The Never-ending EMC Challenge of Complex Wiring Harnesses

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Hand-Assembled Wiring Harnesses
Complexity & Randomness

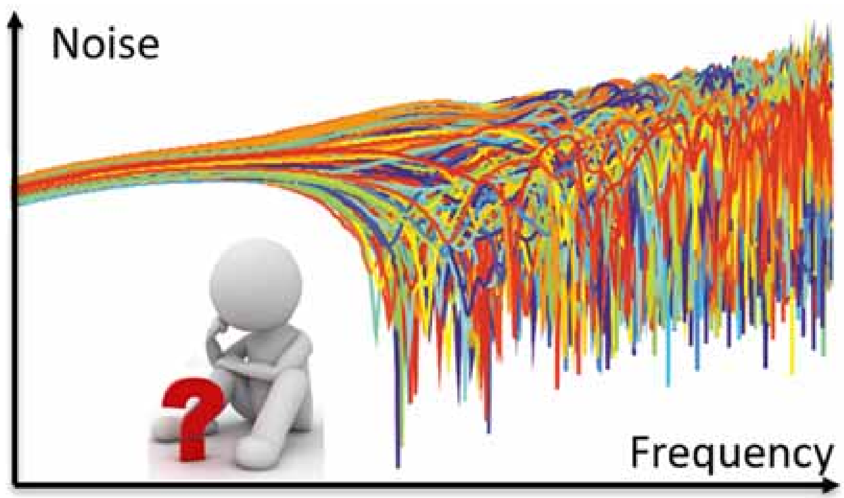
Large number of conductors

- Complex mathematical problem
- Large-size numerical problem

Incomplete information

- Unknown quantities
- Uncontrolled parameters

Large sensitivity of the induced noise



NEED FOR STATISTICAL ESTIMATES

Objectives & Challenges

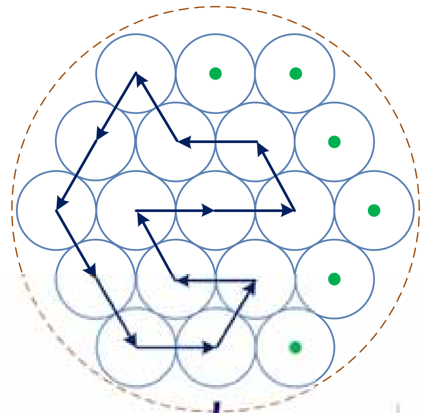
- **Objective**: Developing a **comprehensive framework** for accurate prediction/estimation of EMC properties
- **Challenge**: Reproducing the bundle main geometrical features:
  - Random paths
  - Sparse or dense cross-sections
  - Smooth trajectories
  - Different types and degree of non uniformity
  - Variable bundle path (routing)
  - …

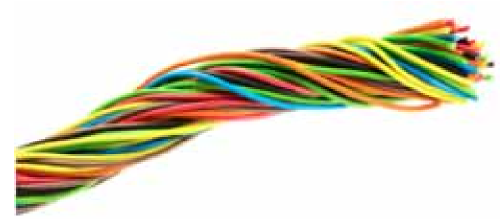
+ Computationally-efficient solution methods: TL-based?

Modeling Randomness in Wire Displacement

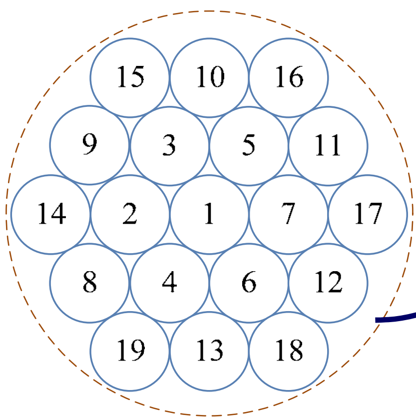
Generation algorithm

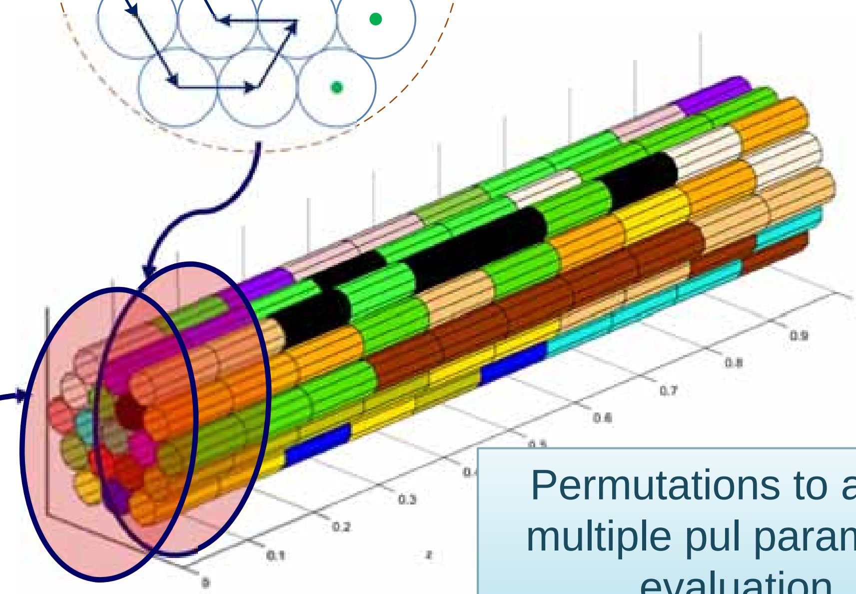
Cycles to generate different cross-sections





