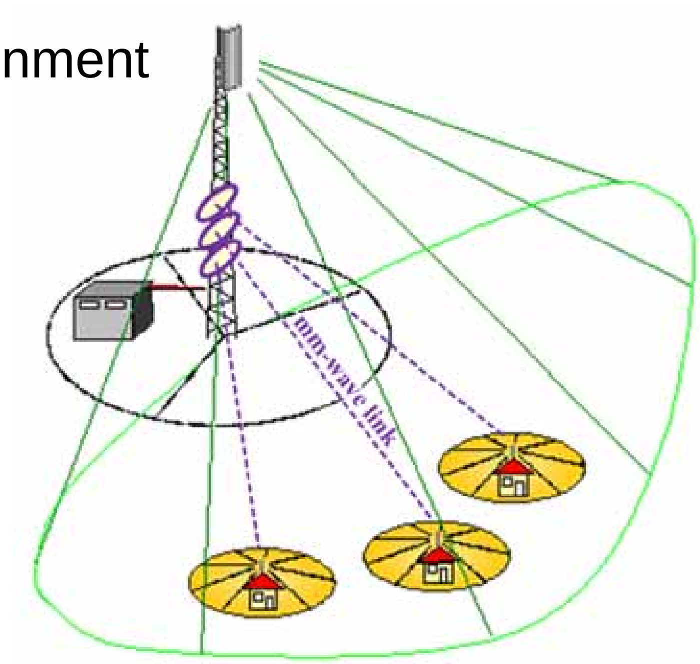
  automatic re-alignment would allow for reduced structural stability

- wide-angle electronic beam steering for meshed backhaul network

  increase of reliabilty and throughput

  same cost reductions as small-angle alignment





Beam steering for mm-wave wireless backhaul

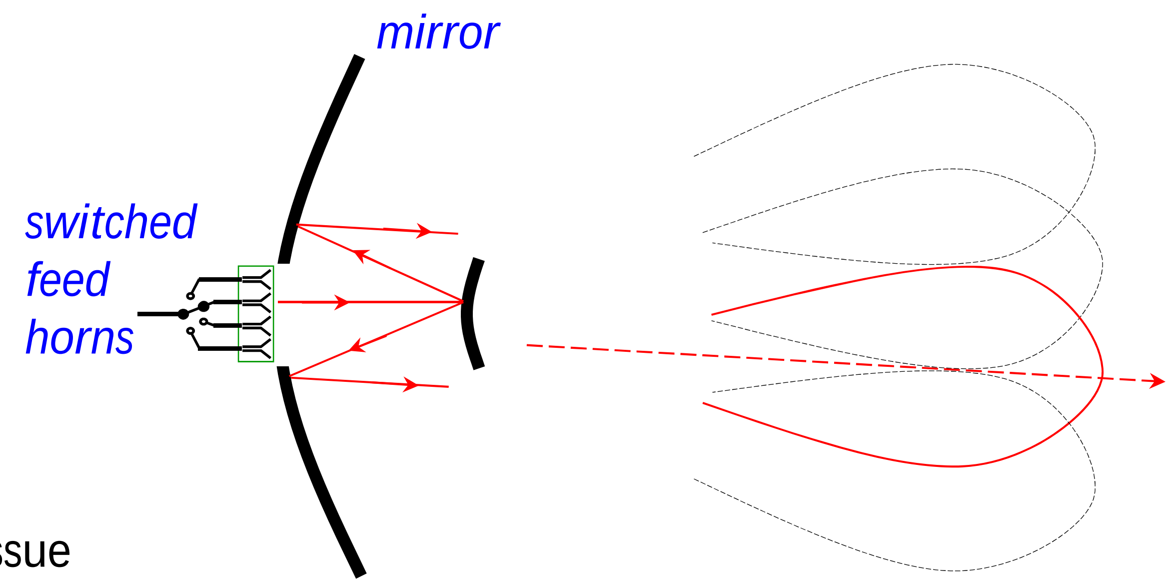
- any possible solution must provide (reasonably) low cost and low loss

- small-angle electronic beam steering:

→ dishes with switched focal plane array for small-angle electronic beam alignment

