Extension of the BLT Equation to Incorporate Electromagnetic Field Propagation

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Outline of Presentation

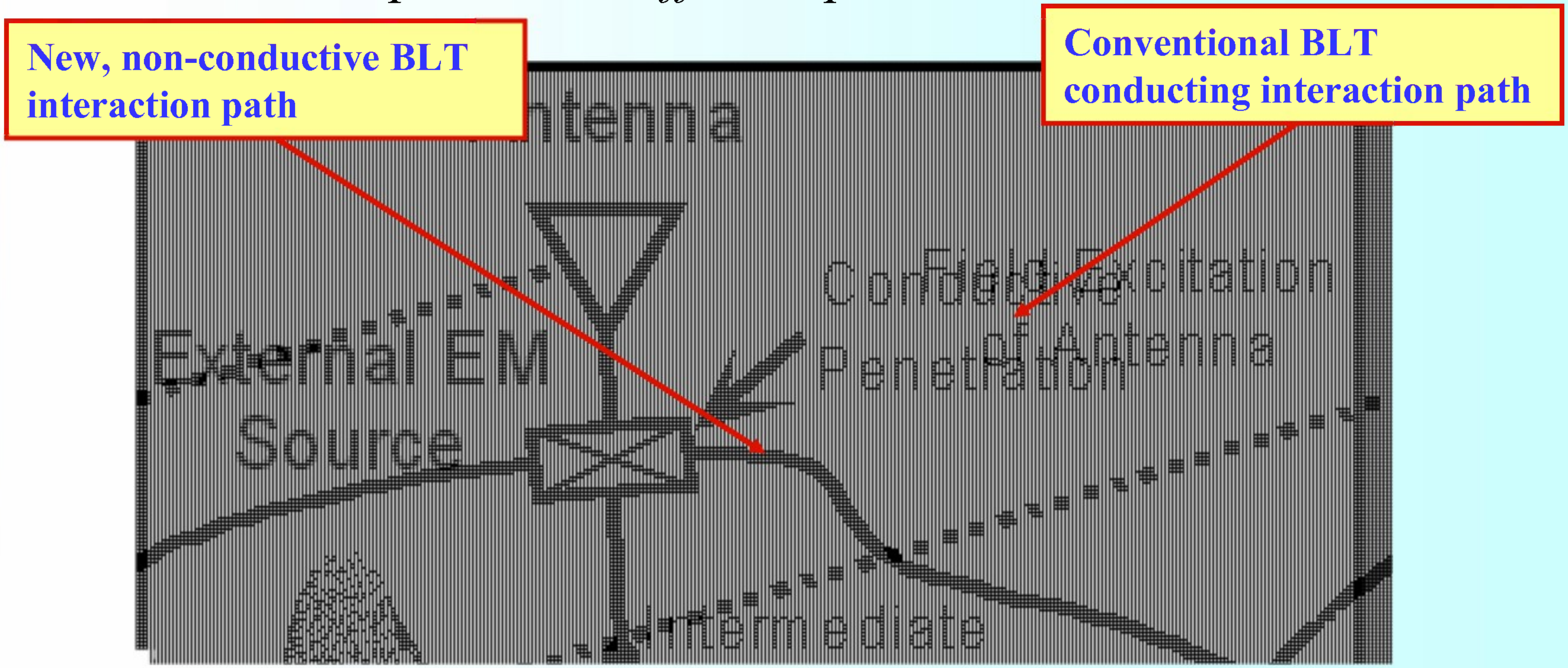
- Introduction
- Review of the Derivation of the BLT Equation
- Extension of the BLT Equation
- Summary

Overview

- The BLT equation for analyzing transmission line networks permits a system-level analysis of the EM effects on large systems
  - This is the basis of the CRIPTE code, and its predecessor, QV7TA
- In this MURI effort, we wish to extend the formulation of the BLT equation to take into account the following:
  - EM field propagation and coupling to the network
  - EM penetration through apertures
  - EM scattering from nearby bodies (including cavities)

Illustration of BLT Equation Extension

- We wish to include non-conducting paths in the interaction sequence diagram
  - To model *aperture* or *diffusive* penetrations



