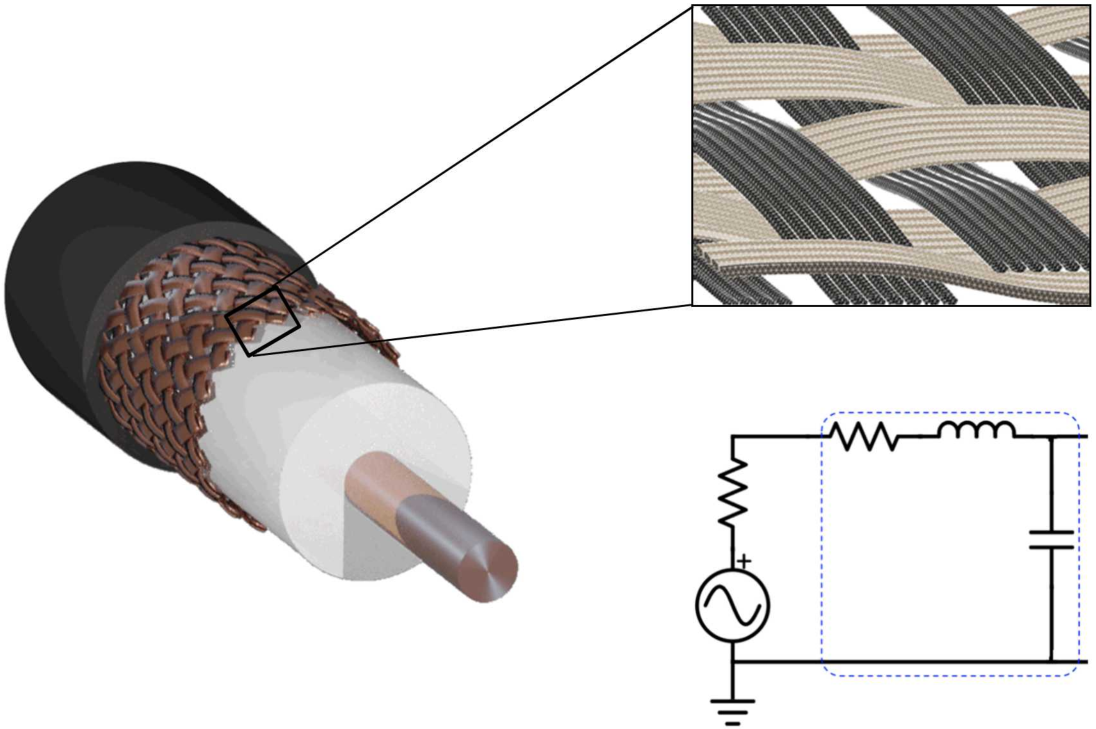
SAND2019-7505C

Modeling shielded cables in Xyce based on transmission-line theory



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Outline

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- Experiment summary
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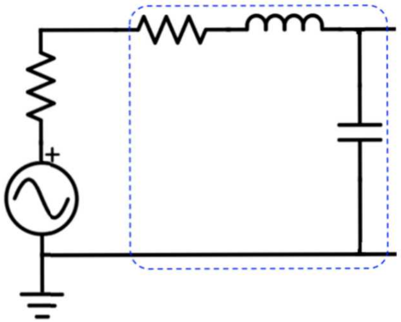
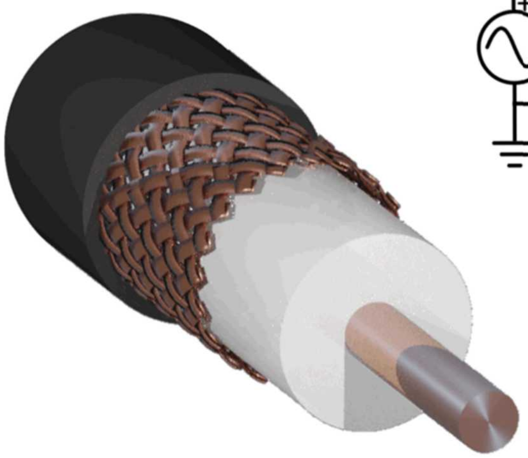
- Summary

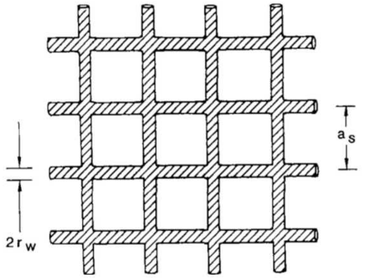




Introduction

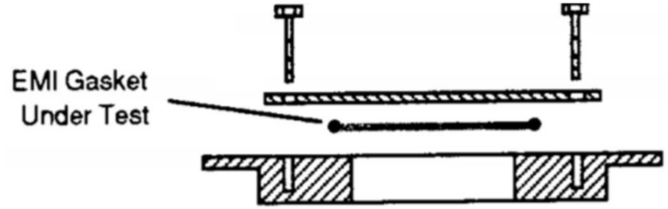
Electronic devices can experience upset from unwanted electromagnetic fields; this can be mitigated using electromagnetic shielding. These include:

