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LAMC 2023
SAN JOSE – COSTA RICA

An Overview of Nonlinear Modeling of RF and Microwave Devices

José Carlos Pedro
Institute of Telecommunications – University of Aveiro – Portugal

Aveiro – A touristic town …

Aveiro – … with Unique Architecture (Art Nouveau) …

Aveiro – … with Unique Architecture …

Aveiro – … and wonderful beaches …

Aveiro – … and a vibrant Research University.

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An Overview of Nonlinear Modeling of RF and Microwave Devices

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Presentation Outline

1. Introduction - Nonlinear Microwave CAD – Simulation
2. Nonlinear Device Modeling Theory
3. Physics-Based Modeling of Microwave Devices
4. Behavioral Modeling of Microwave Devices
5. Summary

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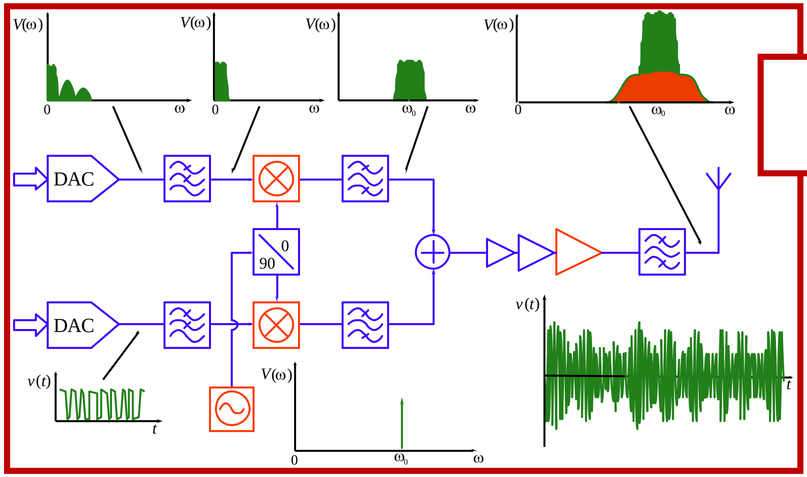
1 – Introduction - Microwave CAD

Numerical Simulation of Nonlinear Microwave Circuits

There are 3 levels of abstraction of electronic circuits:

1. System-level; 2. Circuit-level and 3. Device-level.



System-Level Simulation

Behavioral Modeling

1 – Introduction - Microwave CAD

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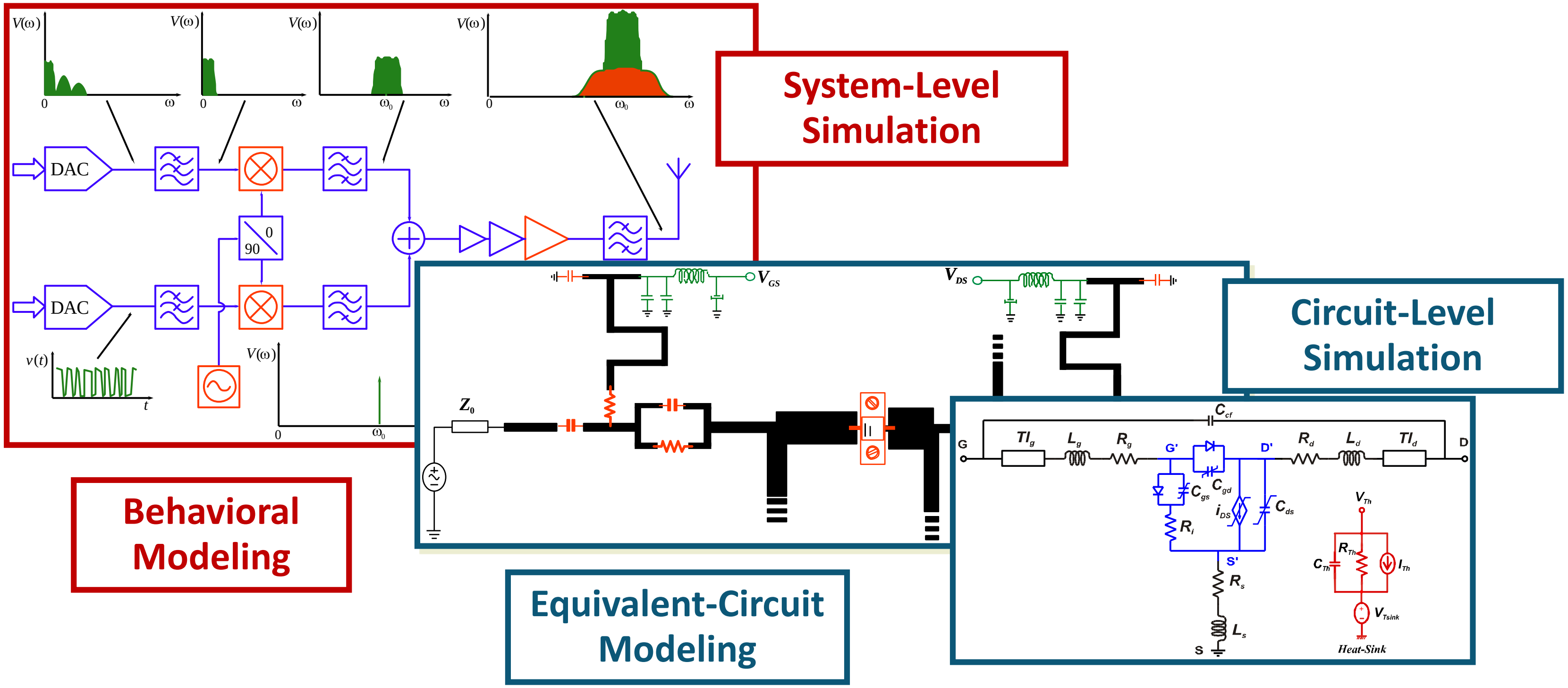

System-Level Simulation

Circuit-Level Simulation

Behavioral Modeling

Equivalent-Circuit Modeling

1 – Introduction - Microwave CAD

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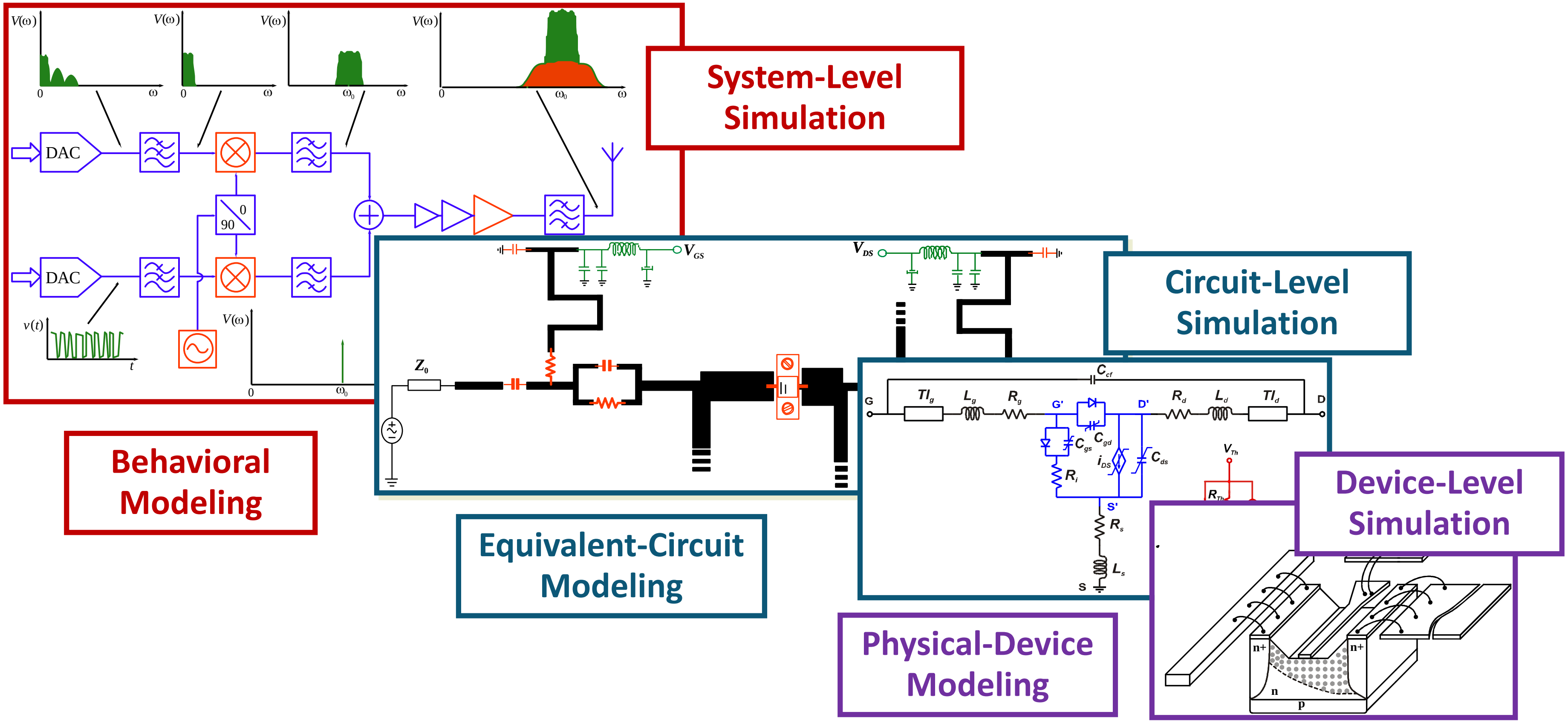


System-Level Simulation

Behavioral Modeling

Circuit-Level Simulation

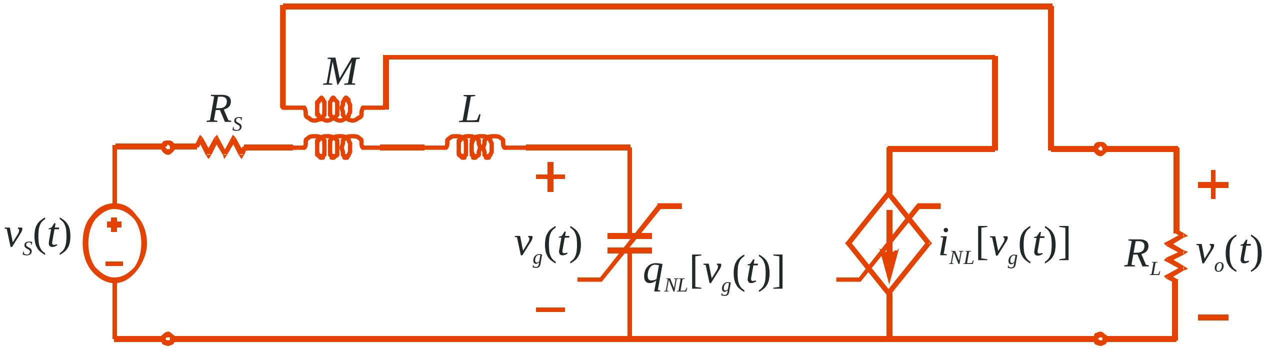
Equivalent-Circuit Modeling

Device-Level Simulation

Physical-Device Modeling

1 – Introduction - Microwave CAD

Time-Domain Simulation – Time-Step Integration



Circuit Analysis leads to a *System of Ordinary Differential Equations*, ODEs, than can be recast in the canonical form of a *State-Equation* and an *Output-Equation*:

Time-Domain Model

$$\frac{d\mathbf{s}(t)}{dt} = \mathbf{f}[\mathbf{s}(t), \mathbf{x}(t)]$$

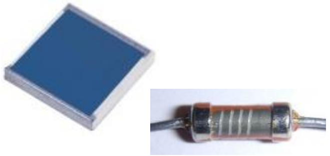
and

$$\mathbf{y}(t) = \mathbf{g}\,[\mathbf{s}(t), \mathbf{x}(t)]$$

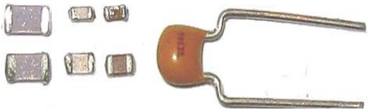
1 – Introduction - Microwave CAD

Time-Domain Models

Time-domain models (SPICE-Models) are mathematical representations of the conduction current, charge and magnetic fluxes as functions of voltages or currents (**Quasi-Static Assumption**):



$$i(t) = f\left[v(t)\right]$$



$$q(t) = f\left[v(t)\right] \quad \rightarrow \quad i(t) = \frac{d\,q[v(t)]}{dt} = \frac{d\,q(v)}{dv}\frac{d\,v(t)}{dt} = C(v)\frac{d\,v(t)}{dt}$$

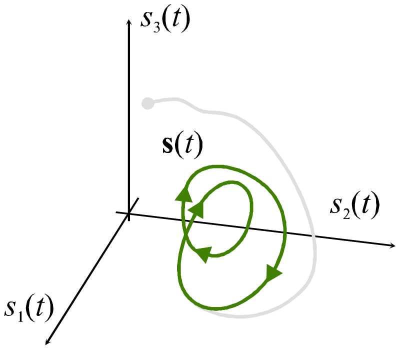
$$\phi(t) = f\left[i(t)\right] \quad \rightarrow \quad v(t) = \frac{d\,\phi[i(t)]}{dt} = \frac{d\,\phi(i)}{di}\frac{d\,i(t)}{dt} = L(i)\frac{d\,i(t)}{dt}$$

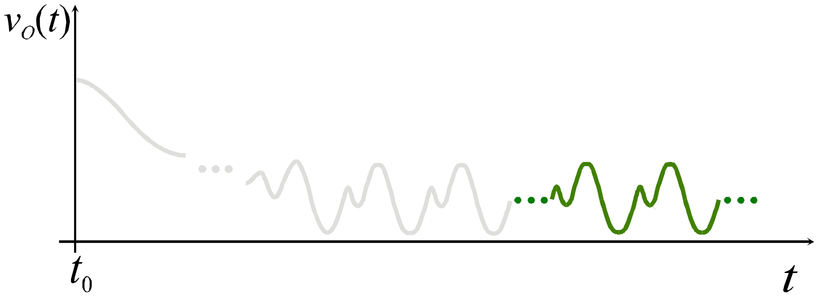
Modified Nodal Analysis (KCL based) is then used to build more complex models.

1 – Introduction - Microwave CAD

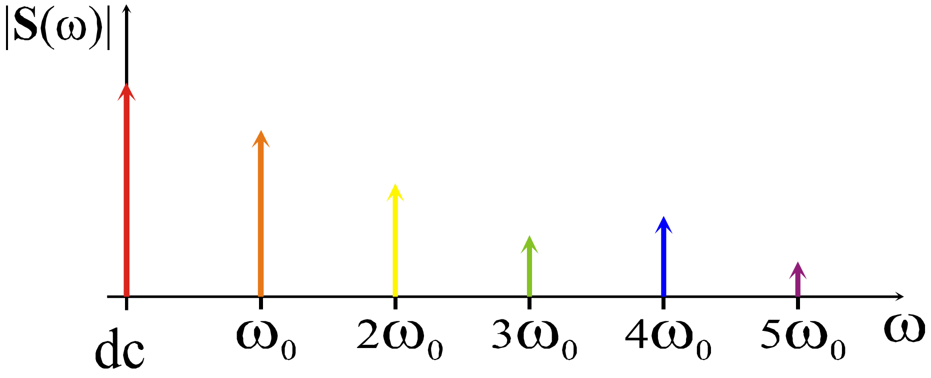
Frequency-Domain Simulation – Harmonic-Balance

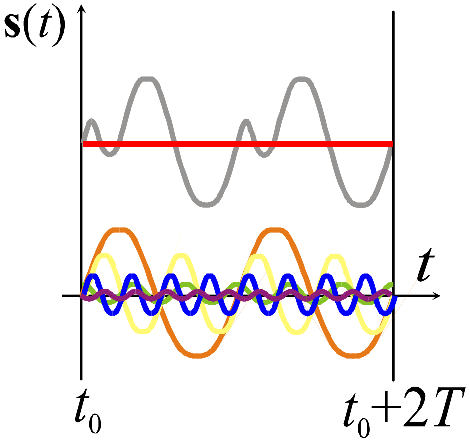
Contrary to time-domain simulators that calculate both the transient and the periodic steady-state, in a time-step by time-step basis,





frequency-domain algorithms can only address the periodic regime, determining the appropriate Fourier components.

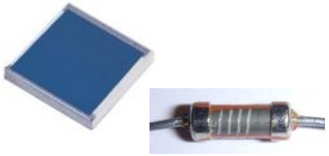




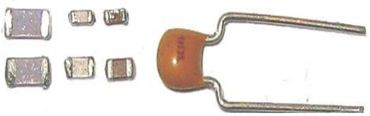
1 – Introduction - Microwave CAD

Frequency-Domain Models

Frequency-domain models are mathematical representations of the conduction current, charge and magnetic fluxes’ Fourier components as functions of their voltages or currents’ Fourier components:



$$\mathbf{i}(\omega) = \mathbf{f}[\mathbf{v}(\omega)]$$



(convolution)

$$\mathbf{q}(\omega) = \mathbf{f}[\mathbf{v}(\omega)] \quad \rightarrow \quad \mathbf{i}(\omega) = j\mathbf{\Omega}\mathbf{q}(\omega) = \mathbf{C}(\omega) * j\mathbf{\Omega}\mathbf{v}(\omega)$$

(convolution)

$$\boldsymbol{\phi}(\omega) = \mathbf{f}[\mathbf{i}(\omega)] \quad \rightarrow \quad \mathbf{v}(\omega) = j\mathbf{\Omega}\boldsymbol{\phi}(\omega) = \mathbf{L}(\omega) * j\mathbf{\Omega}\mathbf{i}(\omega)$$

Modified Nodal Analysis (KCL based) is again used to build more complex models.

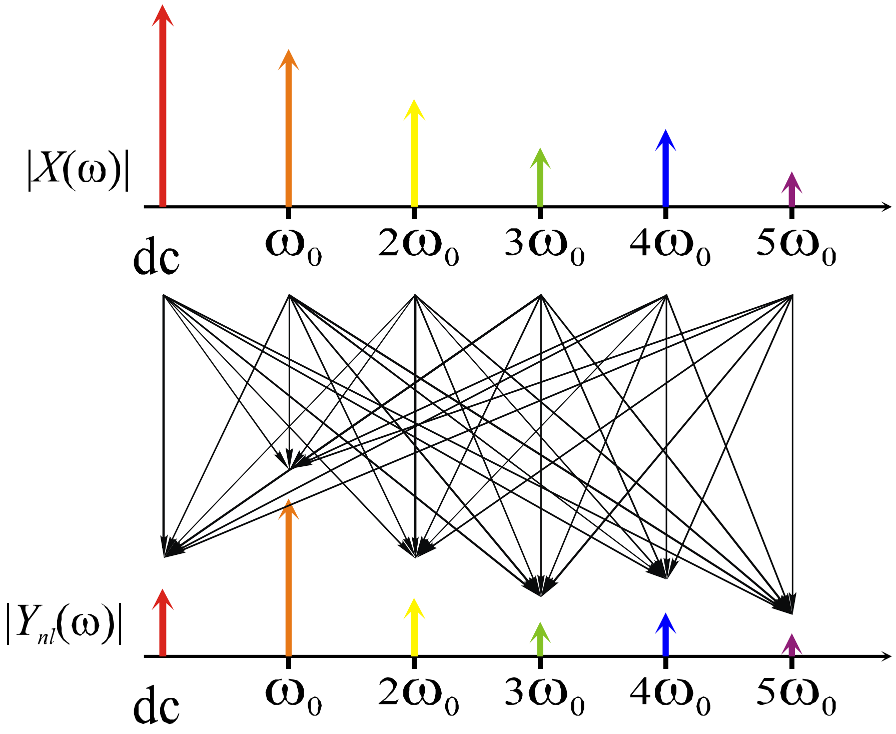
Frequency-Domain Behavioral Modeling of Microwave Devices

Frequency-domain nonlinear models are behavioral models.

Nonlinear Frequency- Domain Model:

$$y(\omega) = \mathbf{f}[x(\omega)]$$

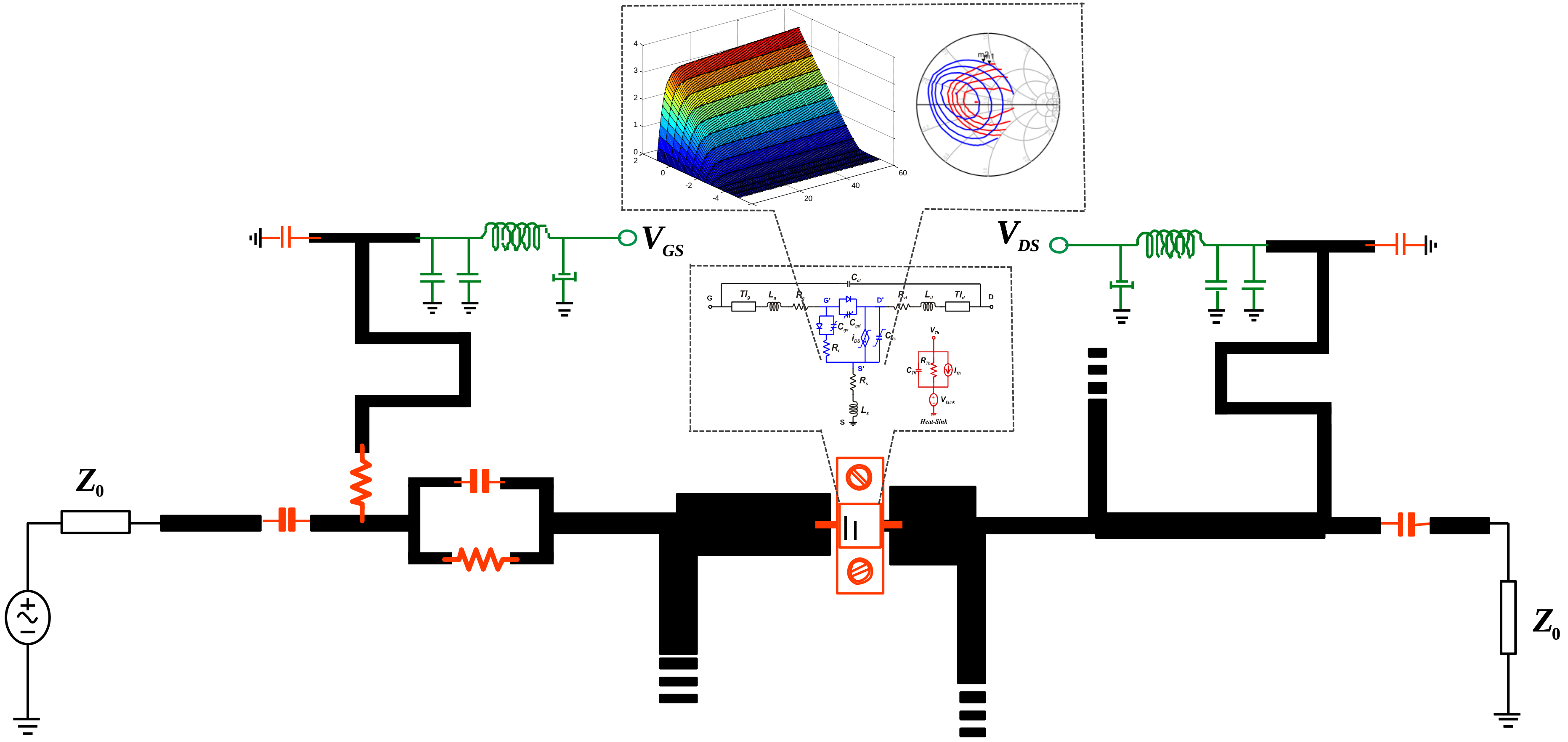
$$\mathbf{y}_k = f_k[\boldsymbol{X}_{-\boldsymbol{K}}, \dots, X_0, \dots, X_k]$$