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Outline of Presentation

- Motivation
- ***Review of the BLT Equation***
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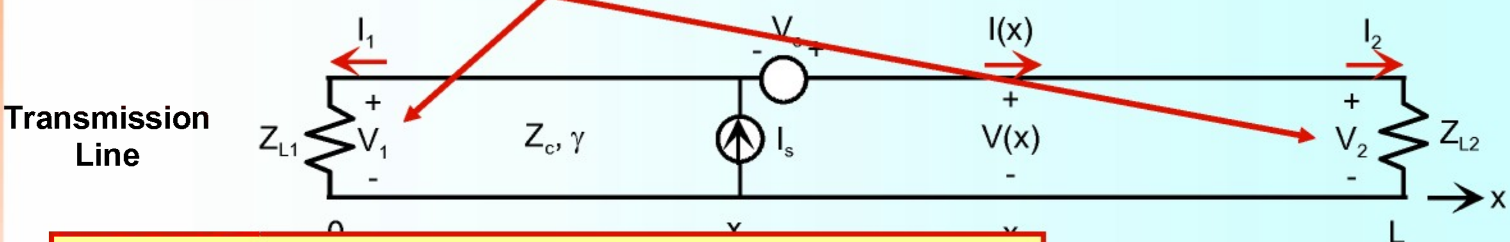
The BLT Equation for a Single Line Network

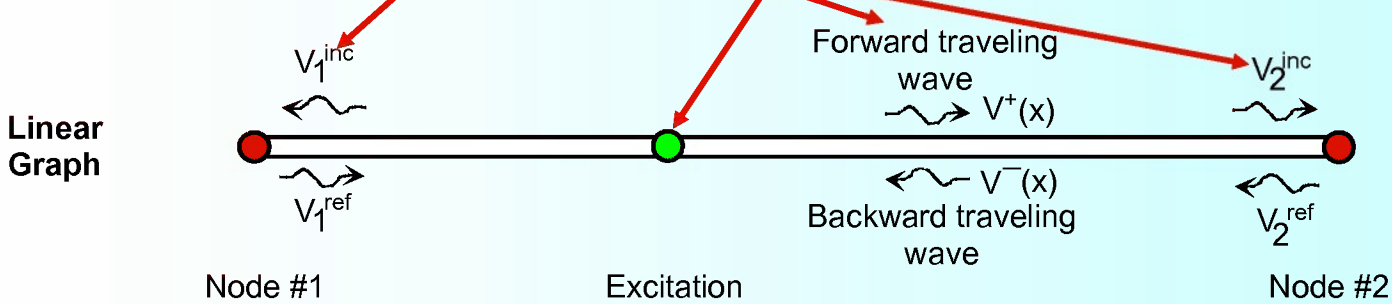
- Consider a single transmission line “network”

The BLT Equation provides the voltage or current responses at the ends (junctions) of the line



This is done by ... incident and r...

And including the excitation of forward and backward traveling wave components on the line by the excitation sources.



The BLT Equation for the Load Voltages

- The BLT equation for the *load voltage responses* is written in a simple matrix form as

$$\begin{bmatrix} V_1 \\ V_2 \end{bmatrix} = \begin{bmatrix} 1+\rho_1 & 0 \\ 0 & 1+\rho_2 \end{bmatrix} \cdot \begin{bmatrix} -\rho_1 & e^{\gamma L} \\ e^{\gamma L} & -\rho_2 \end{bmatrix}^{-1} \cdot \begin{bmatrix} S_1 \\ S_2 \end{bmatrix}$$