Wire-mesh shields



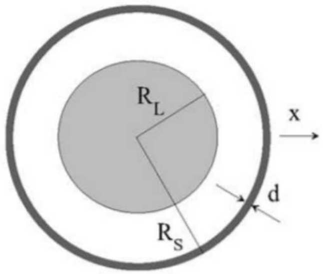
K. F. Casey, *IEEE Transactions on Electromagnetic Compatibility* **30**, 298-306 (1988)

Material shielding



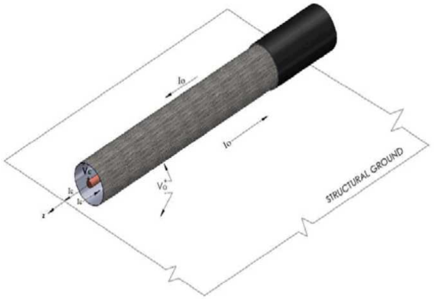
H. W. Denny and K. R. Shouse, *IEEE International Symposium on Electromagnetic Compatibility*, Washington, DC, USA, 1990, pp. 20-24

Metallic enclosures



L. Klinkenbusch, *IEEE Transactions on Electromagnetic Compatibility* **47**, 589-601, (2005)

Braided shields



S. Campione et al., *Progress in Electromagnetics Research C* **65**, 93–102 (2016)

Active, partial, chiral, and metamaterial shielding

S. Celozzi et al., *Electromagnetic Shielding*, John Wiley & Sons, 2008

Braided cable analysis

1934 – S. Schelkunoff examines transmission of high frequency currents of co-axial conducting tubes, defining reflection loss as: $R = 20log_{10}(|H_o|/|H_t|)$.[1]

1959 – H. Kaden develops a theory of coupling through electrically small irises.[2]

1975 – E. Vance adapts this theory to EM coupling through single-layer braided shields. Transfer impedance and admittance of a cable is derived from physical parameters of the braid.[3]

K. Lee and C. Baum derive transmission-line equations for a braided cable using modal analysis and develop a lumped network representation.[4]

M. Tyni introduces the porpoising contribution to the transfer inductance of a cable braid.[5]

1993 – T. Kley derives new formulae for coupling parameters of cables with single-braided shields based on qualitative analysis of coupling mechanisms, improving agreement between theory and experiment.[6]

2011 – Schippers et al. improve on previous models by accounting for the effects of inductance, which heavily influences transfer impedance.[7]

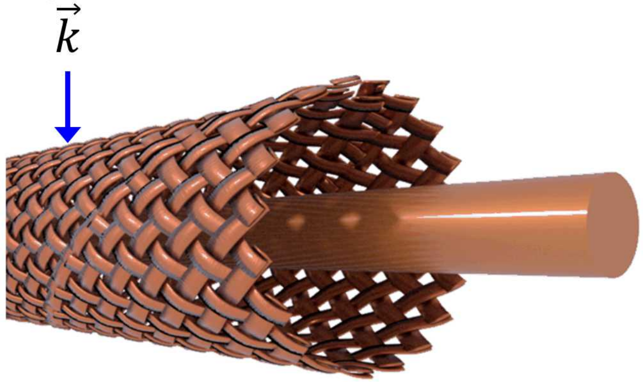
2016, 2018 – Warne et al. and Campione et al. present analysis of a first principles multipole-based cable braid electromagnetic penetration model to account for full dependence on the cable geometry.[8,9]

Motivation: Verify circuit model implementation with a previously proposed analytic model to enable coupling between electromagnetic and circuit simulations.

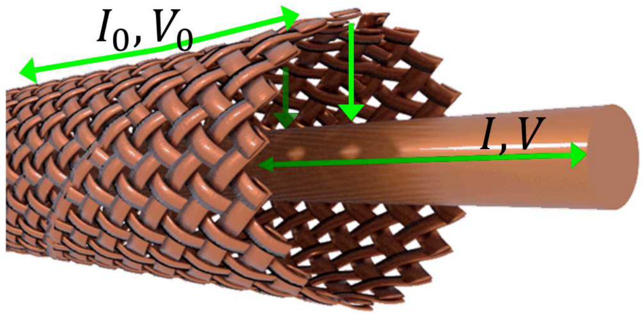
[1] S. A. Schelkunoff, "The electromagnetic theory of coaxial transmission lines and cylindrical shields," *Bell Sys. Tech. J.* **13**, 532-579, 1934.
[2] H. Kaden, *Wirbelstrome und Schirmung in der Nachrichtentechnik* (Springer-Verlag, Berlin, 1959).
[3] E. F. Vance, *IEEE Transactions on Electromagnetic Compatibility* **EMC-17**, 71-77 (1975).
[4] K. S. H. Lee and C. E. Baum, *IEEE Transactions on Electromagnetic Compatibility* **EMC-17**, 159-169 (1975).
[5] Tyni, M., "The transfer impedance of coaxial cables with braided outer conductor,", 410-419, *FV. Nauk, Inst. Telekomum Akust. Politech Wroclaw, Ser. Konfi*, 1975.
[6] T. Kley, *IEEE Transactions on Electromagnetic Compatibility* **35**, 1-9 (1993).
[7] H. Schippers et al., "Electromagnetic analysis of metal braids," *10th International Symposium on Electromagnetic Compatibility*, York, 2011, pp. 543-548.
[8] L. K. Warne et al., Progress in Electromagnetics Research B **66**, 63–89 (2016)
[9] S. Campione et al., *IEEE Transactions on Electromagnetic Compatibility* **60**, 444-452 (2018).

