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A DEPARTMENT OF HOMELAND SECURITY CENTER OF EXCELLENCE

Annual Review: EMP Risk Assessment and Mitigation Prioritization

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5G Infrastructure Resilience

- Electromagnetic Pulse (EMP) attacks have the potential to disrupt and damage electronics throughout our nation's critical infrastructure, posing a serious risk to that infrastructure. Assessing the risk of such events is extremely challenging due to the complexity of our systems.

- This project addressed the threat of EMP to our nation's critical infrastructure, which includes our nation's power grid and mobile communication systems.

Our Approach

- Use uncertainty and randomness as a means of tackling and overcoming complexity for the purpose of mitigation
- This approach differs fundamentally from traditional methods that cannot account for the multi-scale material and geometry complexity and the variabilities and uncertainties inherently present in the EMP problem due to the computational complexities.
- Our goals included both developing this capability and using it to assess EMP effects on the electronics in a 5G communications tower.

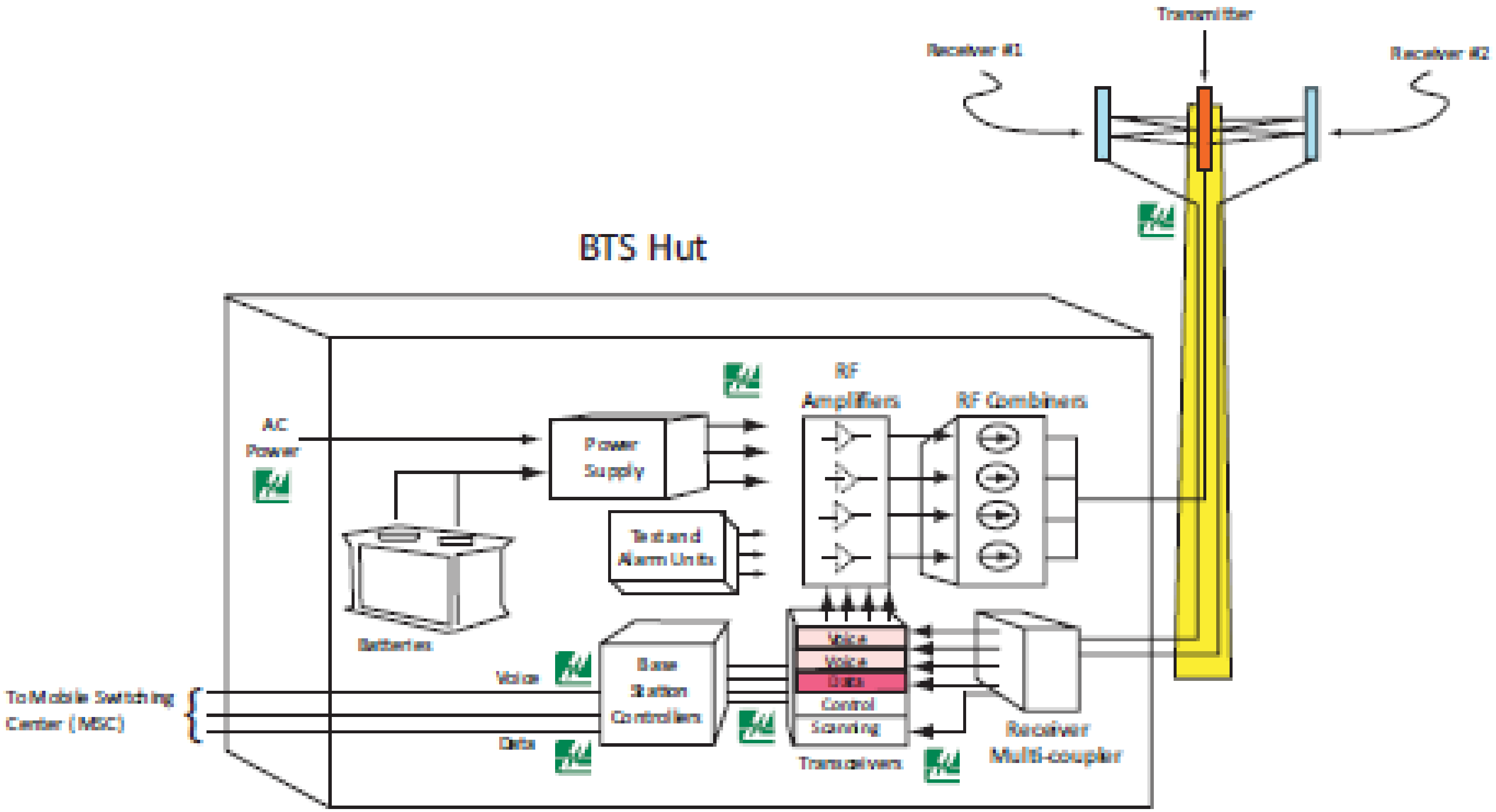
Objectives

- Ability to quickly assess and predict impact of an EMP attack on 5G infrastructure
- Ability to help preemptively mitigate effects of such attacks via Characterization, Validation, Simulation & Mitigation

