ICEAA - IEEE APWC
Verona, September 11-15, 2017

SAND2017-9643C

An Active Thevenin Equivalent Circuit Approach to Problems with Non-Linear Circuit Loads

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Albuquerque, NM

International Conference on Electromagnetics in Advanced Applications

IEEE-APS Topical Conference on Antennas and Propagation in Wireless Communications

September 11-15, 2017
Verona, Italy

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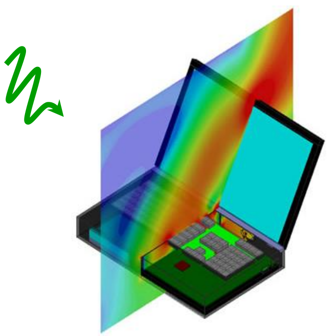
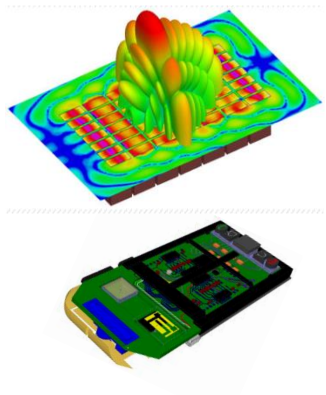
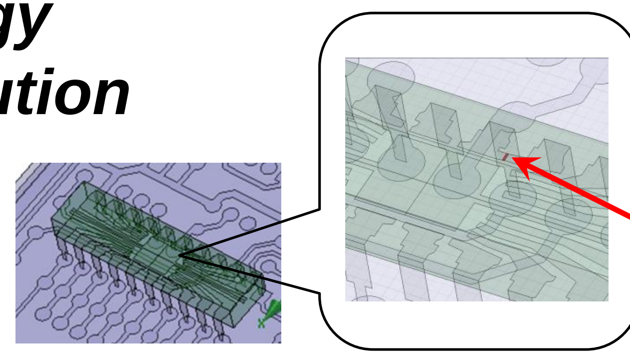
EMI & IEMI Effects Process

Coupling

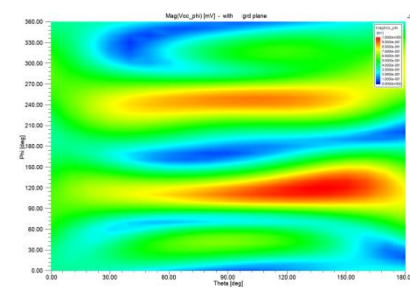


Energy Distribution

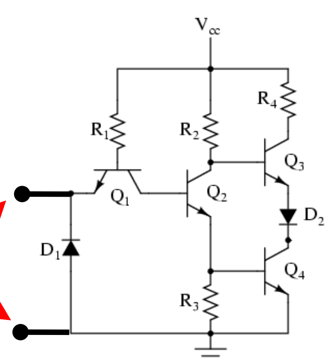


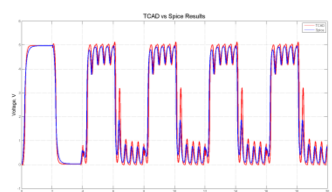


Device Response



available power at port

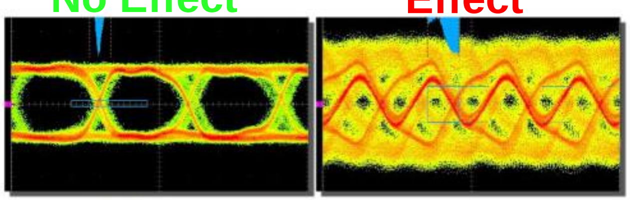




System Impact

No Effect

Effect



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Computing EMI & IEMI Effects

Mechanisms:

Radiated	Radiated/Conducted	Conducted/ Parasitics	State Dependencies
Coupling	Energy Distribution	Device Response	System Impact

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:

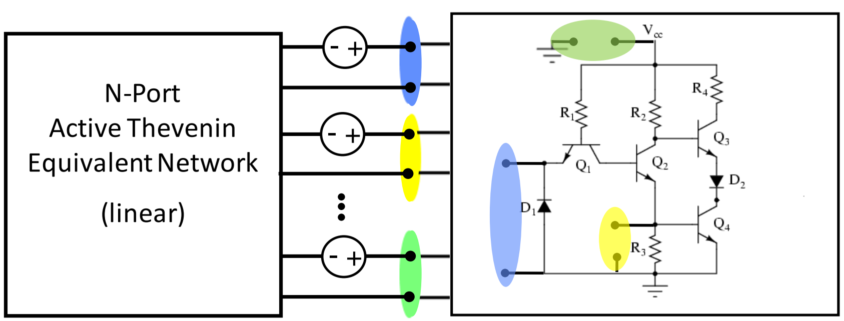
EM Codes — Spice/TCAD — Spice/Mixed Signal