Load voltages at each end of the line

Matrix involving load reflection coefficients

Inverse matrix involving line propagation

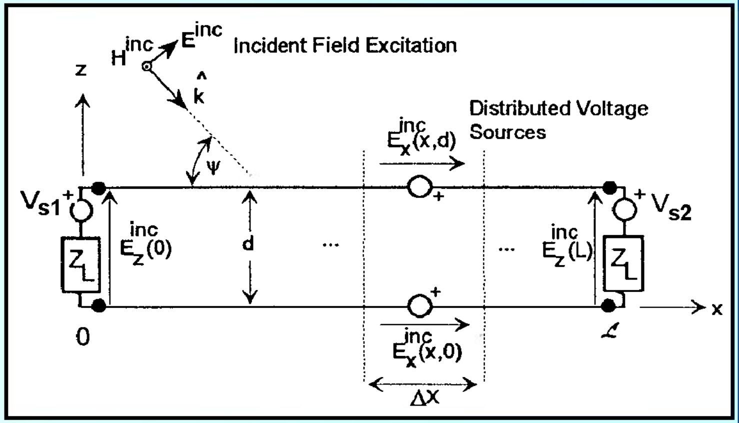
Excitation vector

– where the excitation vector for the *lumped* sources is given as

$$\begin{bmatrix} S_1 \\ S_2 \end{bmatrix} = \begin{bmatrix} \tfrac{1}{2}\left(V_s + Z_c I_s\right)e^{\gamma x_s} \\ -\tfrac{1}{2}\left(V_s - Z_c I_s\right)e^{\gamma (L - x_s)} \end{bmatrix}$$

The BLT Equation for Incident Field Excitation

- The BLT equation for a lumped voltage source can be viewed as a *Green's function*
  - The response is found by integrating over the line to incorporate the tangential E-field excitation of the line.



- The same functional form of the BLT equation is valid for *incident field* (plane-wave) excitation:

$$\begin{bmatrix} V_1 \\ V_2 \end{bmatrix} = \begin{bmatrix} 1+\rho_1 & 0 \\ 0 & 1+\rho_2 \end{bmatrix} \cdot \begin{bmatrix} -\rho_1 & e^{\gamma L} \\ e^{\gamma L} & -\rho_2 \end{bmatrix}^{-1} \cdot \begin{bmatrix} S_1 \\ S_2 \end{bmatrix}$$

☞ Only a change in the source vector is necessary:

$$\begin{bmatrix} S_1 \\ S_2 \end{bmatrix} = \frac{E^{inc} d}{2} \begin{bmatrix} \left(e^{jkL(1-\cos\psi)} - 1\right) \\ e^{jkL}\left(e^{-jkL(1+\cos\psi)} - 1\right) \end{bmatrix} \equiv E^{inc} \begin{bmatrix} F_1(\psi) \\ F_2(\psi) \end{bmatrix}$$

Note the field coupling functions F_1 and F_2

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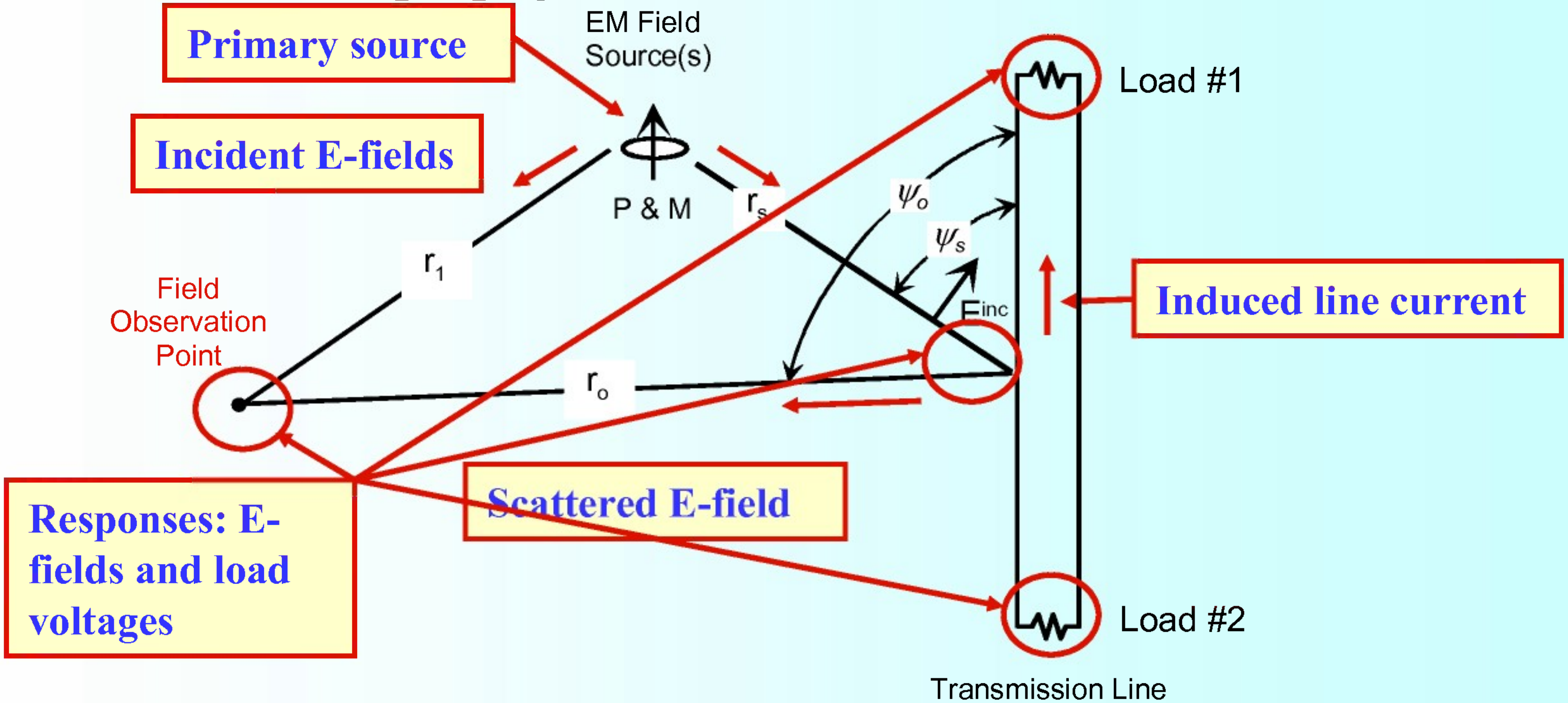
Extension of the BLT Equation to Include EM Field Propagation

