Measurement-Assisted Electromagnetic Extraction of Interconnect Parameters on Low-Cost FR-4 boards for 6-20 Gb/sec Applications

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Outline

- Goals of the project
- Challenges
- Test board overview
- Selection of dispersive dielectric and conductor models and simulation technique
- Measurement methodology
- Identification of dielectric parameters
- Comparisons of measurements are simulations
- Conclusion
Goals of the Project

- **High Confidence Design** Method for 10 Gb/sec
  - Material extraction DK and LT versus frequency
  - Build 3D electromagnet models and confirm with measured data
- Build pristine measurement **de-embedding** capability
- Models versus measurements
  - 1% correspondence performance up to 20GHz
  - No “cheating” with manipulation of final data
  - Models must be easy to develop
  - Allow for weave and material variability, make study realistic and represent practical design
Challenges

- Design of interconnects on PCBs for 6-10 Gb/s data rates requires electromagnetic **modeling from DC to at least 20 GHz**
- Manufacturers of low-cost FR-4 PCBs typically provide values for **DK and LT either at one frequency** or without specifying frequency value at all
  - The properties of the composite dielectrics is frequency-dependent and needs to be modeled accordingly
- Build suitable measurements **de-embedding** methodology
- Build software with suitable **dielectric and conductor loss models**
- Design a **PCB test vehicle** with 30 test structures to validate the extraction methodology and to verify possibilities to predict interconnect parameters with electromagnetic analysis on low-cost FR-4 boards
PLRD-1 Physical Layer Test Vehicle

- 30 test structures – all equipped with SMA connectors with optimized launch

- Differential line
- Differential via-holes
- Coupled via-holes
- Meander
- Beatty resonators
- Low-pass filter
- Single via
- Stub resonators
- Channel with 6 single vias
- T-line segments
- Short
- Open
- Strip lines and via-holes
- Bends in differential lines
- Matched
- T-line segments
Step 1: Materials and Stackup

- **Materials**
  - "Copper", RF=1, SR=0.5
  - "FR4", Dk=4.2, LT=0.02, PLM=WD
  - "Core", Dk=4.7, LT=0.02, PLM=WD
  - "Vacuum"
  - "SolderMask", Dk=3.3, LT=0.02, PLM=WD

- **Stackup: L= (mil), W= (mil), t= (mil), SML=(SolderMask, 1.75mil))
  - 1. Signal: "Signal", T=1.35, Ins= "Vacuum"
  - 2. Medium: T=6.9, Ins="FR4"
  - 3. Plane: "Plane1", Mat="Copper", T=1.35, Ins="FR4"
  - 4. Medium: T=39, Ins="Core"
  - 5. Plane: "Plane2", Mat="Copper", T=1.35, Ins="FR4"
  - 6. Medium: T=3.9, Ins="FR4"
  - 7. Signal: "Signal2", T=1.35, Ins="Vacuum"

- **Start with properties provided by board vendor:**
  - Copper bulk resistivity 1.724e-8 Ohm meters, roughness 0.5 um (roughness factor 2 is guessed)
  - Solder mask: DK=3.3, LT=0.02
  - FR-4 core dielectric: DK=4.7, LT=0.02
  - **FR-4 dielectric between signal and plane layers: DK=4.2, LT=0.02 – will be adjusted on the base of measurements and simulations**
  - Measurement frequency for all dielectrics is guessed to be 1 GHz
Step 2: Selecting Dielectric Dispersion Model

- **Simplest Model**: Constant DK and LT versus frequency
  - Simple, easy to measure, included in all microwave software
  - Model is **non-causal** and does not correspond to the observed behavior – although very popular model, non-causal, BAD!

- **Multi-pole Lorentzian** (used in some researches)
  - No evidence of complex poles for composite dielectrics – not acceptable

- **Multi-pole Debye**
  - Perfectly suitable with 4-5 poles over the investigated frequency band
  - Complicated fitting: At least 4-5 coefficients have to be identified by comparison – not good

- **Wide-band Debye (Djordjevic-Sarkar)**
  - Close to observed behavior of composite dielectrics (supported by multiple publications)
  - Requires only two coefficients to fit - we like it!
Step 4: Review Electromagnetic Analysis Requirements and Select Software

- **3D full-wave** analysis of t-lines and discontinuities
- Causal dispersive dielectric model – multi-pole or wideband Debye
- **Broadband conductor loss and dispersion models** valid and causal over 4-5 frequency decades (skin, edge, and proximity effects, conductor plating)
- Conductor **surface roughness**
- **High-frequency dispersion** effect
- Extract **de-embedded S-parameters** for discontinuities
- Extract frequency-dependent RLGC per unit length parameters for transmission lines
Step 4 - Deal with Surface Roughness

- No roughness model: observed LT may be overestimated – not acceptable
- Conductivity adjustment (Gripos): overestimates conductor losses – not acceptable
- Hammerstad-Bekkadal or Morgan’s models: do not account variation of roughness on opposite surfaces of strip – not acceptable
- Local conductor surface impedance adjustment during electromagnetic extraction: versatile and accurate - we use it!

