S-Parameters Similarity Metric

Yuriy Shlepnev, Simberian Inc.

Abstract: — Formal similarity metric or measure for two sets of S-parameters is constructed with the modified Hausdorff distance applied to S-parameter points in 3D space with real and imaginary parts of S-parameter point and normalized frequencies as the coordinates. **New similarity measure allows automation of the analysis to measurement validation**, comparison of different simulations of the same problem, as well as finding similar S-parameter models or similar elements within S-matrices, etc. The idea was first published in Y. Shlepnev "Evaluation of S-Parameters Similarity with Modified Hausdorff Distance" at http://arxiv.org/abs/2105.10057 on May 20, 2021. This is an extended version of the paper with more examples and code samples.

Introduction: — Bandwidth required for signal integrity analysis of PCB and packaging interconnects is growing with the increase of data rates. **Evaluation of model accuracy requires validation with the measurements – this is a necessary element of successful design process with data rates above 10 Gbps.** A systematic approach to the analysis to measurement validation was recently introduced in [1], [2]. Though, the last step in the process was a visual estimate of the closeness of models to measured data (use of "human visual system"). Automation and formal measures are needed. Feature Selective Validation (FSV) method [3] can be used for such purpose. However, it is rather complicated (not quite straightforward), has too many parameters and can be applied only to amplitudes of S-parameters. A single number measure for S-parameters similarity evaluation is introduced in this paper and illustrated with practical examples.

Definitions: - Let's consider two S-parameter sets *SA* and *SB* defined as follows:

$$SA=\left\{SA\left(fa_k\right),k=1,...,K\right\},\ SA\left(fa_k\right)\in C^{N\times N}$$

$$SB=\left\{SB\left(fb_m\right),m=1,...,M\right\},\ SB\left(fb_m\right)\in C^{N\times N}$$

$SA\left(fa_k\right)$ and $SB\left(fb_k\right)$ are N by N complex matrices with the elements defined at each frequency point as $sa_{i,j}\left(fa_k\right),k=1,...,K$ and $sb_{i,j}\left(fb_m\right),m=1,...,M$ with $i,j=1,...N$. For simplicity, the matrix element indexes *i,j* are omitted in some expressions below. In general, we assume that the frequency points in two data sets are different. *SA* may be a model of a structure with measured results in *SB*. That would be a typical case.

Possible Distance Measures: - If two sets have exactly the same number of collocated frequency points $K=M$ and $f_k=fa_k=fb_k$, each element of S-matrix can be treated as a complex vector with dimension equal to the number of frequency points *K* and L1 or L2 norms can be used to define the distance between two elements of S-matrices as follows (just two practical cases):

$$d_{abs}\left(sa,sb\right)=\frac{1}{K}\sum_{k=1}^{K}\left|sa\left(f_k\right)-sb\left(f_k\right)\right| \qquad (1)$$

$$d_{rmx}\left(sa,sb\right)=\sqrt{\frac{1}{K}\sum_{k=1}^{K}\left|sa\left(f_k\right)-sb\left(f_k\right)\right|^2} \qquad (2)$$

Where $\left|\cdot\right|$ denotes amplitude of the complex vectors or Euclidian vector length in 2D space. Such distances are often used as error measures for optimization, for convergence evaluation. Unfortunately, metrics like d_{abs} and d_{rms} are usually not useful for comparison of simulations with the measurements

during the validation process. A model and measured S-parameters may be sampled at different frequency points. Interpolation can be used, but it may introduce additional errors. **They are also not useful in cases if only similarity of the S-parameter sets has to be evaluated** – cases with slightly shifted resonances for instance.

Modified Hausdorff Distance: - To compare two sets of S-parameter covering the same bandwidth, but with possible different frequency sampling, a modified Haustorff distance (MHD) can be used. The MHD was proposed for image recognition [4]. Similar distance can be defined between two sets of S-parameters in 3D space formed by real, imaginary and normalized frequency axes. First, we convert each element of *SA* and *SB* sets into points with 3 coordinates as follows:

$$sa^k = \left(\mathrm{Re}\left(sa\left(fa_k\right)\right), \mathrm{Im}\left(sa\left(fa_k\right)\right), fa_k / f_{norm}\right)$$

$$sb^m = \left(\mathrm{Re}\left(sb\left(fb_m\right)\right), \mathrm{Im}\left(sb\left(fb_m\right)\right), fb_m / f_{norm}\right)$$

Real part of S-parameter element corresponds to the X-axis, imaginary to the Y-axis and normalized frequency to the Z-axis. f_{norm} is normalization frequency – it defines unit along the Z-coordinate. This is a plot in real-imaginary-frequency (RIF) space. Its projection into XY-plane is just a regular polar plot. It can be called 3D spiral plot (causal S-parameters are always spiral-like with clockwise rotation with increase of frequency). It may be also considered as 3D extension of the Nyquist plot. Note that values of S-parameters are bounded by unit for passive systems such as interconnects.