Transmission-line model: Introduction

In this model, an incident source strikes the outer shield. The model assumes here a single shield, although multiple shields can be modeled using the same method[1].



The external source induces currents and voltages, propagating along the shield. The transfer of energy occurs due to the imperfect conductivity of the outer shield, and EM penetration through the shield.

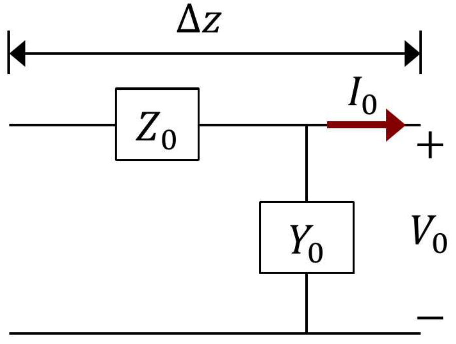


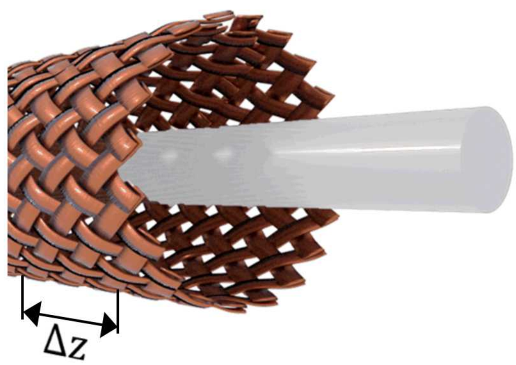
As a result, currents and voltages are then induced on the inner conductor. The ratio of the currents on the inner conductor to those on the outer conductor define the shielding effectiveness:

$$SE(dB) = 20 \cdot log\left(\frac{I_{conductor}}{I_{shield}}\right)$$

[1]S. Campione et al., *Progress in Electromagnetics Research C* **65**, 93–102 (2016)

Transmission-line model: Outer shield





- Y_0 (outer shield admittance) and Z_0 (outer shield impedance) are known from the characteristics of the cable of interest

- In the lossless case,

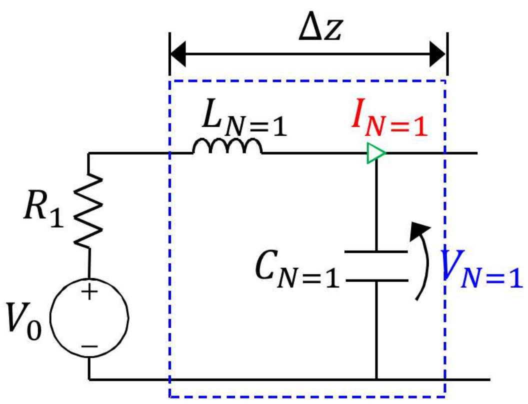
  Y_0 → capacitor

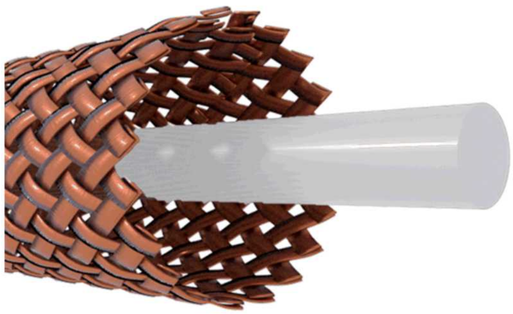
  Z_0 → inductor

- In the lossy case, resistive elements can be added to account for various system losses.

S. Campione et al., *Progress in Electromagnetics Research C* **65**, 93–102 (2016)

Transmission-line model:
Outer shield circuit implementation

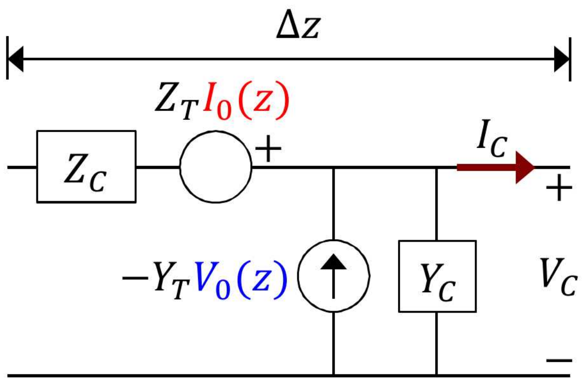




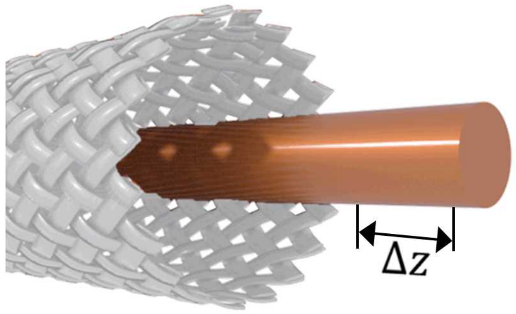
- The transmission line is approximated by N individual cells, each with length Δz.
- V_0 is representative of the external electromagnetic wave and drives the model.
- In the lossless case,
  - Shield impedance → inductor ($L_N = L_0 \Delta z$)
  - Shield admittance → capacitor ($C_N = C_0 \Delta z$)
  - External loads → resistor ($R_{1,2} = R_0$, matched)
- I_N, V_N → Current and voltages collected at each cell for computation of the induced fields on the inner conductor.
- In a more accurate model, each cell contains an additional resistor to account for loss mechanisms.