Reference cross-section



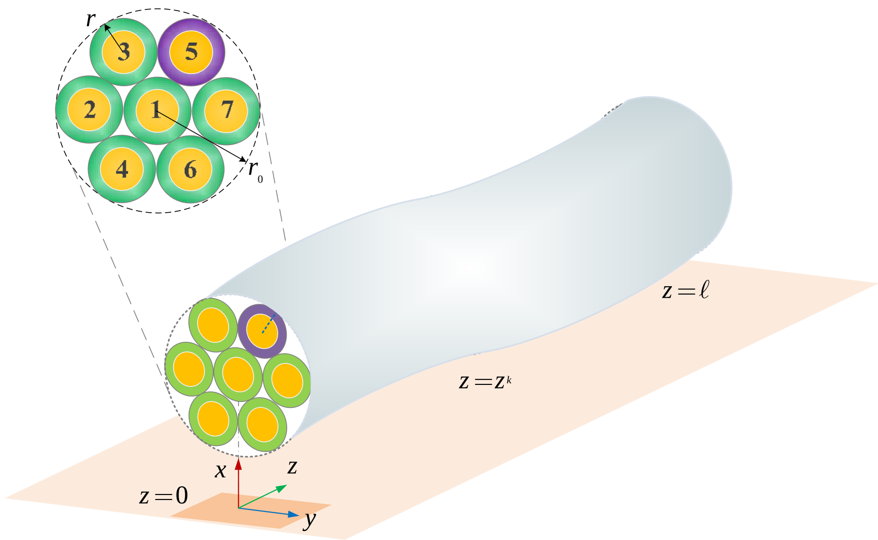


Permutations to avoid multiple pul parameter evaluation

[*] G. Spadacini, F. Grassi, S. A. Pignari, “Field-to wire coupling model for the common mode in random bundles of twisted-wire pairs,” *IEEE Trans. on Electromagn. Compat.*, vol. 57, no. 5, pp. 1246-1254, Oct. 2015.

Wire Trajectories & Physical Constraints

Generation algorithm



Wire trajectories

General **polynomial/Fourier expressions** of wires along the longitudinal axis

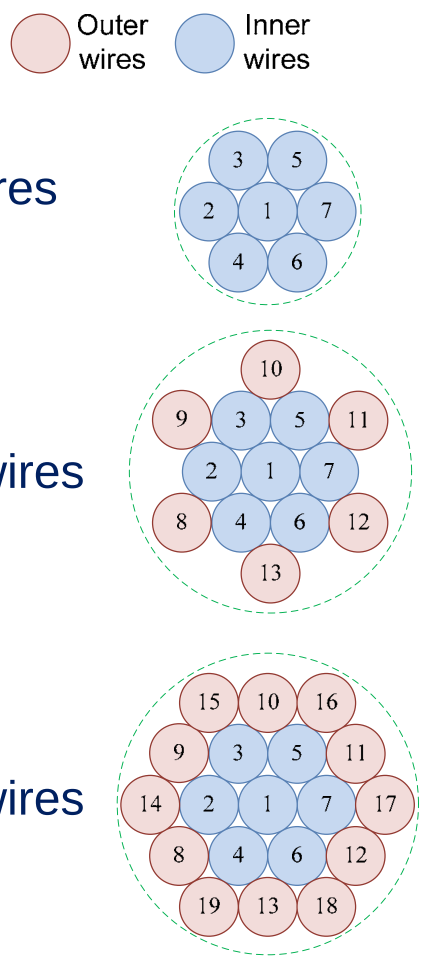
$$\mathbf{x}(z)=\mathbf{C}^{(x)}\mathbf{b}(z) \qquad \mathbf{y}(z)=\mathbf{C}^{(y)}\mathbf{b}(z)$$

Physical Constraints

Constraint	Mathematical representation
Non-overlap	$\sqrt{[x_i(z)-h]^2+y_i^2(z)}+r\le r_0,$ $i=1,\dots,N$
Continuity	$2r\le\sqrt{[x_i(z)-x_j(z)]^2+[y_i(z)-y_j(z)]^2},$ $i,j=1,\dots,N;i<j$
Compactness	$\lim_{z_i\to z^{k+}} x_i(z_i)=\lim_{z_i\to z^{k-}} x_i(z_i)=x_i(z_i),$ $\lim_{z_i\to z^{k+}} y_i(z_i)=\lim_{z_i\to z^{k-}} y_i(z_i)=y_i(z_i),$ $i=1,\dots,N, z^k\in(0,z_{\max})$

