6G: The era of Software Antennas

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Trends in Wireless communications

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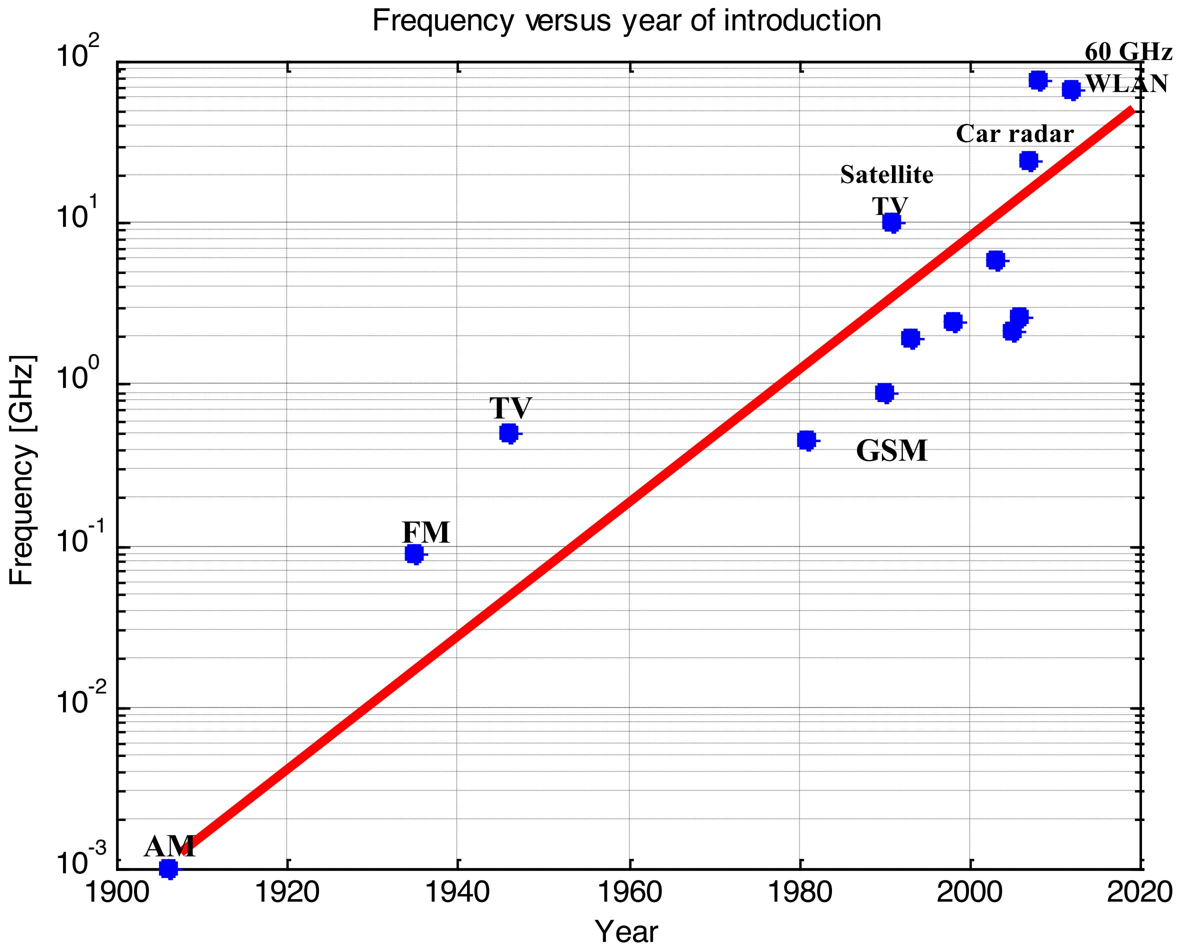
Trend 1: Increase of operational frequency



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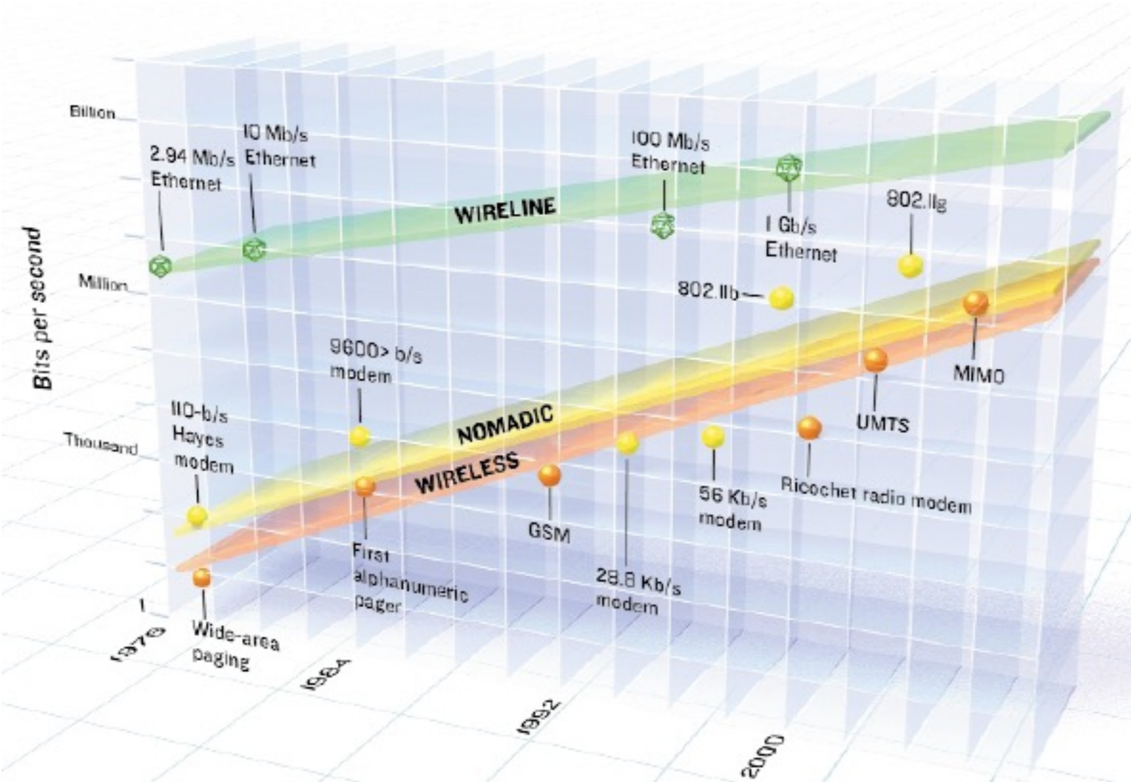
Trend 2: Increase in bandwidth:Edholm’s Law



Wireless growing faster than wired

Required Bandwidth/datarate doubles each 18 months

Source: IEEE spectrum, 2004

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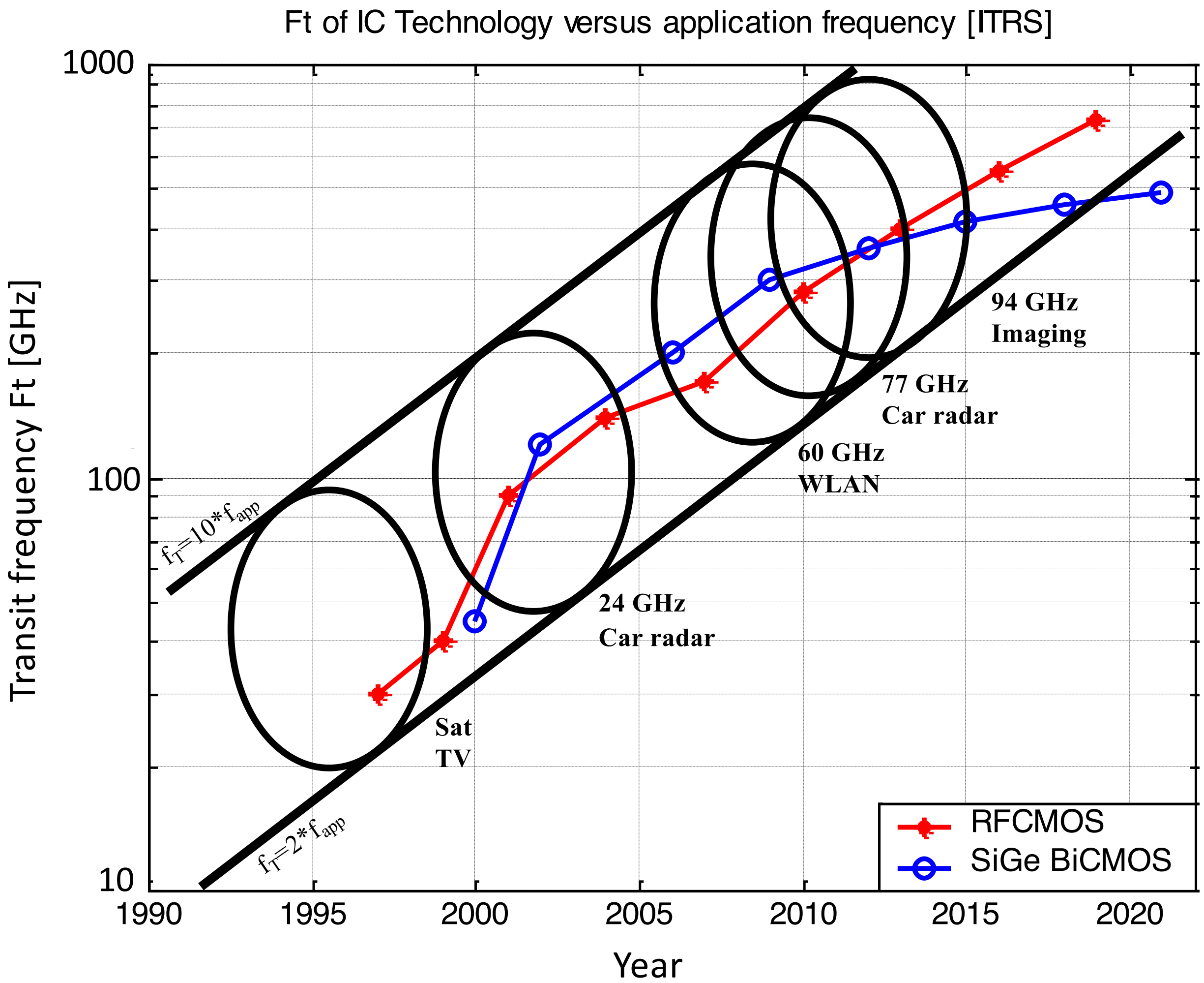
Trend 3: Improved performance Silicon Technologies



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Trend: increase of bandwidth and datarate

Evolution of wireless standards

1G	2G	3G	4G	5G	6G
The foundation of mobile telephony	Mobile telephony for everone	The foundation of mobile broadband	Mobile broadband enhanced	Embracing a networked society	Enabling a smart sustainable society
~1980	~1990	~2000	~2010	~2020	~2030
1st GENERATION wireless network	2nd GENERATION wireless network	3rd GENERATION wireless network	4th GENERATION wireless network	5th GENERATION wirele	6th GENERATION less network
• Basic Voice service • Analog Based Protocols	• Designed for voice • First digital standards (GSM,CDMA)	• Designed for voice and data • First mobile broadband • Voice through circuit & Data-Packet Switching	• Designed Primarily for Data • IP based protocol • True Mobile broadband.		ion to m-wave ies e cloud ng
2.4 Kbps	64 Kbps	2 Mbps	100 Mbps	10 Gbps	1 Tbps

Compare with Edholms law: factor 2 more BW in 1.5 year
2^(10/1.5)=101

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Why software antennas?

