Wireless Communications

OVER-THE-AIR MEASUREMENTS OF ELECTRICALLY LARGE BEAM-FORMING ANTENNA ARRAYS

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Make ideas real

INTRODUCTION

- Active antenna arrays are used in a wide range of applications: mobile devices and networks, satellite communications, radars…

- In wireless communications, arrays offer two essential capabilities:

  - **Beamforming** to focus the radiation towards the user(s)
    - Boosting the realized gain in the wanted direction
    - Reducing the radiated power in unwanted directions
    - Mitigating path loss effects / improving SNR

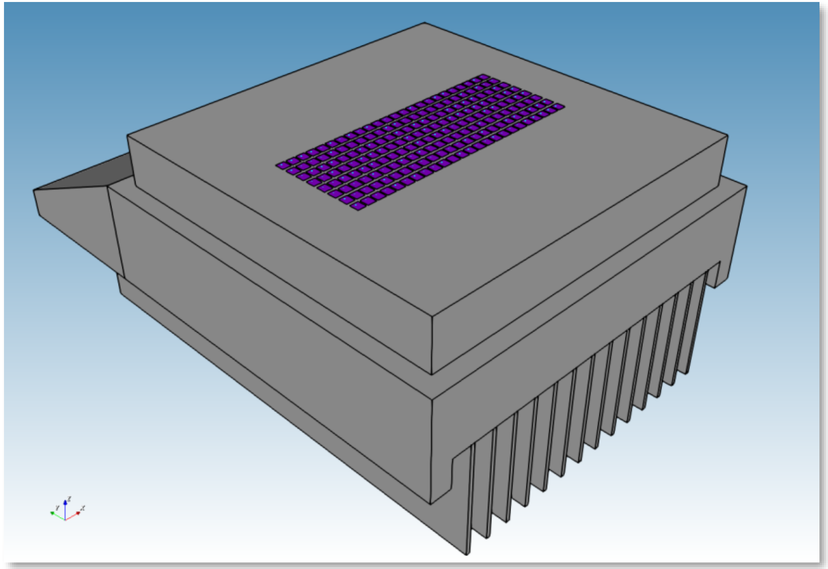
  - **Spatial multiplexing** through beamformed transmission of various data to users located at different locations a.k.a. massive or multi-user MIMO

OUTLINE

OUTLINE

ANTENNA ARRAYS: RELEVANT DEFINITIONS (IEEE STD 145)

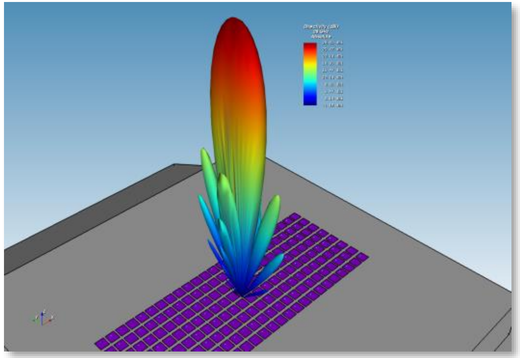
- **Array antenna:** An antenna comprised of a number of radiating elements the inputs (or outputs) of which are combined. Syn: antenna array.
- **Array element:** In an array antenna, a single radiating element or a convenient grouping of radiating elements that have fixed relative excitations.
- **Active array antenna system:** An array in which all or part of the elements are equipped with their own transmitter or receiver, or both.
- **Adaptive antenna system:** An antenna system having circuit elements associated with its radiating elements such that one or more of the antenna's properties are controlled by the received signal.
- Active Antenna Systems (AAS) in 3GPP

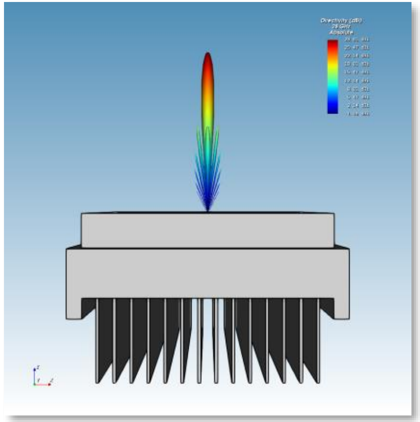


Source: IMST GmbH, numerical model based on: D. Anguiano Sanjurjo, *Investigation of Hybrid Simulation Methods for Evaluation of EMF Exposure in Close Proximity of 5G Millimeter-Wave Base Stations*

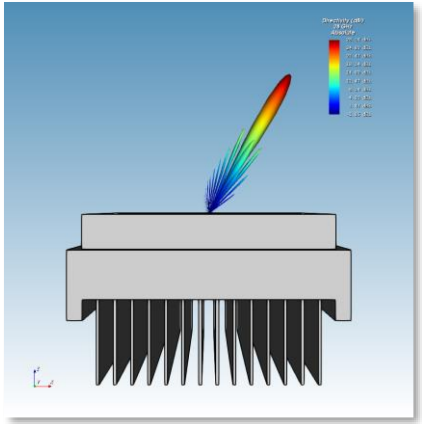
BEAMFORMING: RELEVANT DEFINITIONS (IEEE STD 145)

- **Beam (of an antenna):** the major lobe of the radiation pattern of an antenna.
- **Scan angle:** the angle between the direction of the maximum of the major lobe or a directional null and a reference direction. Syn: beam angle.
- **Beam steering:** changing the direction of the major lobe of a radiation pattern.
- **Digital beamforming array:** an antenna array where beamforming is performed by software rather than hardware.





0° beam steering (broadside)

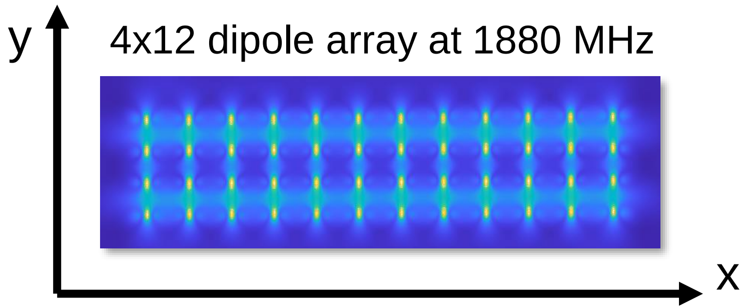


~30° beam steering

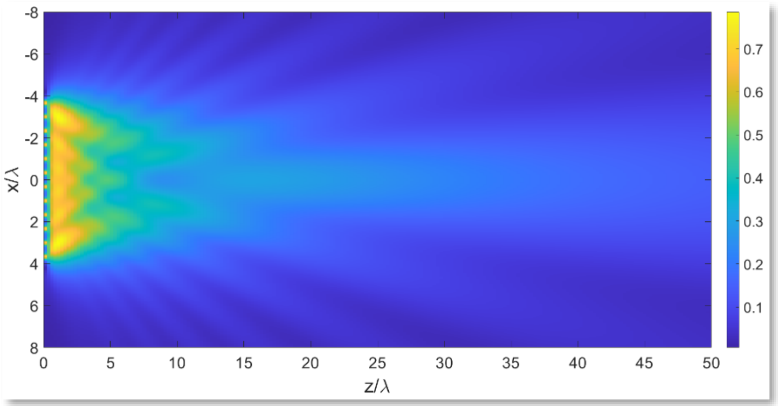
SUPERPOSITION OF SPATIAL FIELDS

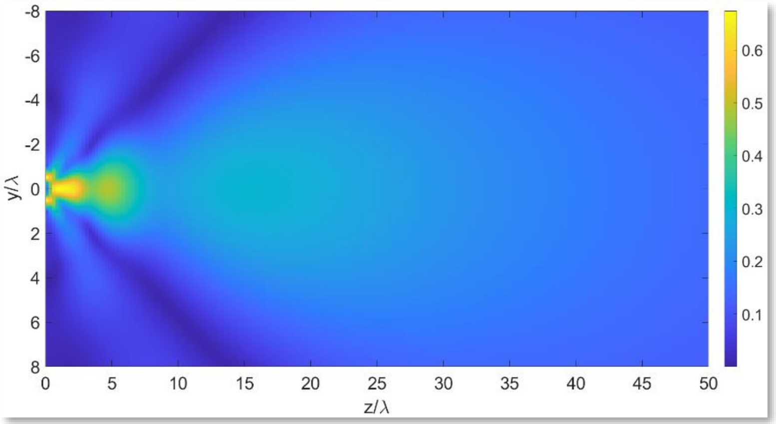
- Arrays utilize the superposition of spatial fields of each element to
  - Form a beam in the wanted direction
  - Improve certain radiation characteristics of the array (e.g. side-lobe level)

