SAND2013-0104C

Predicting EMP and HPM Electronic Circuit Effects using an Active Thevenin Equivalent Network Approach (ATHENA)

Larry D. Bacon, Jeffery T. Williams,
C. David Turner, Michael J. Walker
and Erik C. Zeek

Sandia National Laboratories
Albuquerque, NM

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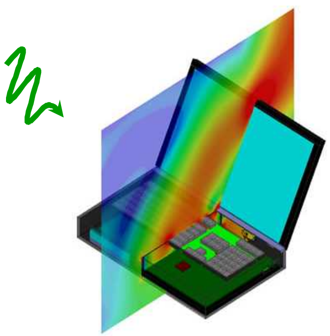
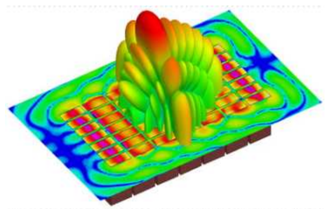
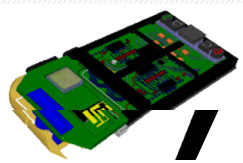
EMP/HPM Effects Process

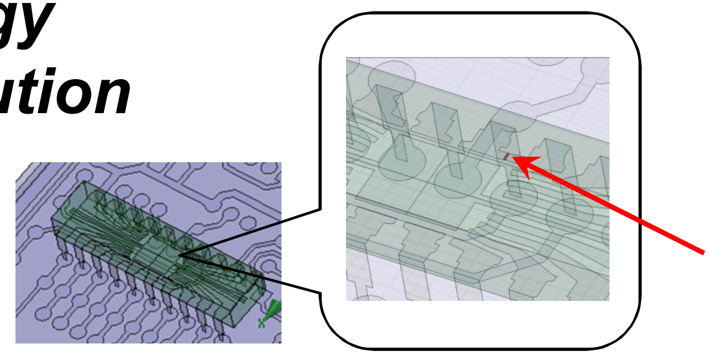
Coupling



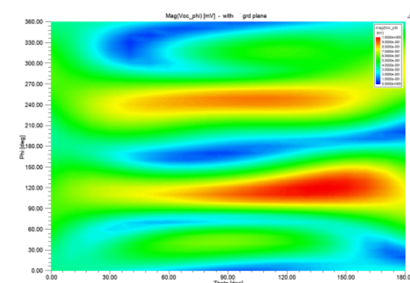
Energy Distribution



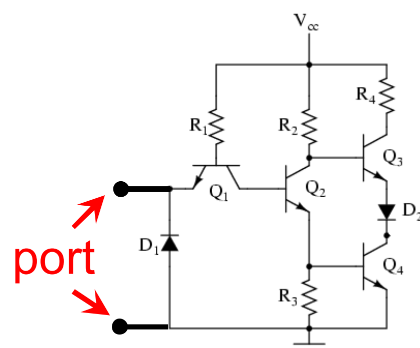


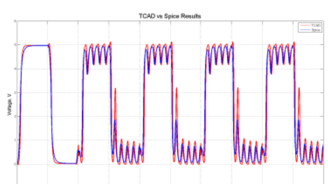


Device Response

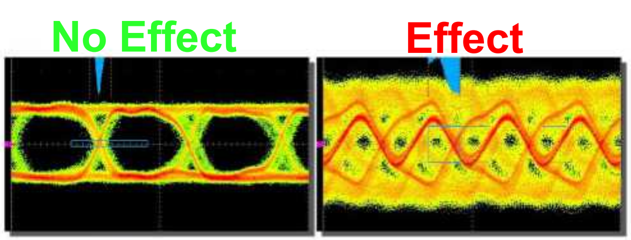


$Z_{11}^{w} = 3.13 - j9.16\ \Omega$





System Impact



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Computing EMP/HPM Effects

Mechanisms:

Radiated — Radiated/Conducted — Conducted/ Parasitics — State Dependencies

Coupling ↔ Energy Distribution ↔ Device Response ↔ System Impact

← linear → ← non-linear →

Computational Tools:

← EM Codes → ← TCAD/Spice (Xyce) ← Spice/Mixed Signal

We need an efficient and accurate approach for linking these different computations together in a self-consistent manner.

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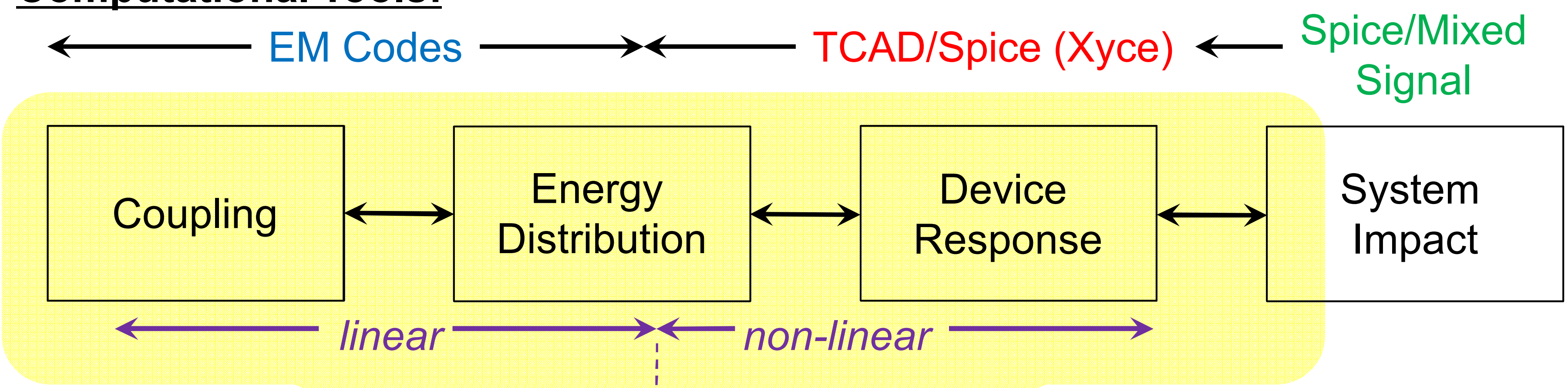
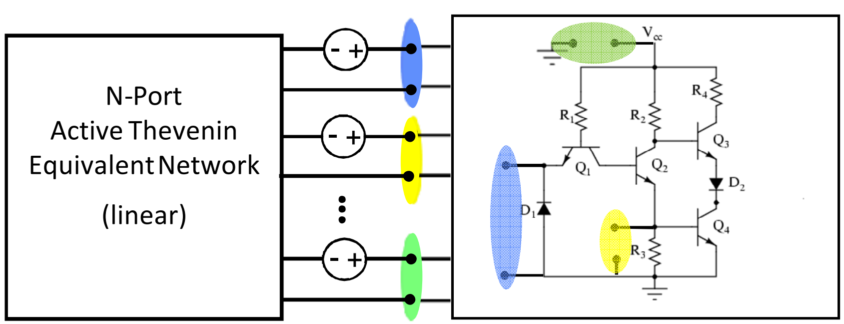
Our Approach: ATHENA