S. Campione et al., *Progress in Electromagnetics Research C* **65**, 93–102 (2016)

Transmission-line model: Inner conductor



(Note: $I_0(z) = I_N$, and $V_0(z) = V_N$)



- Z_C: self-impedance
  Z_T: transfer impedance
  $I_0(z)$: induced current
  Y_C: self-admittance
  Y_T: transfer admittance
  $V_0(z)$: induced voltage

- Transfer impedance and admittance define distributed sources:

$$E_z(z) = Z_T I_0(z) = \frac{dV_C}{dz} + Z_C I_C \quad \text{(Dist. current source)}$$

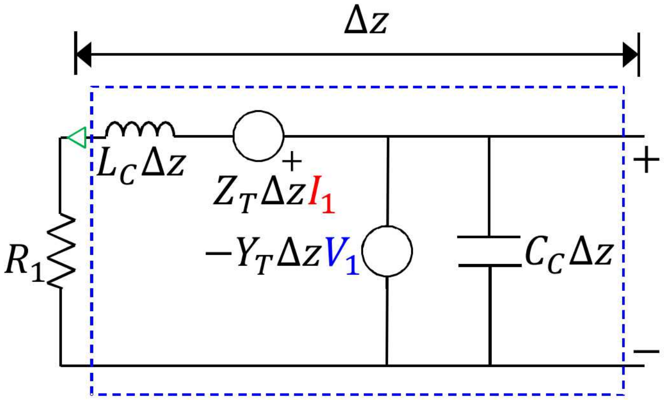
$$J_z(z) = -Y_T V_0(z) = \frac{dI_C}{dz} + Y_C V_C \quad \text{(Dist. voltage source)}$$

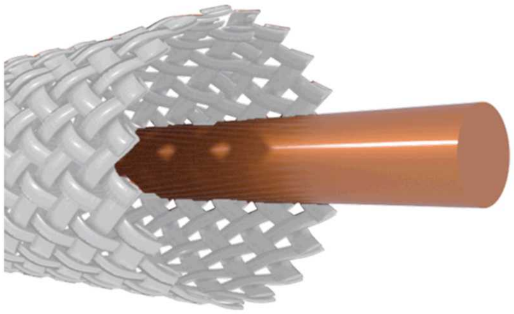
- $Z_T = Z_R + j\omega L_T + Z_S$
  internal transfer impedance (Z_R),
  transfer inductance (L_T),
  shield diffusion (Z_S)

- $Y_T = j\omega C_T$
  transfer capacitance[2] (C_T)

S. Campione et al., *Progress in Electromagnetics Research C* **65**, 93–102 (2016)
[2]T. Kley, IEEE Transactions on Electromagnetic Compatibility 35, 1-9 (1993)

Transmission-line model: Inner conductor circuit implementation





- This model is driven by distributed voltage and current sources representative of the penetration of the external electromagnetic wave through the shield.
- In the lossless case,

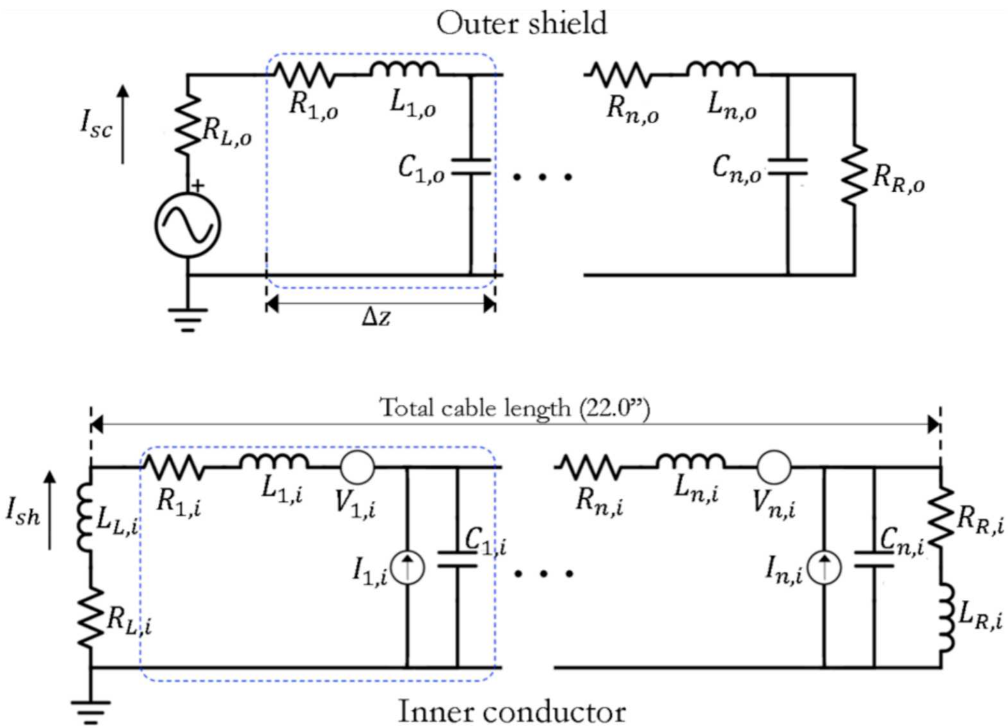
  Conductor impedance → inductor ($L_N = L_C\Delta z$)