- Shaping and steering of the beam is obtained through adequate phase shift and amplitude control of RF path to each element



x-component electric field magnitude





BEAMFORMING IN WIRELESS COMMUNICATIONS TODAY AND TOMORROW

- ► With 5G NR, beamforming in the far-field
  - – at FR1 and FR2 (mmW) for radio base stations (incl. spatial multiplexing, MU-MIMO)
  - – at FR2 for user equipment / mobile devices
- ► 6G sub-THz expected to use electrically larger arrays in the radiative near-field; beamforming turns into NF focusing at depth-of-focus (DF).
  - – Community is talking of *Wavefront Engineering* rather than beamforming.

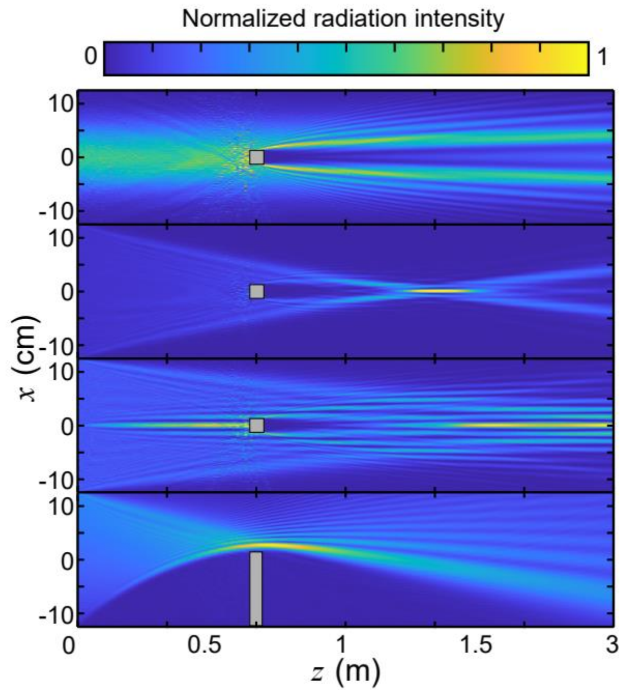


Fig. 4: Blockage mitigation with different wavefronts. From top to bottom: beamforming, beamfocusing, Bessel, Airy-like curved beam. Full wave finite-element-method (FEM) with COMSOL Multiphysics is utilized.

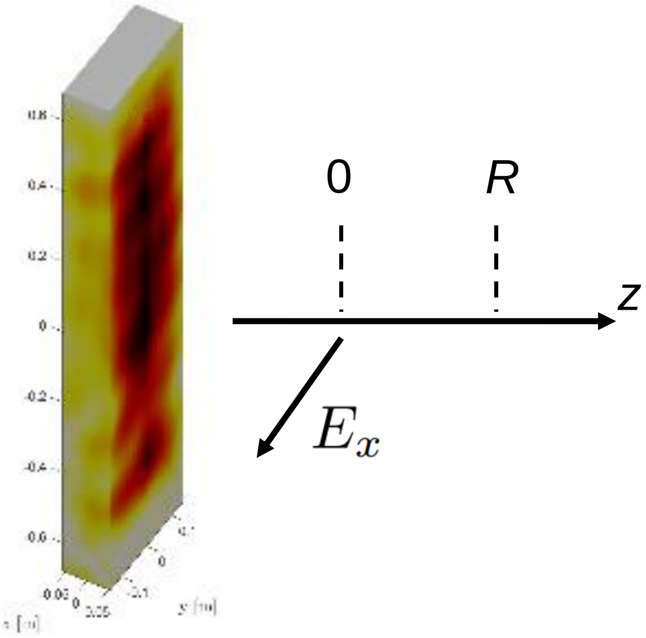
Source: A. Singh et al., *Wavefront Engineering: Realizing Efficient Terahertz Band Communications in 6G and Beyond*

THE PLANE-WAVE SPECTRUM / FOURIER FORMALISM

PWS

$$\boxed{\widehat{E_x}\left(k_x, k_y, 0\right)} = \iint_{-\infty}^{+\infty} E_x(x, y, 0) e^{j\left(k_x x + k_y y\right)} dx dy$$

$$E_x(x, y, 0) = \frac{1}{4\pi^2} \iint_{-\infty}^{+\infty} \widehat{E_x}\left(k_x, k_y, 0\right) e^{-j\left(k_x x + k_y y\right)} dk_x dk_y$$



THE PLANE-WAVE SPECTRUM / FOURIER FORMALISM

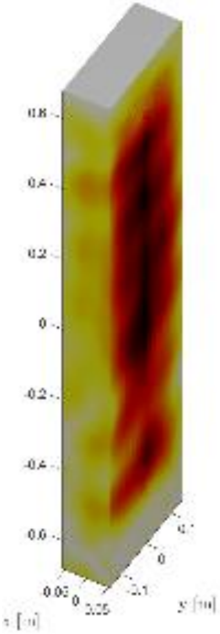
► Propagation of the PWS:

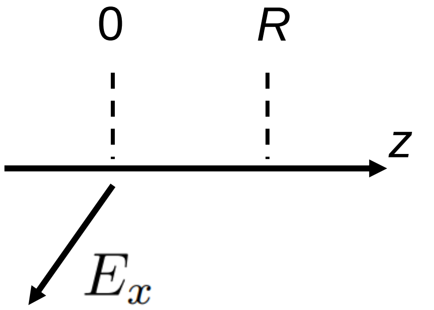
$$\widehat{E_x}\,(k_x, k_y, R) = \widehat{E_x}\,(k_x, k_y, 0)\, e^{-jR\sqrt{k_0^2 - k_x^2 - k_y^2}}$$

- Visible / radiative region within the k_0-circle
- Invisible / reactive region outside the k_0-circle

► Far-field relation:

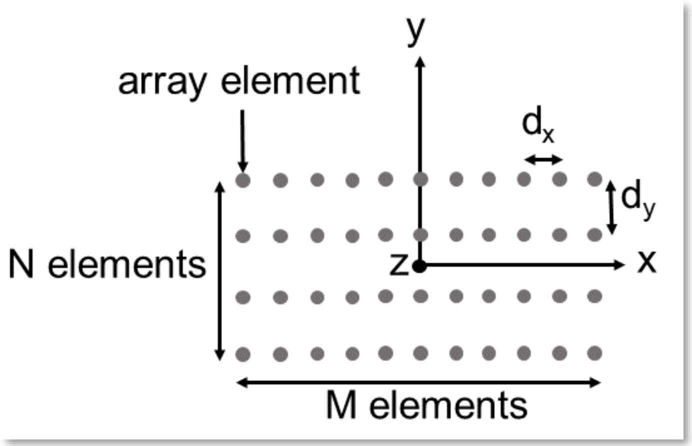
$$\begin{aligned} \mathrm{EIRP}_x(\theta,\phi) &= \frac{2\pi R^2}{\eta}\left|E_x(R,\theta,\phi)\right|^2 \\ &= \frac{2\pi}{\lambda^2\eta}\left|\widehat{E_x}\,(\sin\theta\cos\phi, \sin\theta\sin\phi)\right|^2 \cos^2\theta \end{aligned}$$