Computational Tools:



ATHENA

Active THevenin Equivalent Network Approach

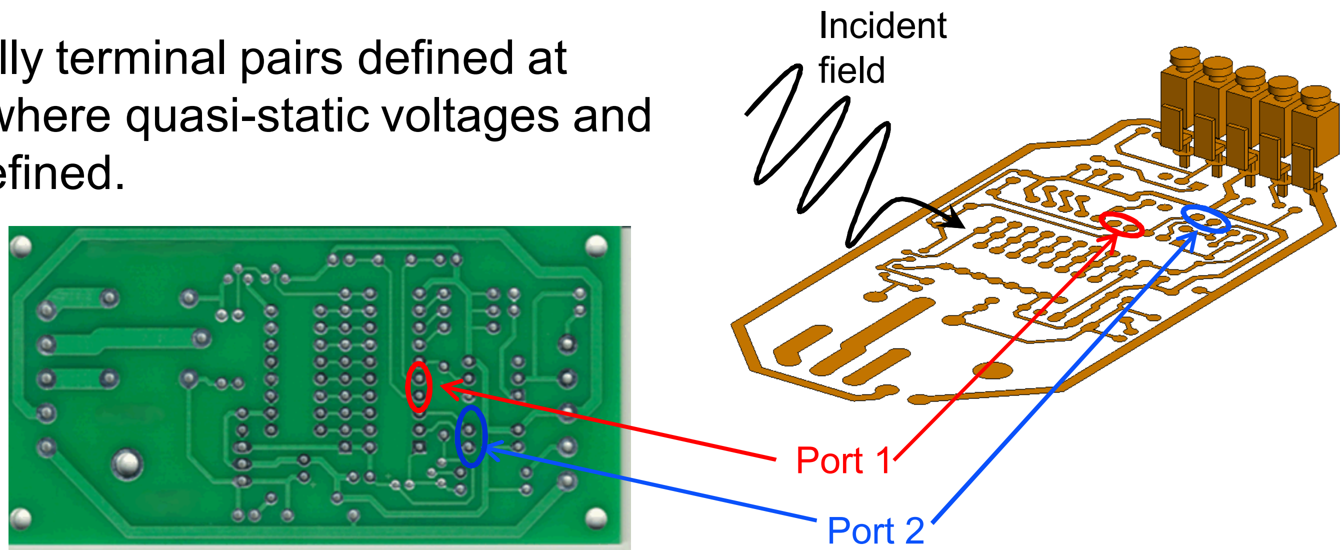


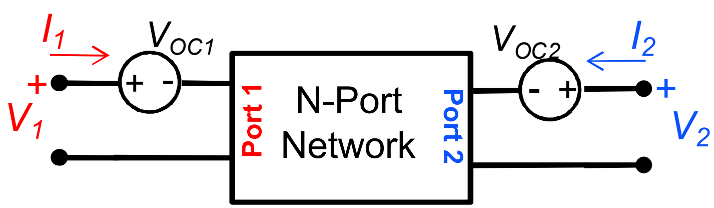
Circuit for demonstration only

Active Thevenin Equivalent Network

Ports are essentially terminal pairs defined at reference planes where quasi-static voltages and currents can be defined.

2-Port Example





Need to determine the *open-circuit voltage* and the *short-circuit currents* at the ports.

Active Thevenin Equivalent Network = "ATHENA device"

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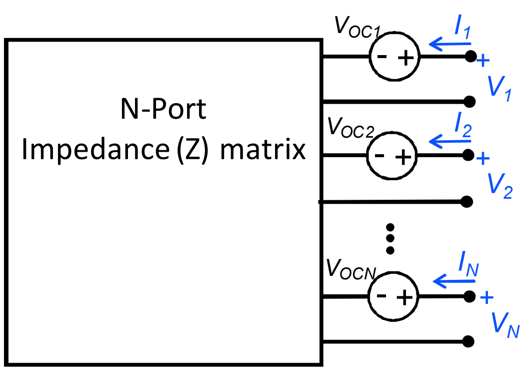
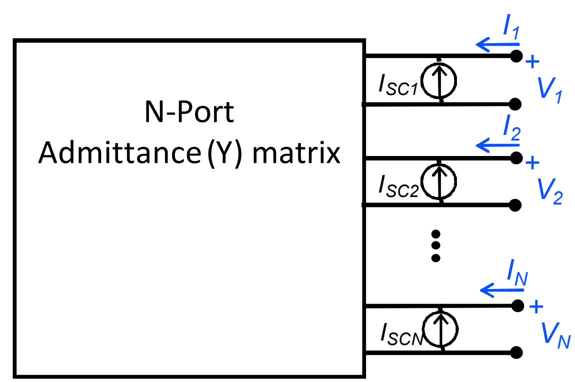
Implementation of ATHENA

- The parameters of the ATHENA device can be computed or measured in the frequency or time domains.
- To link with non-linear loads, the time domain representation of the ATHENA device must be used.



$$\begin{bmatrix} v_1(t) - \sum_{l=1}^{N} \tilde{z}_{1l}(0) i_l(t) \\ v_2(t) - \sum_{l=1}^{N} \tilde{z}_{2l}(0) i_l(t) \\ \vdots \\ v_N(t) - \sum_{l=1}^{N} \tilde{z}_{Nl}(0) i_l(t) \end{bmatrix} = \begin{bmatrix} \sum_{l=1}^{N} \int_0^{t^-} z_{1l}(t-\tau) i_l[v_l(\tau)] d\tau \\ \sum_{l=1}^{N} \int_0^{t^-} z_{2l}(t-\tau) i_l[v_l(\tau)] d\tau \\ \vdots \\ \sum_{l=1}^{N} \int_0^{t^-} z_{Nl}(t-\tau) i_l[v_l(\tau)] d\tau \end{bmatrix} - \begin{bmatrix} v_1^{OC}(t) \\ v_2^{OC}(t) \\ \vdots \\ v_N^{OC}(t) \end{bmatrix}$$



$$\begin{bmatrix} i_1(t) - \sum_{l=1}^{N} \tilde{y}_{1l}(0) v_l(t) \\ i_2(t) - \sum_{l=1}^{N} \tilde{y}_{2l}(0) v_l(t) \\ \vdots \\ i_N(t) - \sum_{l=1}^{N} \tilde{y}_{Nl}(0) v_l(t) \end{bmatrix} = \begin{bmatrix} \sum_{l=1}^{N} \int_0^{t^-} y_{1l}(t-\tau) v_l[i_l(\tau)] d\tau \\ \sum_{l=1}^{N} \int_0^{t^-} y_{2l}(t-\tau) v_l[i_l(\tau)] d\tau \\ \vdots \\ \sum_{l=1}^{N} \int_0^{t^-} y_{Nl}(t-\tau) v_l[i_l(\tau)] d\tau \end{bmatrix} - \begin{bmatrix} i_1^{SC}(t) \\ i_2^{SC}(t) \\ \vdots \\ i_N^{SC}(t) \end{bmatrix}$$

