Modeling Cable Harnesses for EMC in Automotive and Industrial Applications

POLITECNICO MILANO 1863

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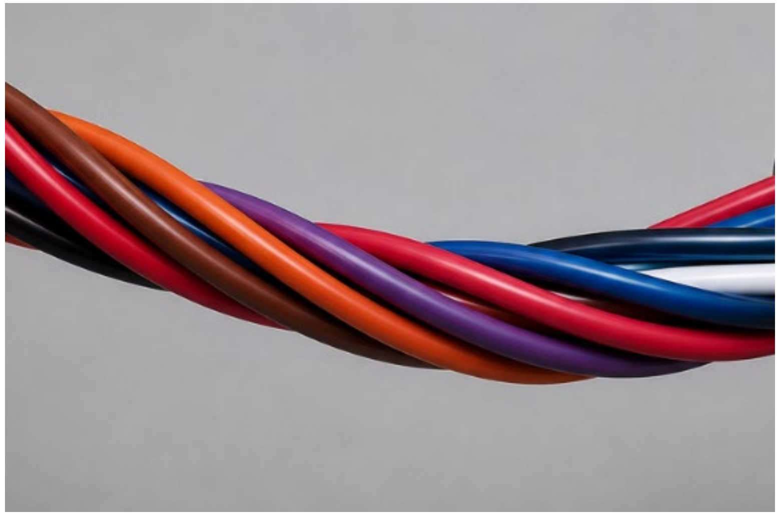
Introduction

The generation, coupling, and propagation of electromagnetic (EM) noise are complex phenomena.

→ EMC modeling techniques



Cable harness

- A common practice in EE devices
- Efficient EMI coupling path
- Efficient antenna

This talk will show 3 cable modelling methods

Cable transmission and crosstalk | Cable Radiation | Susceptibility tests involving cables

Contents

Cable transmission and crosstalk

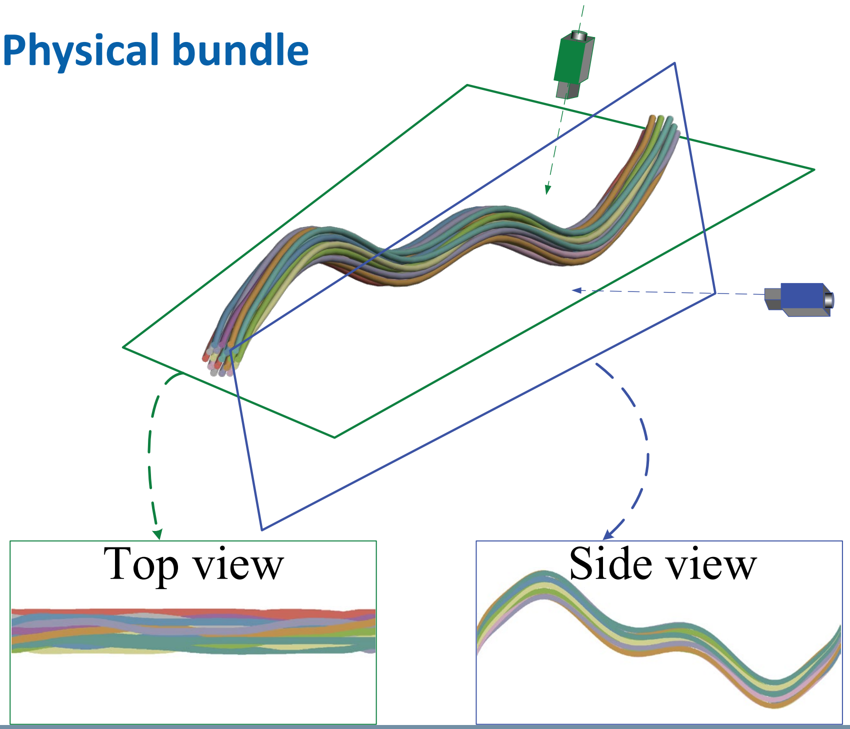
Cable Radiation

Susceptibility tests involving cables

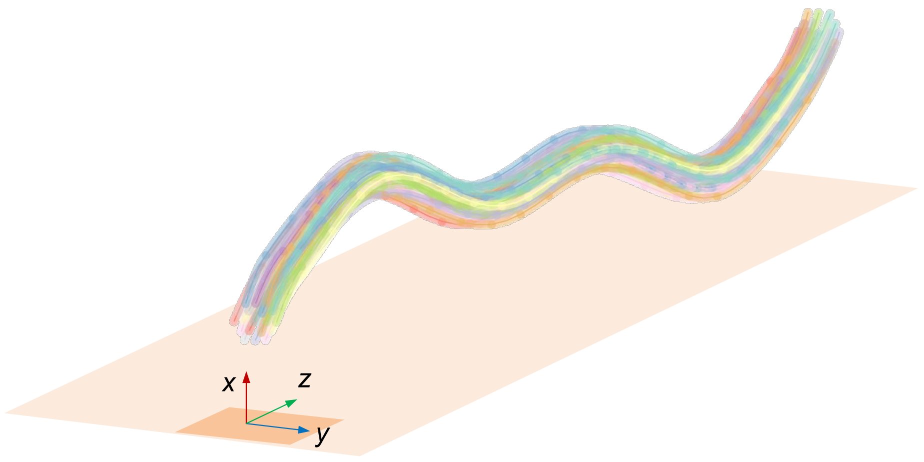
Digital twin modeling of wire harnesses

- **Tightly-packed wire harnesses**: Commonly used in the automotive and industrial sectors
- **Challenges:** 1) EMC behaviors are highly sensitive to the specific cable bundle structure
  2) Difficult to model realistic behavior of physical harnesses
- **Solution:** A digital twin model based on image recognition

Physical bundle

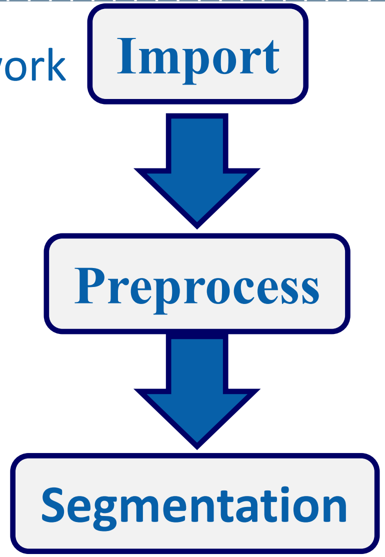


Digital-twin model

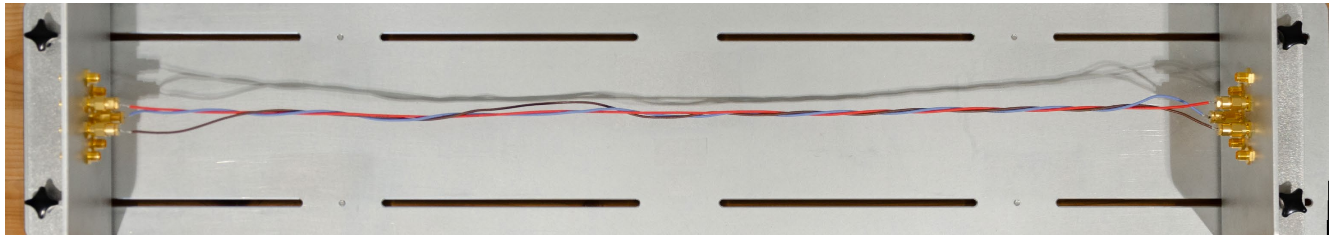


Digital twin modeling of wire harnesses

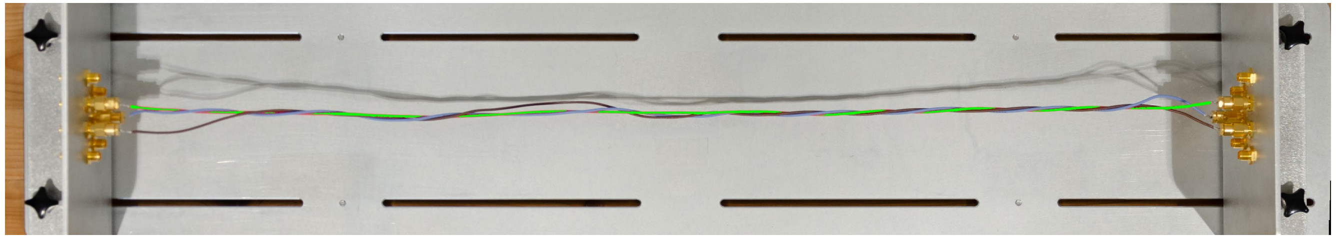
- Geometric model framework



Original image (after pre-processing)



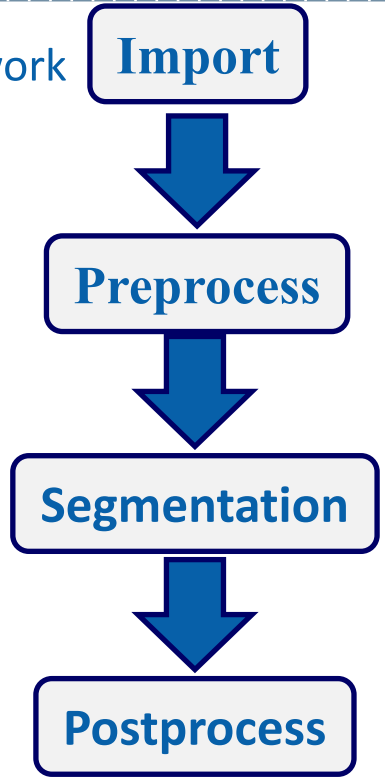
Segmentation



- A binary image is created for each wire of a specific color

Digital twin modeling of wire harnesses

- Geometric model framework



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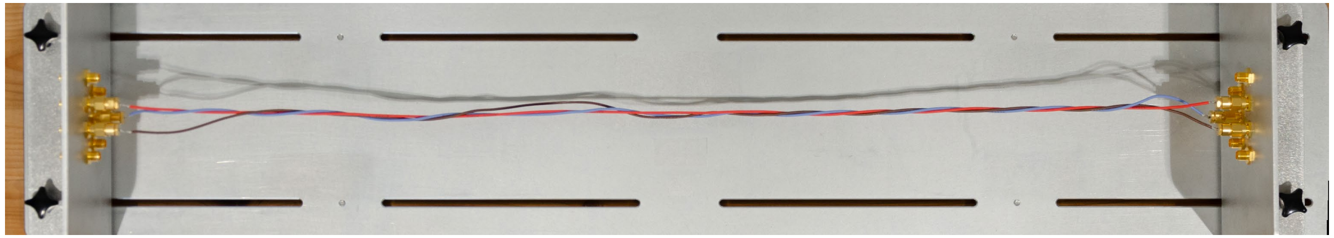

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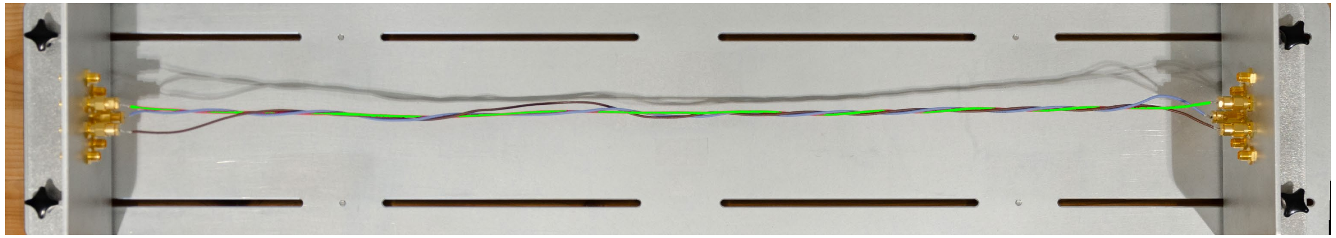
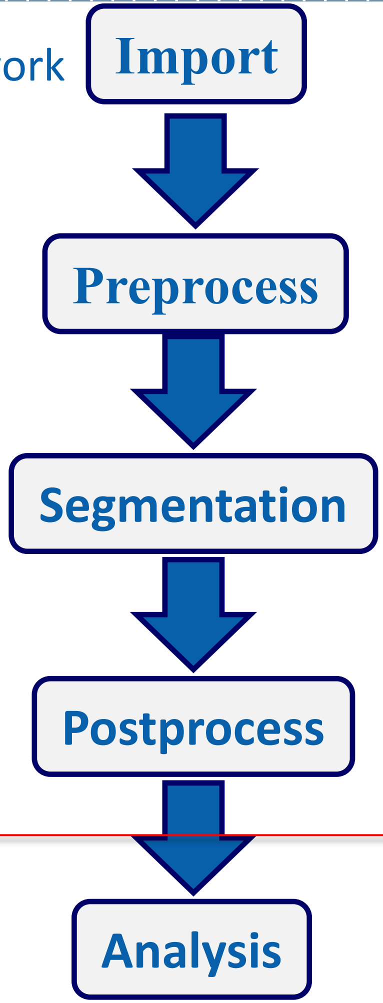


Postprocess

- A morphological operation is used: Remove small features and keep the shape and size of larger objects

Digital twin modeling of wire harnesses

- Geometric model framework



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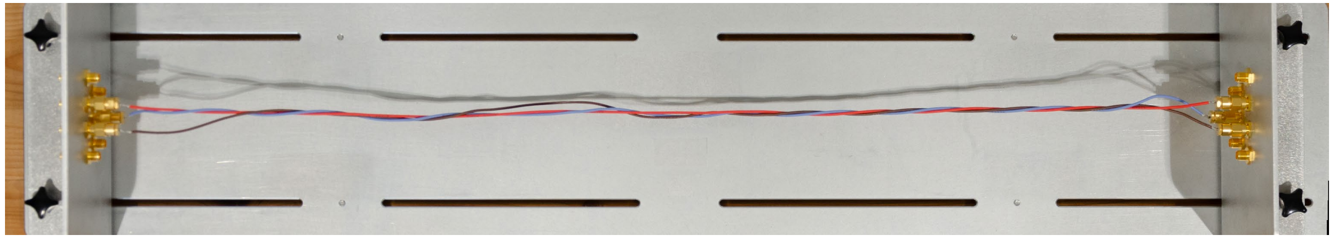

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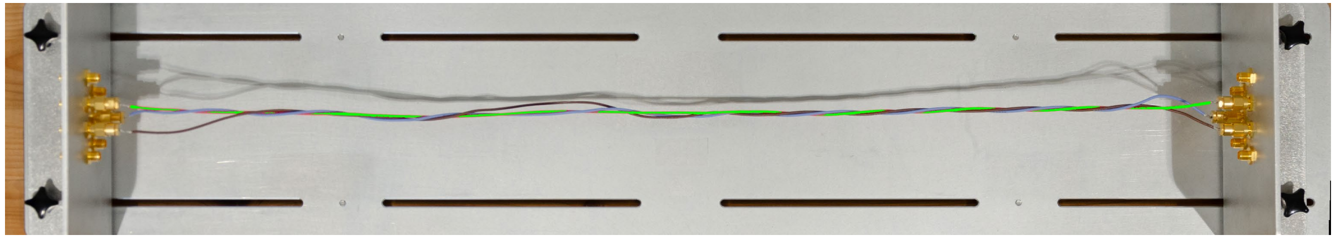


