Multi-physics simulation of mm-wave systems

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SERENA

gan-on-Silicon Efficient mm-wave euRopean systEm iNtegration plAtform

Contributors

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OMMIC innovating with III-V'S

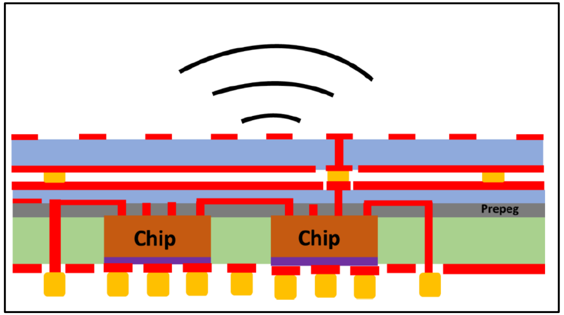
- Fraunhofer IZM
  - I. Ndip, U. Maaß

Fraunhofer IZM

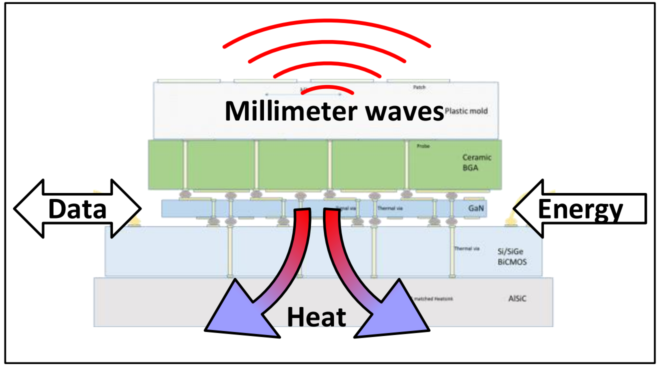
mm-wave RF systems

- Active antenna arrays
- High integration needed to fit within $\lambda/2$

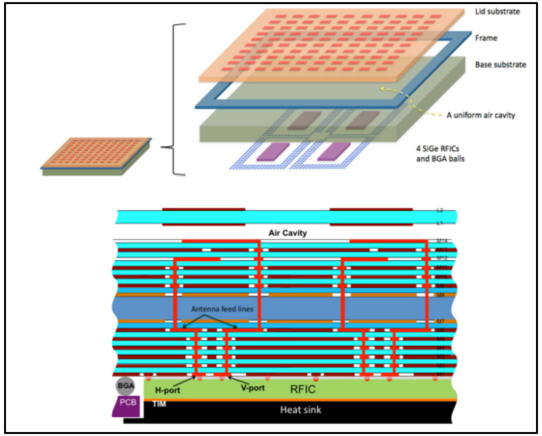
Chip embedding (IZM/SERENA)



Vertical stacking

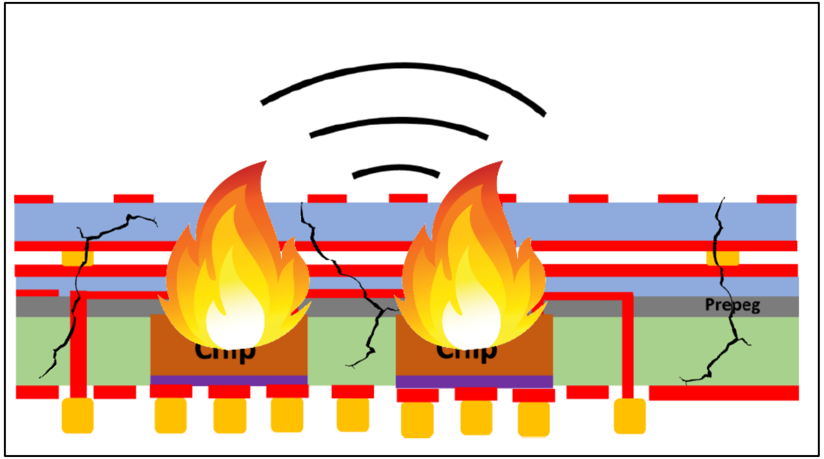


IBM / Ericsson



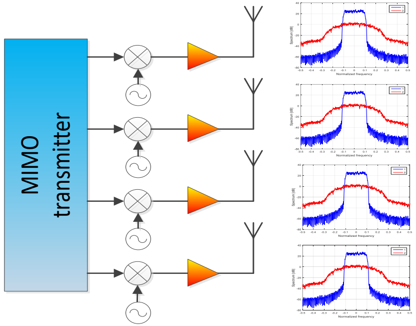
Challenges

- Multi-physical effects
  - Electrical
  - Thermal
  - Mechanical
  - …



- *Efficient simulations and modeling are crucial*
  - Before: Optimization, reliability, margins, time to market
  - After: Troubleshooting, performance optimization, reverse engineering

ELECTRICAL SIMULATIONS



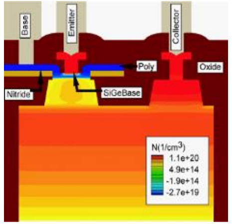
Active antenna arrays

Antenna-circuit interactions

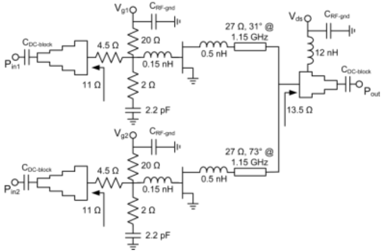
Linearity

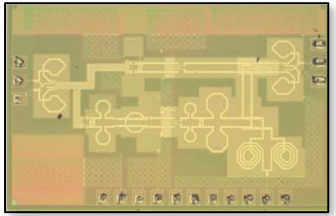
Simulations at many levels...

Transistor

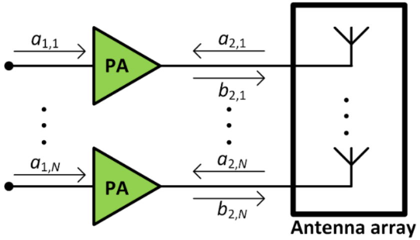


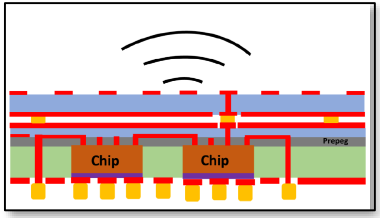
Circuit





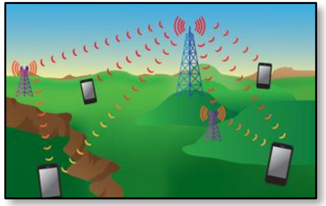
RF Sub-system





System

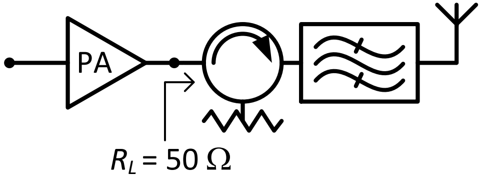
$$\mathbf{y} = \mathbf{H}\mathbf{x} + \mathbf{w}$$

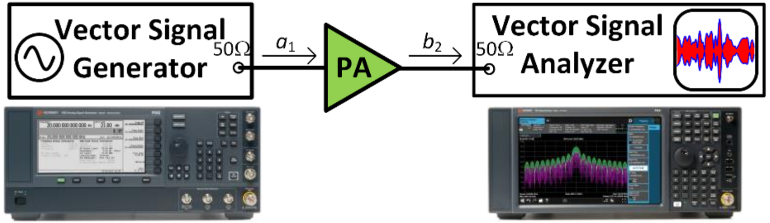


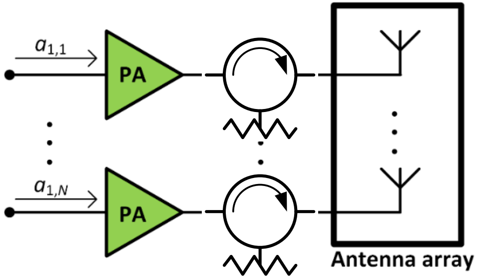
[T. Svensson, Chalmers]

Transmitter modeling

- Traditionally 50Ω assumed

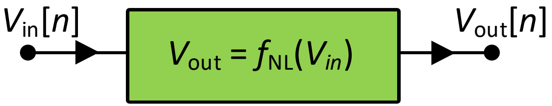






- Single-input-single-output modeling of RF components

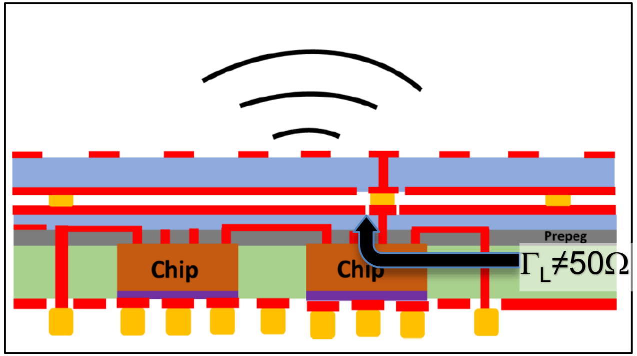
SISO model



$$V_{out} = f(V_{in})$$

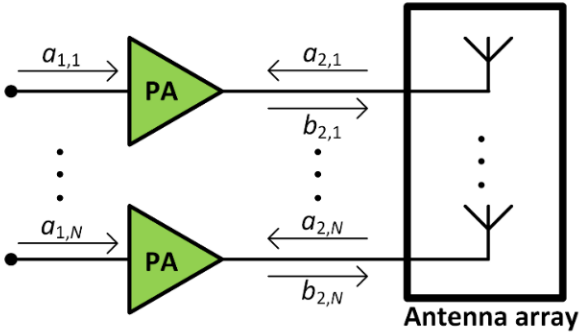
Transmitter modeling

- Integrated transmitters
  - Mismatch and mutual coupling
  - Non-50Ω interfaces