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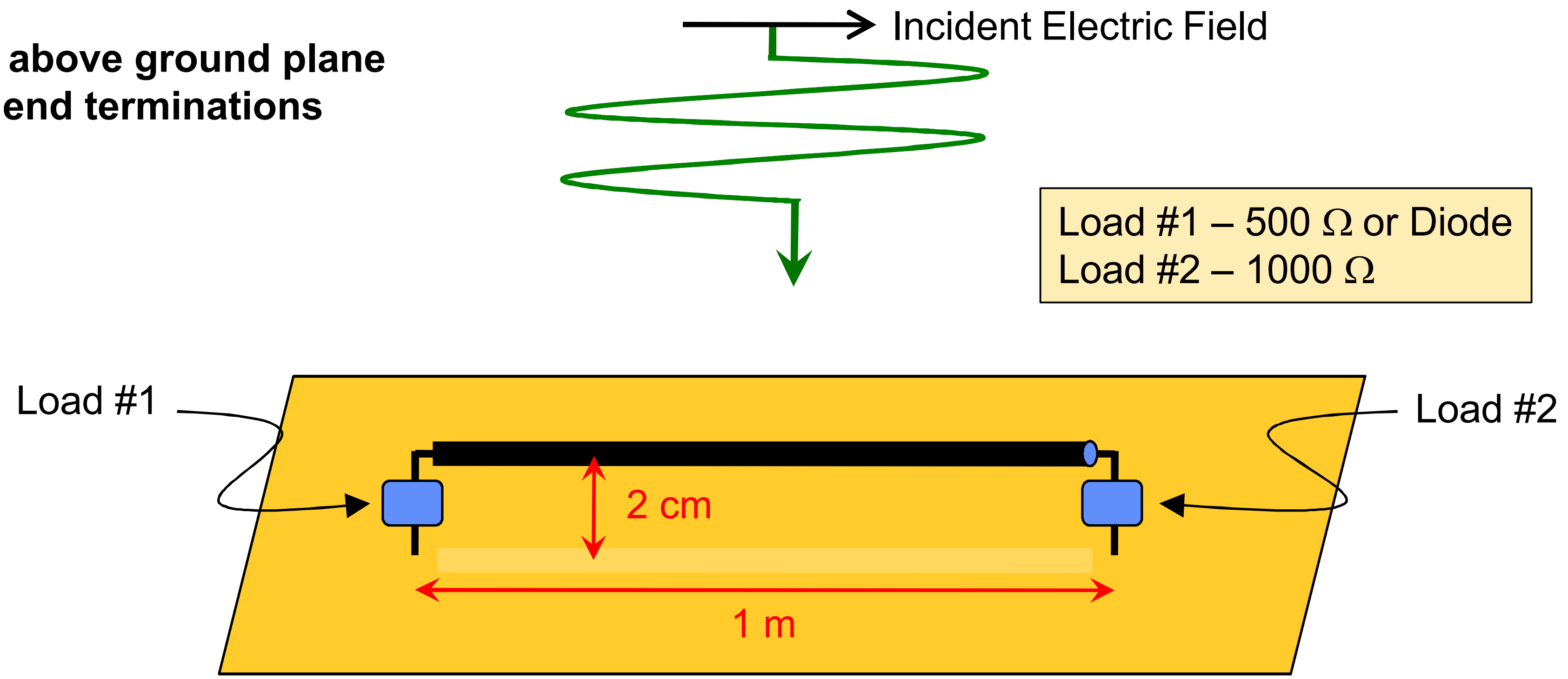
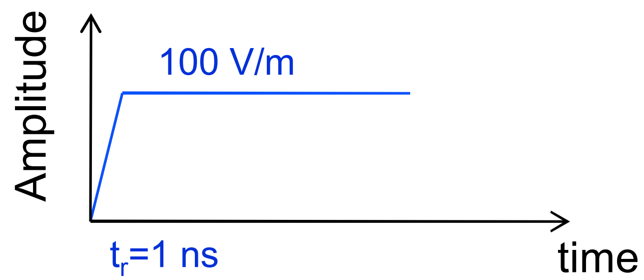
Example Problem Geometry (Intentionally Simple!)

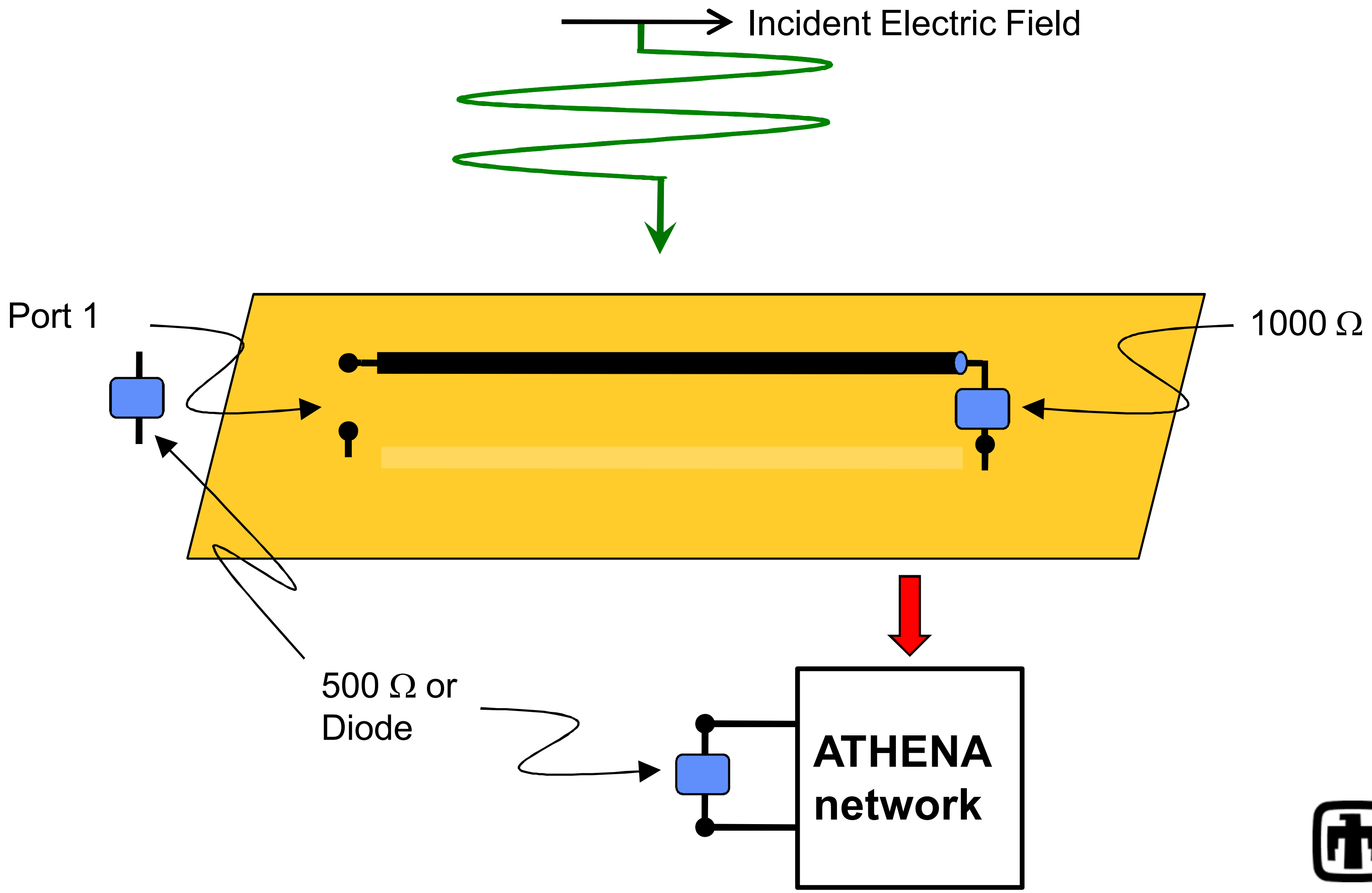
Wire above ground plane with end terminations