A distance between point sa^k and a set of points $sb = \left\{sb^m, m = 1,...,M\right\}$ can be defined as follows:

$$d_{rif}\left(sa^k, sb\right) = \min_{m=1,...,M} \left|sa^k - sb^m\right| \qquad (3)$$

Were $|\cdot|$ is regular Euclidian norm or length of the vectors, but now in 3D RIF space. Modified Hausdorff distance between two elements of S-matrices can be defined as follows:

$$d_{MH}\left(sa, sb\right) = \frac{1}{K}\sum_{k=1}^{K} d_{rif}\left(sa^k, sb\right) \qquad (4)$$

This distance is computed separately for each element of S-matrix (matrix indexes *i,j* are not shown for simplicity). The distance is commutative with the identical sampling. With the different sampling this distance is not commutative, but can be converted into such by defining it as $\max\left(d_{MH}\left(sa, sb\right), d_{MH}\left(sb, sa\right)\right)$. Here we assume that the set *SA* is a model with substantially smaller number of frequency points (adaptive sampling) comparing to the set *SB* (measured data for instance). The one-directional distance is more suitable for such cases. Also, both data sets span the same frequency bandwidth. Multiple other choices for the distance are possible [4], but (4) is selected as the best for the object matching (objects in our case are S-parameter element points in 3D RIF space). Also, it is easy to show that with the equidistant collocated sampling and with $f_{norm} = 1$ (no normalization) $d_{MH}\left(sa, sb\right) = d_{abs}\left(sa, sb\right)$.

Distance between two sets of S-parameters *SA* and *SB* can be defined as follows:

$$d_{MH}\left(SA, SB\right) = \max\left[d_{MH}\left(sa_{i,j}, sb_{i,j}\right),\ i, j = 1,...,N\right] \qquad (5)$$

Note that distances d_{abs} or d_{rms} can be also used in (5) with possible interpolation.

S-Parameters Similarity Metric or Measure: - The distance $d_{MH}\left(SA, SB\right)$ defined by (5) can be directly used to measure similarity of S-parameters. Though, more intuitive similarity measure for S-matrix elements and for the whole matrix can be introduced as follows (similar to the quality measures introduced in [5]):

$$SPS\left(sa_{i,j}, sb_{i,j}\right) = 100 \cdot \max\left(1 - d_{MH}\left(sa_{i,j}, sb_{i,j}\right), 0\right)\% \qquad (6)$$

$$SPS\left(SA, SB\right) = \min\left(SPS\left(sa_{i,j}, sb_{i,j}\right), i, j = 1, ..., N\right)\% \qquad (7)$$

Other distances (1) and (2) can be also used to compute SPS. **SPS measure is technically not a metric, but rather a pre-metric (it is not symmetric and may not satisfy the triangle inequality).** It is bounded by 0 for cases with no similarity at all and 100% for exactly the same sets of data (identical data sets). The other tiers or levels of similarity can be introduced for a particular set of problems as demonstrated in the next section. Similarity measure for each element of S-matrix $SPS\left(sa_{i,j}, sb_{i,j}\right)$ can be also designated simply as SPSij.