1 – Introduction - Microwave CAD

Numerical Simulation of Nonlinear Microwave Circuits

Nowadays, nonlinear device models are the bottleneck of microwave circuit/system simulation accuracy.



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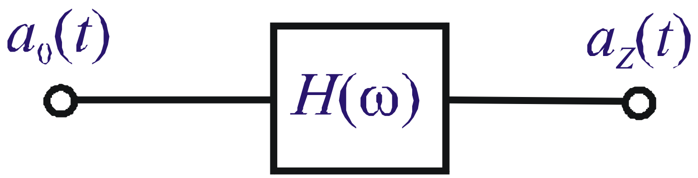
2 – Nonlinear Device Modeling Theory

Physical Modeling vs. Behavioral Modeling

$$\vec{\nabla}.\vec{D} = \rho \qquad \vec{\nabla}.\vec{B} = 0$$

$$\vec{\nabla}\mathrm{x}\vec{E} = -\frac{\partial \vec{B}}{\partial t} \qquad \vec{\nabla}\mathrm{x}\vec{H} = \vec{J} + \frac{\partial \vec{D}}{\partial t}$$

Physics-Based Model



Behavioral Model

Physics-Based Models can be deduced from the **internal structure** of the device and its **physical governing rules.**

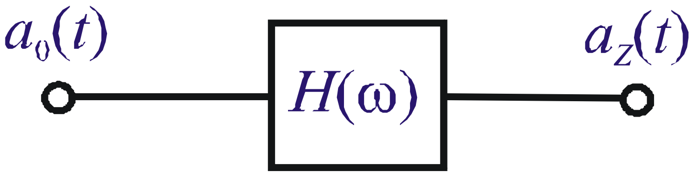
- ➔ Are necessarily approximate.
- ➔ (Ideally) do not need any measurement data.
- ➔ Poor representation capabilities but good predictive behavior.

Physical Modeling vs. Behavioral Modeling

On the other hand,

$$\vec{\nabla}.\vec{D} = \rho \qquad \vec{\nabla}.\vec{B} = 0$$

$$\vec{\nabla}\text{x}\vec{E} = -\frac{\partial \vec{B}}{\partial t} \qquad \vec{\nabla}\text{x}\vec{H} = \vec{J} + \frac{\partial \vec{D}}{\partial t}$$



Physics-Based Model

Behavioral Model

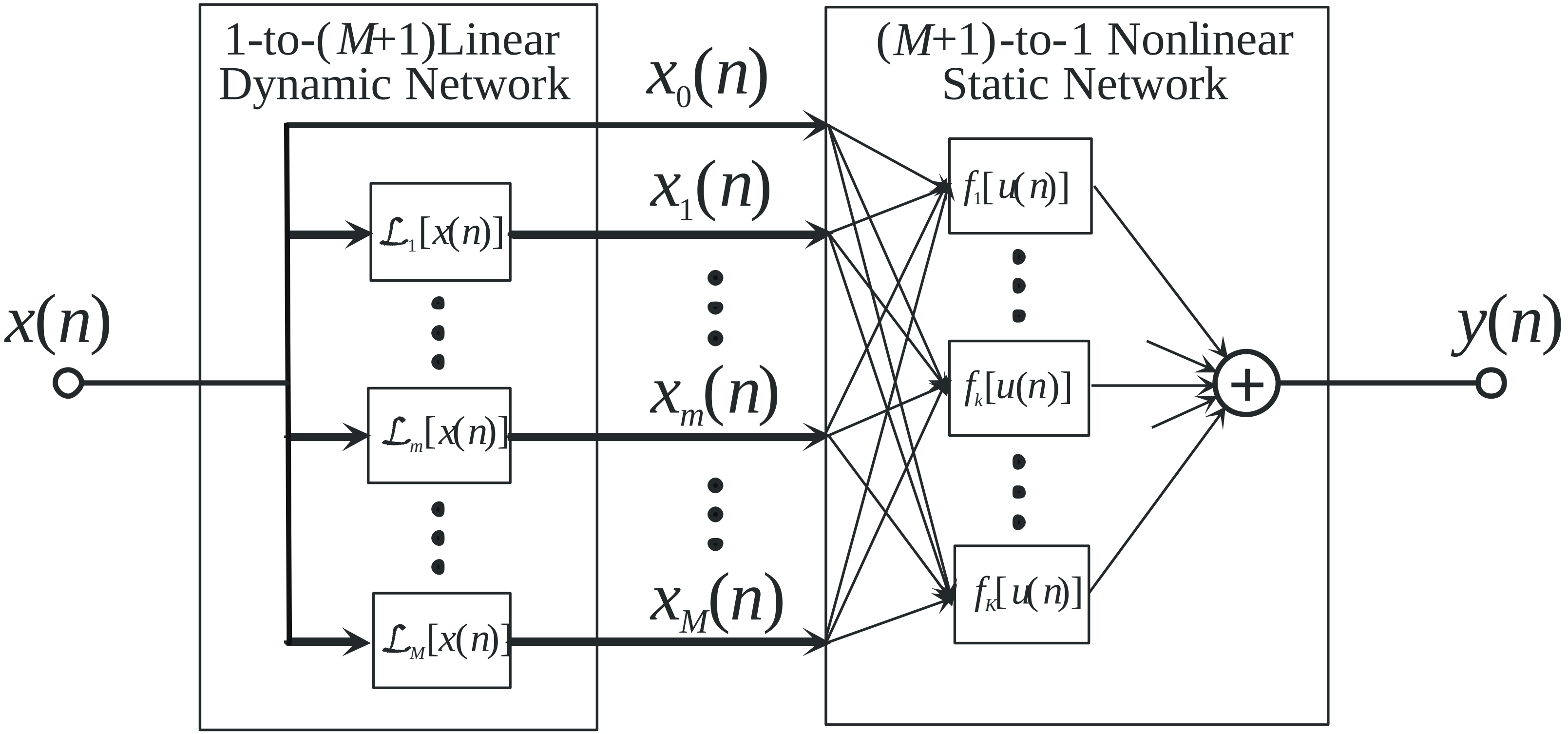
Behavioral Models are Empirical in nature

- Rely on input-output (**Behavioral**) observations,
- Need to compensate the lack of knowledge of device constitution (**Black-Box Models**) with measured data,
- Best in representing measured data - "The device knows best !"
- No predictive capability.

2 – Nonlinear Device Modeling Theory

The Canonical Wiener Model

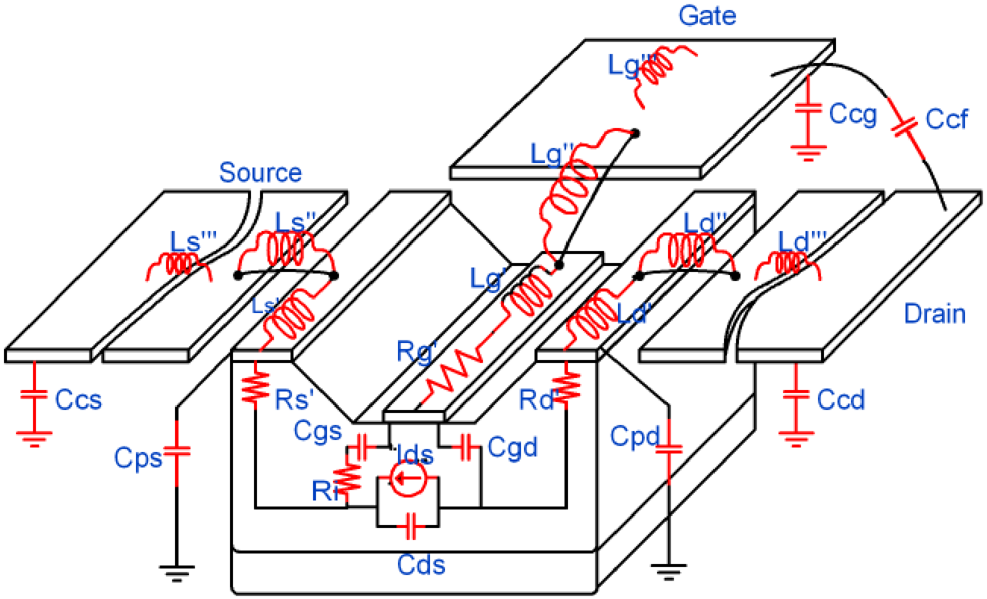
(Interpolated) Look-Up-Tables, Polynomials or ANNs (AI ?!?) are all special cases of a general formulation known as the Canonical Wiener Model (for feed-forward structures):

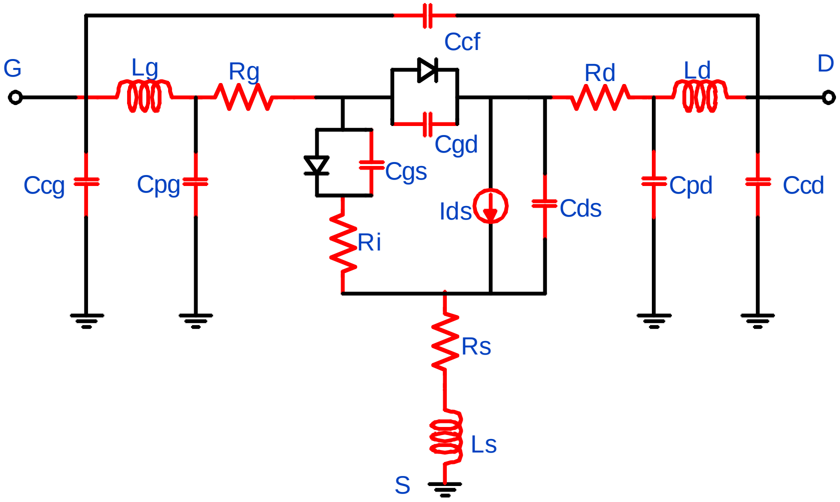


2 – Nonlinear Device Modeling Theory

Physical Modeling vs. Behavioral Modeling

Equivalent Circuit Models can be seen as Behavioral Models using a-priori Physics-Based Knowledge of the topology:





The best of the Two Worlds !