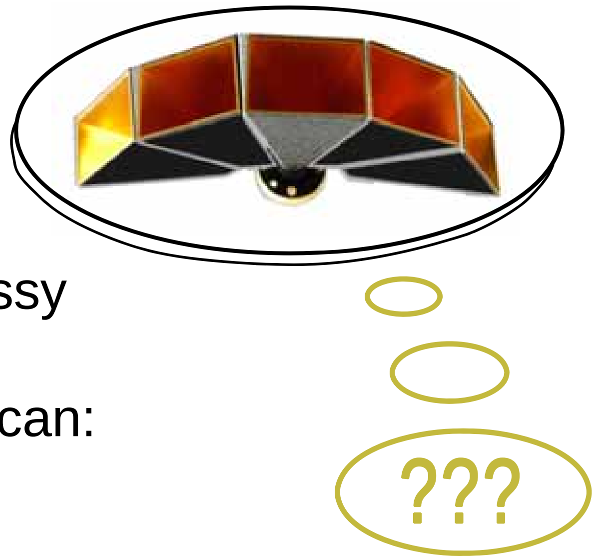
→ based on inexpensive feed-horn array and numbers of switches

... feasible but cost is an issue



Beam steering for mm-wave wireless backhaul

- wide-angle electronic beam steering:

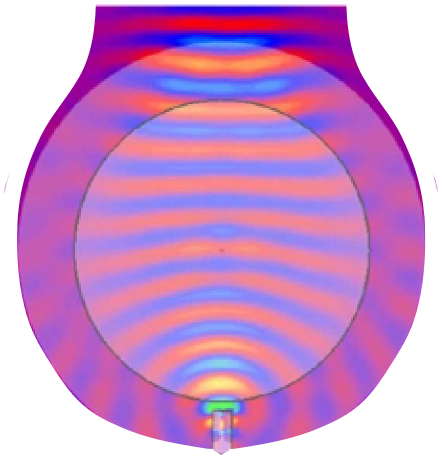


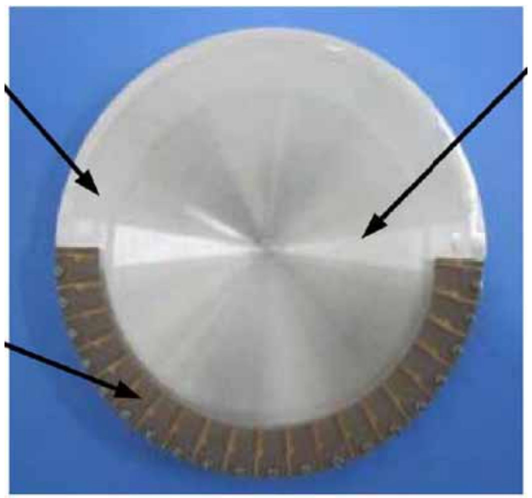
phased arrays are way too expensive

Butler matrix and Rotman lens are way too lossy

low-loss „planar“ TEM Luneburg lens for 1D scan:

→ 30 GHz planar TE mode air/metal Luneburg lens :





[C. Hua *et al.*, IEEE Trans. MTT, vol. 61, no. 1, January 2013, pp. 436-443]