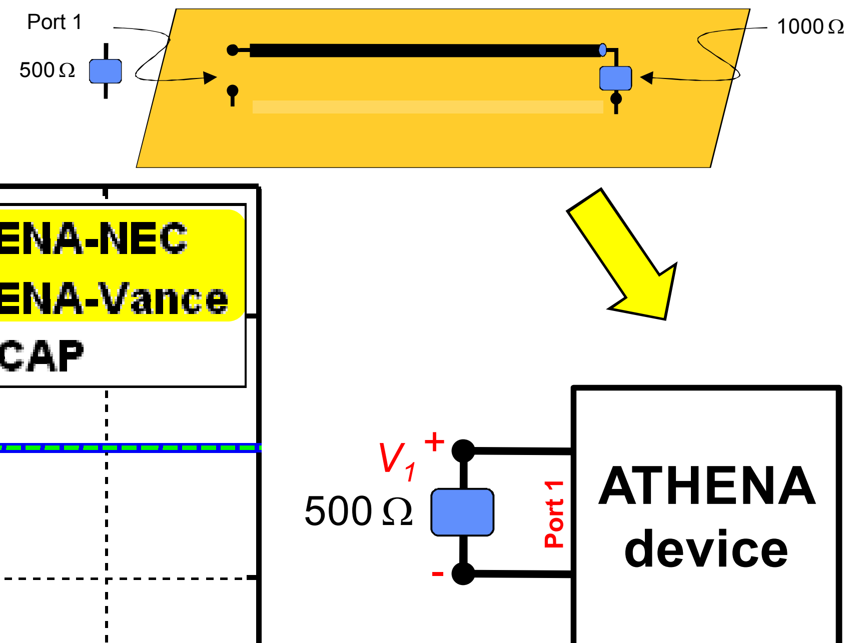


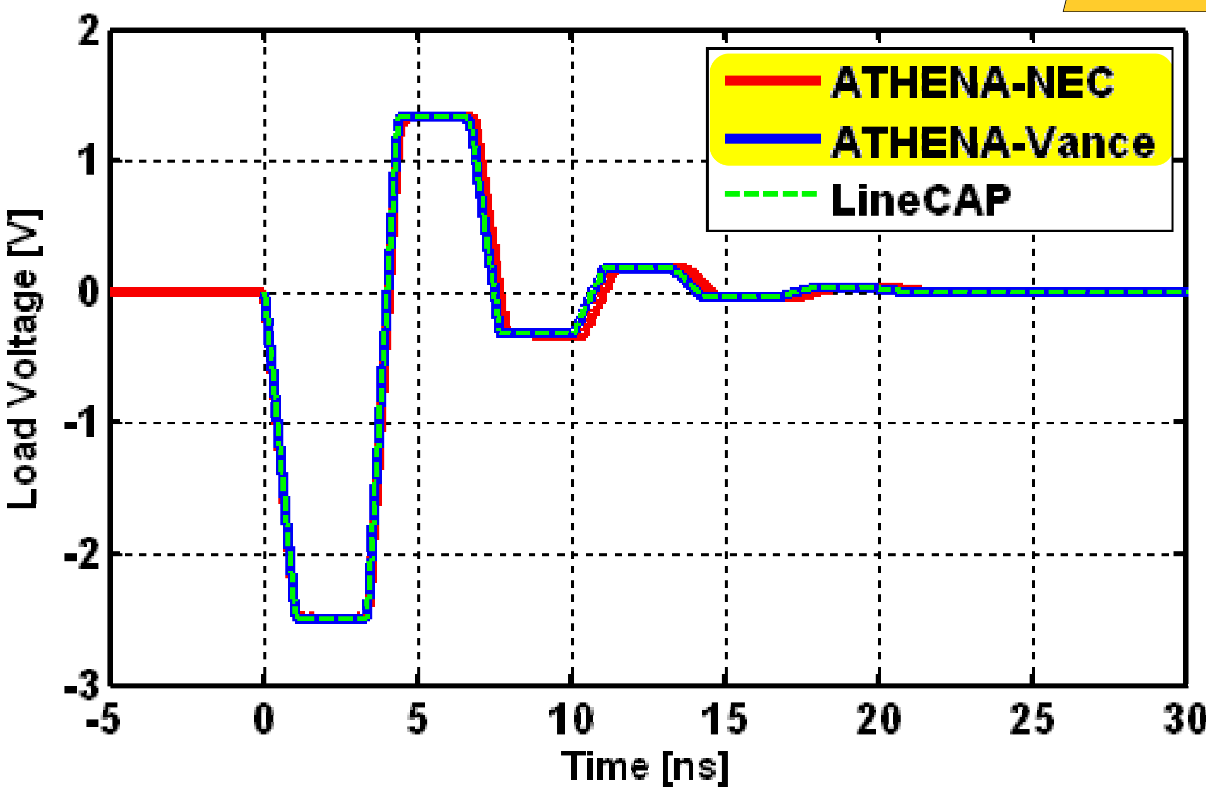
Not to scale

Example: 1-Port Network



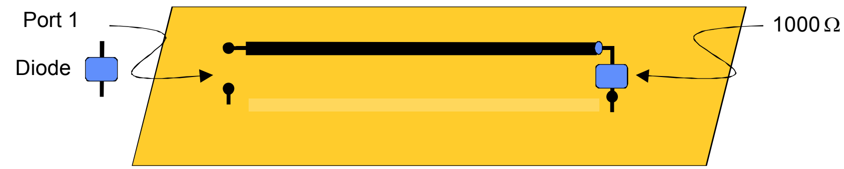
1-Port : Linear Load (500 Ω)