Examples of Bundle Samples

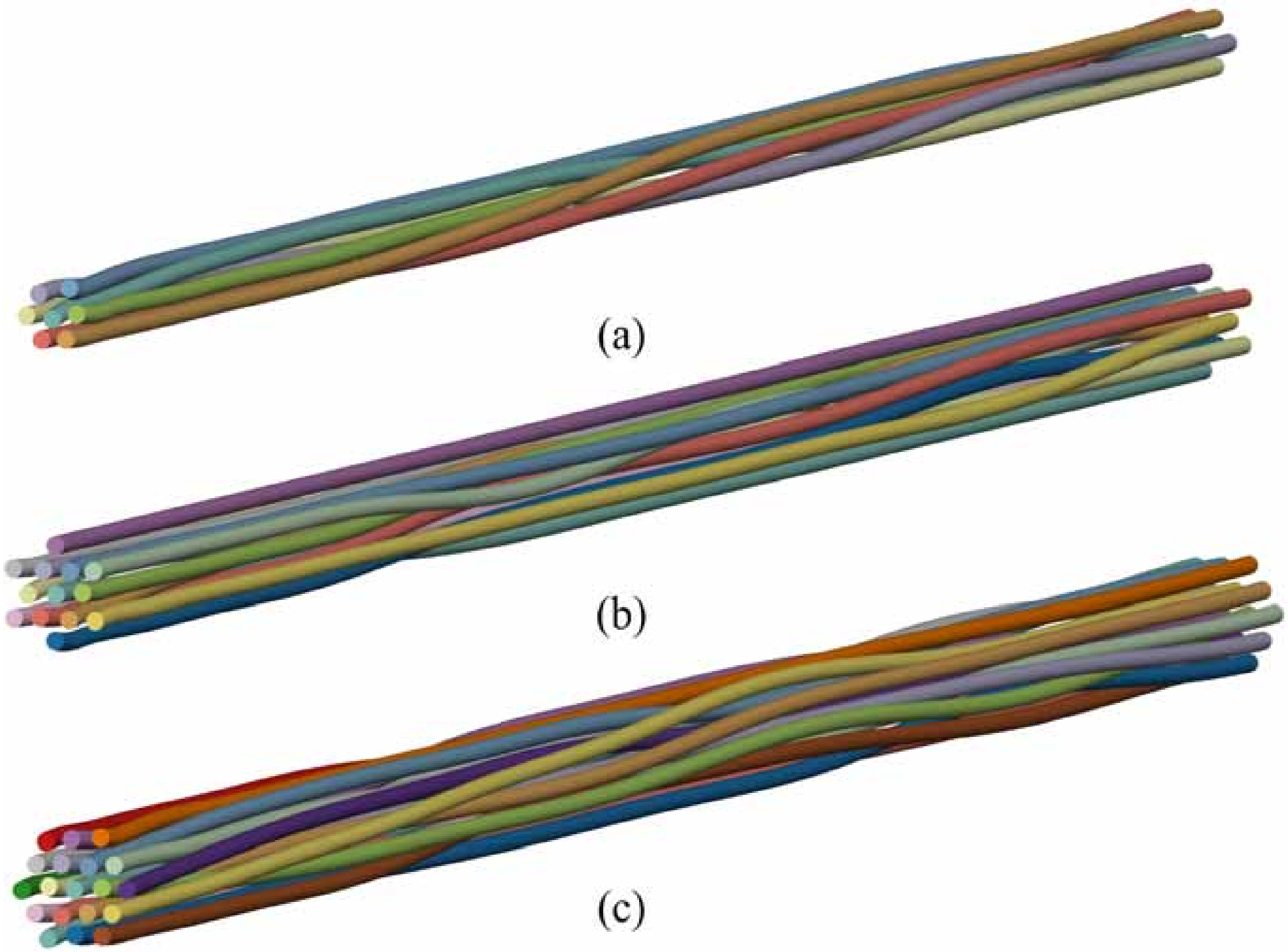
Cable axis parallel to ground



7 wires

13 wires

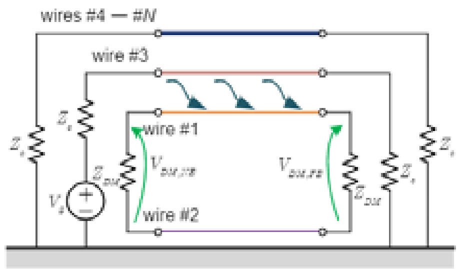
19 wires

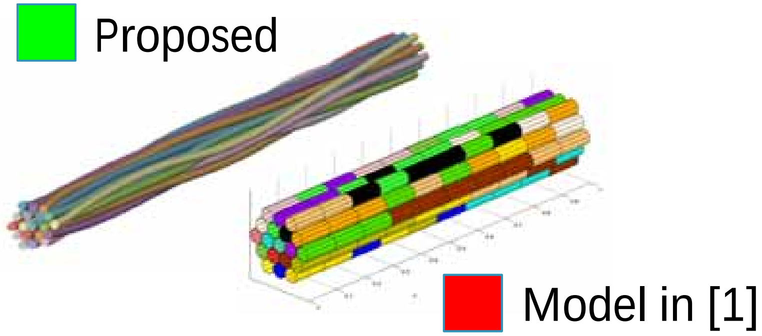


Crosstalk/Radiated Susceptibility Prediction

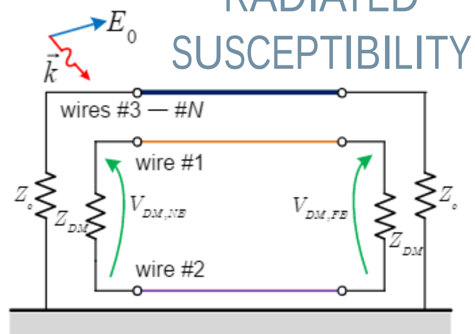
Validation vs MoM simulation

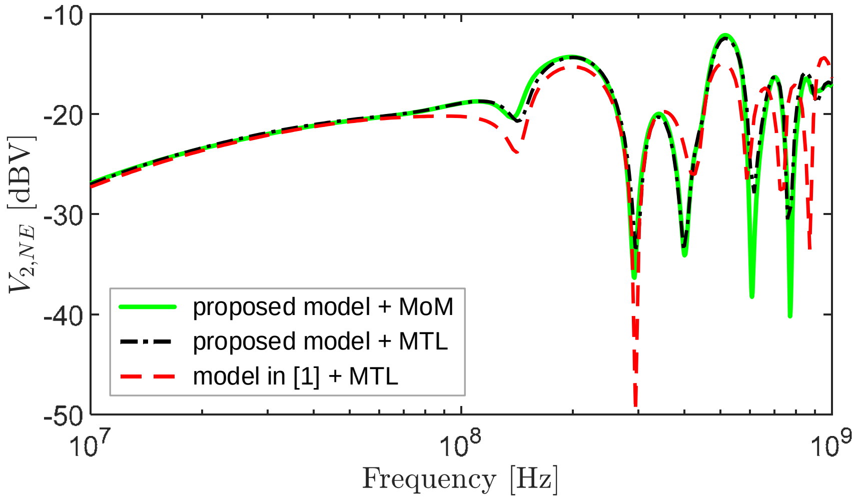
CROSSTALK

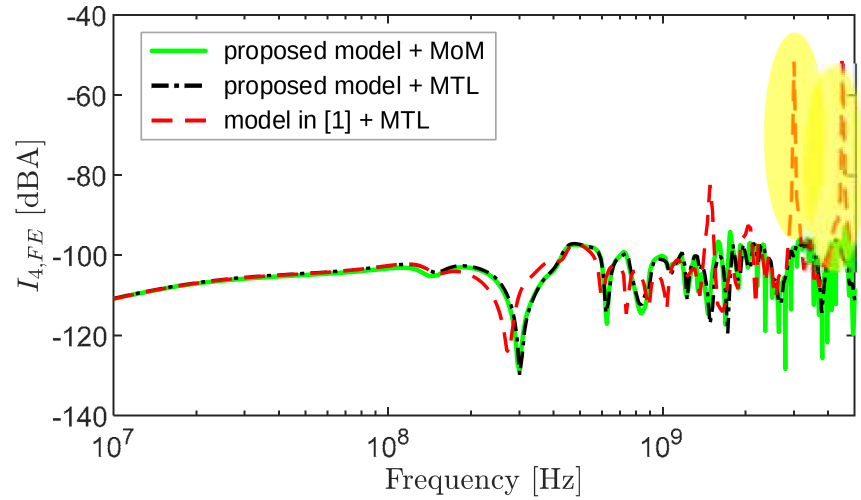




RADIATED SUSCEPTIBILITY





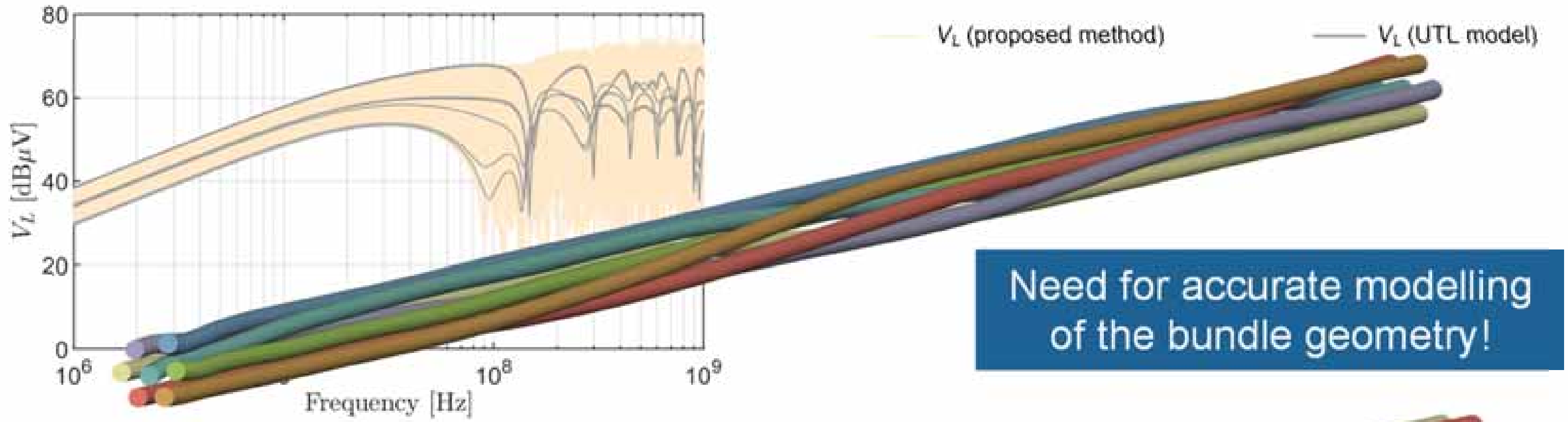