- Consider the following simple problem
  - Involving transmission line responses (the "conventional" BLT problem)
  - And EM field propagation from the source to the line



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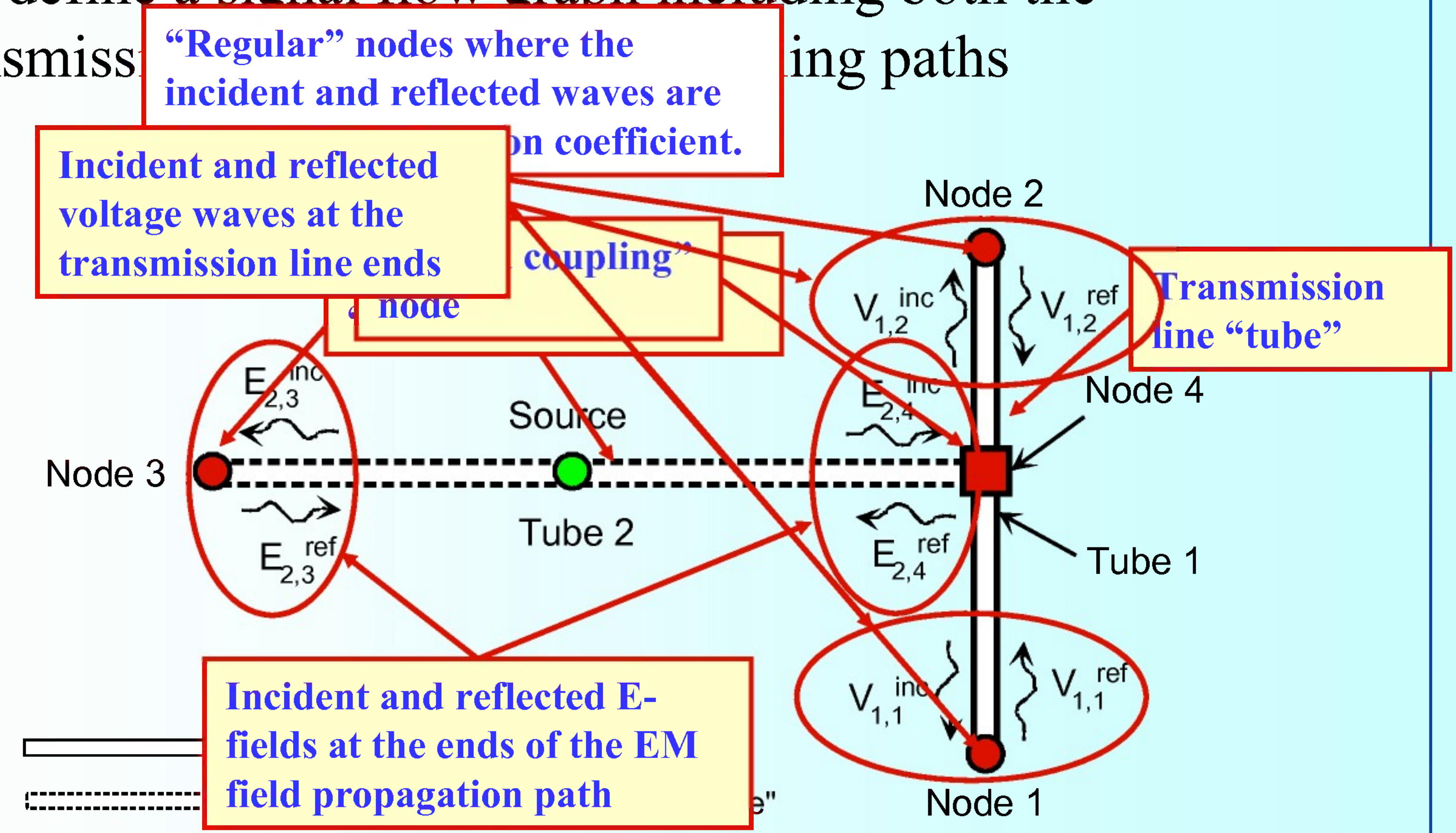
Extension of the BLT Equation (con't.)