BEAMFORMING AS SPECTRAL FILTERING

- Simplifying assumption: the field created by each element is identical, just shifted in space
- A space translation corresponds to a linear phase shift in the *k*-space
- $a_{m,n}$: complex excitation coefficients

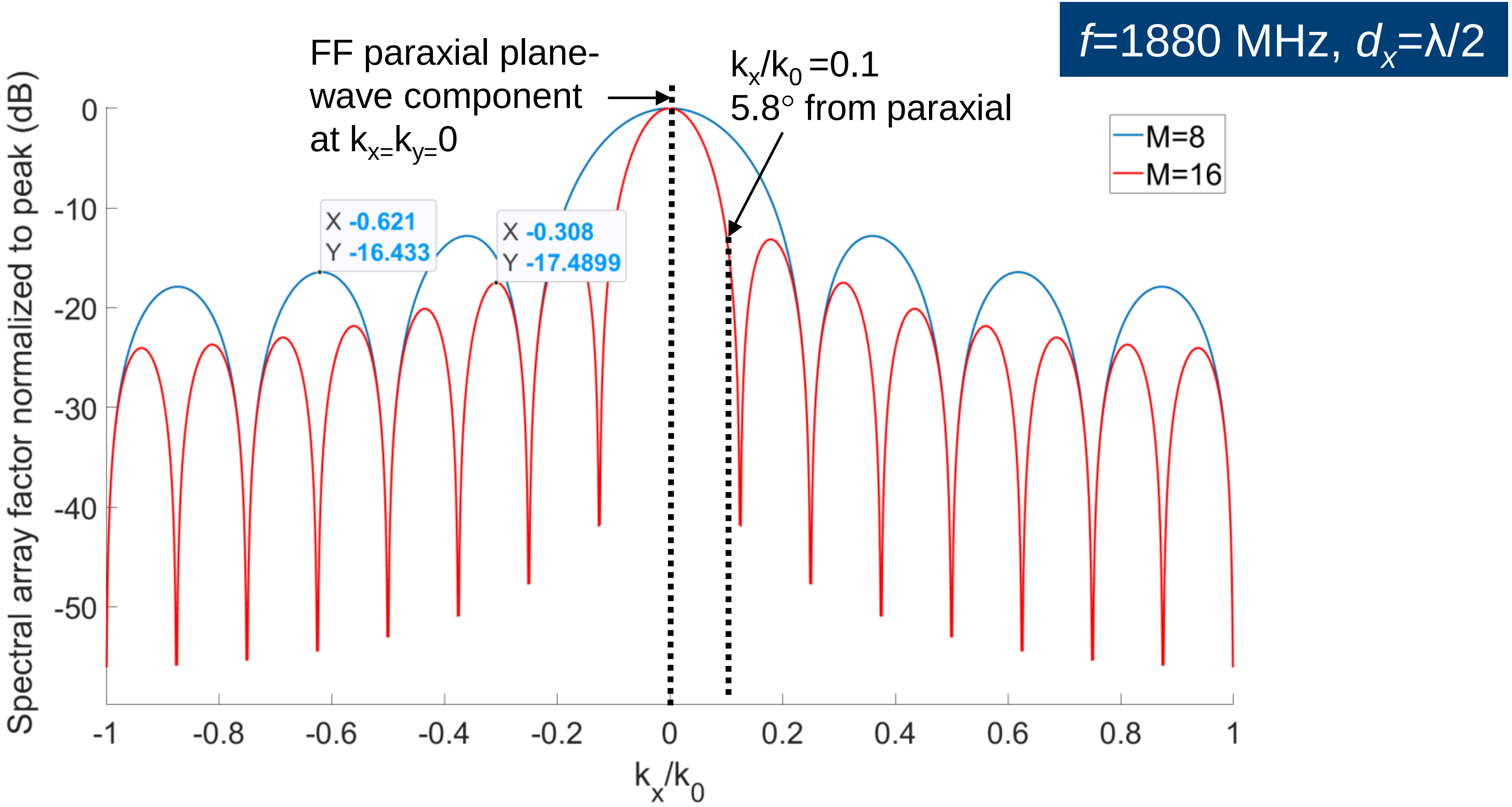


$$\widehat{E_x^{ar}}(X,Y,0) = \widehat{E_x^{el}}(X,Y,0)\,\frac{sin(k_0 M \frac{d_x}{2} X) sin(k_0 N \frac{d_y}{2} Y)}{sin(k_0 \frac{d_x}{2} X) sin(k_0 \frac{d_y}{2} Y)}$$

$X = k_x / k_0$
$Y = k_y / k_0$

$a_{m,n} = 1$ broadside radiation

NORMALIZED SPECTRAL ARRAY FACTOR



BEAM STEERING: FILTER TRANSLATION IN K-SPACE

- Beam steering is obtained by applying a linear phase progression across elements

- Phase shift between adjacent elements (or time delay):

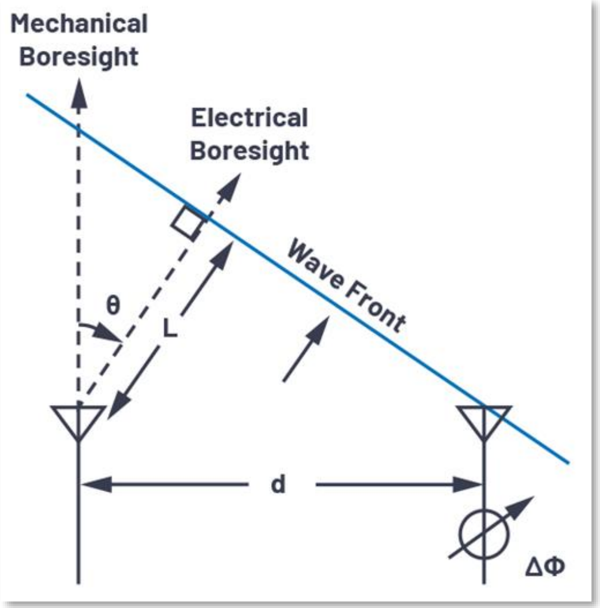
$$\Delta\boldsymbol{\phi} = k_0 d \sin\theta$$

- Impact in *k*-space:

$$\widehat{E_x^{ar}}(X, Y, 0) = \widehat{E_x^{el}}(X, Y, 0) \times \left[\sum_{m=0}^{M-1} \sum_{n=0}^{N-1} a_{m,n} e^{jk_0(md_x X + nd_y Y)} \right]$$

$$\downarrow$$

$$e^{jk_0 m d_x (X + \Delta\boldsymbol{\phi})}$$



Source: P. Delos et al., *Phased Array Antenna Patterns — Part 1, Analog Devices, Analog.com*

SPECIFIC WINDOW FUNCTIONS AND BEAM-SHAPING

$$\left[\sum_{m=0}^{M-1}\sum_{n=0}^{N-1} a_{m,n} e^{jk_0(md_xX+nd_yY)}\right]$$

- Applying specific weightings $a_{m,n}$ or window functions allow shaping of the beam to meet target criteria
  - **Kaiser, Saramäki:** max. energy in the main lobe
  - **Dolph-Chebyshev:** minimum main-lobe width for a specified max side-lobe level
  - **Ultraspherical:** control of side-lobe pattern
- Additional considerations: choice of position of elements within the array, non-regular grids

