# Dielectric and Conductor Roughness Model Identification – Does Bandwidth Matter?

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**Accuracy of PCB and PKG interconnect models (impedance, insertion and reflection loss, dispersion) is mostly defined by availability of broadband dielectric and conductor roughness models.** Estimates of required interconnect model bandwidths (BW, GHz) for different one-lane effective data rates (DR, Gbps) are shown in the last column of the table below:

| DR, Gbps | BT or ST, ps | RT, ps | FN, GHz | BW, GHz |
|----------|--------------|--------|---------|---------|
| 10, NRZ | 100 | 50 | 5 | 20 |
| 16, NRZ | 62.5 | 30 | 8 | 32 |
| 28, NRZ | 35.7 | 18 | 14 | 54 |
| 32, NRZ | 31.25 | 16 | 16 | 61 |
| 56, PAM4 | 35.7 | 18 | 14 | 54 |
| 64, PAM4 | 31.25 | 16 | 16 | 61 |
| 128, PAM4 | 15.625 | 15 | 32 | 89 |
| 128, PAM4 | 15.625 | 10 | 32 | 108 |

The second column in table shows bit time (BT for NRZ or 2-level modulation) or symbol time (ST for PAM4 or 4-level modulation). The bandwidth estimate is based on 25 dB spectrum drop-off for signals with the rise times also shown in the table (RT, ps). Column FN shows corresponding Nyquist frequency, up to which the analysis to measurement correlation is a must for a successful interconnect design. The model accuracy may be allowed to gradually degrade from FN to BW frequency. The table covers multiple common signaling standards such as PCIe 4 and 5, Ethernet, GDDR 5 and 6. The bandwidths requirements may be further reduced for different parts of a link as the rise time degrades farther from a transmitter (sometimes even to 2 Nyquist frequency or 2*FN). Even with such adjustments, the analysis (and possibly measurement) bandwidth requirements are impressive and cover almost all microwave bandwidth (over 3 GHz) and starting from 16 Gbps gets into the millimeter wave bandwidth (over 30 GHz). Note that frequency range for 5G FR2 analog systems also spans up to 52.6 GHz and they are usually implemented on PCB.

**Where to get the dielectric and conductor roughness models with such bandwidths?** Manufacturers of dielectrics usually provide dielectric parameters at a few discrete frequency points. They use standardized resonator-based techniques with the dielectric parameters extracted at the resonance frequencies only. Possible ways to use those points for construction of broadband models and simulations were discussed at "Material World…" tutorial. Wideband Debye (aka Djordjevic-Sarkar or Swensson-Dermer) models can be easily constructed with the data from a laminate manufacturer and the accuracy of such models is usually acceptable or may require small correction only due to manufacturing variations and anisotropic properties of the laminate for instance. **Things are not so good for the copper roughness models.** Signal degradation due to copper roughness may be

devastating at frequencies above 5-10 GHz, especially for interconnects on low-loss dielectrics (with most of the losses due to copper roughness). Manufacturers of copper laminates typically have some mechanical parameters characterizing the copper surface, but do not have parameters for the electrical roughness models (such as Huray-Bracken or Causal Hammerstad) at all. The reason can be explained by the fact that copper is roughened separately by the foil manufacturer (one side) and by PCB manufacturers (the other side). Thus, only PCB manufacturer can identify the roughness model parameters for a particular laminate batch and copper surface treatment process. Only very few of them are already doing it.

**Meaningful interconnect design and compliance analysis must start with the identification or validation of dielectric and conductor roughness models over the frequency band of interest. Availability of accurate broadband material models is the most important element for design success.** Validation or identification of dielectric and conductor models can be done with the reflection-less generalized modal S-parameters (GMS-parameters) as shown in [1]-[2]. Support for material model identification with GMS-parameters was introduced in Simbeor software in 2010 [1]. Recently introduced Simbeor SDK further facilitates the process by providing API and scripted examples in Matlab/C/Python for automated dielectric and conductor roughness model identification. It allows processing of larger batches of measured data or quick experiments such as described in this article.