- We define a signal flow graph including both the transmiss ing paths



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The Extended BLT Propagation Equation

- As in the case of the transmission line BLT equation, we can define a p... onship between ... and reflected v... malized E-field... tubes:

Transmission line propagation sub-matrix

Field coupling terms between the incident E-field on the line and the traveling voltage waves

Extended BLT Equation

EM field propagation sub-matrix

BLT propagation equation for a single transmission line

$$\begin{bmatrix} V_{1,1}^{ref} \\ V_{1,2}^{ref} \\ a_3 E_{2,3}^{ref} \\ a_4 E_{2,4}^{ref} \end{bmatrix} = \left[\begin{matrix} 0 & e^{\gamma L} & 0 \\ e^{\gamma L} & 0 & 0 \\ -\frac{jk Z_o}{2\pi a_3 Z_c} F_1(\psi_o) & -\frac{jk Z_o}{2\pi a_4 Z_c} F_2(\psi_o) & \frac{r_o}{a_4} e^{jk r_o} \end{matrix} \right] \begin{bmatrix} V_{1,1}^{inc} \\ V_{1,2}^{inc} \\ a_3 E_{2,3}^{inc} \\ a_4 E_{2,4}^{inc} \end{bmatrix} + \begin{bmatrix} -\frac{1}{2}(V_s + Z_c I_s) e^{\gamma x_s} \\ +\frac{1}{2}(V_s - Z_c I_s) e^{\gamma (L - x_s)} \\ S_1(\psi_s) \frac{r_o e^{jk(r_o - r_s)}}{r_s} \\ S_2(\psi_s) \frac{r_o e^{jk(r_o - r_1)}}{r_1} \end{bmatrix}$$

$$\begin{bmatrix} V_1^{ref}(0) \\ V_2^{ref}(0) \end{bmatrix} = \begin{bmatrix} 0 & e^{\gamma L} \\ e^{\gamma L} & 0 \end{bmatrix} \cdot \begin{bmatrix} V_1^{inc}(0) \\ V_2^{inc}(0) \end{bmatrix} + \ldots$$

Note that the E-fields are normalized by suitable lengths a_3 and a_4, which are typical dimensions of the nodes

...e that both the coupling an... ...ation terms contain the sa... functions F_1 and F_2 --- a conse... of reciprocity