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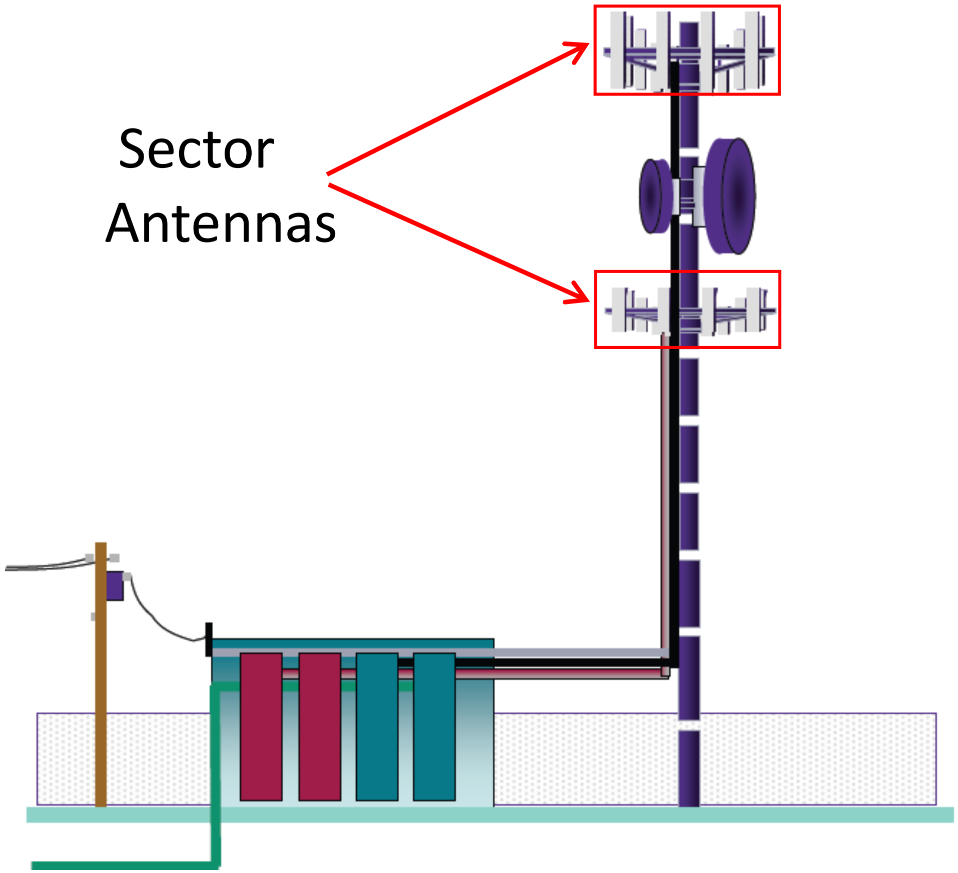
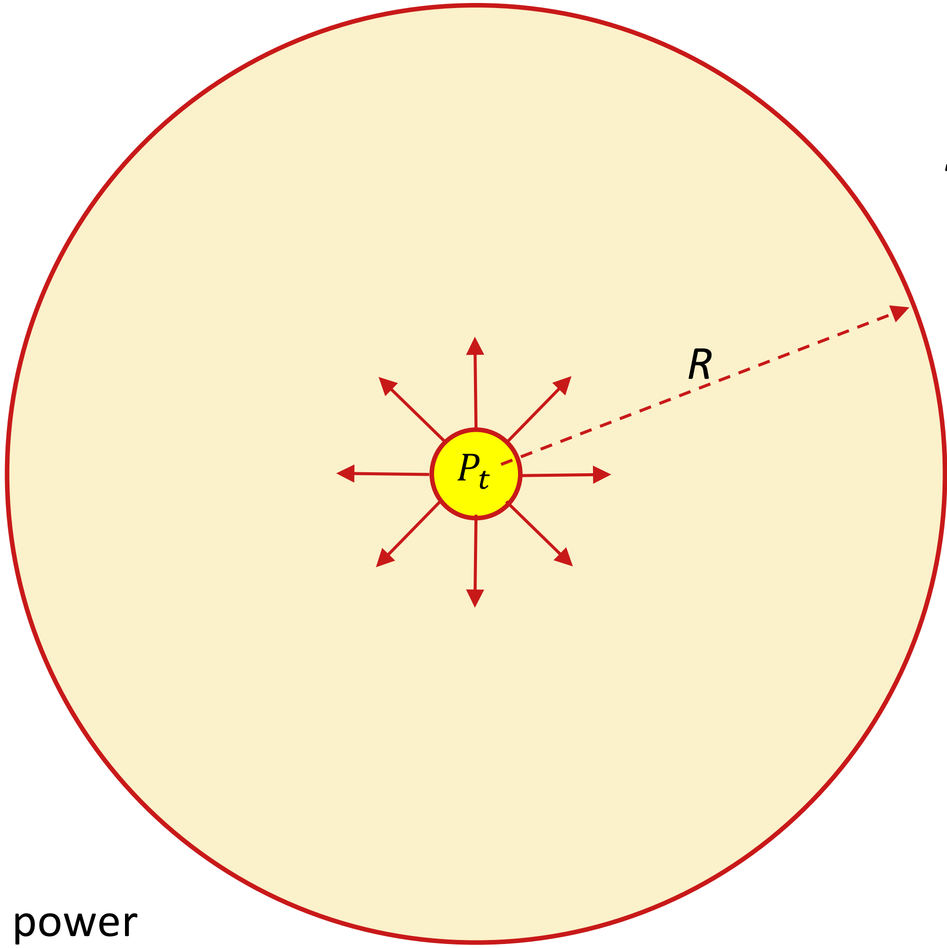
Current situation in 2G-3G-4G, < 3 GHz



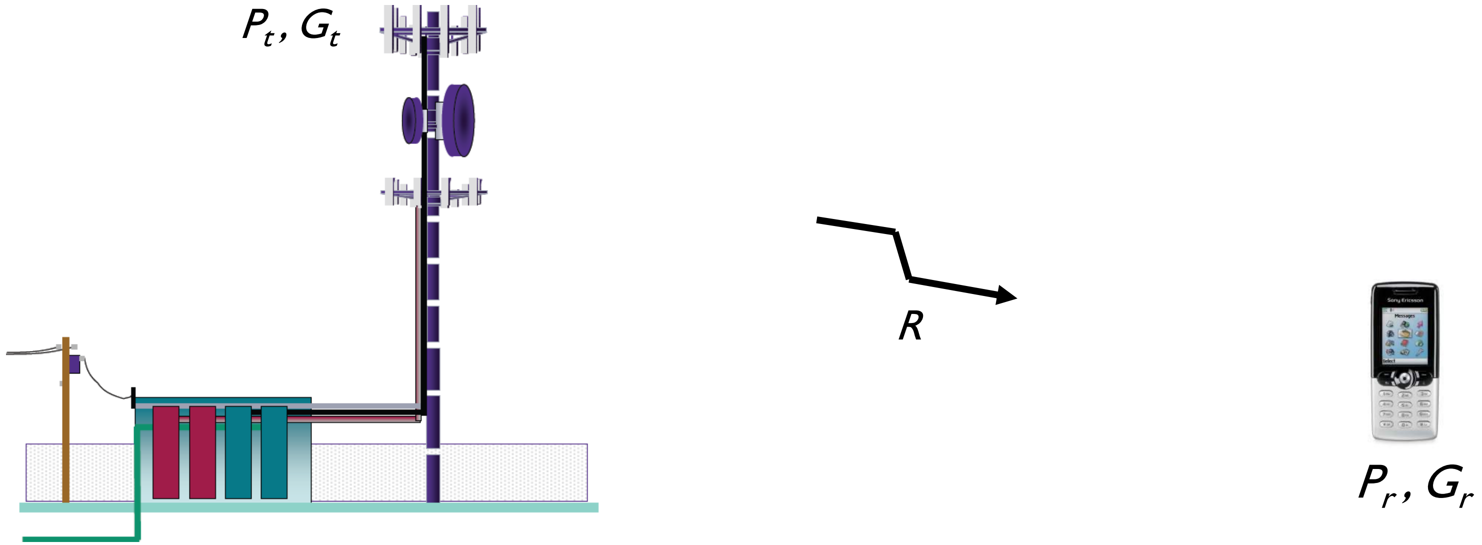
Spherical wave expansion from point source



$$S = \frac{P_t}{4\pi R^2}$$ Power density at surface sphere

P_t: total radiated power

Downlink, Link Budget



$$P_r = \frac{P_t G_t A_e}{4\pi R^2} = \frac{P_t G_t G_r \lambda_0^2}{(4\pi)^2 R^2} \quad \Rightarrow \quad R = \sqrt{\frac{P_t G_t G_r \lambda_0^2}{(4\pi)^2 P_{r,\min}}}$$

Simple "back-of-the-envelope" calculation, 2 GHz vs. 30 GHz

Why is the range reduced?

2 GHz

Wavelength: λ_0=15cm
4 Tx antenna elements with 3dB gain each: G_t=8 (9dBi)
Rx antenna omni-directional: G_r=1.
Output power: 100 W (50 dBm)
Sensitivity $P_{r,min}$ = -70 dBm (=10^{-10}W)

$$R = \sqrt{\frac{P_t G_t G_r \lambda_0^2}{(4\pi)^2 P_{r,\min}}} \approx 33km$$

30 GHz

Wavelength: λ_0=1cm
4 Tx antenna elements with 3dB gain each: G_t=8 (9dBi)
Rx antenna omni-directional: G_r=1.
Output power: 100 W (50 dBm)
Sensitivity $P_{r,min}$ = -70 dBm (=10^{-10}W)

$$R = \sqrt{\frac{P_t G_t G_r \lambda_0^2}{(4\pi)^2 P_{r,\min}}} \approx 2.2km$$

Simple “back-of-the-envelope” calculation, 2 GHz vs. 30 GHz

2 GHz

Wavelength: λ_0=15cm
4 Tx antenna elements, G_t = 9dBi
Rx antenna omni-directional: G_r=1.
Output power: 100 W (50 dBm)
Sensitivity $P_{r,min}$ = -70 dBm (=10^{-10}W)

$$R = \sqrt{\frac{P_t G_t G_r \lambda_0^2}{(4\pi)^2 P_{r,\min}}} \approx 33km$$

30 GHz

Wavelength: λ_0=1cm
4 Tx antenna elements, G_t= 9dBi
Rx antenna omni-directional: G_r=1.
Output power: **22500 W (73.5 dBm)**
Sensitivity $P_{r,min}$ = -70 dBm (=10^{-10}W)

$$R = \sqrt{\frac{P_t G_t G_r \lambda_0^2}{(4\pi)^2 P_{r,\min}}} \approx 33km$$

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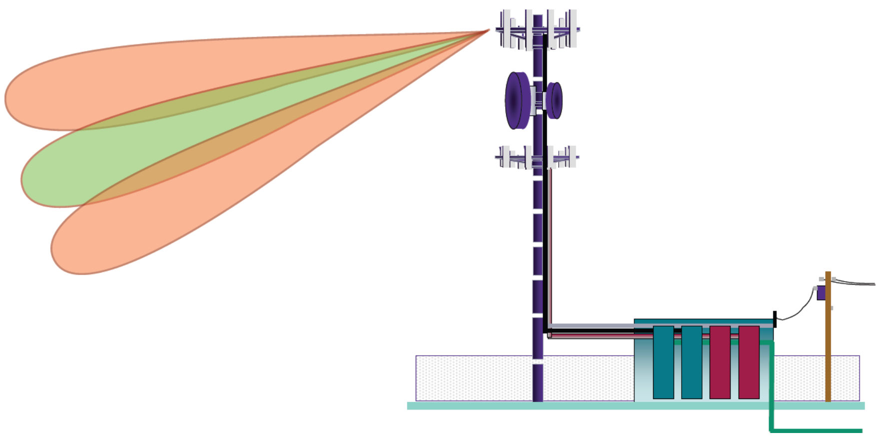
Consequence in Power consumption