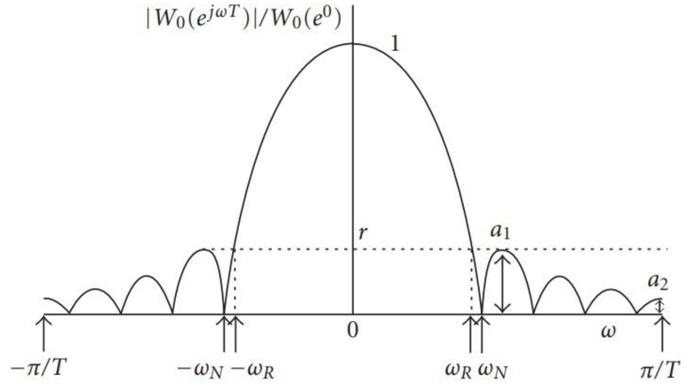
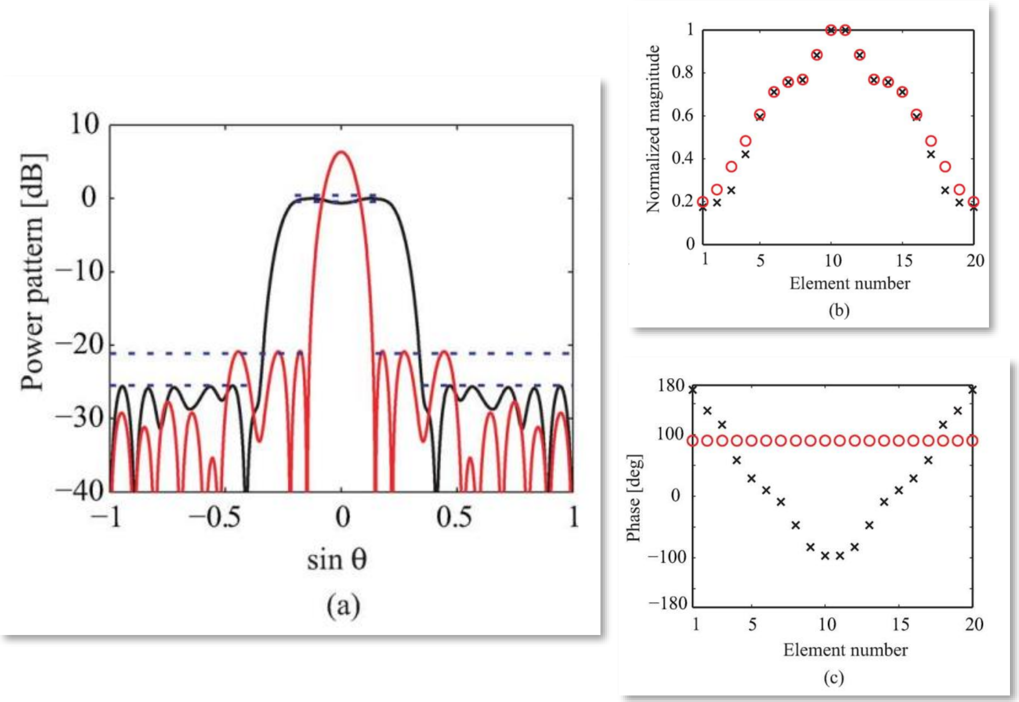


FIGURE 1: A typical window's normalized amplitude spectrum and some common spectral characteristics.

Source: S. W. A. Bergen, and A. Antoniou, *Design of Ultraspherical Window Functions with Prescribed Spectral Characteristics.*

THE PROBLEM OF ARRAY PATTERN SYNTHESIS

- LCMV beamforming: linearly constrained beamforming with min. variance
- Many array synthesis problems are non-convex and hence difficult optimization problems (NP-hard)
- Global optimization approaches: computational cost; non-optimal solutions
- Approaches to find efficient solutions to more complex problems exist, e.g. semi-definite relaxation applied to shaped beam with phase control only

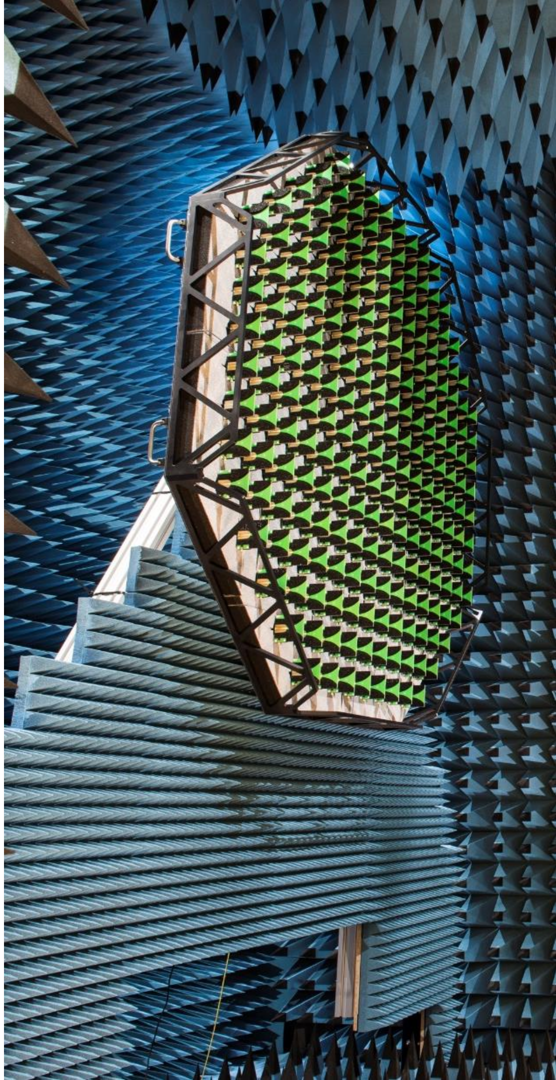


Source: B. Fuchs, *Application of Convex Relaxation to Array Synthesis Problems*.

ADDITIONAL CONSIDERATIONS

- Mutual coupling of the elements within the array and hence their input impedance varies with the weighting:
  - For reference: AP/MTT/EMC Webinar Series with F. Leong, *Antenna Arrays – Active Impedance & Beamforming*: https://youtu.be/nn9fhwkSG_w

- Array calibration
  - Optimal sets of coefficients found in simulation
  - In real life:
    - Non-ideal attenuators, phase shifters, transmission lines, etc…
    - Limitations in ability to qualify specific deviations
    - Phase not accessible in an over-the-air setup
  - For reference: B. Derat, *Over-the-air testing using plane-wave synthesis: from theory to realization*, AMTA 2020 Opening Keynote, available on R&S website.