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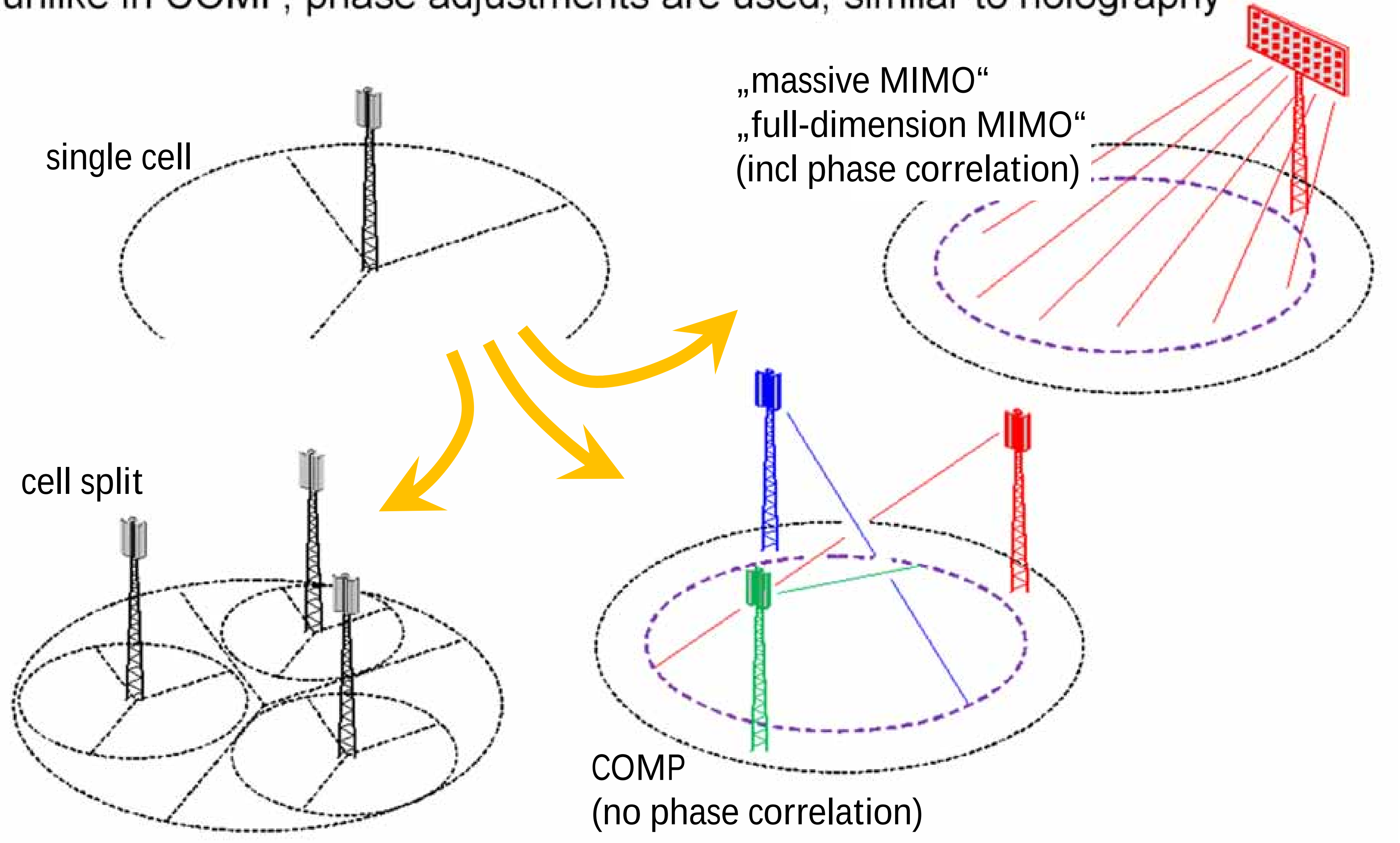
What‘s next — massive MIMO

unlike in COMP, phase adjustments are used, similar to holography



What‘s next — massive MIMO

massive MIMO antenna consequences:

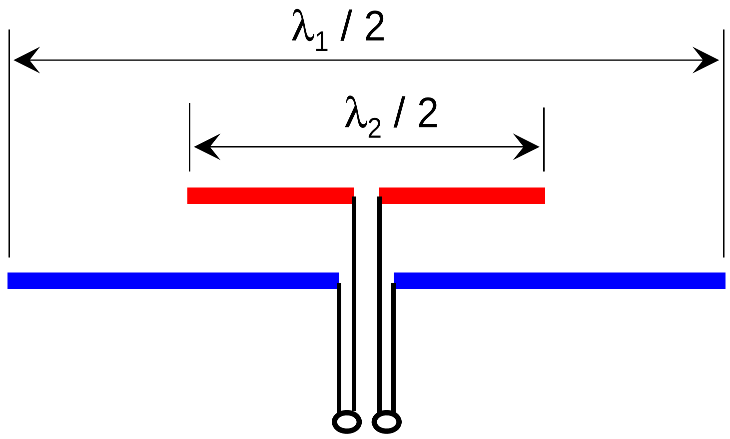
- large number of radiator columns – cost & weight becomes more important
- phase synchronization tricky — current use of compact & dense panels

a research topic at its beginnings:

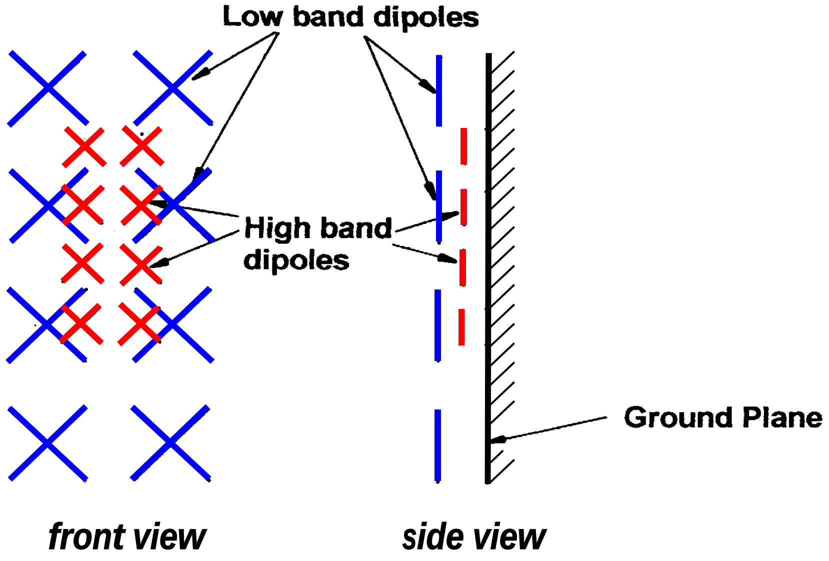
- ok for TD systems, but possible at all for FD systems ?
- wide & sparse panels or fully covered cell circumference much (?) better
- can antennas support synchronization ?
- can non-synchronized repeaters reduce path correlations ?

What‘s next — connected arrays

problem: cellular covers a 4:1 frequency range, but it is useless to develop 4:1 transceivers and 4:1 radiators, because array element spacing must be about $0.6\,\lambda_0$



solution 1: Nortel‘s dual-band array



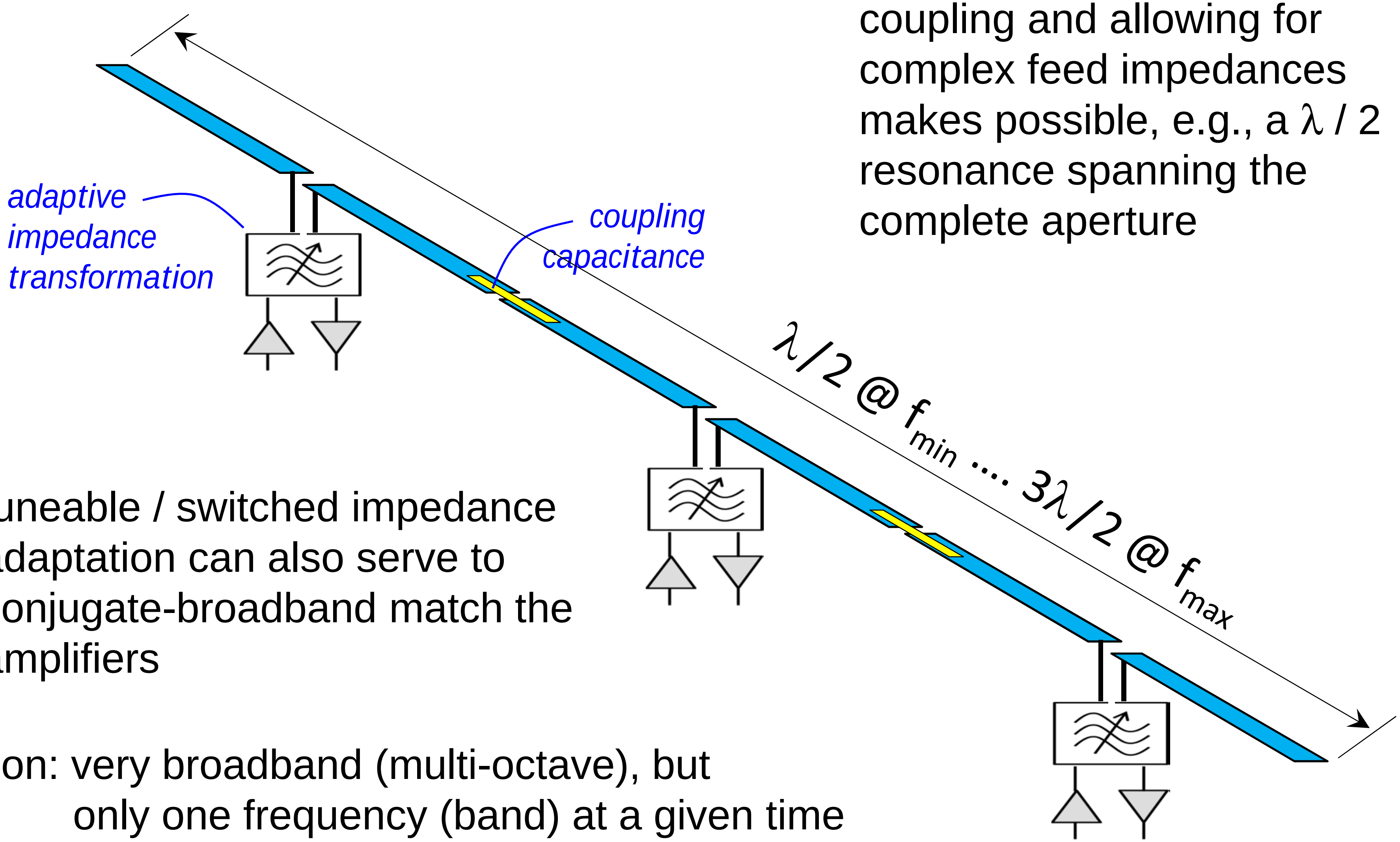
[Nortel, US 6,211,841,B1, 2001]