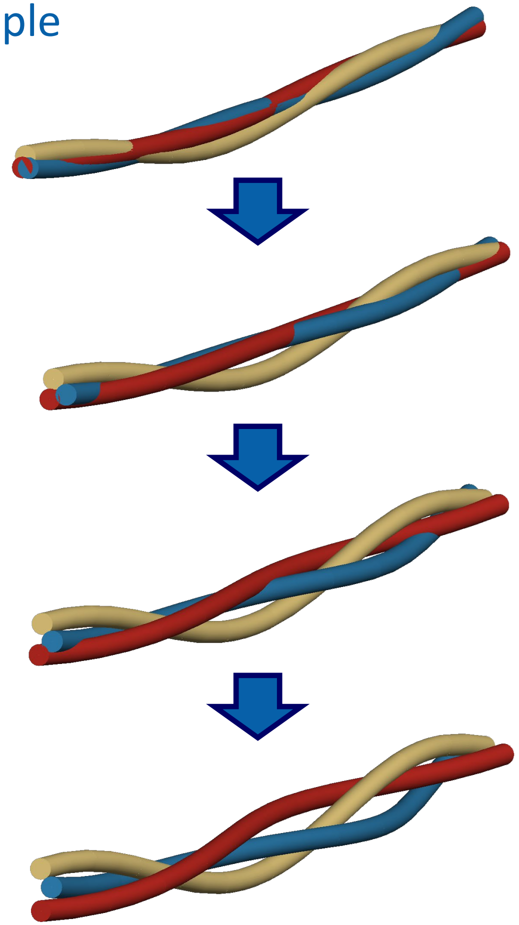
Postprocess

Reconstructed

Digital twin modeling of wire harnesses

- Three principles: **Nonoverlapping** **Continuity** **Compactness**

Example



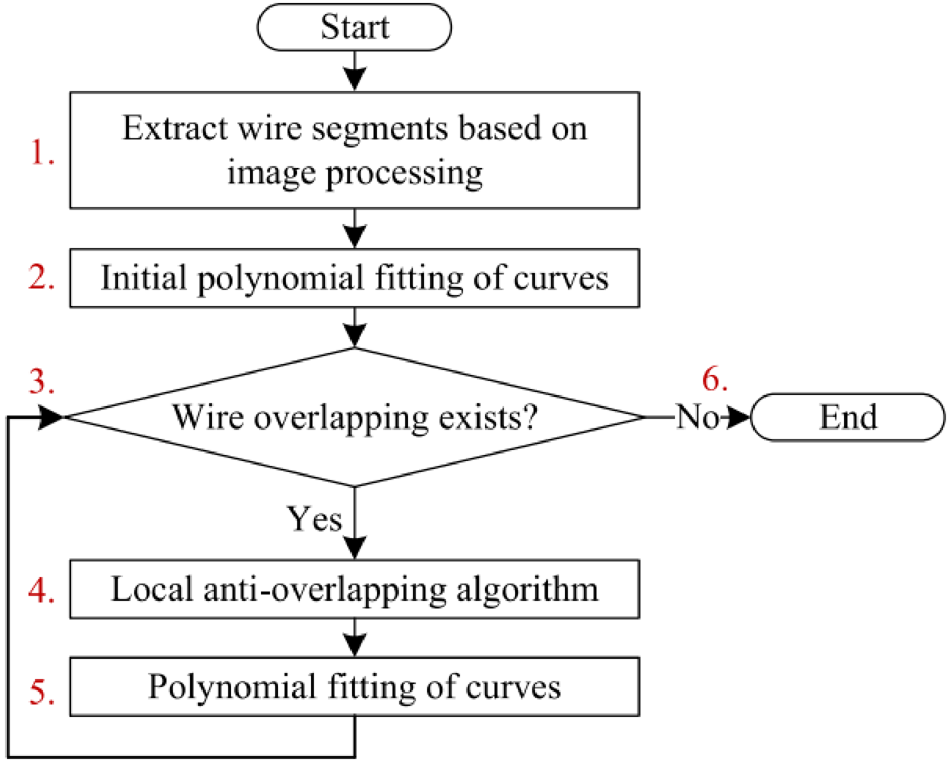
- Flow chart of the model generation

1. Part of data is missing

2. x- and y- data
Polynomial interpolation algorithm

3. Non-overlapping constraint

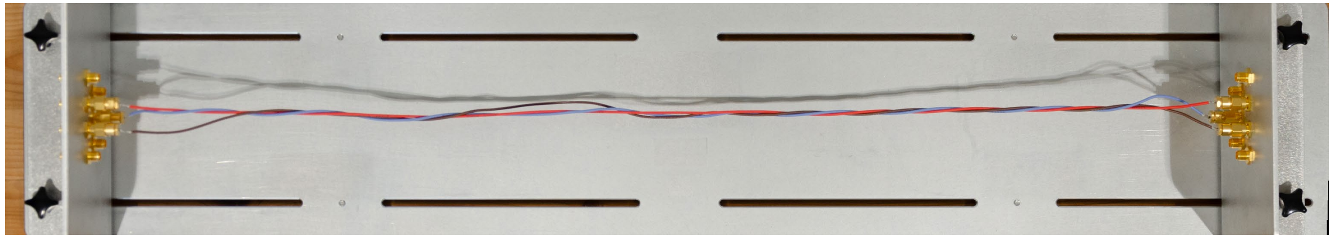
3-6 Iterations



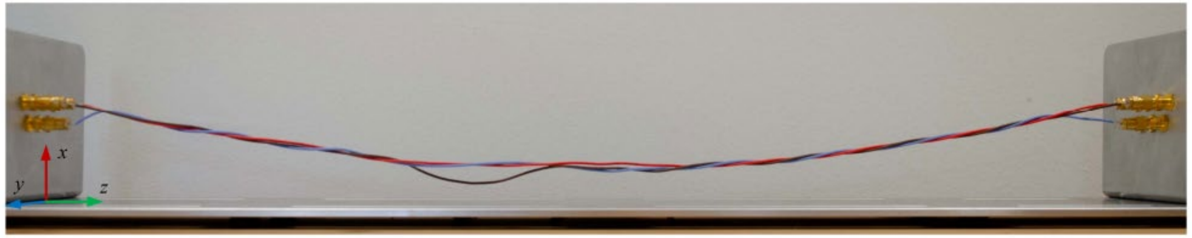
Digital twin modeling of wire harnesses

Original image

Top view



Side view

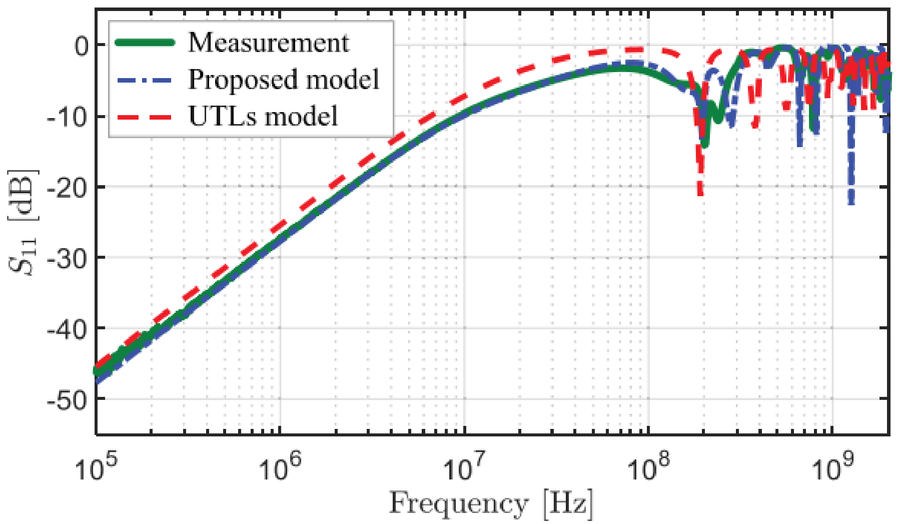


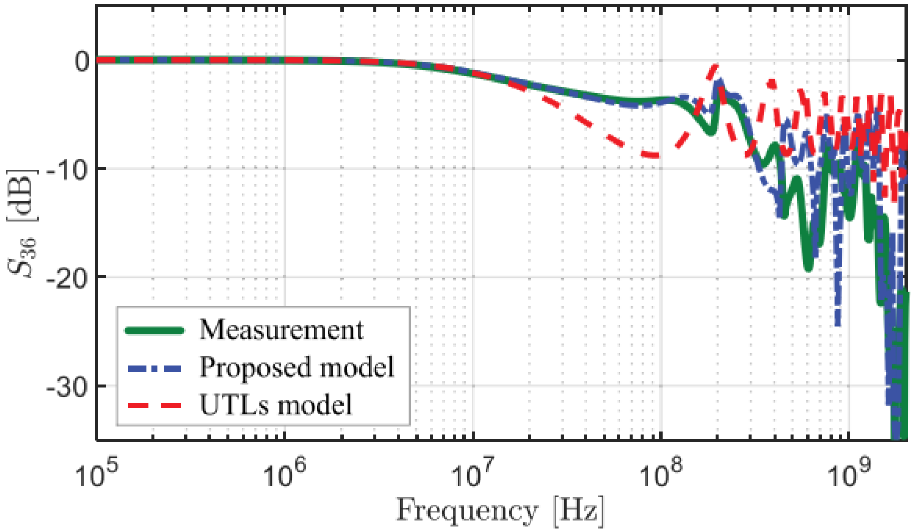
Reconstructed

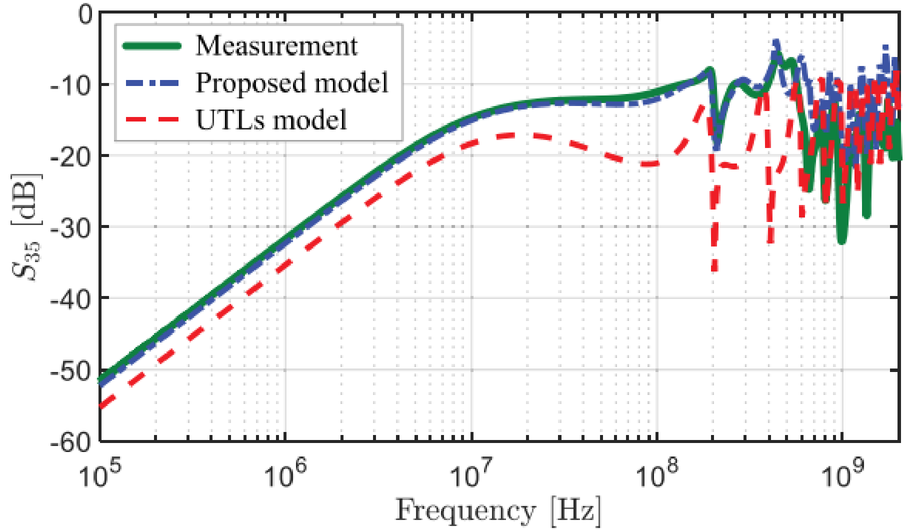
Digital twin modeling of wire harnesses

❑ Proposed model and measurement

This accuracy is not achievable with traditional UTL* models
*UTLs: uniform transmission line model







Digital twin modeling of wire harnesses

❑ Conclusion

Cable transmission and crosstalk

Cable Radiation

Susceptibility tests involving cables

Digital Twin modeling of random wire harnesses

- Image recognition based on two photos
- An iterative process

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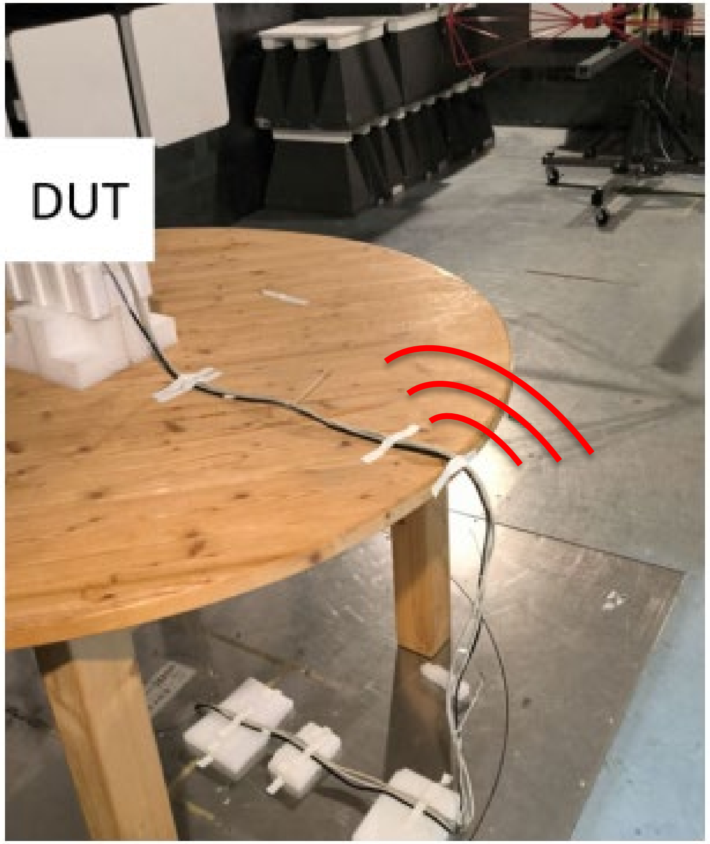
1. Digital Twin Modeling of Hand Assembled Random Wire Harnesses

2. **Simple cable radiated emission evaluation method**

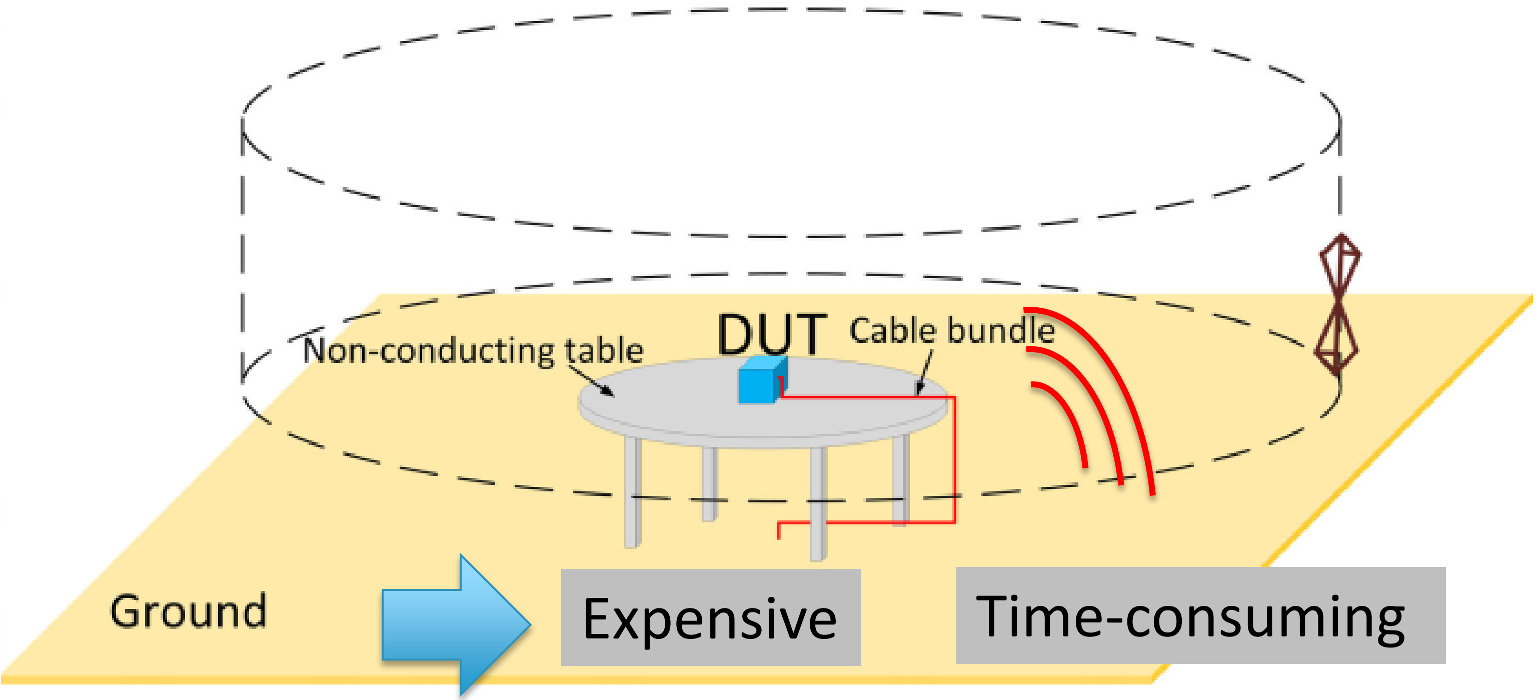
3. A Two-Step Approach for the analysis of BCI tests involving wire harnesses

