SERENA
H2020 PROJECT
Workshop #3: Multi Physical Modeling for Active Antenna Transmitter Systems

The SERENA project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 779305.

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SERENA

gan-on-**S**ilicon **E**fficient mm-wave eu**R**opean syst**E**m i**N**tegration pl**A**tform

SERENA WEBINAR

WITH SPEAKERS FROM:

SAVE THE DATE!

SIGN UP NOW!

Heterogeneous Integration for High Performance mmWave Electronics

28.10.2021, 3-4pm

This workshop will cover requirements and design aspects of the system and its semiconductor components with an emphasis on mmWave heterogeneous integration. Using results from SERENA the system aspects, as well as the RF and thermal design of components and packages will be illustrated base on an em-bedding packaging technology.

UWE MAAß (FRAUNHOFER)

KRISTOFFER ANDERSSON (EAB)

FRANZ DIELACHER (IFAT)

SIGN UP NOW!

GaN-on-Si for mm-wave applications

04.11.2021, 3-4pm

This workshop will cover GaN-on-Si processes and design tools for mm-wave applications as well as GaN-on-Si substrates for RF and mm-wave applications. Another focus will be on 60 nm GaN-on-Si based mm-wave amplifiers for RF sensing and wireless communication.

RÉMY LEBLANC (OMMIC)

MARIANNE GERMAIN (SOITEC)

ROBERT MALMQVIST (FOI)

SIGN UP NOW!

Multi-physical modelling for active antenna transmitter systems

11.11.2021, 3-4pm

During this seminar, speakers from TU Berlin and Chalmers University of Technology, will discuss how thermal, electric, and electromagnetic hardware effects will influence the performance of millimeter wave communication transmitters and communication systems. Both theoretical and experimental studies will be included to illustrate typical applications of the methods discussed.

CHRISTIAN FAGER (CHALMERS)

THOMAS KUEHNE (TUB)

Webinar Outline

Electro-thermal simulation for active antenna transmitters	Christian Fager	Chalmers	30 min
Simulating the Communication Performance of Active Antenna Systems	Thomas Kühne	TU Berlin	20 min
Q&A and wrap-up			10 min

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Electro-thermal simulation for active antenna transmitters

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christian.fager@chalmers.se

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Contributors

- Chalmers (present and past)
  - T. Eriksson, K. Buisman, K. Rasilainen, K. Hausmair, P. Taghikhani, E. Baptista


Prof. T. Eriksson Dr. K. Buisman P. Taghikhani Dr. K. Hausmair Dr. K. Rasilainen E. Baptista

- Ericsson
  - U. Gustavsson, P. Landin, K. Andersson


Dr. U. Gustavsson Dr. P. Landin Dr. K. Andersson

- OMMIC
  - M. Marilier, R. Leblanc, A. Gasmi, M. ElKaamouch
- Fraunhofer IZM
  - I. Ndip, U. Maaß, K. S. Murugesan

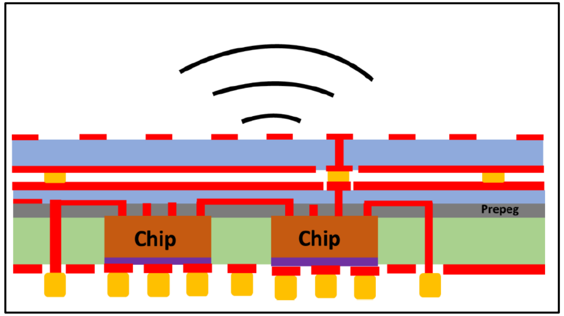
OMMIC innovating with III-V'S

Fraunhofer IZM

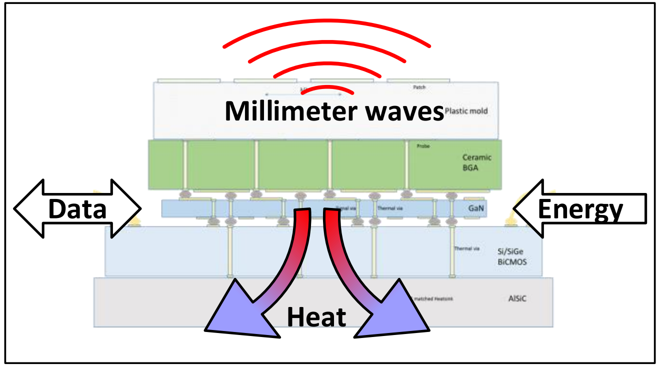
mm-wave RF systems

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

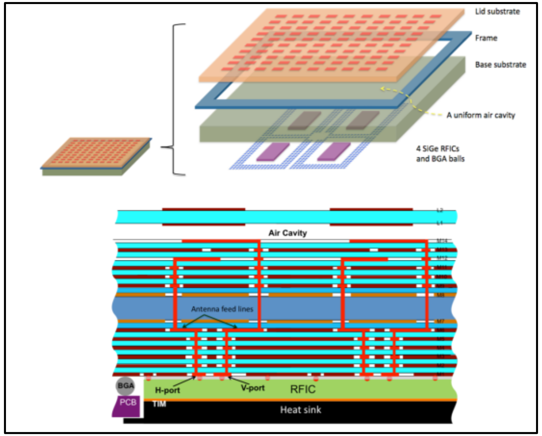
Chip embedding (IZM/SERENA)



Vertical stacking

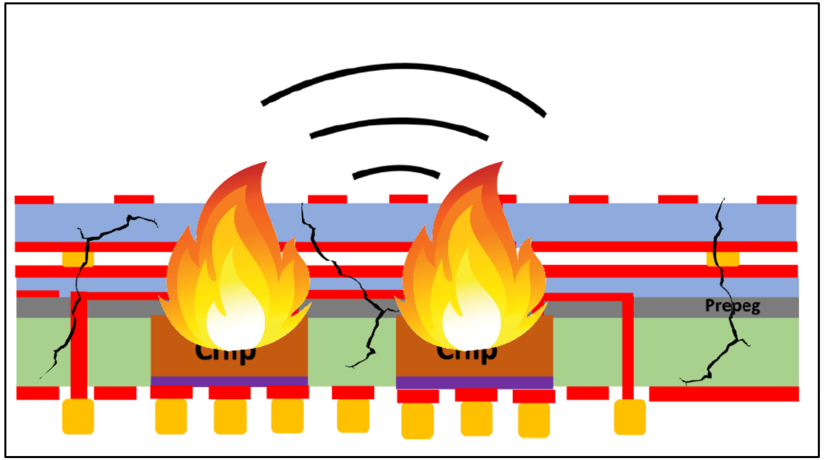


IBM / Ericsson



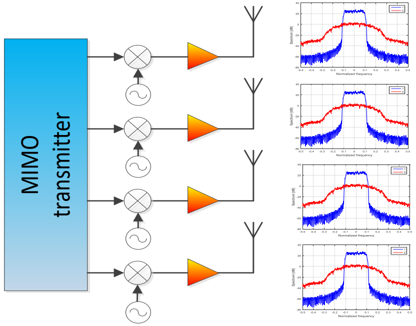
Challenges

- 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



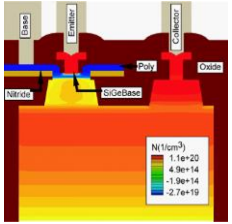
Active antenna arrays

Antenna-circuit interactions

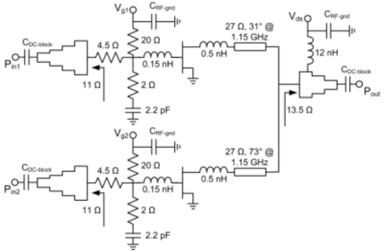
Linearity

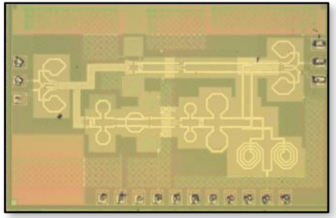
Simulations at many levels...