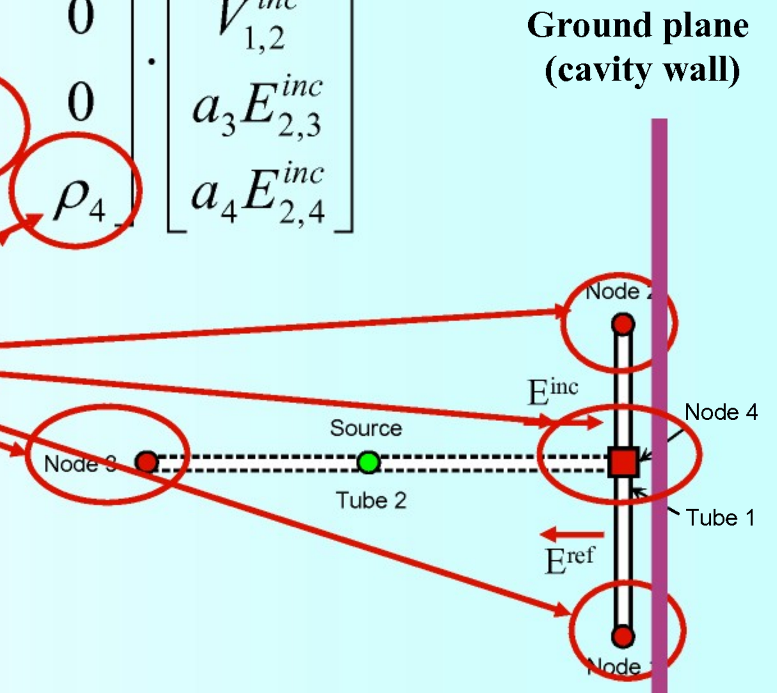
4-vector of incident voltage waves on the tubes

...ith the source functions

The Extended BLT Reflection Coefficient Matrix

- Similarly, we define an *extended* reflection coefficient matrix, which is similar to the 2x2 matrix for the simple transmission line:

$$\begin{bmatrix} V_{1,1}^{ref} \\ V_{1,2}^{ref} \\ a_3 E_{2,3}^{ref} \\ a_4 E_{2,4}^{ref} \end{bmatrix} = \begin{bmatrix} \rho_1 & 0 & 0 & 0 \\ 0 & \rho_2 & 0 & 0 \\ 0 & 0 & \rho_3 & 0 \\ 0 & 0 & 0 & \rho_4 \end{bmatrix} \cdot \begin{bmatrix} V_{1,1}^{inc} \\ V_{1,2}^{inc} \\ a_3 E_{2,3}^{inc} \\ a_4 E_{2,4}^{inc} \end{bmatrix}$$



ρ_3 … re… us… … that … wall … the

ρ_4 (which = 0 in this example) corresponds to E-field reflection at node 4, in the absence of the transmission line. The line has already been taken into account in the propagation and coupling matrix.

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The Extended Voltage BLT Equation

- The BLT reflection and propagation matrix equations can be combined just like the single transmission line case to yield the *extended* BLT equation for the load voltages and normalized E-fields:

$$\begin{bmatrix} V_{1,1} \\ V_{1,2} \\ a_3 E_{2,3} \\ a_4 E_{2,4} \end{bmatrix} = \begin{bmatrix} 1+\rho_1 & 0 & 0 & 0 \\ 0 & 1+\rho_2 & 0 & 0 \\ 0 & 0 & 1+\rho_3 & 0 \\ 0 & 0 & 0 & 1+\rho_4 \end{bmatrix} \cdot \begin{bmatrix} -\rho_1 & e^{\gamma L} & 0 & -\frac{1}{a_4} F_1(\psi) \\ e^{\gamma L} & -\rho_2 & 0 & -\frac{1}{a_4} F_2(\psi) \\ 0 & 0 & -\rho_3 & \frac{r_o}{a_3} e^{jkr_o} \\ -\frac{jk}{2\pi a_4}\frac{Z_o}{Z_c} F_1(\psi_o) & -\frac{jk}{2\pi a_4}\frac{Z_o}{Z_c} F_2(\psi_o) & \frac{r_o}{a_4} e^{jkr_o} & -\rho_4 \end{bmatrix}^{-1} \cdot \begin{bmatrix} 0 \\ 0 \\ S_1(\psi_s)\frac{r_o e^{jk(r_o - r_s)}}{r_s} \\ S_2(\psi_1)\frac{r_o e^{jl(r_o - r_1)}}{r_1} \end{bmatrix}$$

BLT voltage equation for a single transmission line

$$\begin{bmatrix} V_1 \\ V_2 \end{bmatrix} = \begin{bmatrix} 1+\rho_1 & 0 \\ 0 & 1+\rho_2 \end{bmatrix} \cdot \begin{bmatrix} -\rho_1 & e^{\gamma L} \\ e^{\gamma L} & -\rho_2 \end{bmatrix}^{-1} \cdot \begin{bmatrix} S_1 \\ S_2 \end{bmatrix}$$

