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An Active Thevenin Equivalent Network Approach to EMI/EMC Problems

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EMI & IEMI Effects Process

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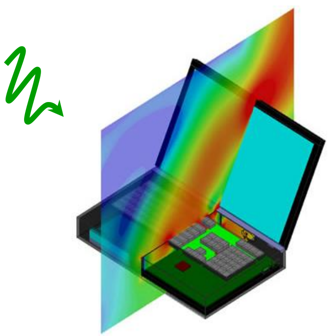
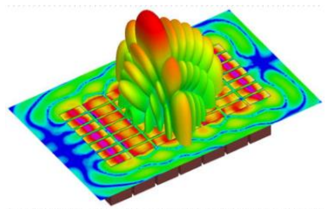
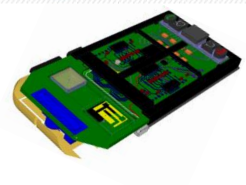
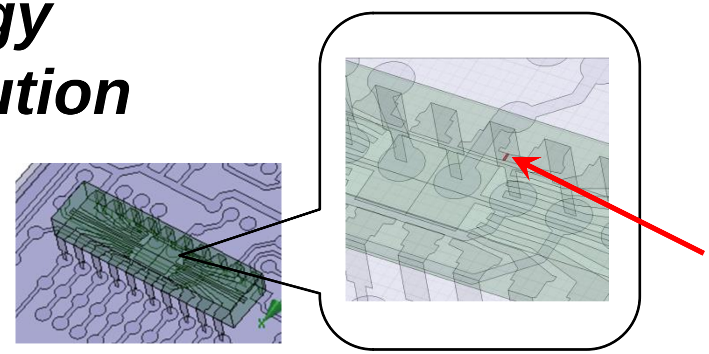
Coupling

Energy Distribution



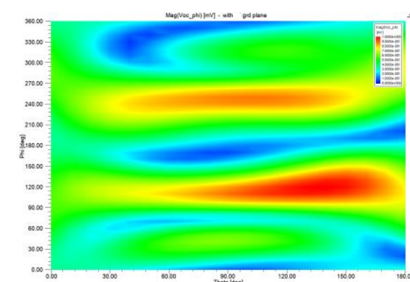






port

Device Response

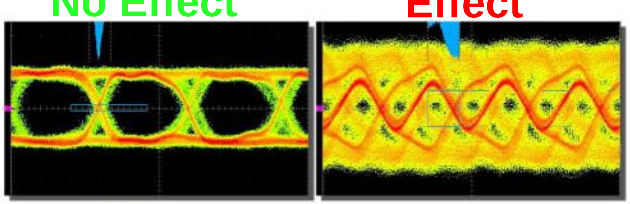


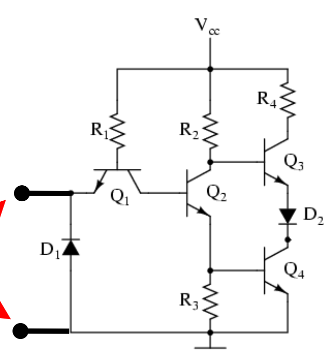
available power at port

System Impact

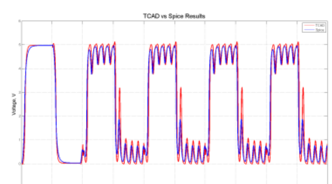
No Effect

Effect





port



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Computing EMI & IEMI Effects

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Mechanisms:

Radiated | Radiated/Conducted | Conducted/ Parasitics | State Dependencies

Coupling ↔ Energy Distribution ↔ Device Response ↔ System Impact

← *linear* → ← *non-linear* →

Computational Tools:

← EM Codes → ← Spice/TCAD ← 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:

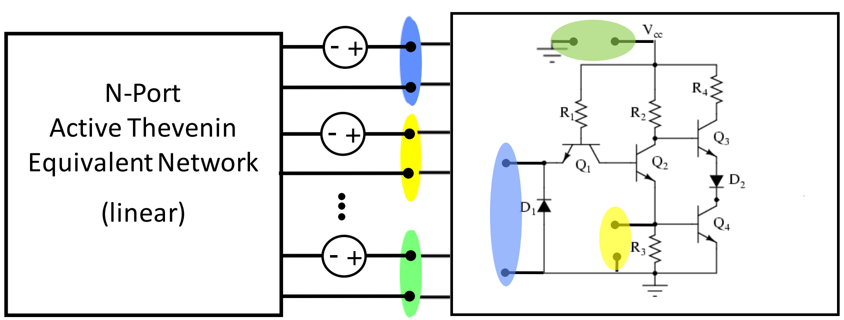
EM Codes — Spice/TCAD — Spice/Mixed Signal