Transistor

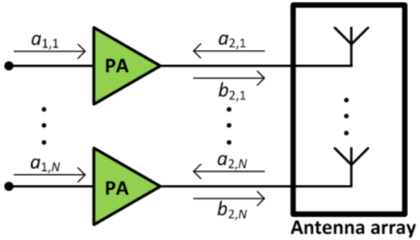


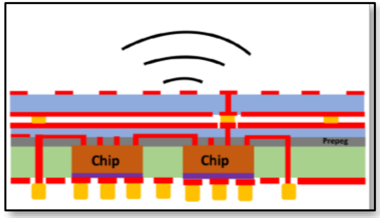
Circuit





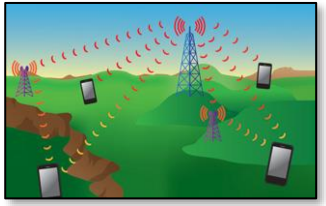
RF Sub-system





System

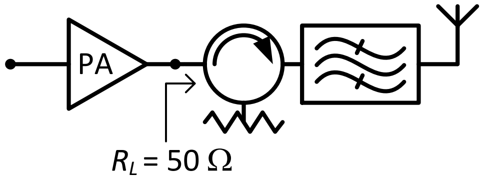
$$\mathbf{y} = \mathbf{H}\mathbf{x} + \mathbf{w}$$

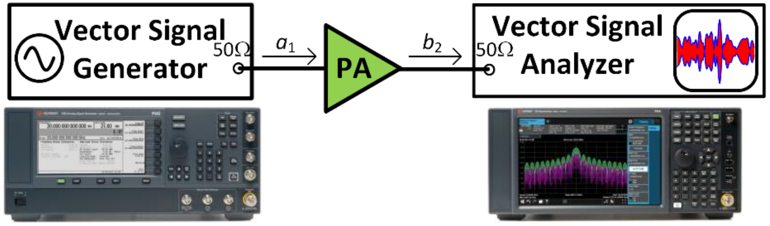


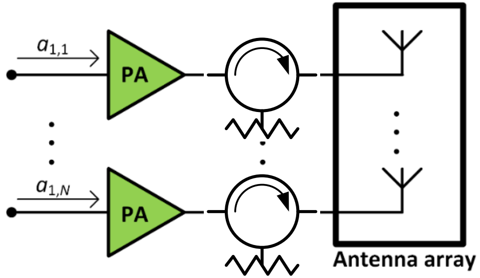
[T. Svensson, Chalmers]

Transmitter modeling

- Traditionally 50Ω assumed

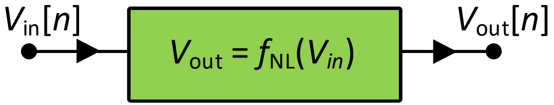






- Single-input-single-output modeling of RF components

SISO model

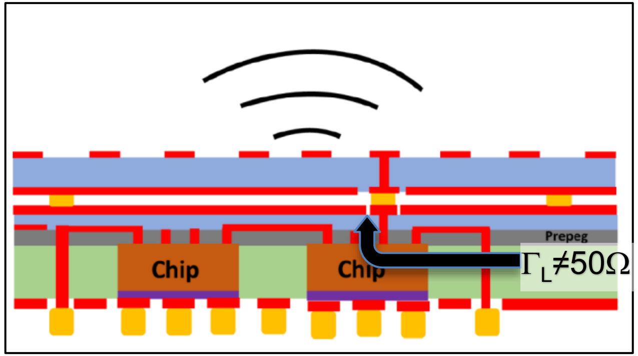


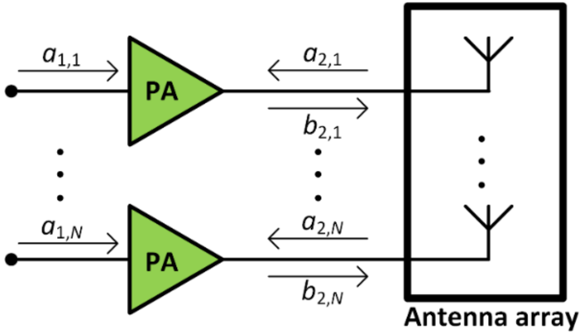
$$V_{out} = f(V_{in})$$

Transmitter modeling

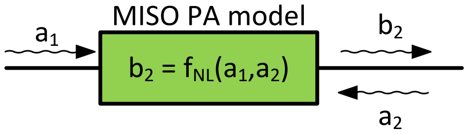
- Integrated transmitters
  - Mismatch and mutual coupling
  - Non-50Ω interfaces

- Dual-input models needed:
  $b_2 = f(a_1, a_2)$





Dual-input behavioral modeling



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

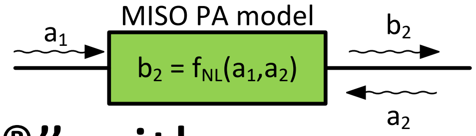
Nonlinear
50Ω SISO-terms

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



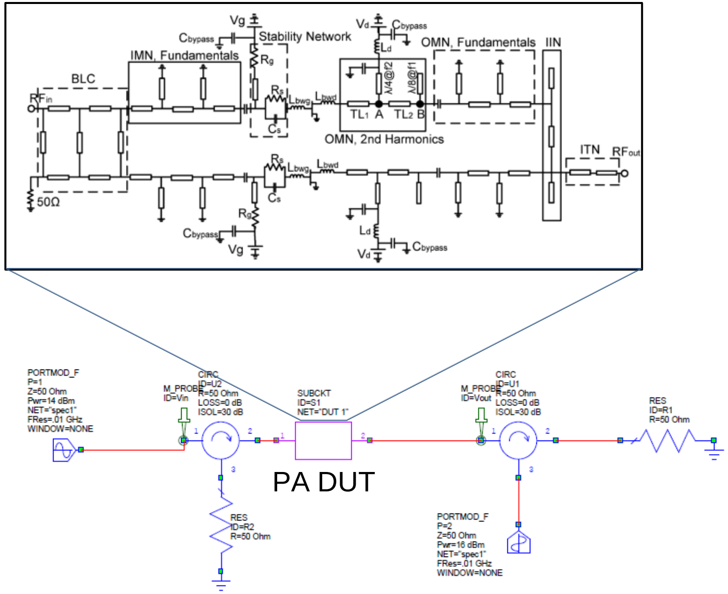
- "X-parameters®" with memory

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

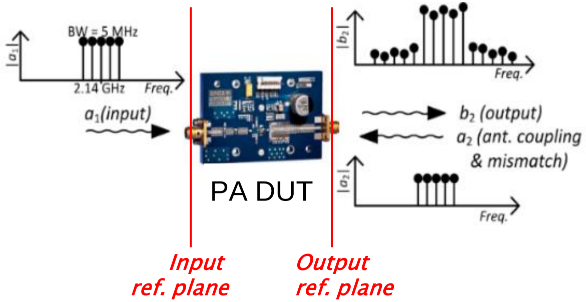
[C. Fager et al., "Prediction of Smart Antenna Transmitter Characteristics Using a New Behavioral Modeling Approach," *Proc. IMS*, 2014]