The extended BLT voltage equation

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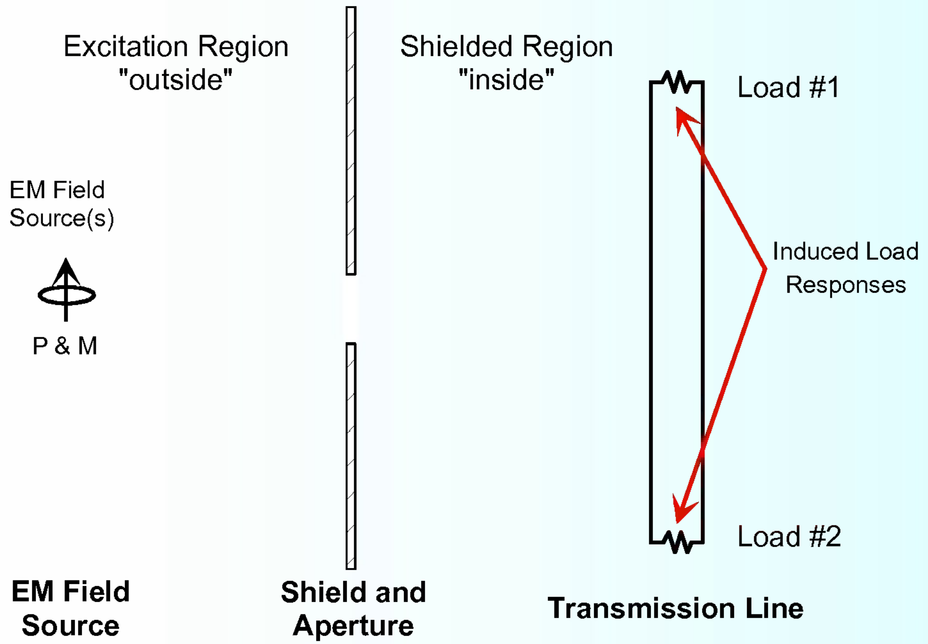
Summary

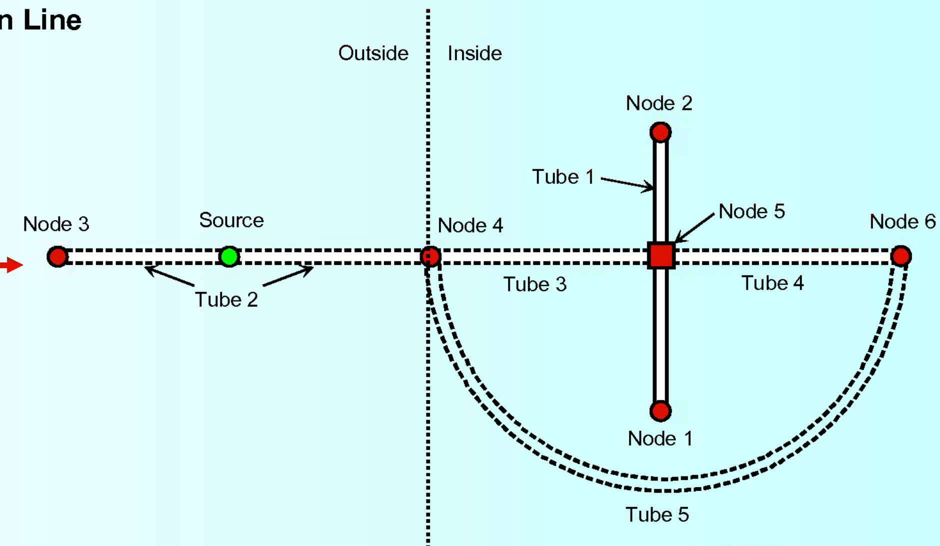
- A modified BLT equation, taking into account EM field propagation paths in addition to the usual transmission line propagation mechanisms, has been developed.
  - This required modifying the BLT propagation matrix to include the field coupling to the transmission line and the EM scattering from the line.
  - These features have been illustrated with a very simple example.
- The next step in this development will be to include the more general case of EM shields with apertures, and multiple field paths, as shown in the next slide …….

Work Currently Underway …



Transmission line within a simple shielded region with an aperture

Interaction diagram, showing both field propagation and transmission line propagation paths



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