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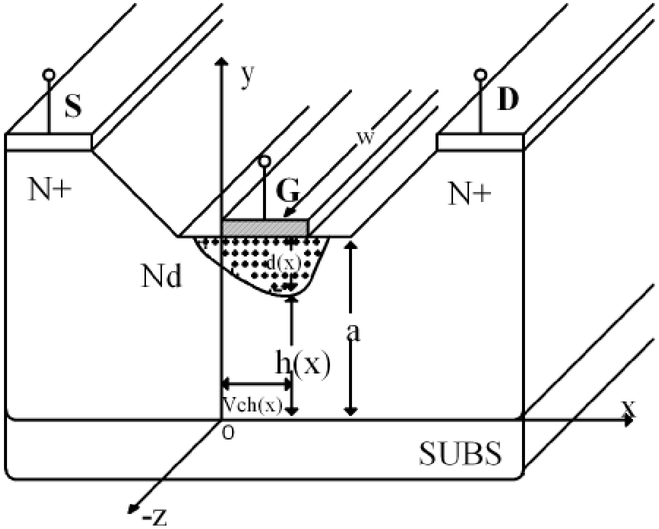
Drift-Diffusion Model and its Variables

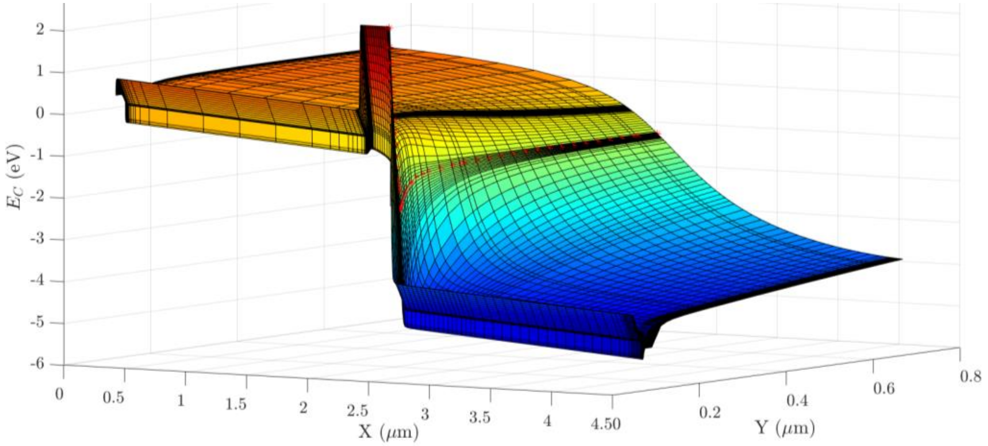
Physics-based models describe the device at its fundamental level using **Gauss's Law**,

$$\nabla . E = \frac{\rho}{\epsilon} \qquad \nabla^2\psi - \frac{q}{\epsilon}[N_d^+ - n]$$

… **Transport and Charge Conservation Laws**:

$$\underbrace{J = -q.n.\mu(E)\nabla\psi}_{\textit{drift}} + \underbrace{D_n\nabla n}_{\textit{diffusion}} \qquad \nabla . J = q\frac{\partial n}{\partial t}$$





A Much Simpler 1-D Drift Model

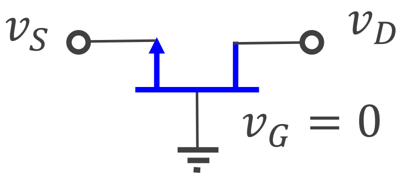
2-D TCAD model is too complex to be useful for equivalent-circuit model extraction. So, a much simpler 1-D model was developed:

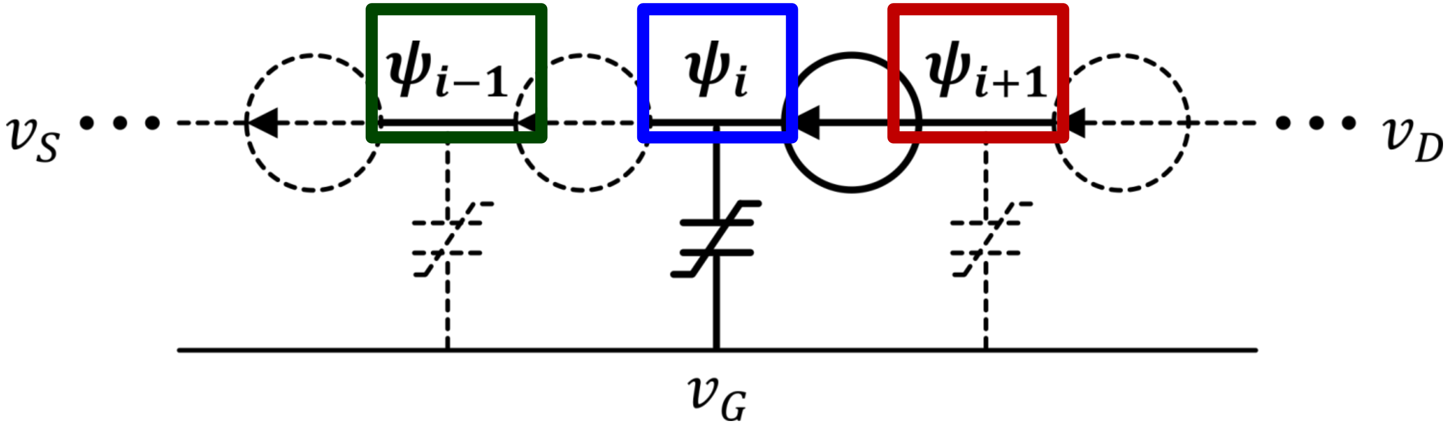
$$n_{s_i} = \frac{\epsilon}{q} \cdot V_{ST} \ln\left[1 + e^{\left(h\frac{\psi_{i+1}+\psi_{i-1}-2\psi_i}{\delta x^2} + \frac{v_G - V_T - \psi_i}{d_{AlGaN}}\right)/V_{ST}}\right]$$

$$i_{DS} = -qWn_s v\left(\frac{\psi_{i+1} - \psi_{i-1}}{2\delta x}\right)$$

and

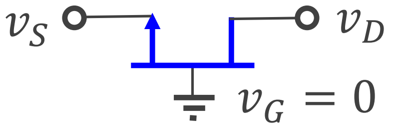
$$\frac{i_{i+1} - i_{i-1}}{2\delta x} = qW\frac{dn_s}{dt}$$

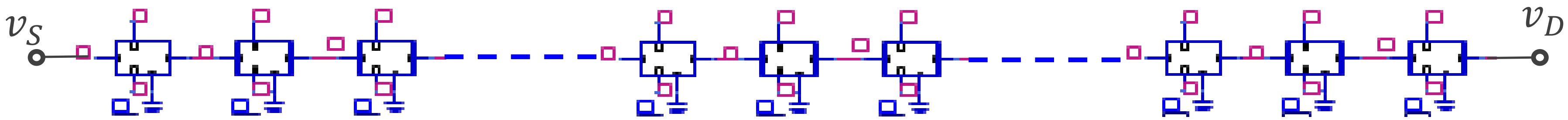


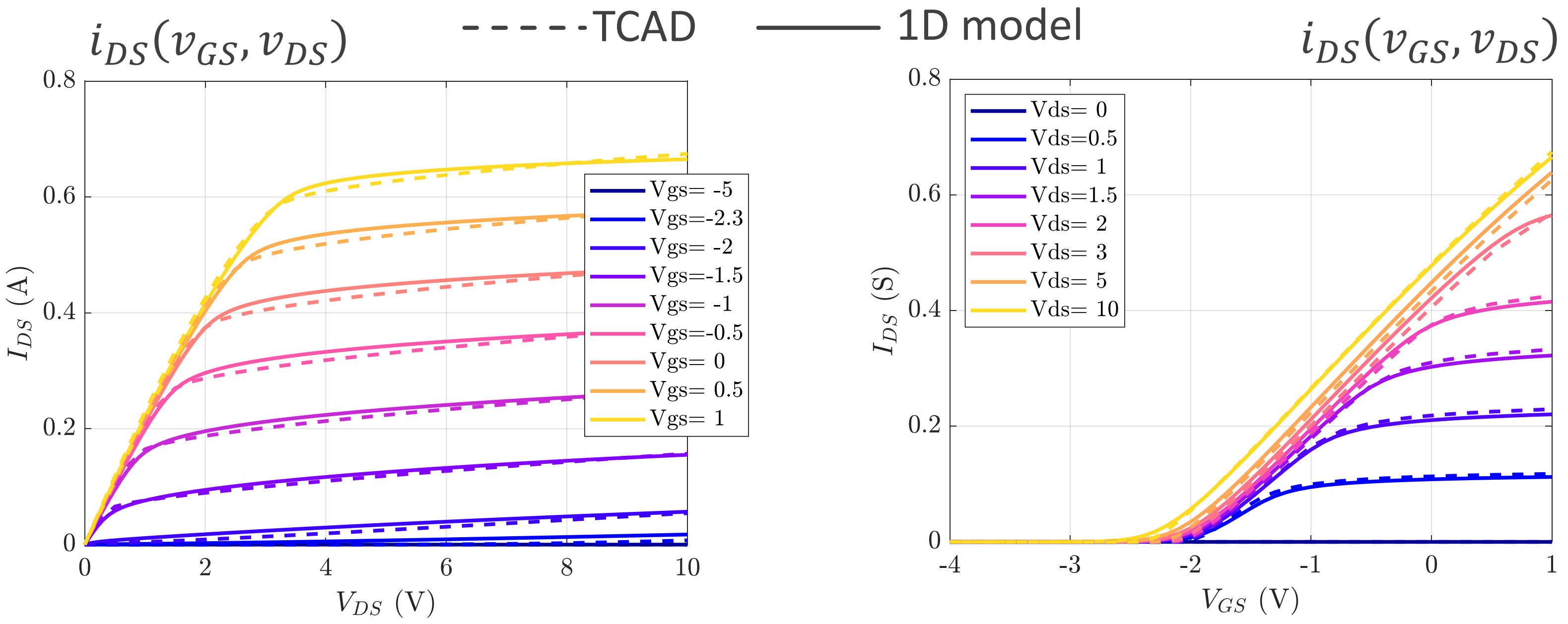


A Much Simpler 1-D Drift Model

Actually, this 1-D model allowed to separate GaN HEMT “intrinsic” characteristics from the access regions we were willing to study.