Benefits & Potential Impact

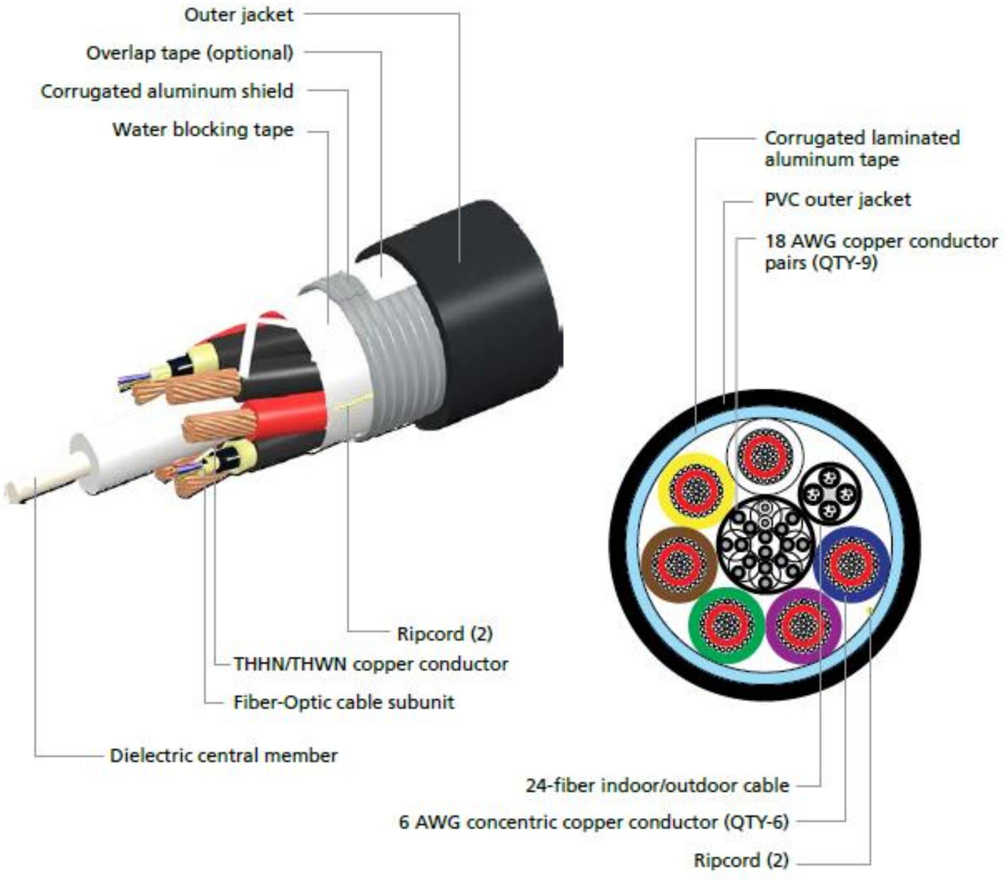
- Critical to CISA
- Accurate risk assessment of EMP attack
- Help increase resilience to EMP attack
- Facilitate mitigation measures

5G Infrastructure



Radio tower and BTS equipment used in a typical cell site location.

Hybrid Cable & Surge Protection Devices



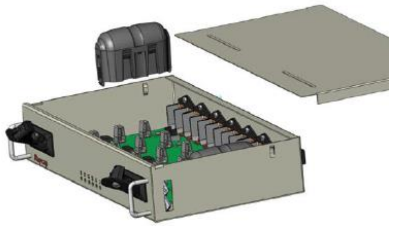
The internal structure of a hybrid cable

Typical surge protection devices (SPDs)

A gas tube surge arrestor used to ground the inner conductive layer

Inside an RRH surge protector module, cover removed

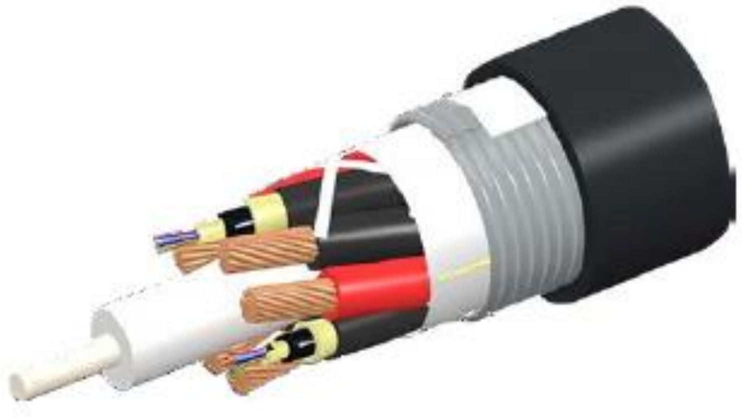
An SPD assembly mounted in a dc power and battery enclosure