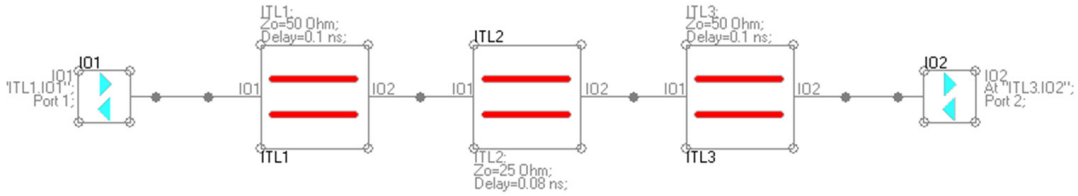
Implementation: Computation of the modified Hausdorff distance (4) is relatively straightforward. Here is an example of Matlab code (brute-force approach):

```
% (c) 2021 - Simberian Inc.
% This function computes Modified Hausdorff distance between 2 sets
% of S-parameters.
%
% PARAMETERS:
% SA - array of 3D vector coordinates (Re(SAk),Im(SAk),fk), Sk is S-parameter
% value at frequency fk, fk is normalized frequency
% SB - array of 3D vector coordinates (Re(SBk),Im(SAk),fk), SBk is S-parameter
% value at frequency fk, fk is normalized frequency
% Distance is computed for points in SA from fmin to fmax (both are also
% normalized frequencies)
% Distance is one-directional from SA to SB (Model to Measured data)
%
% Modified Housdorff distance D22 from the SA to SB data set
% M. P. Dubuisson and A. K. Jain. A Modified Hausdorff distance for object
% matching. In ICPR94, pages A:566-568, Jerusalem, Israel, 1994.
% http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=576361
% https://citeseerx.ist.psu.edu/viewdoc/summary?doi=10.1.1.1.8155

function [bResult, MHD] = ModifiedHousdorffDistanceA2B(SA, SB, fmin, fmax)
    bResult = false;

    SAsize = size(SA);
    iamax = SAsize(1);
    if(iamax==0)
        return;
    end

    SBsize = size(SB);
    ibmax = SBsize(1);
    if(ibmax==0)
        return;
    end

    sumdist = 0;
    ifmax = 0;
    for ka = 1:iamax   % loop over SA to find avg of d(SA,SB)
        if SA(ka,3) >= fmin % if point within frequency range
            mindist = Inf;
            for kb = 1:ibmax      %find min(d(SA,SB))
                tempdist = norm(SA(ka,:)-SB(kb,:)); %Euclidean distance
```

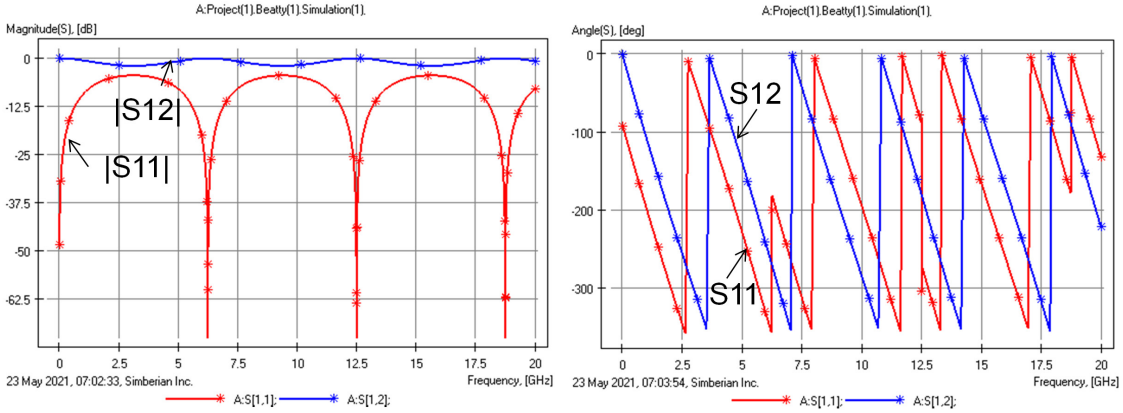
```
                if tempdist < mindist
                    mindist = tempdist;
                end
            end
            sumdist = sumdist + mindist;    % sum of the distances
            ifmax = ifmax + 1;
            if SA(ka,3) >= fmax % end of frequency range
               break;
            end
        end
    end

    if ifmax ~= 0 % no frequency points in specified bandwidth
        MHD = sumdist/ifmax; % Distance d6 from "Modified Housdorff Distance" paper
        bResult = true;
    else
        MHD = 1.0; % failure
    end
end
```

Compared S-parameters are stored as the arrays of triplets in the RIF space. The code can be easily optimized by reducing the internal loop over the elements of SB to just a vicinity of each point from array SA. The script is available as a part of Simbeor SDK in matlab/utils folder. There are also scripts for loading Touchstone models or complete solutions and comparison within a particular solution.