Simple cable radiated emission evaluation method

Targeted setup: a table-top RE test setup according to CISPR 11 / CISPR 32

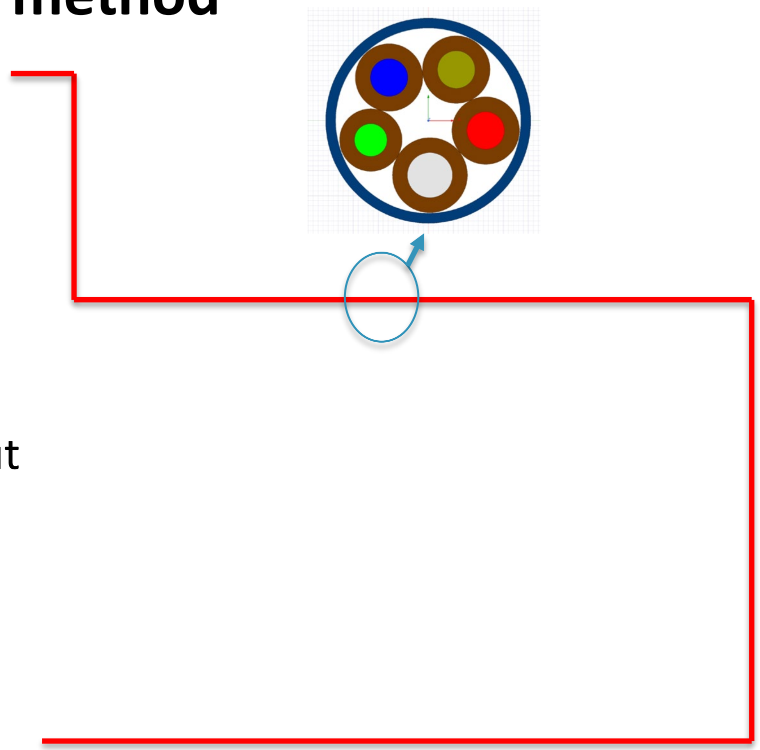


Reference test setup
in **a semi-anechoic chamber**



Simple cable radiated emission evaluation method

Proposed method

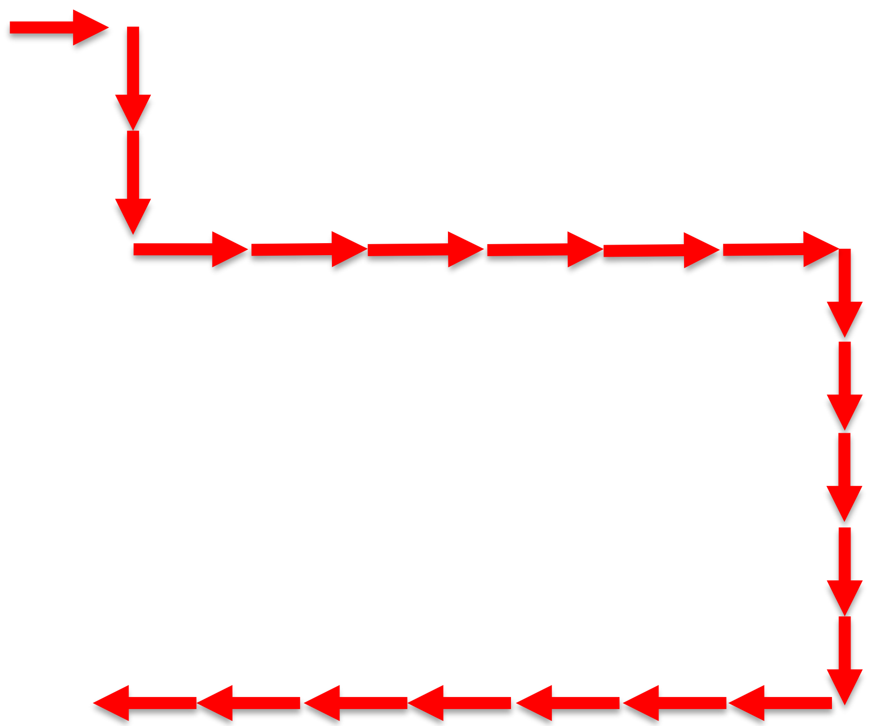


Cable layout

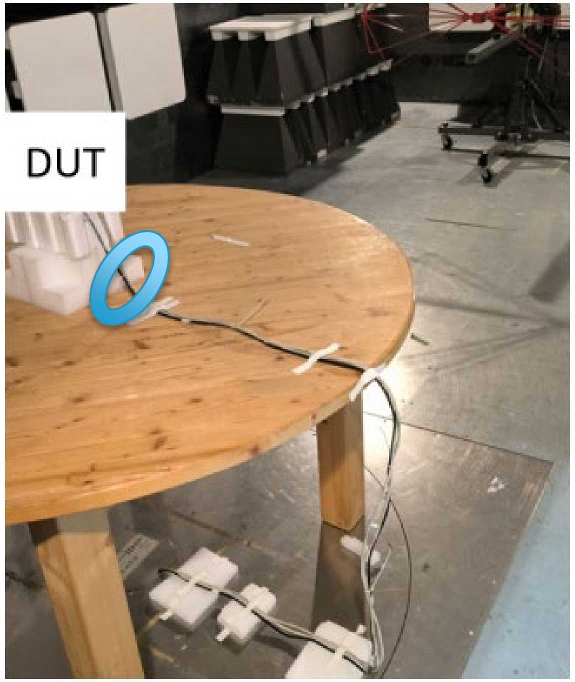
Electrically long

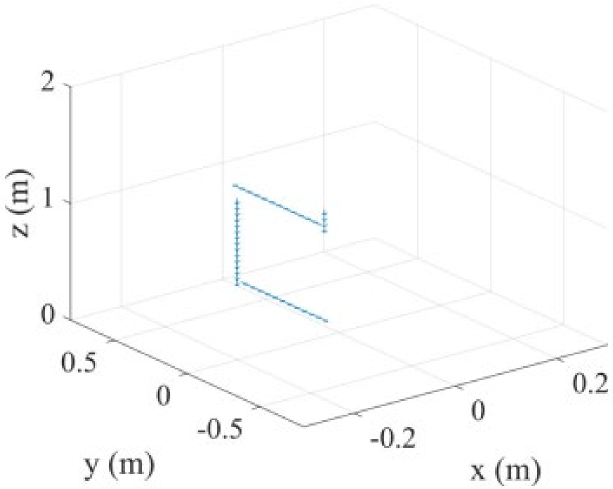
Complex cable bundle

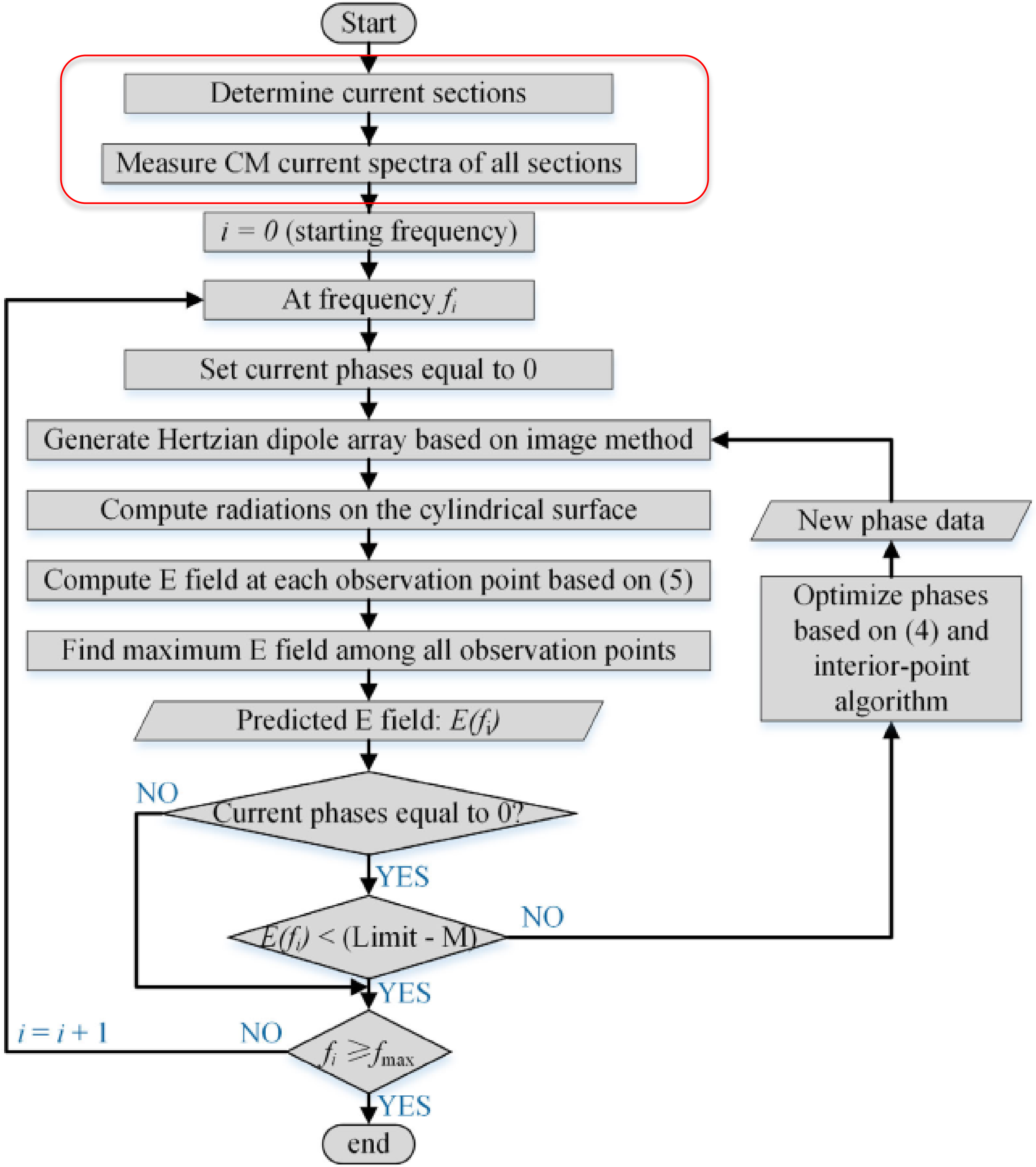
Cascaded electrically-short sectional CM currents



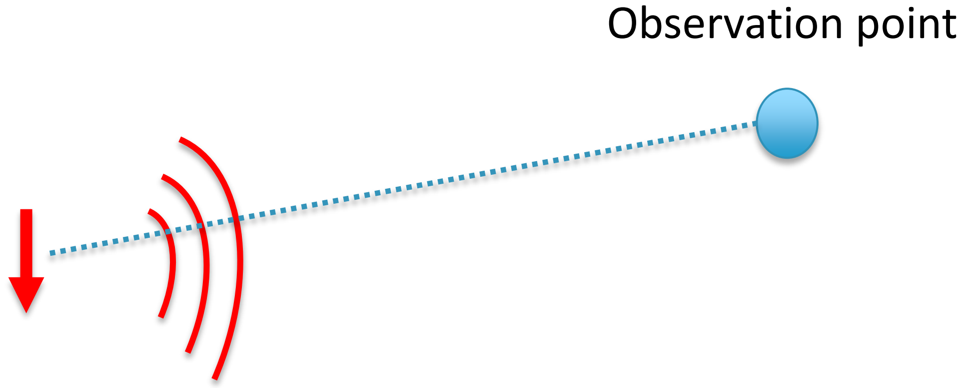
Simple cable radiated emission evaluation method





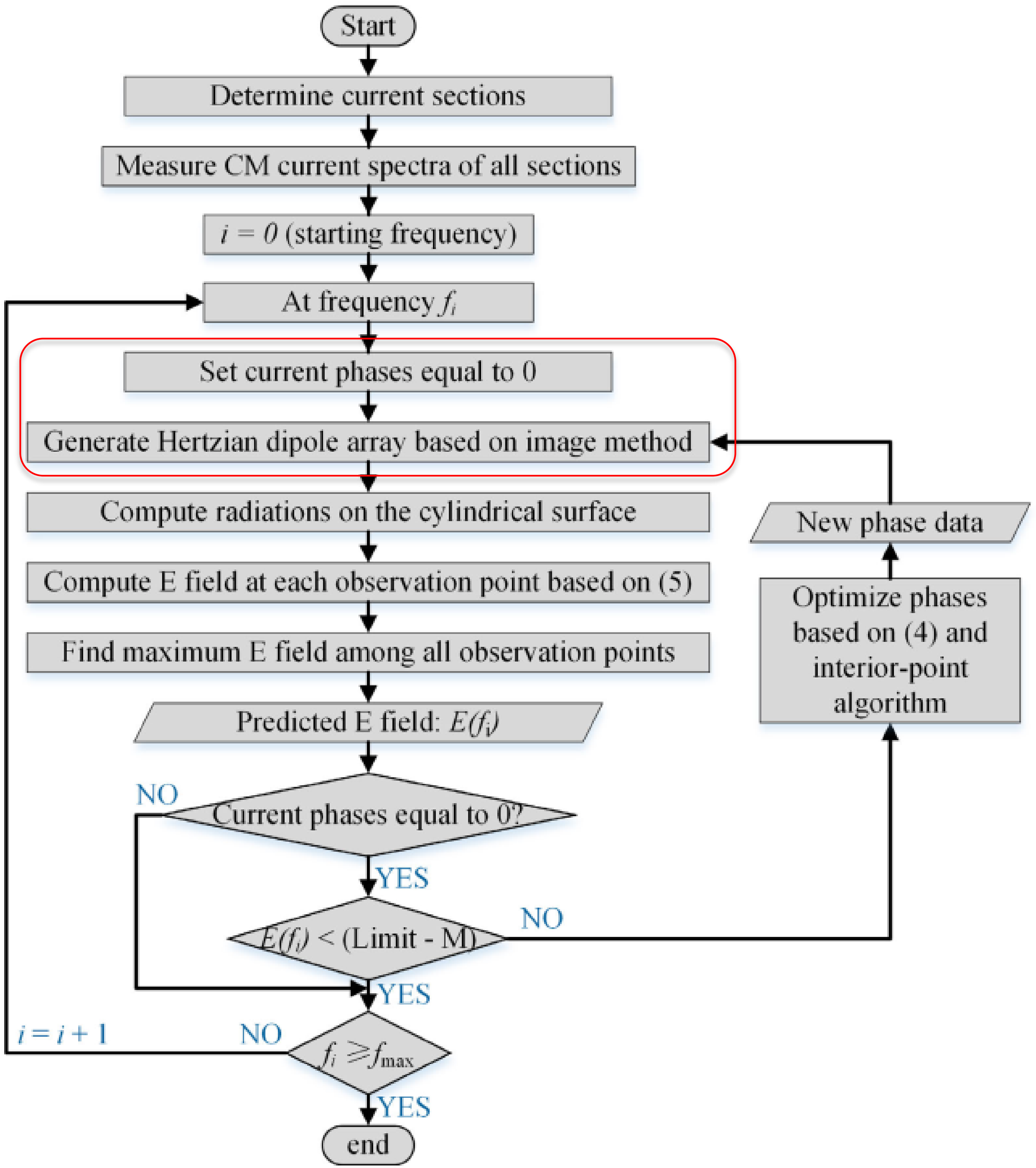


Simple cable radiated emission evaluation method



$$\begin{cases} \hat{E}_r(\theta,r,n,f) = 2I_s\cos\theta\left(\frac{1}{\beta_0{}^2r^2} - j\frac{1}{\beta_0{}^3r^3}\right)e^{-j\beta_0 r} \\ \hat{E}_\theta(\theta,r,n,f) = I_s\sin\theta\left(j\frac{1}{\beta_0 r} + \frac{1}{\beta_0{}^2r^2} - j\frac{1}{\beta_0{}^3r^3}\right)e^{-j\beta_0 r} \\ \hat{E}_\phi(\theta,r,n,f) = 0 \end{cases}$$

$$I_s = \frac{\hat{I}_{CM}(n,f)\Delta l}{4\pi}\eta_0\beta_0{}^2.$$



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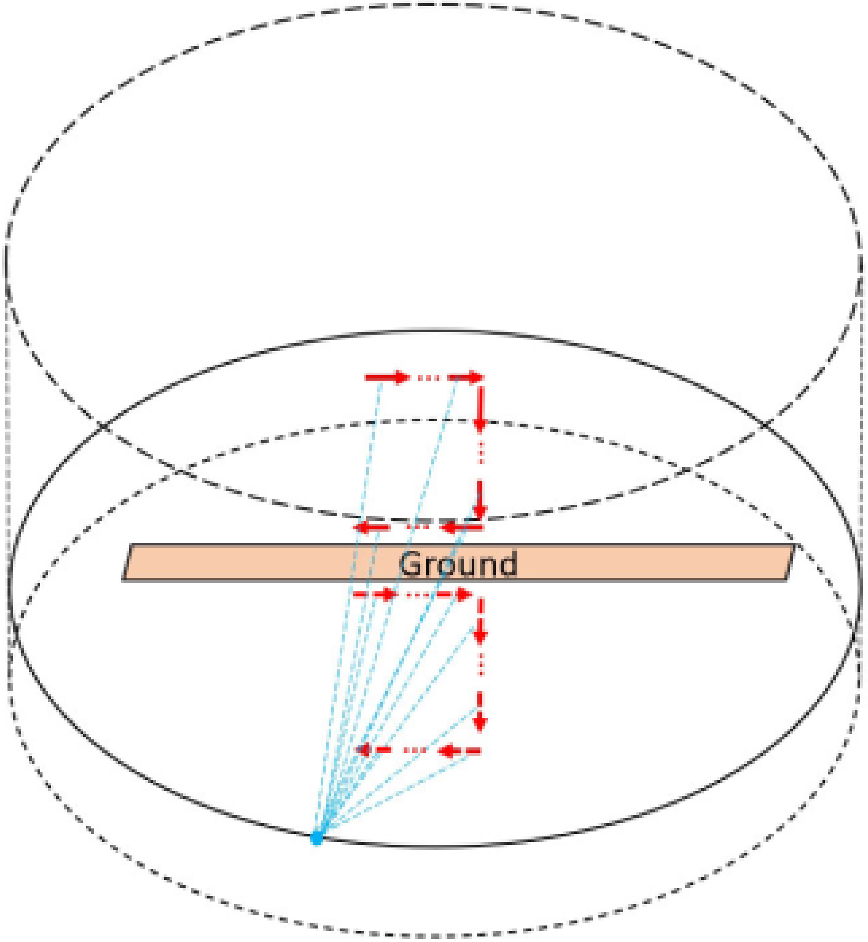