OUTLINE

1 Antenna Array and Beamforming Principles

2 Over-The-Air Characterization of Active Antenna Systems

3 Example of Active Antenna Array Technology: the IMST Santana V4

4 OTA Measurement of the Example Array in the ATS1800C CATR

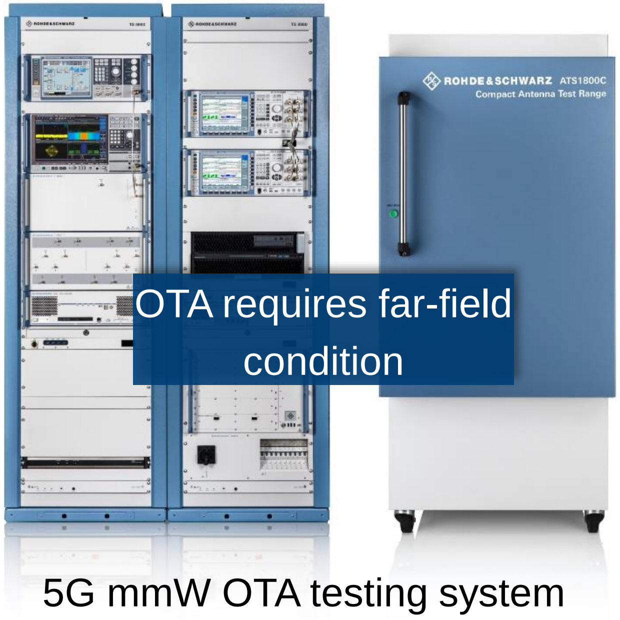
OTA VS. ANTENNA TEST: FUNDAMENTAL DIFFERENCES

- Antenna measurement: evaluation of fundamental antenna radiation properties
- OTA: assessment of the transceiver performance, including the antenna pattern

- In OTA
  - No cable access to the DUT
  - Wideband modulated signals with complex waveforms
  - DUT TX / RX RF chains are different
  - Measurement of system parameters (EIRP, EIS, TRP, TIS, EVM, ACLR, etc…)
  - Dynamic capabilities of the DUT

ANTENNA MEASUREMENT VS. OTA TESTING

5G mmW antenna measurement system

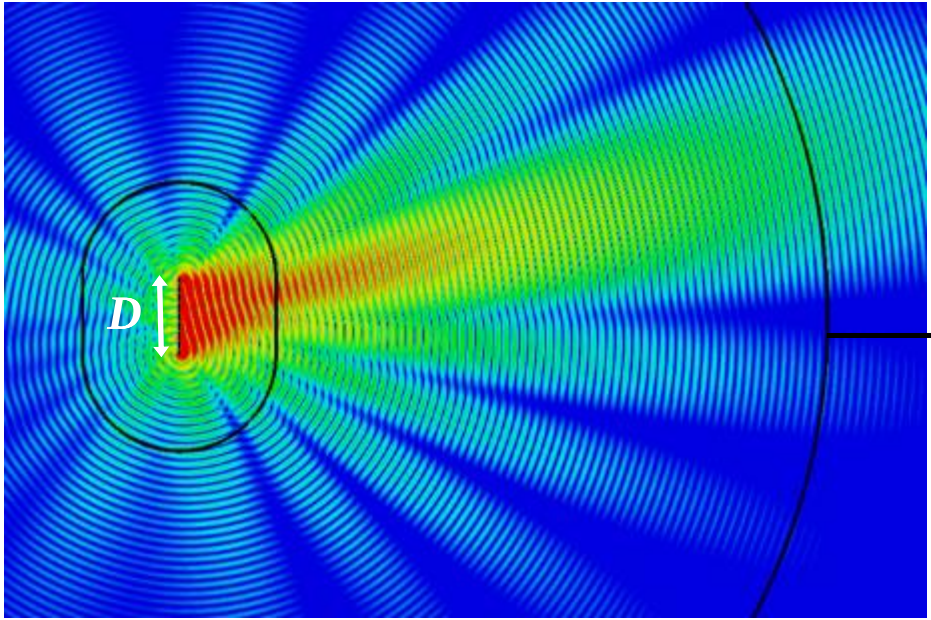


OTA requires far-field condition

5G mmW OTA testing system

TYPICAL "FAR-FIELD" TEST DISTANCE

If *D* is an array aperture of 30 cm at 30 GHz



Fraunhofer distance (FHD)

$$\frac{2D^2}{\lambda} = 18\,m$$

DIRECT FAR-FIELD MEASUREMENTS BELOW FRAUNHOFER

C63®

American National Standards Committee C63®

Electromagnetic Compatibility

Subcommittee 4 – Wireless & ISM Measurements

C63.xx – Millimeter wave Massive MIMO Distance Study

Chair: Dave Case **Vice-Chair: Benoit Derat** **Secretary: Jerry Ramie**

White paper Draft Outline Revision 21 12/2/2022

Discussion on Measurement Test Distance for Determining EIRP or TRP for Active Antenna Systems

Abstract: *This document discusses general requirements and methodologies for the determination of far-field peak gain, Equivalent Isotropic Radiated Power (EIRP) and Total Radiated Power (TRP) of Active Antenna systems (AAS), at ranges shorter than the classical Fraunhofer distance.*

Find more details on our R&S Demystifying EMC (DEMC) 2023 on-demand videos

THE FHD IS NOT ENOUGH

- ► Accurate sidelobes and nulls measurement requires good phase uniformity within the quiet zone

- ► This requires going beyond the FHD

"IEEE Recommended Practice for Antenna Measurements," in IEEE Std 149-2021 (Revision of IEEE Std 149-1977) , vol., no., pp.1-207, 18 Feb. 2022.

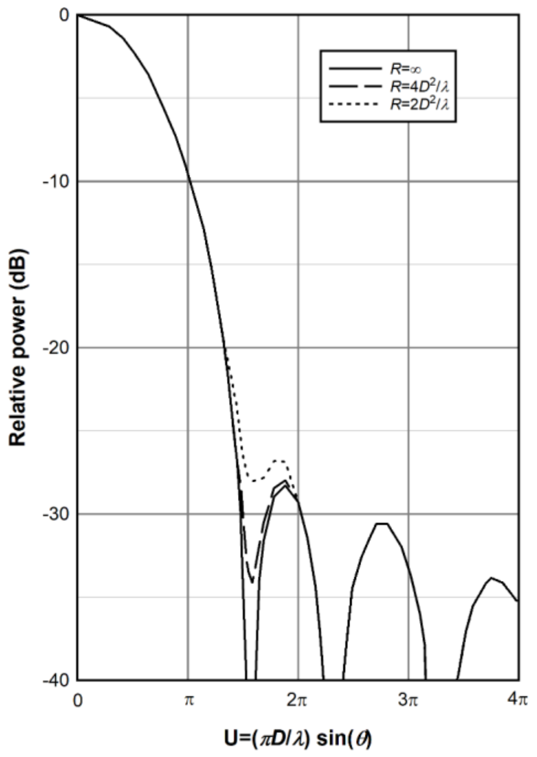
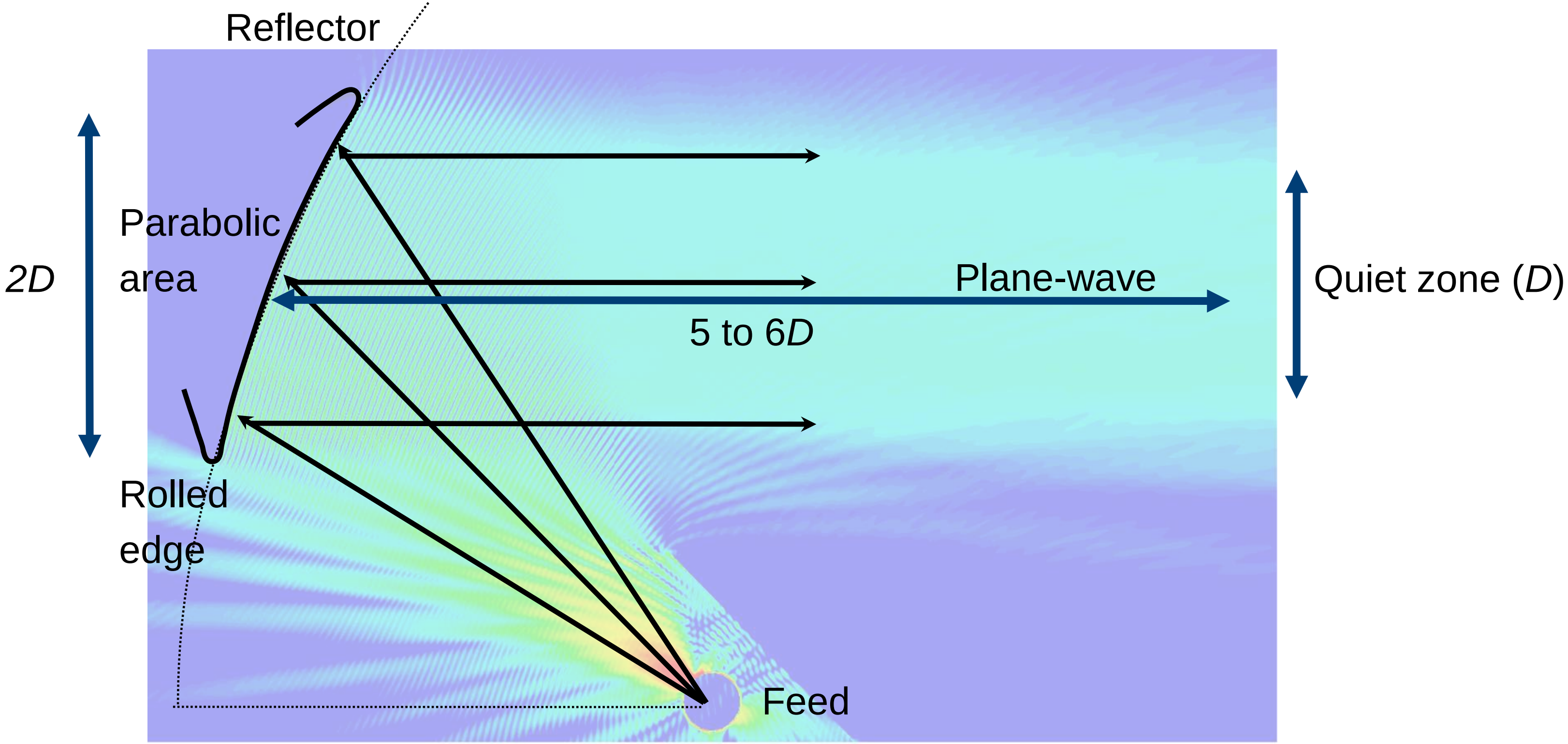