Two parameters SR and RF have to be measured on microphotograph for instance

\[ RF = \frac{L_{\text{rough}}}{L_{\text{straight}}} \]

**Roughness Factor: RF = L\_rough / L\_straight**

![Graph showing attenuation vs. SR and RF values](image)
Step 5: Making Measurements – Developing the Approach

1. Create TRL/LRM cal kit
2. Perform Calibration
3. Confirm de-embedding using THRU
4. Measure S-parameters of LINES 1,2,3, THRU, OPEN, LOAD, and all test structures
5. Restore passivity, reciprocity and symmetry and filter the measured S-parameters to increase accuracy of the multiport model conformance
TRL/LRM Design Approach

1. Decide on a maximum frequency – we typically like to make max frequency higher than the VNA
2. Determine frequency span (30 to 150 degrees, span of 5)
3. Use the Molex spreadsheet for TRL calculation of lengths (be careful, this chart uses effective Dk, don’t use 4.2 with FR4 for Microstrip!)
### TRL Calibration Calculator for Microstrip

<table>
<thead>
<tr>
<th>Inputs:</th>
<th>Effective Dk</th>
<th>Reference Length(mm)</th>
<th>Reference Length(in)</th>
<th>Frequency Ratio</th>
<th>Low Phase</th>
<th>High Phase</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3.2</td>
<td>44.45</td>
<td>1.75</td>
<td>5</td>
<td>30°</td>
<td>150°</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Outputs</th>
<th>Start Frequency (Ghz)</th>
<th>Stop Frequency (Ghz)</th>
<th>Time Delay (ps)</th>
<th>Line Length (mm)</th>
<th>Line Length (in)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Short/Open</td>
<td></td>
<td></td>
<td>0</td>
<td>44.45</td>
<td>1.75</td>
</tr>
<tr>
<td>Load</td>
<td>0</td>
<td>183.31</td>
<td>0</td>
<td>44.45</td>
<td>1.75</td>
</tr>
<tr>
<td>Line 3</td>
<td>183.31</td>
<td>916.55</td>
<td>454.61</td>
<td>165.0873</td>
<td>6.4995</td>
</tr>
<tr>
<td>Line 2</td>
<td>917.92</td>
<td>4589.6</td>
<td>90.79</td>
<td>104.1146</td>
<td>4.0999</td>
</tr>
<tr>
<td>Line 1</td>
<td>4585.76</td>
<td>22928.8</td>
<td>18.17</td>
<td>91.94546</td>
<td>3.6199</td>
</tr>
<tr>
<td>Thru</td>
<td></td>
<td></td>
<td>0</td>
<td>88.9</td>
<td>3.5</td>
</tr>
</tbody>
</table>
Line Length Frequencies Stripline, 30 and 150 Degrees – From Molex Spreadsheet

Line Frequency Ranges

- Line 1
- Line 2
- Line 3
- High Phase
- Low Phase

Phase (°) vs. Frequency (MHz) chart
Caveat on Lengths for TRL/LRM Cal Kit

1. Carefully determine all lengths in pre-layout verification using a Gerber or Allegro viewer
2. Make sure all lengths are measured consistently

Start at boundary of VIA pad for all cases
Caveat – Relieve TRL reference plane

2. Relieve reference planes by 100-250mils
Used TDR to Insure SMA Connector Repeatability, 3% Zo variation through System!