The interior detail of an SPD unit designed to protect an RRH

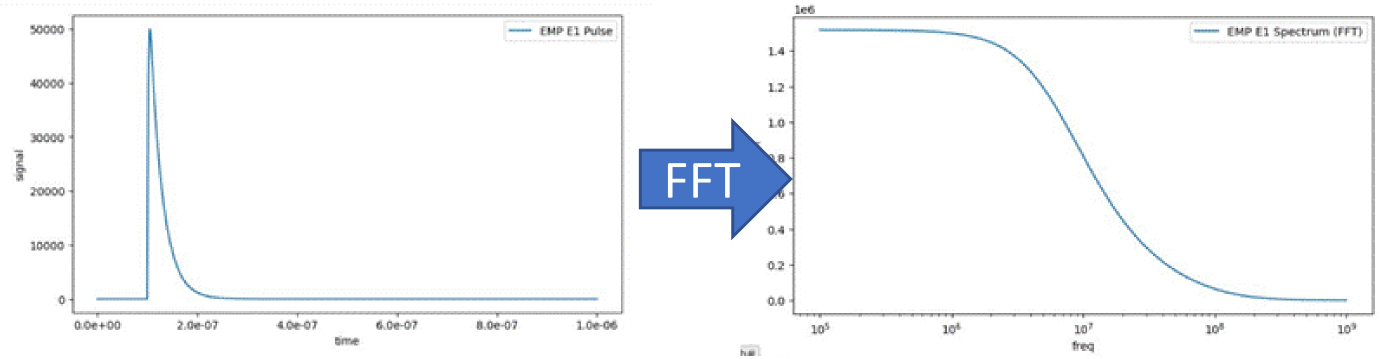
Hybrid Cable

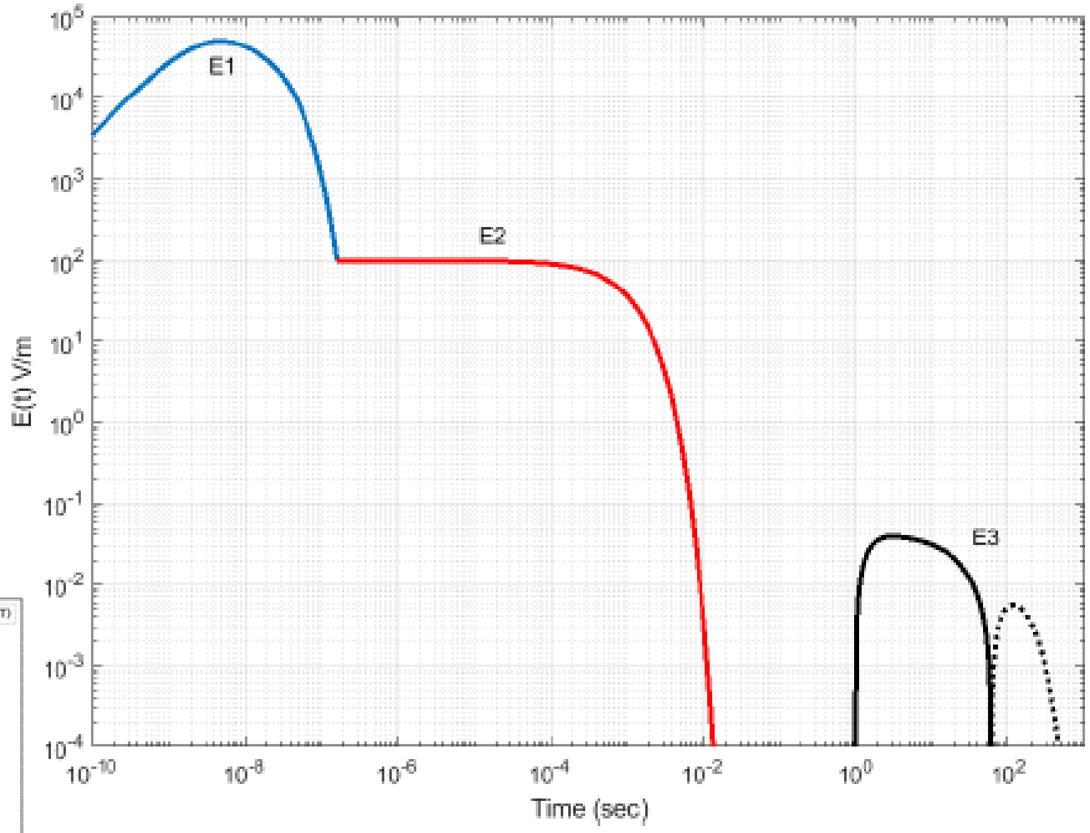
- Since fiber-optic cable uses light, not electricity, to propagate signals, it does not carry power to remote radios. A power cable must be added to provide the power to these devices: ➔ hybrid cable contains both types in a single sheath.



EMP Waveform

- Initial Focus on E1 Pulse:
  - $V = E_0 k\left(e^{-at} - e^{-bt}\right)$, where
  - $E_0 = 50kV$,
  - $k = 1.3$,
  - $a = 4e7$, and
  - $\mathrm{b} = 6\mathrm{e}8$





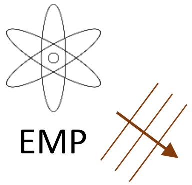
E1-EMP: 50kV/m - 400MHz

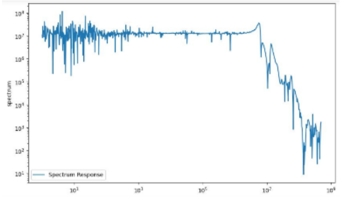
E2-EMP: 0.1kV/m - 100kHz-1MHz

E3-EMP: 10V/m - < 1Hz

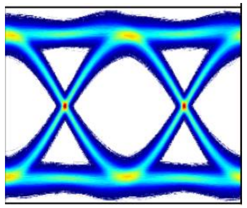
Cellular Tower EMP Model Flow

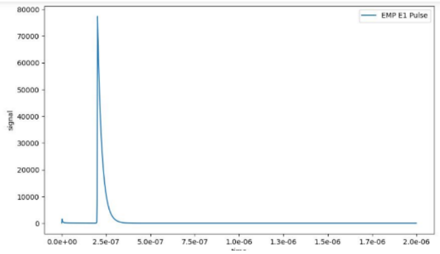
EMP Source (EMP E1 Pulse) → FFT (convert Pulse to frequency domain) → Electromagnetic Solver (SENTRi/HFSS) → Surface Fields on Cable → Compute Cable Coupling Model → LIM to produce final waveform