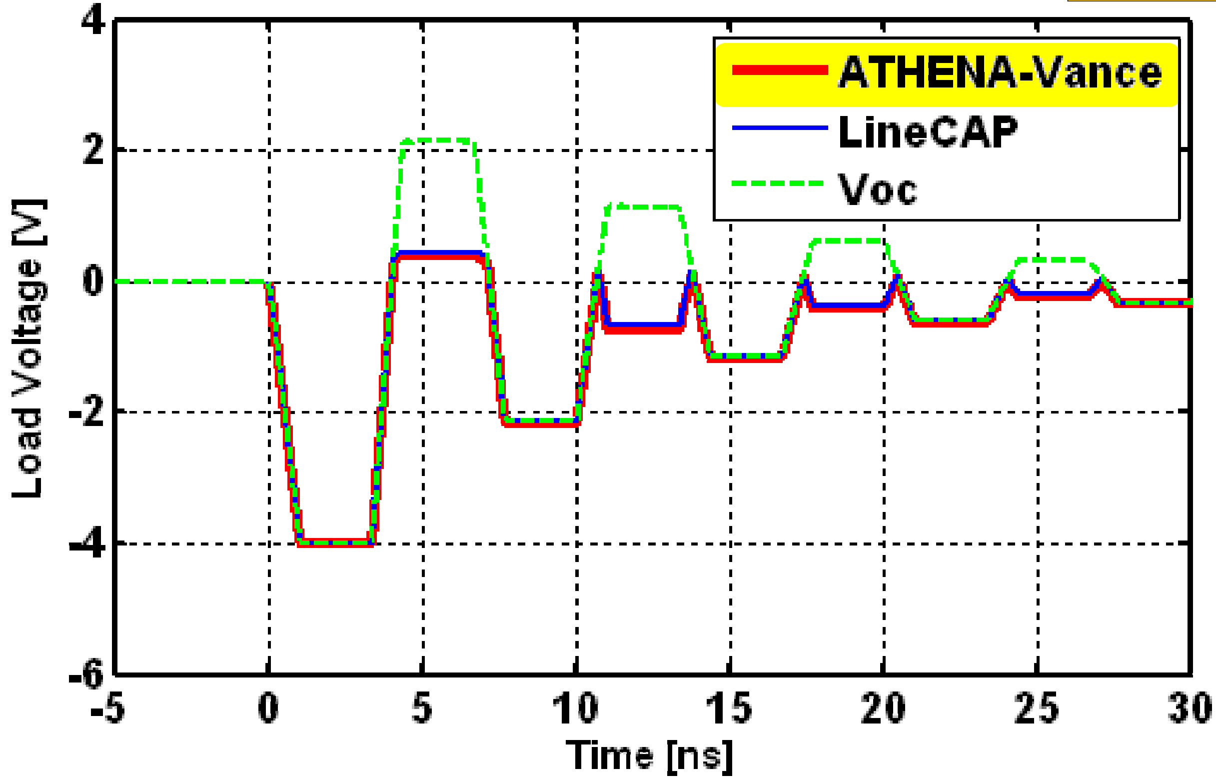


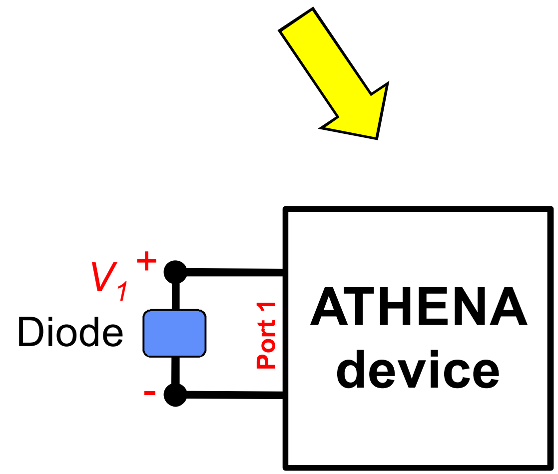


E_{max} =100 V/m

1-Port : Non-Linear Load (Diode)