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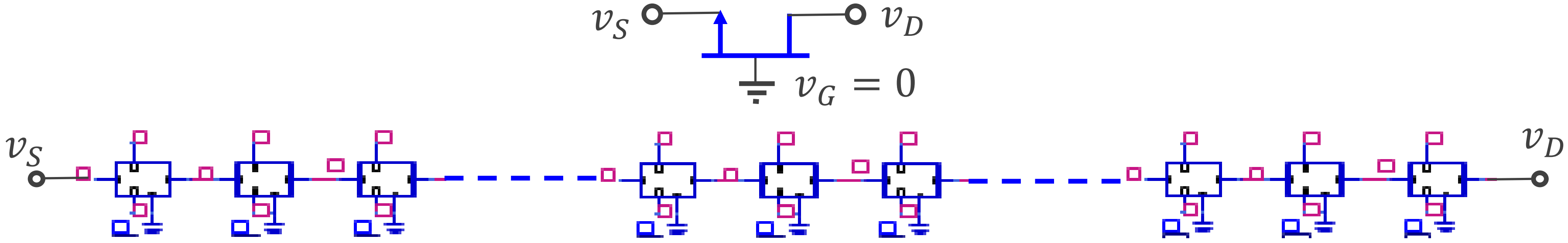

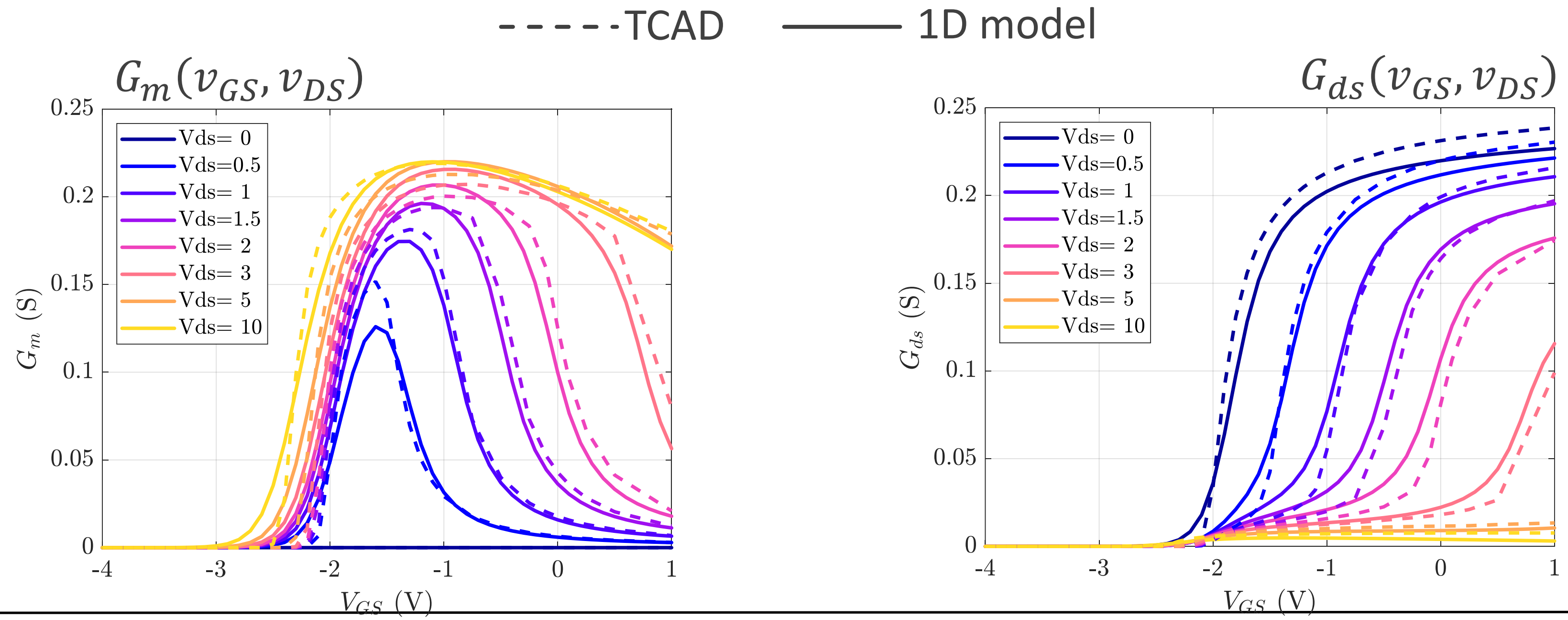

3 – Physics-Based Modeling of μWave Devices

A Much Simpler 1-D Drift Model

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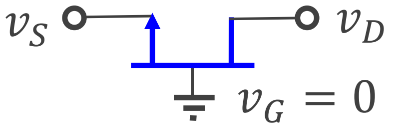
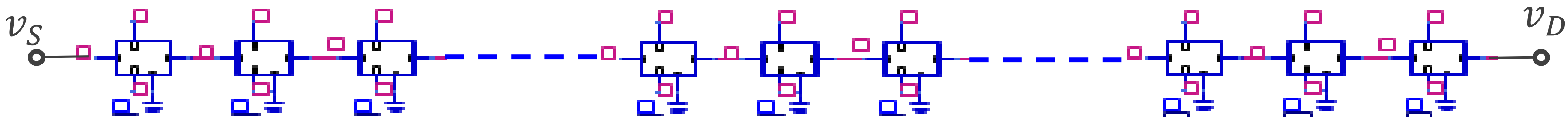
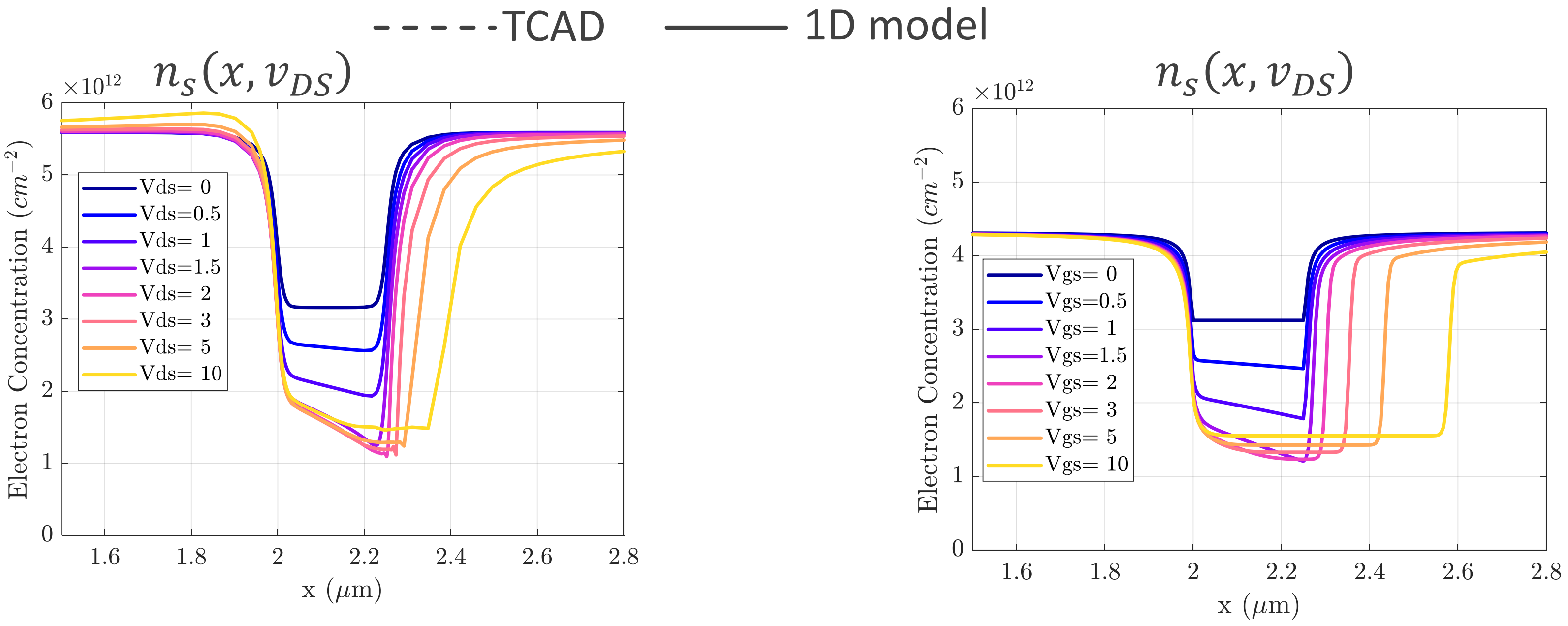
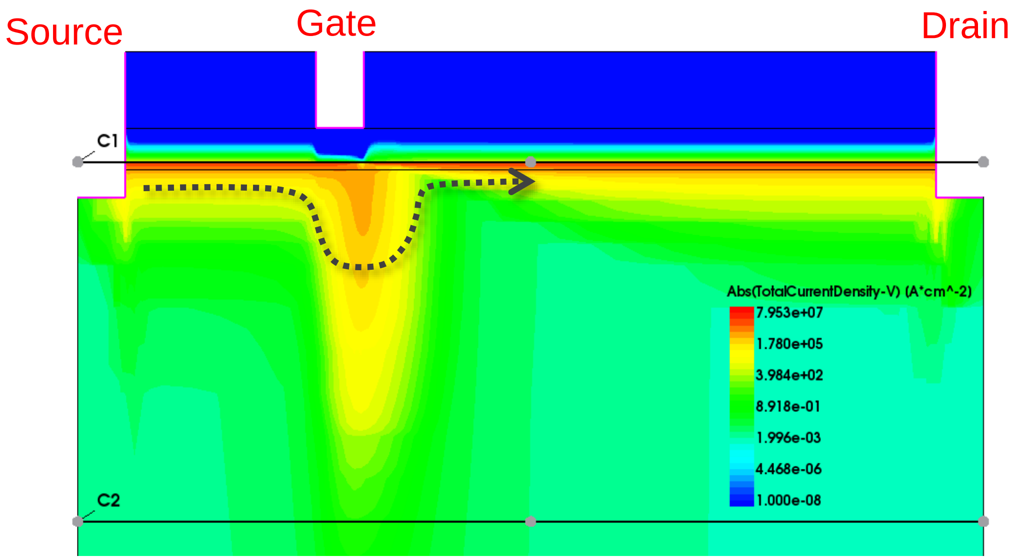


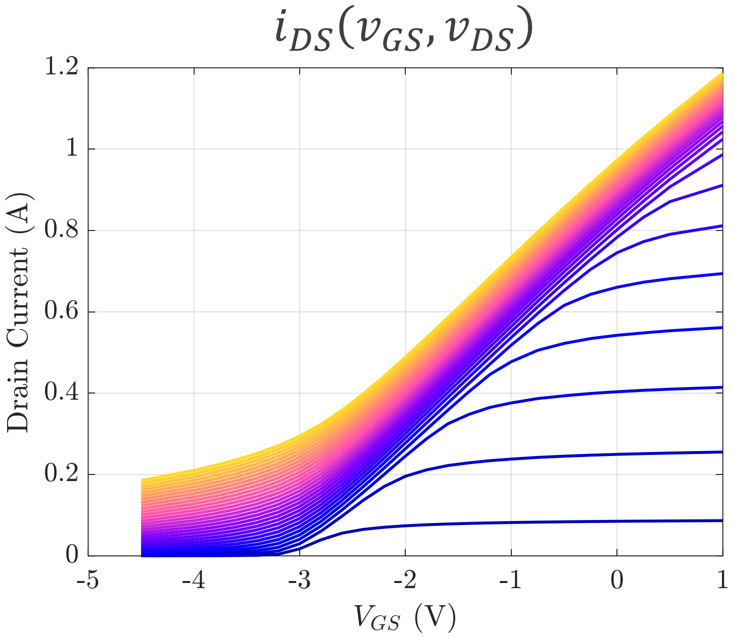




2-D TCAD Model for Studying Trapping Effects

The full 2-D TCAD model has been used to study the origins of non-quasi-static behavior due to buffer current and trapping effects:



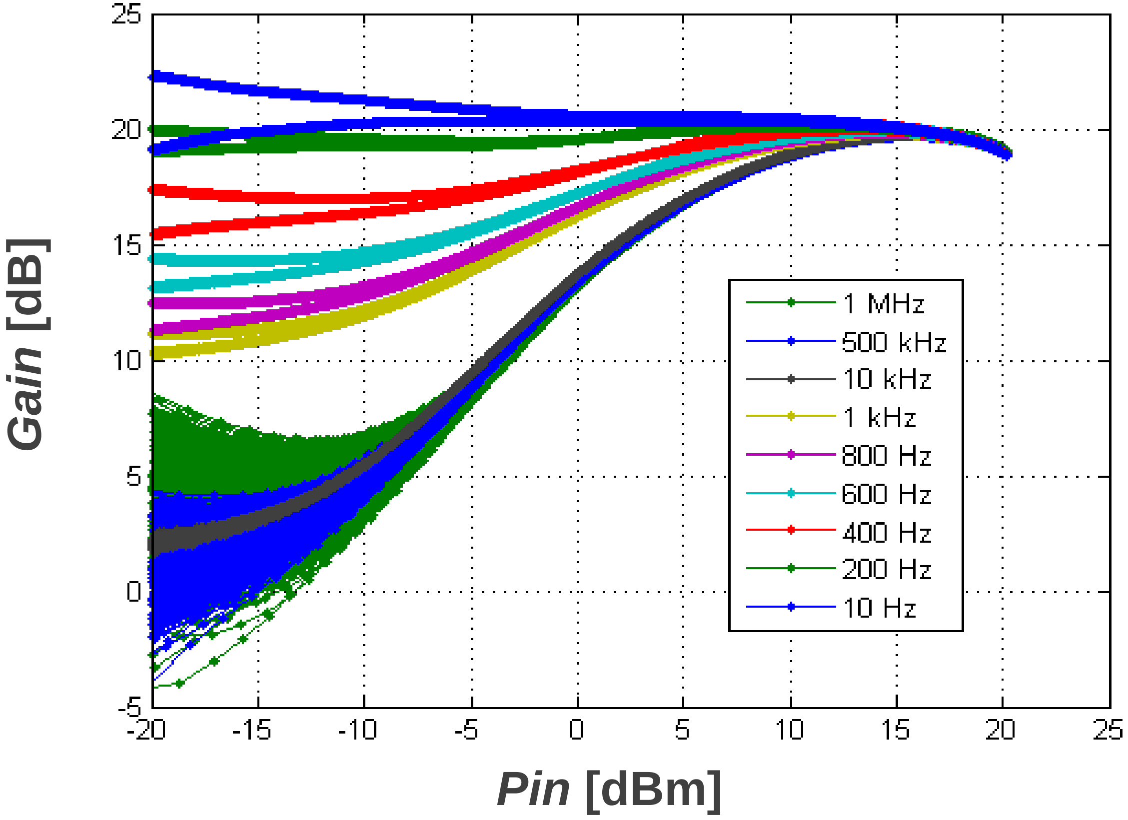


Without buffer traps, an AlGaN/GaN HEMT could not cutoff.

3 – Physics-Based Modeling of μWave Devices

2-D TCAD Model for Studying Trapping Effects

These were known for a long time as trap-induced memory effects of PAs or transistor self-biasing:



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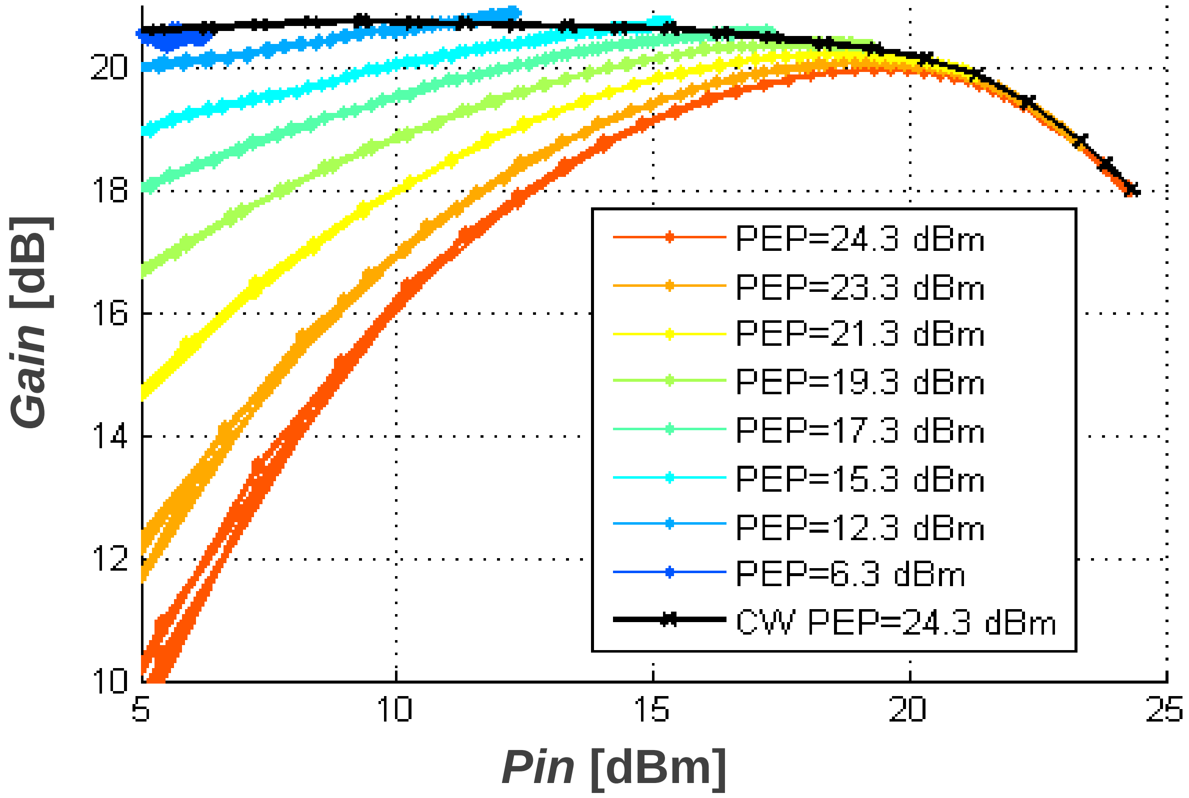
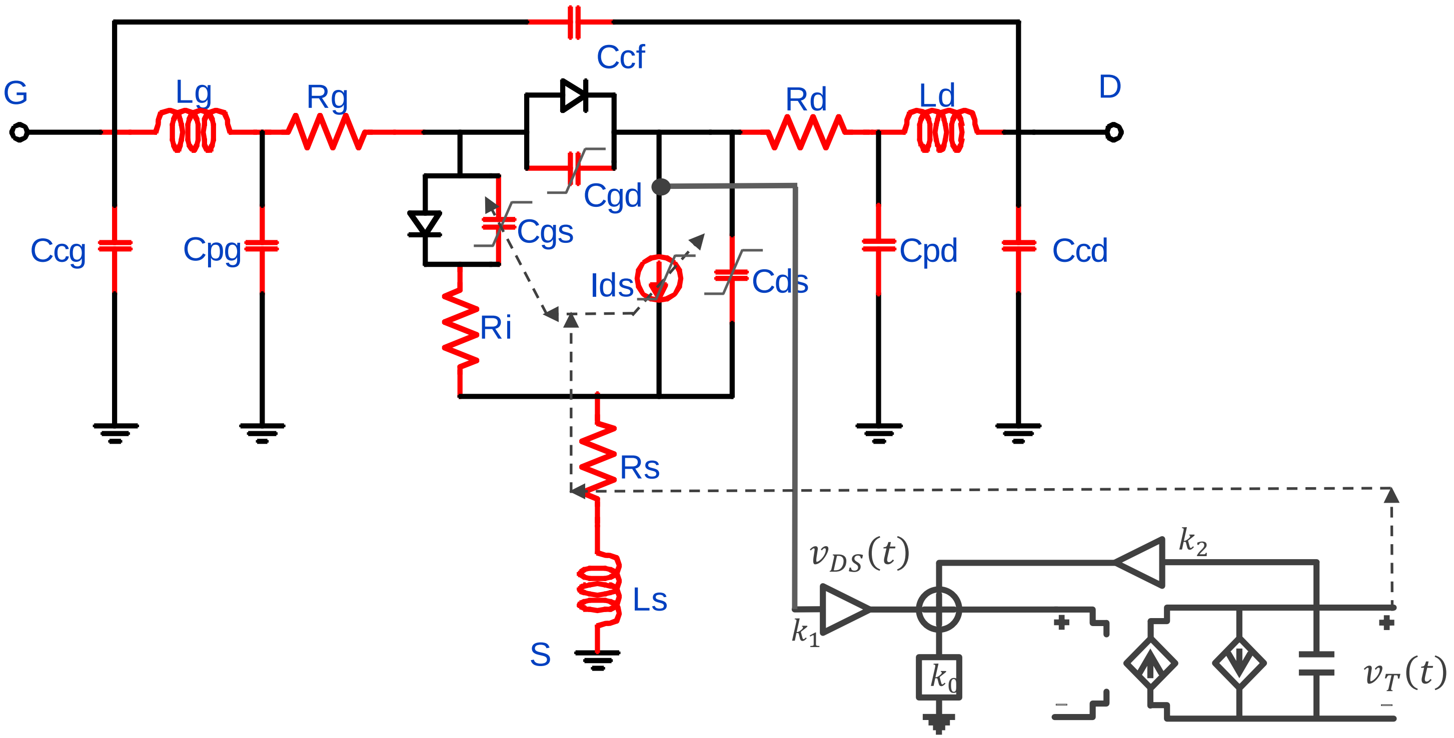