  Conductor admittance → capacitor ($C_N = C_C\Delta z$)

  External loads → resistor ($R_{1,2} = 0.5\Omega$)

- In the lossy case, a resistor is added to account for various system losses.

Numerical circuit analysis: Xyce Parallel Electronic Simulator[3]

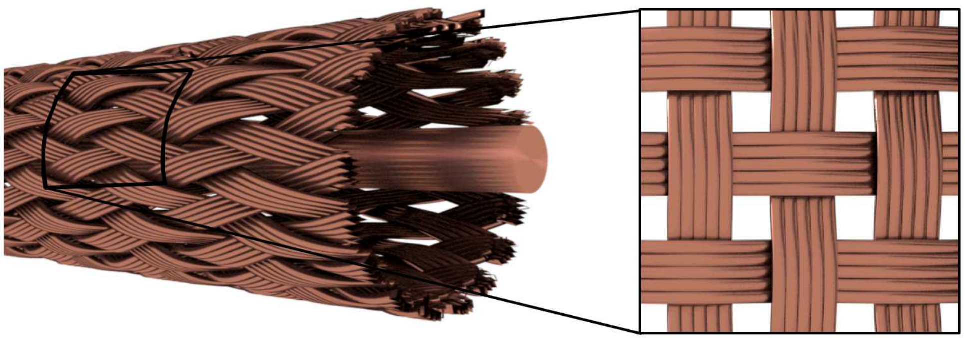


- High-performance analog circuit simulator
- Open-source, SPICE-compatible
- Supports large-scale parallel computing platforms
- Multiple analysis options (steady state, transient)
- This analysis was done in the frequency-domain.

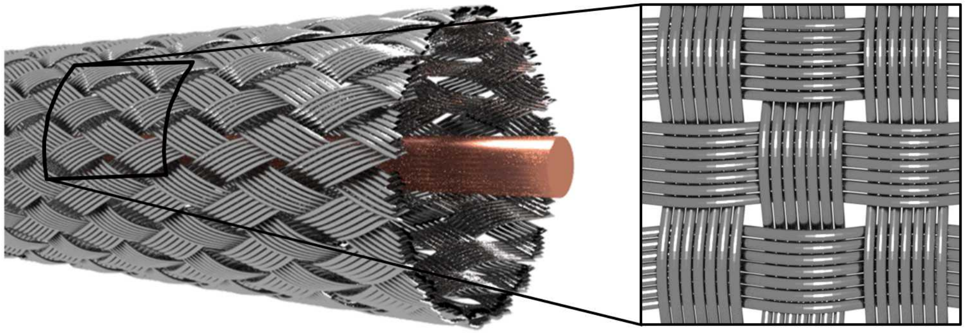
[3]Xyce Parallel Circuit Simulator. http://xyce.sandia.gov.

Cable parameters

Length [in.]	22.0
Wire diam. [in.]	0.005
Braid inner diam. [in.]	0.116
Inner conductor diam. [in.]	0.033
Jacket outer diam. [in.]	0.193



Belden 9201	
Optical coverage [%]	78
Strands/carrier	5
Braid angle [°]	22.0
Braid outer diam. [in.]	0.134