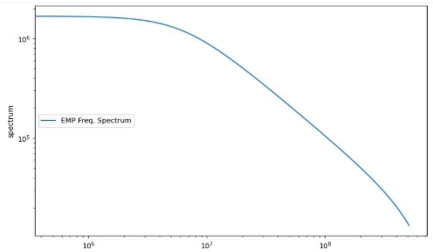


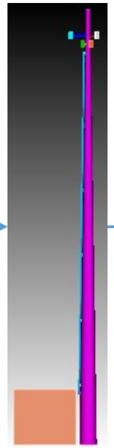


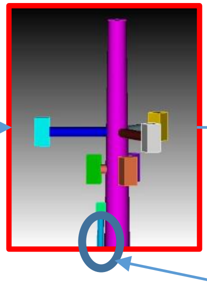
netlist

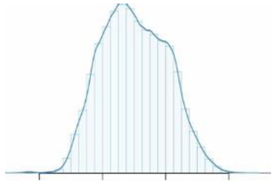












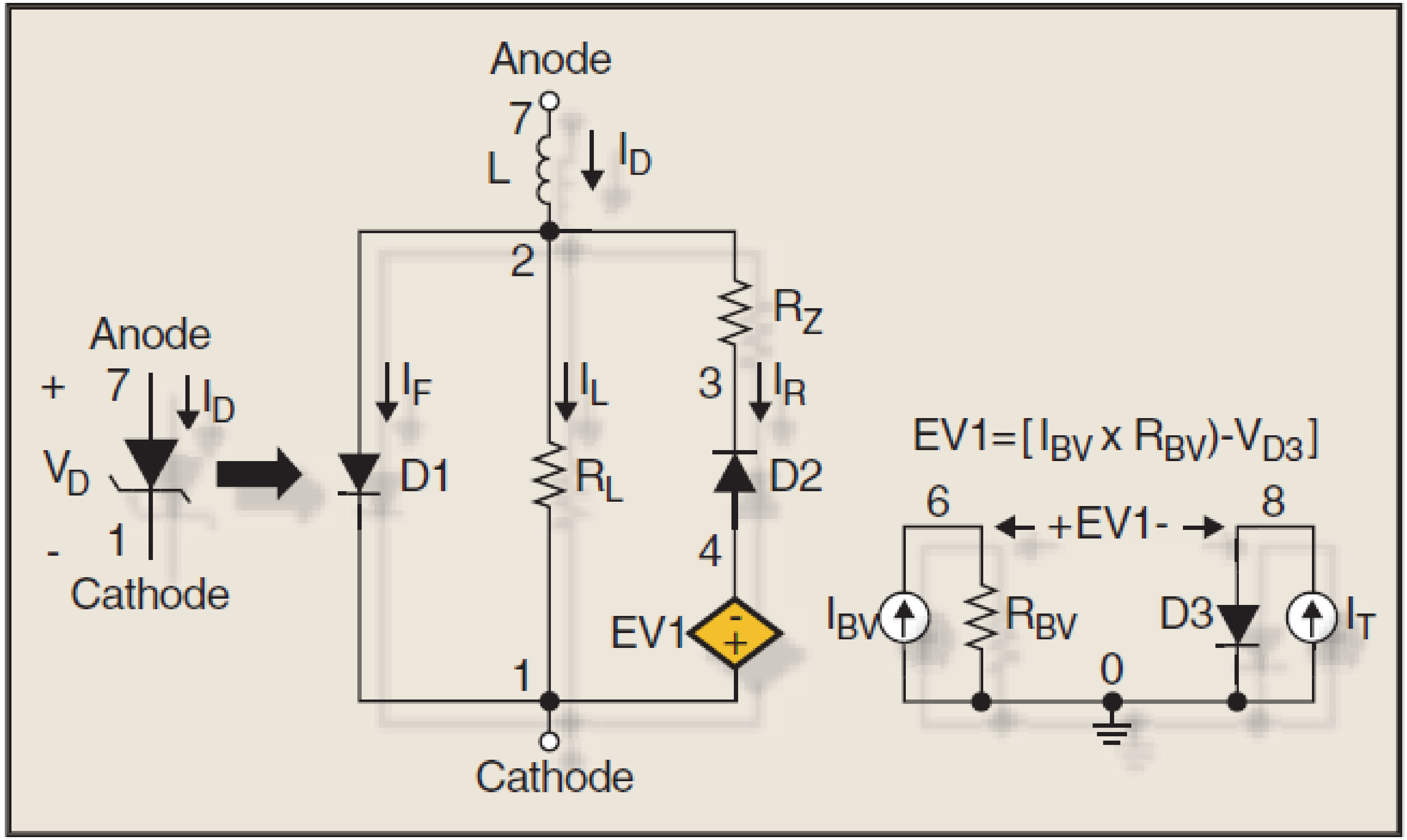
Cable runs from just below top of tower down to outside of the base station.

Accomplishments

- Extraction of Hybrid cable parameters as a function of frequency (code)
- Transient simulation of hybrid cable (code)
- Implement TVS device into simulator
- Implement MOV device into simulator
- Preliminary stochastic analysis of system

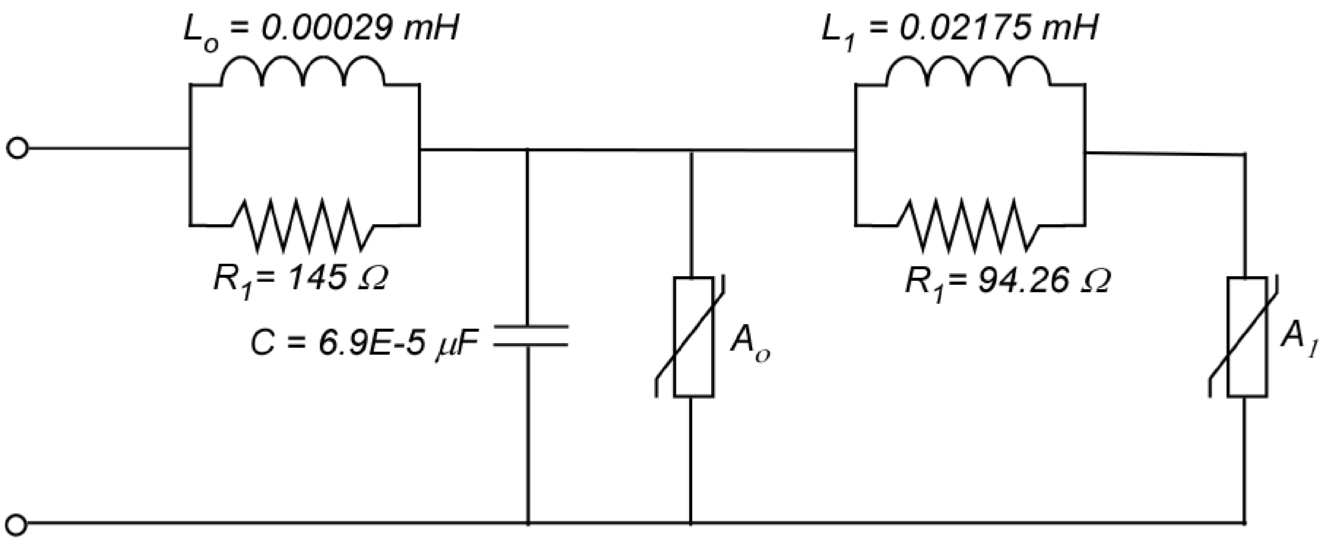
Transient Voltage Suppressors (TVS)