2-D TCAD Model for Studying Trapping Effects

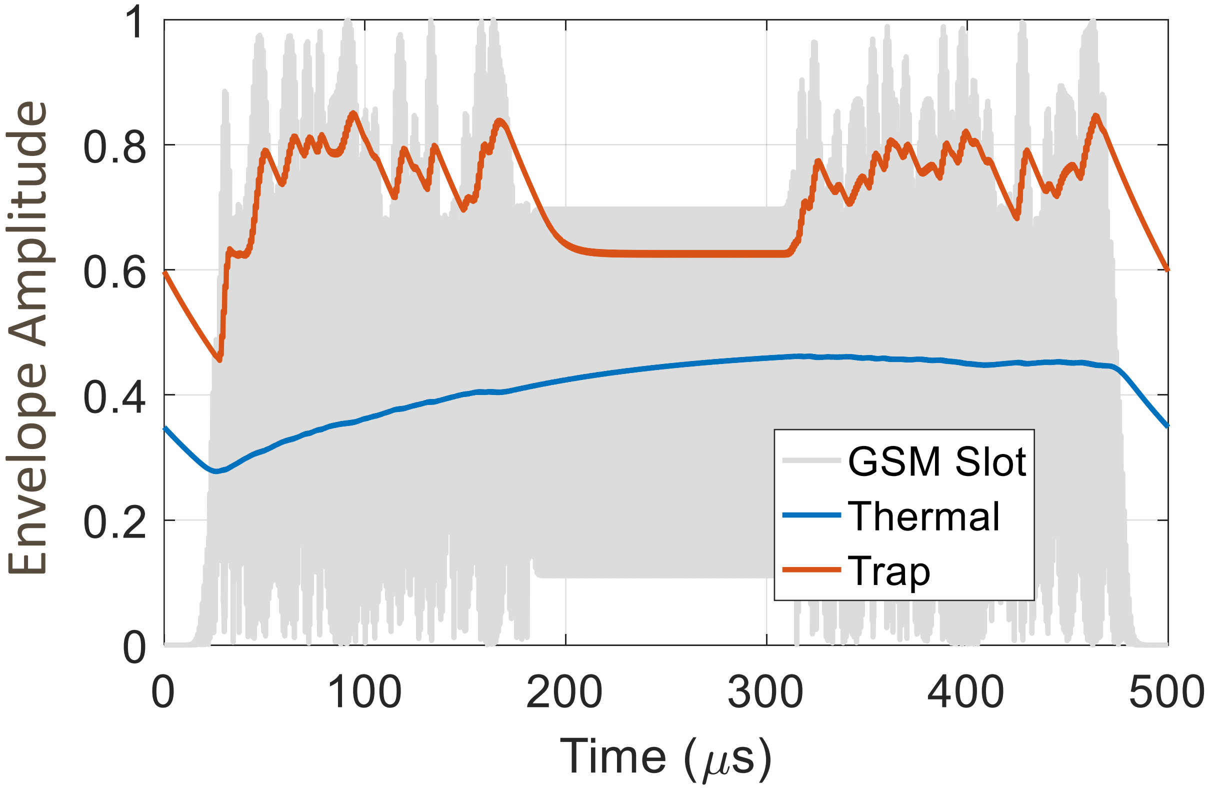
The inclusion of trapping in our 1-D model allowed us to propose the desired physically inspired equivalent circuit-model of a AlGaN/GaN HEMT for trapping effects ...



3 – Physics-Based Modeling of μWave Devices

2-D TCAD Model for Studying Trapping Effects

… and thus predict trap-induced memory effects of a PA under real modulated signals:



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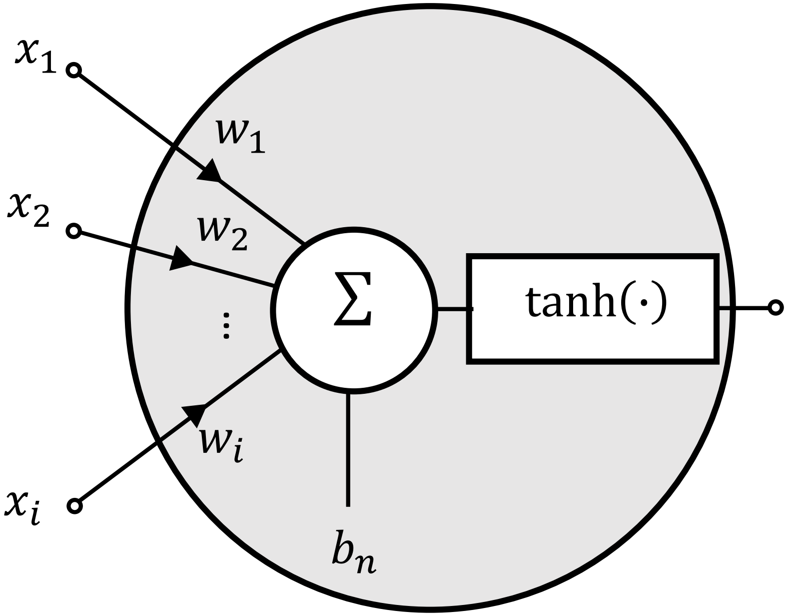
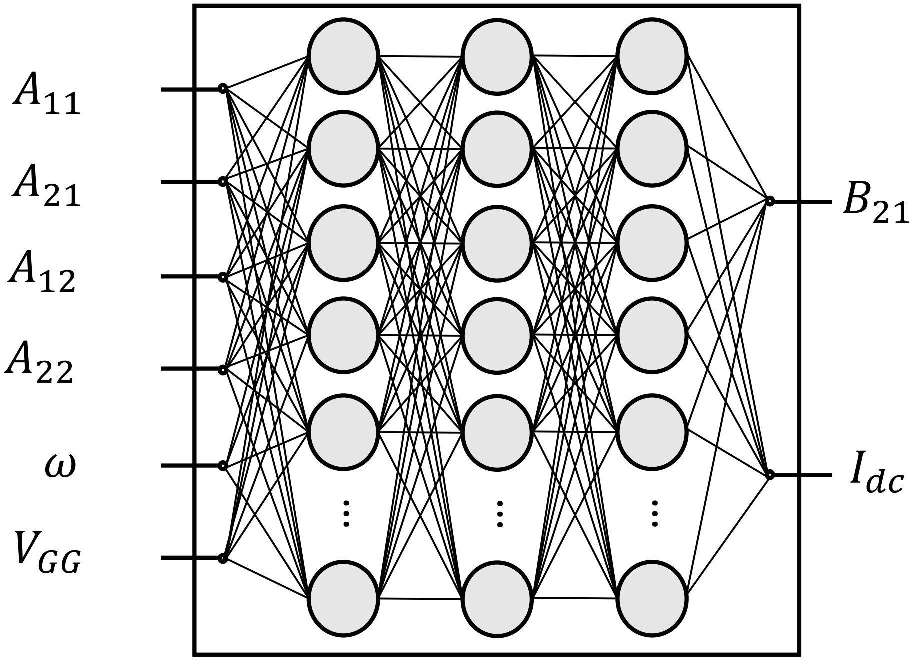
A Neural Network F-D Behavioral Model for PA Design

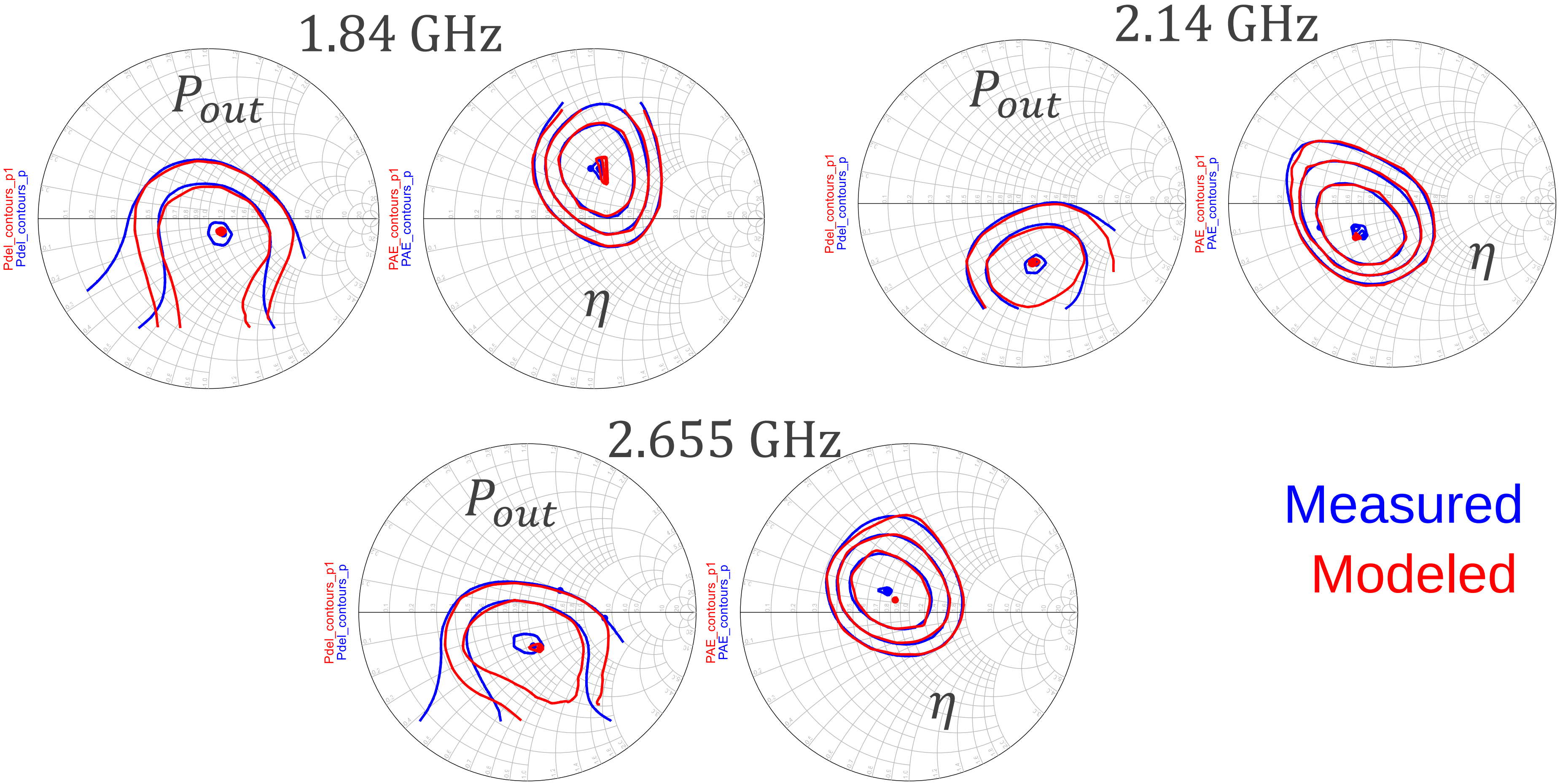
Having no equivalent-circuit model for large packaged devices, we implemented an ANN model capable of representing the load-pull, AM/AM and AM/PM and I_{dc} of a GaN HEMT, the essential device information for PA design.