9-wire bundle. (a) XT voltage at the near end of wire #2, voltage source on wire #1. (b) Current induced at the right termination of wire #4 by a plane wave with E-field strength 1 V/m, and incidence angles $\vartheta = 45°, \eta = 45°, \psi = 45°$

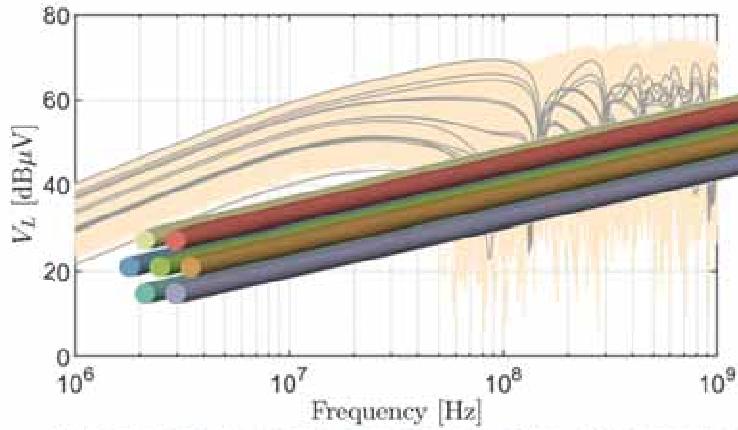
Relevance of Accurate Modelling

RS: Examples of statistical estimates

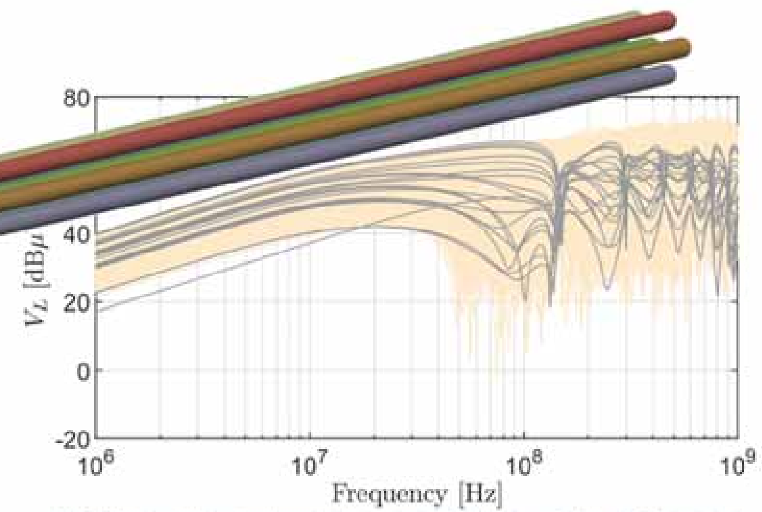
Voltages induced at the left termination: L=1 m, L_s=10 cm, r=0.5 mm