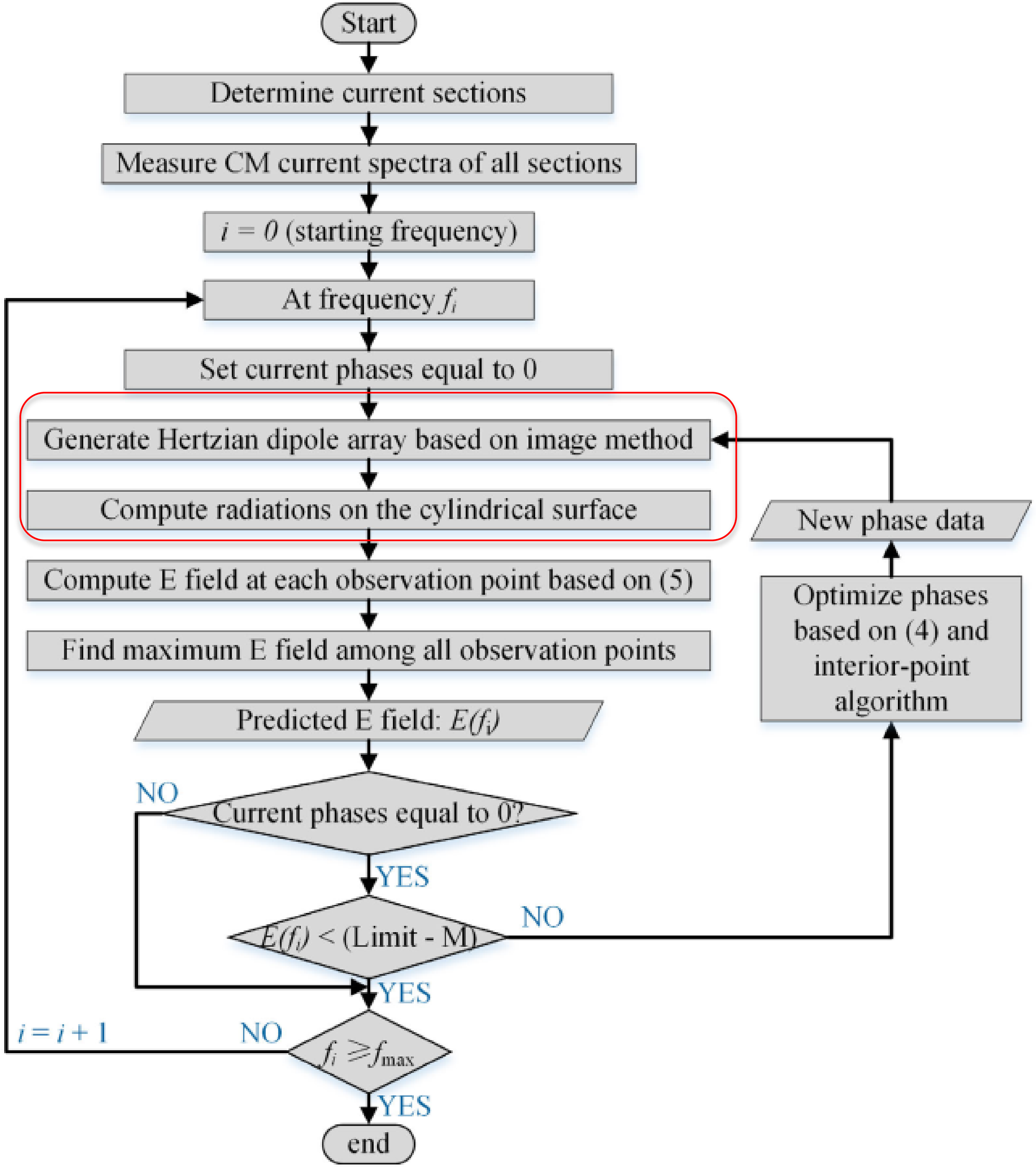

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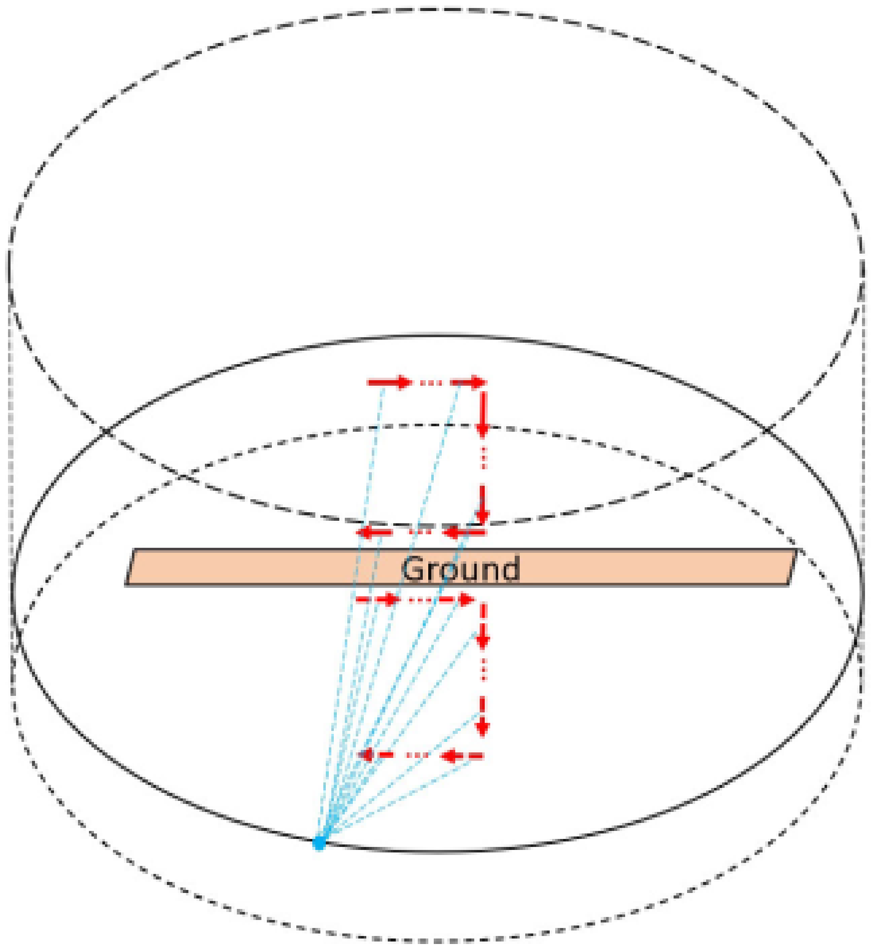