Circuit Model



Jim Lepkowski, Evaluating TVS Protection Circuits with SPICE, Power Electronics Technology January 2006

Modeling MOVs



Nonlinear Resistors

A0

I(kA) V(pu) V(kV)
0.01 1.40 217.0 --- 21.7 kohms
0.1 1.54 238.7 -- 2.38 kohms
1 1.68 260.4 -- 260 ohms
2 1.74 269.7 --- 134 ohms
4 1.80 279.0 --- 69.75 ohms
6 1.82 282.1 --- 47.01 ohms
8 1.87 289.9 --- 36.23 ohms
10 1.90 294.5 --- 29.45 ohms
12 1.93 299.1 --- 24.91 ohms
14 1.97 305.3 --- 21.78 ohms
16 2.00 310.0 --- 19.37 ohms
18 2.05 317.7 --- 17.65 ohms
20 2.10 325.5 -- 16 ohms

A1

I(kA) V(pu) V(kV)
0.1 1.23 190.50 --- 1.9 kohms
1 1.36 210.80 -- 210 ohms
2 1.43 221.65 -- 110.8 ohms
4 1.48 229.40 --- 57.35 ohms
6 1.50 232.50 --- 38.75 ohms
8 1.53 237.15 --- 29.64 ohms
10 1.55 240.25 --- 24.025 ohms
12 1.56 241.85 --- 20.1 ohms
14 1.58 244.95 --- 17.49 ohms
16 1.59 246.45 --- 15.4 ohms
18 1.60 248.00 --- 13.777 ohms
20 1.61 249.55 --- 12.47 ohms

LIM Simulator

synclesis

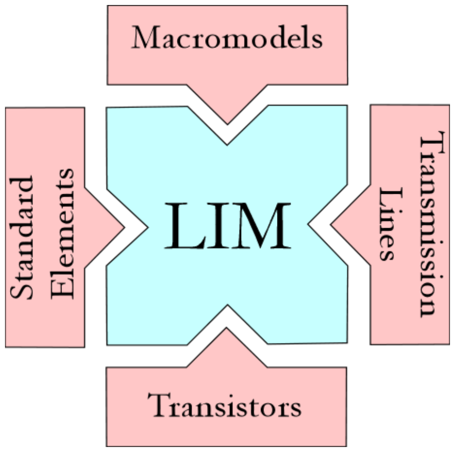
The LIM platform is optimal for accurate simulation of signals in hybrid cable

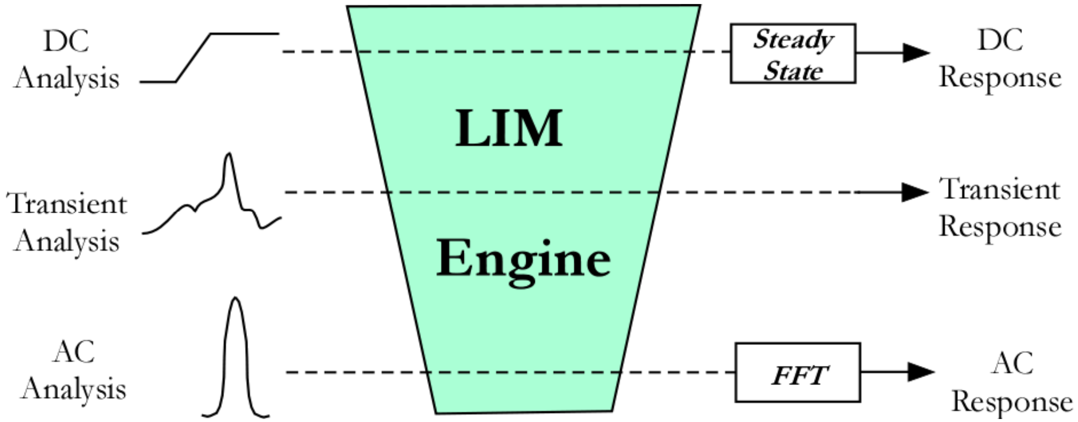
Features

- Rapid transient analysis
- Transistor-level simulations
- Frequency-dependent components
- Fast transmission-line analysis
- Large netlists
- Time step control
- Tunable accuracy and speed
- Chip, package or board

Applications

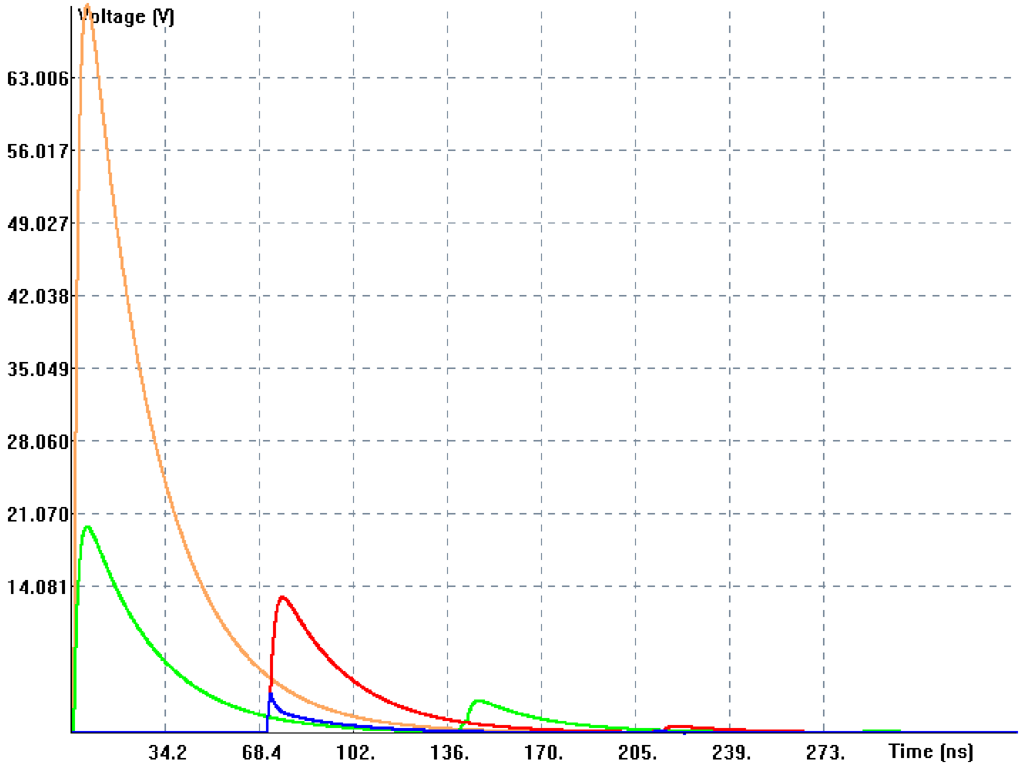
- Power Delivery Networks
- IR Drop Analysis
- Analog/Mixed Signal Simulation
- Macromodel Analysis
- IC Verification
- High-Speed Link Design