300 random-bundle samples with 7 conductors



150 random-bundle samples with 13 conductors



100 random-bundle samples with 19 conductors

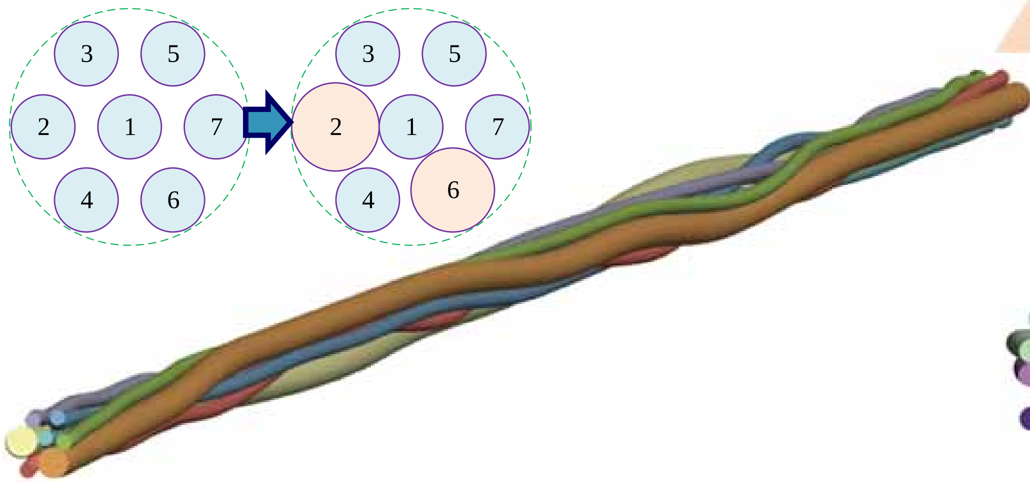
Model Generalization & Extension

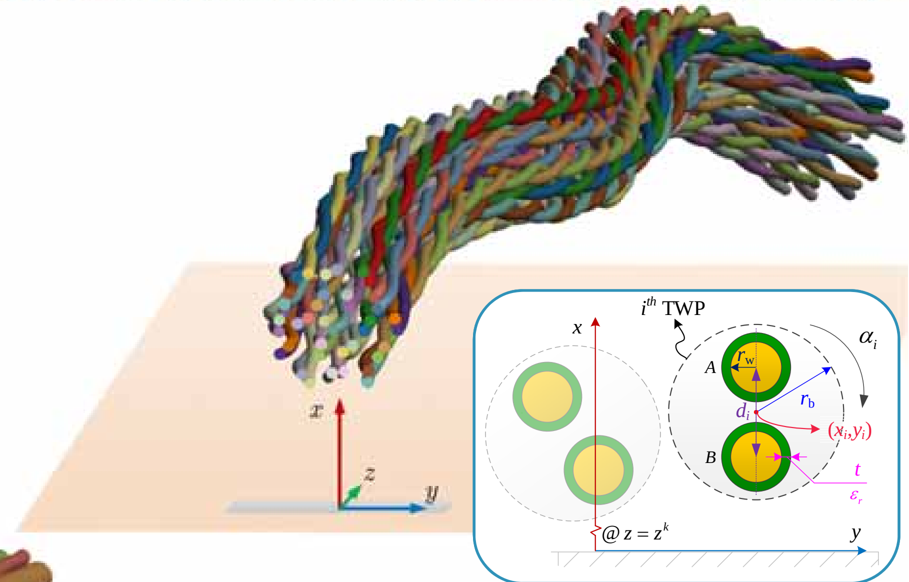
Complex bundles: Arbitrary wires and axes

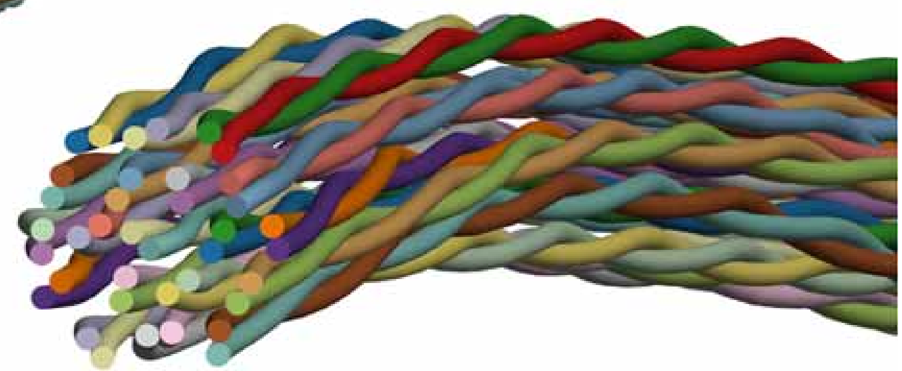
- Algorithm extension to:
  - Wires with different radii
  - Geometrical variations in 3-dimensions

$$h(z) \sim \mathcal{N}(h_{nom}, \sigma)$$

  - Bundles of TWPs

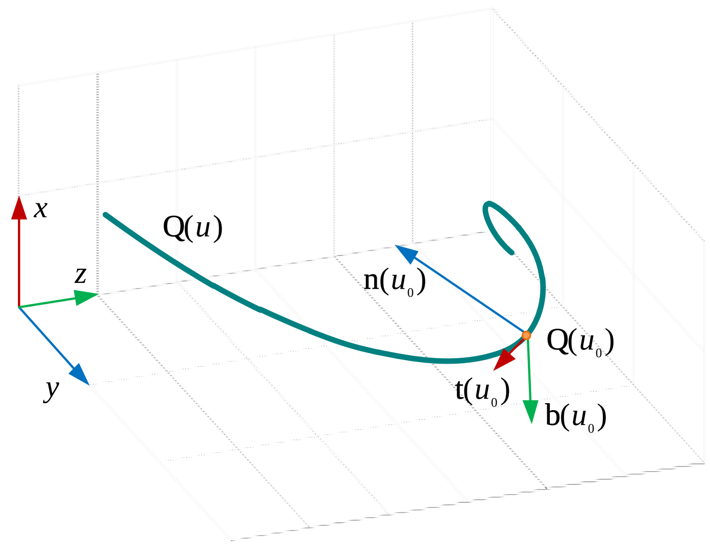






Arbitrarily-shaped Wire Bundles

Parametric representation



Basic framework

The cable geometry is modeled by its center trajectory via a **parametric curve** in a 3D Euclidean space

Smoothly varying coordinate system

e.g.: Frenet frame

$$\mathbf{t}(u) = \frac{\mathbf{Q}'(u)}{\| \mathbf{Q}'(u) \|}$$

$$\mathbf{b}(u) = \frac{\mathbf{Q}'(u) \times \mathbf{Q}''(u)}{\| \mathbf{Q}'(u) \times \mathbf{Q}''(u) \|}$$

$$\mathbf{n}(u) = \frac{\mathbf{b}(u) \times \mathbf{t}(u)}{\| \mathbf{b}(u) \times \mathbf{t}(u) \|}$$