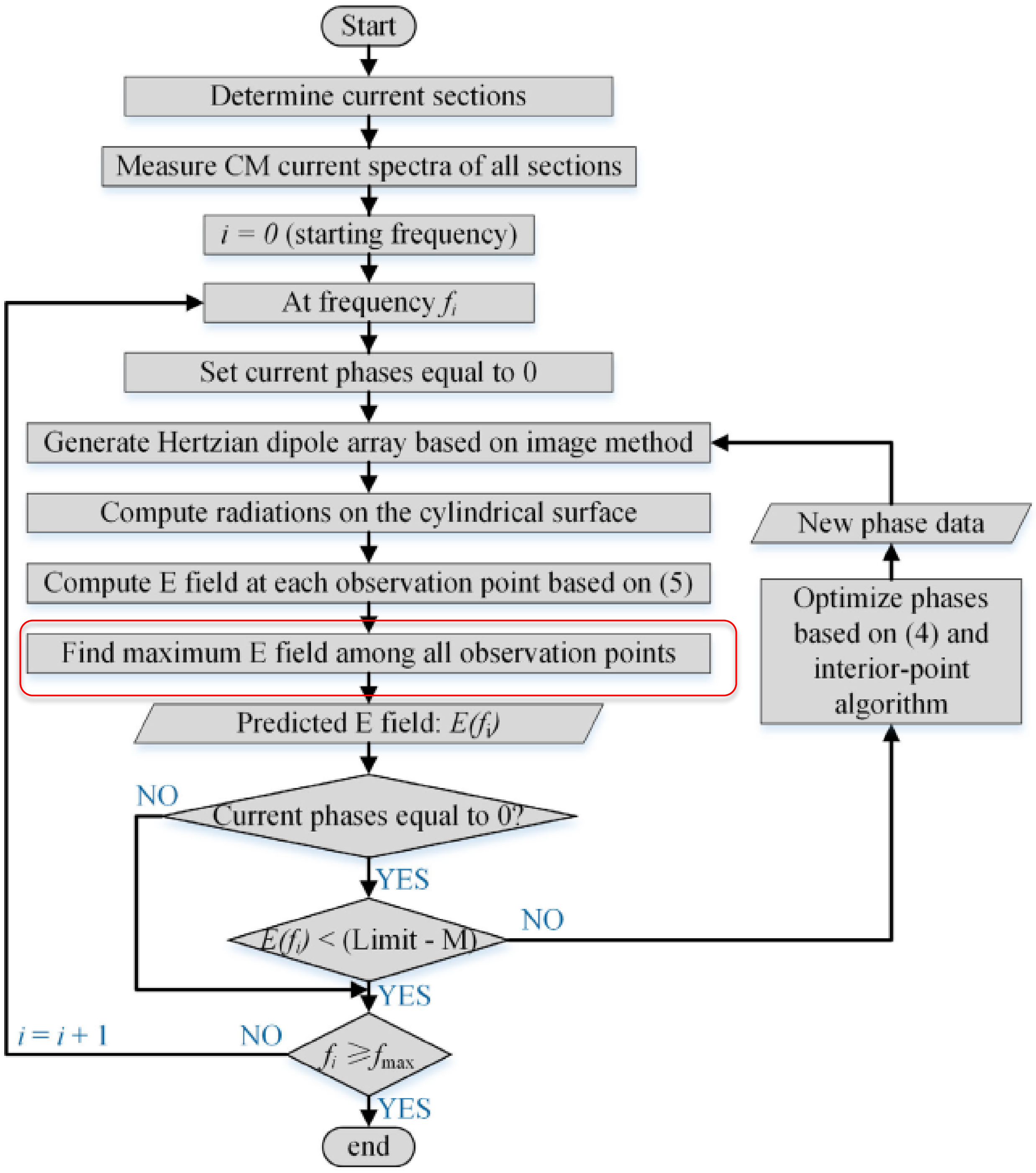

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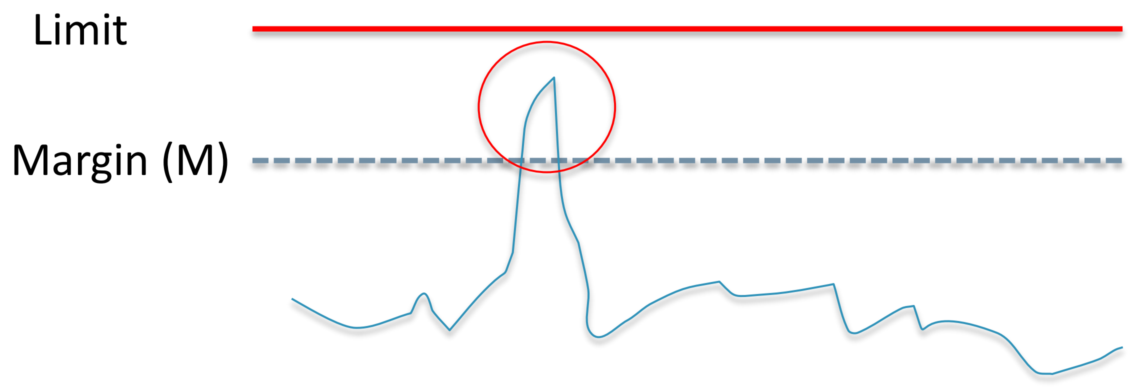
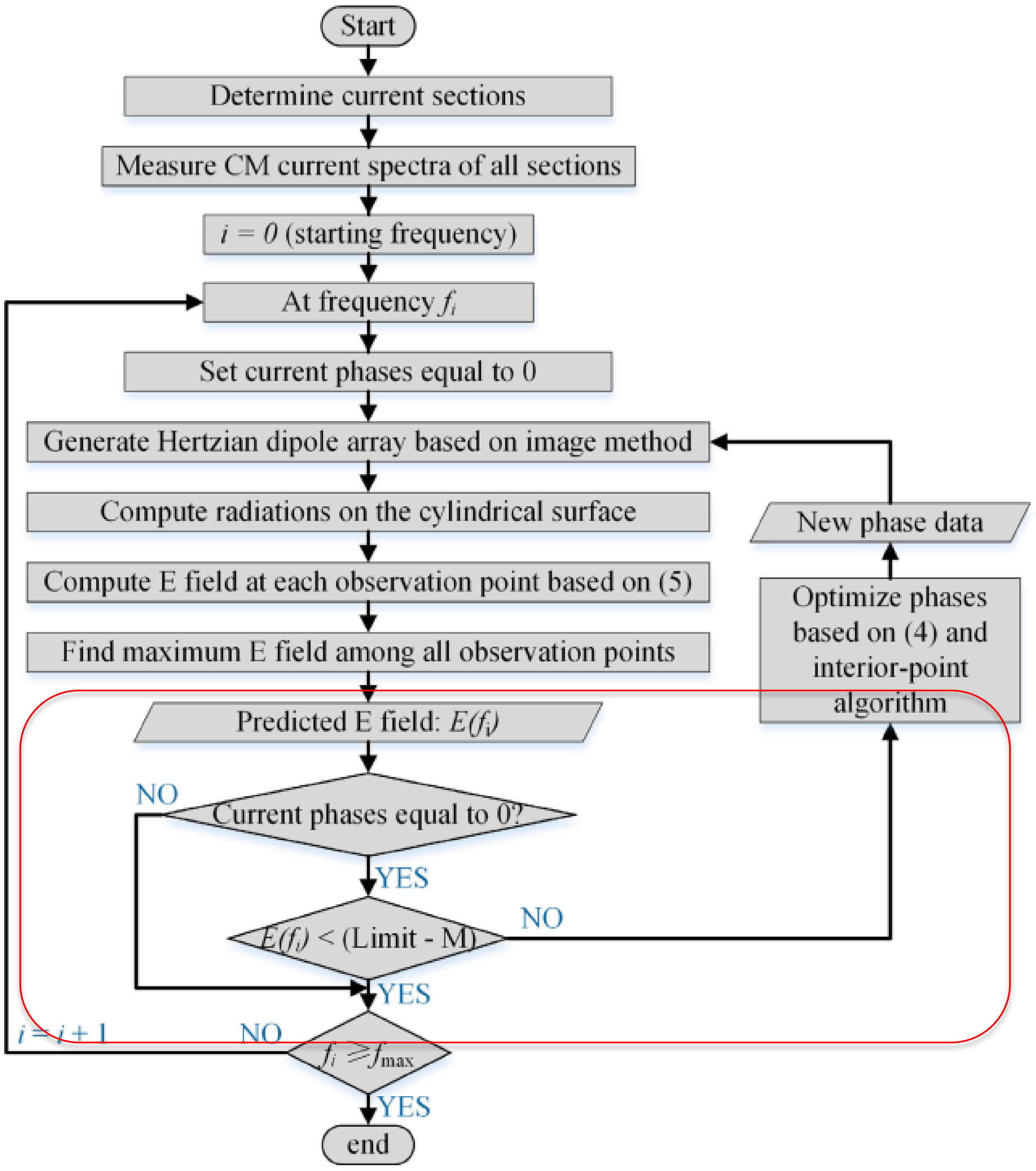
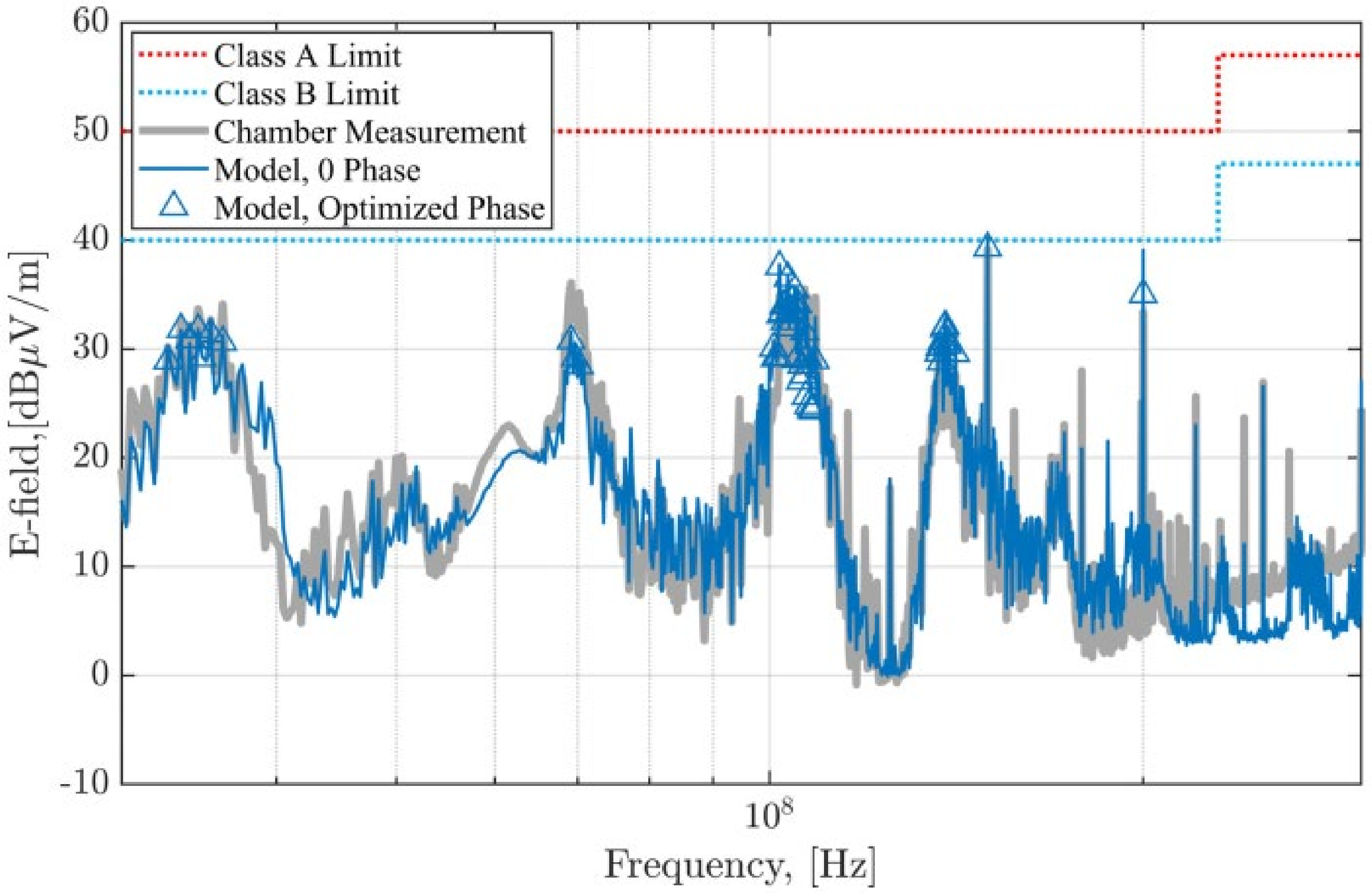




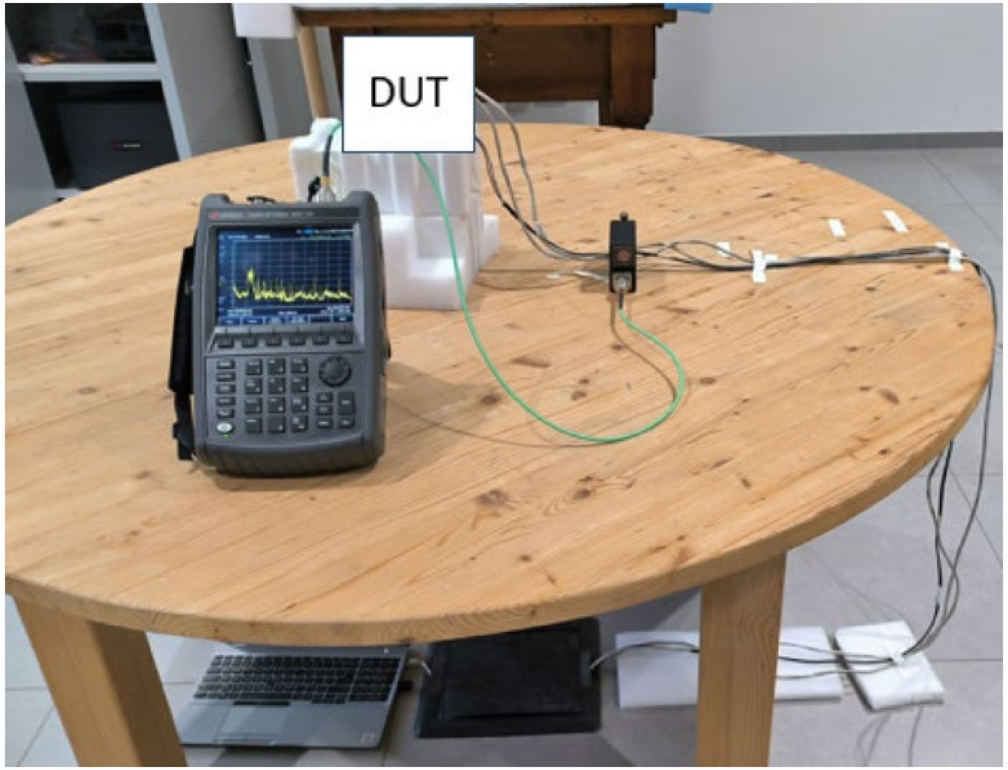
Simple cable radiated emission evaluation method

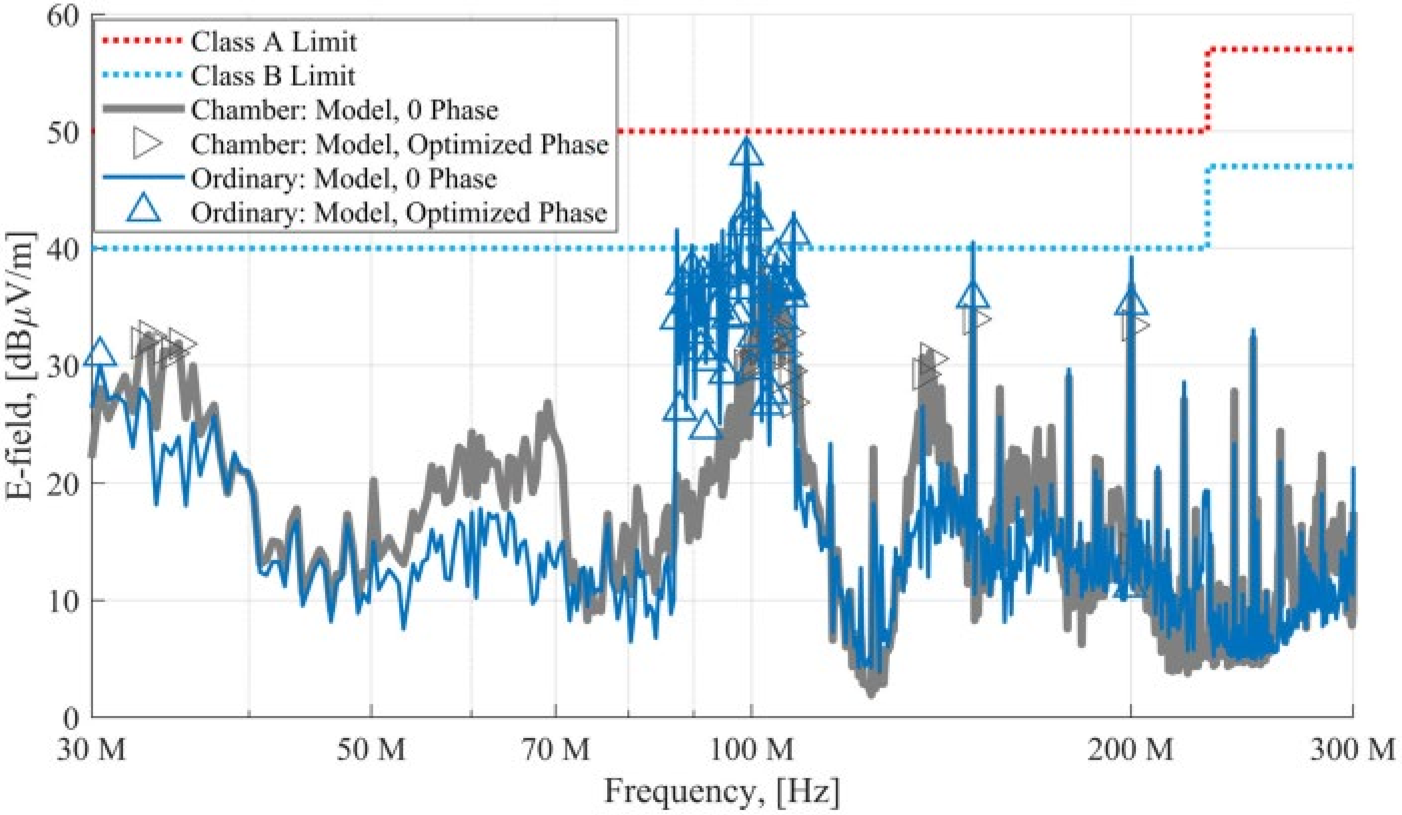
Test results:



Simple cable radiated emission evaluation method

Test in an ordinary room





Digital twin modeling of wire harnesses

❑ Conclusion

Cable transmission and crosstalk

Cable Radiation

Susceptibility tests involving cables

Digital Twin modeling of random wire harnesses

- Image recognition based on two photos
- An iterative process

Fast pre-compliance radiation evaluation method

- CM current measurement + Infinitesimal dipole radiation
- Available for the evaluation in an ordinary environment

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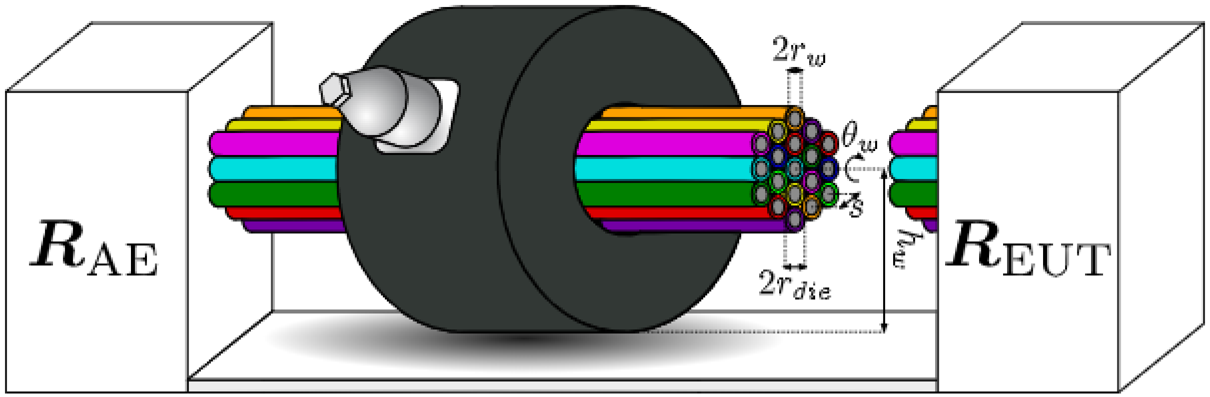
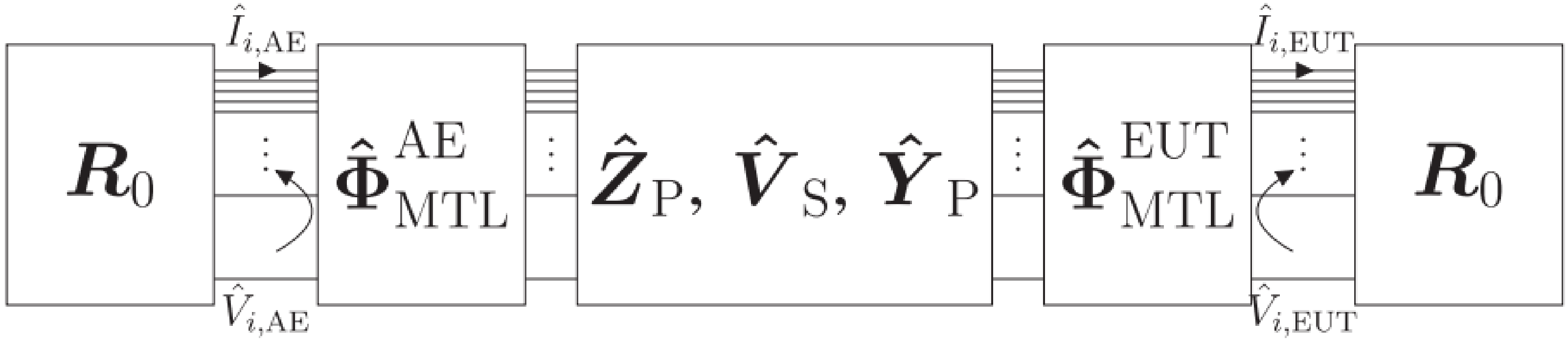
3. **A Two-Step Approach for the analysis of BCI tests involving wire harnesses**