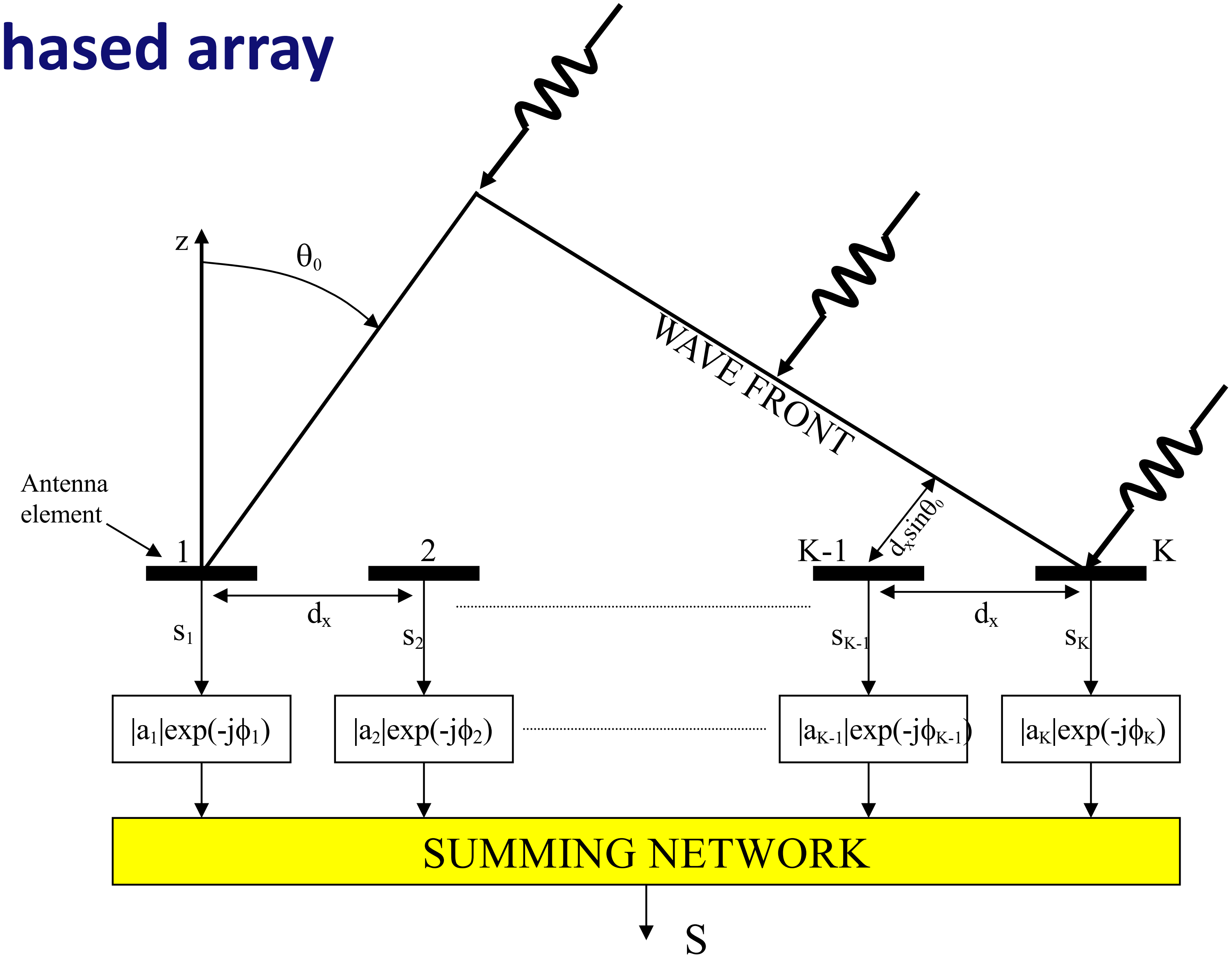
Estimations!

	3G/4G	5G
Frequency	2 GHz	30 GHz
Power per BST*	4+1=5 kW	4+225*5=1129 kW
Total Power in Netherlands*	219 MW	49 GW
#Wind mills (2 MW each) in NL	109	24500



[1]In May 2017, The Netherlands hosted 43933 2G/3G/4G antennes, see https://www.antennebureau.nl/onderwerpen/algemeen/antenneregister
At this moment the PA efficiency is about a factor 5 worse at 30 GHz as compared to 2GHz. 10% of RF energy effectively radiated

Solution: Phased array



Solution: Use a large antenna array: *software antennas*

2 GHz

Wavelength: λ_0=15cm
4 Tx antenna elements, G_t = 9dBi
Rx antenna omni-directional: G_r=1.
Output power: 100 W (50 dBm)
Sensitivity $P_{r,min}$ = -70 dBm (=10^{-10}W)

$$R = \sqrt{\frac{P_t G_t G_r \lambda_0^2}{(4\pi)^2 P_{r,\min}}} \approx 33km$$

30 GHz

Wavelength: λ_0=1cm
4 Tx antenna elements, G_t= 9dBi
Rx antenna omni-directional: G_r=1.
Output power: 22500 W (73.5 dBm)
Sensitivity $P_{r,min}$ = -70 dBm (=10^{-10}W)

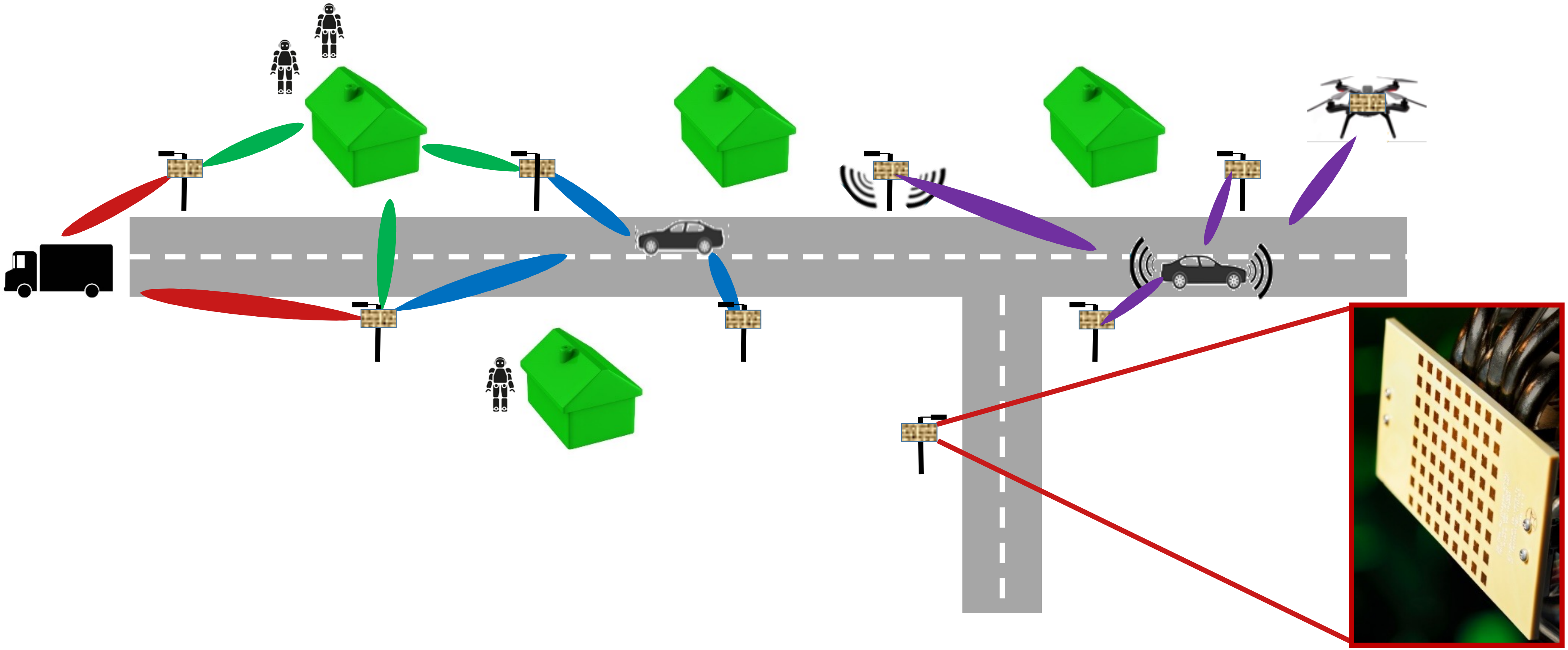
$$R = \sqrt{\frac{P_t G_t G_r \lambda_0^2}{(4\pi)^2 P_{r,\min}}} \approx 33km$$

30 GHz

Wavelength: λ_0=1cm
871 Tx antenna elements, G_t=32.4 dBi
Rx antenna omni-directional: G_r=1.
Output power: 100 W (50 dBm)
Sensitivity $P_{r,min}$ = -70 dBm (=10^{-10}W)

$$R = \sqrt{\frac{P_t G_t G_r \lambda_0^2}{(4\pi)^2 P_{r,\min}}} \approx 33km$$

Towards Software Antennas in 6G, >24 GHz



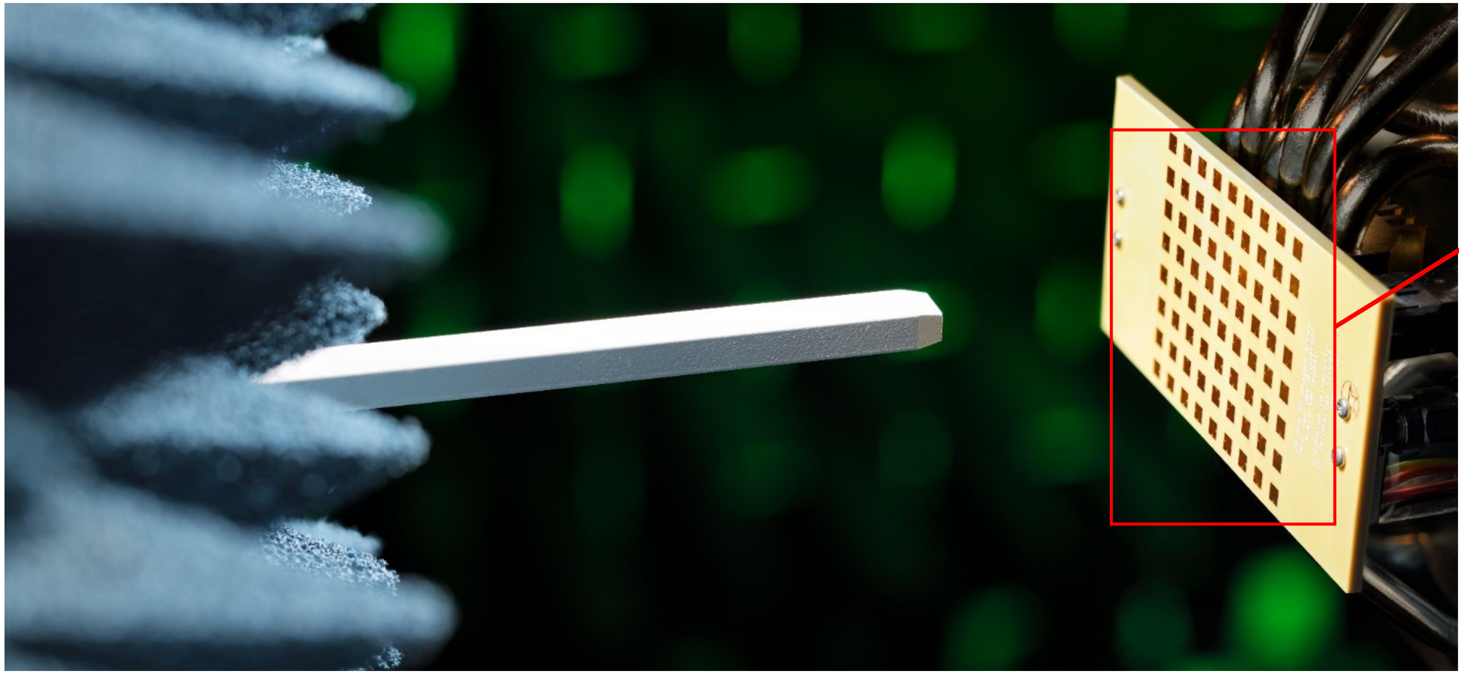
Examples of software antennas

Realized and measured by TU/e

in cooperation with NXP, Ericsson, Chalmers, TNO and others.