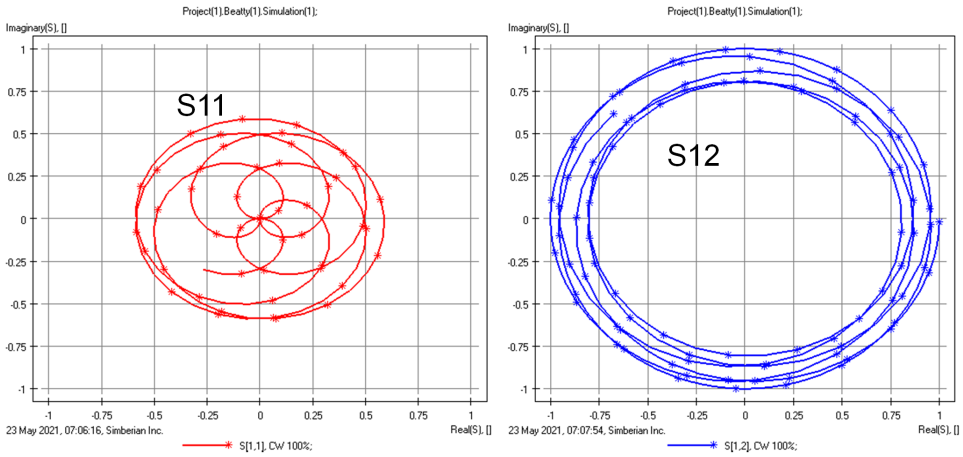
Simple Test Case: As a simple test case, let's investigate Beatty resonator that looks like that:



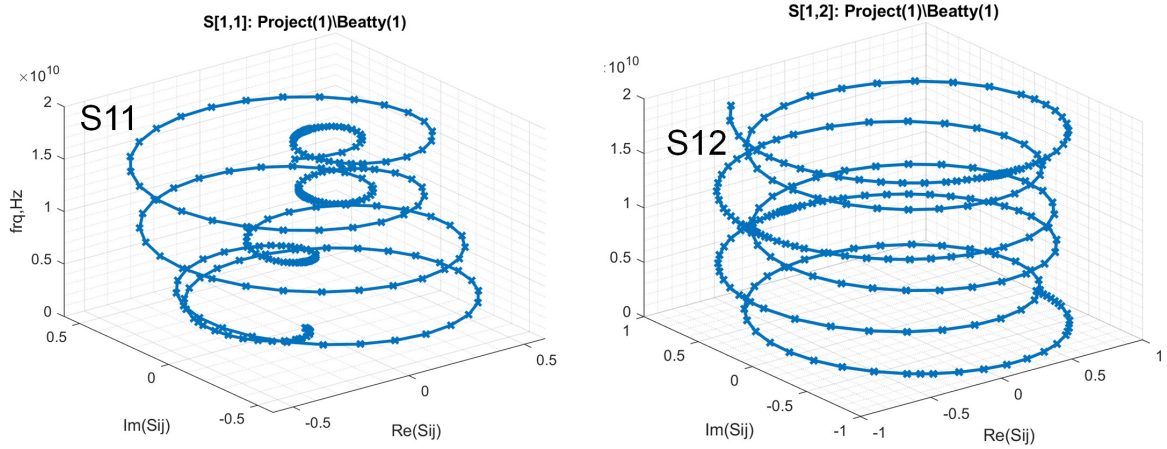
It has a segment of 25 Ohm ideal transmission line in the middle of an ideal 50 Ohm transmission line. Bode plots for such structure are shown below (3 resonances):



Corresponding polar plots are shown below:



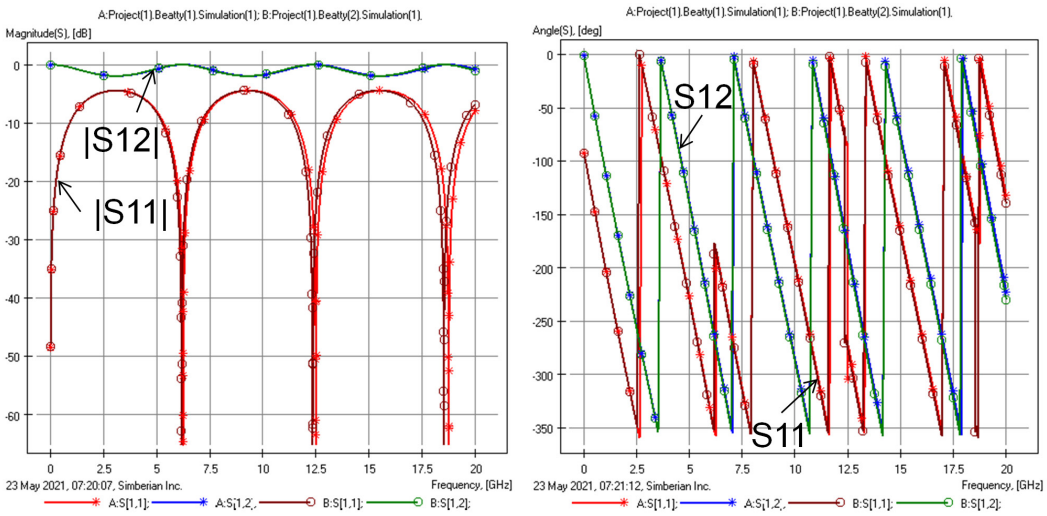
3D spiral plots of the reflection and transmission parameters for similarity evaluation are shown below:



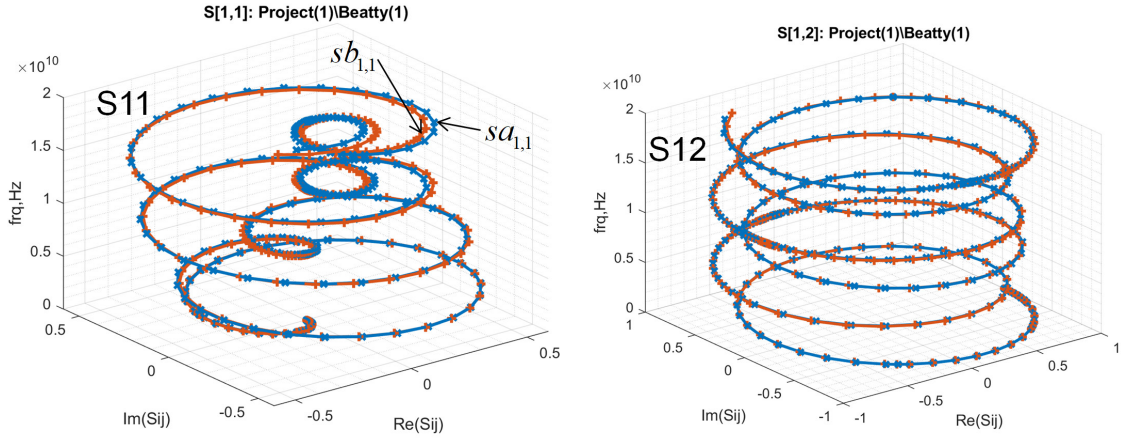
Adaptive frequency sampling is used with the tolerance parameter 0.01 (defines possible deviation from linear interpolation) – frequency points are shown with "+" symbol on the 3D spiral plots above. The normalization frequency is defined as 1 GHz.

The first case is the comparison of identical resonators. As expected, it gives SPS value 100%.

Next, the second resonator is adjusted to have slightly offset resonances (delay in the middle section is changed from 80 ps to 81 ps). Here are Bode plots of the reflection (S11) and transmission (S12) parameters for comparison (first resonator - plots with *, second resonator – plots with o):



Corresponding 3D spiral plots with the similarity values are shown below (first resonator – blue plots with x, second resonator – brown plots with +):