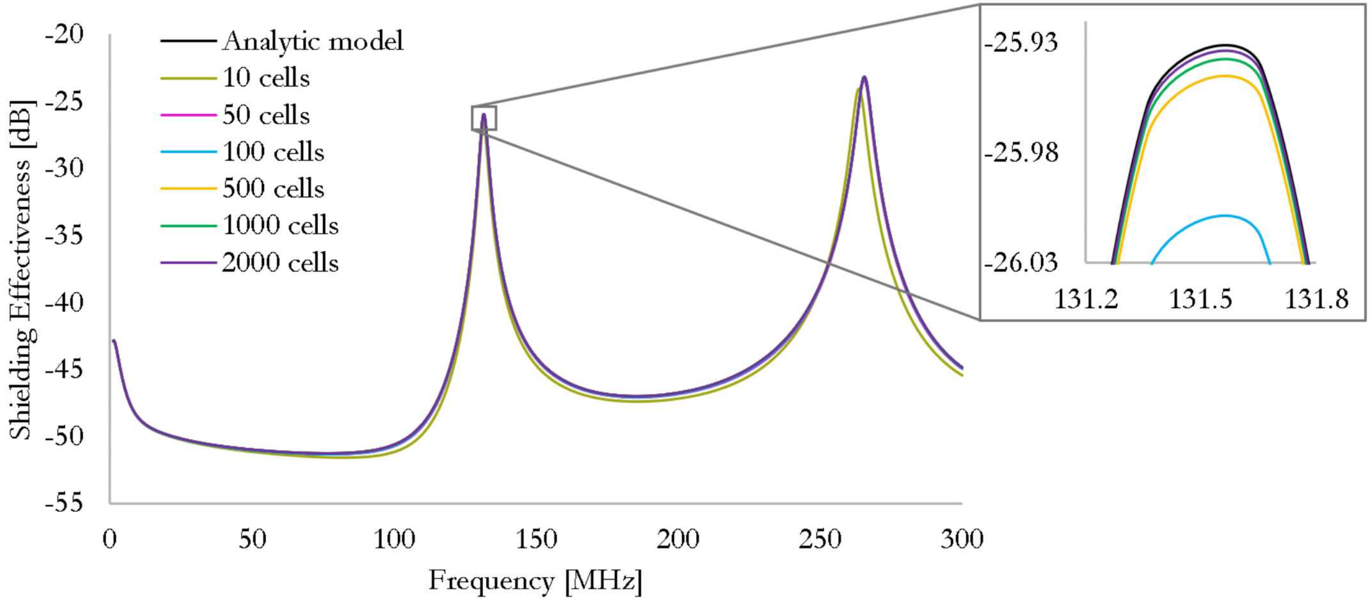
Belden 8240	
Optical coverage [%]	95
Strands/carrier	7
Braid angle [°]	24.4
Braid outer diam. [in.]	0.130

Differences in braid parameters lead to a change in capacitance, inductance, and resistance values.

Modeled SE: Analytic vs. Xyce

22-inch Belden 9201

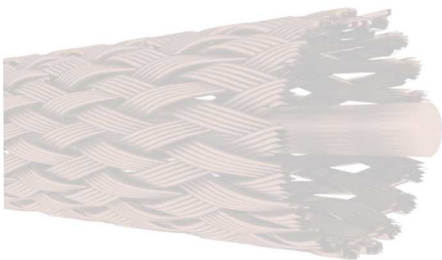
~0.03% disagreement for 2000 cells



- Each cell is the same length, and contains lossy components.
- The convergence study uses 10 – 2000 cells.
- 50 cells is sufficient for agreement between the analytic and numerical models.

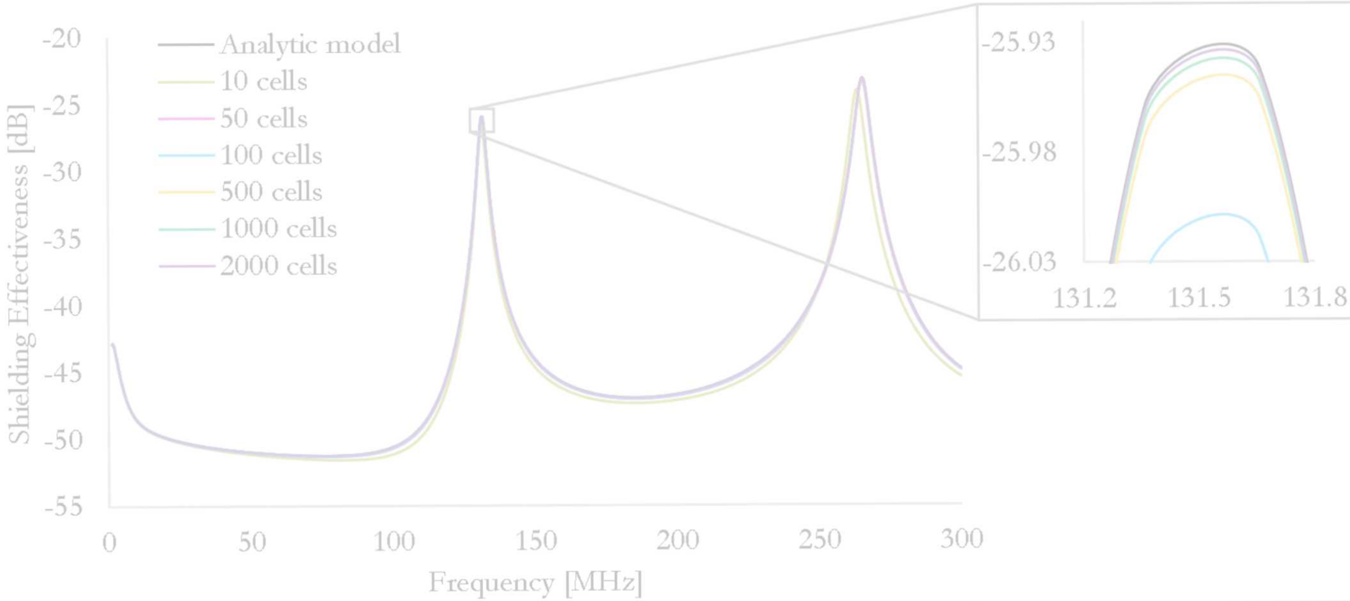
This study verifies convergence of the circuit solution.