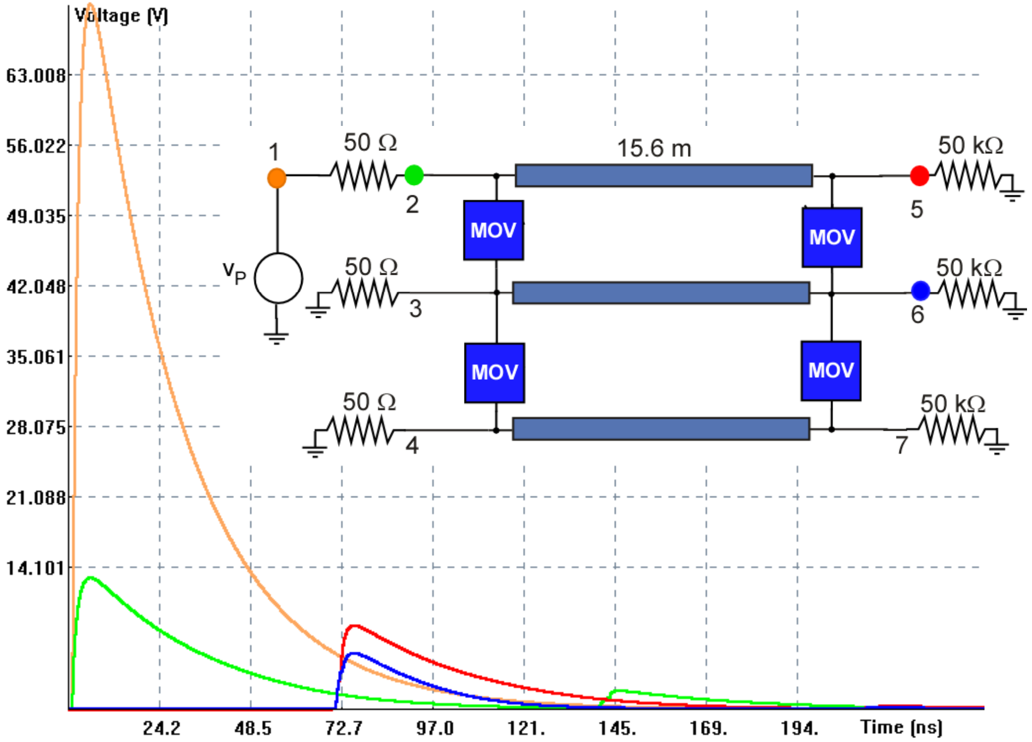


LIM Results

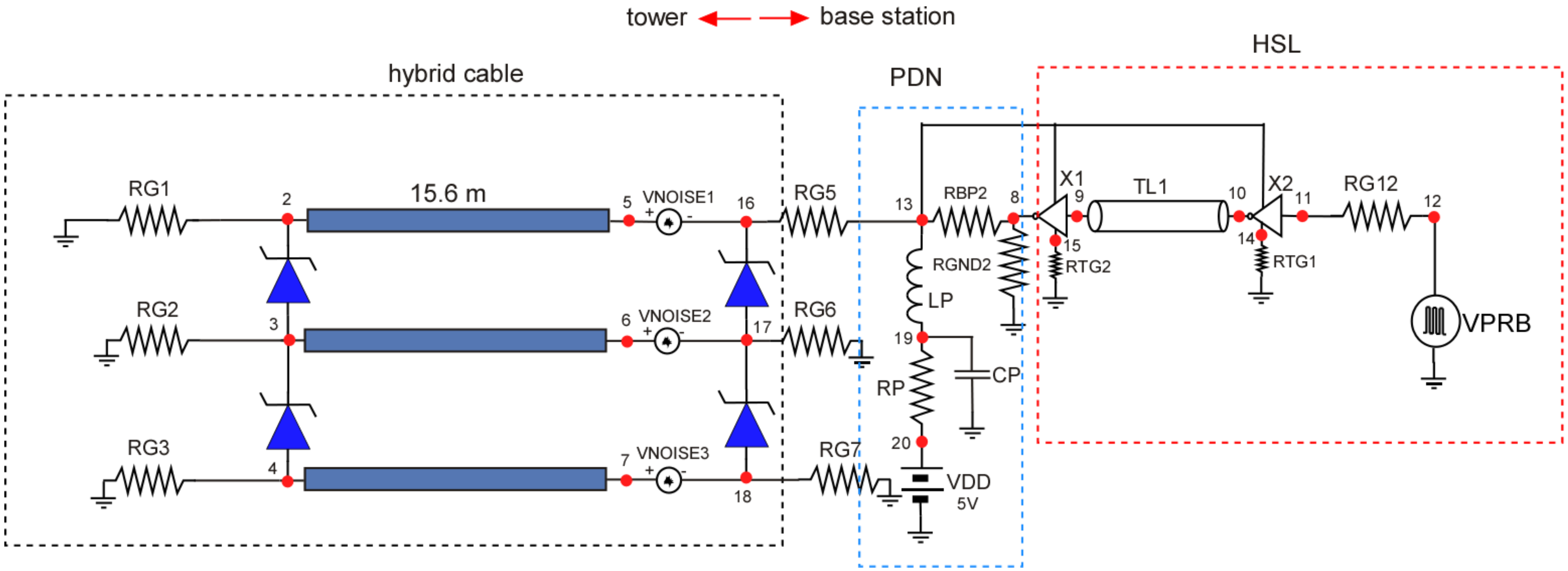
Hybrid Cable – No Suppression



Hybrid Cable – With Suppression

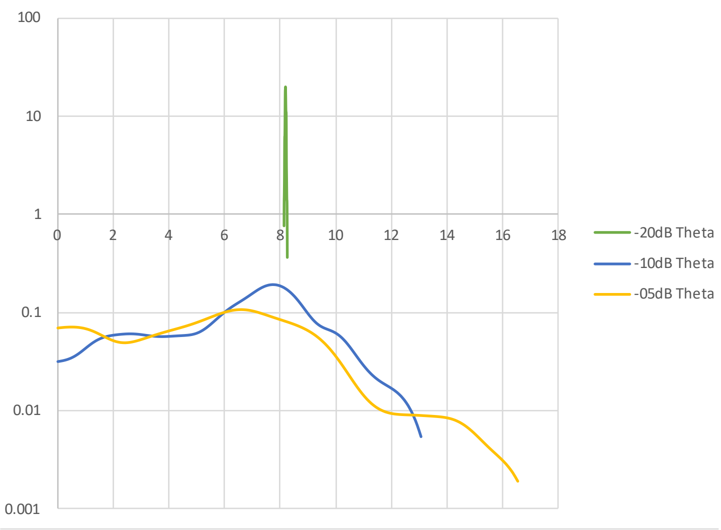


High-Speed Link Simulation

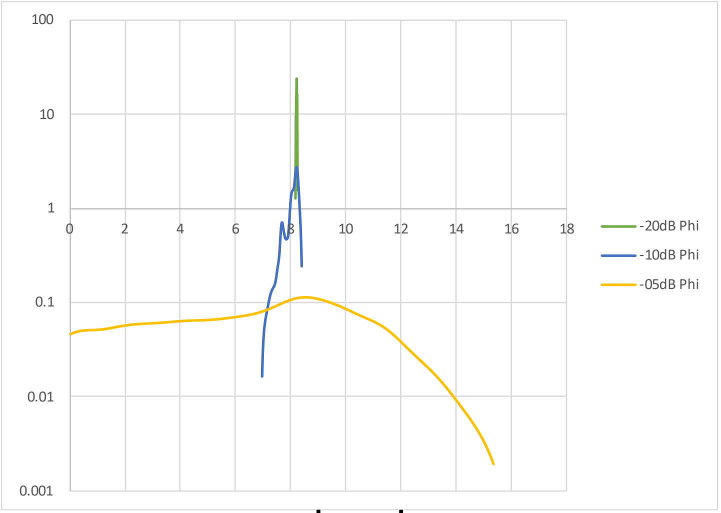


Initial Stochastic Results

- Varied Incident Angle of EMP
  - Θ and ϕ
- Evaluated at stochastic collocation points on sparse grid
  - Final Metric: Signal Eye Width