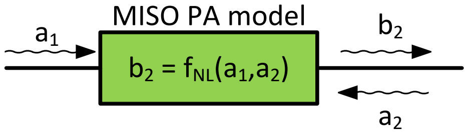


- Dual-input models needed:

$b_2 = f(a_1, a_2)$



Dual-input behavioral modeling



$$b_2 = \underbrace{\sum_{p_1=1}^{P_1} \alpha_{p_1} |a_1|^{2(p_1-1)} a_1}_{S_{21}(|a_1|)} + \underbrace{\sum_{p_2=1}^{P_2} \beta_{p2} |a_1|^{2(p_2-1)} a_2}_{S_{22}(|a_1|)} + \underbrace{\sum_{p_2=2}^{P_2} \gamma_{p2} a_1^2 |a_1|^{2(p_2-2)} a_2^*}_{T_{22}(a_1)}$$

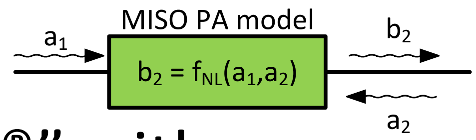
Nonlinear
50Ω SISO-terms

Nonlinear mismatch terms

- “PHD” or “X-parameter®” model

[Verspecht and D. E. Root, “Polyharmonic distortion modeling,” IEEE Microw. Mag., vol. 7, no. 3, pp. 44–57, Jun. 2006.]

Dual-input behavioral modeling



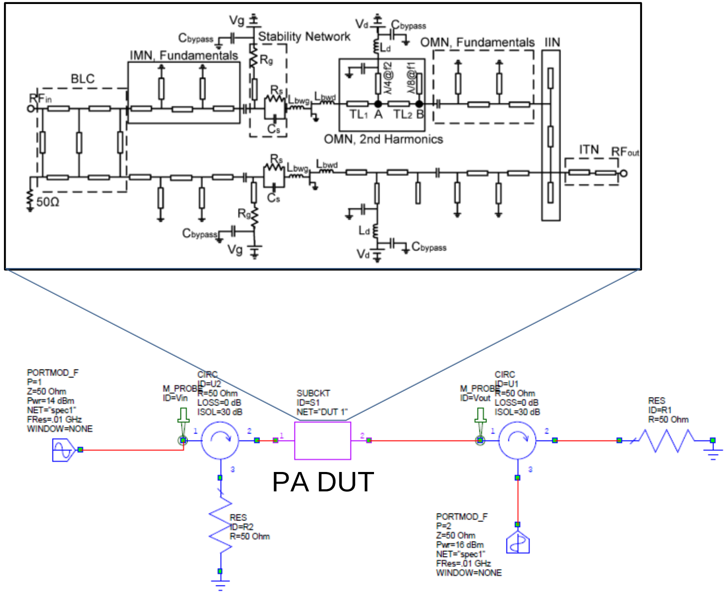
- "X-parameters®" with memory

$$
\begin{aligned}
b_2[n] = {} & \sum_{m_1=0}^{M_1} \underbrace{\sum_{p_1=1}^{P_1} \alpha_{m1,p1} \left| a_1[n-m_1] \right|^{2(p_1-1)}}_{S_{21}(|a_1|)} a_1[n-m_1] + \\
& \sum_{m_2=0}^{M_2} \underbrace{\sum_{m_1=0}^{M_1} \sum_{p_2=1}^{P_2} \beta_{m1,m2,p2} \left| a_1[n-m_1] \right|^{2(p_2-1)}}_{S_{22}(|a_1|)} a_2[n-m_2] + \\
& \sum_{m_2=0}^{M_2} \underbrace{\sum_{m_1=0}^{M_1} \sum_{p_2=2}^{P_2} \gamma_{m1,m2,p2} a_1^2[n-m_1] \left| a_1[n-m_1] \right|^{2(p_2-2)}}_{T_{22}(a_1)} a_2^*[n-m_2]
\end{aligned}
$$

[C. Fager et al., "Prediction of Smart Antenna Transmitter Characteristics Using a New Behavioral Modeling Approach," *Proc. IMS*, 2014]

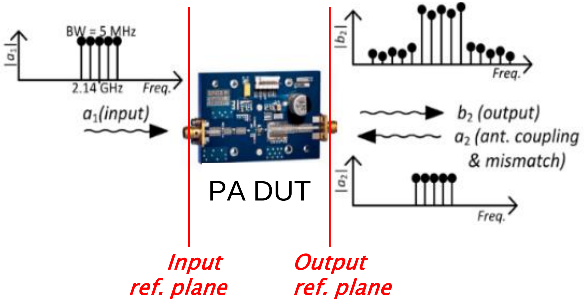
Model identification

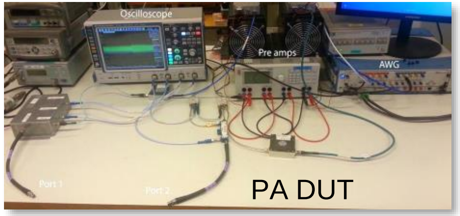
Simulation based



[C. Fager et al., "Prediction of Smart Antenna Transmitter Characteristics Using a New Behavioral Modeling Approach," *Proc. IMS*, 2014]

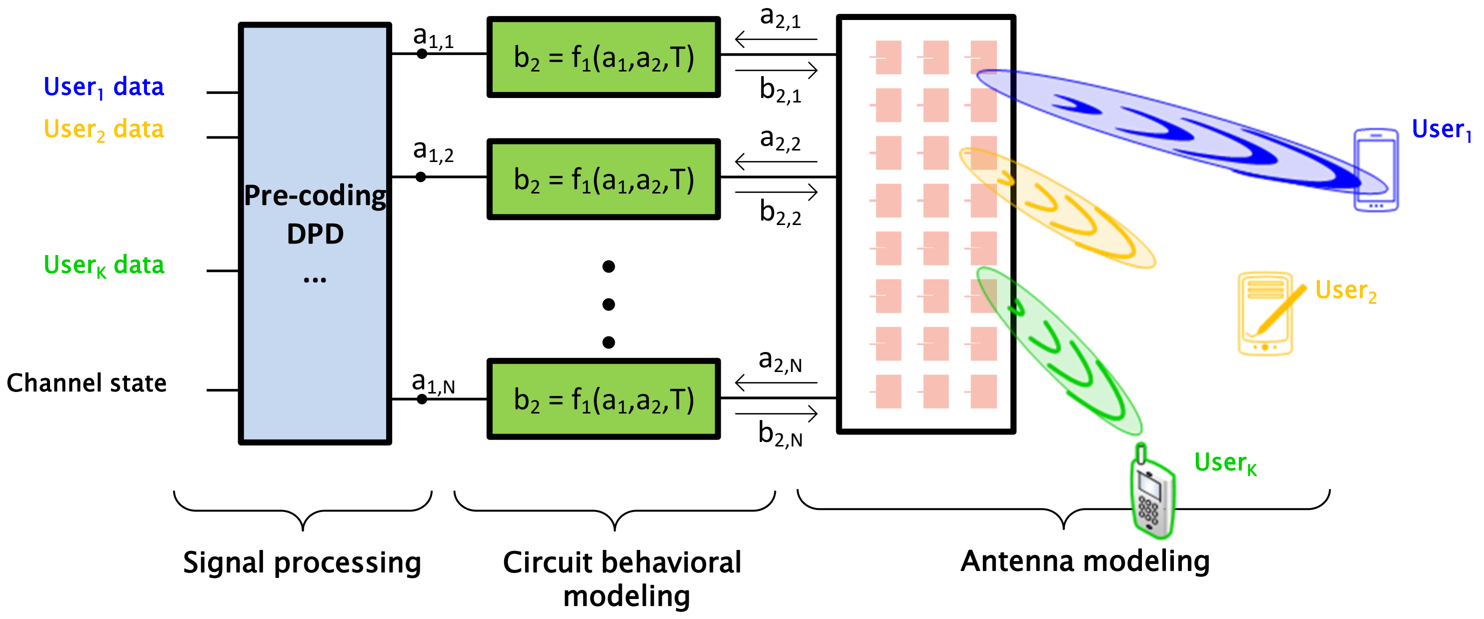
Measurement based



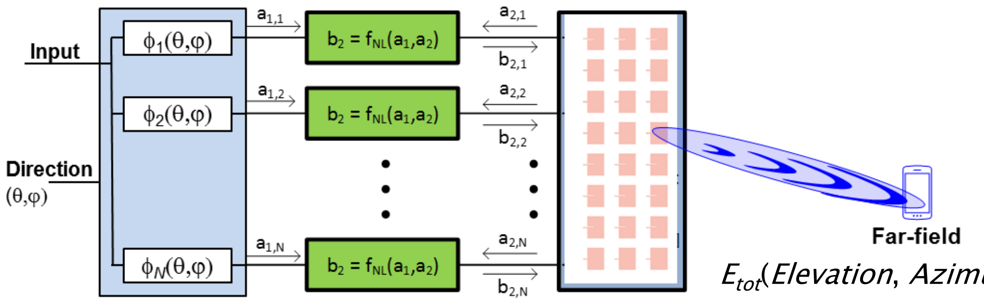


[S. Gustafsson et al., "A Novel Active Load-pull System with Multi-Band Capabilities," ARFTG, 2013]