Modeled SE: Analytic vs. Xyce



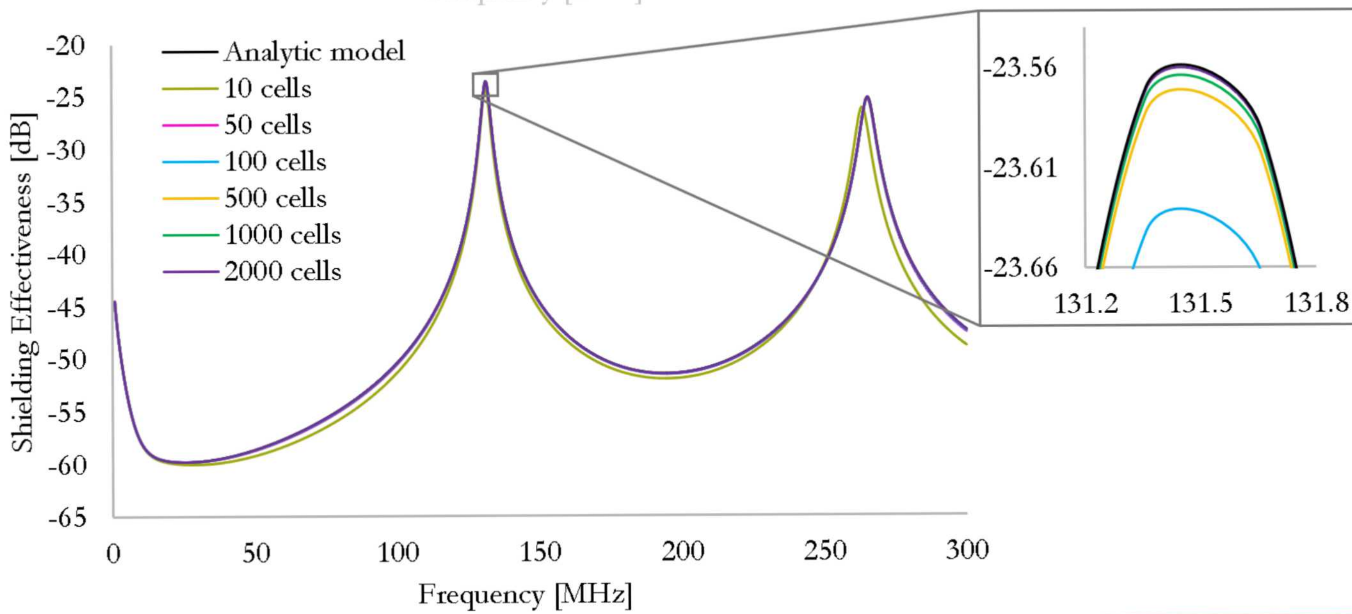
22-inch Belden 9201

~0.03% disagreement for 2000 cells



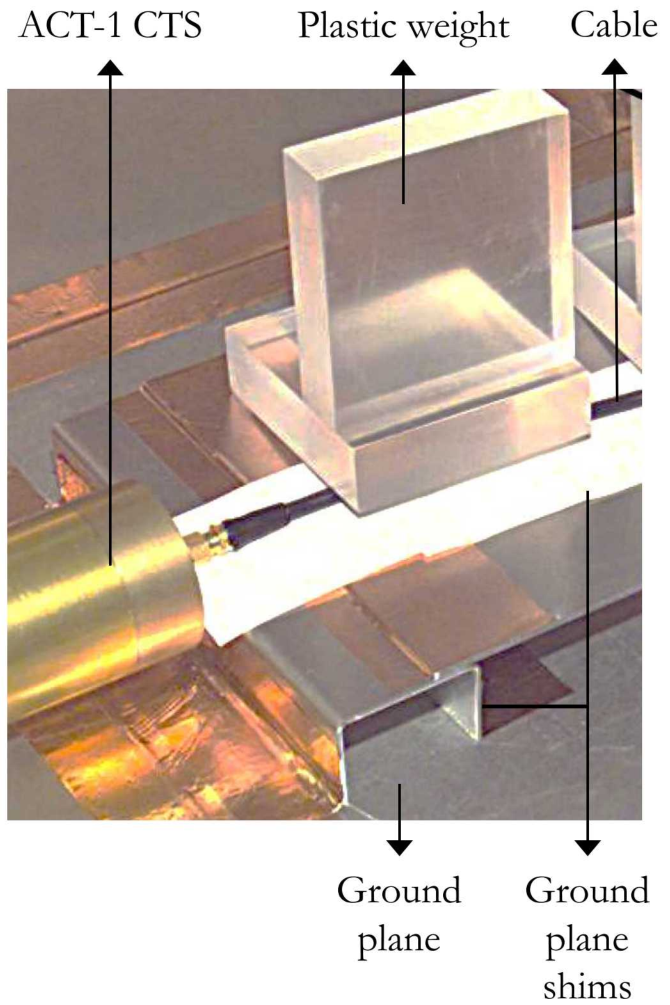
22-inch Belden 8240

~0.01% disagreement for 2000 cells

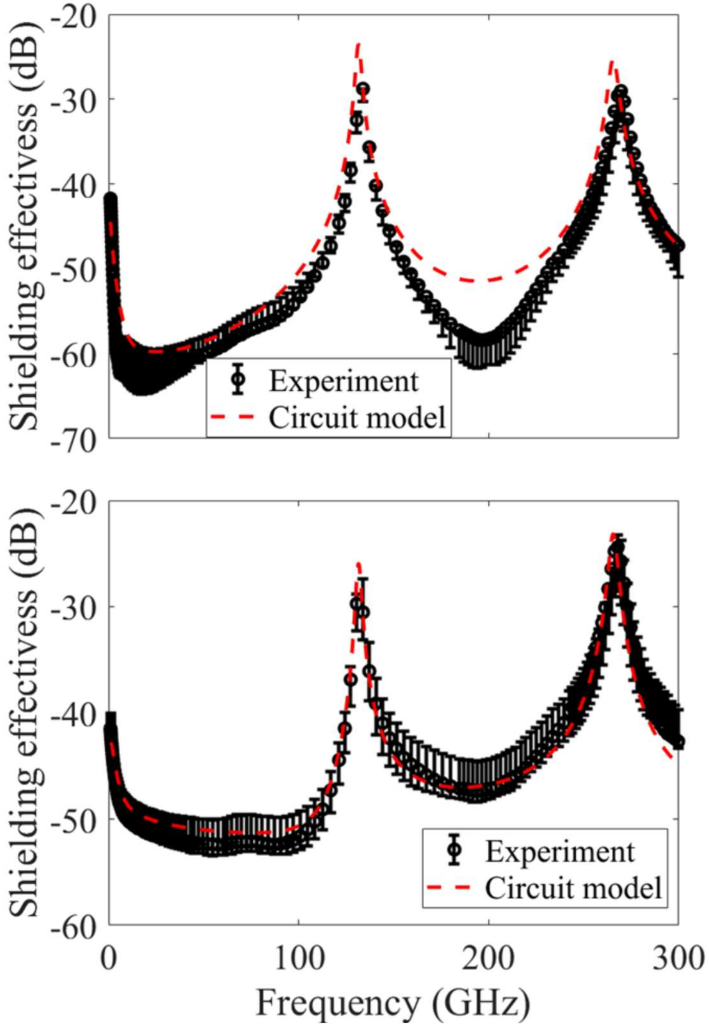


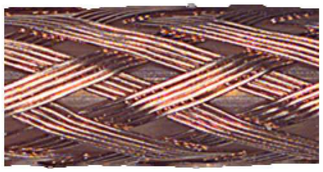
Experiment summary

- Two 22-inch cables were fabricated, terminated with SMA connectors at each end.
- Shields are soldered to the connector to reduce leakage into the center conductor from the shield termination.
- ACT-1 Cable Test System (CTS) measures effective attenuation provided by the shield of a cable assembly.
- Test cable aligned with centerline of CTS using metal and paper shims, adjusting cable impedance.
- Plastic weights keep cable flat against shims to maintain goal impedance value (50 ohms).
- CTS calibration is performed, and reproducibility was examined. Variations in measured SE are summarized with error analysis.