Software Antennas

Phased-array for 5G-NR Basestations (26.5-29.5 GHz)



8x8 phased array

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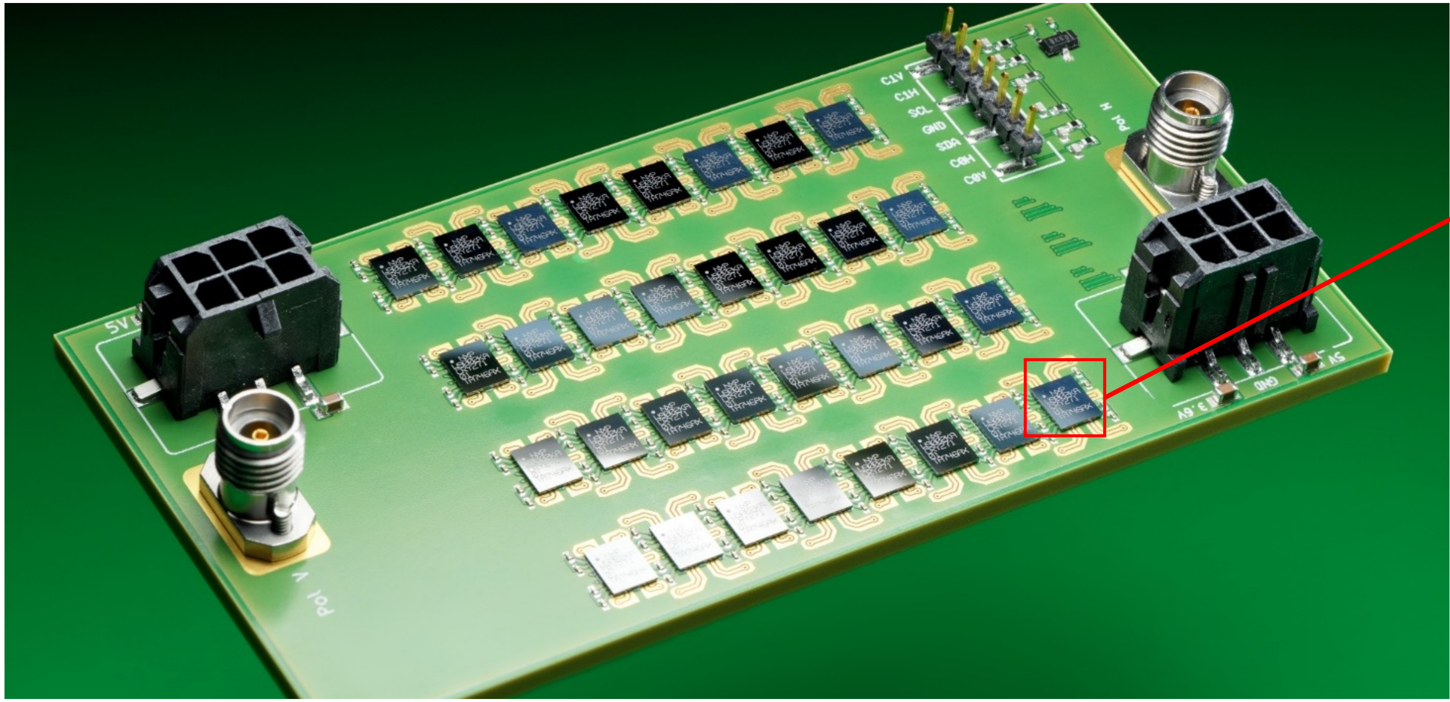
Software Antennas

Phased-array for 5G NR Basestations (26.5-29.5 GHz)



Active Ka-band Transmitarray

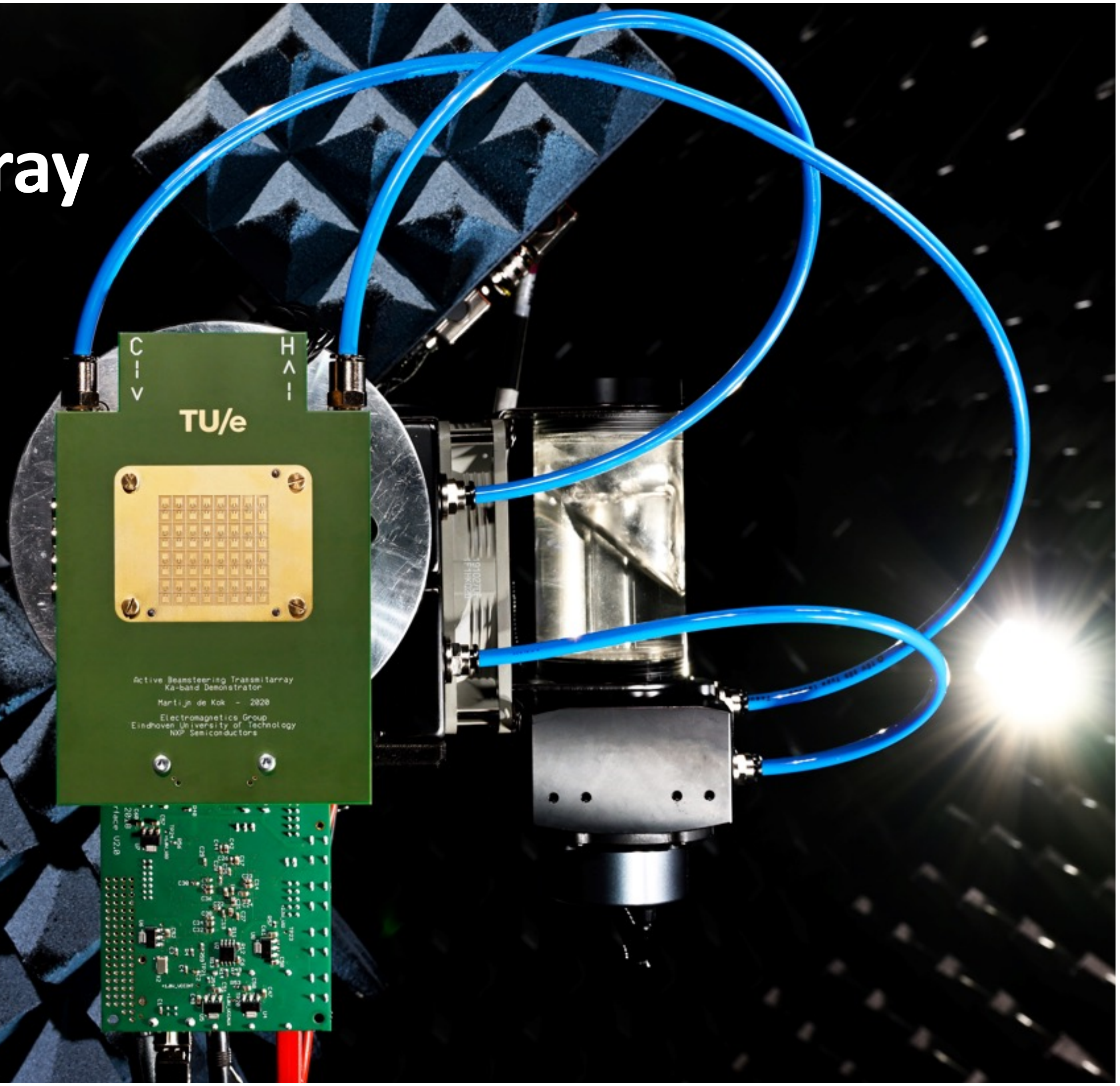
Tracking radar applications

Commercial 5G beamforming ICs

- Fast electronic beamforming
- Power amplification

Small-scale demonstrator

- Realized & measured



M. de Kok, A.B. Smolders, and U. Johannsen, "Active Ka-band Transmitarray for Ka-band Monopulse Tracking Radar," *publication pending,* 2022.

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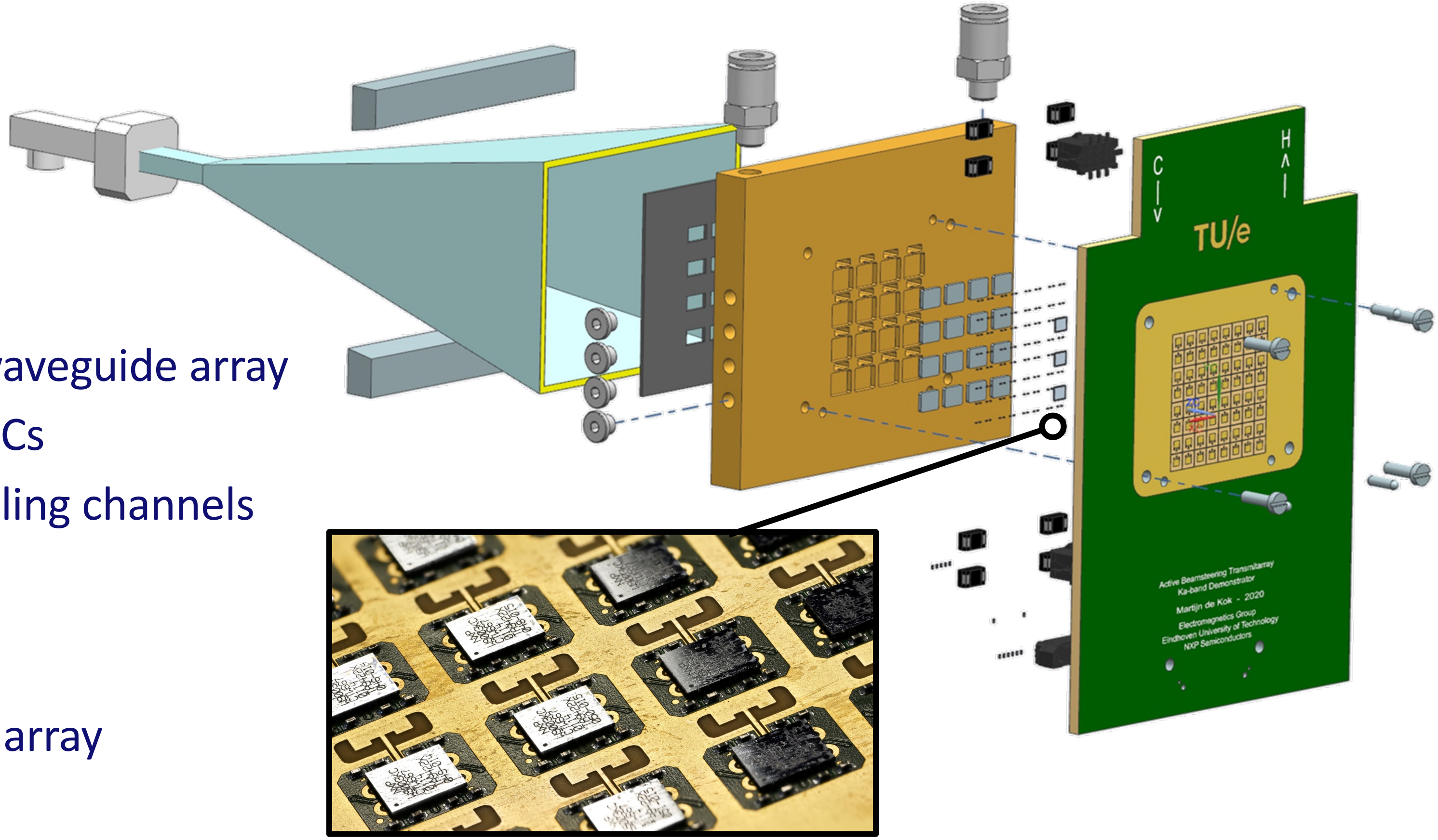
Demonstrator overview