Transmitter simulation framework



Phased array application



$E_{tot}(Elevation, Azimuth)$

Beam steering

$$\begin{cases} \mathbf{a}_1 = a_1 \left[e^{j\phi_1} \quad e^{j\phi_2} \quad \cdots \quad e^{j\phi_N} \right]^T \\ \mathbf{b}_2 = \mathbf{S}_{21}(|\mathbf{a}_1|)\mathbf{a}_1 + \mathbf{S}_{22}(|\mathbf{a}_1|)\mathbf{a}_2 + \mathbf{T}_{22}(\mathbf{a}_1)\mathbf{a}_2^* \\ \mathbf{a}_2 = \mathbf{S}_{ant}\mathbf{b}_2 \end{cases}$$

Antenna circuit interactions

$$\mathbf{b}_2 = \underbrace{\mathbf{S}_{21}(|\mathbf{a}_1|)\mathbf{a}_1}_{\text{Regular } 50\Omega \text{ nonlinear distortion}} + \underbrace{\mathbf{S}_{22}(|\mathbf{a}_1|)\mathbf{S}_{ant}\mathbf{b}_2 + \mathbf{T}_{22}(\mathbf{a}_1)\mathbf{S}_{ant}^*\mathbf{b}_2^*}_{\text{Antenna coupling and mismatch effects}}$$

Regular 50Ω nonlinear distortion

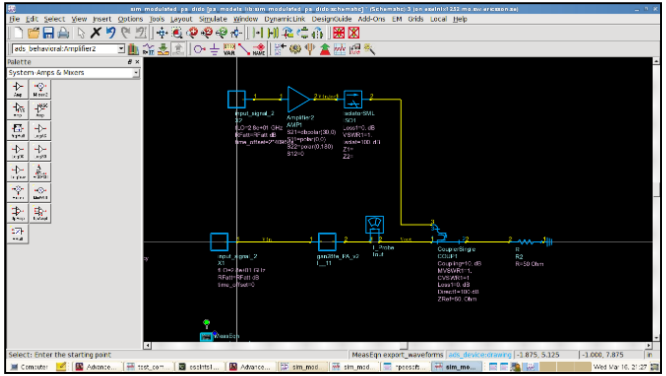
Antenna coupling and mismatch effects

Far field radiation

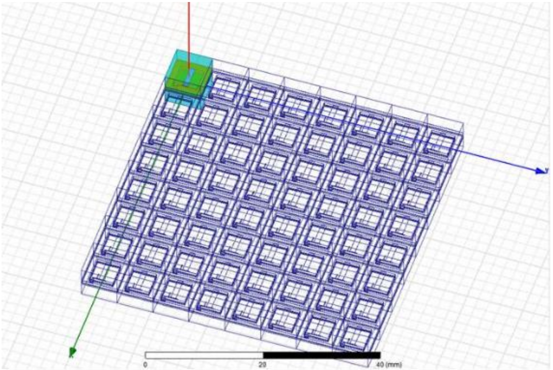
$$E_{tot}(El, Az)[n] = \sum_{i=1}^{N} b_{2,i}[n]\bar{E}_i(El, Az)$$

Phased array example

IC design



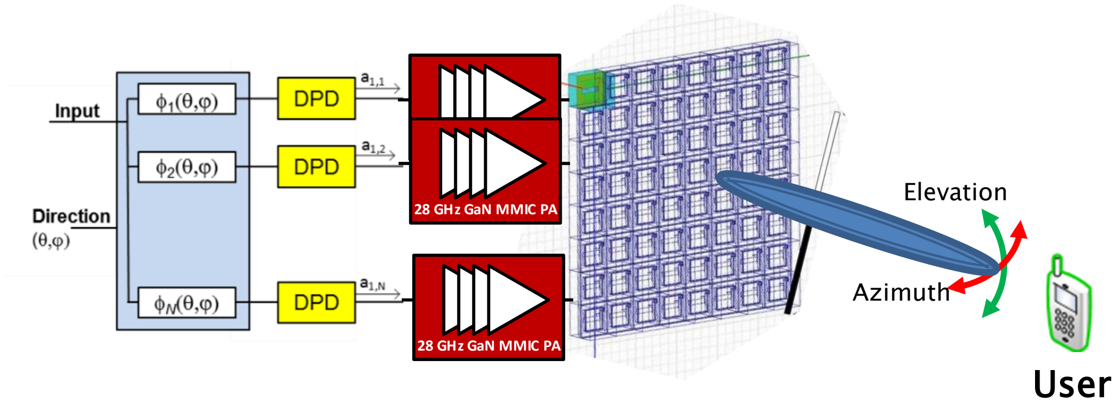
64 element antenna array



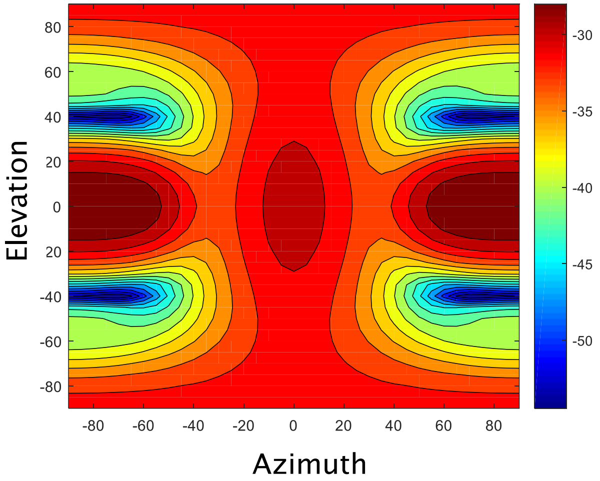
- PA model extracted from IC CAD
- Antenna parameters from EM CAD
- Each PA perfectly linearized for 50Ω load ($a_2 = 0$)
- Ideal phased array beam steering. No amplitude tapering

[C. Fager et al., "Analysis of Nonlinear Distortion in Phased Array Transmitters," Proc. INMMiC, 2017]

Phased array example

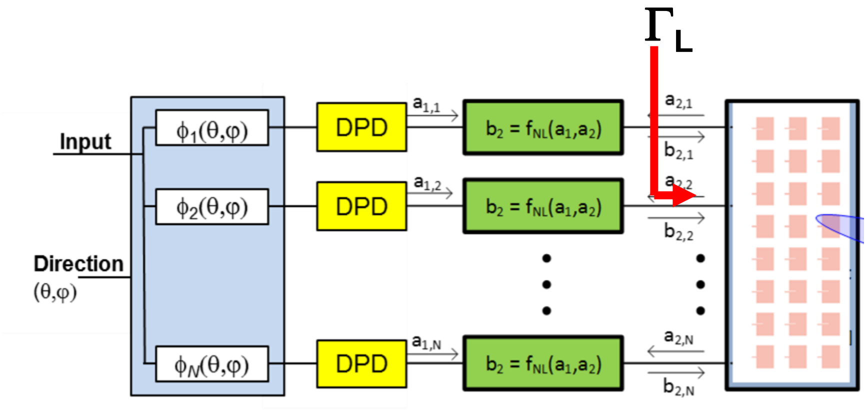


User EVM vs. scan direction

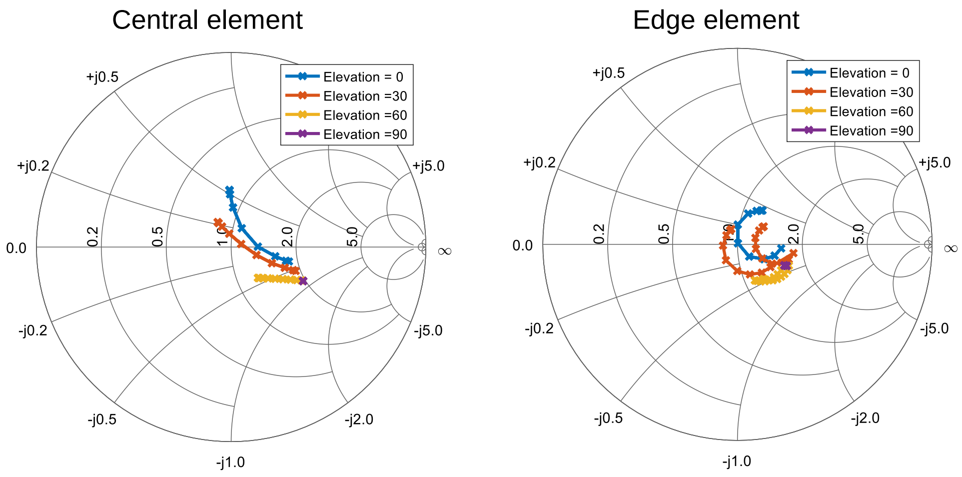


- Distortion highly direction dependent. *Why?*

Phased array example



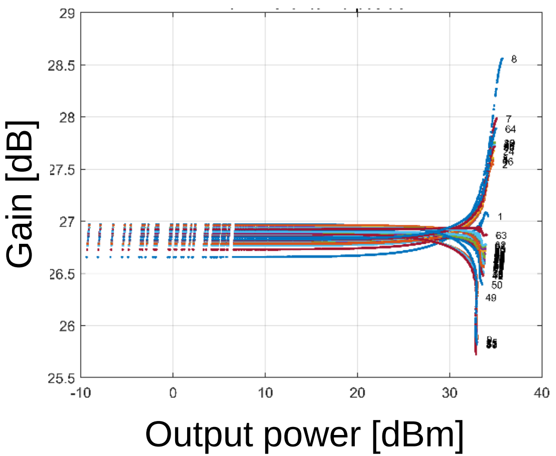
Γ_L vs. scan direction



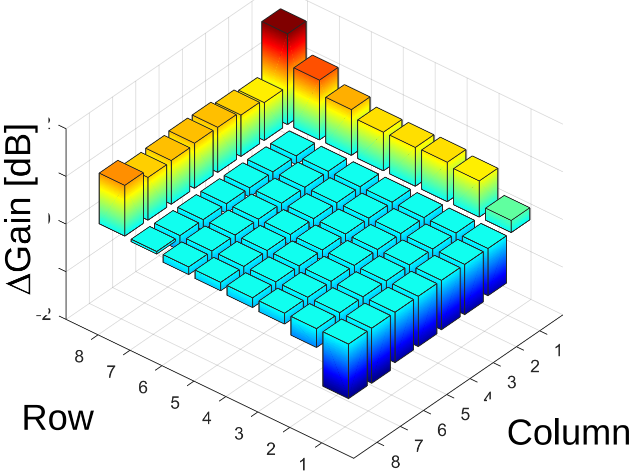
- Significant variation of PA load impedance vs. beam steering