A Two-Step Approach for the analysis of BCI tests involving wire harnesses

Traditional equivalent circuit

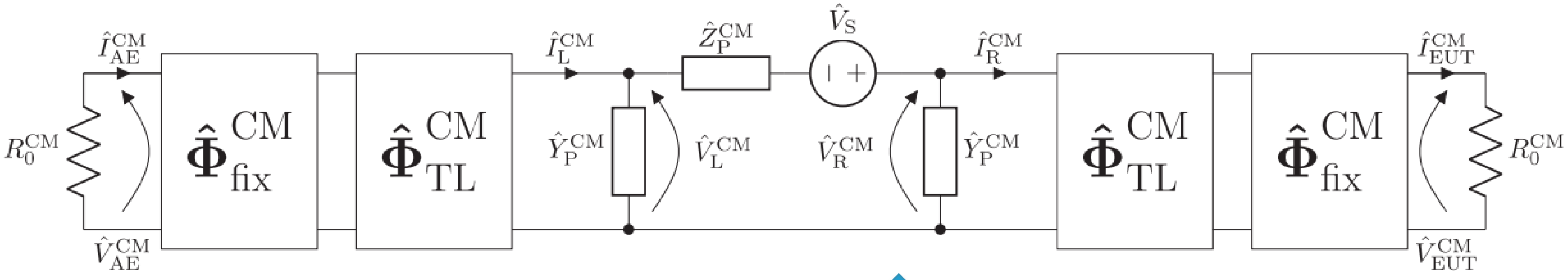




A Two-Step Approach for the analysis of BCI tests involving wire harnesses

Modal equivalent circuit: Two steps

Step 1: CM



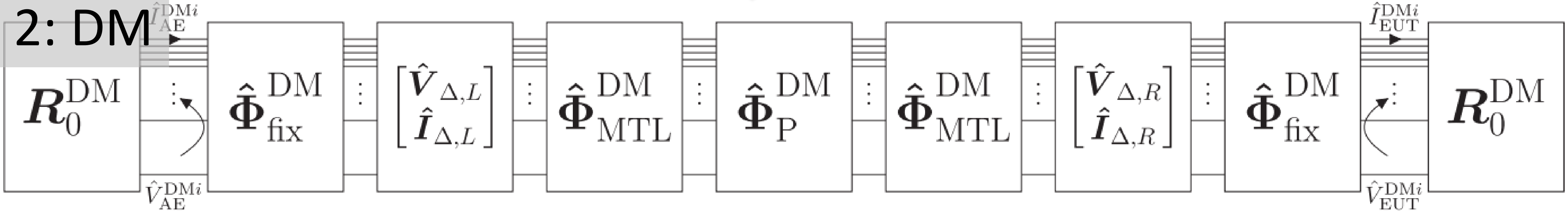
$$
\boldsymbol{L}_m = \begin{bmatrix}
l_{\mathrm{CM}} & 0 & \dots & \dots & \dots & 0 \\
l_{1-\mathrm{CM}} & l_1 & l_{1-2} & \dots & \dots & l_{1-6} \\
l_{2-\mathrm{CM}} & l_{2-1} & l_2 & l_{2-3} & \dots & l_{2-6} \\
\vdots & \vdots & \ddots & \ddots & \ddots & \vdots \\
l_{5-\mathrm{CM}} & l_{5-1} & \dots & l_{5-4} & l_5 & l_{5-6} \\
l_{6-\mathrm{CM}} & l_{6-1} & \dots & \dots & l_{6-5} & l_6
\end{bmatrix}
$$

CM-to-DM conversion

Neglect the back interaction

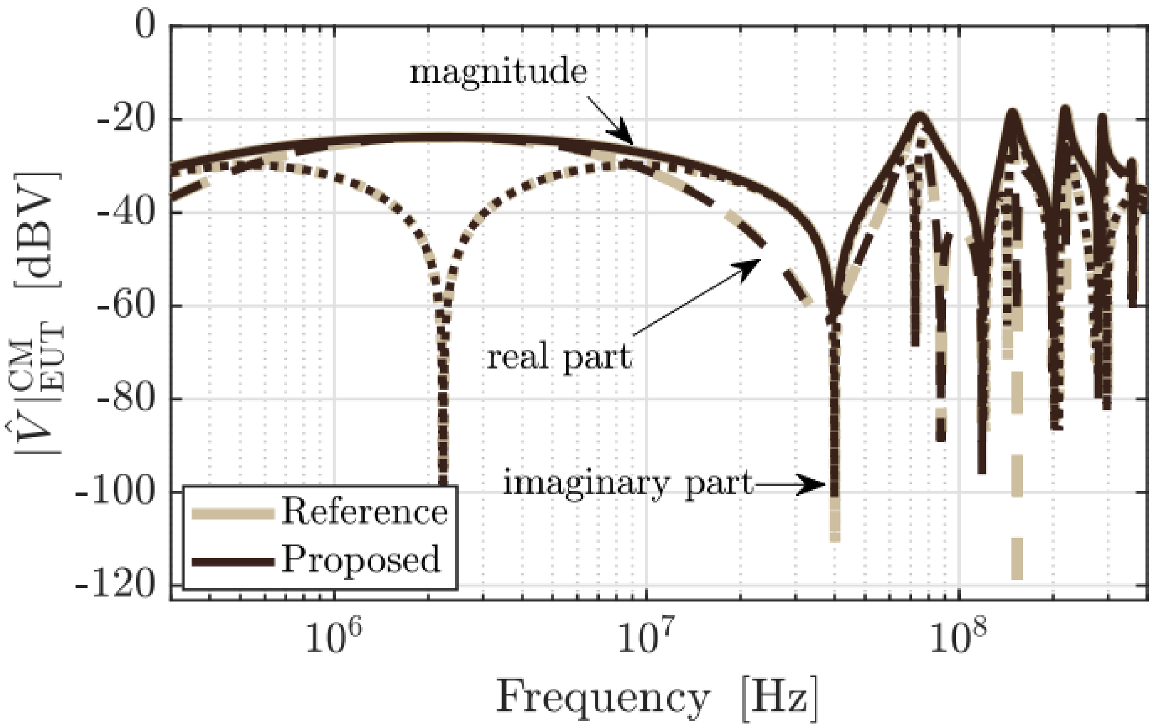
Step 2: DM

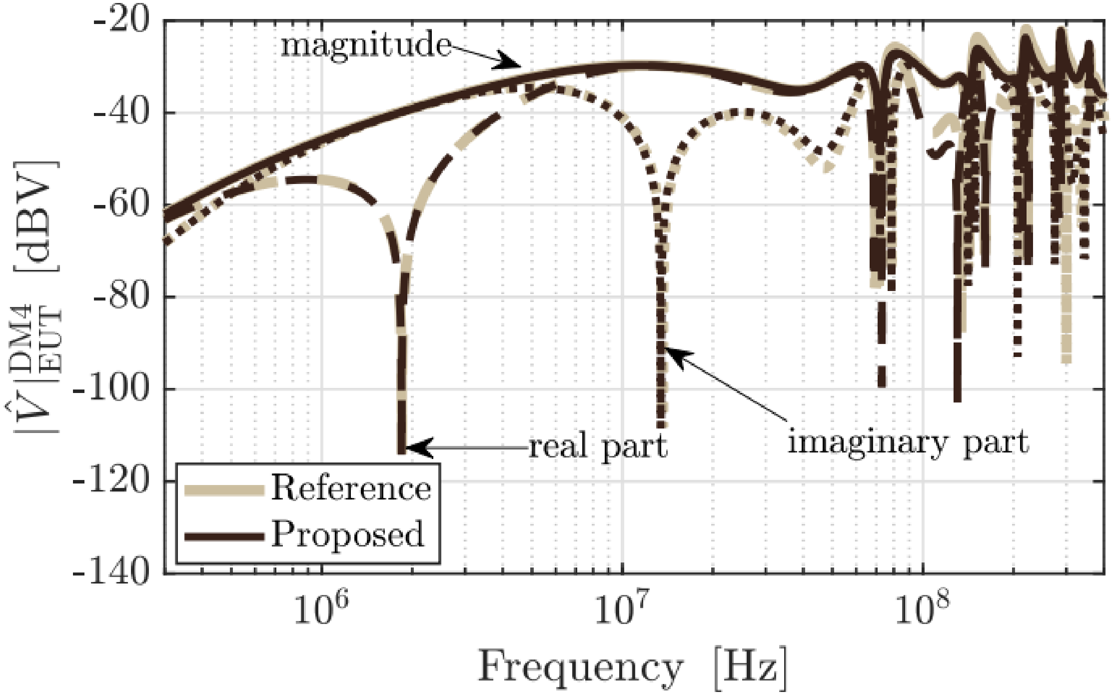
DM



A Two-Step Approach for the analysis of BCI tests involving wire harnesses

Prediction results





A Two-Step Approach for the analysis of BCI tests involving wire harnesses

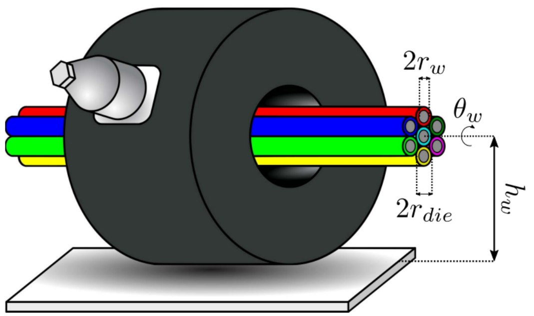
Physical quantities

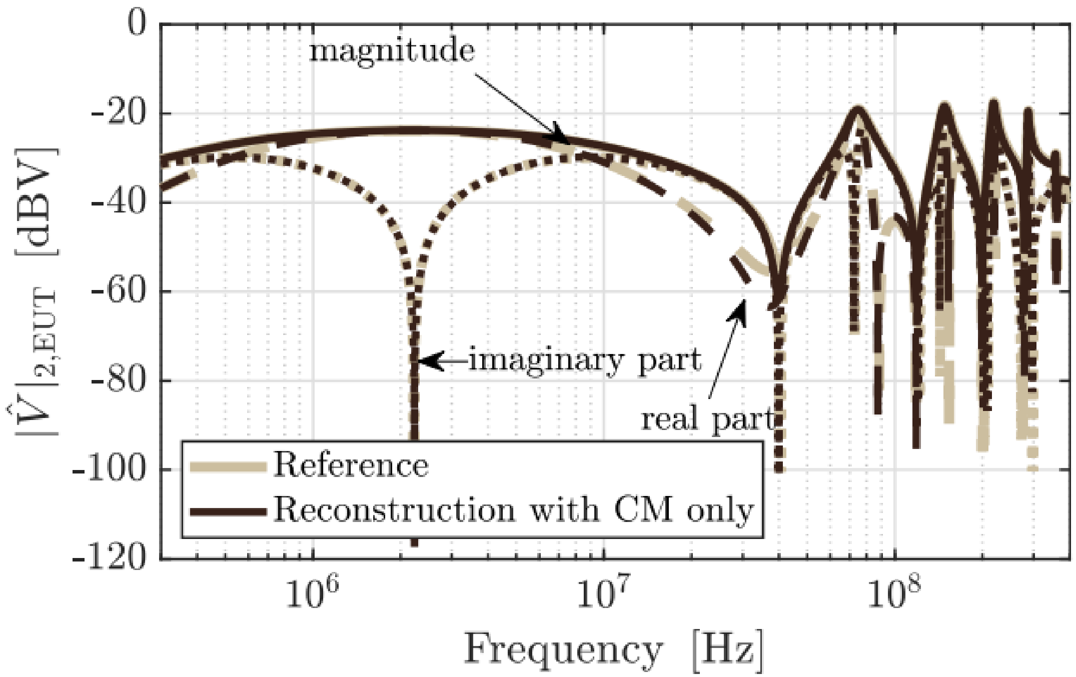
$$\hat{\boldsymbol{V}}_m = \begin{bmatrix} \hat{V}_{\mathrm{CM}} \\ \hat{V}_{\mathrm{DM1}} \\ \vdots \\ \hat{V}_{\mathrm{DM}(N-1)} \end{bmatrix} = \boldsymbol{T}_V^{-1}\hat{\boldsymbol{V}}$$

$$\hat{\boldsymbol{I}}_m = \begin{bmatrix} \hat{I}_{\mathrm{CM}} \\ \hat{I}_{\mathrm{DM1}} \\ \vdots \\ \hat{I}_{\mathrm{DM}(N-1)} \end{bmatrix} = \boldsymbol{T}_I^{-1}\hat{\boldsymbol{I}}.$$

$\underbrace{\text{CM} \quad \cancel{\text{DM}}}_{\text{Line voltage}}$

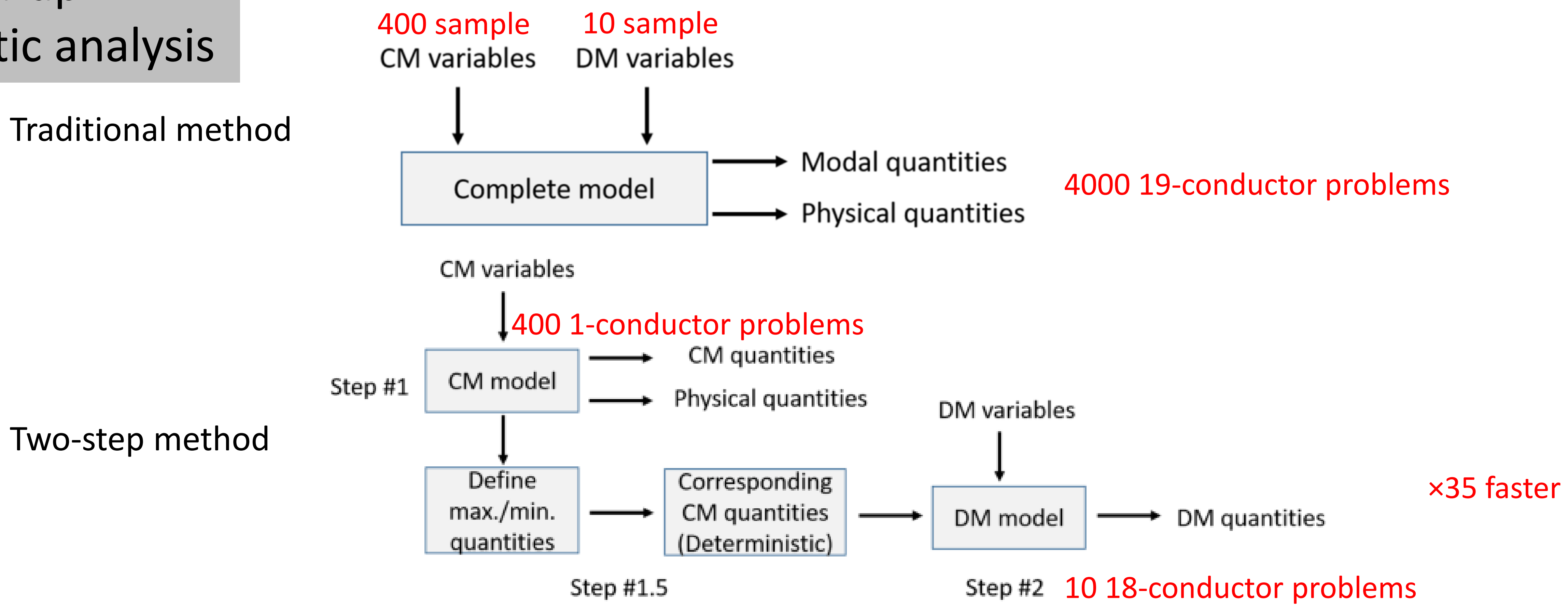
0





A Two-Step Approach for the analysis of BCI tests involving wire harnesses

Speed-up statistic analysis



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Susceptibility tests involving cables

a two-step approach for modeling of BCI tests with wiring harness

- Modal analysis:

1st Step: CM analysis -> CM-to-DM conversion -> 2nd step: DM analysis

- Physical quantities obtained only from one-wire CM eq. circuit.
- Speed up also statistic analysis.

They offer simple, accurate and easy-to-be-implemented prediction tools for EMC assessment.