Back:

- Horn antenna feed
- 4 × 4 Open-ended waveguide array
- 4 × 4 Beamforming ICs
- Integrated liquid cooling channels

Front:

- 8 × 8 Patch antenna array



M. de Kok, A.B. Smolders, and U. Johannsen, “Active Ka-band Transmitarray for Ka-band Monopulse Tracking Radar,” *publication pending,* 2022.
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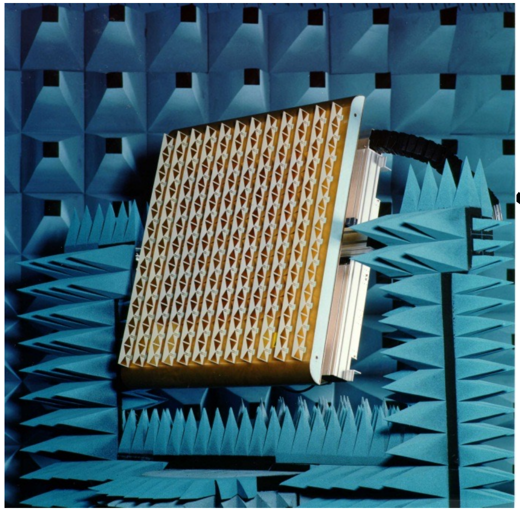
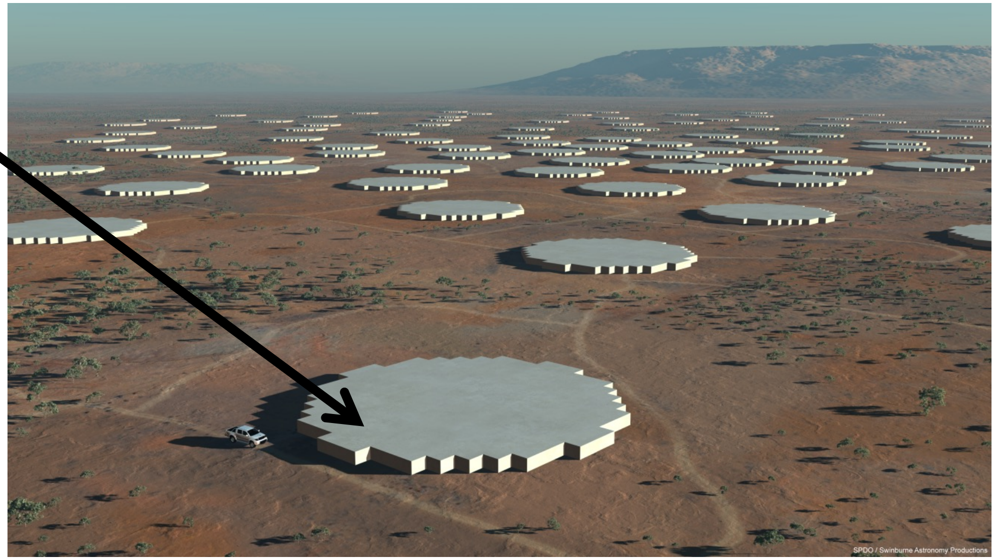
Square Kilometer Array, largest phased array in the world!, 1000-2500 MHz





[1] SKA, www.astron.nl
[2] A.B. Smolders, G.Hampson, IEEE AP Magazine, 2002
[3] Rob Maaskant, "Analysis of large antenna systems, "PhD thesis, 2010

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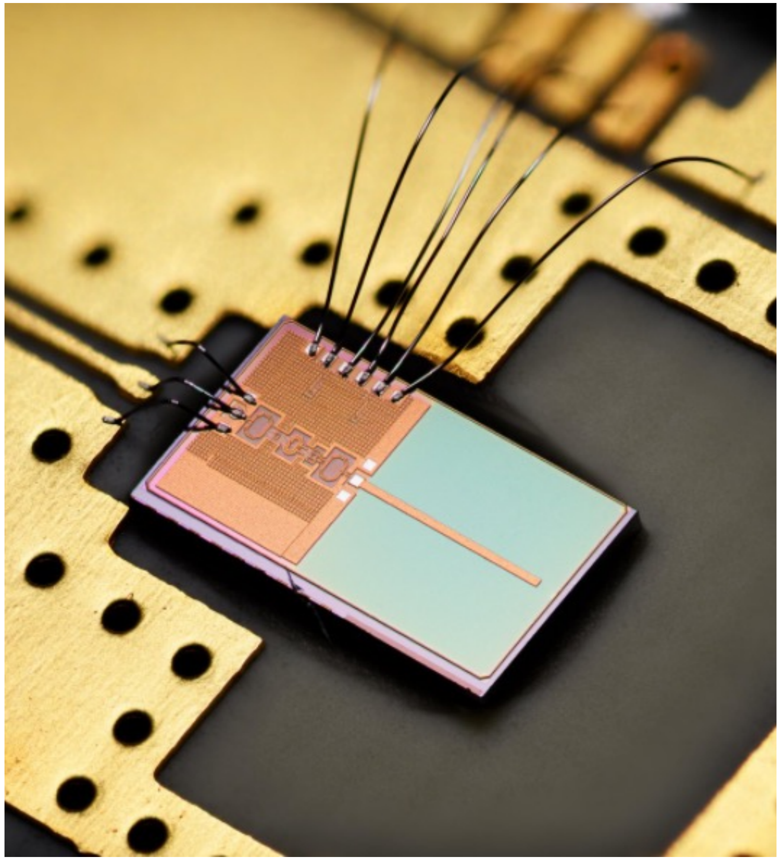
Towards

Antenna-Array-in-Package (AAiP)
Antenna Array-on-Chip (AAoC)

Antenna-on-Chip



BiCMOS silicon technology

LNA

Antenna on chip

30 GHz

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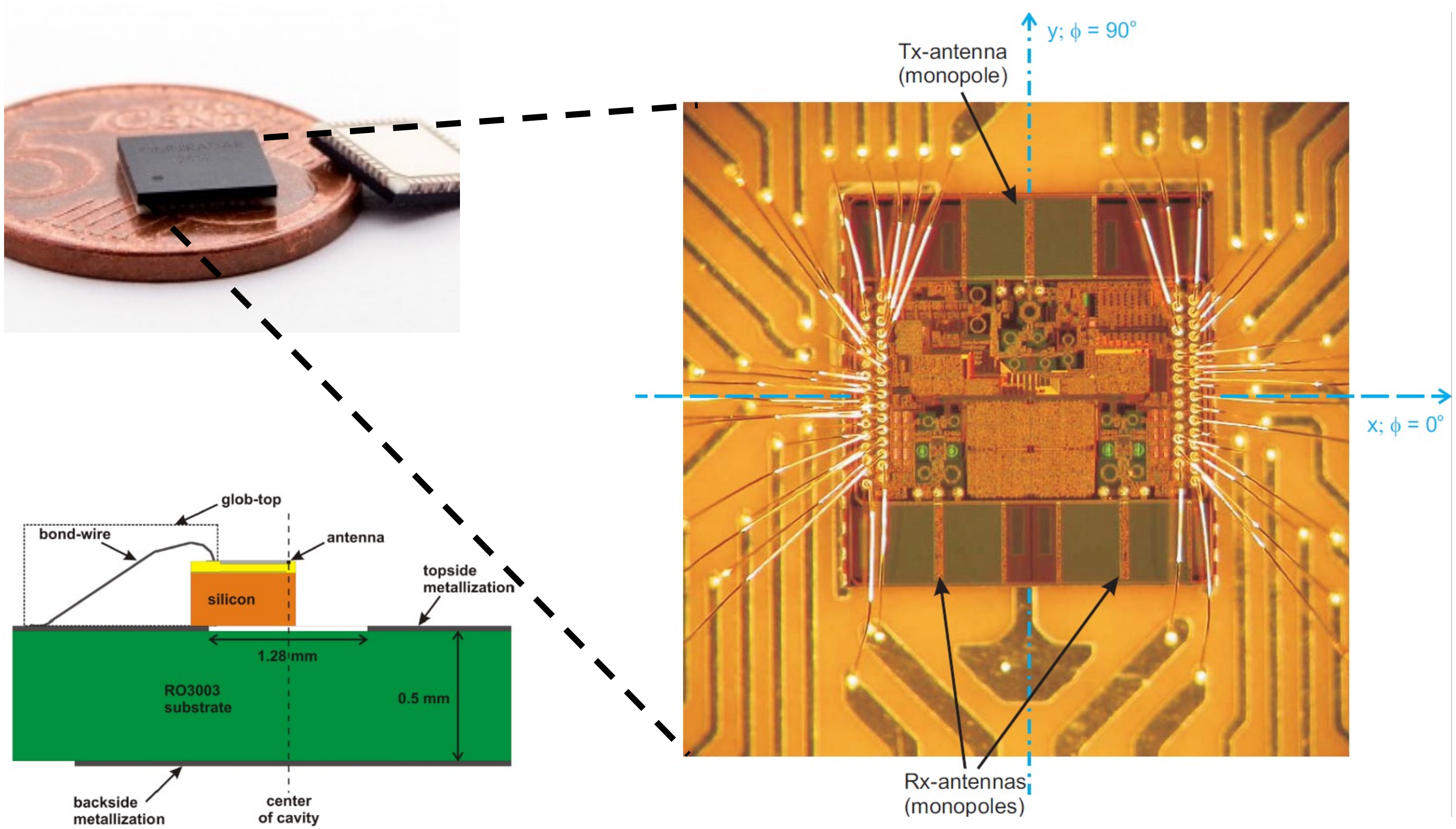
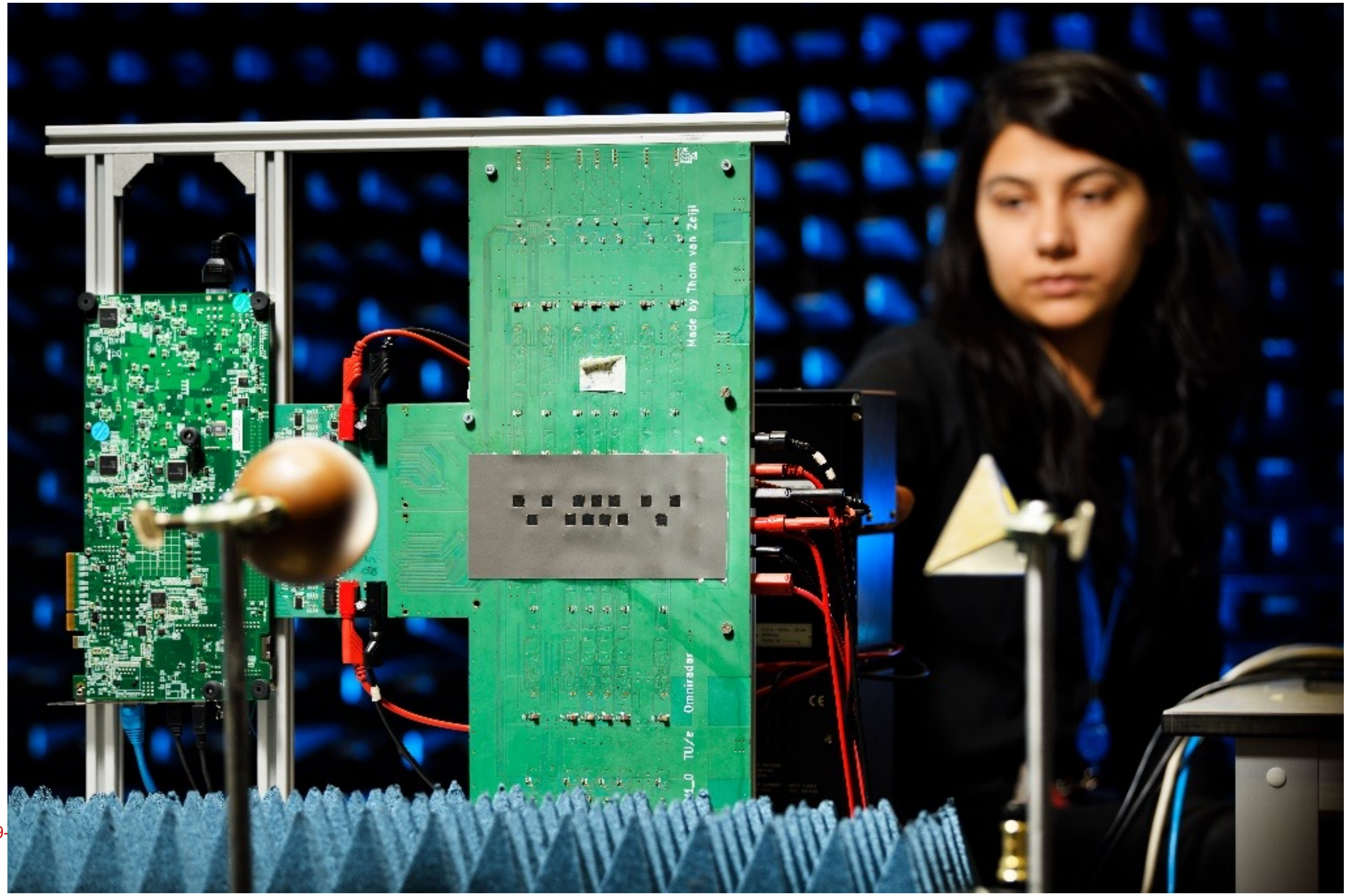
Single-chip 60 GHz FMCW radar