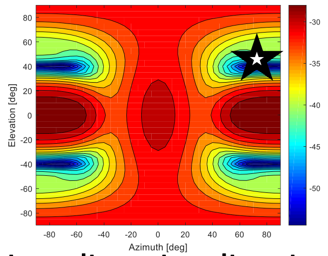
Phased array example

AM/AM for each of the 64 branches



Gain compression/expansion

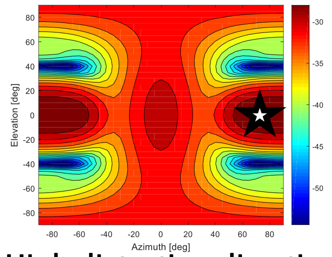




Low distortion direction

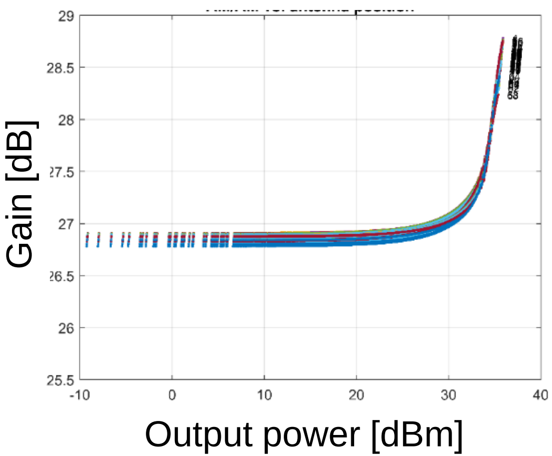
- Distortion averaging effects happening inside the array

Phased array example

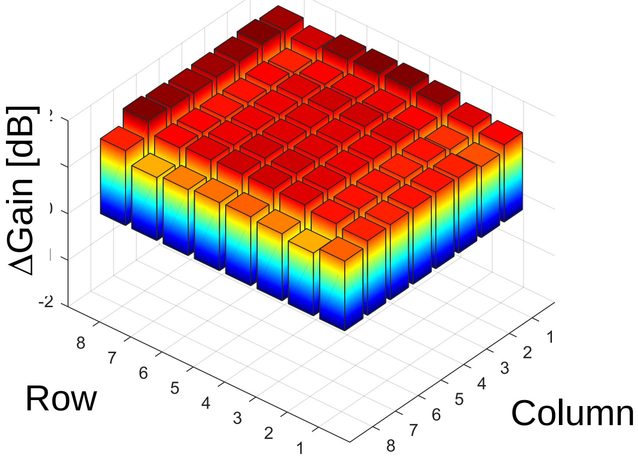


High distortion direction

AM/AM for each of the 64 branches

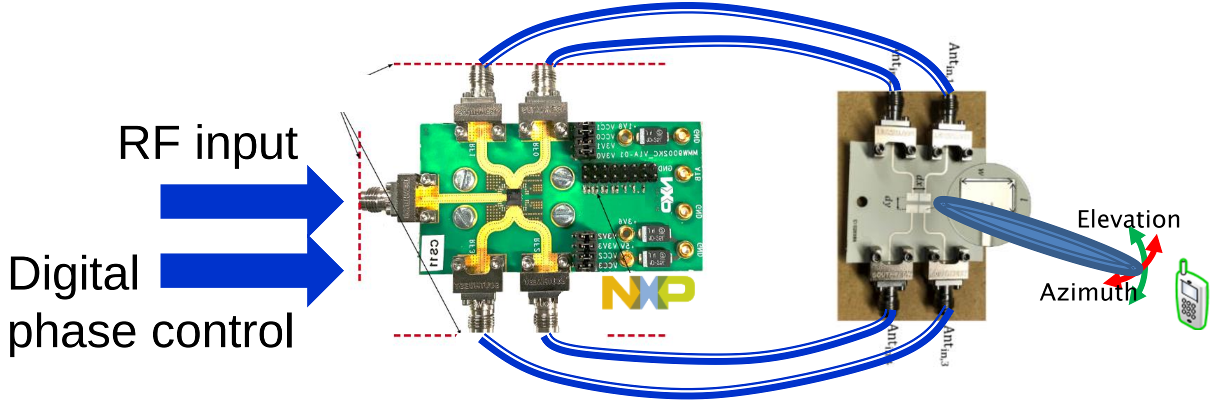


Gain compression/expansion

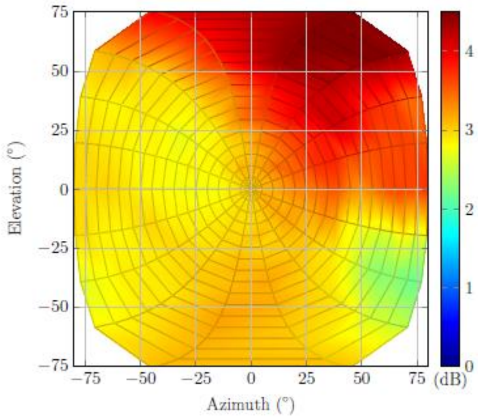


- Distortion addition for some directions
- Direction dependent user distortion → Direction dependent DPD needed

Experimental verification

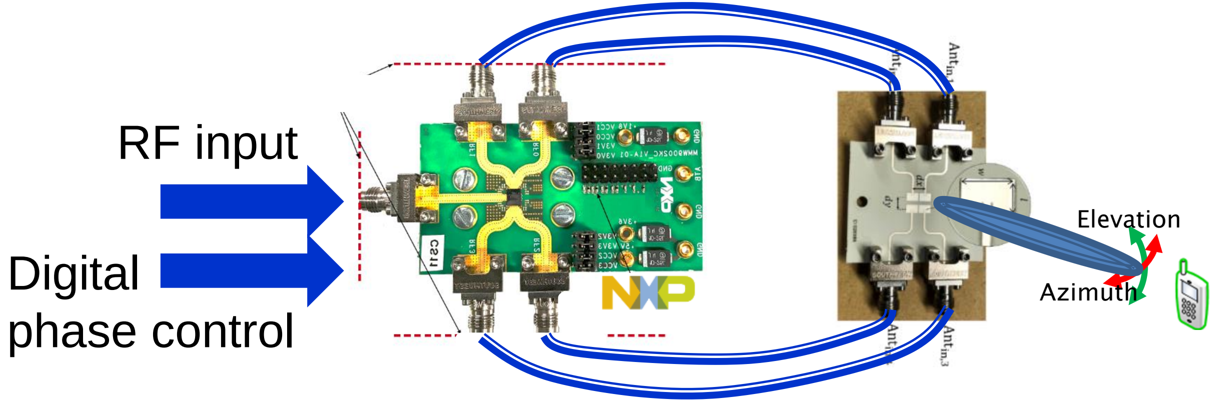


AM–AM compression measurement

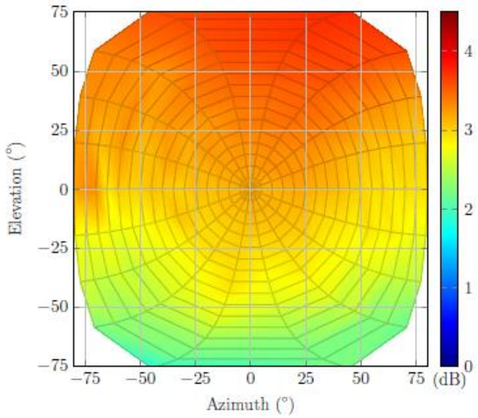


- Nonlinear effects observed also in mm-wave measurements
- 30 GHz beamforming chip

Experimental verification

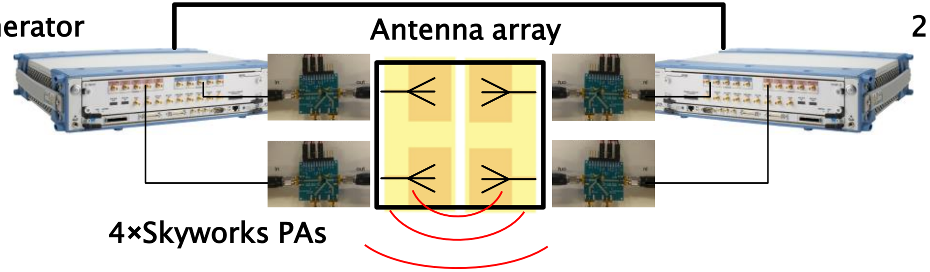


AM–AM compression modeling

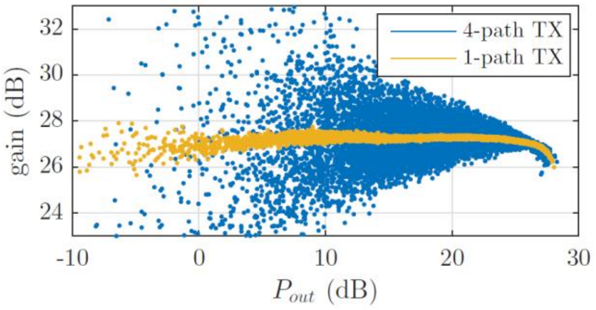


- Load-pull based nonlinear modeling
- 4 element patch antenna: EM simulation based modeling
- Reasonable modeling accuracy