solution 2: connected array

What‘s next — connected arrays

linear (1D) 3:1 example:

very strong („mutual“) coupling and allowing for complex feed impedances makes possible, e.g., a λ / 2 resonance spanning the complete aperture



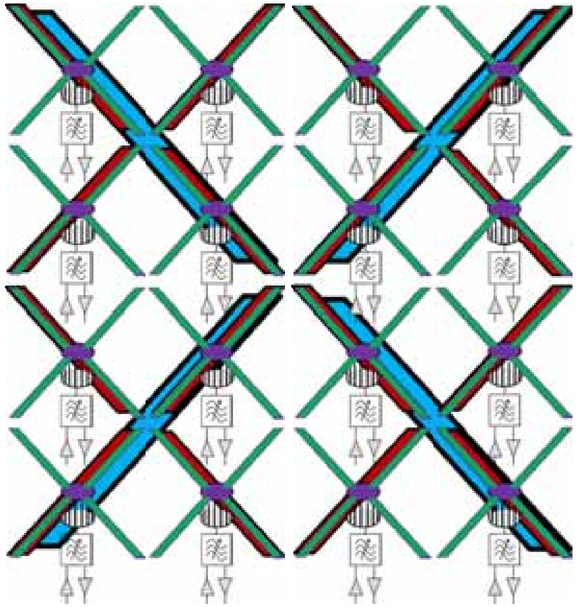
tuneable / switched impedance adaptation can also serve to conjugate-broadband match the amplifiers

con: very broadband (multi-octave), but
only one frequency (band) at a given time