E_{max} =100 V/m

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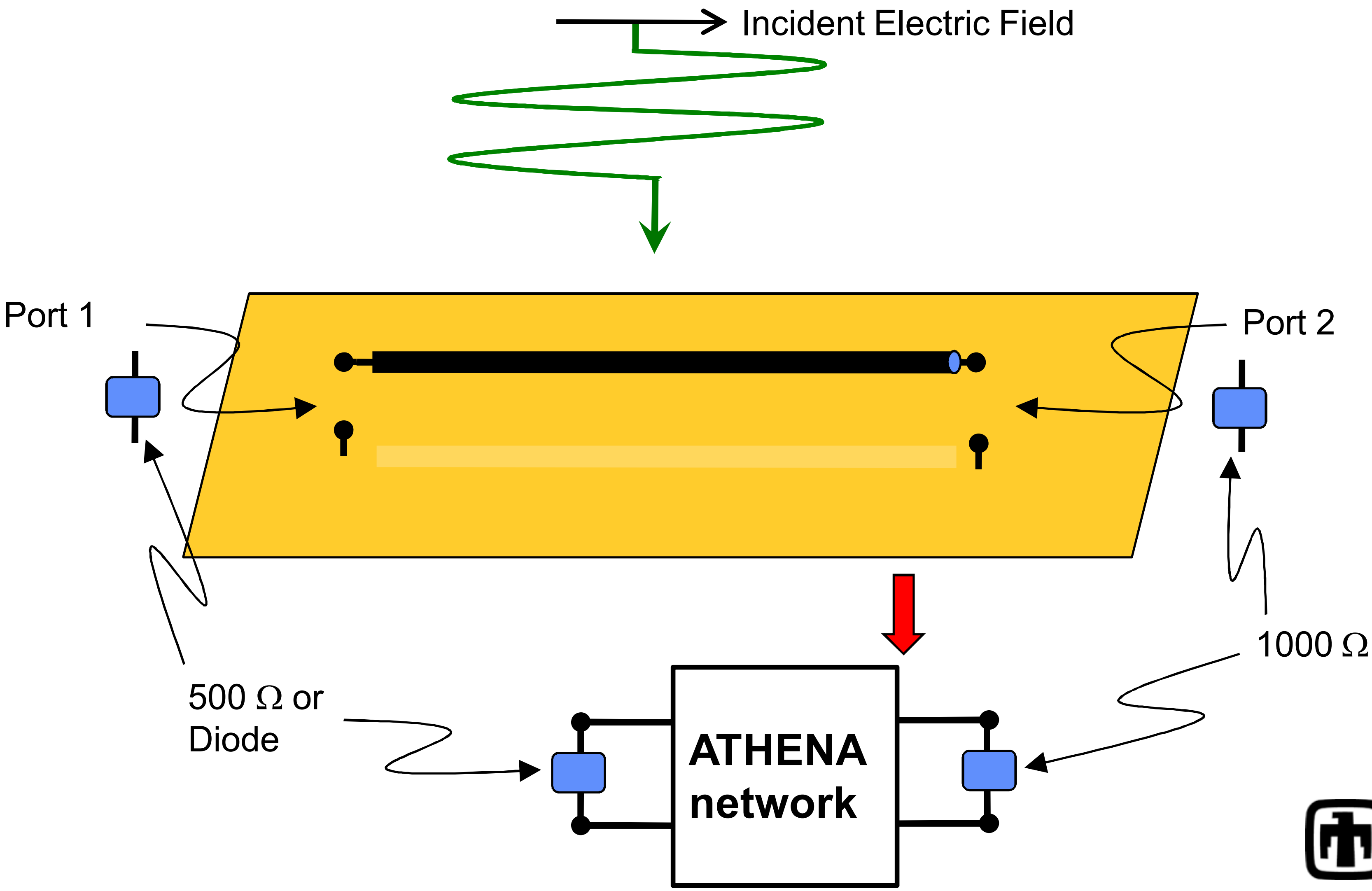
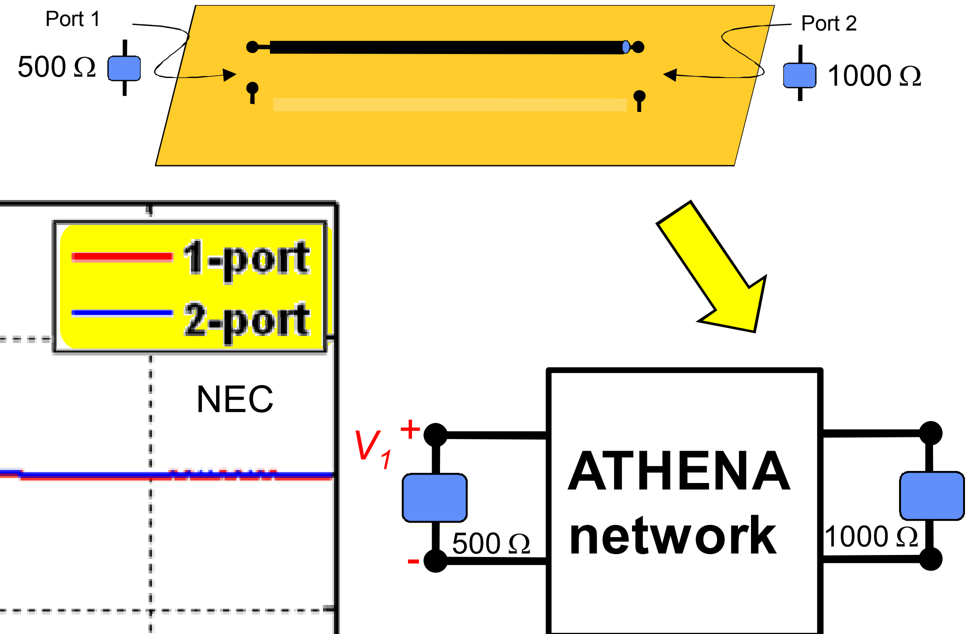
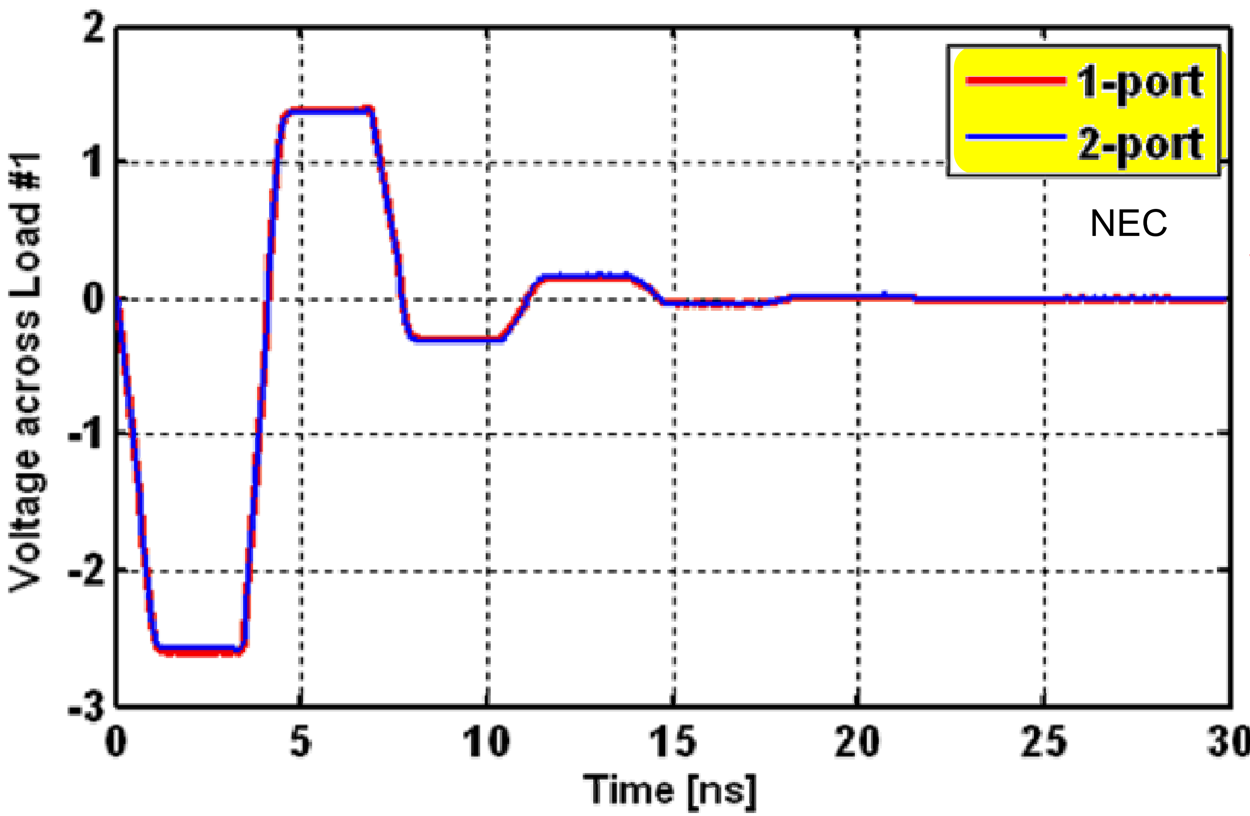
Example: 2-Port Network



2-Port : Linear Loads (500 Ω and 1000 Ω)