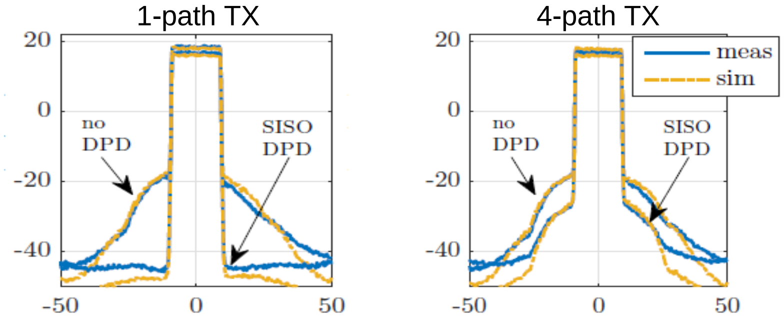
MIMO transmitter distortion



Nonlinear PA–antenna interactions

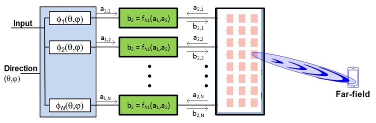


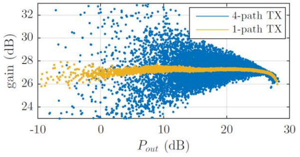
Far field distortion

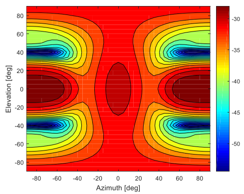


[K. Hausmair et al. “Prediction of Nonlinear Distortion in Wideband Active Antenna Arrays,” IEEE T-MTT, 2017]

Summary – transmitter RF modeling

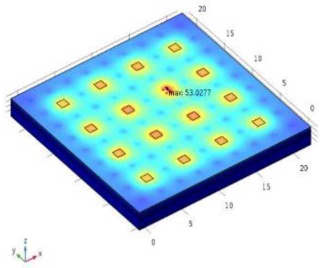






- Framework for efficient simulation of active antenna systems
- Improved understanding of circuits-antenna interactions with realistic signals
- New nonlinear effects predicted in phased array and MIMO systems

ELECTRO-THERMAL SIMULATIONS

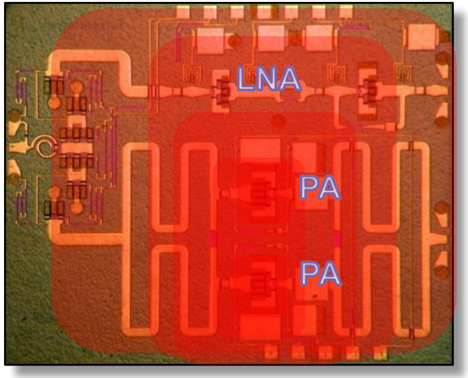


Thermal modeling
Power dissipation modeling
mm-wave transmitter example

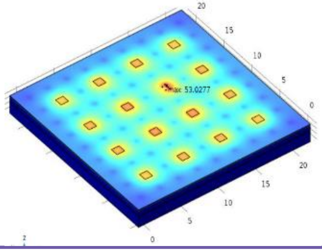
Heating concerns

- Heat concentration in active antenna arrays

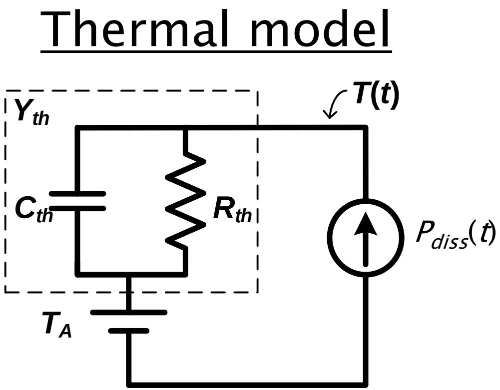
- Chip level heating effects
  - Thermal coupling
  - Efficient power amplifiers

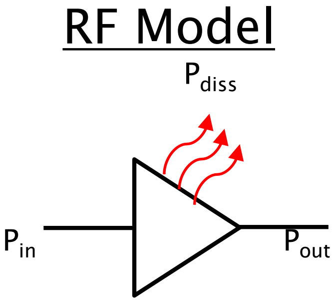


- System level effects
  - Performance degradation
  - Reliability



Linear heating model



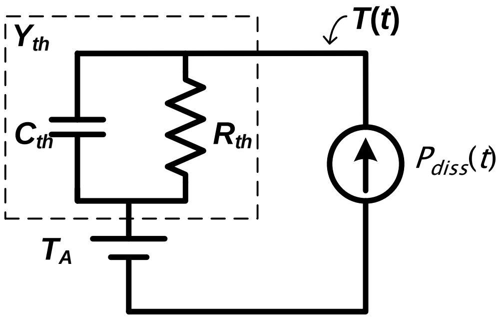


$$P_{diss}(t) = P_{diss}(|a_1(t)|, T(t))$$

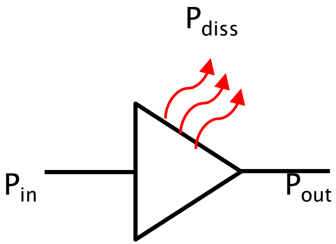
- $T(t) = T_A + P_{diss}(t) * z_{th}$
- Thermal admittance: $Y_{th} = G_{th} + j\omega C_{th}$

Linear heating model

Thermal model



RF Model

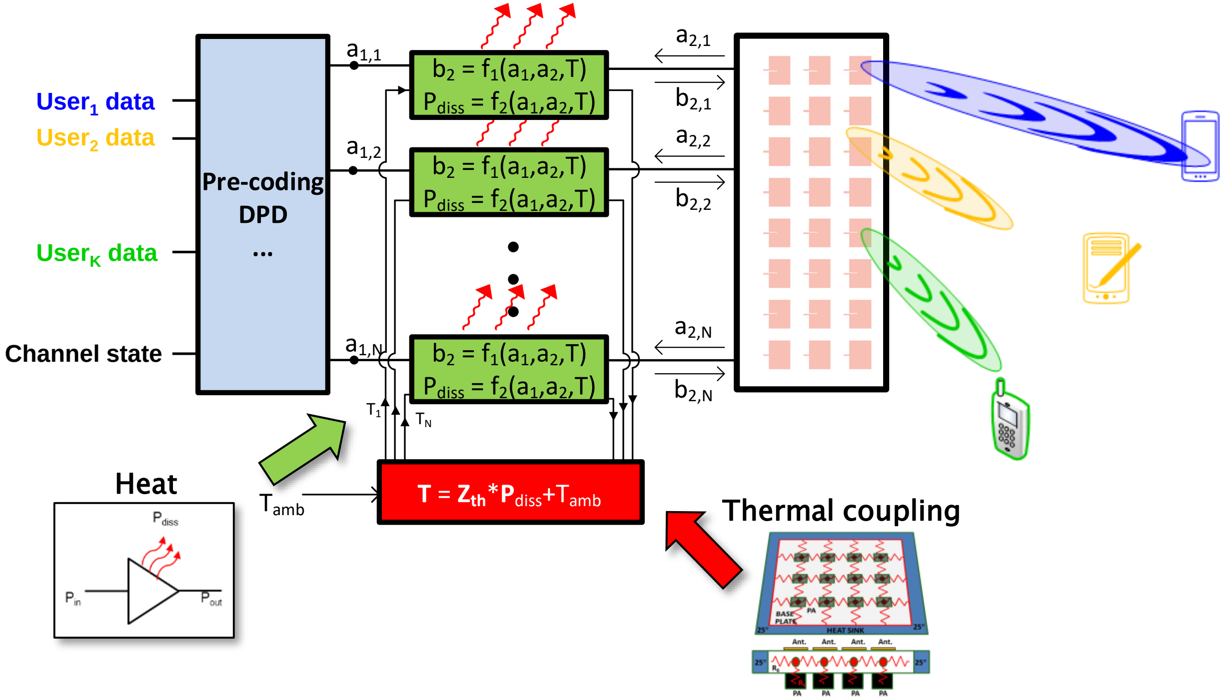


$$P_{diss}(t) = P_{diss}(|a_1(t)|, T(t))$$

- Envelope time-stepped solution for T(t)

$$\mathbf{T}_{n+1} = T_{\text{amb}} + \left(\mathbf{G}_{\text{th}} + 2\pi f_s \mathbf{C}_{\text{th}}\right)^{-1}\left(\mathbf{P}_{\text{diss},n} + 2\pi f_s \mathbf{C}_{\text{th}}\left(\mathbf{T}_n - T_{\text{amb}}\right)\right)$$

Incorporating thermal effects



[C. Fager et al. “Analysis of Thermal Effects in Active Antenna Array Transmitters…,” *Proc.* INMMiC, 2015]