Coupling ↔ Energy Distribution ↔ Device Response ↔ System Impact

linear — *non-linear*

ATHENA

Active THevenin Equivalent Network Approach

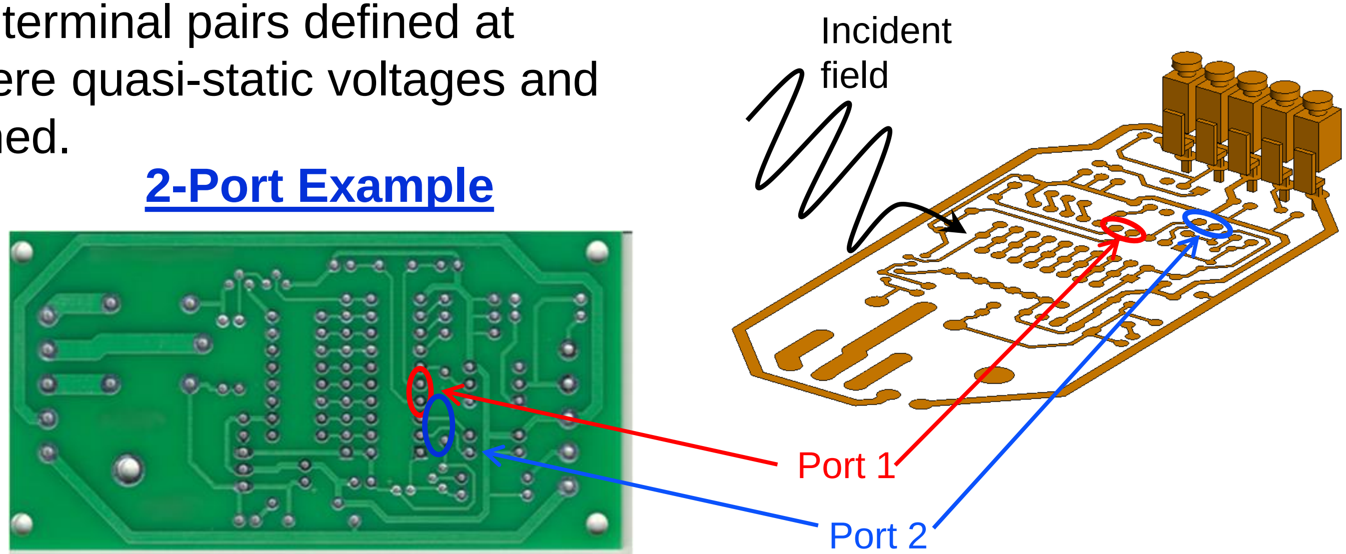


Circuit for demonstration only

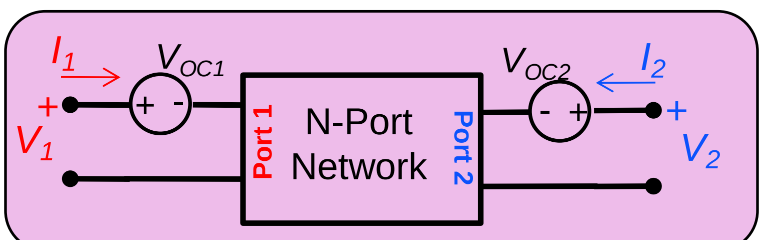
Active Thevenin Equivalent Network

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

2-Port Example

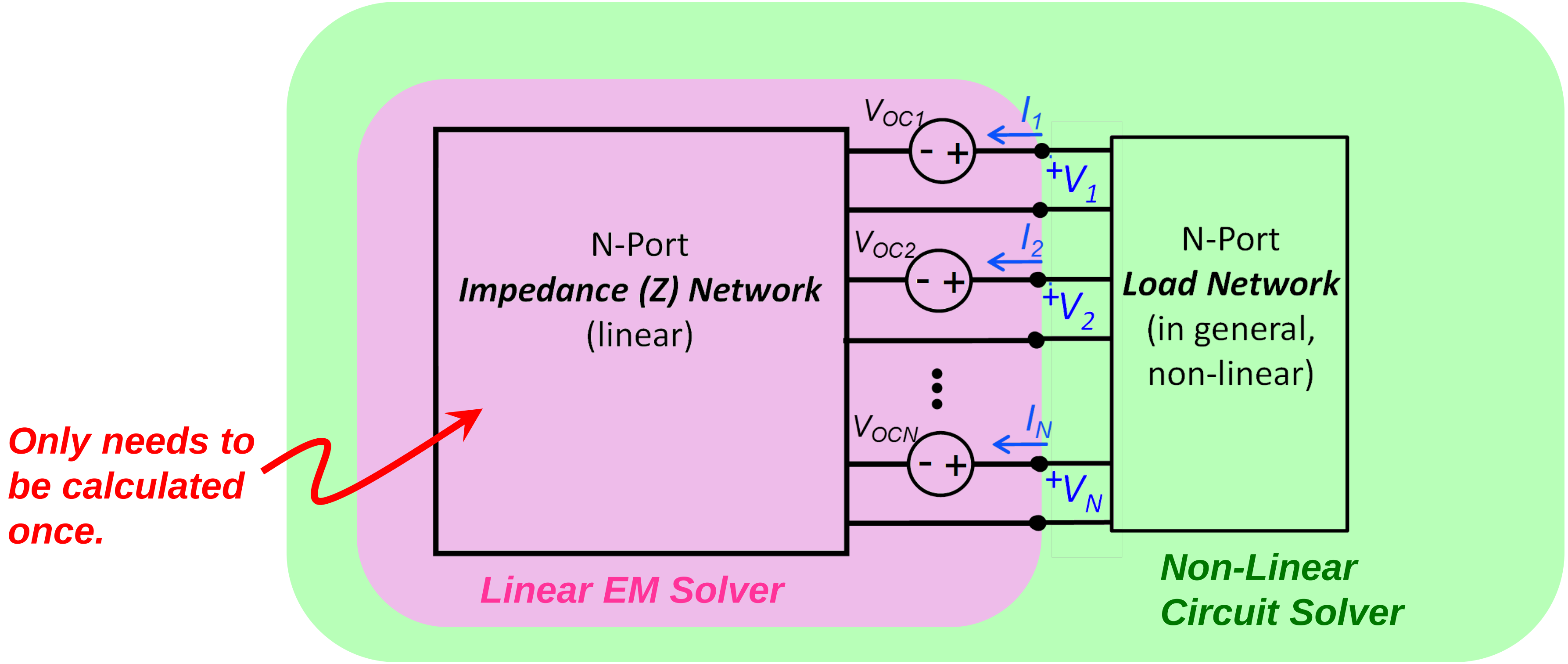


Excluding the port loads, ***linear*** time or frequency domain EM simulators are used to determine the *open-circuit voltage* and *impedance parameters* at the ports.



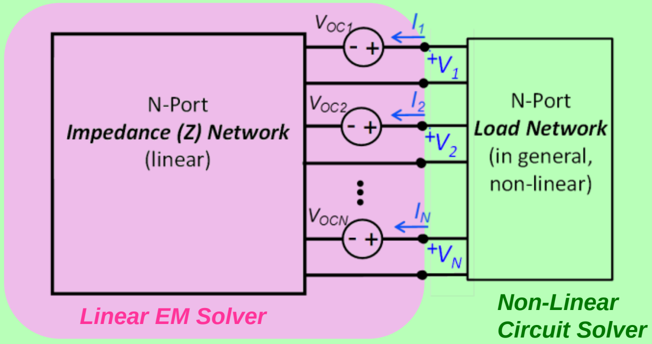
Active Thevenin Equivalent Network = "ATHENA device"

Coupling of ATHENA Device to a Load Network



- **Implicitly, for non-linear loads this coupling is performed in the time-domain. Hence, any frequency domain quantities have to be inverse-Fourier transformed to the time-domain.**

Coupling of ATHENA Device to a Load Network



Using reciprocity, the open-circuit voltage at m^{th}-port due to a **p**-polarized, unit plane wave

$$V_m^{OC} = \frac{1}{j\omega\mu_0}(4\pi r e^{+jk_0 r})(\mathbf{p}\cdot\mathbf{E}_\mathbf{m}^\mathbf{T}(\theta,\phi))$$

Radiated field from unit current at port m.