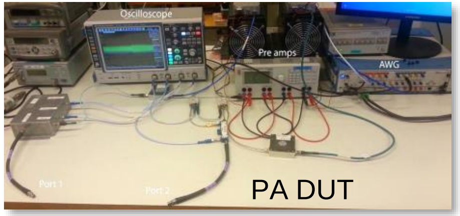
Model identification

Simulation based



Measurement based

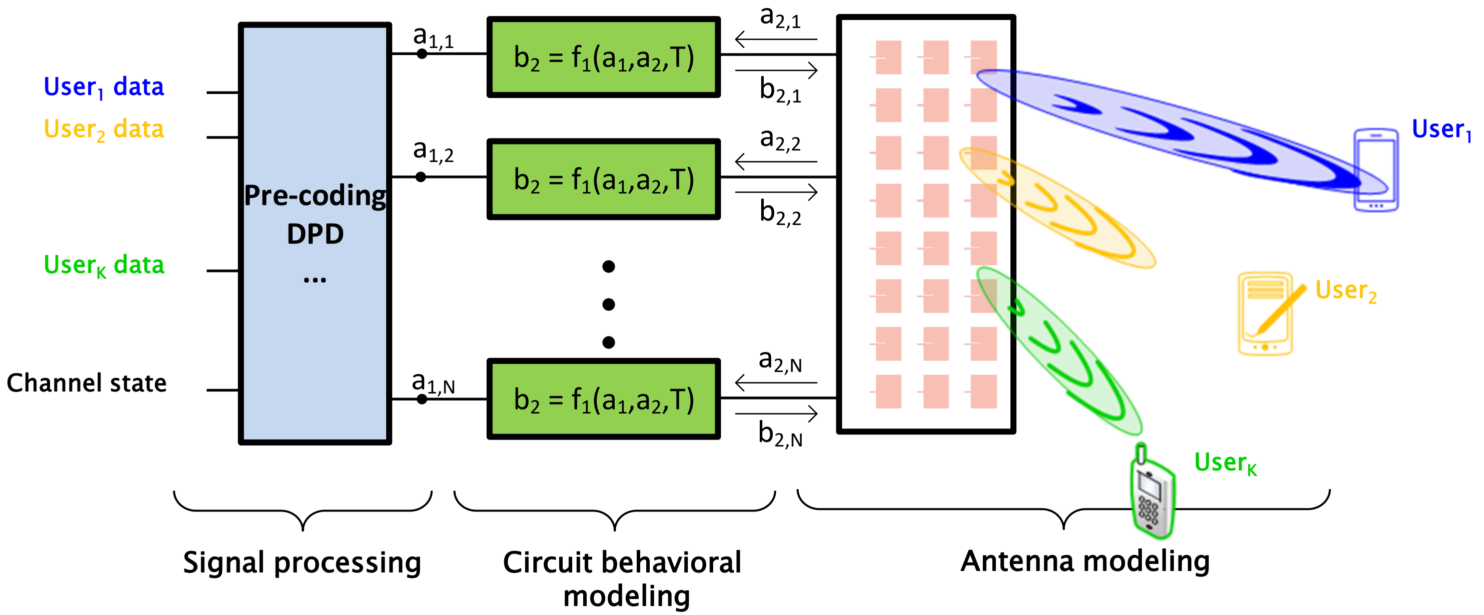




[S. Gustafsson et al., "A Novel Active Load-pull System with Multi-Band Capabilities," ARFTG, 2013]

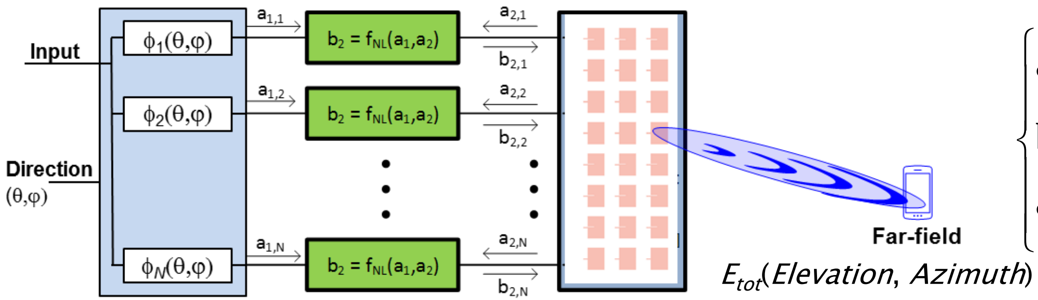
[C. Fager et al., "Prediction of Smart Antenna Transmitter Characteristics Using a New Behavioral Modeling Approach," *Proc. IMS*, 2014]

Transmitter simulation framework



[C. Fager et al., “Linearity and Efficiency in 5G Transmitters: New Techniques for Analyzing Efficiency, Linearity, and Linearization in a 5G Active Antenna Transmitter Context,” IEEE Microw. Mag., 2019]

Phased array application



Beam steering

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

Antenna circuit interactions

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

Regular 50Ω nonlinear distortion

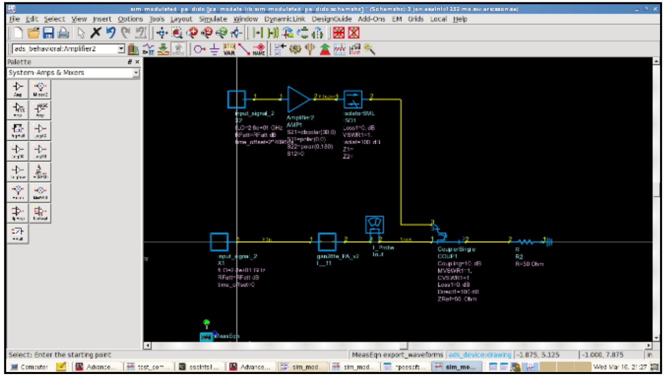
Antenna coupling and mismatch effects

Far field radiation

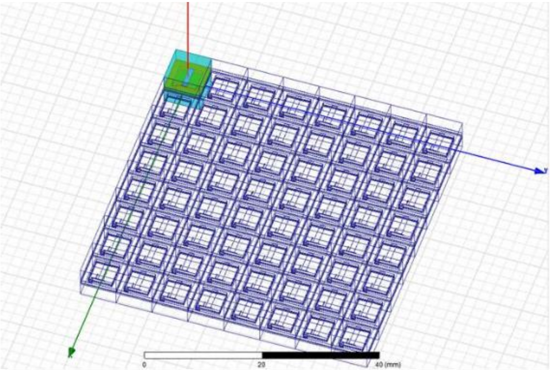
$$E_{tot}\left(El, Az\right)[n] = \sum_{i=1}^{N} b_{2,i}[n]\bar{E}_i\left(El, Az\right)$$

Phased array example

IC design



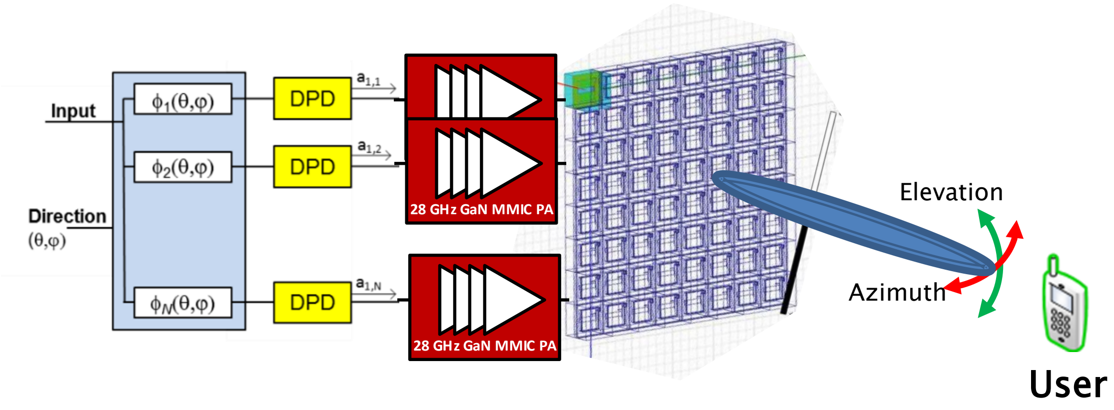
64 element antenna array



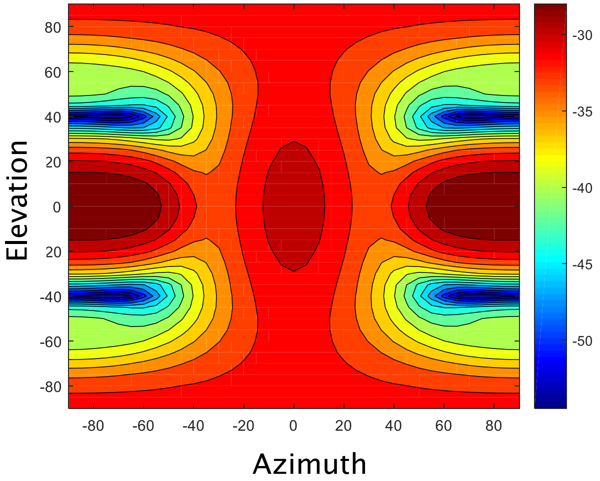
- PA model extracted from IC CAD
- Antenna parameters from EM CAD
- Each PA perfectly linearized for 50Ω load ($a_2 = 0$)
- Ideal phased array beam steering. No amplitude tapering