What‘s next — connected arrays

planar (2D) 4:1 example: identical geometrical aperture area over frequency

common feeds @ f_0 , 2 f_0 , 4 f_0

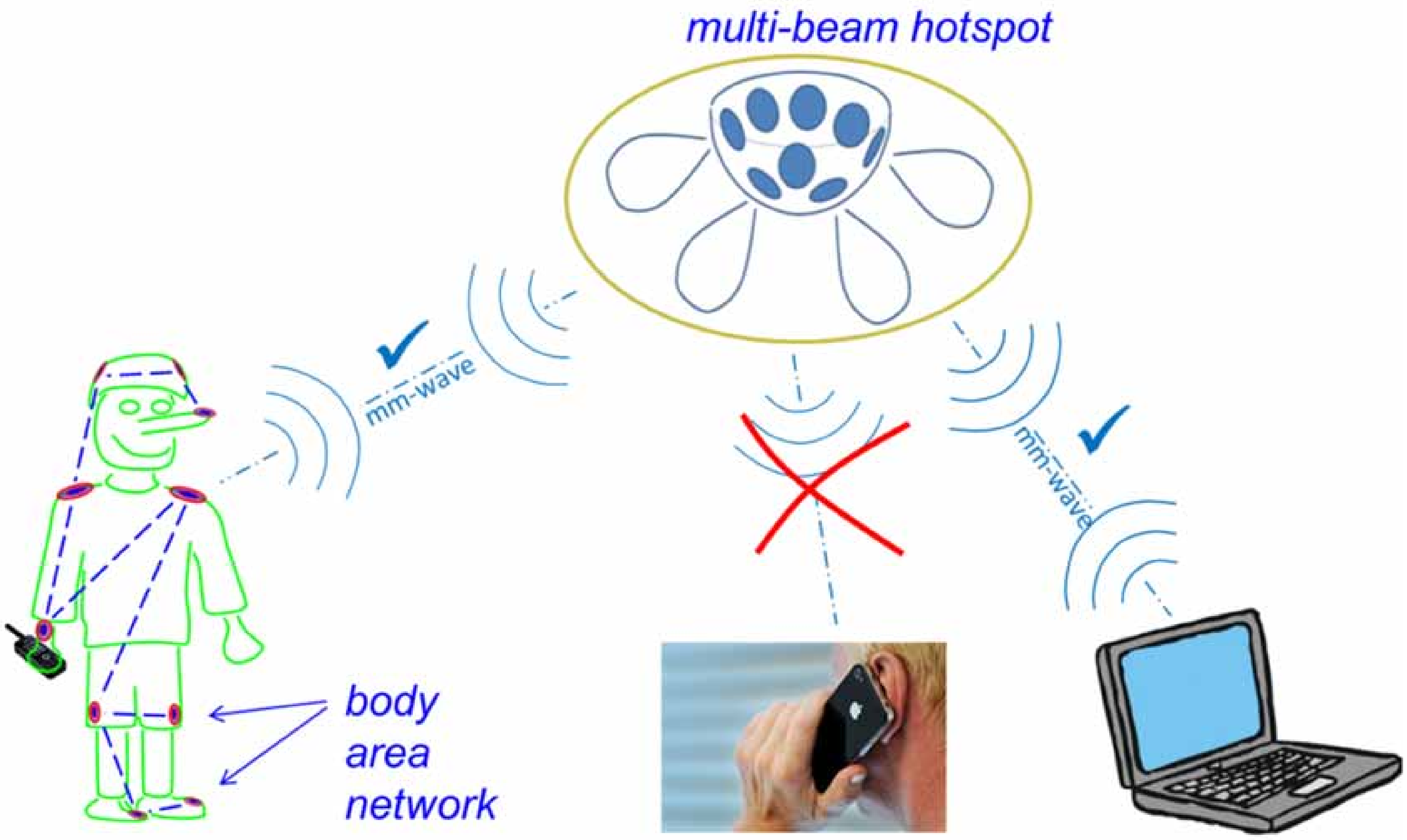


maximum directivity & maximum beamforming capability at very different (here: 4:1) frequencies from a given, common aperture

What‘s next — GBps-speed mm-wave UE connections

scenario:

mm-wave directed beams using switched-beam hemispherical hotspot



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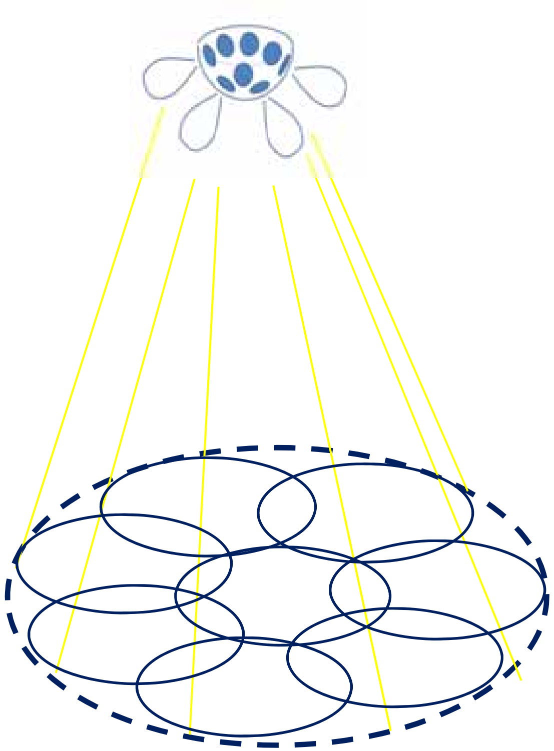
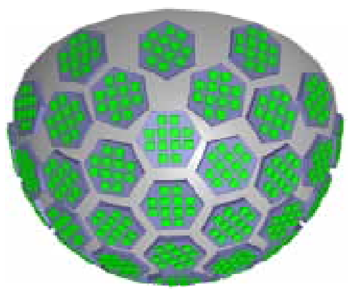


e.g., 1‘000 beams of 32 dBi :

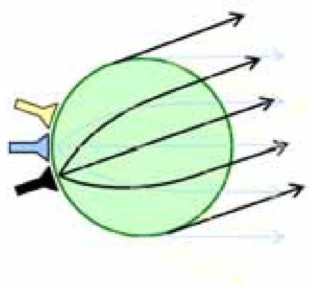
→ on the surface of a sphere: $\varnothing_{sphere} \approx$ 280 λ

→ using a graded lens: $\varnothing_{sphere} \approx$ 14 λ

multitude of patch arrays on a hemi-spherical surface



principle of Luneburg lens



modified Luneburg lens allowing for planar feed array