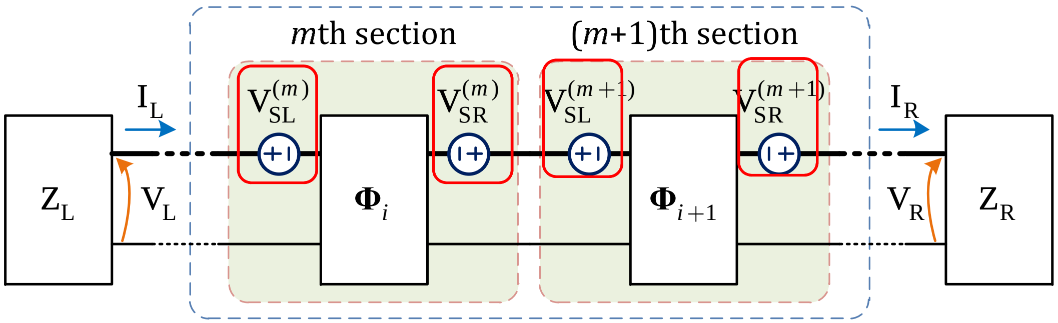
Trajectory of the n-th wire

$$\mathbf{Q}_n(\boldsymbol{u}) = \mathbf{Q}(u) + \kappa_{1,n}(u)\mathbf{n}(u) + \kappa_{2,n}(u)\mathbf{b}(u)$$

reference path — offset in the orthonormal plane

Numerical TL-Based Solution Scheme

RS Prediction



$$V_{SX,n}^{(l)} = \sum_{k=x,y,z} \xi_k\left[(a_k + jc_k)\Sigma_X + (b_k + jd_k)\Psi_X\right]$$

$$V_{SX,n}^{(v)} = -\left[E_{x,RE}\left(\mathbf{Q}_n(U_{X,n})\right) + jE_{x,IM}\left(\mathbf{Q}_n(U_{X,n})\right)\right] \cdot x_n(U_{X,n})$$

$$\xi_x = \left[x_n(U_{R,n}) - x_n(U_{L,n})\right]/\mathcal{L}_n$$

$$\xi_y = \left[y_n(U_{R,n}) - y_n(U_{L,n})\right]/\mathcal{L}_n$$

$$\xi_z = \left[x_n(U_{R,n}) - x_n(U_{L,n})\right]/\mathcal{L}_n$$

$$a_k = \left[E_{k,RE}\left(\mathbf{Q}_n(U_{R,n})\right) - E_{k,RE}\left(\mathbf{Q}_n(U_{L,n})\right)\right]/\mathcal{L}_n$$

$$b_k = E_{k,RE}\left(\mathbf{Q}_n(U_{L,n})\right)$$

$$c_k = \left[E_{k,IM}\left(\mathbf{Q}_n(U_{R,n})\right) - E_{k,IM}\left(\mathbf{Q}_n(U_{L,n})\right)\right]/\mathcal{L}_n$$

$$d_k = E_{k,IM}\left(\mathbf{Q}_n(U_{L,n})\right)$$

$$X = L, R$$

$$\Sigma_L = \frac{sin(\beta_0\mathcal{L}_n) - \beta_0\mathcal{L}_n}{\beta_0^2\, sin(\beta_0\mathcal{L}_n)}$$

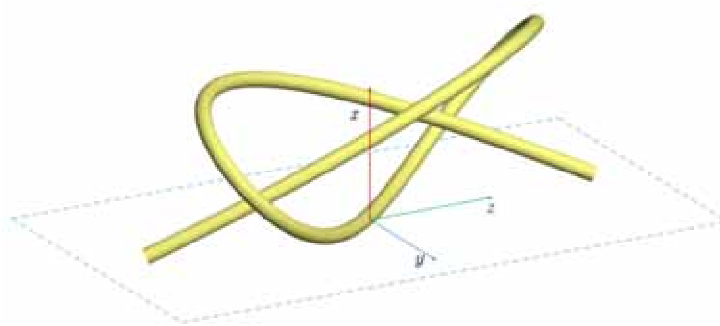
$$\Sigma_R = \frac{sin(\beta_0\mathcal{L}_n) - \beta_0\mathcal{L}_n\, cos(\beta_0\mathcal{L}_n)}{\beta_0^2\, sin(\beta_0\mathcal{L}_n)}$$

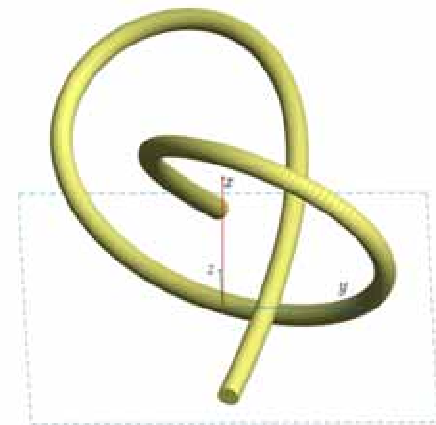
$$\Psi_{\substack{L\\R}} = \pm\frac{cos(\beta_0\mathcal{L}_n) - 1}{\beta_0\, sin(\beta_0\mathcal{L}_n)}$$

- ☺ Accurate prediction of the induced noise
- ☺ Overcomes the limitations of analytical models
  - ✓ *Computationally efficient*
  - ✓ ***Can be used when the cable geometry or the field are available by samples***
- ☺ W.r.t traditional numerical models
  - ✓ *Applicable to arbitrarily-directed bundle geometry*