Main references:

- X. Liu, X. Wu, F. Grassi, G. Spadacini and S. A. Pignari, "**Digital Twin Modeling of Hand Assembled Random Wire Harnesses**," in IEEE Transactions on Industrial Informatics, vol. 21, no. 4, pp. 3177-3185, April 2025
- X. Wu *et al*., "**A Simple Cable Radiated Emission Evaluation Method for Table-Top Setups According to CISPR 11 and CISPR 32**," in *IEEE Access*, vol. 13, pp. 19040-19048, 2025
- N. Toscani, X. Wu, D. Spina, D. V. Ginste and F. Grassi, "**A Two-Step Approach for the Analysis of Bulk Current Injection Setups Involving Multiwire Bundles**," in IEEE Transactions on Electromagnetic Compatibility, vol. 65, no. 1, pp. 126-137, Feb. 2023

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Simple cable radiated emission evaluation method

- **Motivation**: Cable radiation is critical, especially in MHz – GHz ranges

1) Cables carrying CM/antenna-mode currents radiate with extreme efficiency.
Rough calculation based on [1] shows CM current **in tens of µA generate EMI exceeding the limits**

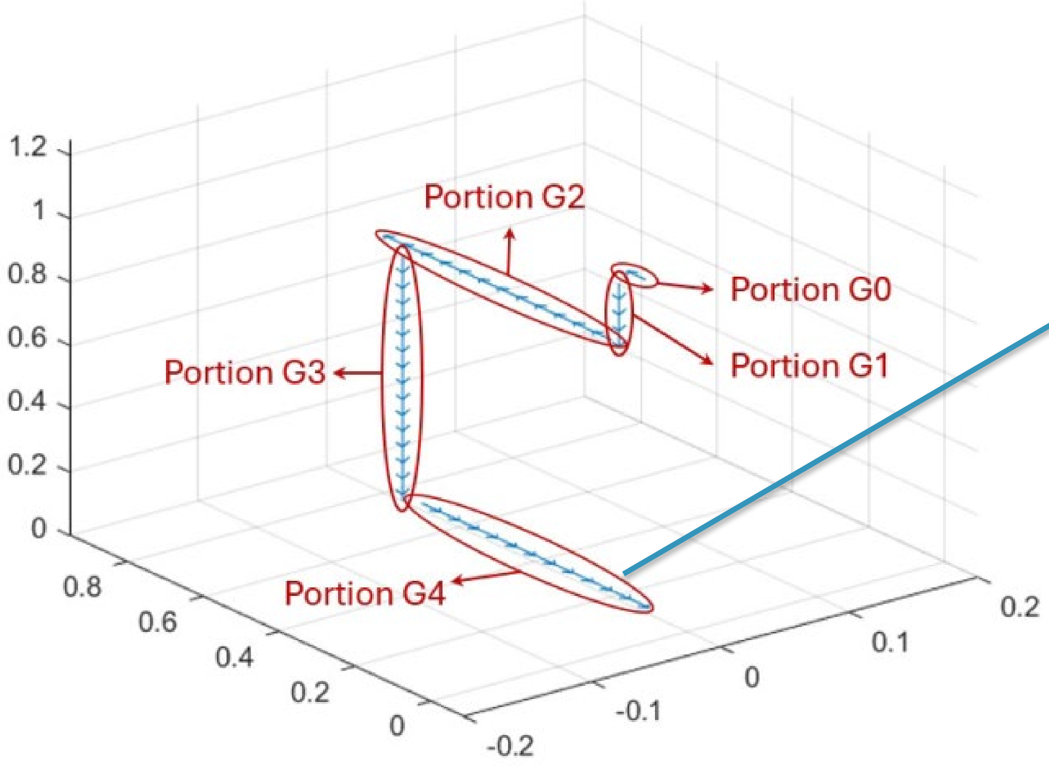
2) Roughly speaking, longer cable -> Higher emission

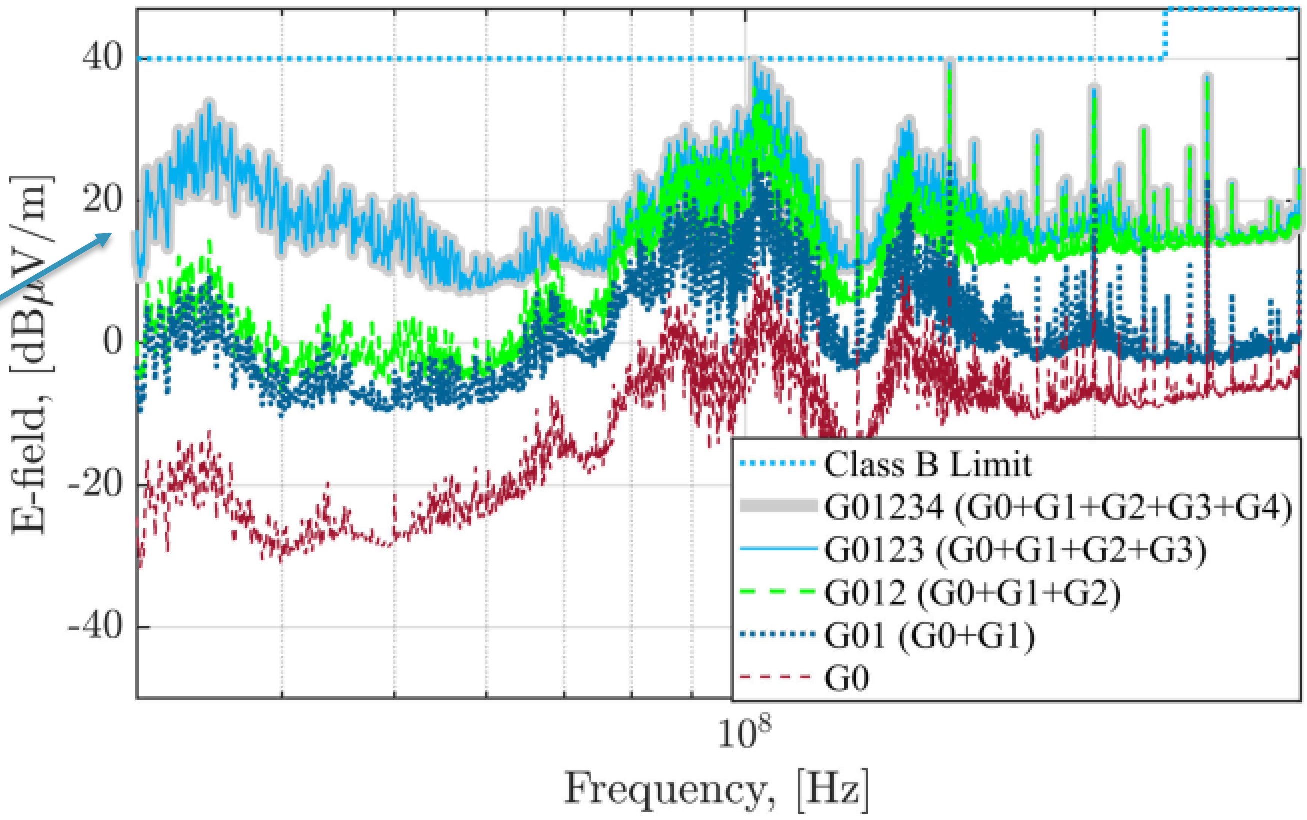
3) Applying noise suppression techniques (e.g. shielding and beads) on external cables is not preferable.

[1] C. R. Paul, Introduction To Electromagnetic Compatibility. Hoboken, NJ, USA: Wiley, 2006.

Simple cable radiated emission evaluation method

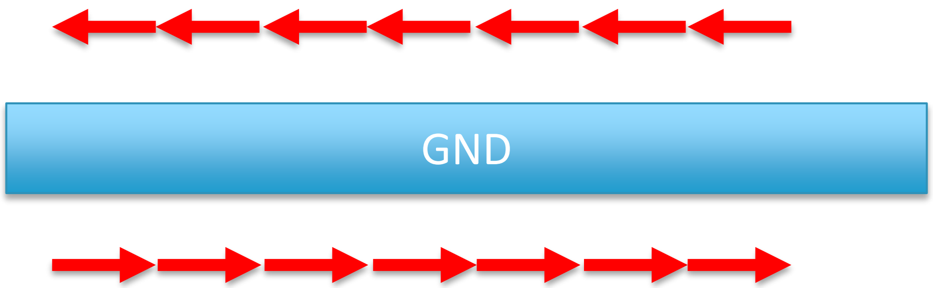
Impact of different cable portions



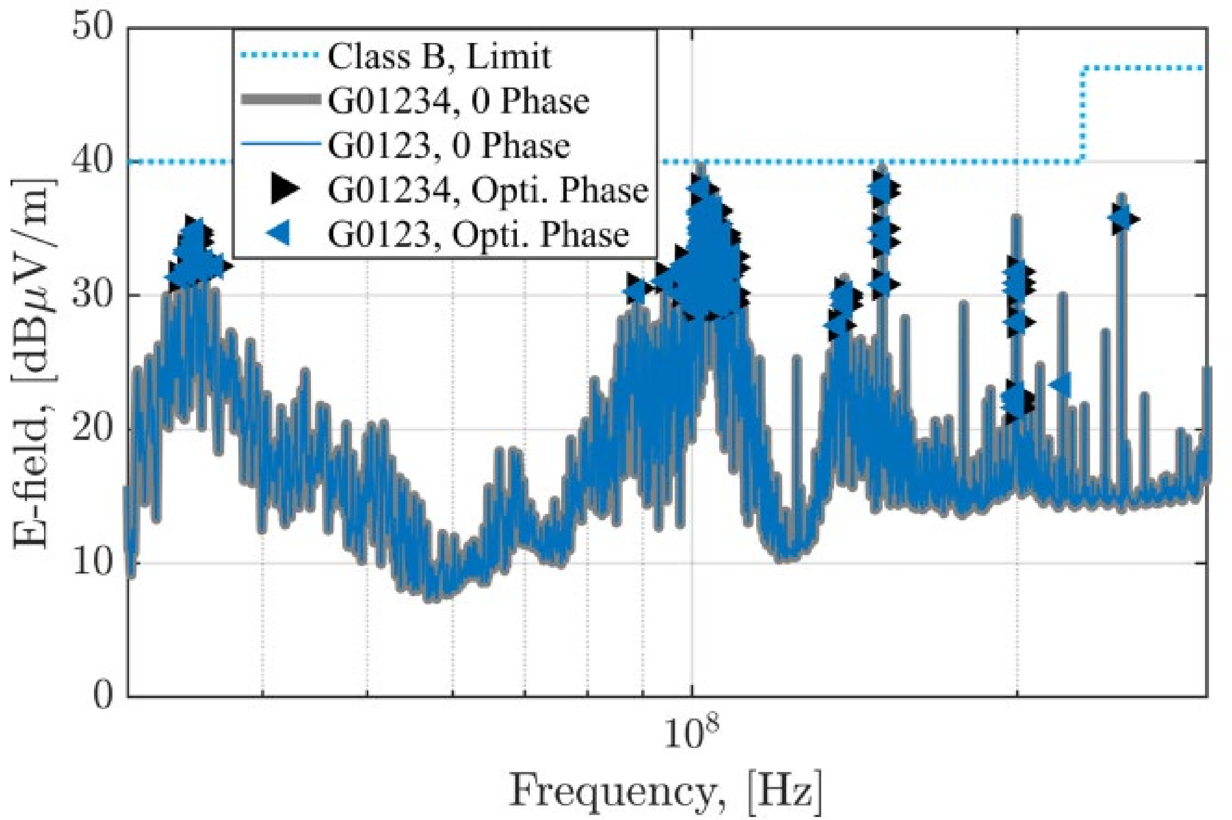


Simple cable radiated emission evaluation method

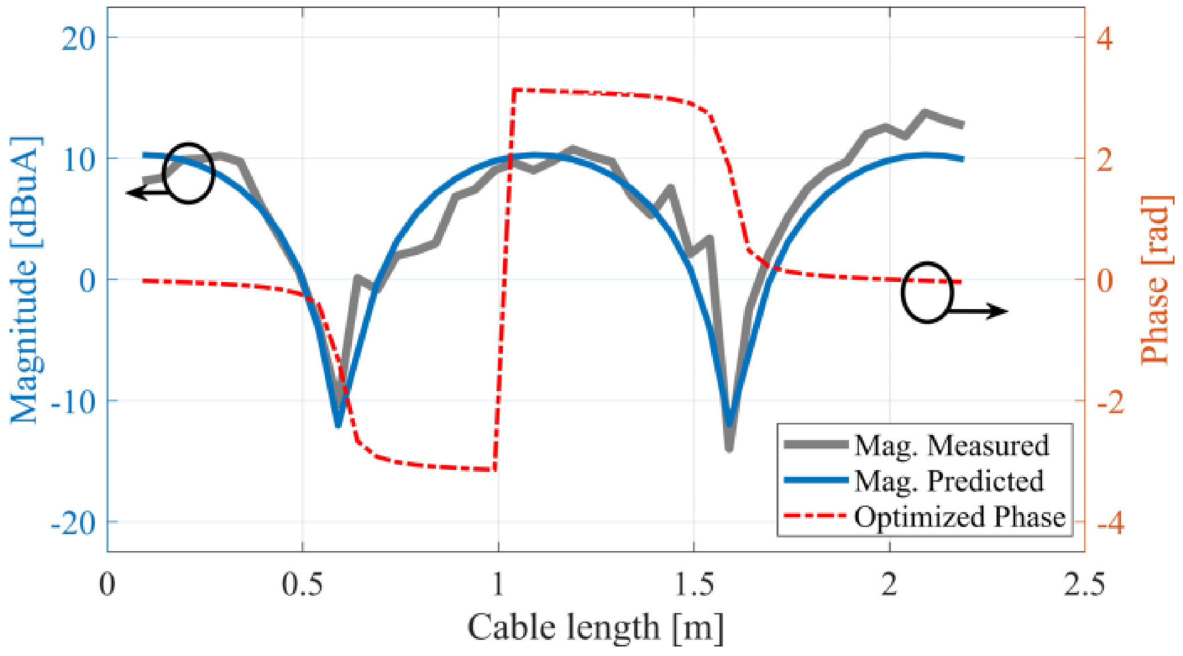
Impact of different cable portions



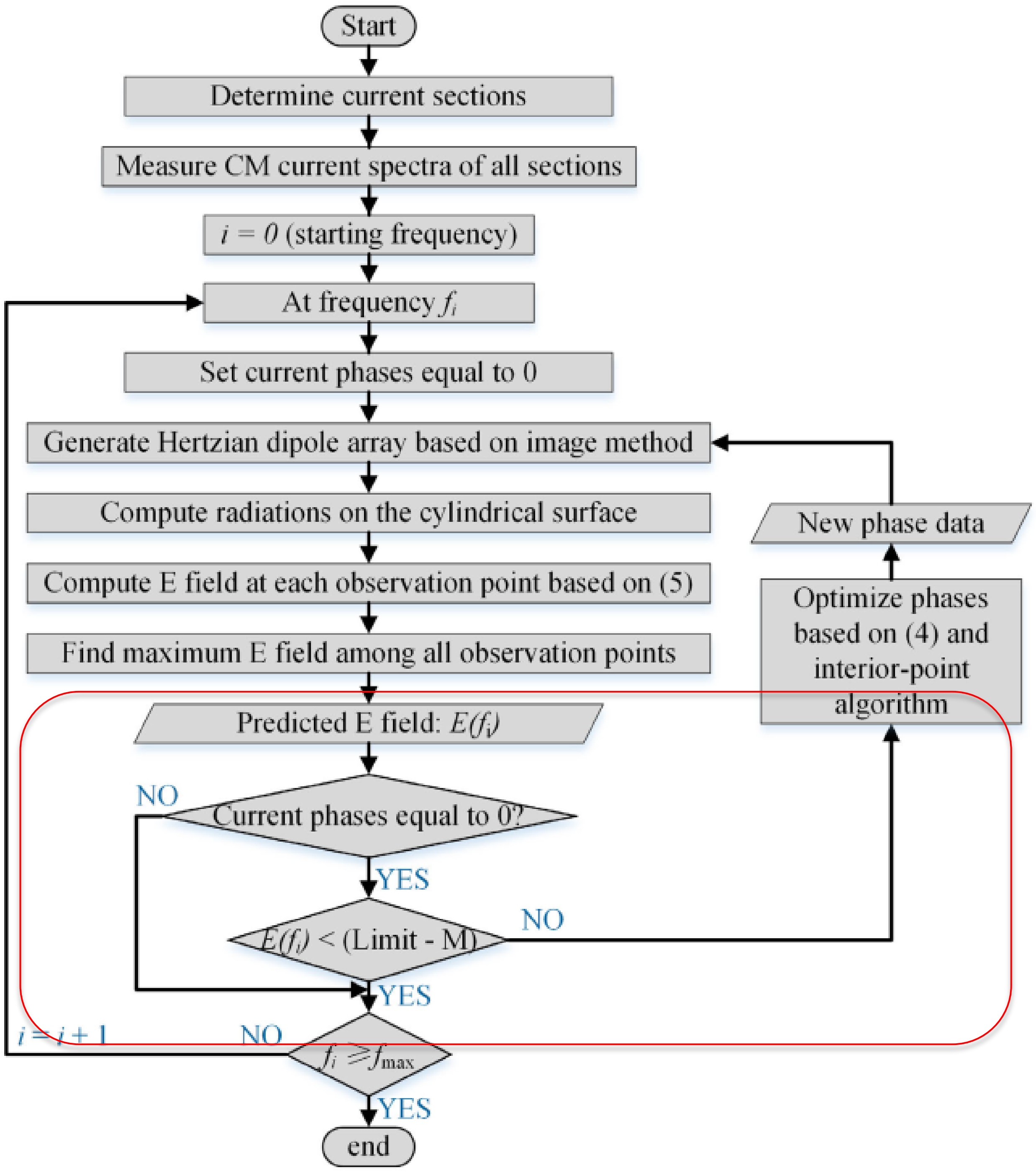
DM!