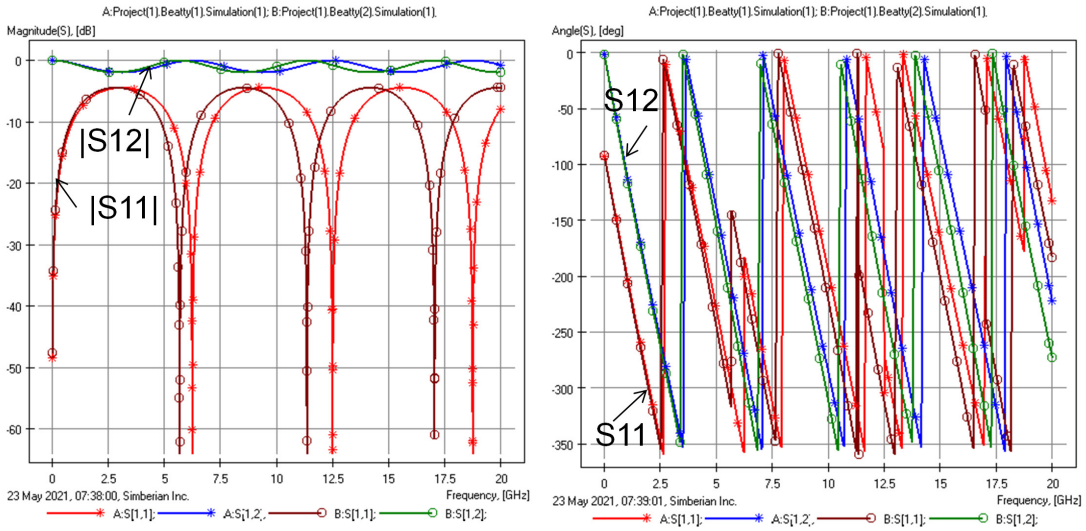


SPS11=95.35%

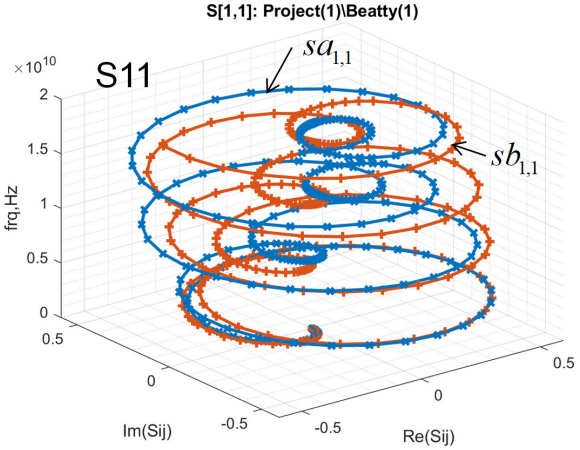
SPS12=94.94%

The responses are similar, that is reflected in the final value of SPS=94.94%.

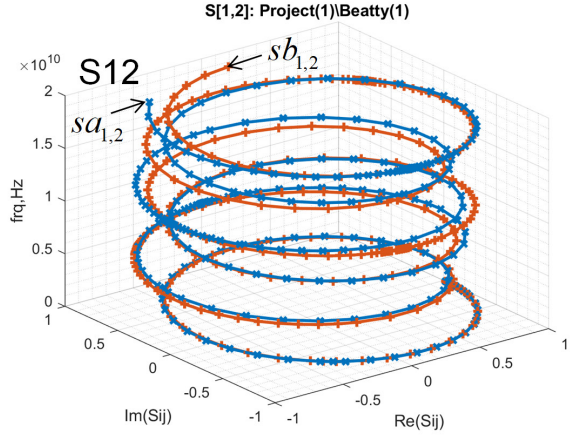
Let's further de-tune the second resonator by increase of the delay in the middle section to 88 ps – causes over 1 GHz difference in the resonances. Bode plots of the reflection and transmission parameters are shown below (first resonator - plots with *, second resonator – plots with o):



Corresponding 3D spiral plots used for the comparison are shown below together with the similarity values for each parameter (first resonator – blue plots with x, second resonator – brown plots with +):