Freq. Domain

$$[\mathrm{V}]=[\mathrm{Z}][\mathrm{I}]+[V^{OC}]$$

Time Domain

$$[v(t)] = [z(t)] \otimes [i(t)] + [v^{OC}(t)]$$

Convolution operator

2-Port Example:

$$\begin{bmatrix} v_1(t) \\ v_2(t) \end{bmatrix} = \begin{bmatrix} \int_0^t z_{11}(t-\tau)\, i_1[v_1(\tau)]d\tau + \int_0^t z_{12}(t-\tau)\, i_2[v_2(\tau)]d\tau \\ \int_0^t z_{21}(t-\tau)\, i_1[v_1(\tau)]d\tau + \int_0^t z_{22}(t-\tau)\, i_2[v_2(\tau)]d\tau \end{bmatrix} + \begin{bmatrix} v_1^{OC}(t) \\ v_2^{OC}(t) \end{bmatrix}$$

Relationships between port voltages and currents dictated by the Load Network

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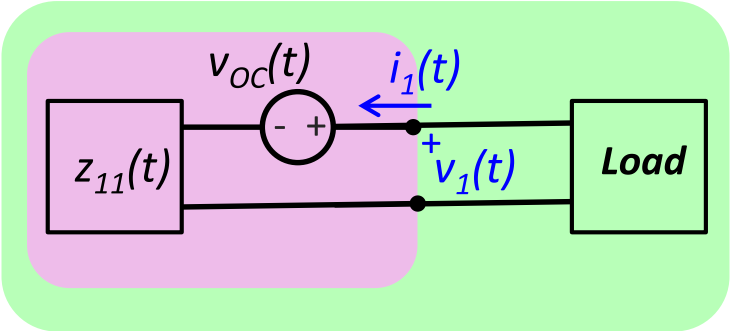
Coupling of ATHENA Device to a Load Network

To discuss details associated with the implementation, consider a **one-port network** example:

$$v_1(t) = \int_0^t z_{11}(t-\tau)\, i_1[v_1(\tau)]d\tau + v_1^{OC}(t)$$



For distributed coupling problems the self-impedances (z_{mm}) are impulsive near $t=0$.

$$v_1(t) - \int_{t_-}^{t} z_{11}(t-\tau)\, i_1[v_1(\tau)]d\tau = \int_0^{t_-} z_{11}(t-\tau)\, i_1[v_1(\tau)]d\tau + v_1^{OC}(t)$$

$$t_- = \lim_{\delta \to 0}(t-\delta)$$

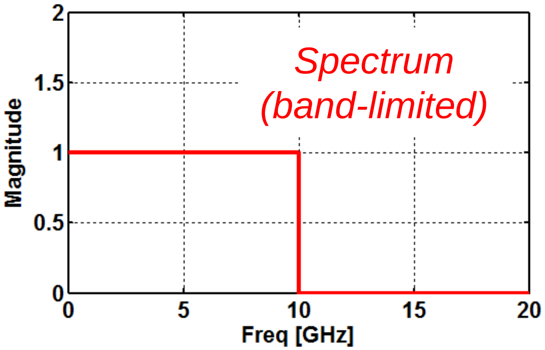
$$v_1(t) - z_{11}(t)\, i_1[v_1(t)] = \int_0^{t_-} z_{11}(t-\tau)\, i_1[v_1(\tau)]d\tau + v_1^{OC}(t)$$