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

Phased array example

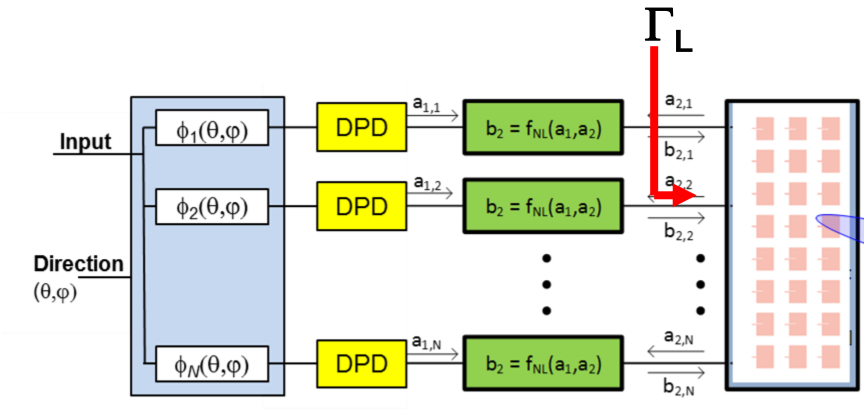


User EVM vs. scan direction

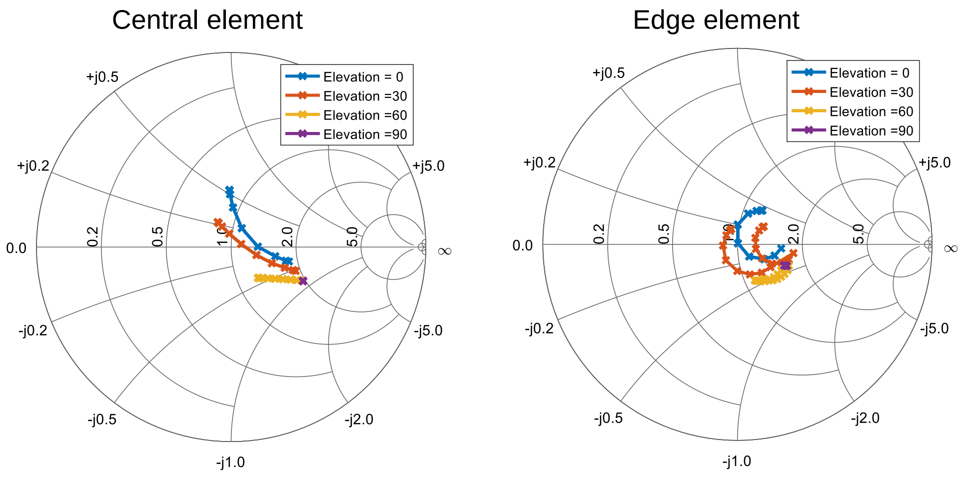


- Distortion highly direction dependent. *Why?*

Phased array example



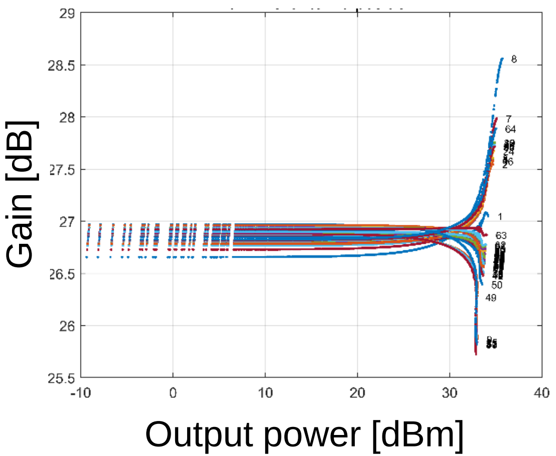
Γ_L vs. scan direction



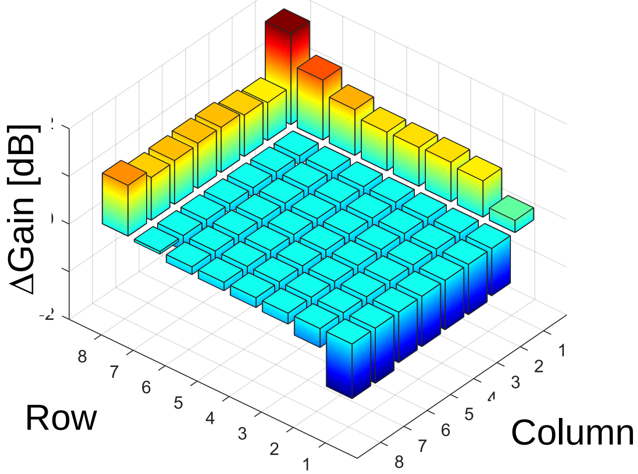
- Significant variation of PA load impedance vs. beam steering

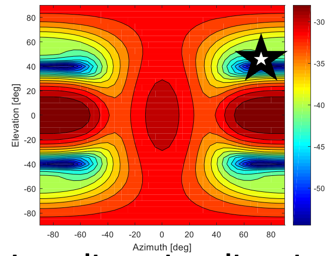
Phased array example

AM/AM for each of the 64 branches



Gain compression/expansion



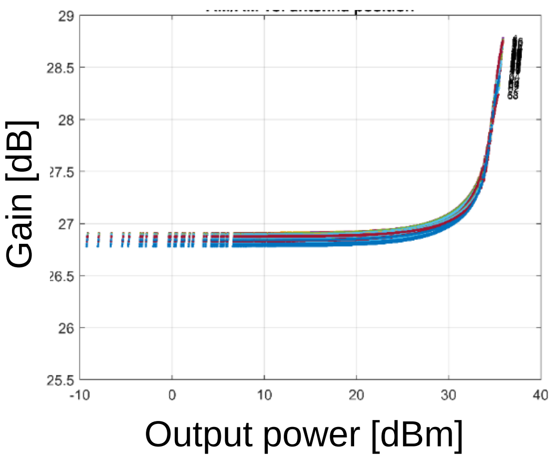


Low distortion direction

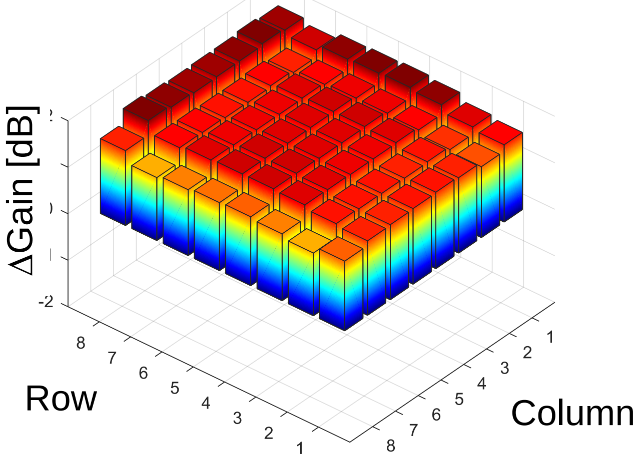
- Distortion averaging effects happening inside the array

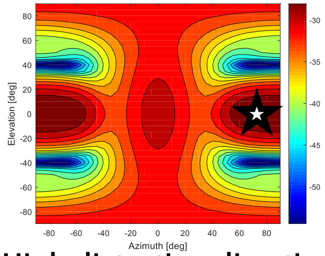
Phased array example

AM/AM for each of the 64 branches



Gain compression/expansion

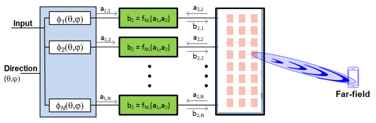


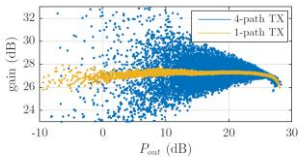


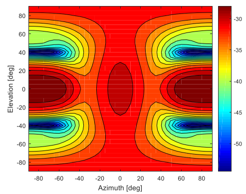
High distortion direction

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

Summary – transmitter RF modeling

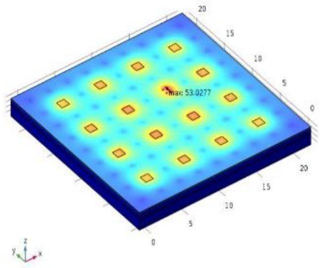






- Framework for efficient simulation of active antenna systems
- Improved understanding of circuits-antenna interactions with realistic signals
- New nonlinear effects predicted in phased array and MIMO systems