A Neural Network F-D Behavioral Model for PA Design

The obtained fit to the measured load-pull with the proposed LPM is remarkably good:



A Neural Network F-D Behavioral Model for PA Design

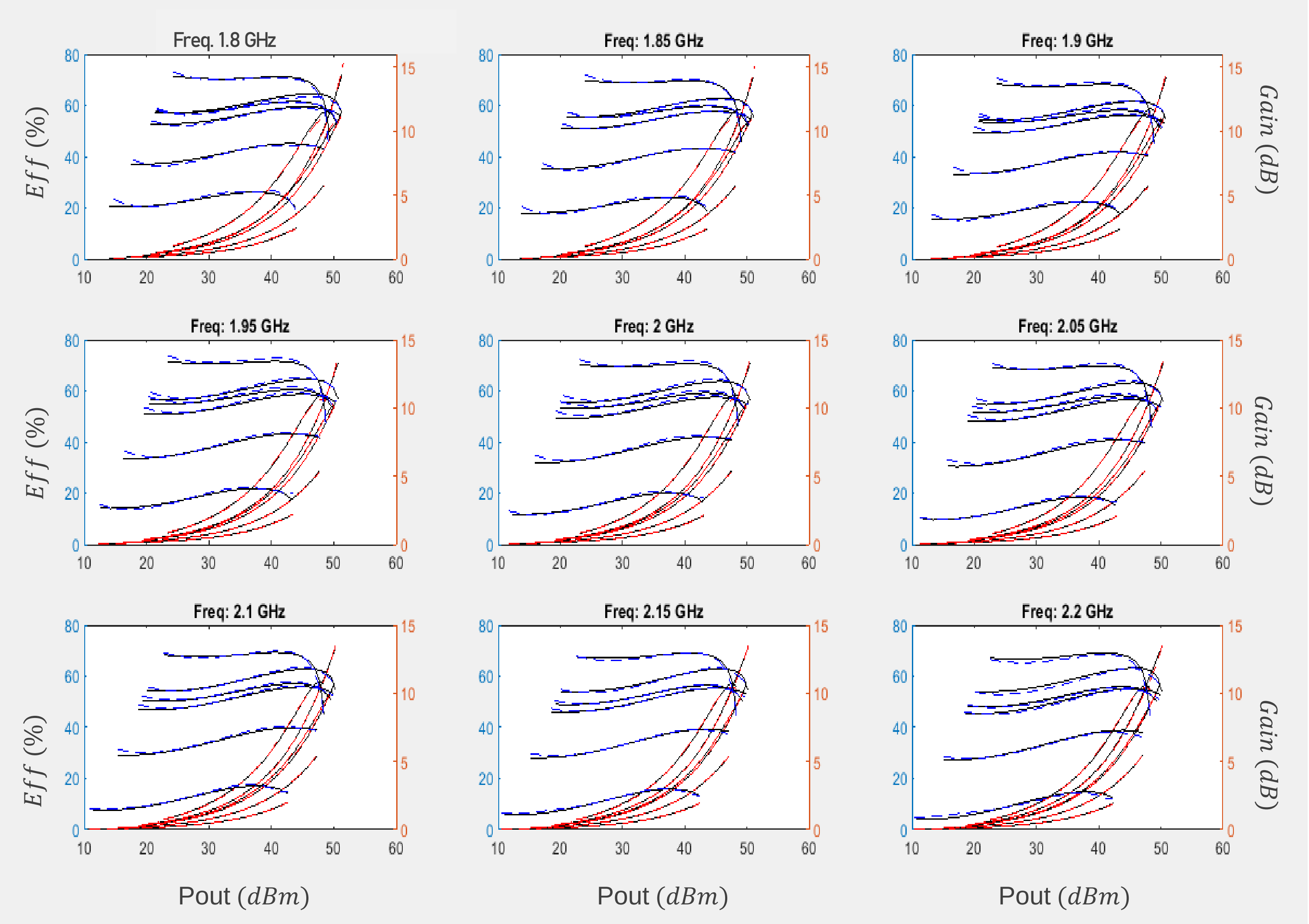
Results for a F-D Neural Network extracted with:

7 P_{av}

15 Γ_L

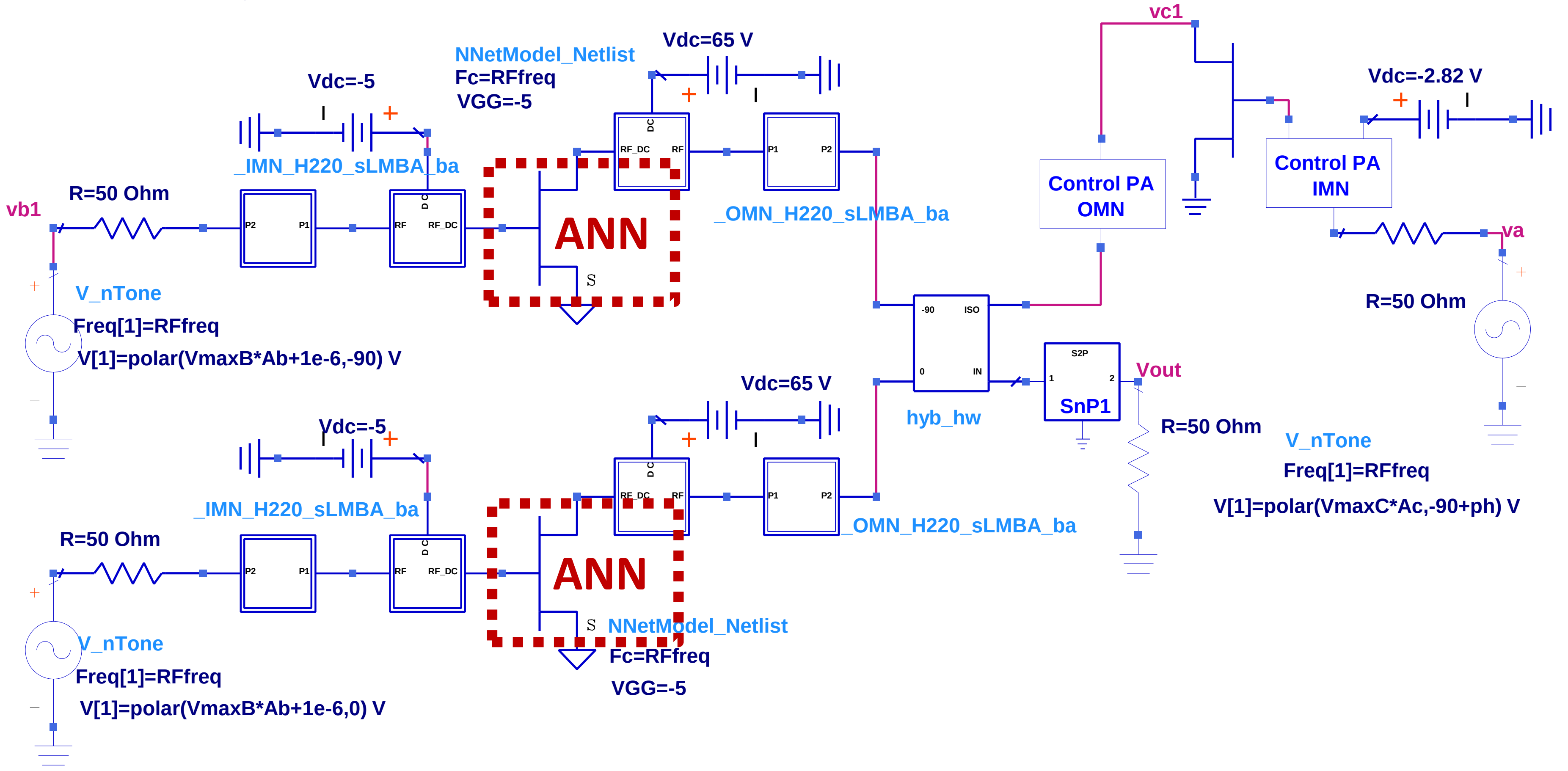
3 frequencies:

[1.8 2.0 2.2] GHz



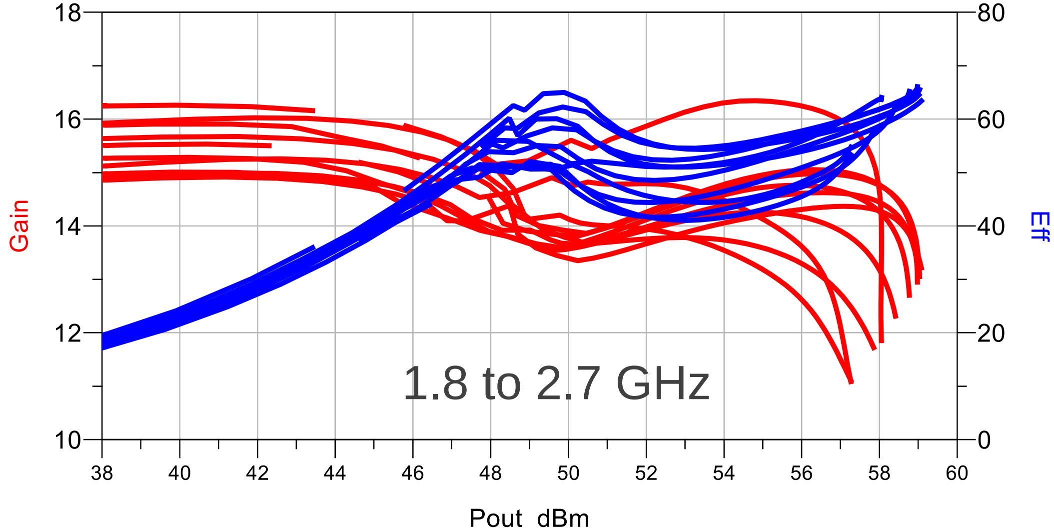
A Neural Network F-D Behavioral Model for PA Design

F-D ANN model was used for designing the Balanced PAs of a SMLBA via nonlinear optimization:



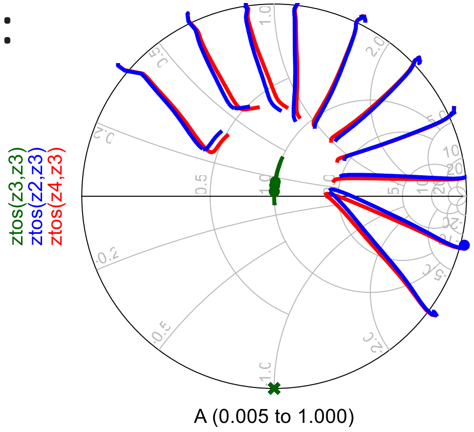
A Neural Network F-D Behavioral Model for PA Design

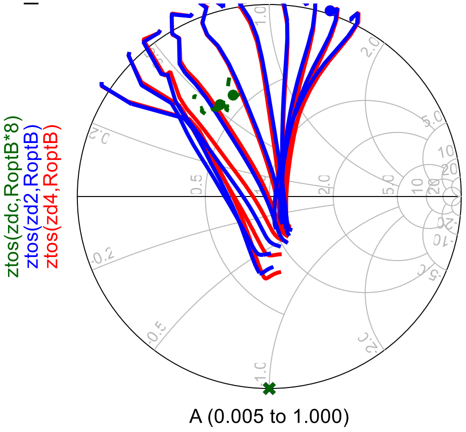
Efficiency and Gain versus Output Power simulation results across 40% relative bandwidth:



Device load-puling:

Hybrid Reference Plane





Device Reference Plane

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5 – Summary

1 – Nowadays, most RF/microwave designs rely on computer simulators, for which accurate nonlinear models are needed.

2 – For most usual cases, the bottleneck of microwave nonlinear simulators' accuracy is in their device models.

3 – There are time-domain and frequency-domain models as well as physics-based, measurement-based, or equivalent-circuit models.

4 – Equivalent circuit-models have been the standard for circuit simulation, but TCAD models and much simpler behavioral models are also playing a role in nonlinear microwave simulation.