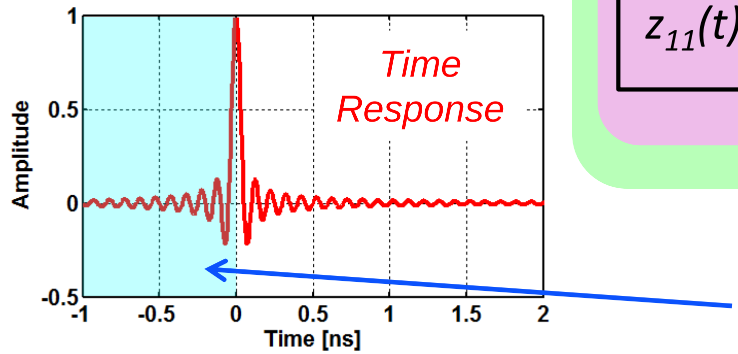
Surge impedance

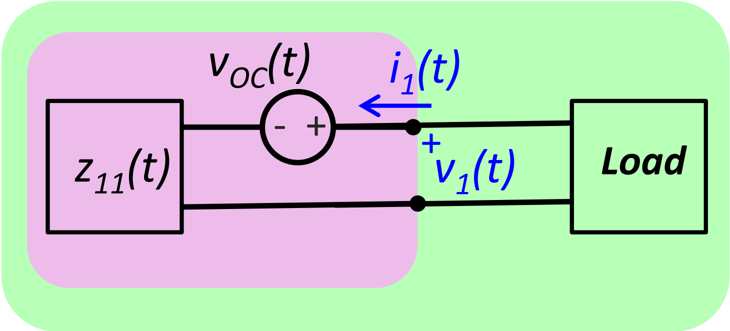
- Time domain simulations capture this response.
- Frequency domain simulations must be corrected.

Coupling of ATHENA Device to a Load Network

Frequency domain simulations are band-limited. Hence, impulse-like responses in the time-domain appear as *sinc* functions.







If the surge impedance is not corrected

- amplitude errors
- aliasing errors (causality)
- instability in non-linear solvers

$$v_1(t) - z_{11}(t)\, i_1[v_1(t)] = \int_0^{t_-} z_{11}(t-\tau)\, i_1[v_1(\tau)] d\tau + v_1^{OC}(t)$$

Since the impulsive nature of surge impedance is known, it is evaluated analytically and *sinc* behavior is analytically removed.

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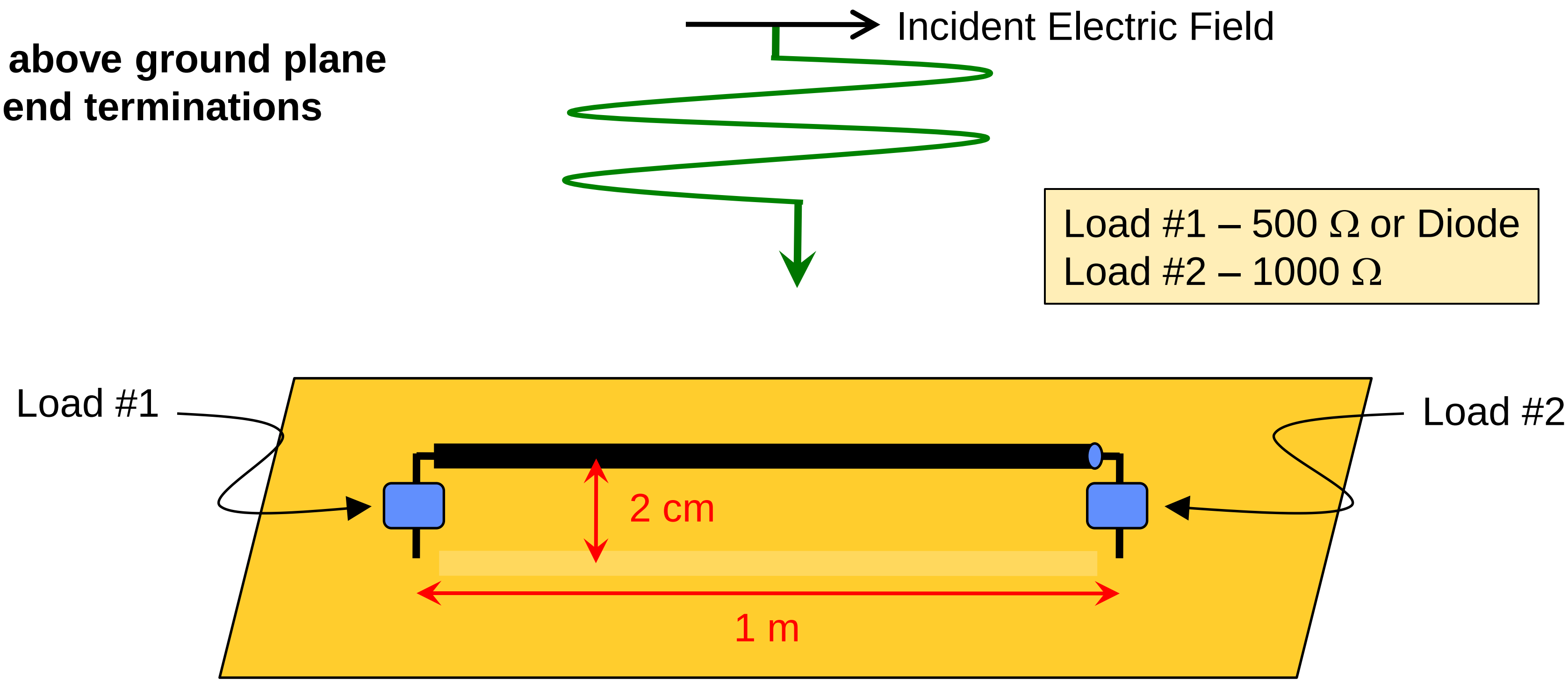
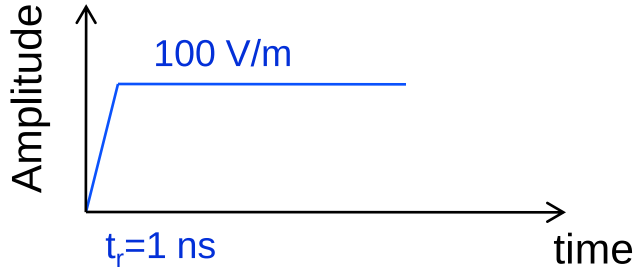
Example Problem Geometry (Intentionally Simple!)