B. Adela; P.van Zeijl; U. Johannsen; A. B. Smolders "On-chip Antenna Integration for Millimeter-wave Single-chip FMCW Radar, Providing High Efficiency and Isolation"
IEEE Transactions on Antennas and Propagation, 2016.

MUSIC: MIMO radar Demonstrator

FMCW MIMO radar with 13 TX and 26 RX nodes @ 60 GHz



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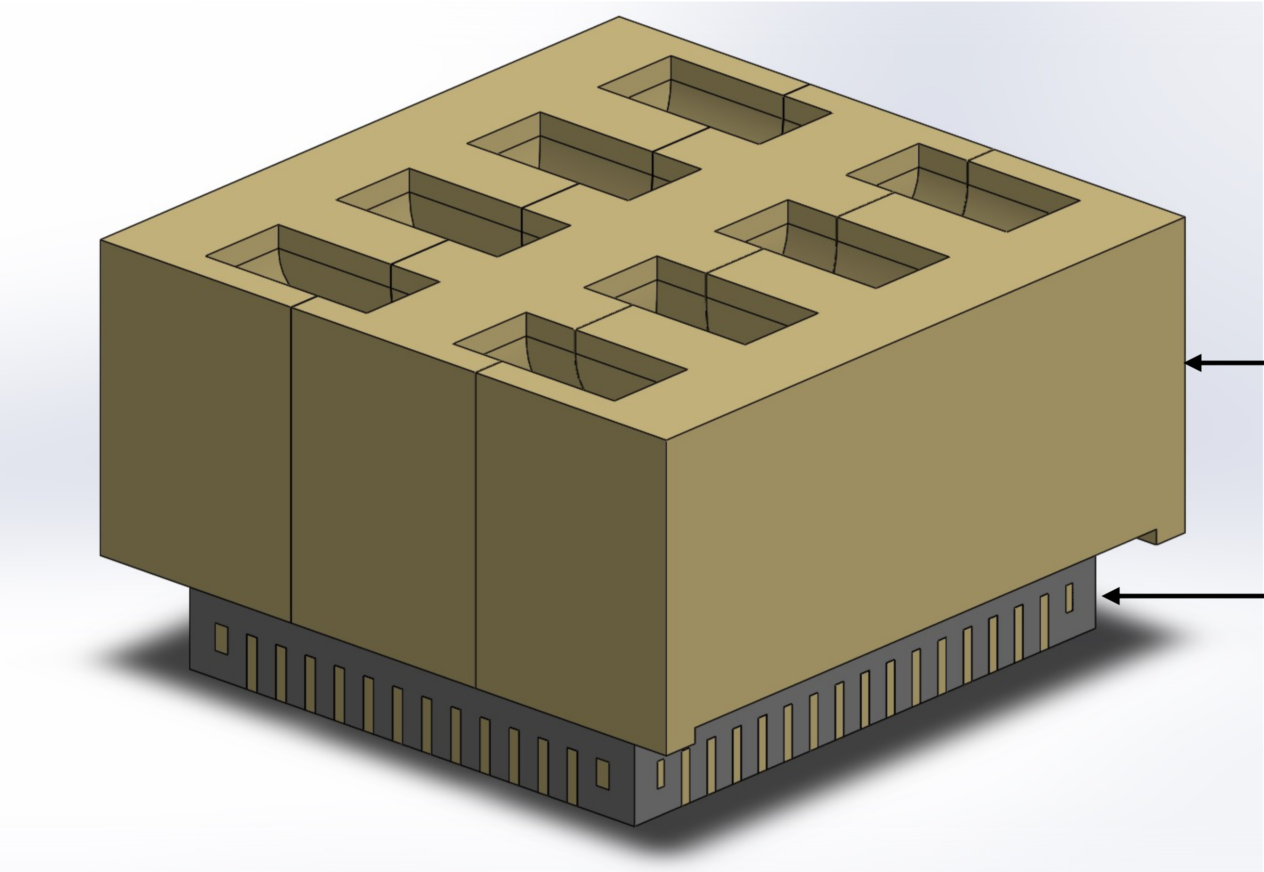
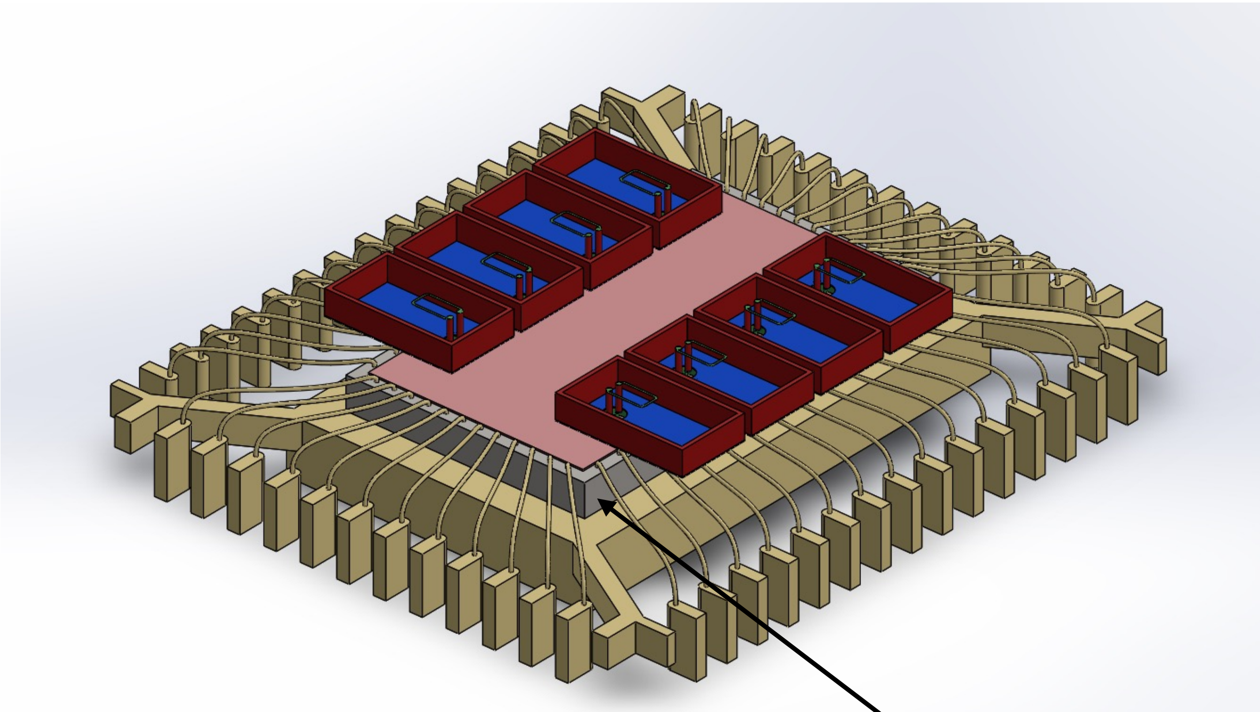
Low loss transition: Integrated waveguides Antenna-Array-in-Package (AAiP) @ 77 GHz



Low-loss waveguide radiators

Plastic package with RFIC using 3D interconnect

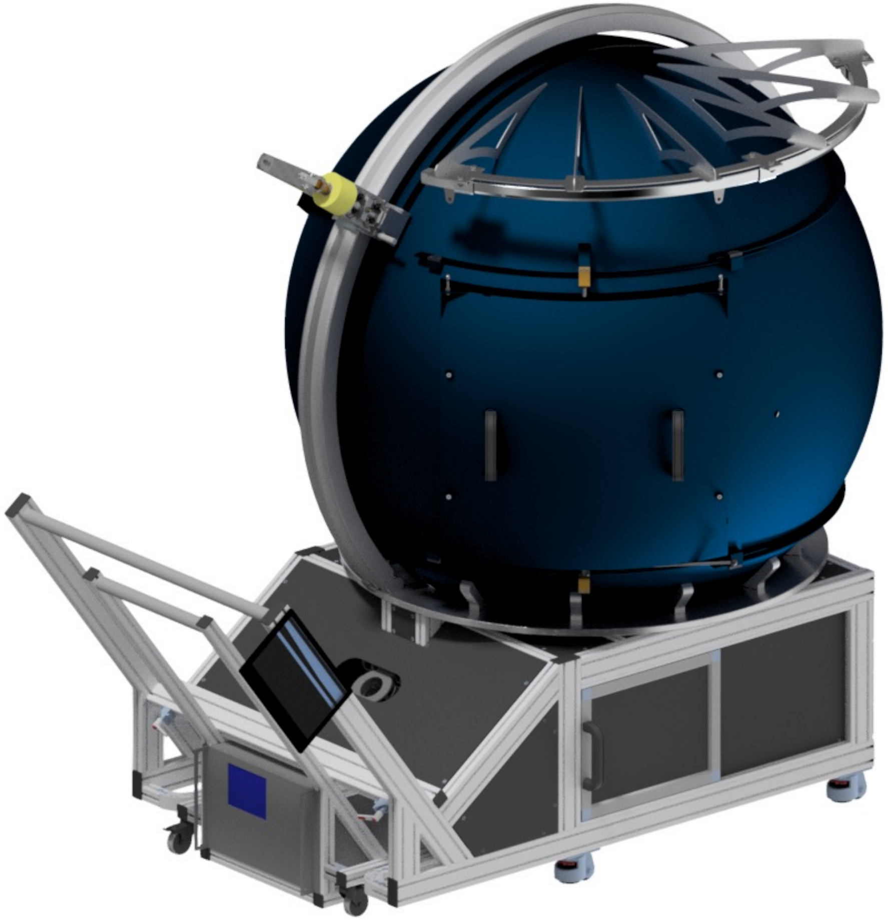
Low loss transition: Integrated waveguides Antenna-Array-in-Package (AAiP) @ 77 GHz