**Suppose we need to run PCB interconnect analysis and compute compliance metrics such as COM or ERL for signal with data rates up to 28 Gbps.** To have realistic analysis that correlates with the measurement, dielectric and conductor roughness models valid up to 50 GHz are needed. Without such models the exercise would be just a waste of time. Unfortunately, as it follows from the introduction, usually, we need to build or validate such models ourselves. It is a big task, especially if you did not do it before. Test fixtures with connectors and launches (2 transmission lines for GMS-parameters extraction) have to be designed, manufactured and S-parameters measured with a VNA. **Measured up to what frequency?** Ideally, up to 50 GHz or even above. Though what if the existing equipment allows measurements up to 10 GHz or 20 GHz? Can we still build frequency-continuous dielectric and conductor roughness models that will predict the material behavior up to 50 GHz? To answer those questions, we will use CMP-28 platform with all measured and board description data provided by Wild River Technology https://www.wildrivertech.com/ Complete CMP-28 description is available at #2014_06 at https://www.simberian.com/TechnicalPresentations.php Two stripline segments highlighted on the picture below are used for the identification example here.
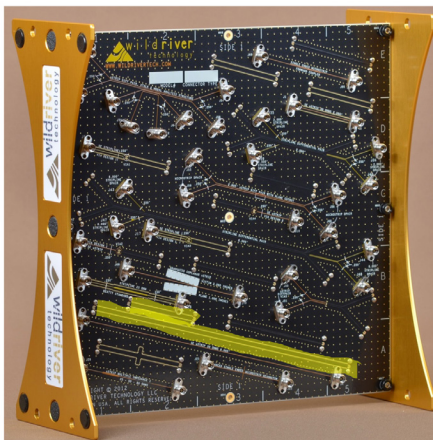
Data from [Simbeor CMP-28 Kit Rev. 4, 2014](#) are used here (complete kit is available on request). Matlab script from advanced material identification kit (AdvMaterialKit) available as a part of Simbeor SDK installation is used to do all experiments. It supports different scenarios for dielectric and conductor roughness losses separation – loss separation by the bandwidth of influence technique is used here. All details of the scripts with CMP-28 examples description are available in [3]. The script is parameterized with the maximal frequency for the model identification. Frequency-continuous and causal Wideband Debye model is selected for the dielectric – it can be defined with dielectric constant (Dk) and loss tangent (LT) at just one frequency point. Though, the model is dispersive – it predicts changes in Dk and LT with frequency. Huray-Bracken model (causal version of Huray snowball model) is selected for conductor roughness. As all unified roughness models in Simbeor, it can be defined with just 2 parameters SR and RF – see details and references in [3]. The model predicts growth of losses with the frequency due to conductor roughness. It also predicts increase of characteristic impedance due to inductive effect of the rough conductor.

The results of the dielectric and conductor roughness identification with use of GMS-parameters extracted up to 10, 20, 30 and 35 GHz are shown in the table below:

| Parameter\Fmax | 10 GHz | 20 GHz | 30 GHz | 35 GHz |
|---|---|---|---|---|
| Dk @ 1 GHz | 3.7549 | 3.7502 | 3.7479 | 3.7479 |
| LT @ 1 GHz | 0.0101 | 0.0101 | 0.0101 | 0.0101 |
| SR, um | 0.0748 | 0.0892 | 0.0958 | 0.0958 |
| RF | 19.4651 | 18.4484 | 18.1324 | 18.0638 |

In addition to that, relative bulk resistivity of copper was identified first at lowest frequencies as RR=1.155. The older version of CMP-28 available for this experiment does not allow extraction of GMS-parameters at frequencies above 35 GHz due to the manufacturing variations and loss of localization in launches. Though, it may be done with the newer versions of it – the script for extraction is available with Simbeor SDK. As we can see the loss tangent at 1 GHz does not depend on the identification bandwidth, because of it is identified at frequencies below 1 GHz where there is no significant effect of roughness on the losses. The roughness model parameters SR and RF change less and less as the bandwidth increases. It also insignificantly affects the dielectric constant at 1 GHz.