E_{max} =100 V/m

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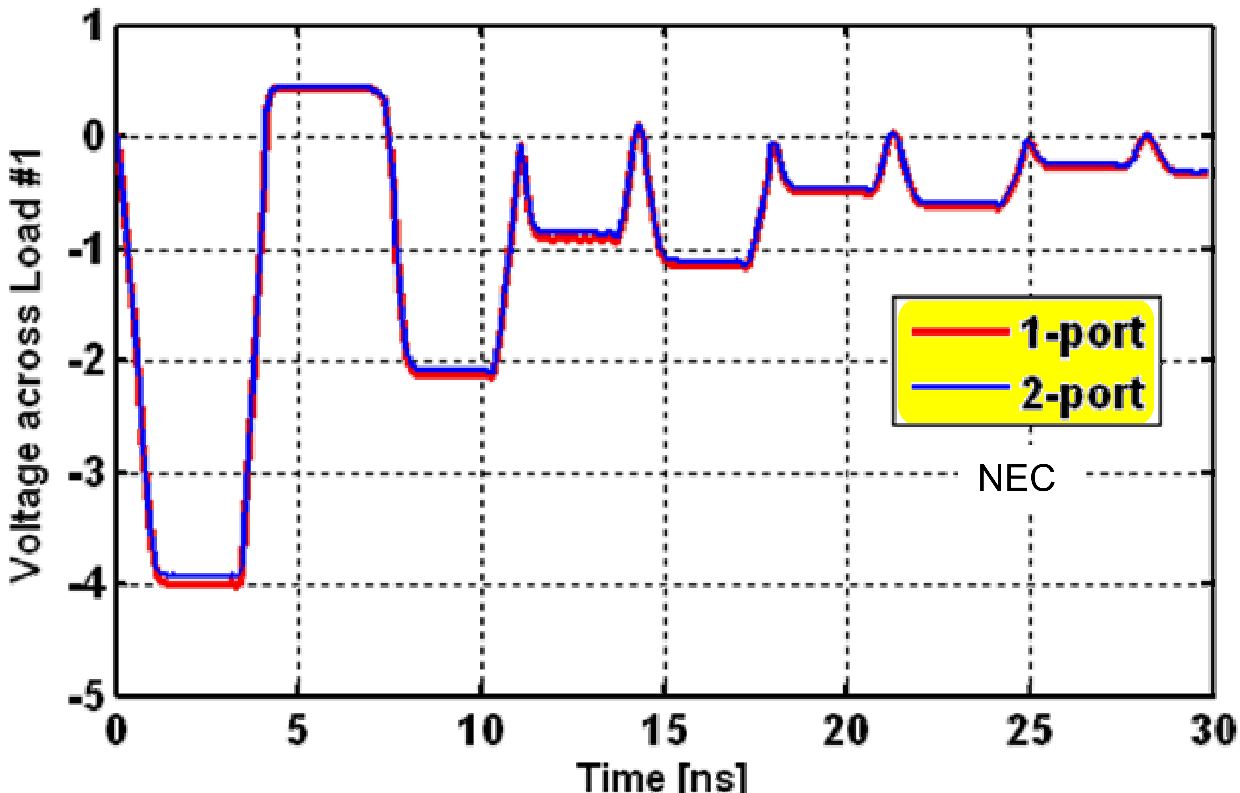
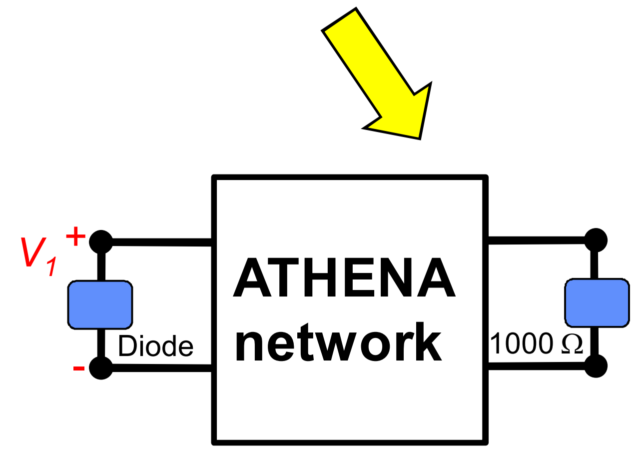
2-Port : Linear (500 Ω) and Non-Linear (Diode) Loads