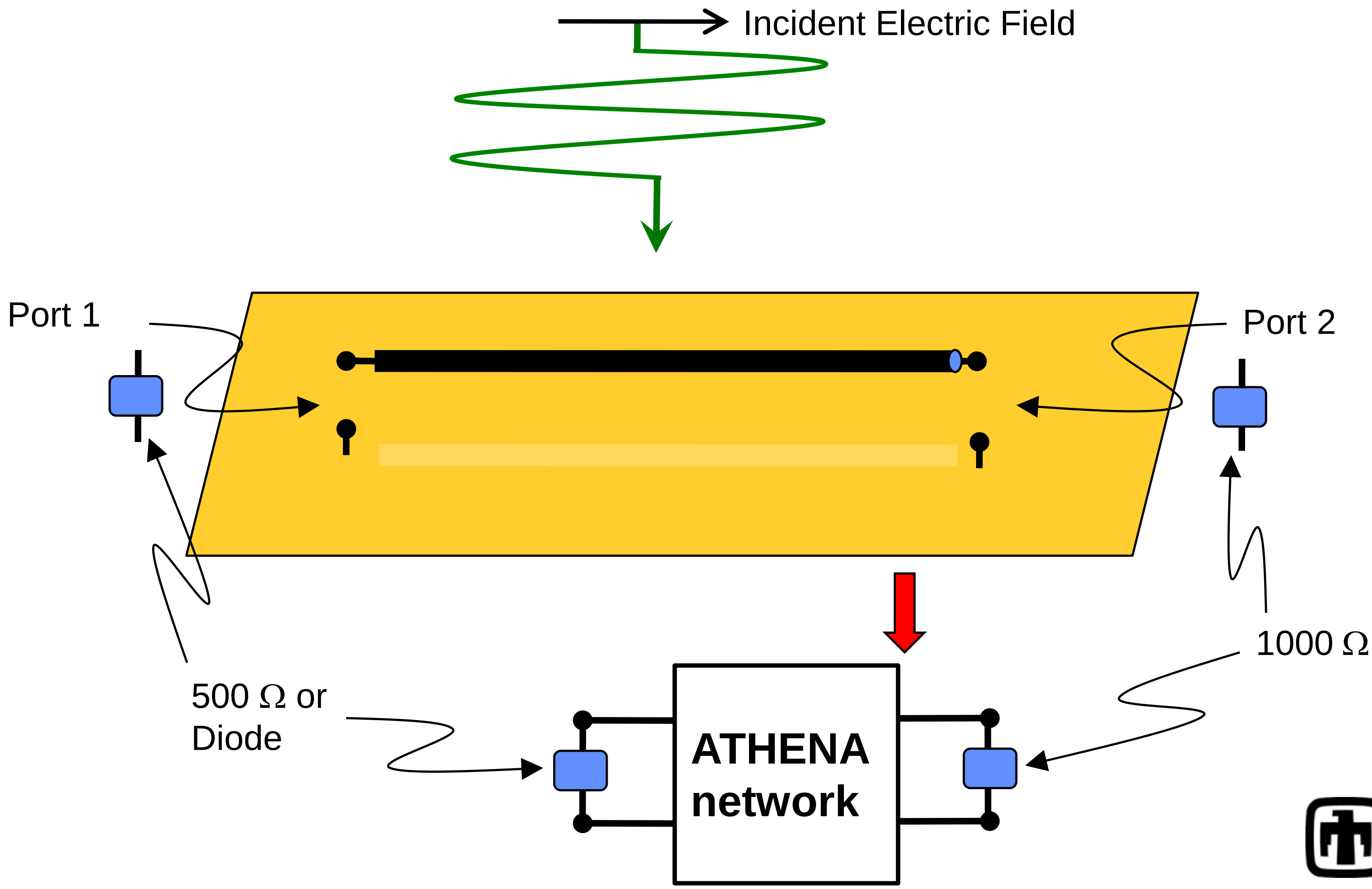
Wire above ground plane with end terminations