Coupling ↔ Energy Distribution ↔ Device Response ↔ System Impact

linear — *non-linear*

ATHENA

Active THevenin Equivalent Network Approach

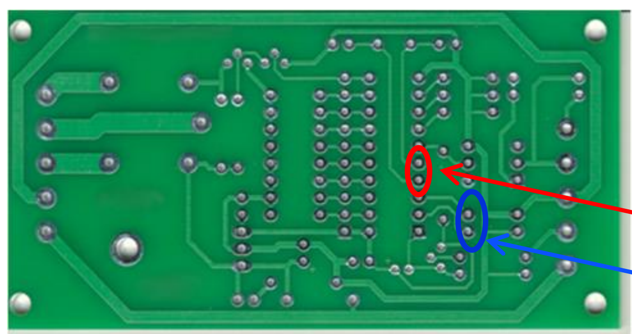


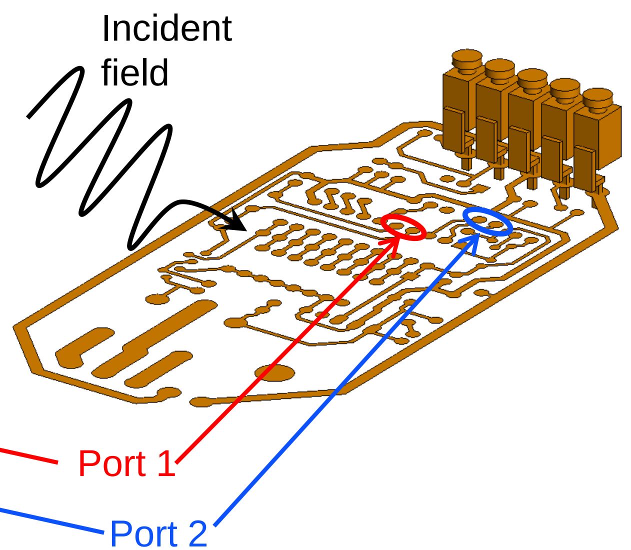
Circuit for demonstration only

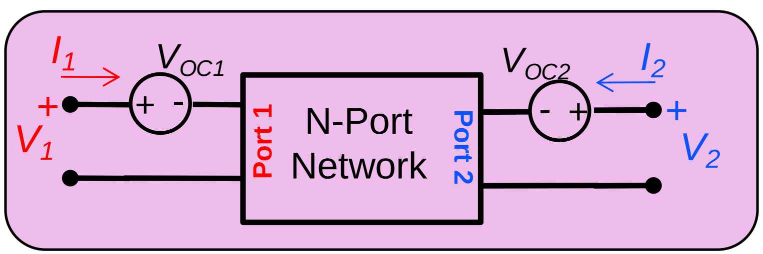
Active Thevenin Equivalent Network

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

2-Port Example



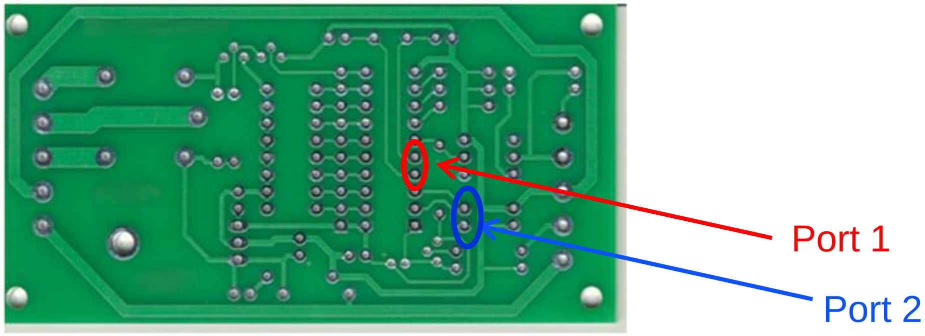


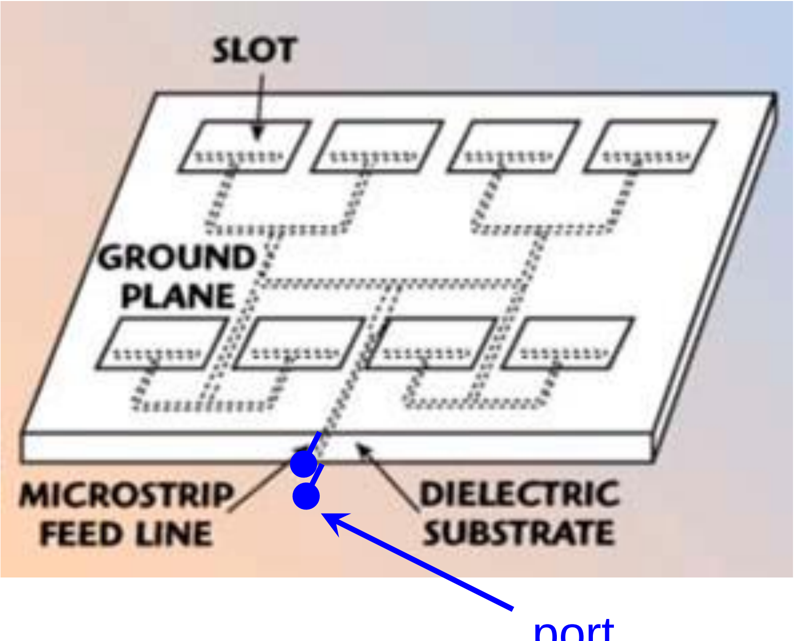


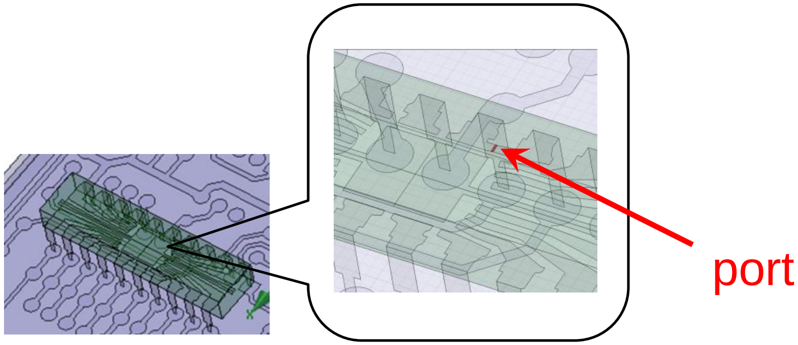