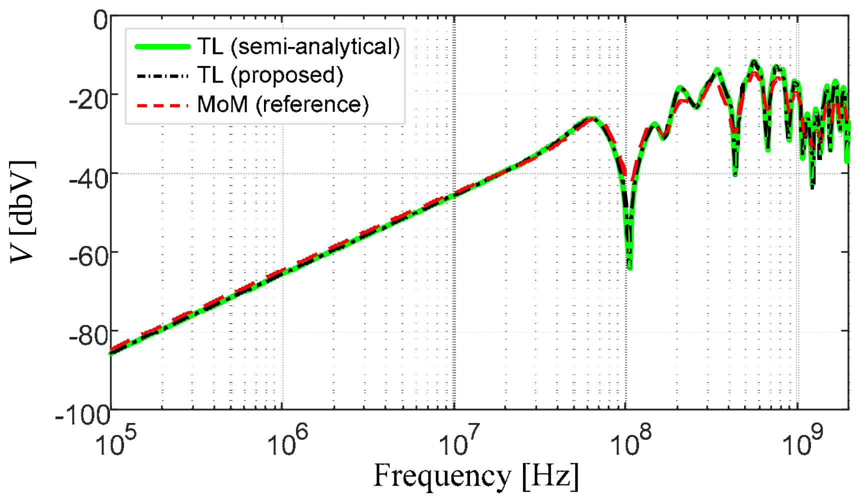
Examples of RS Prediction

Knot structures

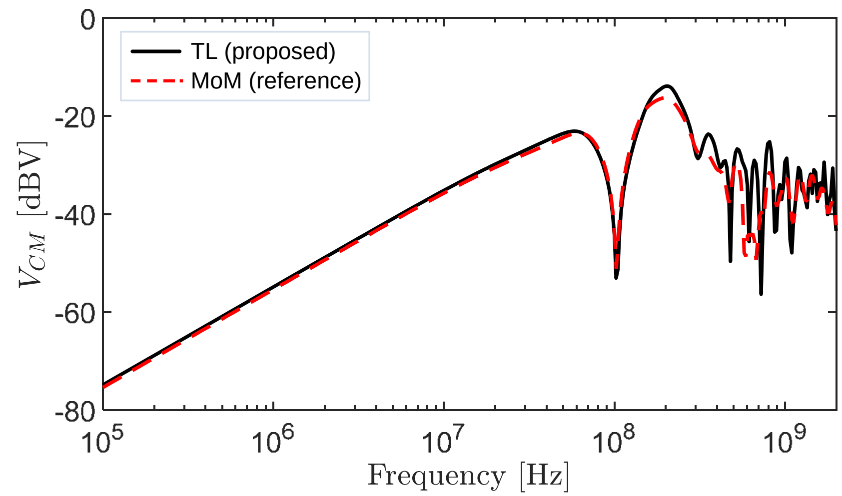




Single-wire knot: voltage at the right end



Parallel-wire knot: DM voltage at the left end



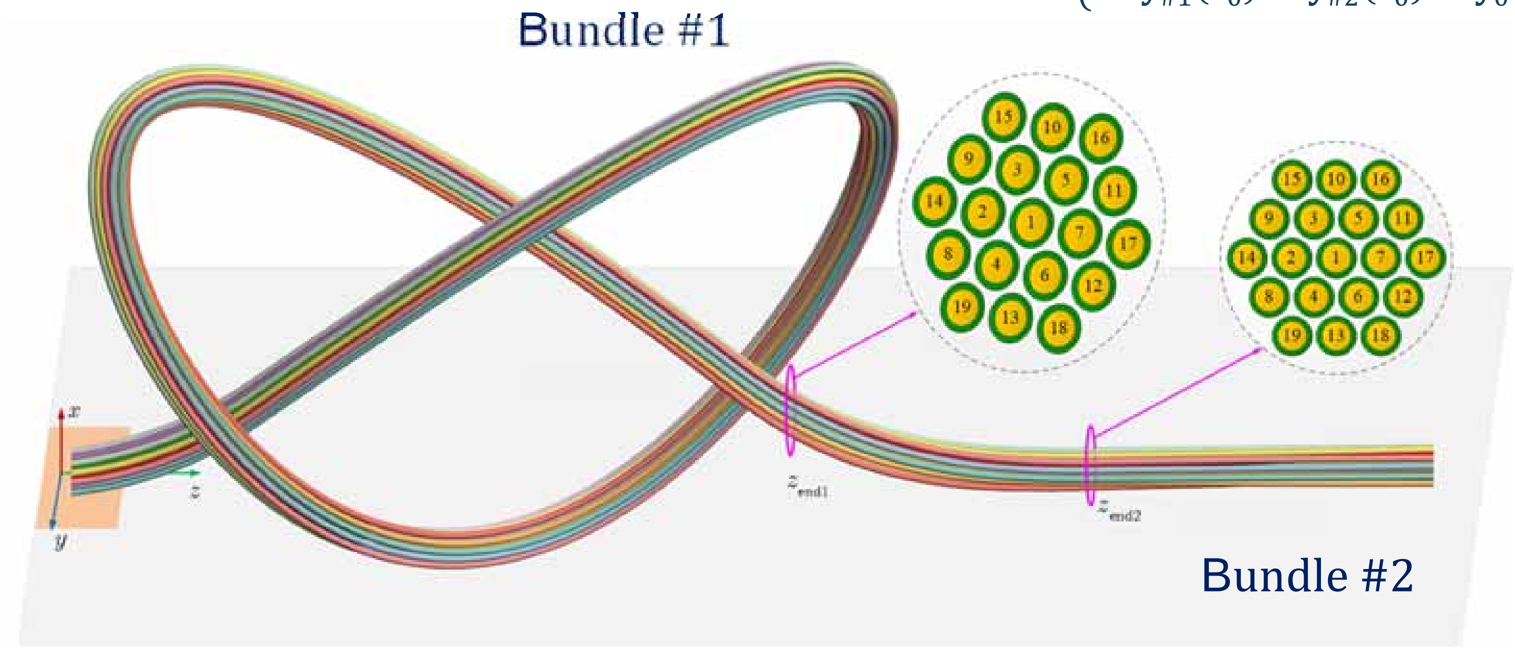
Towards a More General Framework …

Combination of previous models

- Complex geometries are generated by properly interconnecting previous models

$$\begin{cases} \mathbf{x}_{\#1}(z) = \mathbf{C}_{\#1}{}^{(x)}\mathbf{b}_{\#1}(z) \\ \mathbf{y}_{\#1}(z) = \mathbf{C}_{\#1}{}^{(y)}\mathbf{b}_{\#1}(z) \\ \mathbf{x}_{\#2}(z) = \mathbf{C}_{\#2}{}^{(x)}\mathbf{b}_{\#2}(z) \\ \mathbf{y}_{\#2}(z) = \mathbf{C}_{\#2}{}^{(y)}\mathbf{b}_{\#2}(z) \end{cases},$$