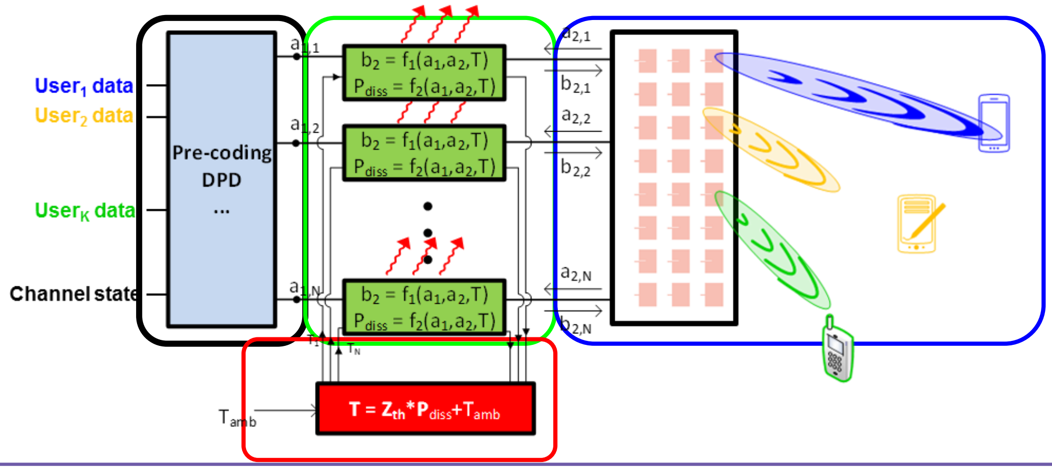
Combined RF/EM/Thermal simulation

$$\mathbf{a}_{1,n} = \mathbf{G}\mathbf{x}_n$$

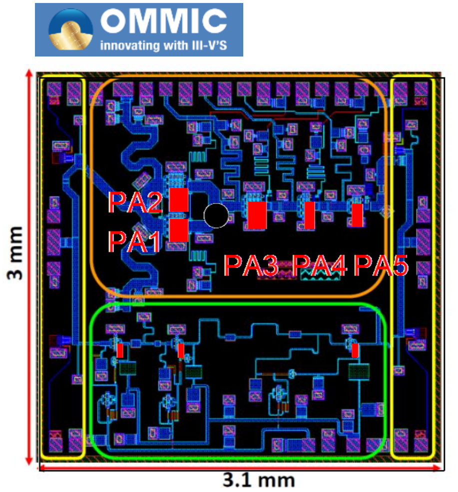
$$\mathbf{b}_{2,n} = \mathbf{S}_{21}(|\mathbf{a}_{1,n}|,\mathbf{T}_n)\mathbf{a}_{1,n} + \mathbf{S}_{22}(|\mathbf{a}_{1,n}|,\mathbf{T}_n)\mathbf{S}_{ant}\mathbf{b}_{2,n} + \mathbf{T}_{22}(\mathbf{a}_{1,n},\mathbf{T}_n)\mathbf{S}^{*}_{ant}\mathbf{b}^{*}_{2,n} + \boldsymbol{\rho}_{n-1}$$

$$E_n(\theta,\varphi) = \mathbf{b}^{T}_{2,n}\bar{\mathbf{E}}(\theta,\varphi)$$

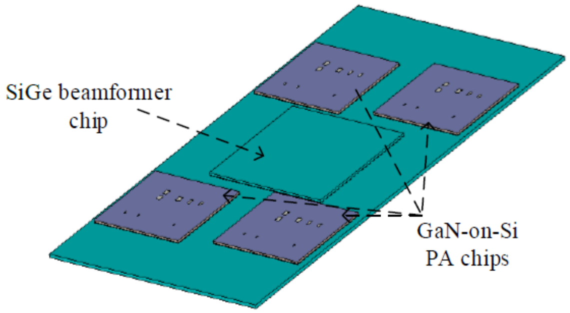
$$\mathbf{T}_{n+1} = T_{\mathrm{amb}} + (\mathbf{G}_{\mathrm{th}} + 2\pi f_s \mathbf{C}_{\mathrm{th}})^{-1}\left(\mathbf{P}_{\mathrm{diss},n}(|\mathbf{a}_{1,n}|,\mathbf{T}_n) + 2\pi f_s \mathbf{C}_{\mathrm{th}}(\mathbf{T}_n - T_{\mathrm{amb}})\right)$$



Example: SERENA 4-channel transmitter



1. PA1: $8 \times 115\,\mu m = 920\,\mu m$ ($\approx 0.255 w_{tot}$)
2. PA2: $8 \times 115\,\mu m = 920\,\mu m$ ($\approx 0.255 w_{tot}$)
3. PA3: $8 \times 115\,\mu m = 920\,\mu m$ ($\approx 0.255 w_{tot}$)
4. PA4: $8 \times 57\,\mu m = 456\,\mu m$ ($\approx 0.126 w_{tot}$)
5. PA5: $6 \times 65\,\mu m = 390\,\mu m$ ($\approx 0.108 w_{tot}$)



Material	Density ρ (kg/m^3)	Thermal conductivity k (W/m·K)	Specific heat C_p (J/kg·K)
Megtron 7	1820	0.4	0.88
Si	2330	148	0.7
SiGe	3950	8.8	0.5

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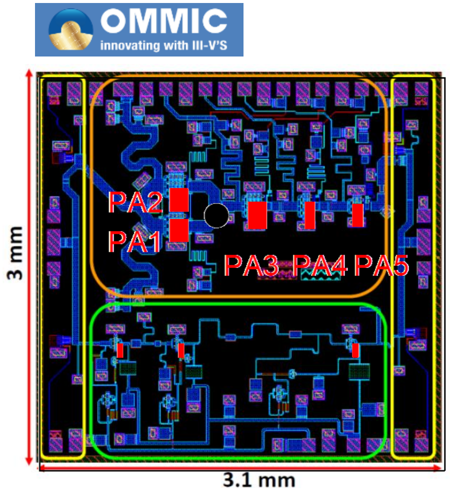

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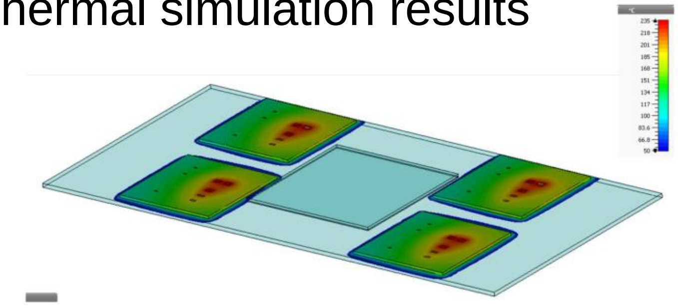
Thermal simulation results



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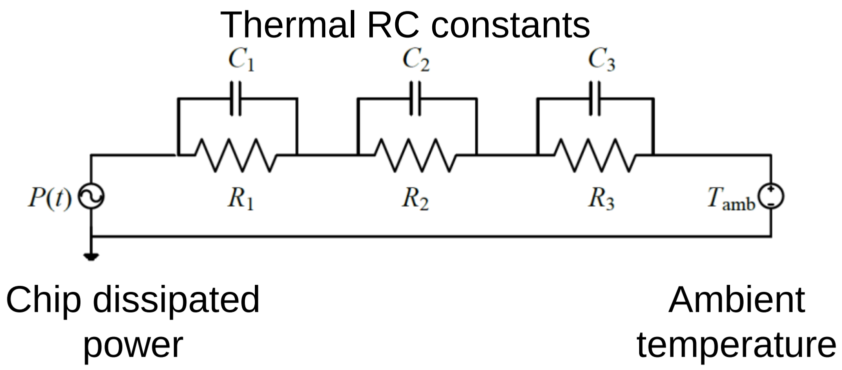
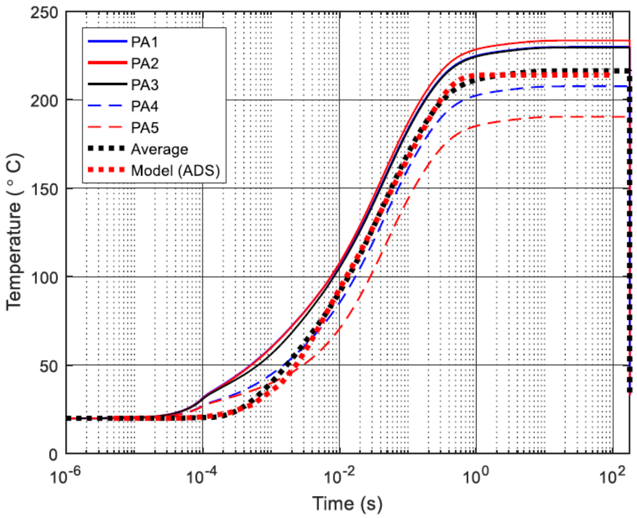
Thermal RC modeling