- Adjusted shielding level
  - 5dB, 10db and 20dB
- Created interpolant function from results and generated probability distribution function



Θ pol



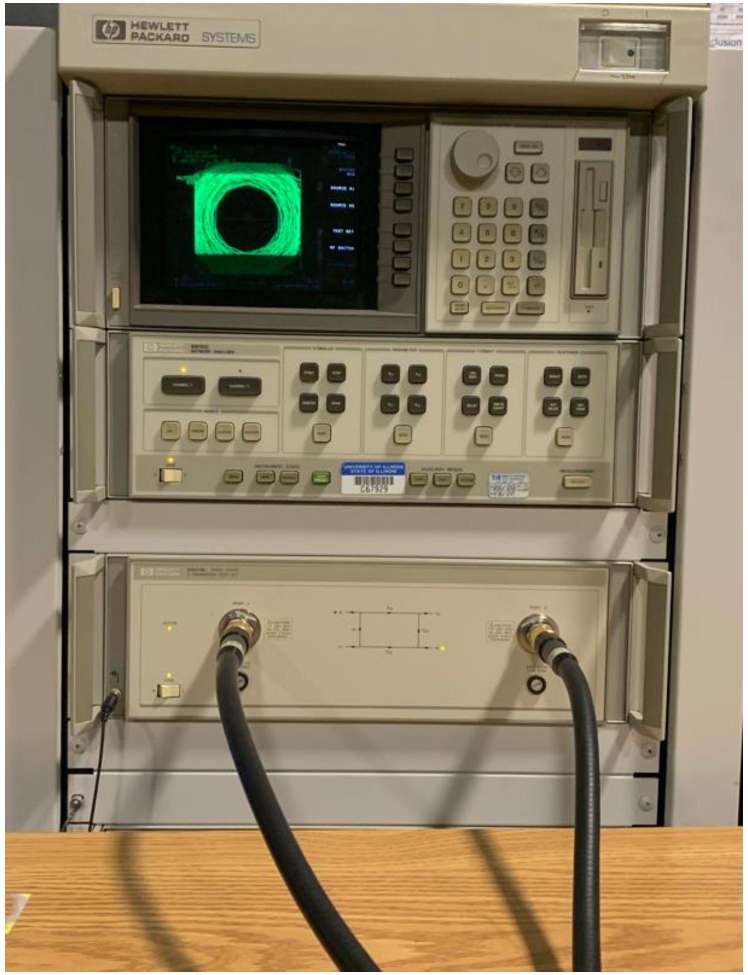
ϕ pol

Activities Remaining

- Validation & model enhancement of hybrid cable, arresters
- Behavioral modeling of PCB
- Refine EM coupling solution for surface currents
- Mitigation study via stochastic analysis→ LIM Enhancement