- SMA Launches
- Board Traces

- 52 Ohms
- 48 Ohms
Tuned SMA launch used in BLUE
TRL/LRM Measurement of THRU

THRU should have 0dB of magnitude loss, 0dB of phase, 0psec of Group Delay.
Very Low Reciprocity MAGNITUDE Error, less than 0.005dB
Reciprocity PHASE Error and Reciprocity for THRU Insertion, less than 0.4 degrees
Group Delay and Box Car Average of THRU
Step 5: Improving TRL De-Embedded Data

Given a simple structure such as Beatty standard:

- Structure has 1st order geometric symmetry if (left half) = (right half), or reflection coefficients are equal: \( S_{11} = S_{22} \)
- Structure is reciprocal if no anisotropic materials used or \( S_{21} = S_{12} \)
- Structure is passive if no energy generated of eigenvals(\( S \)) \( \leq 1.0 \)

\[
\begin{bmatrix}
S_{11} & S_{12} \\
S_{21} & S_{22}
\end{bmatrix}
\]
Step 6: Choose Dielectric Identification Technique

- **Measurements**
  - **S-parameters** measured with VNA (*de-embedded* or not)
  - TDR/TDT measurements
  - Combination of both

- Correlated with a numerical model
  - Analytical or closed-form
  - Static or quasi-static field solvers
  - **3D full-wave solvers**

- For test structures
  - Transmission line segments
  - Patch or parallel-plate resonators
  - **Resonators coupled or connected to a transmission line**
Pain-Free Dielectric Properties Extraction

- **Measure** and de-embed S-parameters of two classes of structures:
  - **Line** segments - low reflective structure, very low S11
  - **Resonator** Class - high reflective structure, periodic S21, S11

- Create full-wave model of the structure with **wideband Debye** dielectric model

- **Fit model at one frequency (1 GHz for instance):**
  - Sweep **DK** @ 1 GHz and find value with the best correspondence of resonances, transmission coefficient phase and group delay
  - Sweep **LT** @ 1 GHz and find value with the best correspondence in transmission coefficient magnitude
Step 7: Dielectric Identification - Start with Simple T-line Segment

- 17-mil wide and 3-inch long micro-strip line, TRL de-embedding of the fixture
- Wideband Debye model: DK adjusted to 4.15 @ 1 GHz to have 1% error in phase and LT is adjusted to 0.018 @ 1 GHz to have 1% deviation in magnitude of S[2,1]

Transmission coefficients magnitude and phase

Measured – stars, simulated - circles
**TRL Post Processing Improvement**

- Reflection coefficients magnitude of 3-inch micro-strip line

Original measured data – noise and non-symmetry of extracted S-parameters

After passivity, symmetry and reciprocity is enforced and data are filtered with 16th order filter

Measured – stars, simulated - circles

Good correspondence in level of the magnitude!

Differences in $S[1,1]$ and $S[2,2]$
Dispersion Model Confirmation: Insertion Loss and Phase Delay

- Magnitude and angle of the transmission coefficient $S[2,1]$ of 3-inch micro-strip line

Measured

Substrate $\text{DK}=4.15$, $\text{LT}=0.018$ @ 1 GHz; solder mask $\text{DK}=3.3$, $\text{LT}=0.02$ @ 1 GHz; roughness 0.5 um, $\text{RF}=2$

Wideband Debye model is on top of measured data

Flat non-causal model

64 deg. error in phase with the flat non-causal model of dielectric!
Dispersion Model Confirmation: Group Delay

- Group delay in 3-inch micro-strip line

**Measured**

- 3D full-wave model with flat non-causal dielectric model
- 3D full-wave model with wideband Debye dielectric model

Error is 10 ps or 65 mil in trace length with flat non-causal dielectric model!

Measured and de-embedded data (filtered)

Substrate DK=4.15, LT=0.018 @ 1 GHz; solder mask DK=3.3, LT=0.02 @ 1 GHz; roughness 0.5 um, RF=2
Dielectric Identification with Beatty 25-Ohm Resonator (TRL)

Wideband Debye model: DK adjusted to 3.9 @ 1 GHz to have 1% error in phase of transmission coefficient and in position of the resonances in the reflection coefficient.

Reflection coefficients magnitude

Transmission coefficients phase

Measured – stars, simulated - circles
Dielectric Identification with Beatty 25-Ohm Resonator (TRL)

Wideband Debye model: LT adjusted to 0.018 @ 1 GHz to minimize the difference in measured and calculated transmission coefficient.

Transmission coefficients magnitude

Reflection coefficients phase

Good correspondence!
S-parameters Quality Improvement

- Group delay of Beatty 25-Ohm resonator

Measured – stars, simulated - circles

Original measured data

Filtered with FIR of 16th order

Good correspondence!
Dielectric Loss and Dispersion Model
Extracted with the Beatty 25-Ohm Resonator

- DK=3.9 and LT=0.018 @ 1 GHz – this is all we need to restore frequency-dependent loss and dispersion!