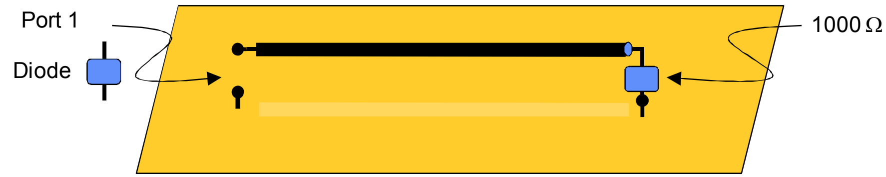


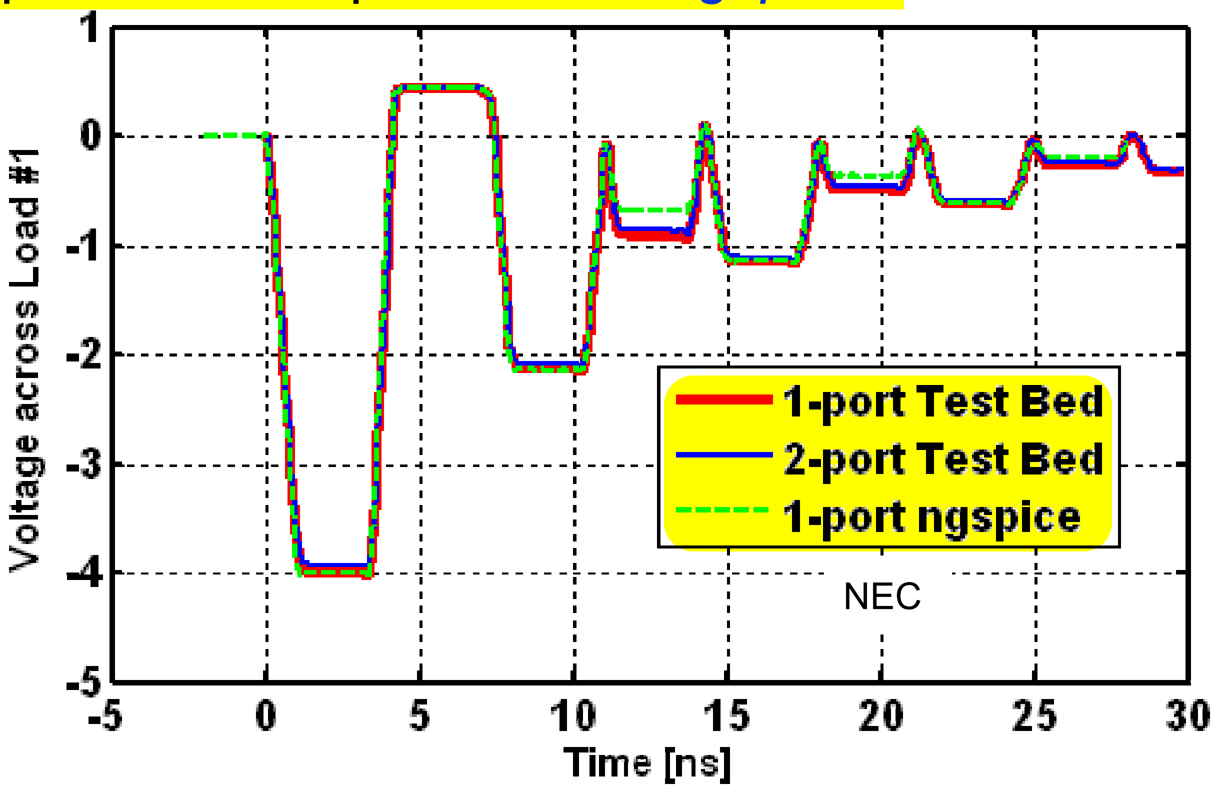


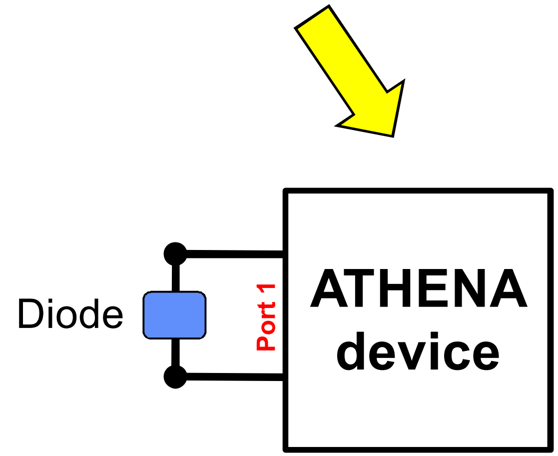
E_{max} =100 V/m

Implementation in Spice (ngspice)

1-port and 2-port ATHENA devices have now been implemented in the open-source Spice variant *ngspice*.







E_{max} =100 V/m

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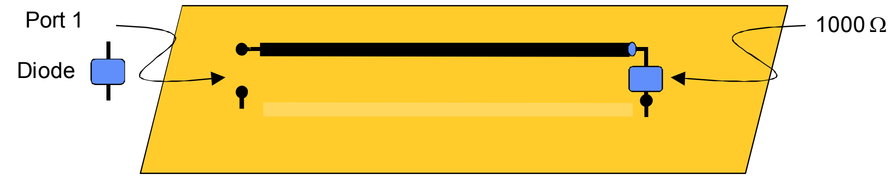
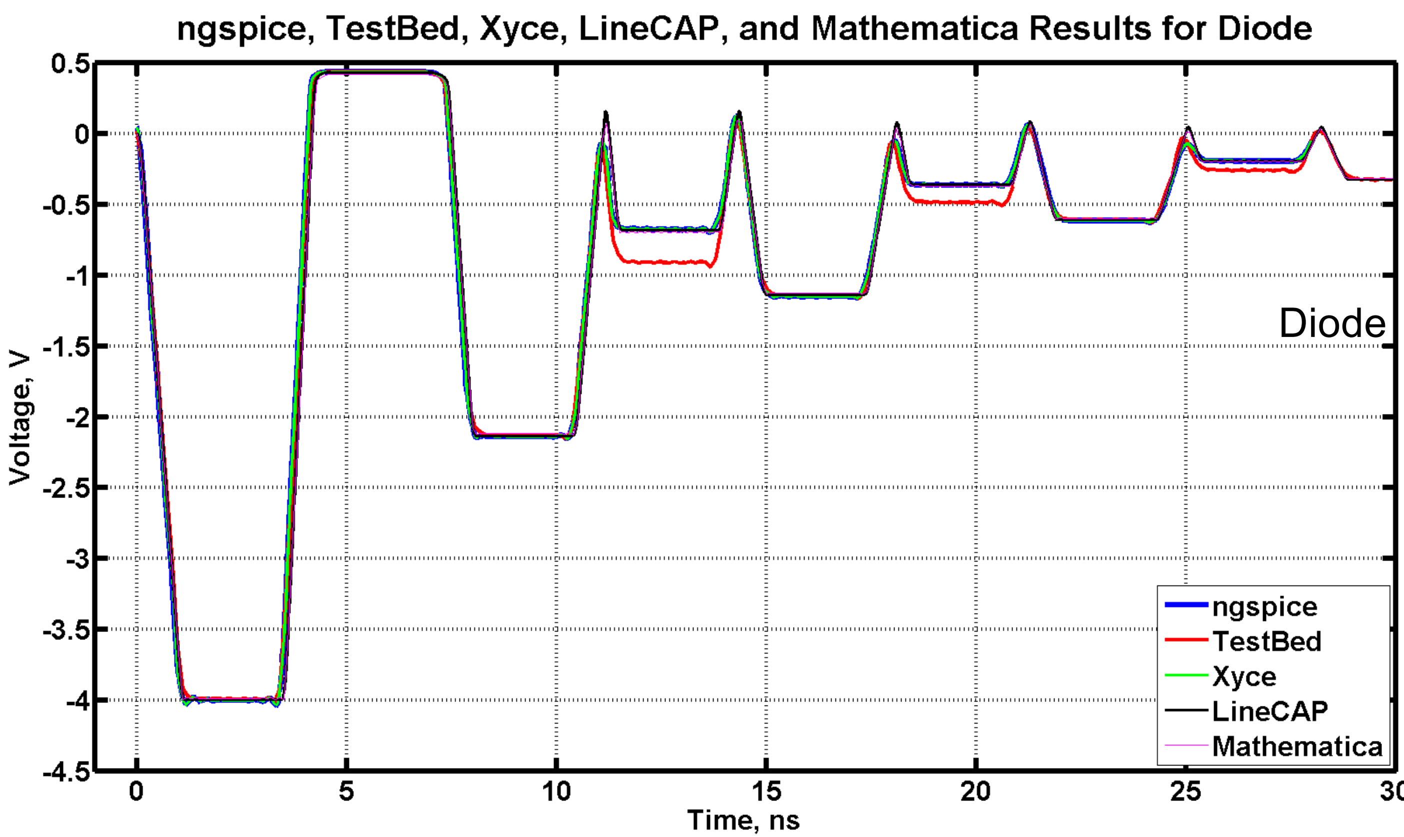
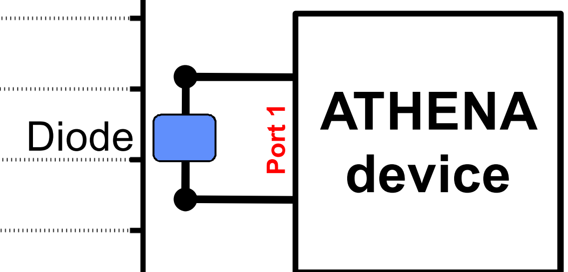
Implementation in Spice (Xyce)

1-port and *uncoupled* 2-port ATHENA devices have now been implemented in Xyce.







E_{max} =100 V/m

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Summary and Next Steps

- The Active THevenin Equivalent Network Approach (ATHENA) allows us to link HPM/EMP coupling to nonlinear circuit simulations in a fully consistent, bidirectional way.
- This is important because it allows us to predict responses to high-power transient waveforms efficiently. This opens the way to predicting response statistics.
- ATHENA is now implemented in the Spice code *ngspice*. Test case were successfully run with good agreement with previous results.
- Implementation in Sandia's massively parallel Spice code *Xyce* is now working for the general one-port case. Two-ports without cross-terms are also working.
- Measurements for test-case validation are underway.

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