Excluding the port loads, ***linear*** time or frequency domain EM simulators are used to determine the *open-circuit voltage* and *impedance parameters* at the ports.

Active Thevenin Equivalent Network = “ATHENA device”

Port Examples





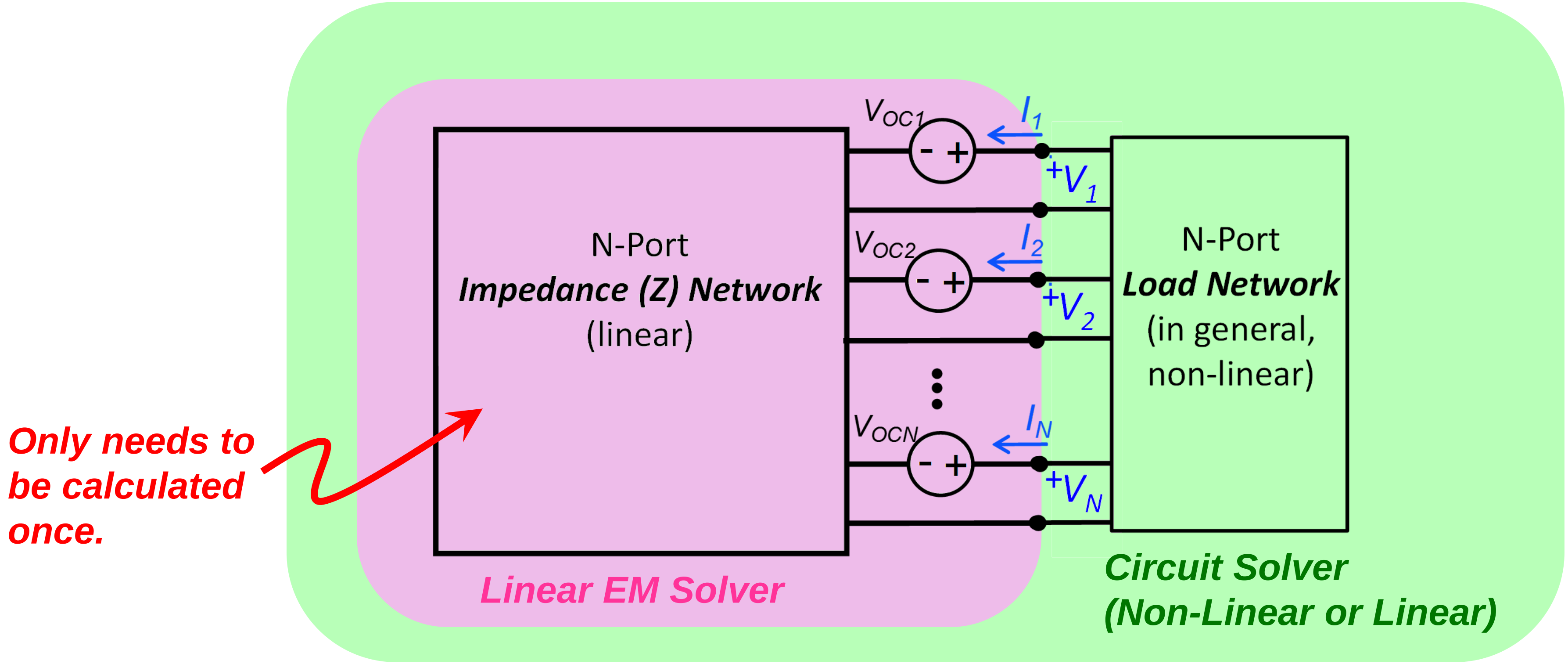


General Aspects of ATHENA

The overriding goals in developing ATHENA are to

- not be restricted to specific EM simulators
  - time domain (FDTD, TLM,…)
  - frequency domain (FEM, MOM, …)
- be general enough to be implemented in any linear/non-linear circuit solver
  - transient time domain
  - harmonic balance