Dielectric constant (DK)
- ~10% variation over the frequency band
- 4.2 @ 1 MHz
- 3.9 @ 1 GHz
- 3.77 @ 20 GHz

Loss tangent (LT)
- 0.018 @ 1 GHz
Dispersion Model Confirmation

Stars – measured, circles – simulated with wideband Debye model for substrate and solder mask with DK=3.9, LT=0.02 and DK=3.3 and LT=0.02 @ 1 GHz, crosses – simulated with flat non-causal models with the same DK and LT not changing with frequency.

It is 1-inch resonator! The difference will be up to 1 GHz in 3-inch structures. (see E.L. Holzman, IEEE Trans. on MTT, v. 54, N7, p. 3127)

The effect is stronger for strip-lines (no compensation with high-frequency dispersion)!
Results of Dielectric Identification with T-Line Segments and Beatty Standards

- Wideband Debye model confirmed to be best dispersion model
- Established 2 corner values of Dk and LT using Lines
  - DK ranges from 3.9 to 4.25 (about 8%)
  - LT ranges from 0.018 to 0.02 (about 10%)
- Extraction with S-parameters of 4 resonators (2 Beatty and 2 stub)
  - Extracted DK ranges from 3.9 to 4.0 (about 2.5%)
  - Extracted LT ranges from 0.018 to 0.02 (about 10%)
- Possible sources of variations in identified parameters
  - Fiber and resin mixture is different below each structure – TDR shows different impedances and variation of impedance along the lines
  - Differences in investigated samples and de-embedding fixtures
  - Differences in physical dimensions of the actual and investigated structures
Open End: Comparison with TRL De-Embedded Measurements

- Line width 17 mil, FR4 Wideband Debye, Dk=4.0, LT=0.02 at 1 GHz
- Solder mask: Wideband Debye, Dk=3.3, LT=0.02 at 1 GHz
- RMS roughness 0.5 um, roughness factor 2

Good correspondence!

Measured – stats, simulated - circles

Radiation loss!
Offset Stubs: Comparison with TRL De-Embedded Measurements

- Magnitudes of S-parameters

**Measured (stars)**

**Simulated (circles)**

Transmission

Reflection

Double resonances is the effect of high-order modes between two tees (can be captured only with the full-wave analysis)

Good correspondence!
Meandering Line: Comparison with TRL De-Embedded Measurements

- Magnitudes of S-parameters

Measurements (stars) vs. Simulations (circles)

Works as a band-stop filter

17-mil micro-strip, 390 mil of straight line on both sides, DK=4.0, LT=0.02 @ 1 GHz

Acceptable correspondence!
Multiple Via-Hole Transitions Through Board

- 6 through via-holes with 4 stitching vias, separated by 1 inch segments of 17 mil micro-strip line, de-embedded to reference planes RP1 and RP2

Single via geometry:

Top and bottom substrate: DK=4.0, LT=0.02 @ 1 GHz
Core: DK=4.7, LT=0.02 @ 1 GHz
Diameters of all vias are 12 mil
Pad diameter for all via is 22 mil
Antipad diameter is 40 mil
Distance between signal and stitching via is 40 mil
Multi-Via Transition: Comparison with TRL De-Embedded Measurements

Transmission coefficients magnitude and phase

Measured – stars, simulated - circles

Acceptable correspondence!
Differential Micro-Strip Line Segment (TDR)

1-inch long coupled micro-strip line with 250-mil segment of 17-mil micro-strip lines

From 93 to 95 Ohm instead of expected 100!

Possible effect of plating, wider traces and conformal solder mask layer
Effect of Strip Width on Differential Impedance

- Metallization is 3 mil thick (instead of expected 1.35 mil), strips are wider

The variations 1.5 mil are within the manufacturing tolerance!

We will use w=15 mil, s=22 mil as the closest to measured on the board and to TDR profile and

\[ \text{DK}=4.25, \text{LT}=0.02 \text{ at 1 GHz} \]
Differential Segment: Comparison with TRL De-Embedded Measurements

- Magnitudes of single-ended S-parameters (1 row)

![Graph showing measured and simulated data for transmission, FEXT, NEXT, and reflection.