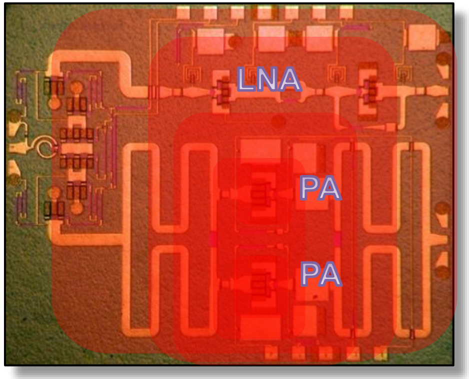
ELECTRO-THERMAL SIMULATIONS

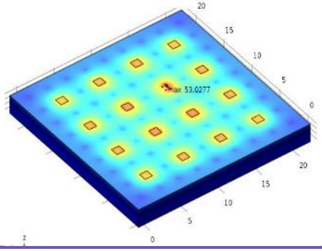


Thermal modeling
Power dissipation modeling
mm-wave transmitter example

Heating concerns

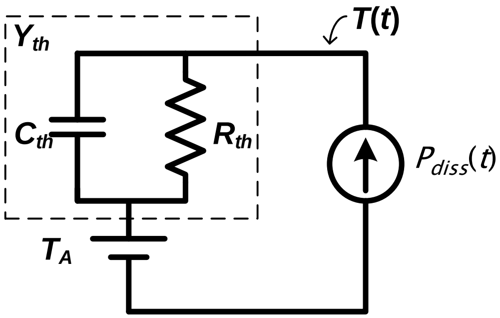
- Heat concentration in active antenna arrays
- Chip level heating effects
  - Thermal coupling
  - Efficient power amplifiers
- System level effects
  - Performance degradation
  - Reliability



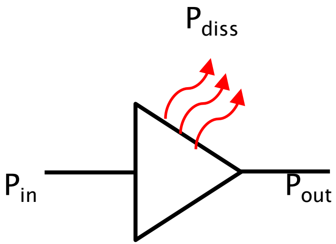


Linear heating model

Thermal model



RF Model

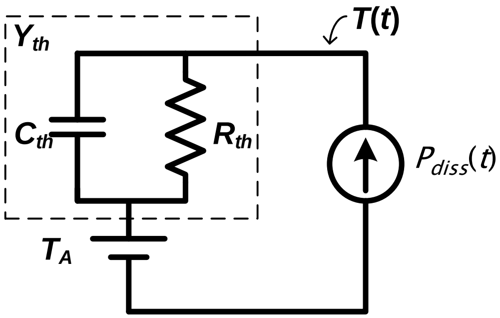


$$P_{diss}(t) = P_{diss}(|a_1(t)|, T(t))$$

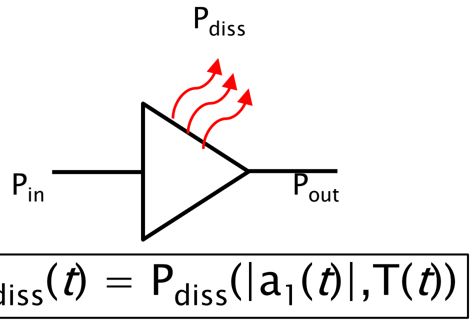
- $T(t) = T_A + P_{diss}(t) * z_{th}$
- Thermal admittance: $Y_{th} = G_{th} + j\omega C_{th}$

Linear heating model

Thermal model



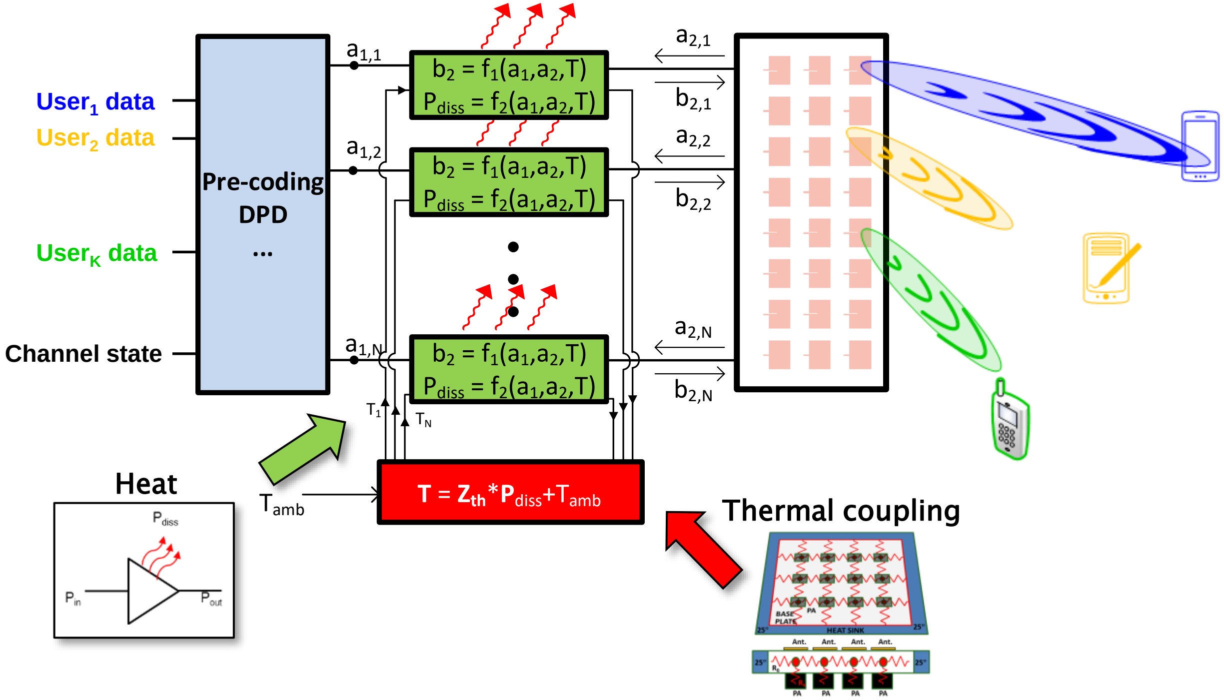
RF Model



- Envelope time-stepped solution for T(t)

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

Incorporating thermal effects



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

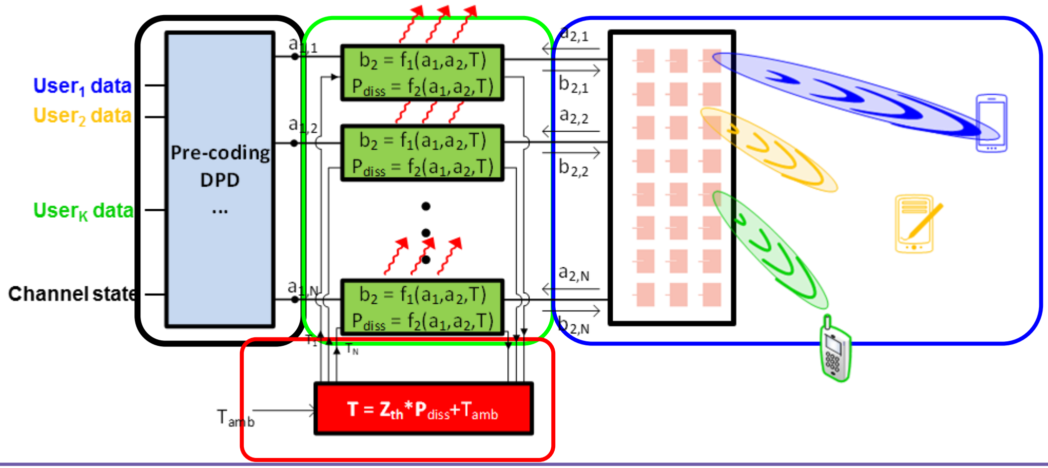
Combined RF/EM/Thermal simulation

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

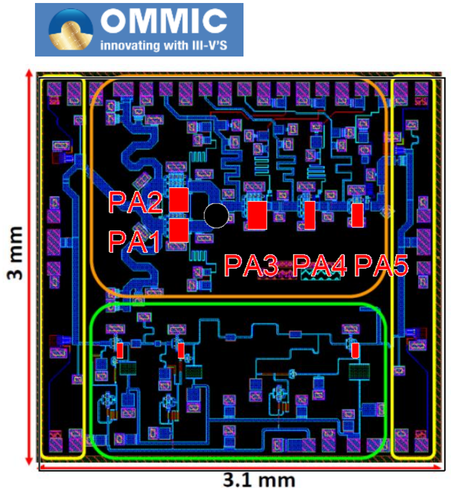
$$\mathbf{b}_{2,n} = \mathbf{S}_{21}\left(|\mathbf{a}_{1,n}|, \mathbf{T}_n\right)\mathbf{a}_{1,n} + \mathbf{S}_{22}\left(|\mathbf{a}_{1,n}|, \mathbf{T}_n\right)\mathbf{S}_{ant}\mathbf{b}_{2,n} + \mathbf{T}_{22}\left(\mathbf{a}_{1,n}, \mathbf{T}_n\right)\mathbf{S}^*_{ant}\mathbf{b}^*_{2,n} + \boldsymbol{\rho}_{n-1}$$