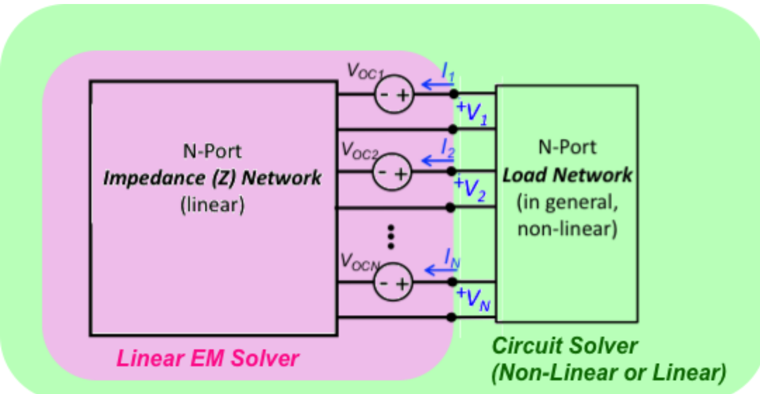
Coupling of ATHENA Device to a Load Network



- **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.**

ATHENA Device

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



Using reciprocity, the open-circuit voltage at m^{th}-port due to an incident wave from a far-field source

$$V_m^{OC} = \mathbf{h_m}(\theta,\phi)\cdot\mathbf{E_{inc}}$$

where

$$\mathbf{h_m}(\theta,\phi) = \frac{1}{j\omega\mu_0}\left(\frac{4\pi r e^{+jkr}}{I_m}\right)\mathbf{e_m^T}(\theta,\phi)$$

Radiated field from current I_m driving 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

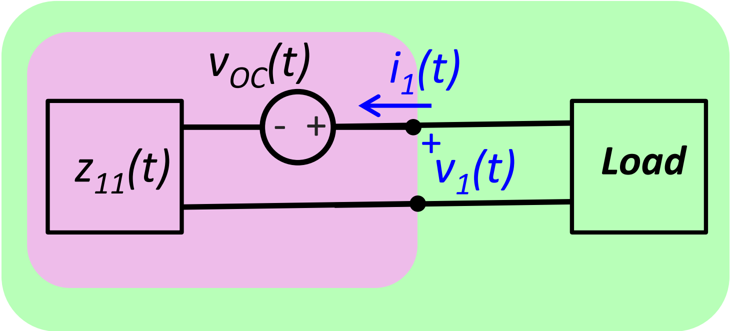
2-Port Example:

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

Relationships between port voltages and currents dictated by the Load Network

Surge Impedance

To discuss details associated with 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 $t=0$.

$$v_1(t) - \int_{t_-}^{t} z_{11}(t-\tau)\, i_1[v_1(\tau)] d\tau = \int_0^{t_-} z_{11}(t-\tau)\, i_1[v_1(\tau)] d\tau + v_1^{OC}(t) \qquad t_- = \lim_{\delta \to 0}(t-\delta)$$

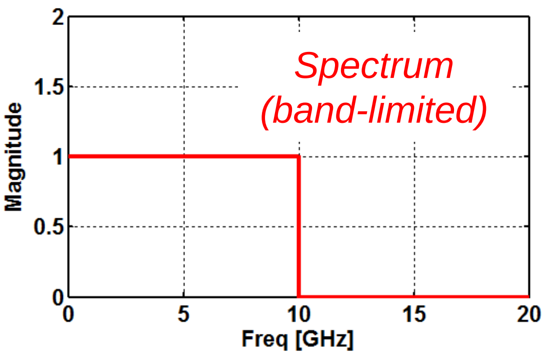
$$v_1(t) - z_{11}(t)\, i_1[v_1(t)] = \int_0^{t_-} z_{11}(t-\tau)\, i_1[v_1(\tau)] d\tau + v_1^{OC}(t)$$