- One GaN chip in a simplified package environment

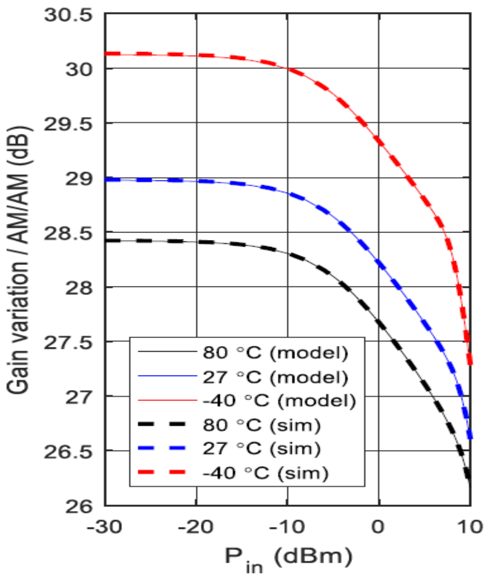


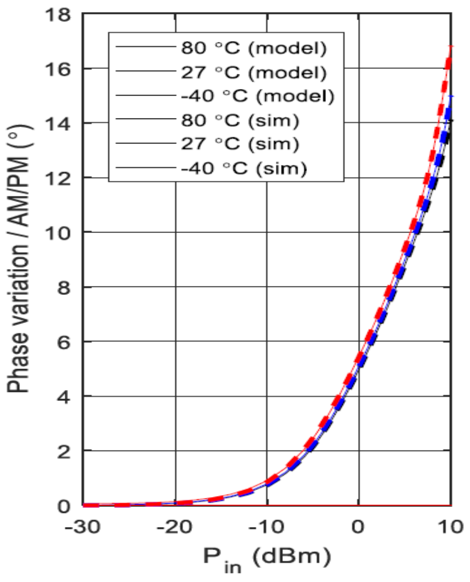
Thermal response @ 7W step



Power amplifier modeling

- Temperature dependent gain

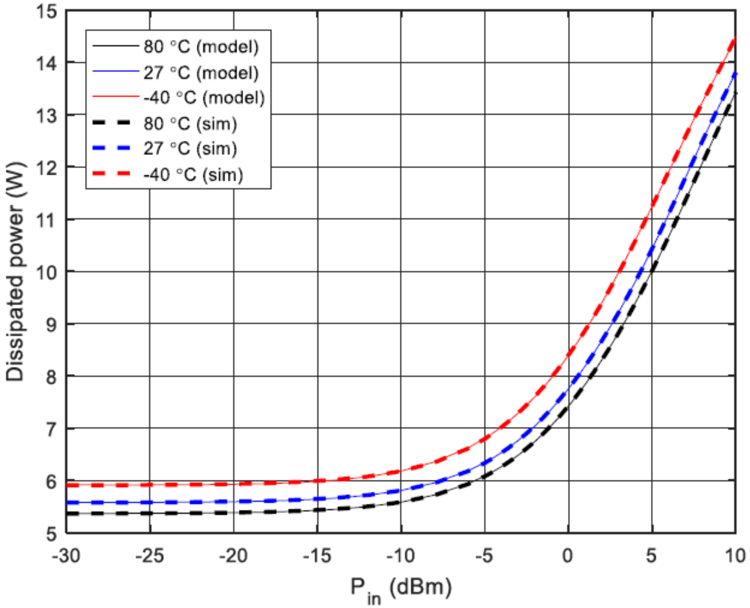




$$b_2(a_1, T) = \sum_{p_1=1}^{P_1} \alpha_{p_1}(T) a_1 |a_1|^{2(p_1-1)}$$

Power amplifier modeling

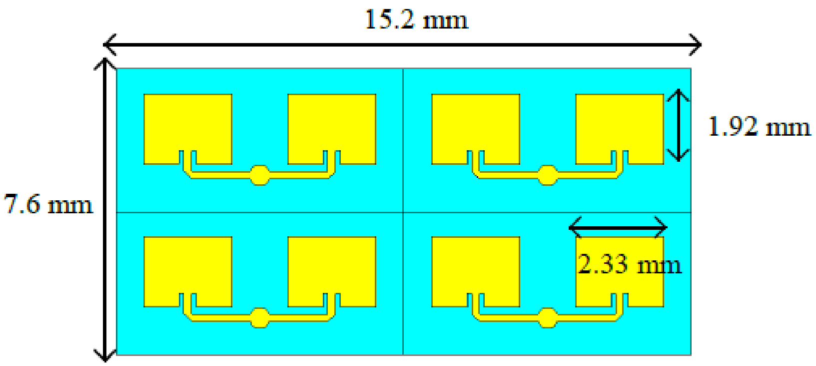
- Dissipated power vs. temperature



$$P_{\mathrm{diss}}(|a_1|, T) = P_{\mathrm{dc}} + P_{\mathrm{in}} - P_{\mathrm{out}}$$

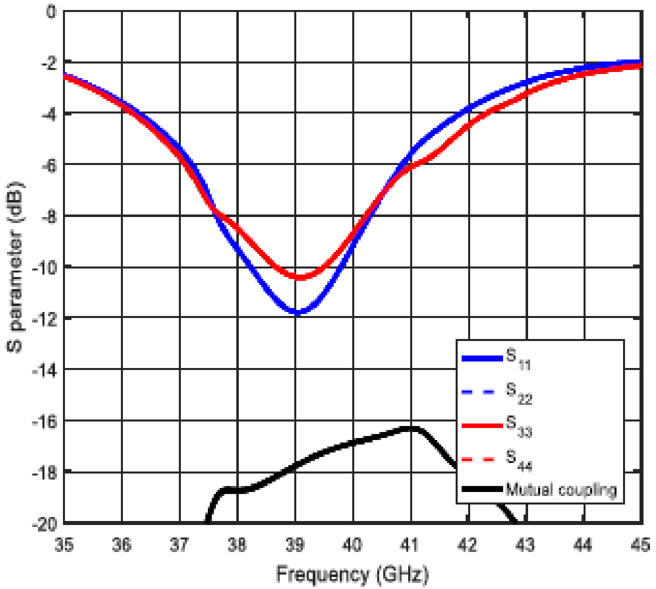
$$= \sum_{p_\mathrm{d}=0}^{P_d} \xi_{p_d}(T)|a_1|^{p_d}$$