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

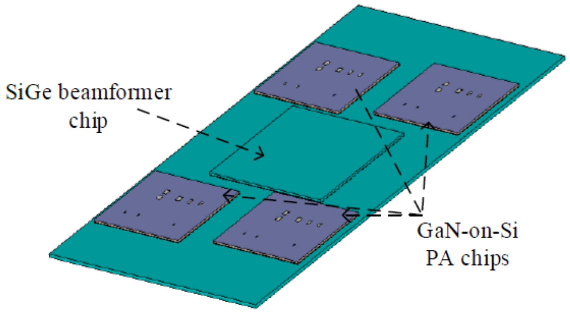
$$\mathbf{T}_{n+1} = T_{\mathrm{amb}} + \left(\mathbf{G}_{\mathrm{th}} + 2\pi f_s \mathbf{C}_{\mathrm{th}}\right)^{-1}\left(\mathbf{P}_{\mathrm{diss},n}\left(|\mathbf{a}_{1,n}|, \mathbf{T}_n\right) + 2\pi f_s \mathbf{C}_{\mathrm{th}}\left(\mathbf{T}_n - T_{\mathrm{amb}}\right)\right)$$



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: $6 \times 65\,\mu m = 390\,\mu m\ (\approx 0.108 w_{tot})$

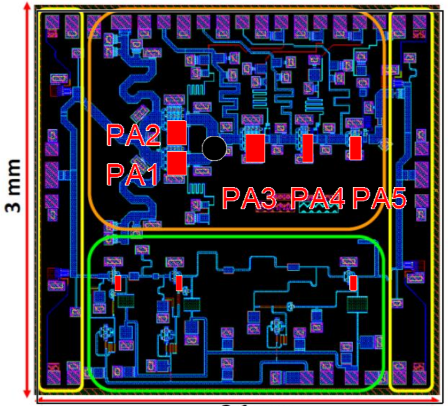


Material	Density ρ (kg/m^3)	Thermal conductivity k (W/m·K)	Specific heat C_p (J/kg·K)
Megtron 7	1820	0.4	0.88
Si	2330	148	0.7
SiGe	3950	8.8	0.5

[K. Rasilainen et al., "Multi-Physical Simulations and Modelling of an Integrated GaN-on-Si Module Concept for Millimetre-Wave Communications," Proc. IEEE ECTC, 2020].

Example: SERENA 4-channel transmitter

OMMIC innovating with III-V'S



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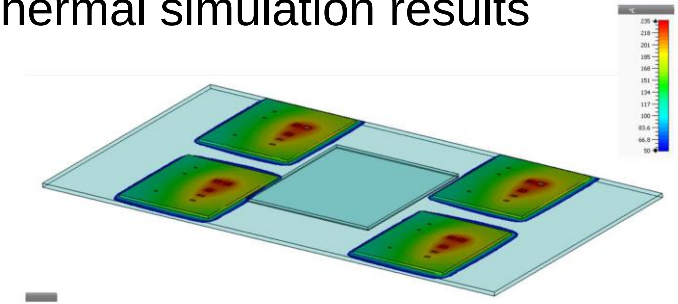
Thermal simulation results



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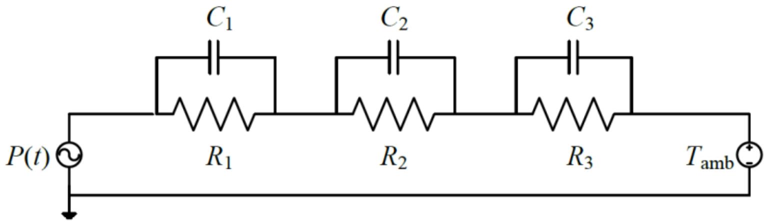
Thermal RC modeling