Figure 2—Calculated radiation patterns illustrating the effect of quadratic phase errors encountered in measuring patterns at the ranges indicated. A 30 dB Taylor aperture current distribution is assumed.

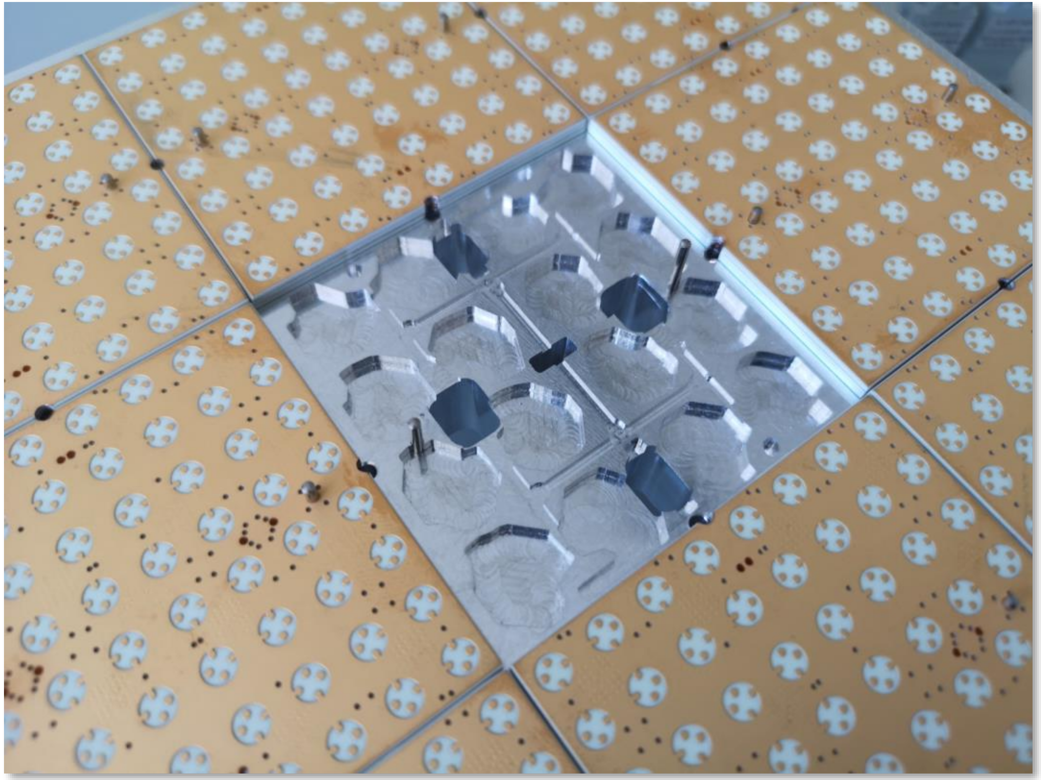
THE COMPACT ANTENNA TEST RANGE (CATR)



OUTLINE

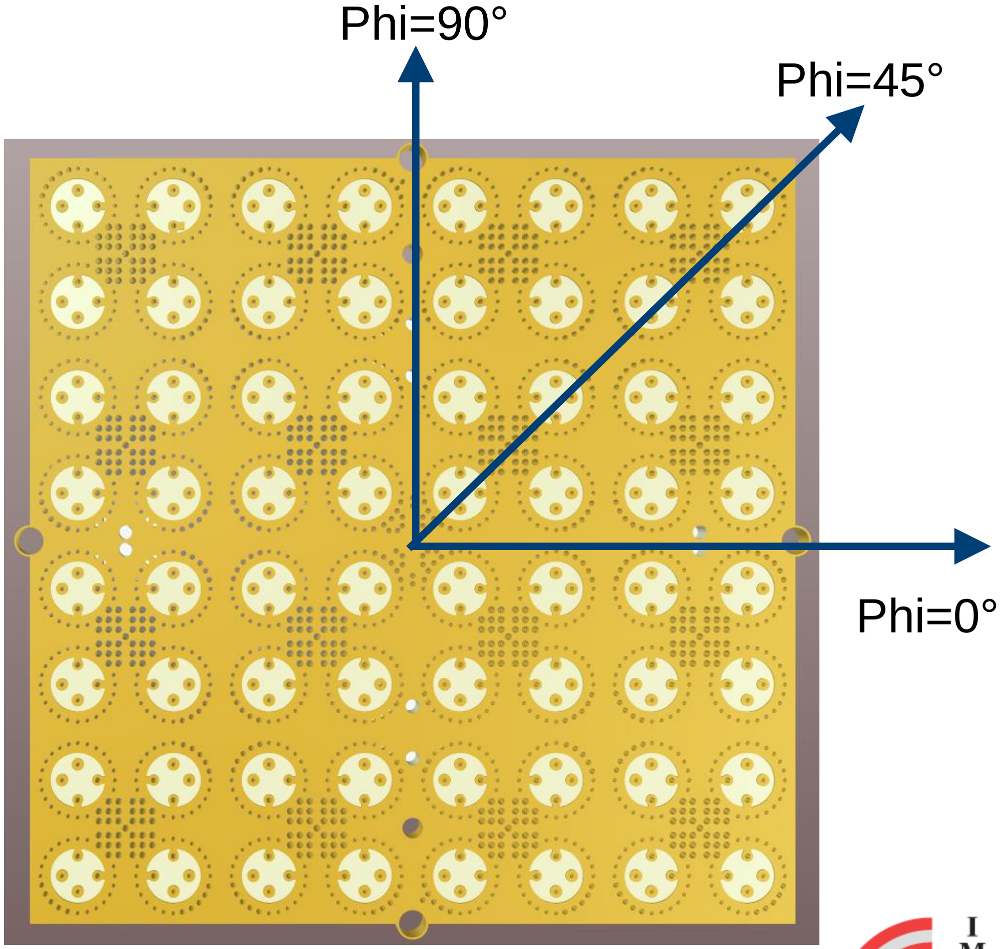
IMST SANTANA V4 BEAMFORMING ARRAY

- 8x8 Ka band Tx phased array module with integrated front end
- Satcom communication applications
- Dual linear and circular polarization supported
- Modules can be integrated into larger arrays