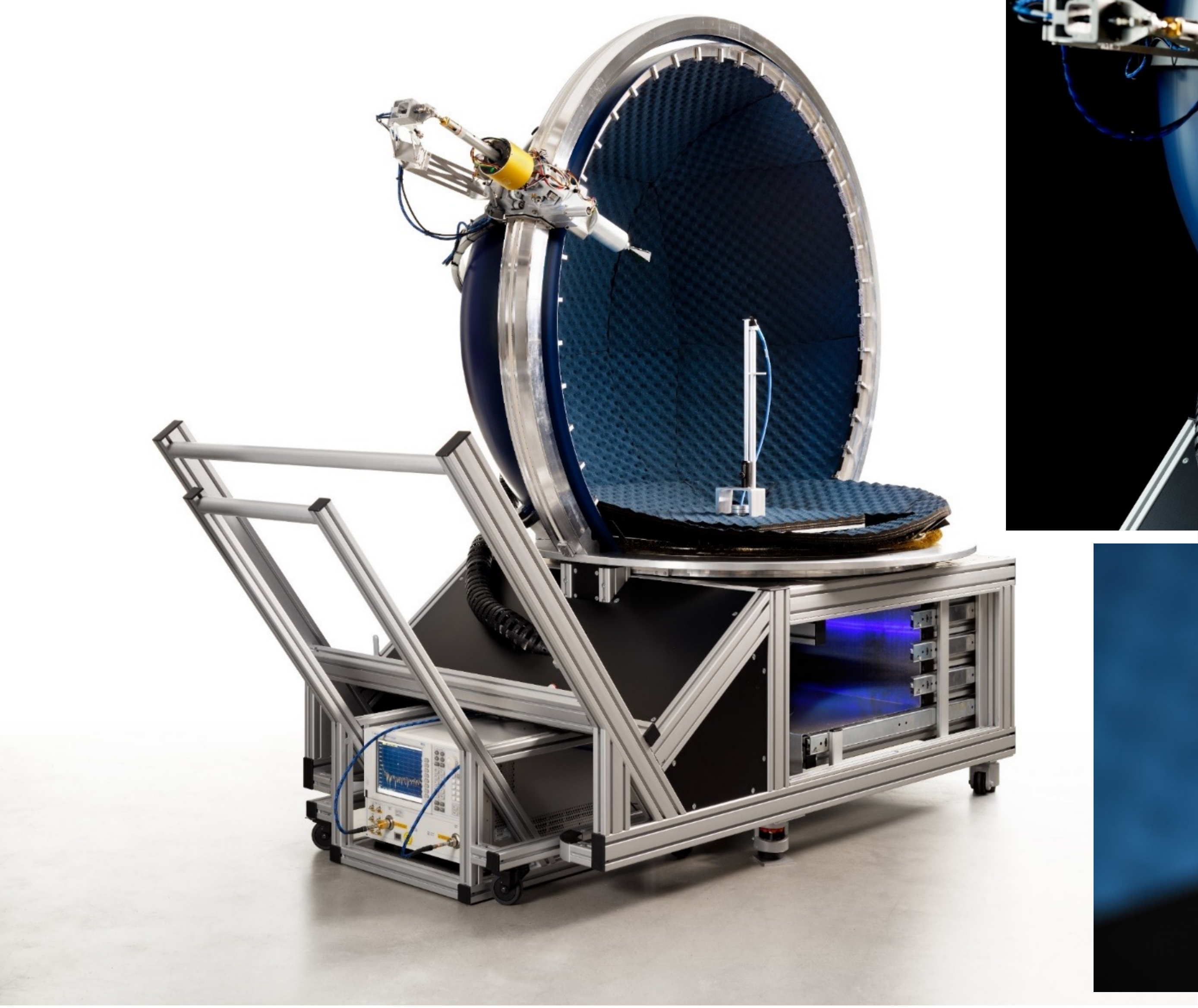


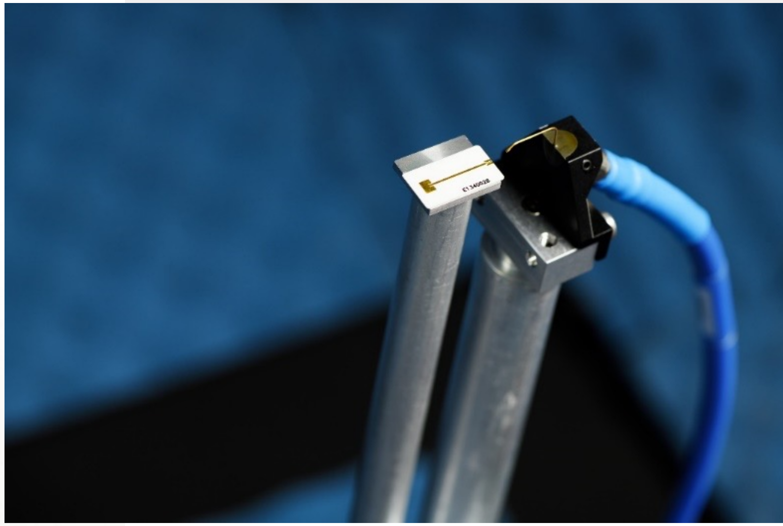
RFIC

Testing of Software Antennas

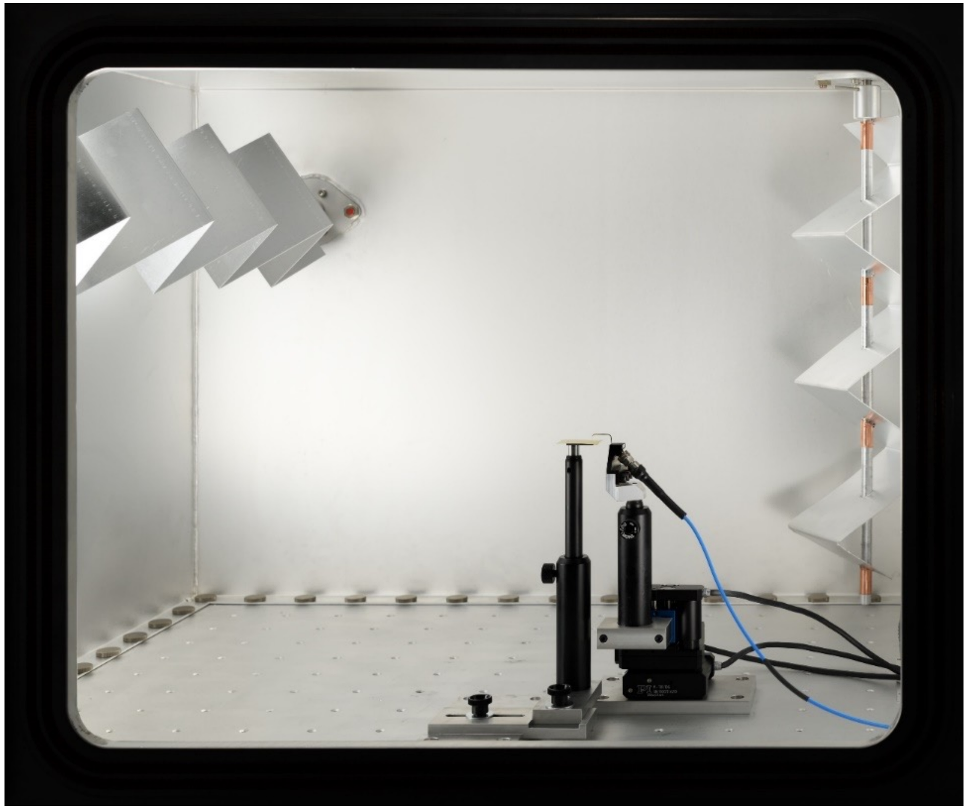
Integrated antenna test-facility at TU/e







Over-the-Air (OTA) measurements in Reverb



System-level parameters

- Noise Figure
- Total Radiated Power
- Total efficiency

Type of system under test

- Phased-array systems
- Antenna-in-package/on-Chip using probe

And more to come….

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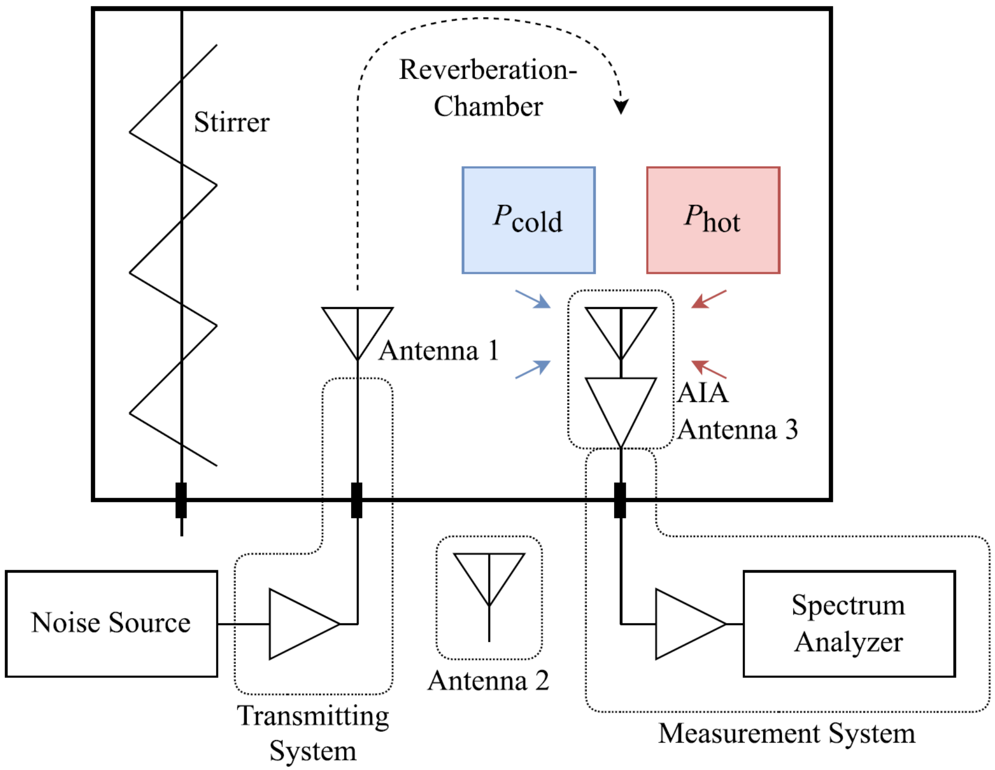
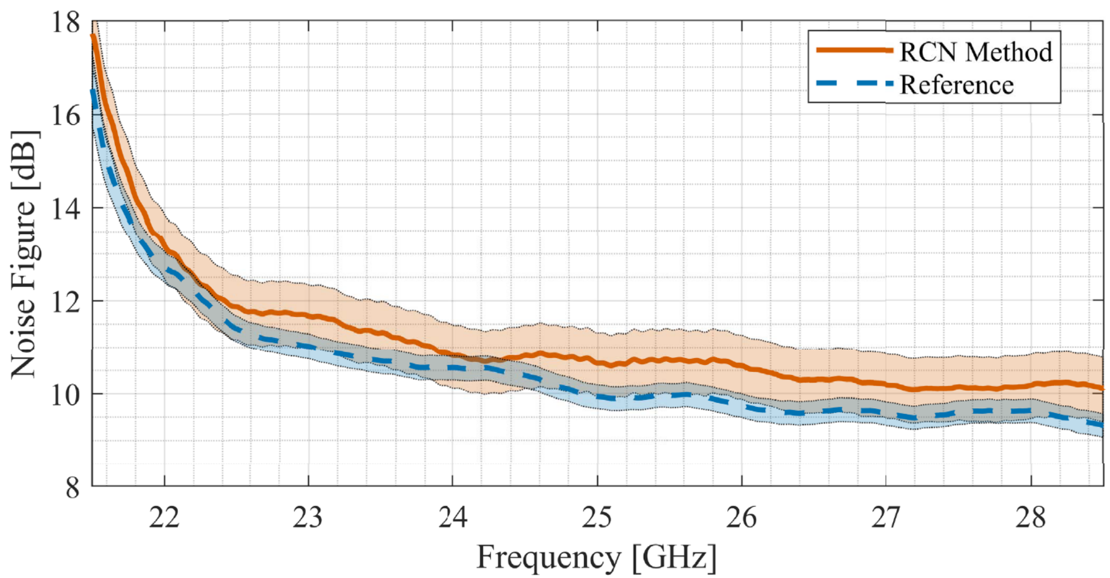
Over-the-Air Noise figure measurement with Reverb





[1] T. Stek, A. Hubrechsen, D. S. Prinsloo and U. Johannsen, "Over-the-Air Noise Figure Characterization of mm-Wave Active Integrated Antennas Using a Reverberation Chamber," in IEEE Transactions on Microwave Theory and Techniques, 2022.