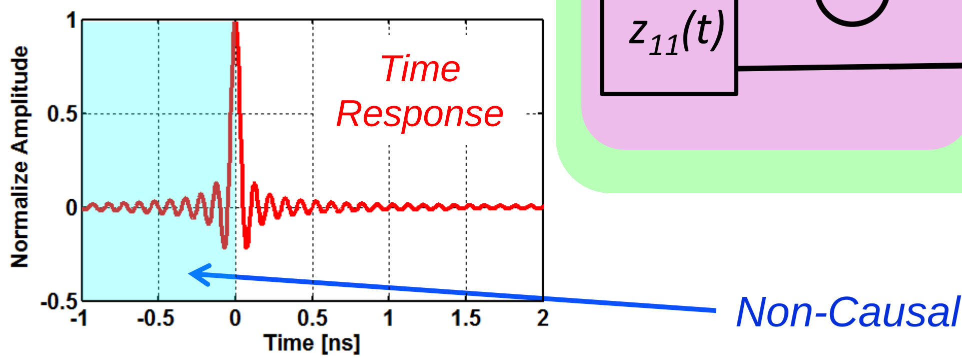
Surge impedance

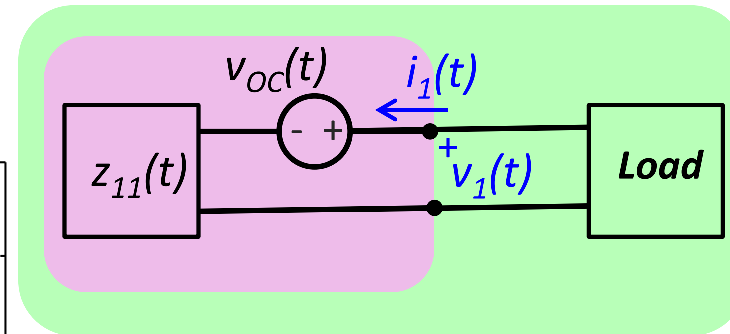
- Time domain simulations typically capture this response.
- Frequency domain simulations must be corrected.

When using Frequency Domain Simulations

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

- causality errors
- aliasing errors
- instability in non-linear solvers

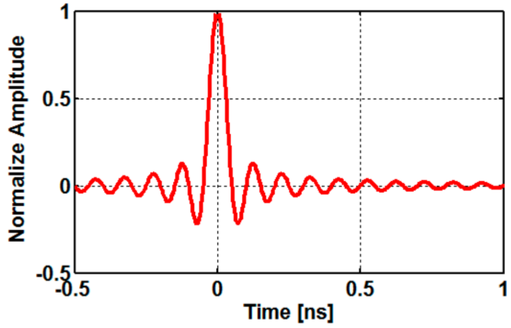
$$v_1(t) - z_{11}(t)\, i_1[v_1(t)] = \int_0^{t_-} z_{11}(t-\tau)\, i_1[v_1(\tau)]d\tau + v_1^{OC}(t)$$

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

Non-Impulsive Surge Impedance

This is a continuing area of investigation.

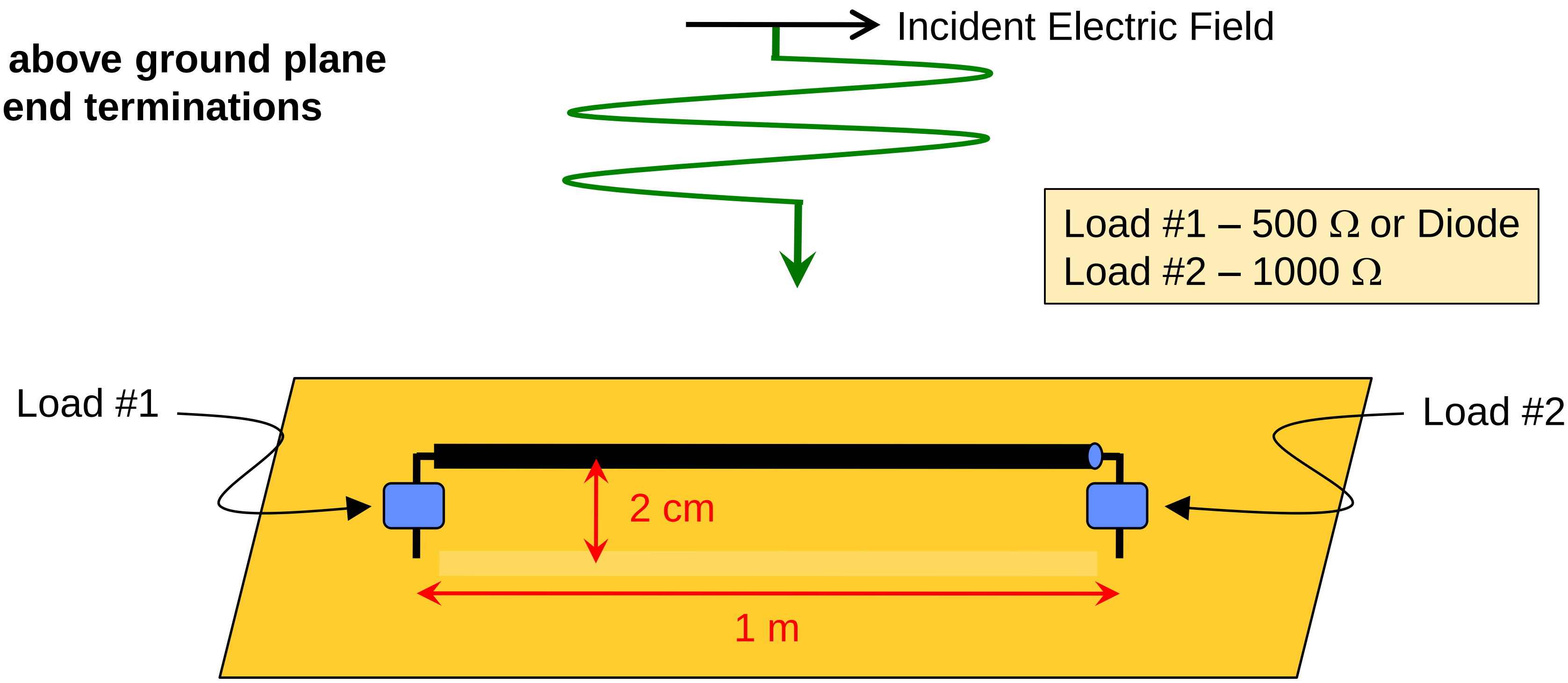
- Windowing (filtering) frequency response to reduce amplitude of time domain "ripples."
  - ➢ relaxes required time resolution