**How different are the material models produced with 10 GHz and 35 GHz measurement bandwidths?** To investigate that, the final models for 6 inch segment of transmission line (same length as for difference of the measured segments) are simulated up to 50 GHz and GMS-parameters are plotted below (brown lines) together with the measured GMS-parameters (blue lines) for comparison - GMS insertion loss (left plots) and GMS transmission phase delay (right plots). Models extracted with the 10 GHz measured data is shown on the two top graphs and models extracted with 35 GHz measured data are compared on two bottom graphs below:
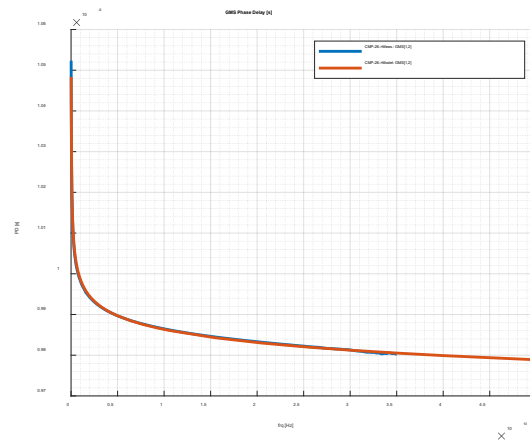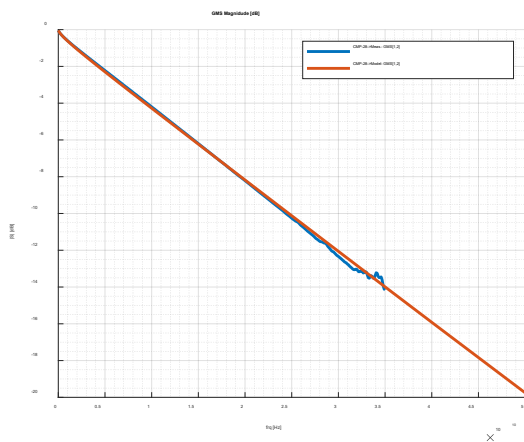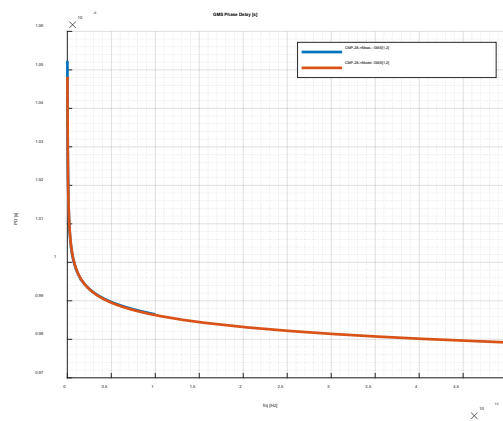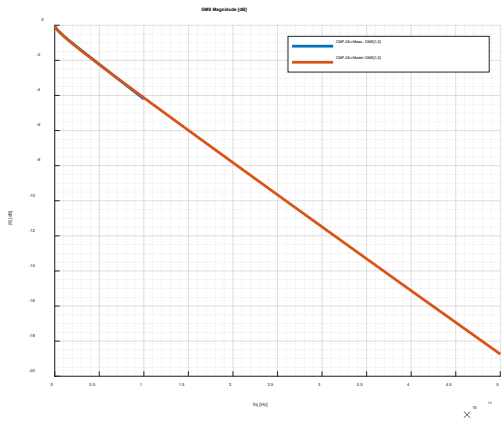
We can see that the difference between models built with 10 GHz and 35 GHz bandwidth is only about 0.11 dB/inch (GMS-parameters above are for 6-inch segment). There is no significant differences in the phase delay.  If we use models constructed with 35 GHz fitting bandwidth and with 10 GHz bandwidth for analysis of the original 2 inch segment with connectors and launches, the result of simulations practically overlap:
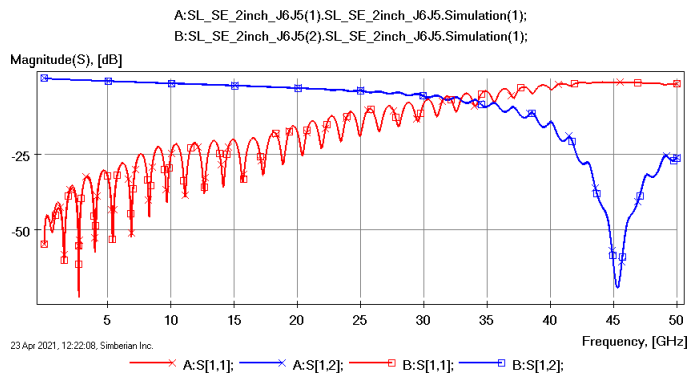
The phases are even closer, because of mostly the losses are affected by the fitting bandwidth selection. The model produced with 20 and 30 GHz bandwidth are practically the same as with 35 GHz bandwidth. **This is the main advantage of the frequency-continuous model identification!** 20 GHz VNA (or even low-cost USB VNA with 10 GHz bandwidth) would be sufficient in this case to get the material models usable up to 50 GHz and may be above that frequency. **This is also a proof that the material model selection and extraction process are correct – it would not be possible to have accurate extrapolation otherwise.** Note that GMS-parameters are reflection-less – no correlation in the reflection parameters is needed. If all data and assumptions are correct, the correlation in GMS-transmission magnitude and phase should also produce correct transmission line impedance and reflectioni, as shown in [3] with discussion of possible reasons for not perfect correlation of the impedance.

    **Finally, note that material model identification is a difficult task with multiple steps.** It requires design of test fixtures, manufacturing of test boards and accurate measurements. Those steps are not covered in this article – see examples of what can go wrong in "expectation vs. reality" experiment [4]. Getting everything right may be tedious and time consuming process, but **it is necessary condition for the analysis to measurement correlation**.  No other way. This is especially important for the conductor roughness models. The copper foil surface is roughened by two manufacturers – one side by the copper foil manufacturer and another by PCB manufacturer. No way to get such so far. Thus, build the test fixtures (two line segments) and measure S-parameters – this is the simplest way to do it. From the point when you get good test fixtures and high-quality measurements, **Simbeor SDK provides tools to facilitate the dielectric and conductor roughness model building with scripting in Matlab, C and Python**. Such models are frequency-continuous and usable well above of the measurement frequency as was demonstrated in this article.

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