Antenna modeling

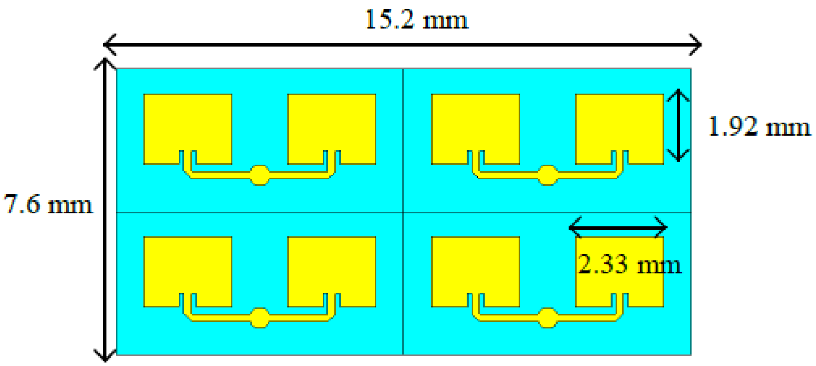


- Mismatch and mutual-coupling neglected in model

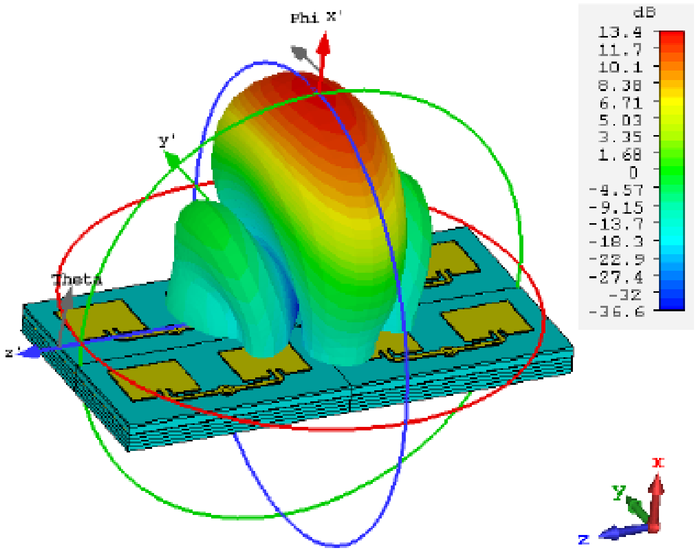
Simulated S-parameters



Antenna modeling

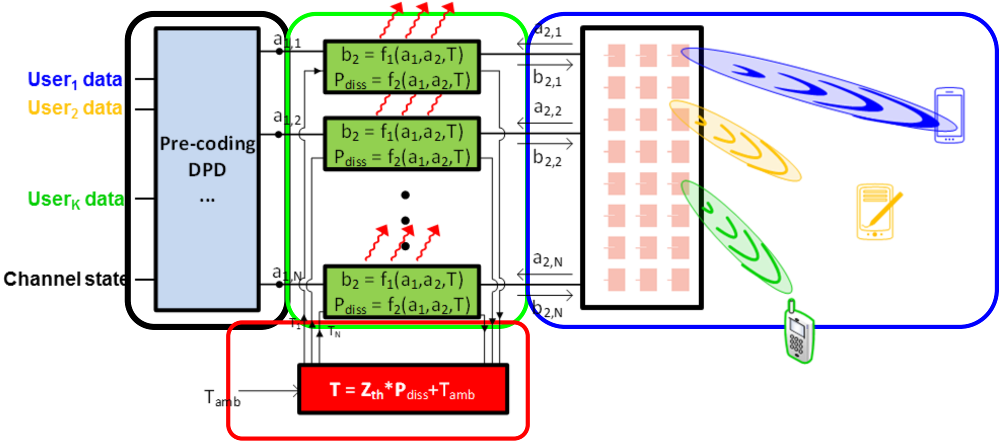


Far-field radiation patterns

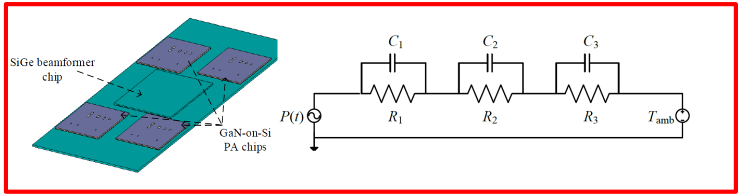


- Embedded element patterns for unity excitations

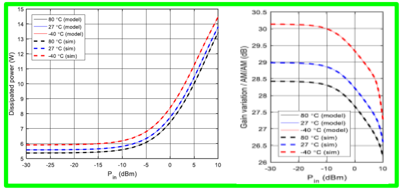
Electro-thermal simulation framework



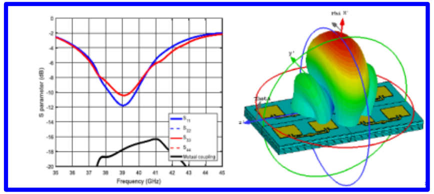
Thermal modeling



RF circuit modeling

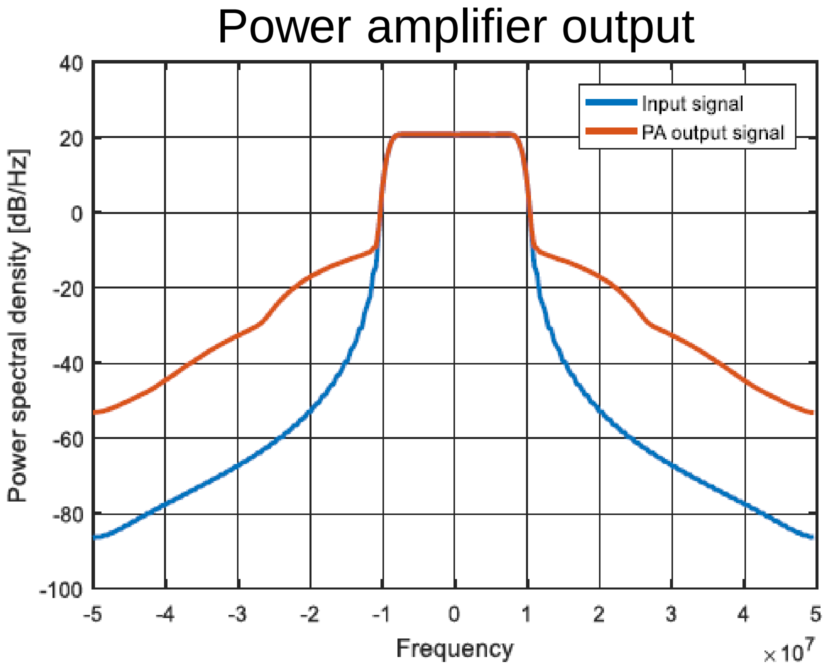


Antenna modeling



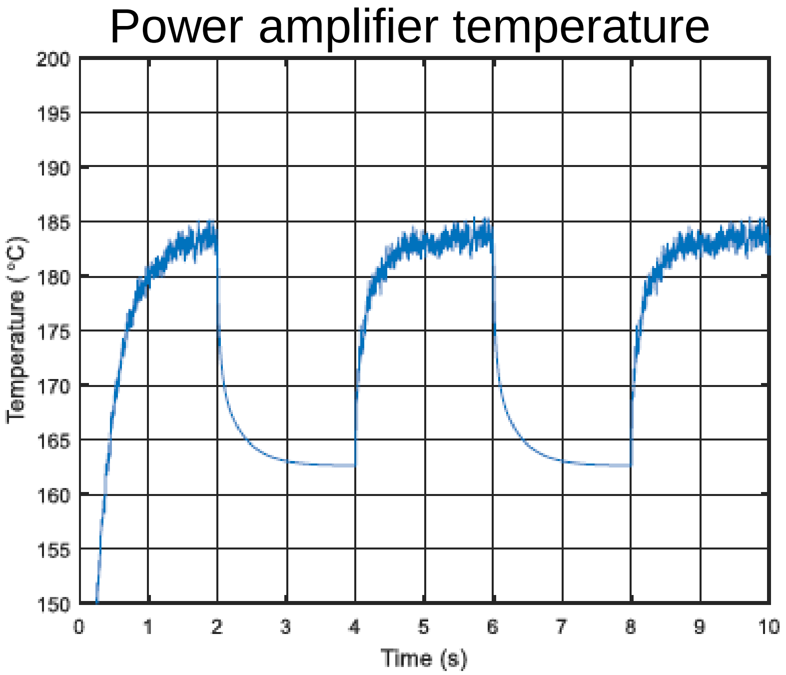
Prediction of transmitter RF nonlinearities

- PA input-/output spectrum for modulated signals
- PA-to-PA nonlinear interactions

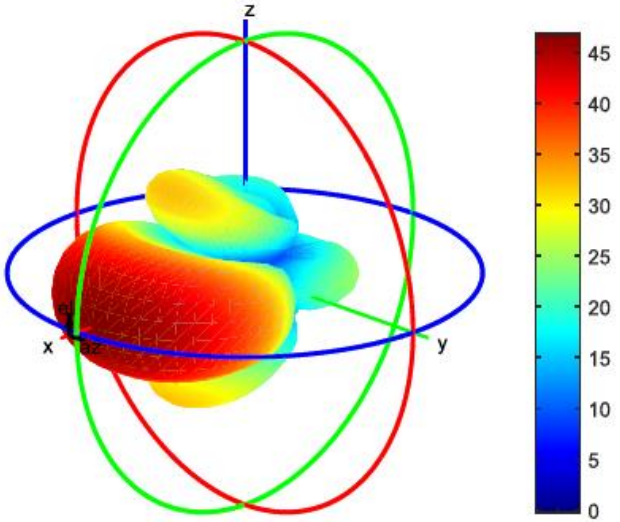


Prediction of PA temperature dynamics

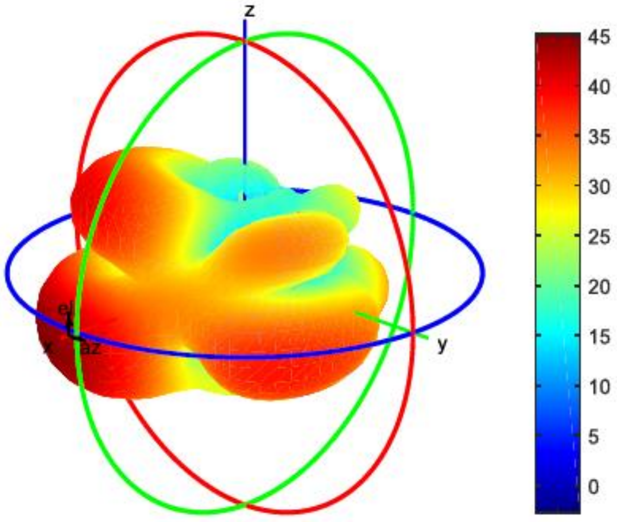
- Thermal transients
- On-off switching, e.g. between T/R in TDD systems
- Heat spreading in arrays



Prediction of radiation patterns



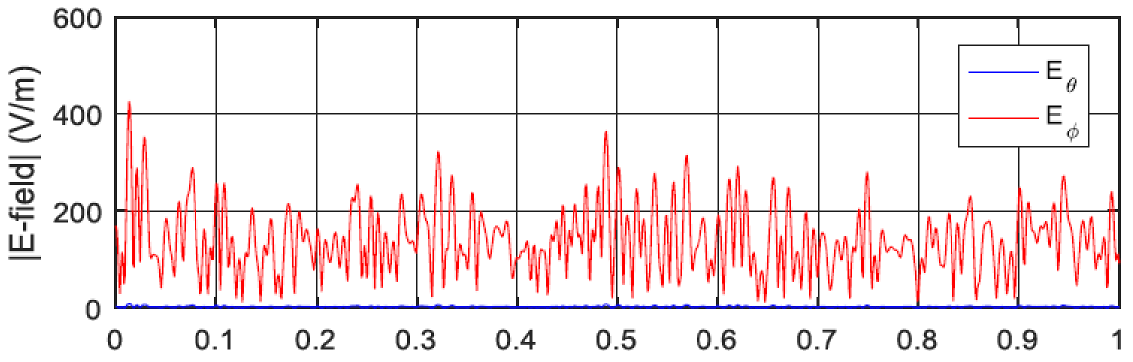
[θ = 90°, φ = 0°]



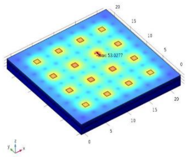
[θ = 90°, φ = -25°]

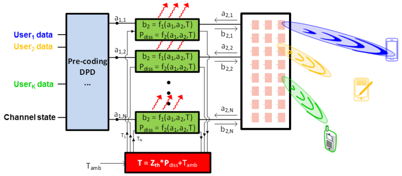
Prediction of modulated field at user

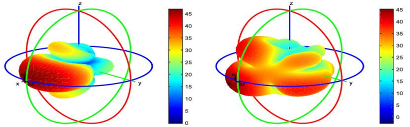
- Modulated fields in both polarizations considering both PA, thermal, antenna and beam-forming settings



Summary – Electro-thermal simulations







- Thermal effects at circuit- and package levels
- Framework for electro-thermal transmitter simulations
- Prediction of joint electrical- and thermal effects in mm-wave antenna arrays

CONCLUSIONS

Conclusions

- mm-wave transmitter design is cross-disciplinary
  - Co-design between signals, circuits & antennas
- New nonlinear distortion phenomena
  - Both circuit and array level linearization needed
  - Low complexity MIMO linearization proposed
- Power dissipation a great challenge
  - Thermal coupling effects
- Understanding linearity and power dissipation effects through accurate multi-physics simulations is critical for successful 5G system design

Acknowledgments

GHz CENTRE VINNOVA SEREN SILIKA

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Simulation of RF Systems

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