Thank you !

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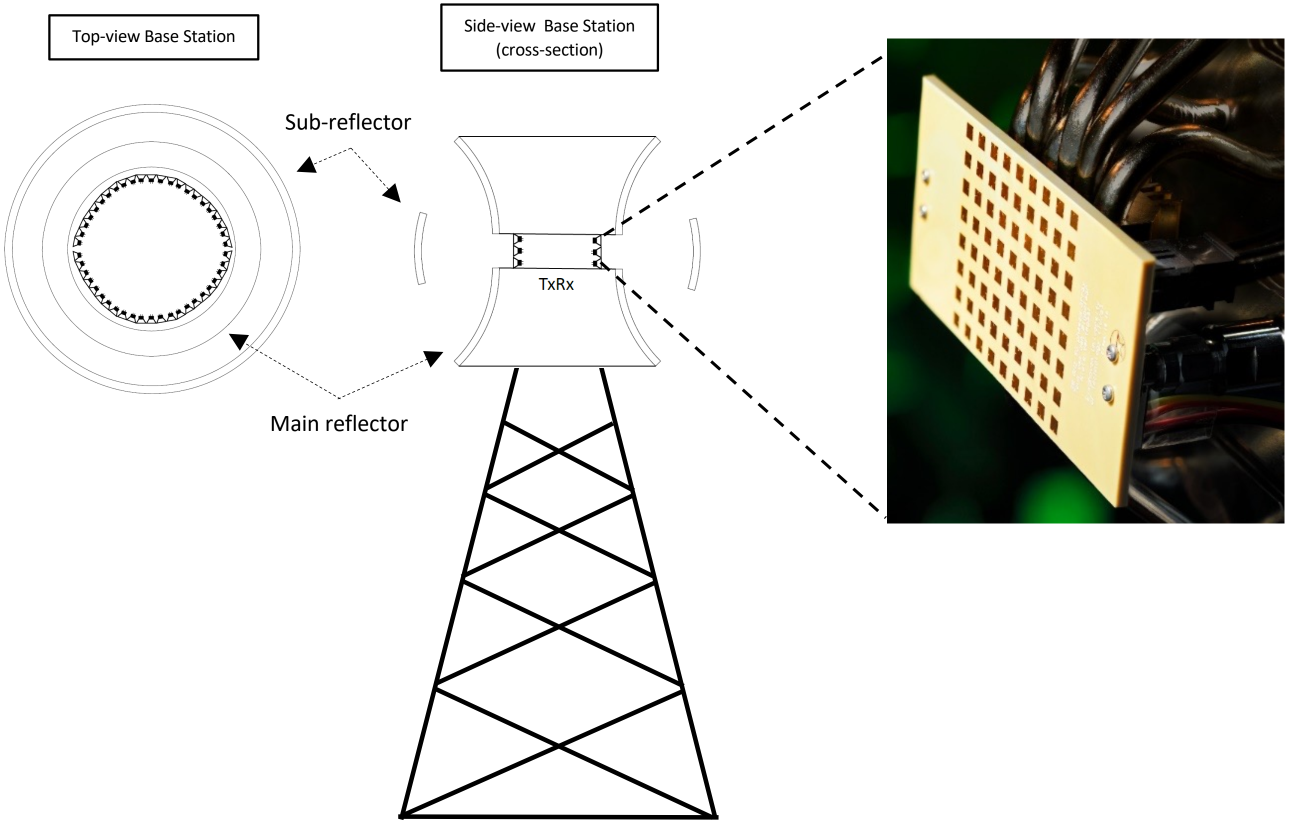
Focal-Plane Arrays



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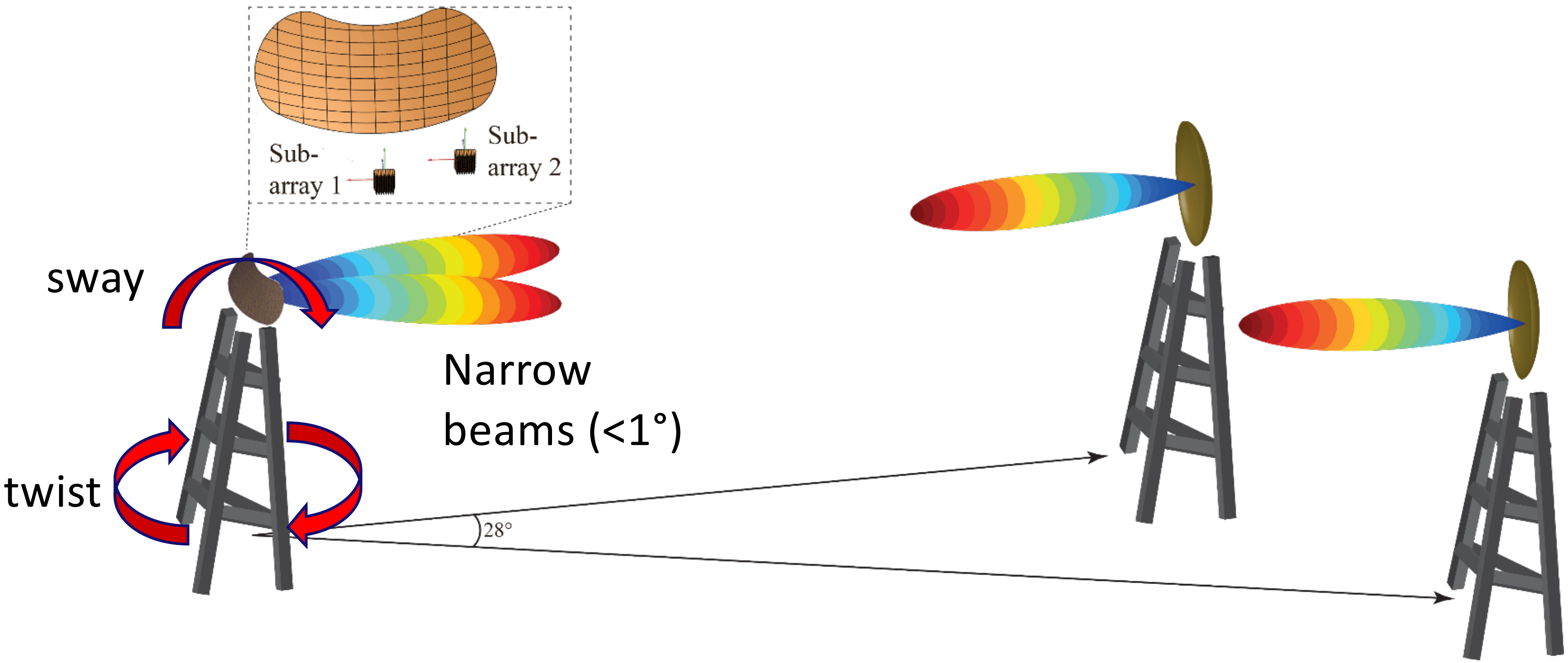
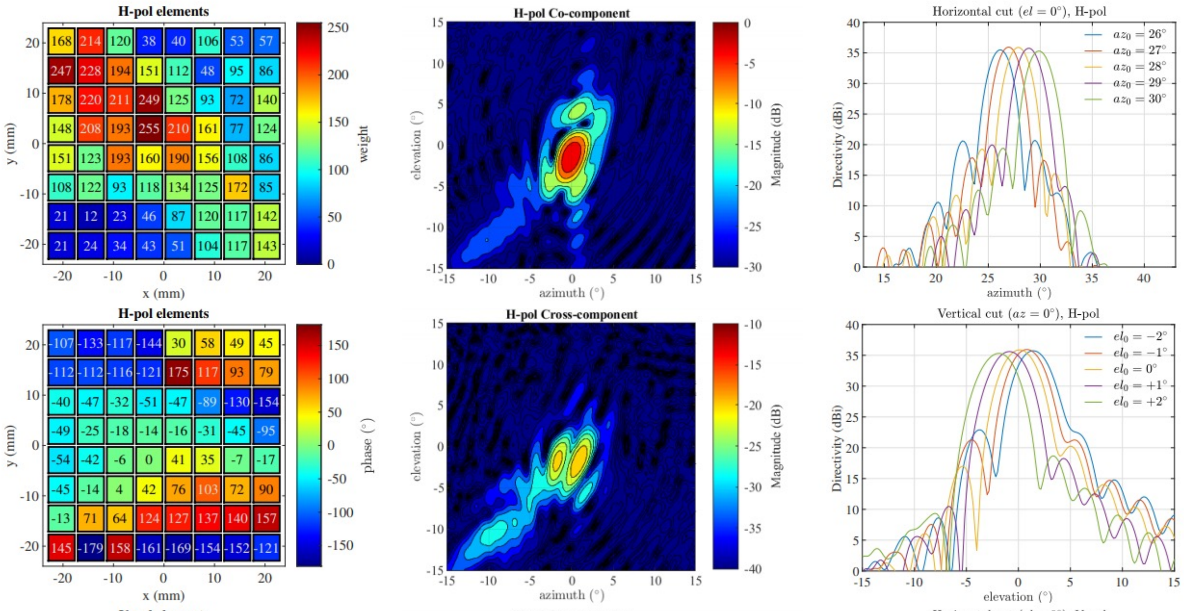
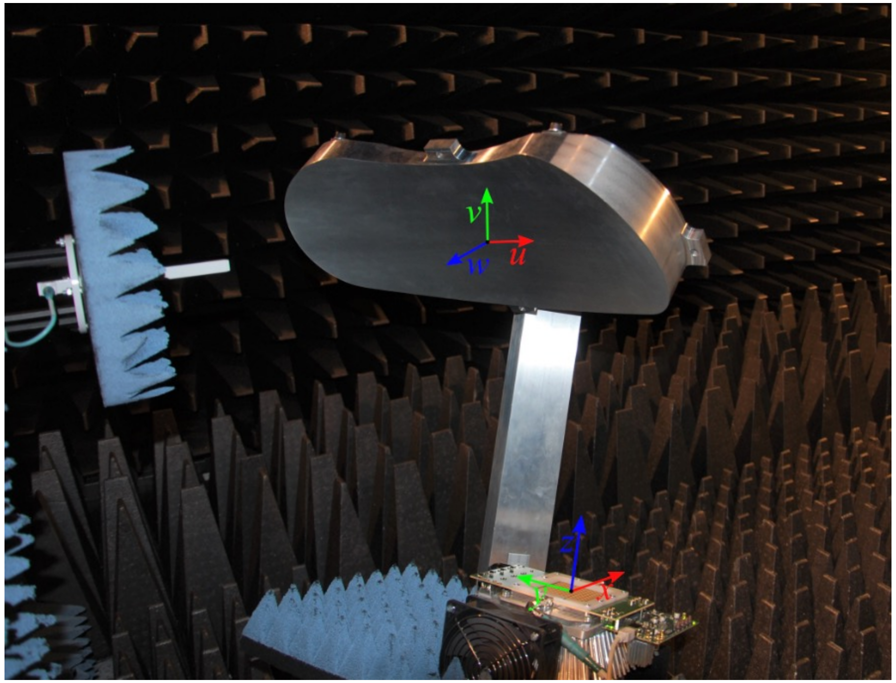
Point-to-multipoint focal plane array antennas



Measurements at 25.9GHz, scanning to 28° in azimuth





R. X. F. Budé, A. Elsakka, U. Johannsen and A. B. Smolders, "Wide-Scan Focal Plane Arrays for mmWave Point-to-Multipoint Communications," in *IEEE Open Journal of Antennas and Propagation*, vol. 3, pp. 112-123, 2022, doi: 10.1109/OJAP.2021.3136721.

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