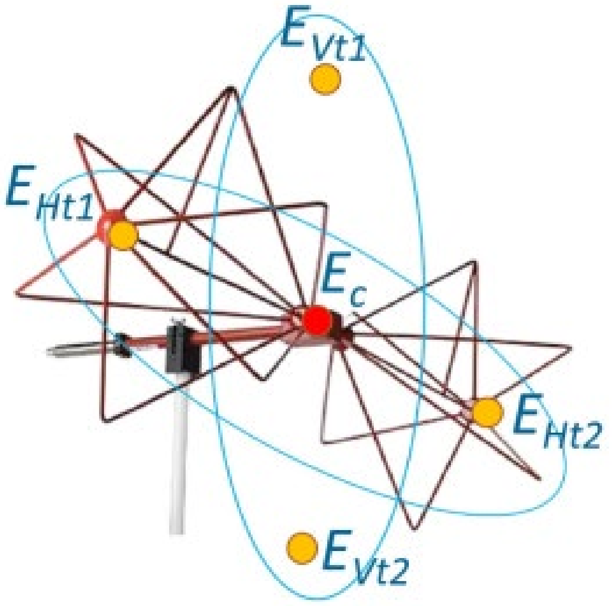
Simple cable radiated emission evaluation method



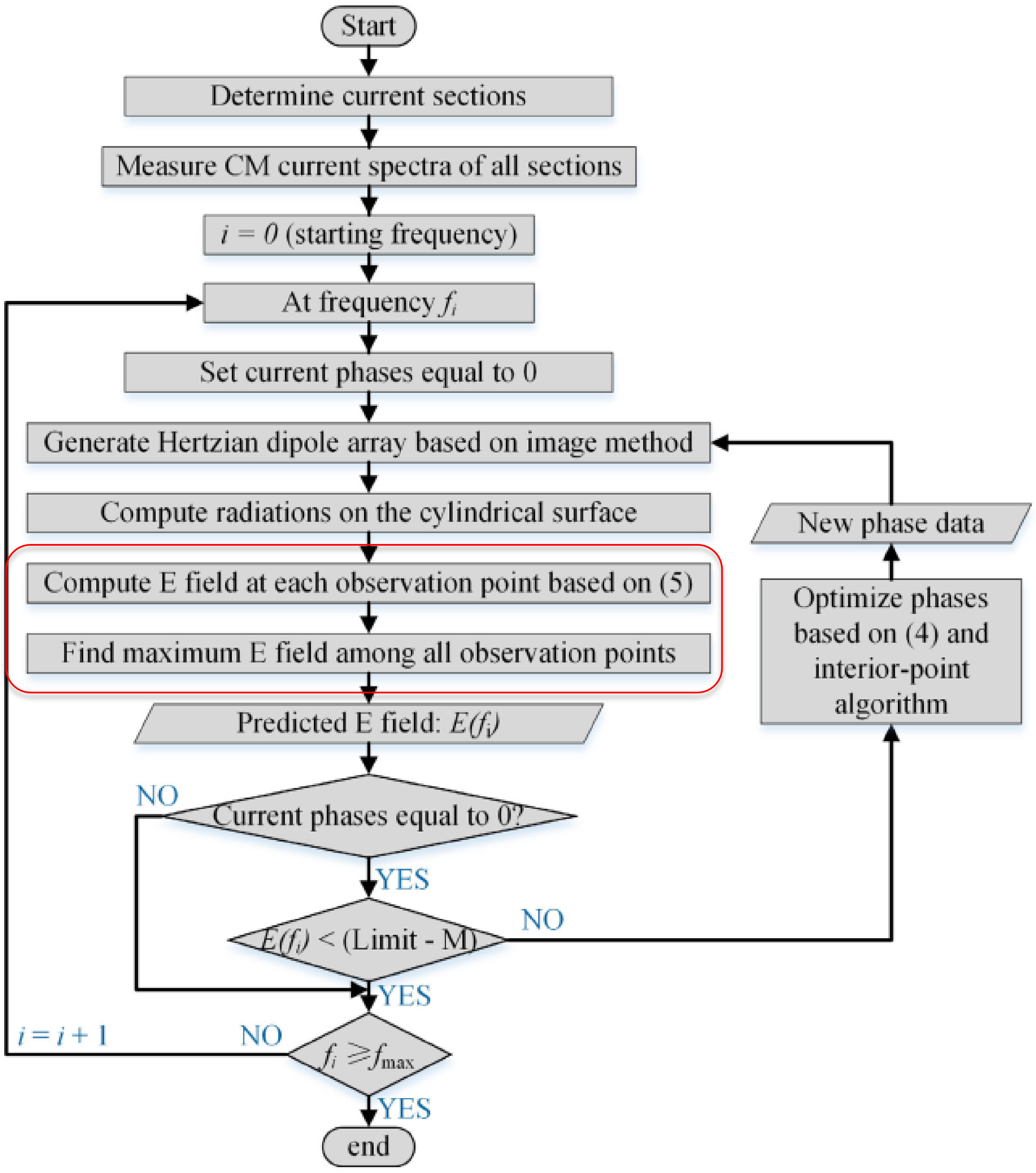
$$\hat{I}_{CM}(n) = \frac{1 - \hat{\Gamma}_L e^{-j2\beta L} e^{j2n\beta \Delta l}}{1 - \hat{\Gamma}_L e^{-j2\beta L}} \hat{I}_{CM}(0) e^{-jn\beta \Delta l}$$



Simple cable radiated emission evaluation method



$$\hat{E}_k = \max[\underbrace{(4\hat{E}_{Hc} + \hat{E}_{Ht1} + \hat{E}_{Ht2})/6}_{\text{Horizontal E-field}}, \underbrace{(4\hat{E}_{Vc} + \hat{E}_{Vt1} + \hat{E}_{Vt2})/6}_{\text{Vertical E-field}}],$$



Simple cable radiated emission evaluation method

Impact of phases

Phase	Max. radiation (Location)	E-field at (-3 m, 0 m, 1 m)
Zero phase	41.00 dBμV/m (-3 m, 0 m, 1 m)	Ex: 29.82 dBμV/m Ey: 30.36 dBμV/m Ez: 40.22 dBμV/m
Optimized phase	40.24 dBμV/m (0 m, 3 m, 1 m)	Ex: 25.88 dBμV/m Ey: 21.78 dBμV/m Ez: 36.03 dBμV/m

@ 150 MHz

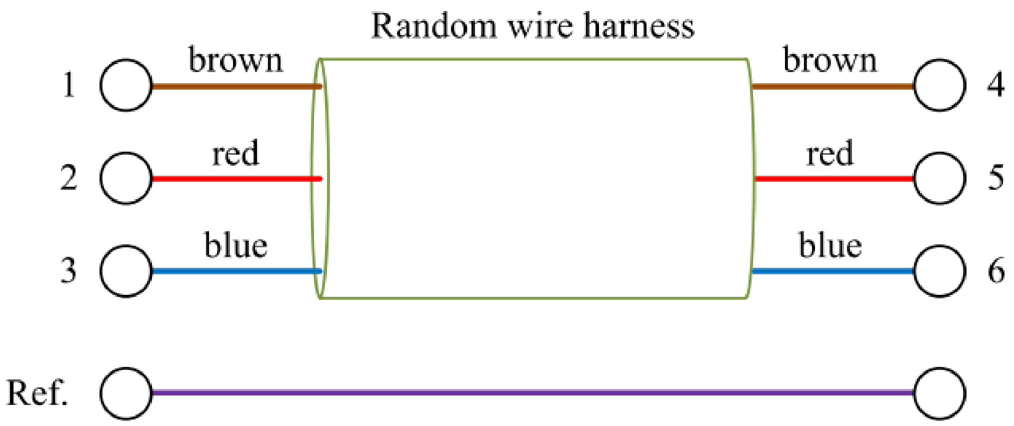
Phase info.

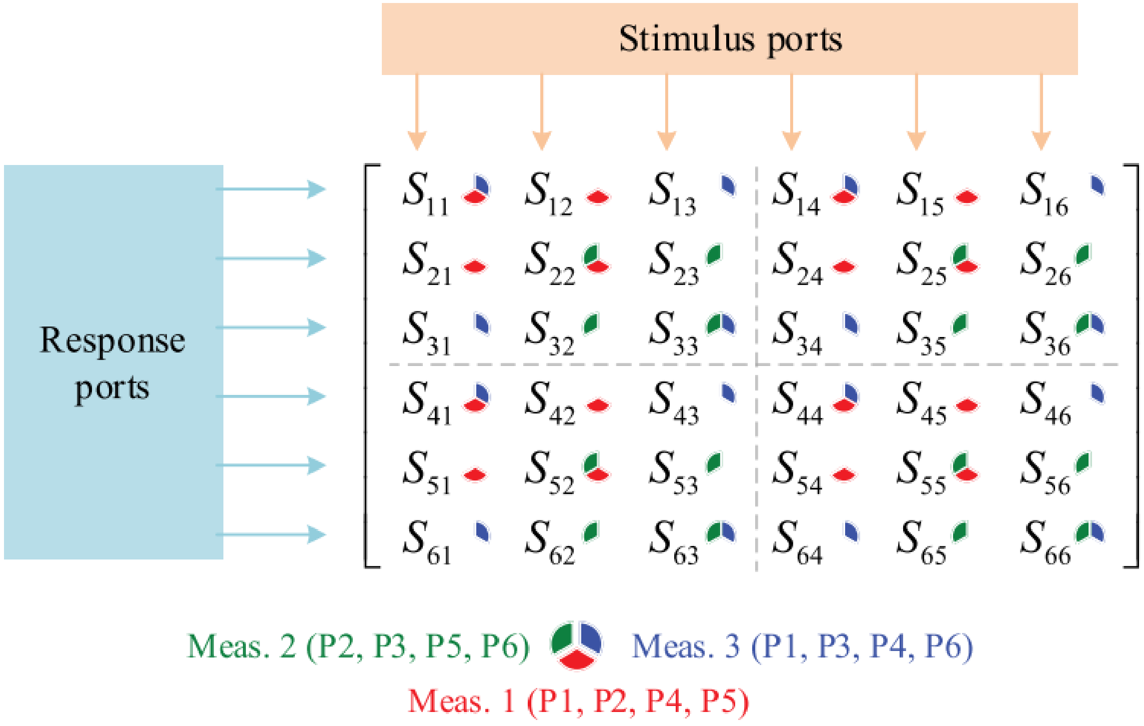
➔ Important for fields at specific point

➔ Less important for overall radiation evaluation

Digital twin modeling of wire harnesses

❑ Characterize the three-wire system





Digital twin modeling of wire harnesses

❑ Conclusion

- A procedure for DT modeling of random wire harnesses, starting from image recognition, has been presented.

- Model constructs based on photos taken from two perspectives, and the generation procedure involves an iterative process.

- As proved by the experiments, accurate prediction can be achieved.

Simple cable radiated emission evaluation method

❑ Conclusion

- a fast pre-compliance radiation evaluation method is proposed, with a focus on cable radiation.

CM current measurement + Electric infinitesimal dipole radiation theory

- Available for the evaluation in an ordinary environment (as long as the critical frequencies are not in the frequency range of environmental noise)

- The radiation from the cable portion close to the metallic ground can be neglected in the prediction

It offers a complete, cheap, and easy-to-implement solution for pre-compliance radiation prediction.

A Two-Step Approach for the analysis of BCI tests involving wire harnesses

Modal analysis

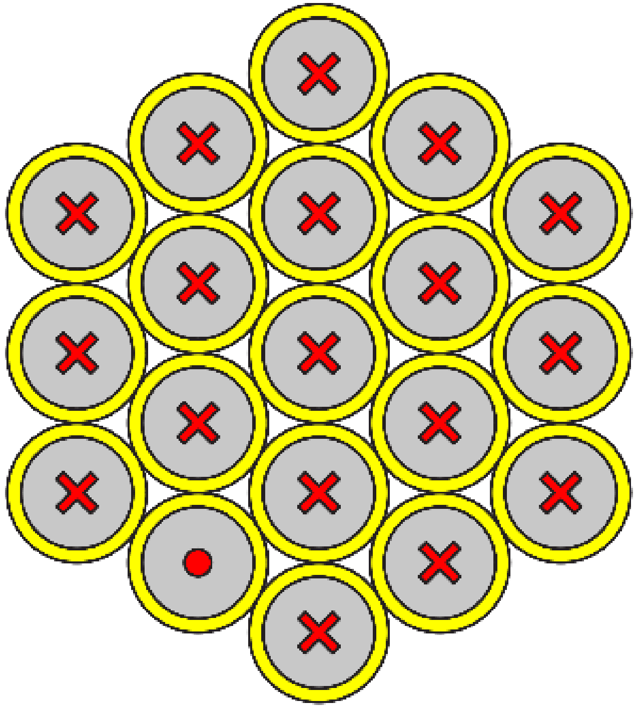
$$\hat{\boldsymbol{V}}_m = \begin{bmatrix} \hat{V}_{\mathrm{CM}} \\ \hat{V}_{\mathrm{DM1}} \\ \vdots \\ \hat{V}_{\mathrm{DM}(N-1)} \end{bmatrix} = \boldsymbol{T}_V^{-1}\hat{\boldsymbol{V}}$$

$$\boldsymbol{T}_V = \begin{bmatrix} 1 & 1/N & \dots & \dots & \dots & 1/N \\ 1 & -1/N & 0 & \dots & \dots & 0 \\ 1 & 0 & -1/N & 0 & \dots & 0 \\ \vdots & \vdots & \ddots & \ddots & \ddots & \vdots \\ 1 & 0 & \dots & 0 & -1/N & 0 \\ 1 & 0 & \dots & \dots & 0 & -1/N \end{bmatrix}$$

$$\hat{\boldsymbol{I}}_m = \begin{bmatrix} \hat{I}_{\mathrm{CM}} \\ \hat{I}_{\mathrm{DM1}} \\ \vdots \\ \hat{I}_{\mathrm{DM}(N-1)} \end{bmatrix} = \boldsymbol{T}_I^{-1}\hat{\boldsymbol{I}}.$$

$$\boldsymbol{T}_I = \begin{bmatrix} 1/N & 1 & \dots & \dots & \dots & 1 \\ 1/N & -1 & 0 & \dots & \dots & 0 \\ 1/N & 0 & -1 & 0 & \dots & 0 \\ \vdots & \vdots & \ddots & \ddots & \ddots & \vdots \\ 1/N & 0 & \dots & 0 & -1 & 0 \\ 1/N & 0 & \dots & \dots & 0 & -1 \end{bmatrix}$$

One example of DM current



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Susceptibility tests involving cables

A Two-Step Approach for the analysis of BCI tests involving wire harnesses

Conclusion

- a two-step approach for modeling of BCI tests with wiring harness is proposed.

Modal analysis: 1st Step: CM analysis -> CM-to-DM conversion -> 2nd step: DM analysis

- Weak-imbalance assumption is used, and 2nd effect DM-to-CM can be neglected
- Physical quantities can be approximately obtained only from the CM quantities (one-wire analysis is usually enough)
- Based on this idea, a novel hybrid probabilistic-possibilistic framework is also developed -> speed up statistic analysis.