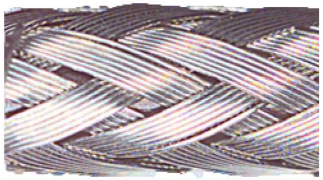


SE: Measured vs. Modeled





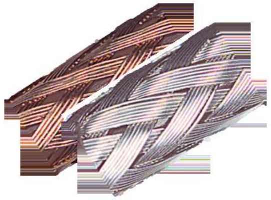
Belden 9201



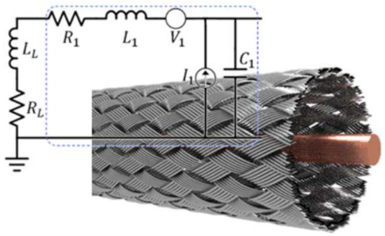
Belden 8240

Variations in experiment data were characterized using error analysis.
Despite these variations, strong agreement is achieved.

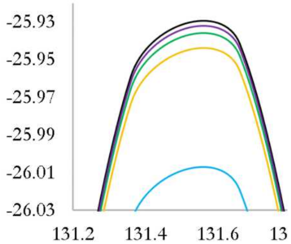
Summary



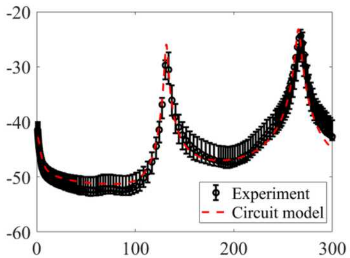
Upset of electronic circuits can be mitigated by use of EM shielding, such as braided cables.



Knowledge of the braid's geometry enable equivalent circuit analysis for prediction of shielding effectiveness.



Strong agreement between analytic transmission line models and validated numerical circuit analysis tools.



This agreement also matches shielding effectiveness data gathered from experiment of Belden 9201 and Belden 8240 cables.

This circuit model represents a step toward multi-physics electromagnetic and circuit simulations.