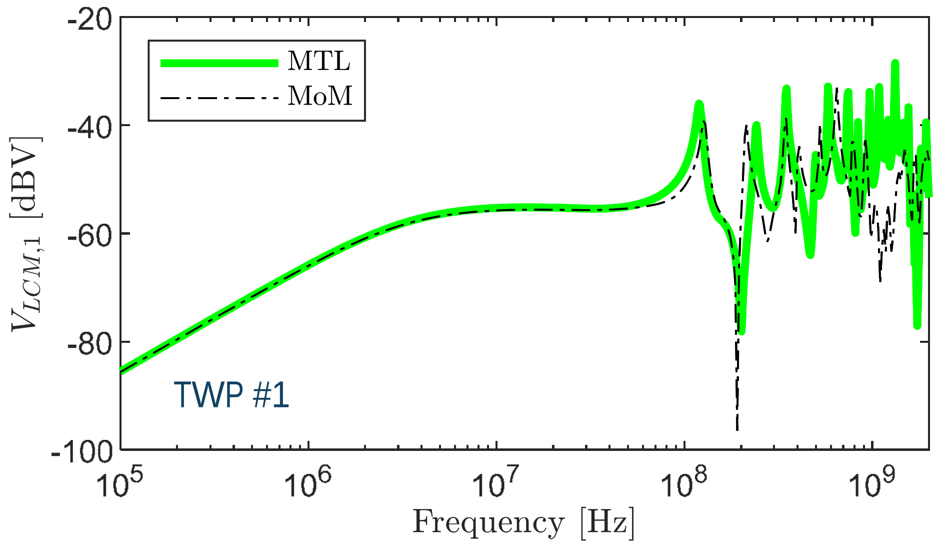
$$s.t. \begin{cases} \mathbf{x}_{\#1}(z_0) = \mathbf{x}_{\#2}(z_0) = \mathbf{x}_0 \\ \mathbf{y}_{\#1}(z_0) = \mathbf{y}_{\#2}(z_0) = \mathbf{y}_0 \end{cases}$$

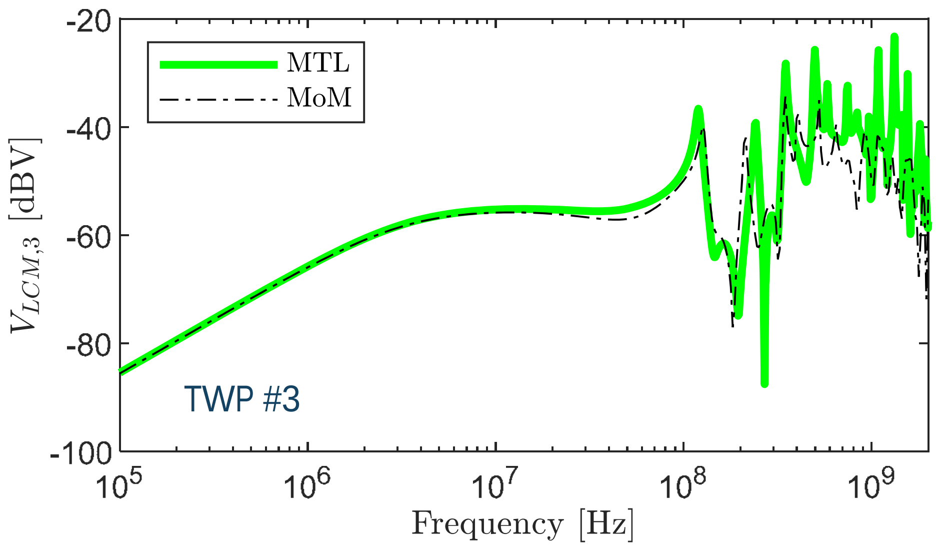


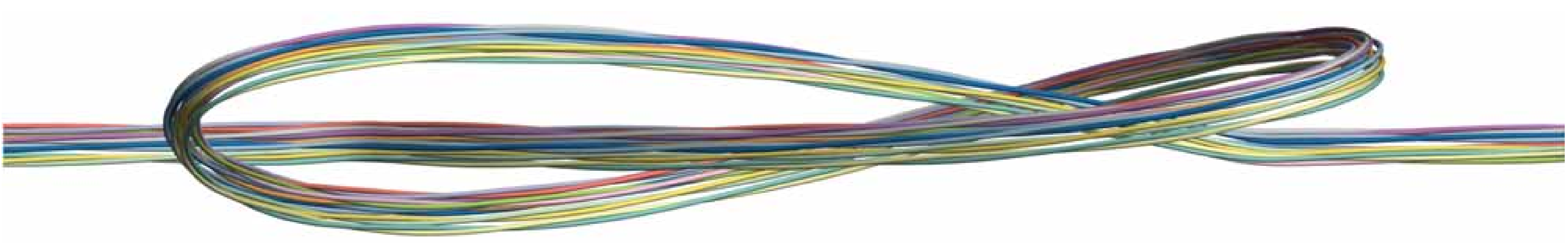
Examples of RS Prediction

Comparison vs MoM simulation

CM voltage prediction







Take-Home Message

- Modelling of complex wiring harnesses represents a **challenge for EMC prediction.** Need for:
  - Realistic representation of the bundle geometry
  - Generation of multiple samples (random and uncontrolled parameters)
  - Computationally-efficient simulation tools
- The proposed generation algorithms
  - Retain **physical constraints**, i.e., wire smoothness, continuity, no-overlapping
  - Allow representing **random displacement of wires** & **arbitrarily-oriented bundles**
- Numerical methods based on transmission line theory
  - Provide **accurate prediction** of the induce noise **even** in the presence of strong non-uniformity and when the TEM assumption is not satisfied
  - Can be easily combined with field prediction obtained by full-wave solvers
  - Can be used for statistical analyses thanks to their computational efficiency

Thank you for your participation!

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