- One GaN chip in a simplified package environment

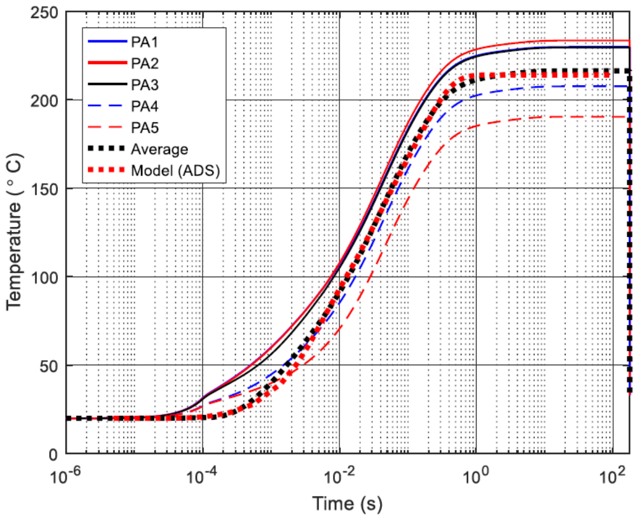
Thermal RC constants



Chip dissipated power

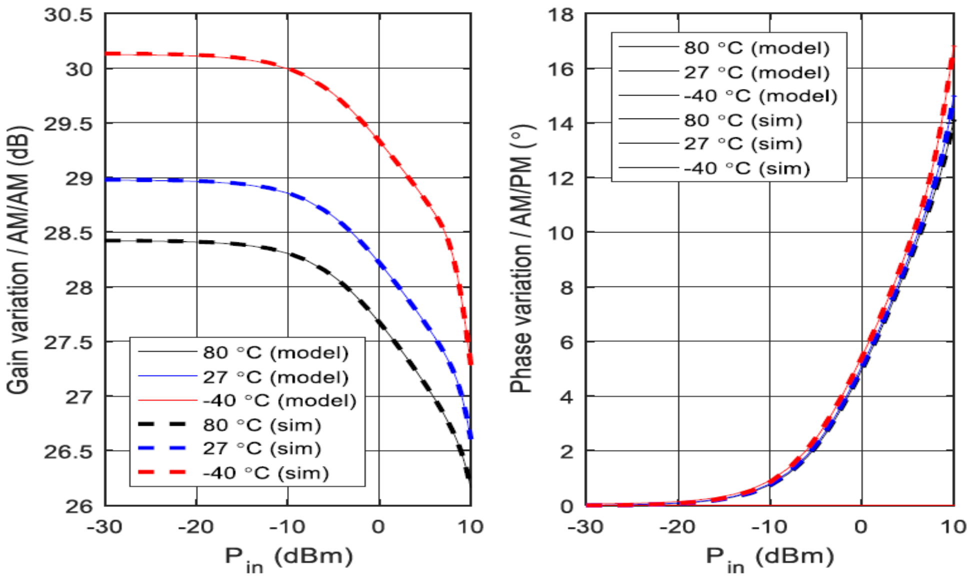
Ambient temperature

Thermal response @ 7W step



Power amplifier modeling

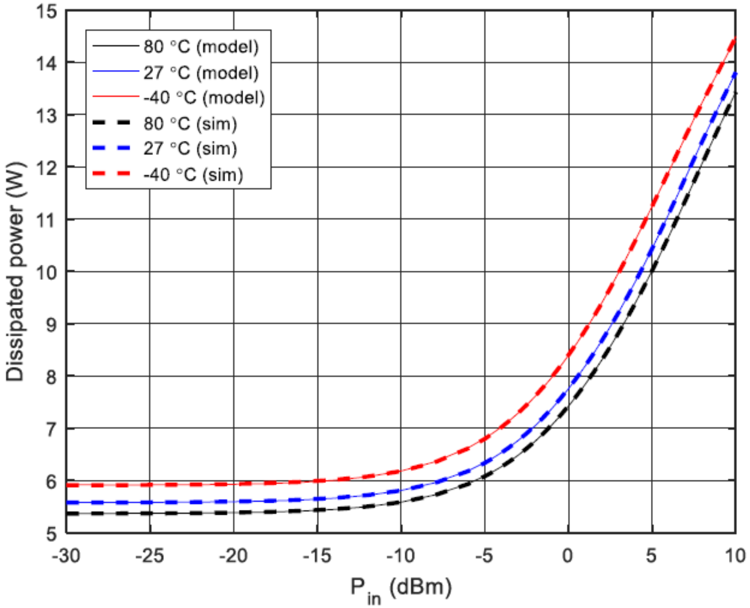
- Temperature dependent gain



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

Power amplifier modeling

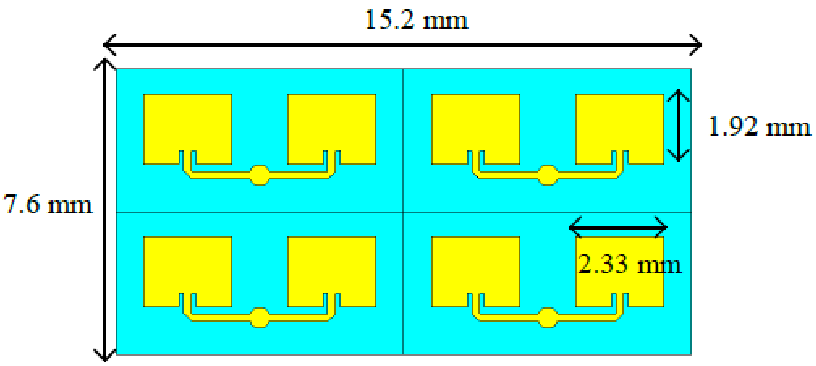
- Dissipated power vs. temperature



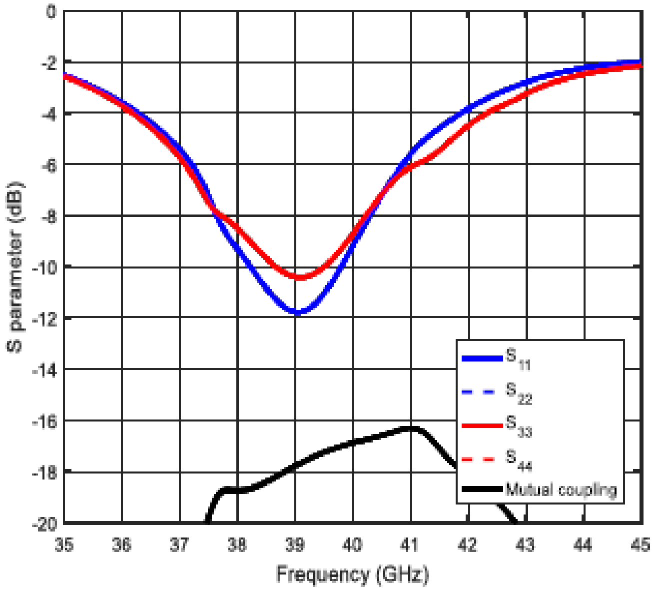
$$P_{\text{diss}}(|a_1|, T) = P_{\text{dc}} + P_{\text{in}} - P_{\text{out}}$$