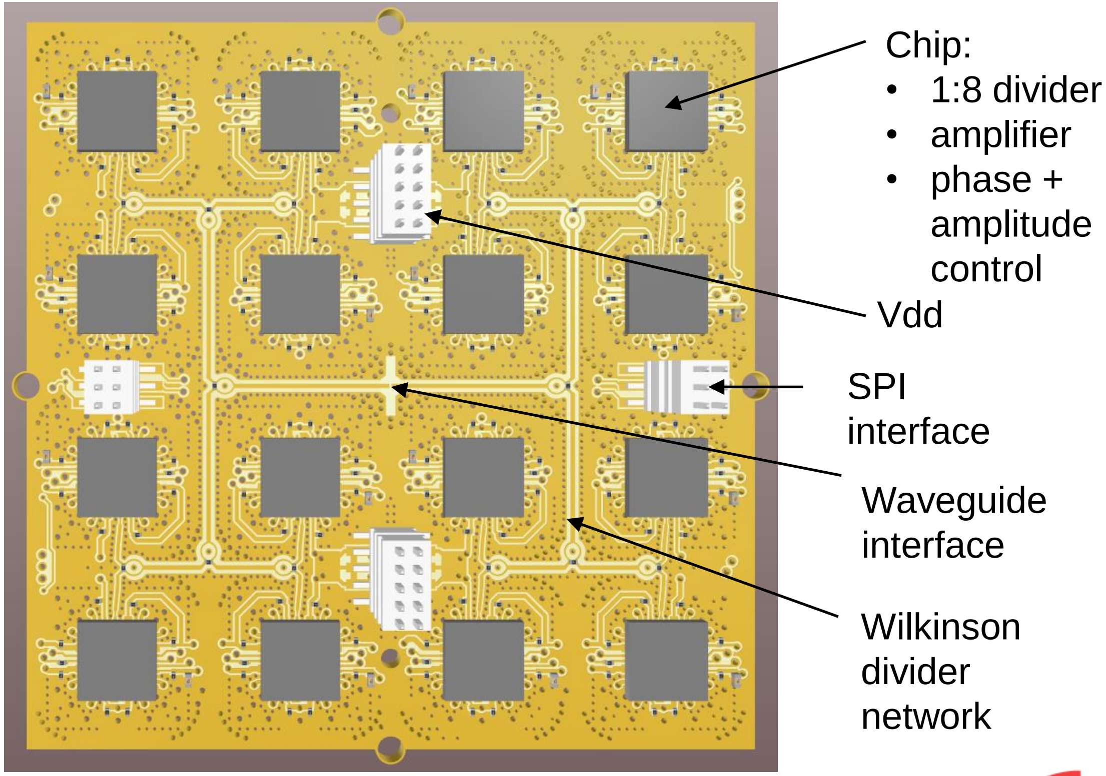
ANTENNA SPECIFICATIONS

- 64 elements: dielectric waveguide aperture antennas
- Matching: S11 < 10 dB
- Directivity: 25 dBi
- 3dB beamwidth: 11°
- Scanning performance diagonal (± 45°): ± 55°
- Scanning performance phi=0° and 90°: ± 27.5°
- Scan loss: < 5 dB

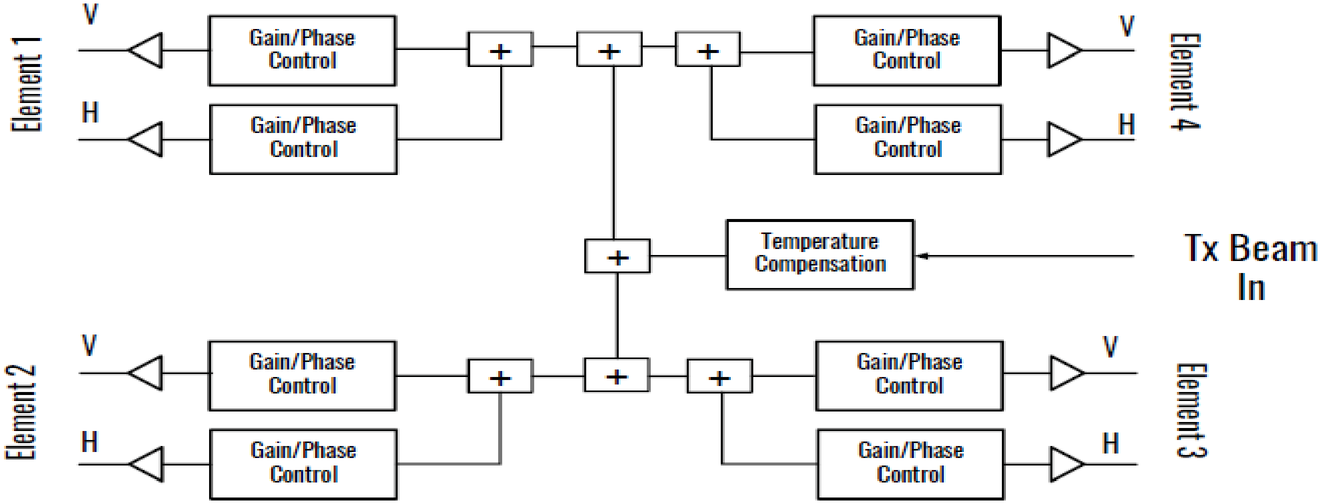


RF AND PRODUCT SPECIFICATIONS

- RF input: 29.5 GHz – 30 GHz
- WR28 waveguide interface
- RF max. output power/module : 1 Watt (0 dBW)
- EIRP: ~ 57 dBm
- 2 x 64 channel phased array (dual polarized)
- Size PCB: 56mm x 56mm x 2.7mm