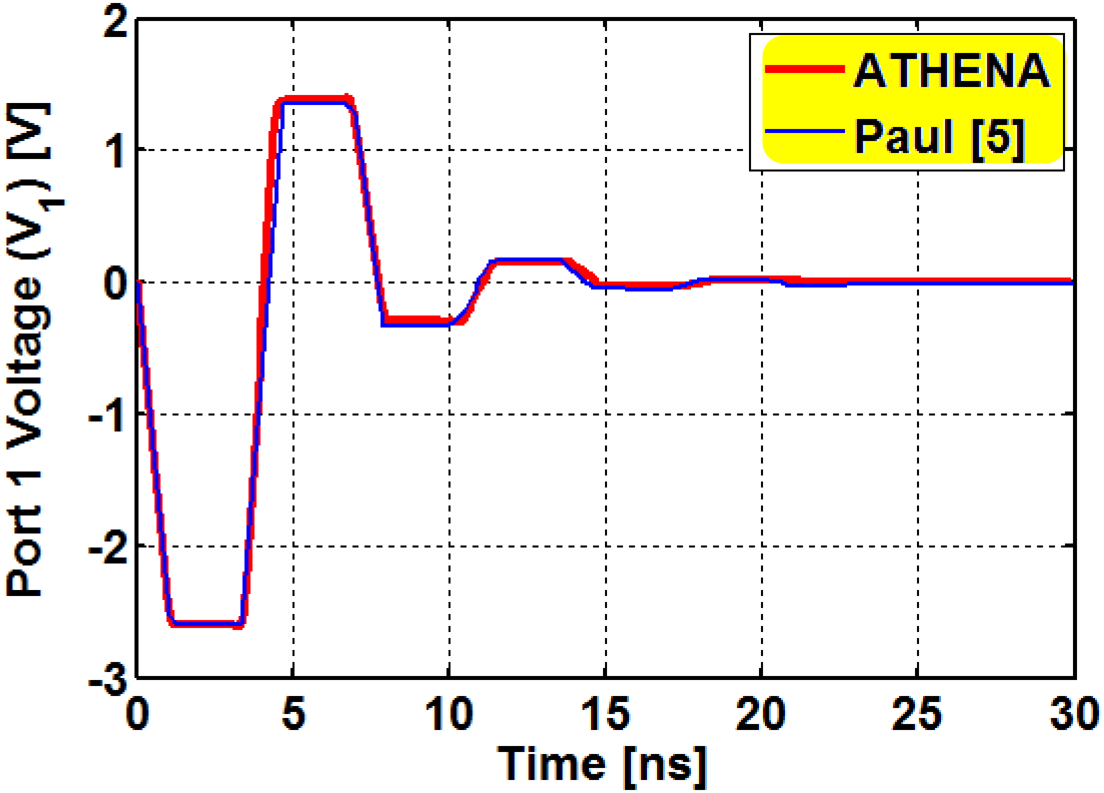


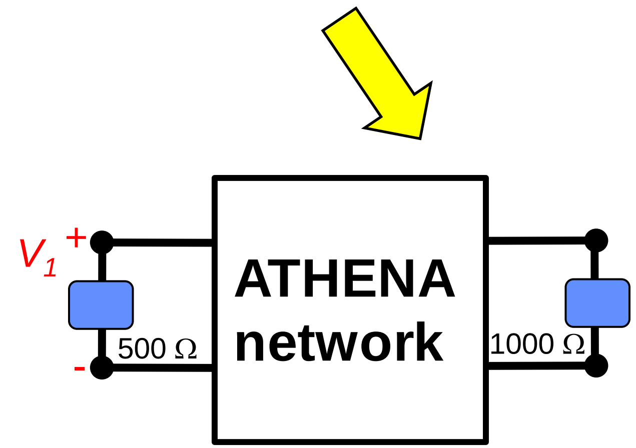
Not to scale

Example: 2-Port Network



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

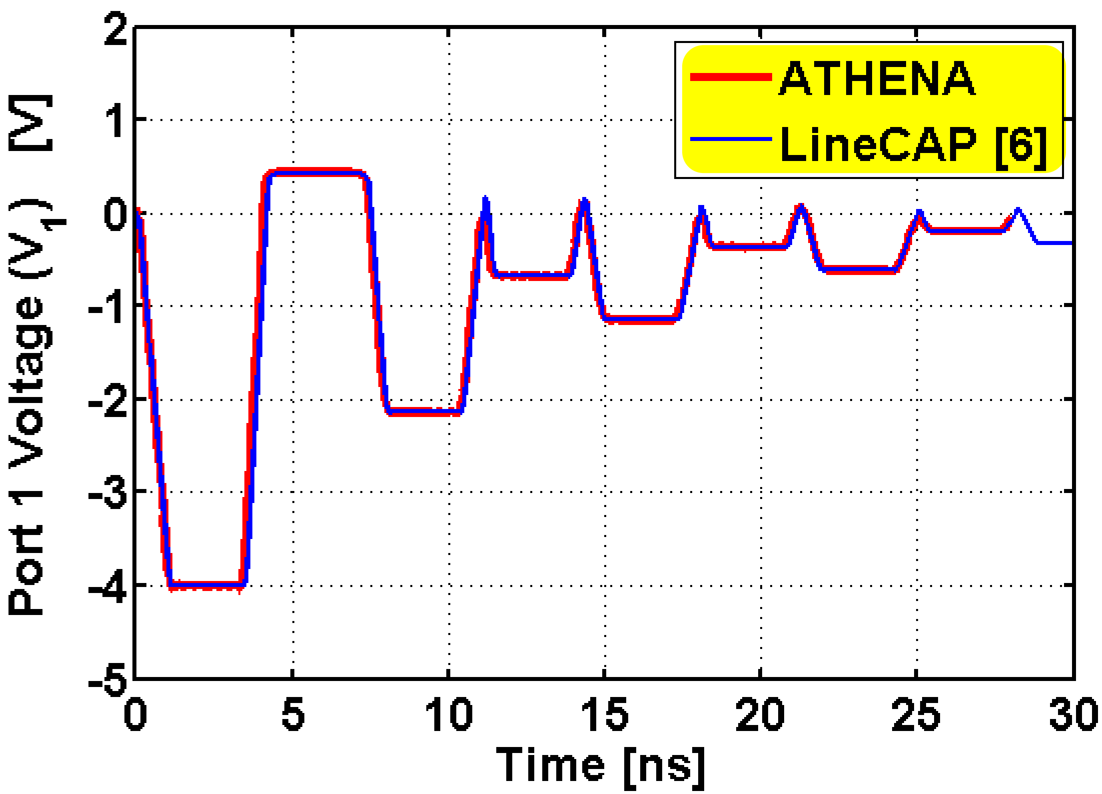




E_{max} =100 V/m

ATHENA device in Xyce

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



E_{max} =100 V/m

ATHENA device in Xyce

Summary and Next Steps

- **The Active THevenin Equivalent Network Approach (ATHENA) allows us to link EMI & IEMI coupling to nonlinear circuit simulations in a fully consistent, bidirectional way.**
- **ATHENA is now implemented in the Spice code *ngspice* and Sandia's parallelized circuit code *Xyce*. Test cases have been successfully completed with good agreement with independent results.**
- **Validation measurements for test-cases are underway.**