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

Antenna modeling

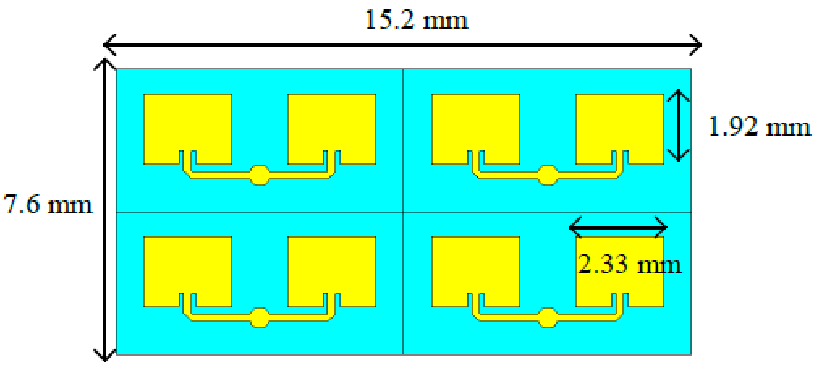


Simulated S-parameters

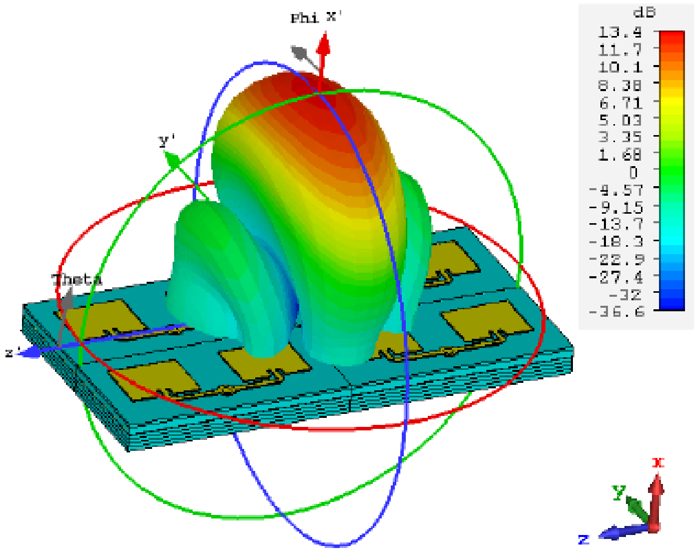


- Mismatch and mutual-coupling neglected in model

Antenna modeling

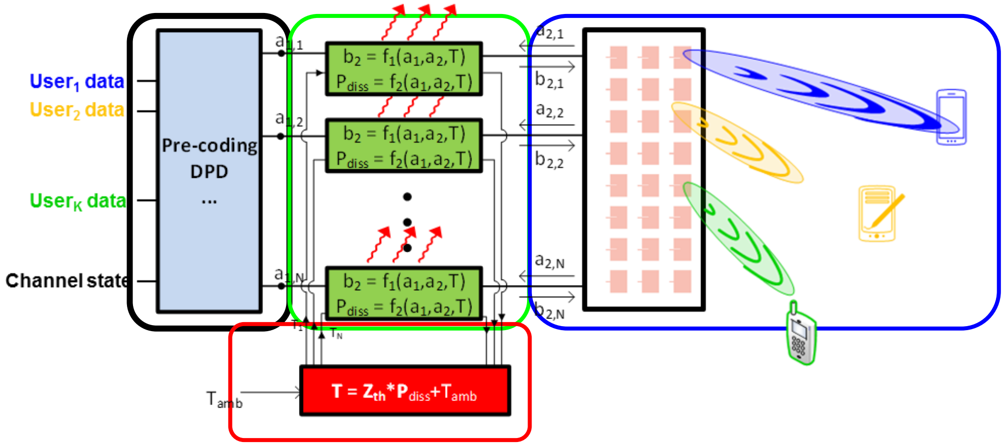


Far-field radiation patterns

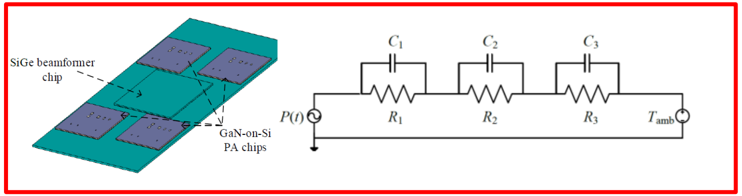


- Embedded element patterns for unity excitations

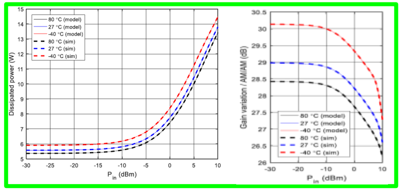
Electro-thermal simulation framework



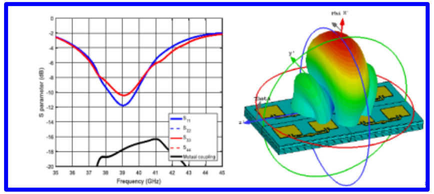
Thermal modeling



RF circuit modeling

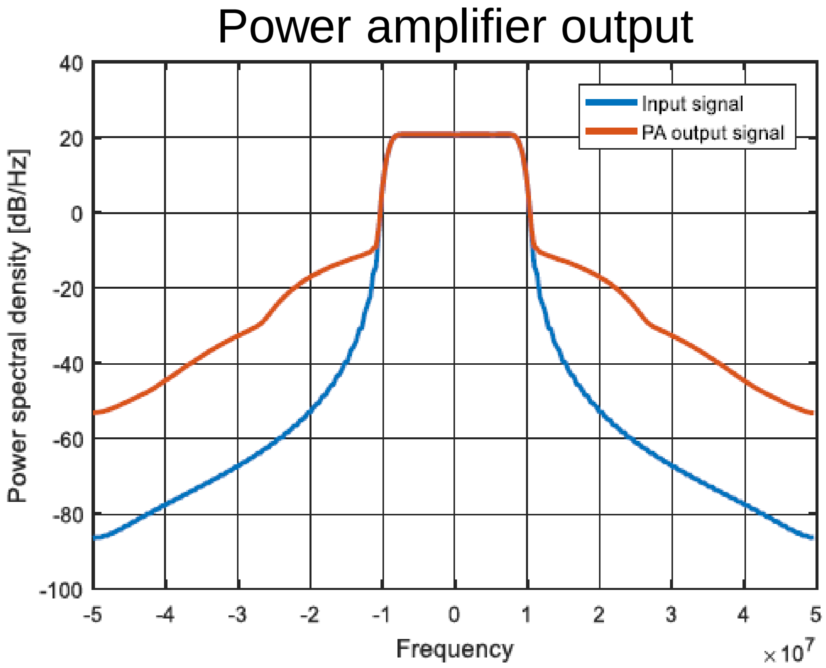


Antenna modeling



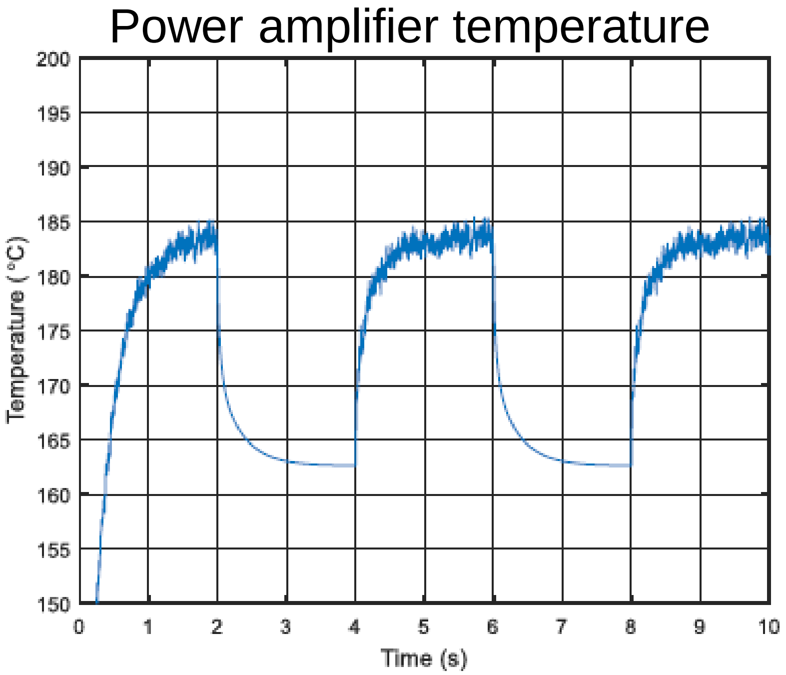
Prediction of transmitter RF nonlinearities

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

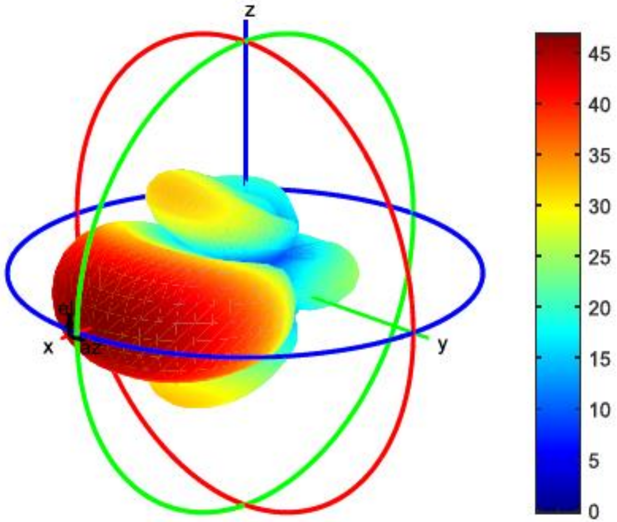


Prediction of PA temperature dynamics

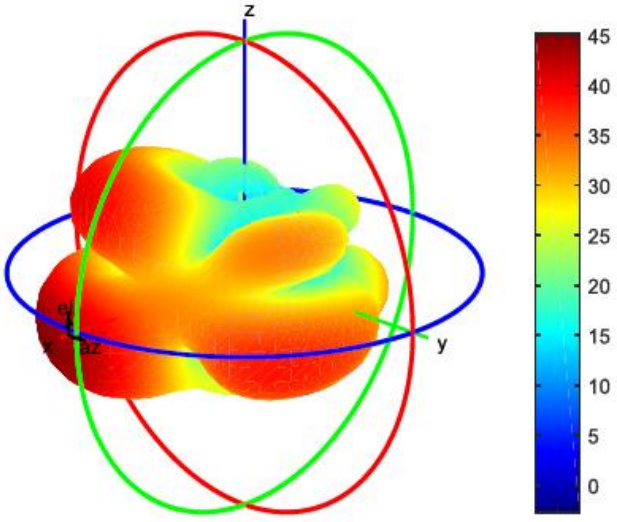
- Thermal transients
- On-off switching, e.g. between T/R in TDD systems
- Heat spreading in arrays



Prediction of radiation patterns



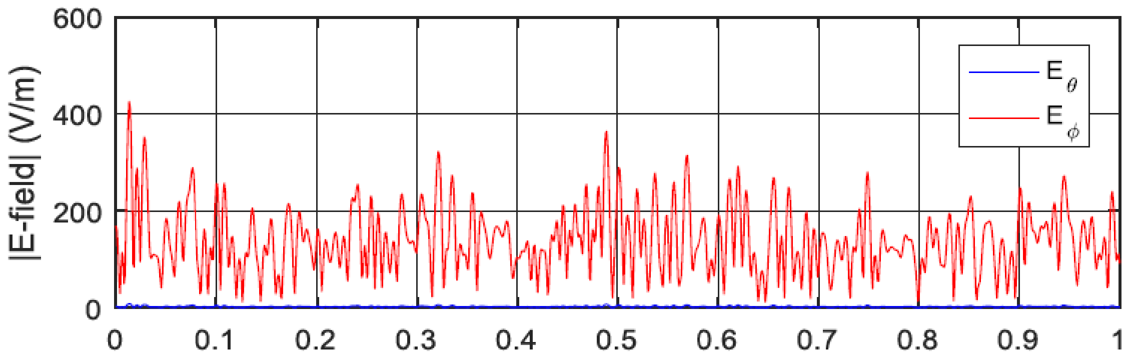
[θ = 90°, φ = 0°]



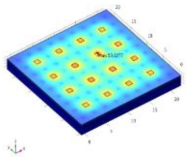
[θ = 90°, φ = -25°]

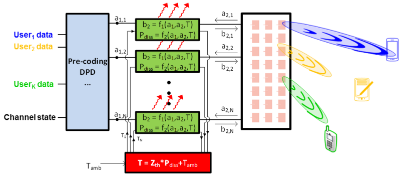
Prediction of modulated field at user

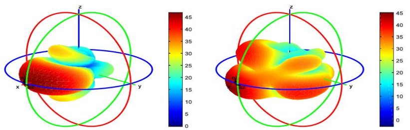
- Modulated fields in both polarizations considering both PA, thermal, antenna and beam-forming settings



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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