Good correspondence!}
Differential Segment: Comparison with TRL
De-Embedded Measurements

Differential mode transmission

Common mode transmission

Measured – stars; Simulated - circles
Differential Bends: Comparison with TRL De-Embedded Measurements

- Two bends in differential micro-strip line with 250 mil 17-mil micro-strip segments (DK=4.25, LT=0.02 @ 1 GHz, 15 mil strips, 22 mil separation)

**Measured** (stars)

Simulated (circles)

D1 to C2 (far end)

D1 to C1 (near end)

Mode transformations

Theoretical and experimental differential to common conversion despite the identical lengths!
Differential Via-Holes

Substrate DK=4.25, core DK=4.7, LT=0.02 @ 1 GHz
15 mil strips separated by 22 mil
Diameter of vias is 12 mil
Pad diameters are 22 mil
Differential vias: Comparison with TRL De-Embedded Measurements

Differential mode transmission

Common mode transmission

Measured – stars, simulated - circles

Good correspondence!
Conclusion

The main result of this investigation is a simple and practical methodology to identify properties of low-cost FR-4 dielectric on the base of two key components:

- Precisely de-embedded S-parameters of resonators or line segments
- Accurate full-wave electromagnetic analysis with wideband Debye dielectric model and with conductor-related and high-frequency loss and dispersion effects included

It is shown that behavior of interconnects on low-cost PCBs can be reliably predicted by electromagnetic analysis with the identified material properties.

Future work:

- Practical methodology to identify conductor parameters (roughness), core dielectric parameters (vias and strip lines), effect of fibers,…
- Investigate possibilities of extraction without de-embedding of launch to create simple on board coupons
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Dielectric properties of composite materials

- Multiple researches show considerable decline of DK and slight increase of LT with the frequency from DC to 20 GHz
  - A. Deutsch at al. (IBM), Extraction of eps(f) and tand(f) for Printed Circuit Board Insulators Up to 30 GHz Using the Short-Pulse Propagation Technique, – IEEE Trans. on Adv. Packaging, v. 28 N 1, 2005, p. 4-12
  - Z. Zhang at al. (UMR-Apple), Signal Link-Path Characterization Up To 20 GHz Based On A Stripline Structure, - in Proc. of EMC symposium, 2006
  - W. Kim at al. (Rambus), Implementation of Broadband Transmission Line Models with Accurate Low-Frequency Response for High-Speed System Simulations, - DesignCon2006
  - D.-H. Han at al. (Intel), Frequency-Dependent Physical-Statistical Material Property Extraction for Tabular W-element Model Based on VNA Measurements, - DesignCon2006
  - J. Miller at al. (Sun), Impact of PCB Laminate Parameters on Suppressing Modal Resonances – DesignCon2008
  - B.O. McCoy at al. (Mayo), Broadband Resonant-Plate Permittivity Measurement Technique for Printed Wiring Boards Aided by Electromagnetic Simulations – DesignCon2008
  - C. Morgan (Tyco), Solutions for Causal Modeling and A Technique for Measuring Causal, Broadband Dielectric Properties – DesignCon2008
Wideband Debye dielectric model

\[ \varepsilon_{wd}(f) = \varepsilon_r(\infty) + \varepsilon_{rd} \cdot F_d(f) \]

\[ F_d(f) = \frac{1}{(m_2 - m_1)} \cdot \ln(10) \cdot \ln \left[ \frac{10^{m_2} + if}{10^{m_1} + if} \right] \]

- Suggested in two papers independently and confirmed by multiple researchers
- Can be specified with DK and LT at one frequency only!
  - Reproduces causal frequency-dependent dielectric loss and dispersion
  - Very convenient for measurements and fitting the experimental data

Dielectric Constant

- Dk=4.2 at 1 GHz
- LT=0.02 at 1 GHz

Frequency, Hz

Loss Tangent

Frequency, Hz

3D full-wave analysis with Simbeor software

Solve Maxwell’s equations in 3D to find frequency-dependent matrix RLGC per unit length parameters for transmission lines and S-parameters for discontinuities:

\[ \nabla \times \vec{E} = -i\omega \mu \vec{H} \]
\[ \nabla \times \vec{H} = i\omega \varepsilon \vec{E} + \sigma \vec{E} + \vec{J} \]

Plus additional boundary conditions at the metal and dielectric surfaces

- Method of Lines (MoL) for multilayered media
  - High-frequency dispersion in multilayered dielectrics
  - Losses in metal planes including roughness
  - Causal wideband Debye dielectric polarization loss and dispersion models

- Trefftz Finite Elements (TFE) for metal interior
  - Metal interior and surface roughness models to simulate proximity edge effects, transition to skin-effect and skin effect in rough and plated conductors

- Method of Simultaneous Diagonalization (MoSD) for lossy multiconductor line and multiport S-parameters extraction
  - Advanced 3-D extraction of modal and RLGC(\(\omega\)) p.u.l. parameters of lossy multi-conductor lines
  - Precise numerical de-embedding of extracted S-parameters
De-embedding methods