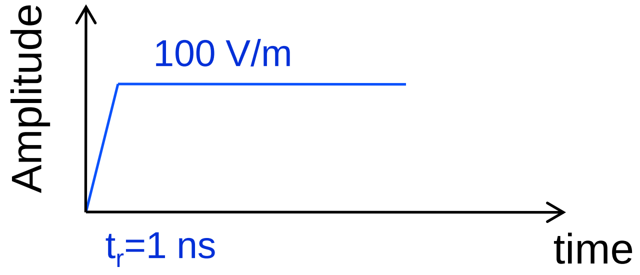


- Extract reactive parasitic effects near the port.
  - ➢ have successfully employed this technique by "manually" identifying reactive elements

Example Problem Geometry (Intentionally Simple!)

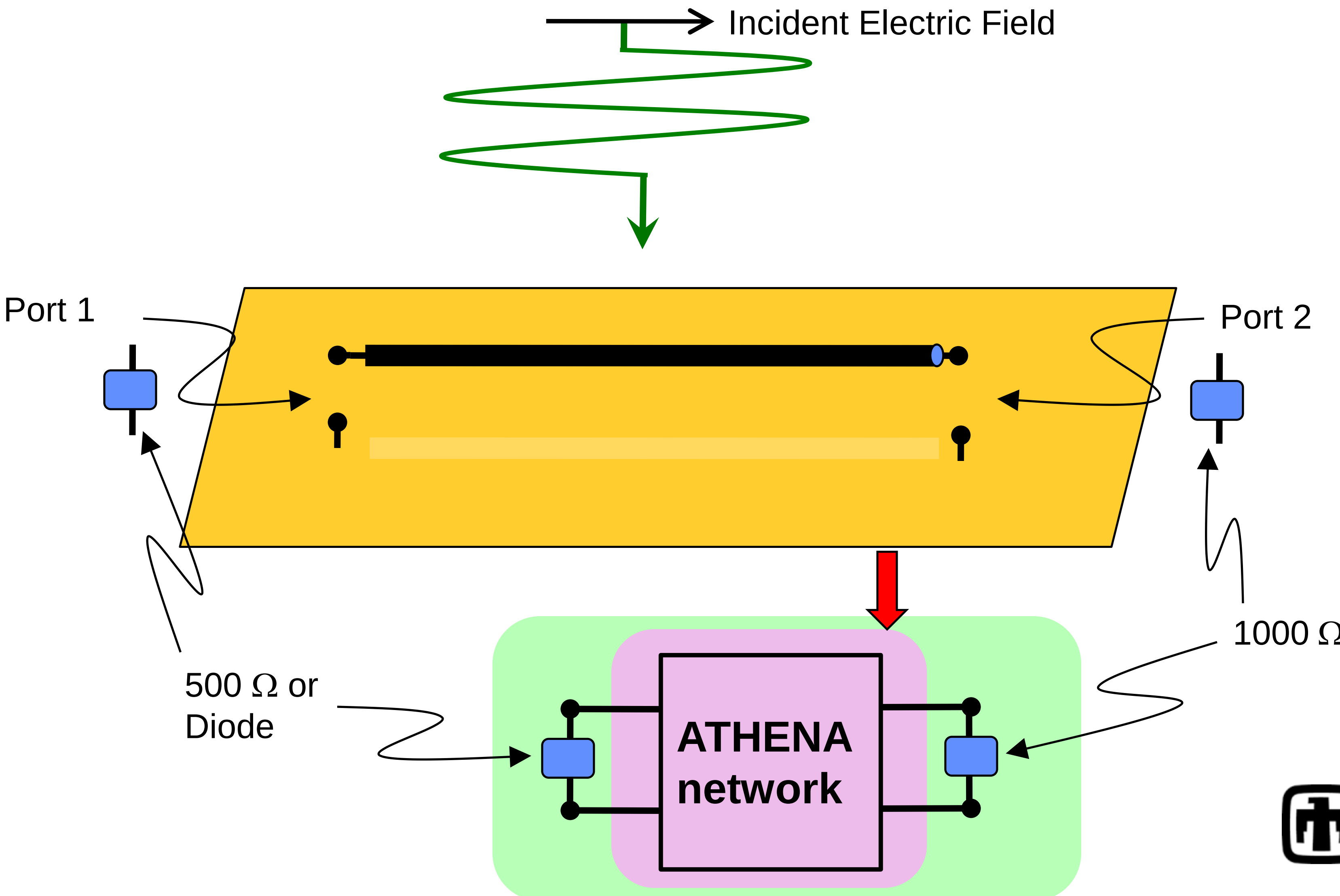
Wire above ground plane with end terminations