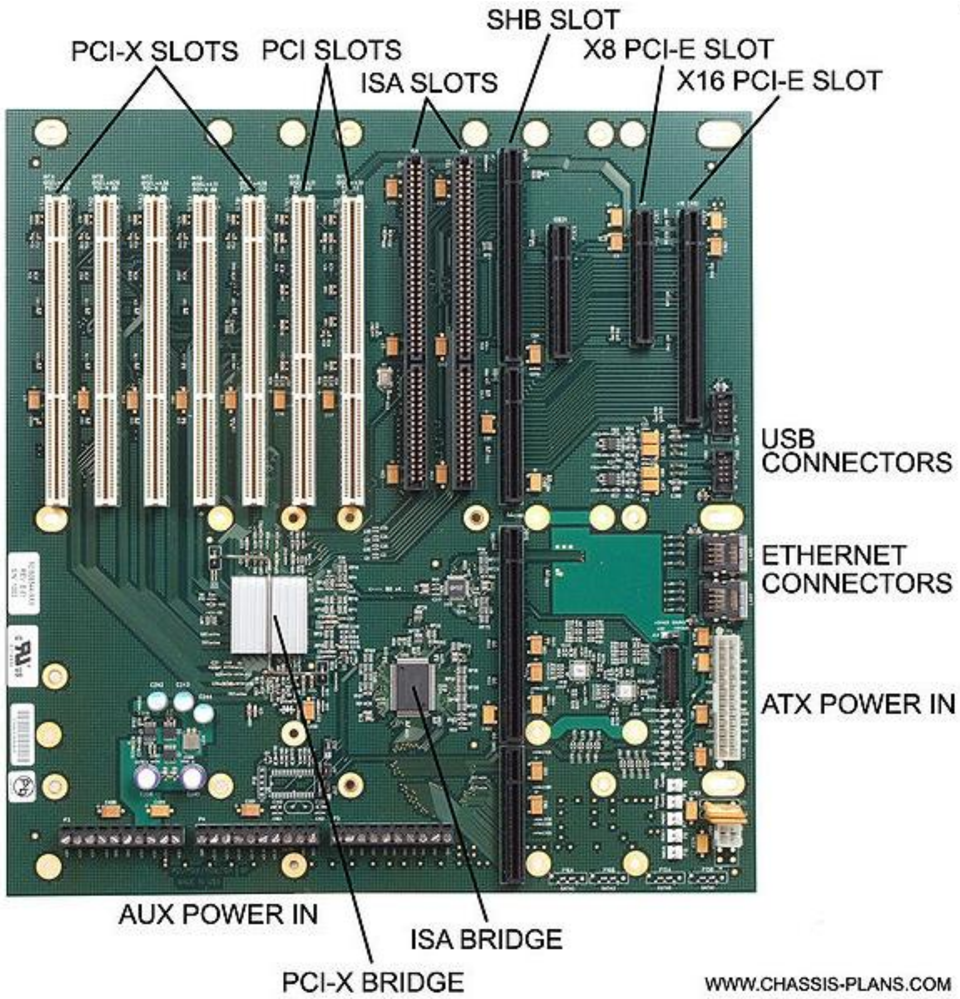
Hybrid Cable Model Validation

- Measure Cable S Parameters (VNA)
- Optimize with field solver
- Assess frequency dependence
- Perform iteration

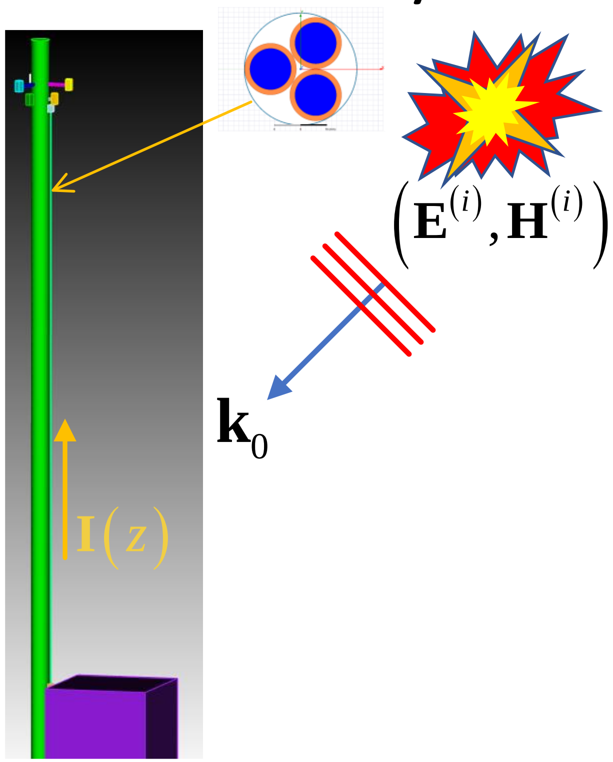


PCB Modeling

- Identify points of entry (e.g. PDN)
- Reduce complexity via behavioral modeling
- Macromodels via MOR
- IBIS model implementation
- X parameters



Accurate Computation of the Surface Currents on Hybrid Cable over Lossy Ground Illuminated by EMP Waves



- Motivation
  - Hybrid cables with lean to an 5G RF tower is a multi-scale geometry. Finite element approx-imation of multi-scale geometries are prone to ill-conditioning over EMP frequency spectra range. Numerical experiments show that US Government code SENTRi and ANSYS' HFSS break down at EMP frequencies.
- Proposal and Implementation
  - We are developing a customized code that utilizes the mixed potential integral equation together with graph-based loop-tree decomposition technique, for the accurate computation of the external currents on the shielding conductor of the hybrid cables under EMP excitation at the whole EMP spectra range.
  - Lossy ground effects will be included.

Summary

- Proof of concept established
- Electromagnetic extraction and circuit simulation are key components
- FEM field solver
- LIM simulation engine
- Validation & refining of model will provide robust tool for mitigation