CHIPSET DETAILS

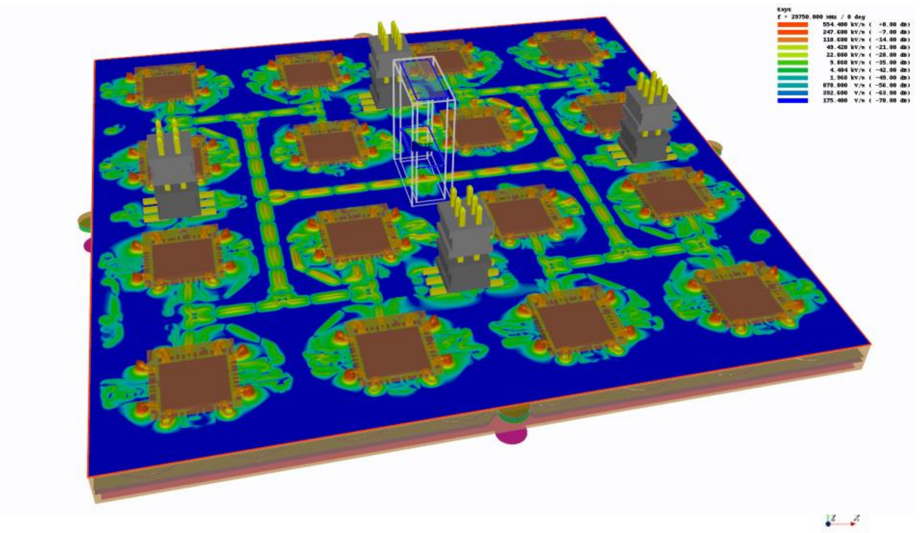


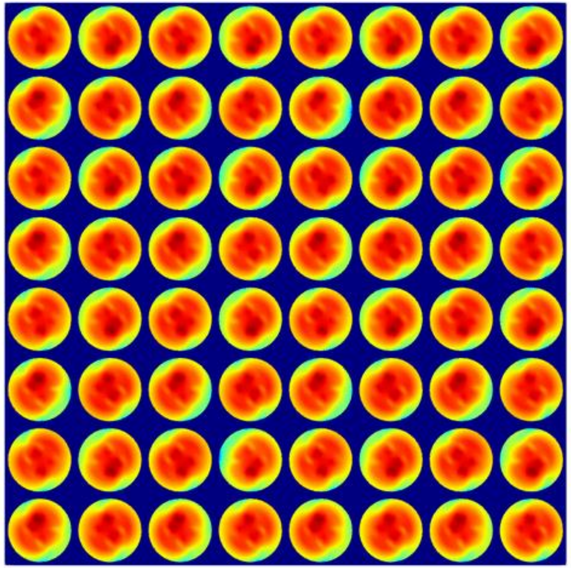
Amplitude
5bit (16dB / 0.5dB steps)

Phase
5bit (360°/
11.25°steps)

Telemetry data:
chip temperature
chip output power

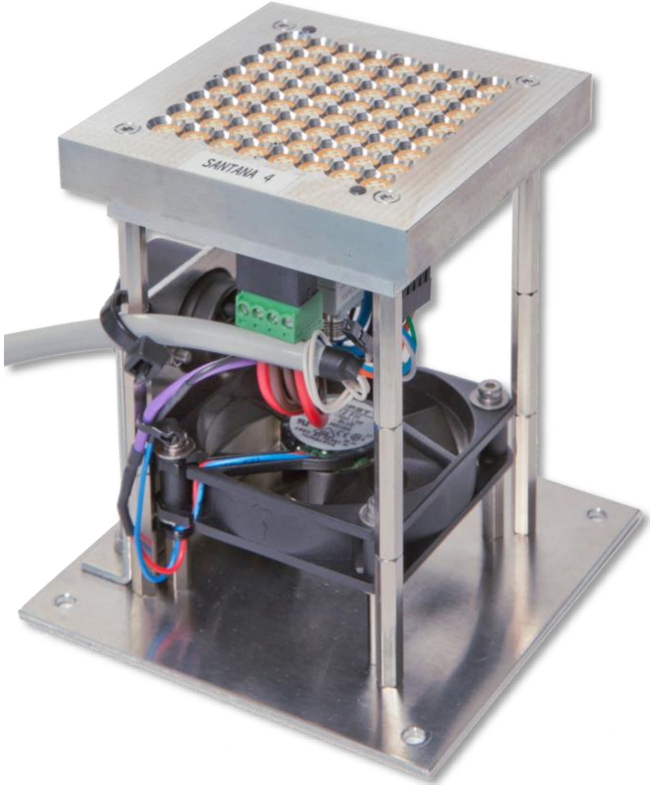
SIMULATION RESULTS – CIRCULAR POLARIZATION



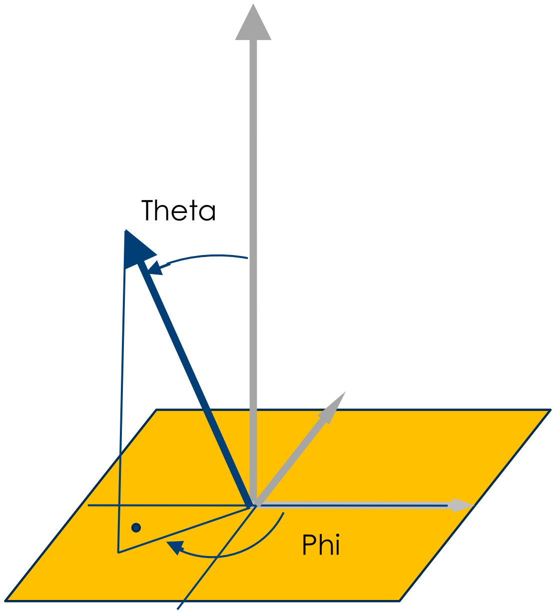


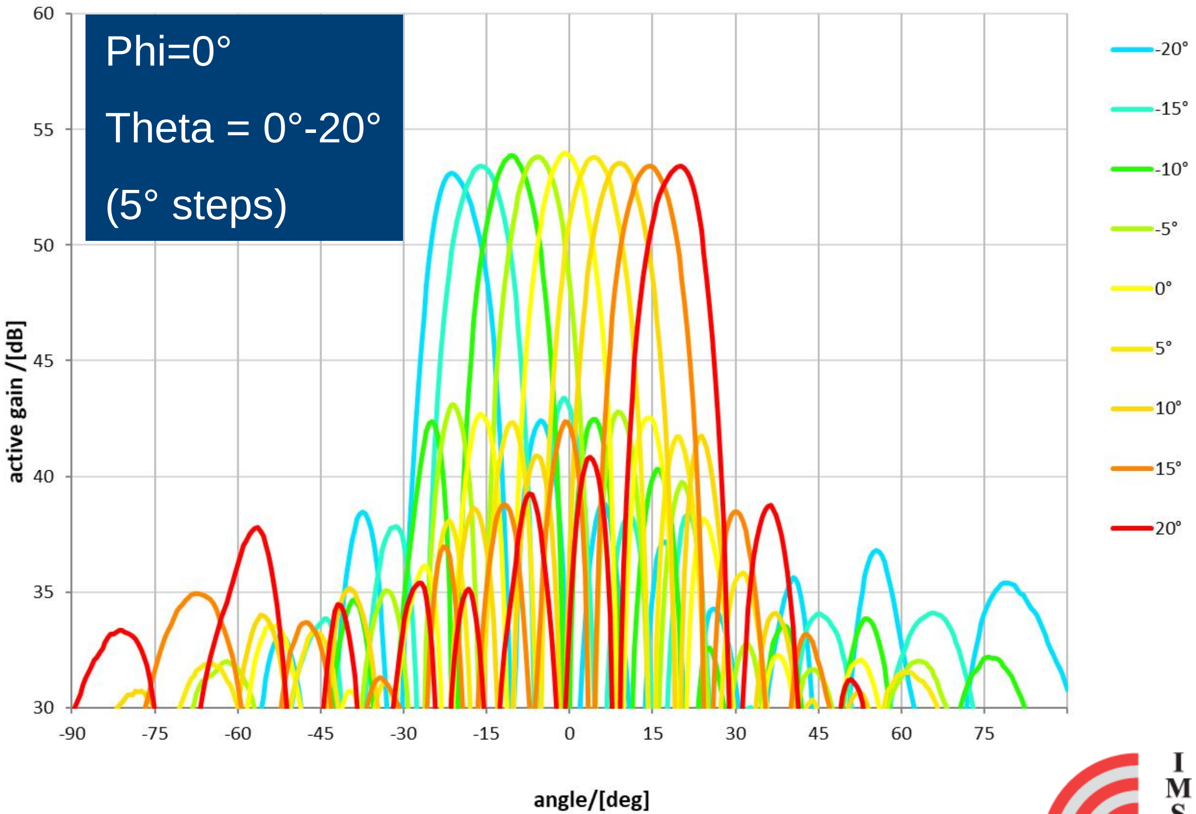
Electric field @ 29.75 GHz at divider network and antenna aperture

DUT – SANTANA MODULE TX EVAL KIT



TYPICAL ANTENNA SCAN





AGENDA

Find out more

www.rohde-schwarz.com/5G

THANK YOU

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Make ideas real