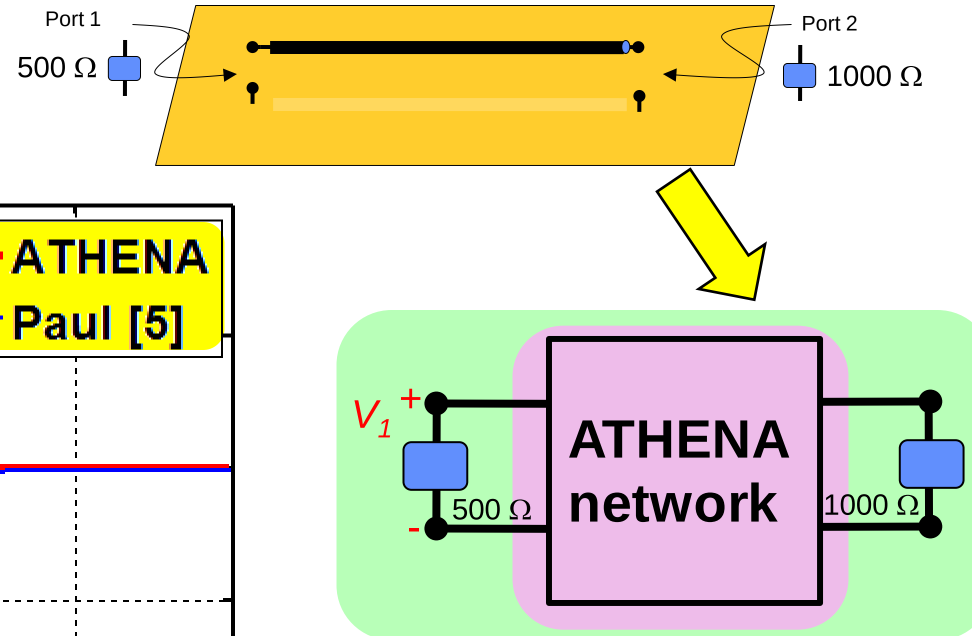


Not to scale

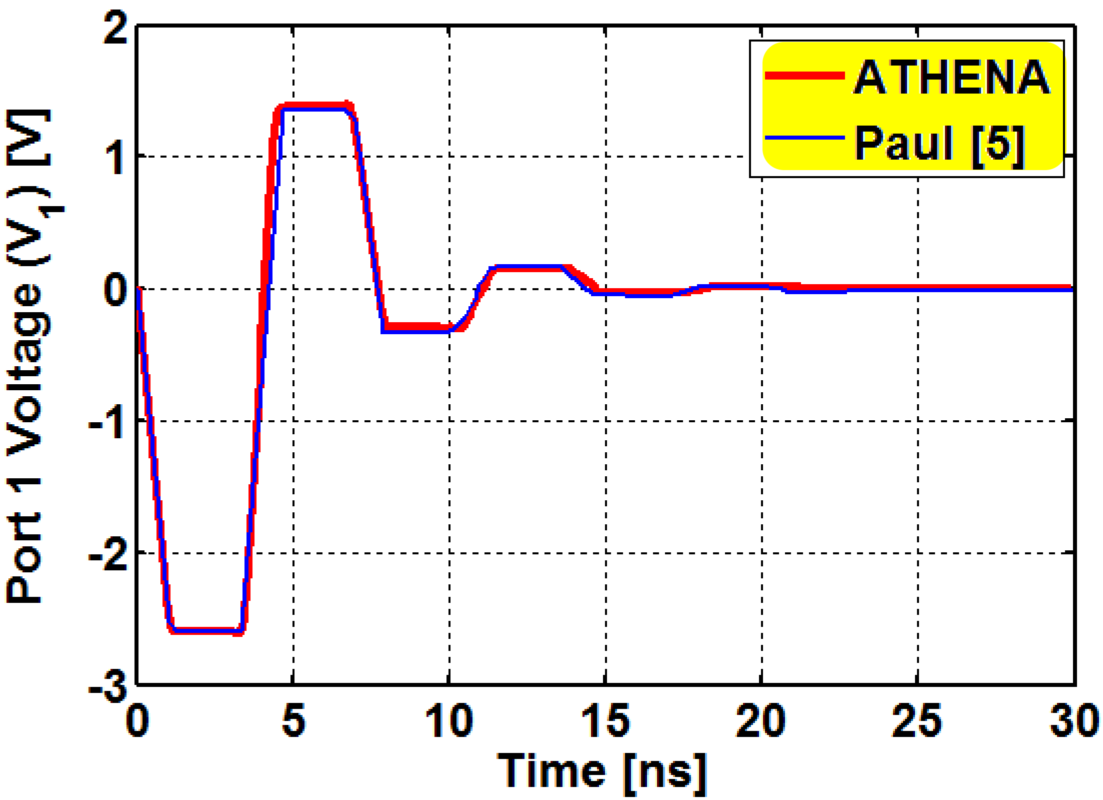
Example: 2-Port Network



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



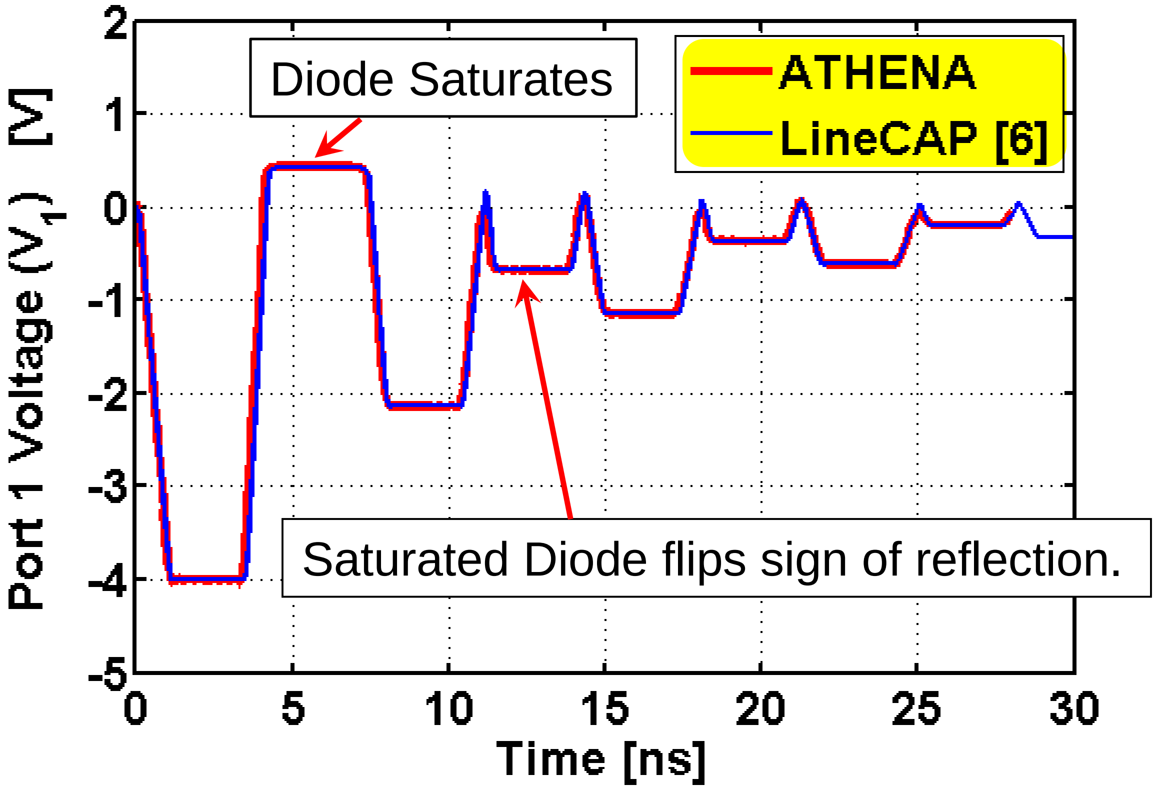
E_{max} =100 V/m

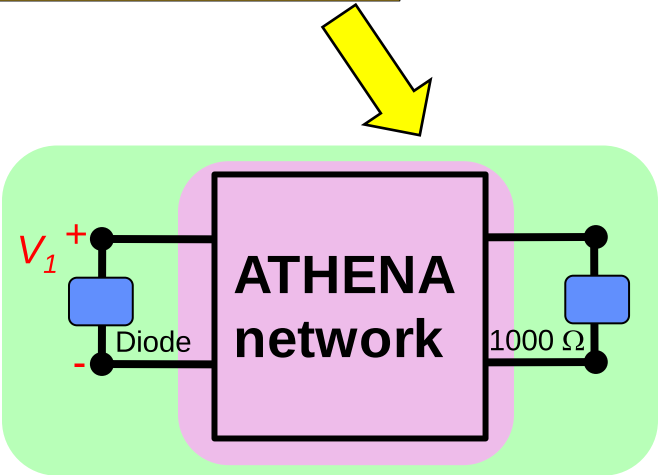


Parameters of ATHENA device determined using the freq. domain MOM code FEKO.

ATHENA device implemented in Xyce.

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





E_{max} =100 V/m

Parameters of ATHENA device determined using the freq. domain MOM code FEKO.

ATHENA device implemented in Xyce.

Athena allows us to feed back nonlinear electronic response into the coupling problem.

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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.**

- **The ATHENA approach is general. It can utilize both time and frequency domain linear EM simulators, and harmonic balance and transient time domain non-linear circuit solvers.**

- **ATHENA is now implemented in the Spice code *ngspice* and Sandia's parallelized circuit code *Xyce*.**

- **Test cases (numerical and experimental) are continually being investigated to further the validation and development of the approach.**

- **Investigating causality issues associated this approach with the EM simulations are done in the frequency domain.**