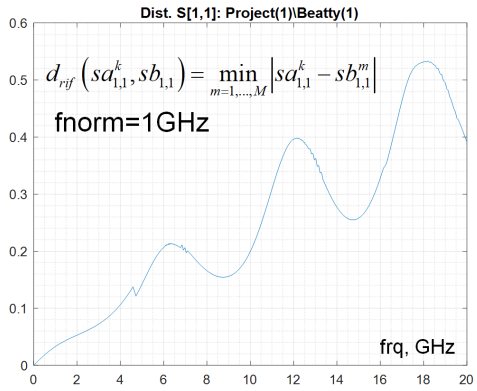


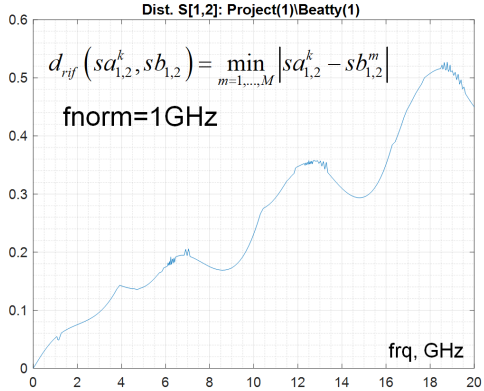
SPS11=70.02%



SPS12=70.15%

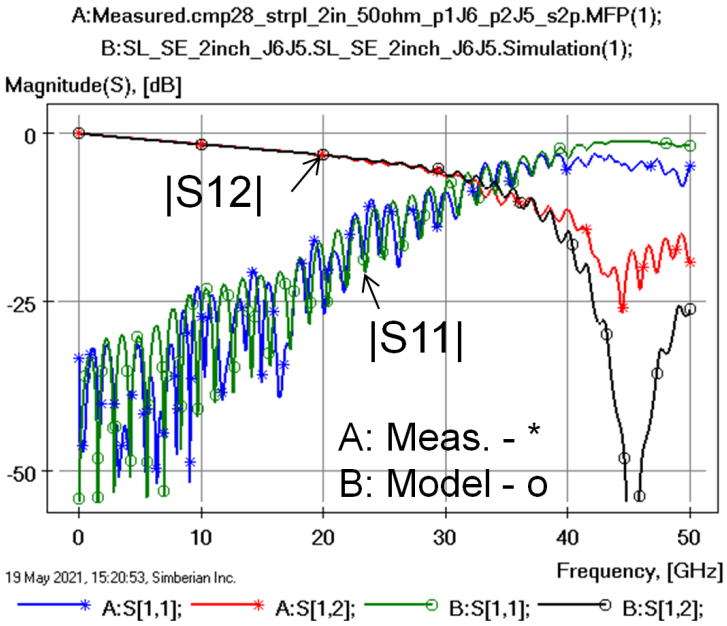
The similarity values dropped as expected to SPS=70.02% for the whole matrix.
The distance between the first resonator (SA) and the second resonator (SB) data sets is illustrated below:



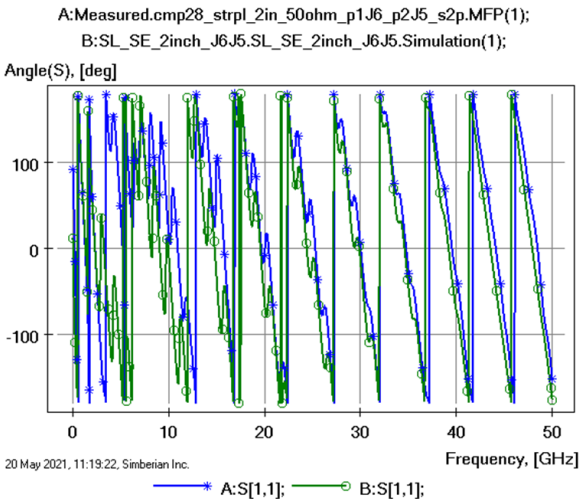


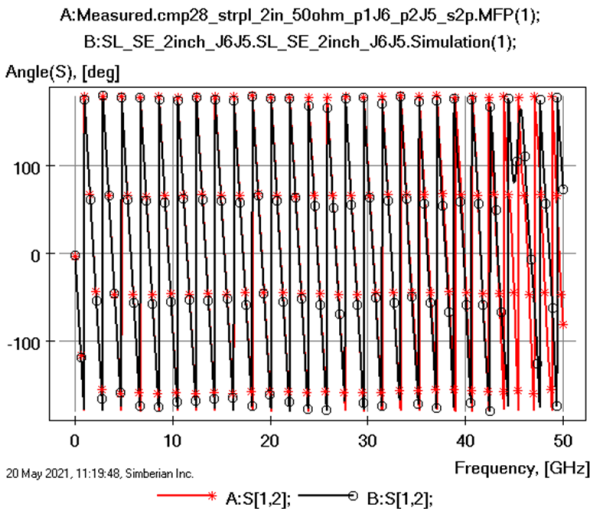
© 2021 Simberian, Inc. • www.simberian.com

CMP-28 Validation Platform: As the first example let's apply the algorithm to analysis to measurement validation for a simple 2-inch strip line segment with two launches and connectors from CMP-28 validation platform from Wild River Technology (WRT) [6]. Magnitudes of simulated and measured transmission and reflection parameters are shown on the next Bode plot:



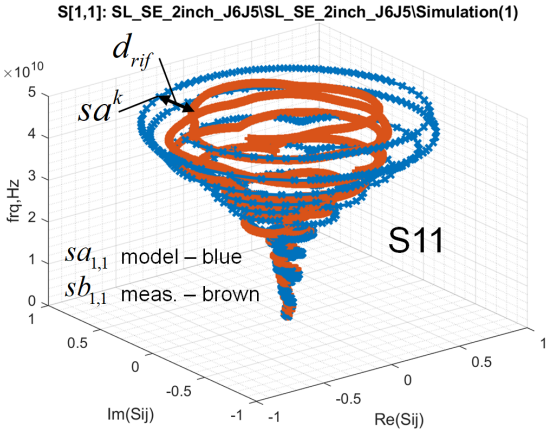
Angles of the reflection parameter S11 (left plot) and transmission parameter S12 are plotted next:

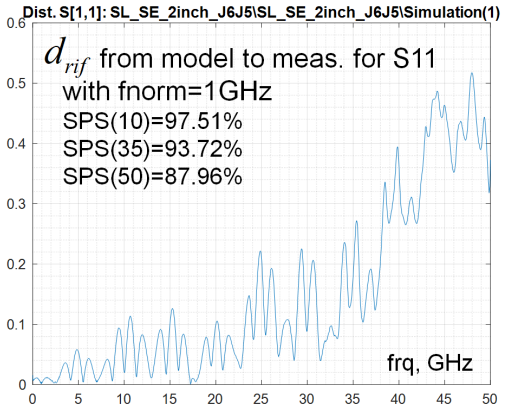


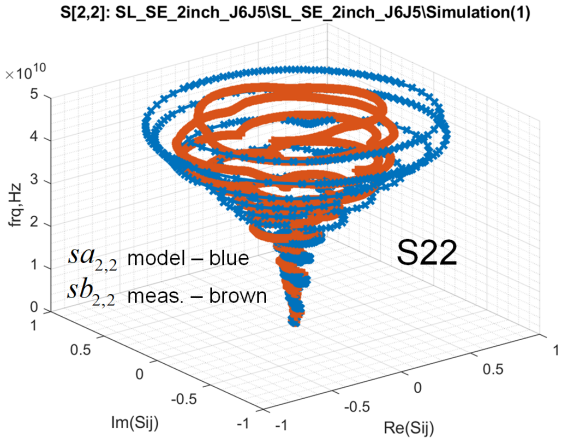


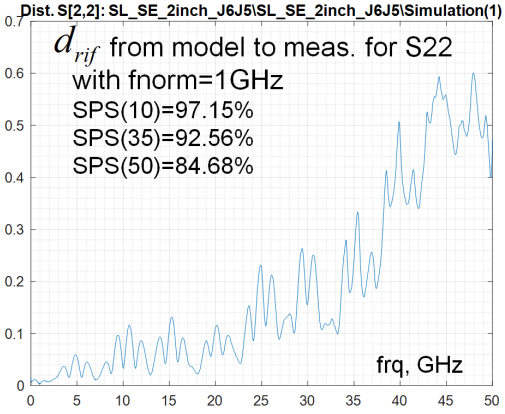
Simulation was done with de-compositional analysis [5] in Simbeor software and measurements are provided by WRT. The models are measurements are from CMP-28 Simbeor Kit [6] with all data available at https://drive.google.com/drive/folders/0B6jLiKYCgxAnbFE0WFRmamxvLVE?usp=sharing. The correlation of magnitudes and angle of the transmission parameter looks good up to 30-35 GHz. However, it is difficult to say what is going on with the angle of the reflectioin parameter – is it good correlation or not?

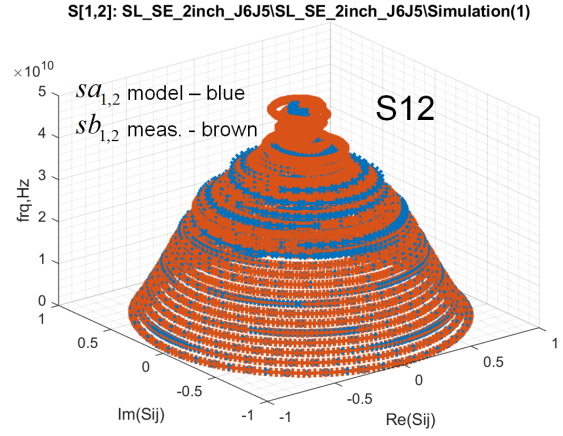
Now, let's take a look at the S-parameters of 2-inch segment structure in the RIF space - 3D spiral plots for reflection and transmission elements of S-matrix are shown next on the left with corresponding distance vs. frequency plots on the right:

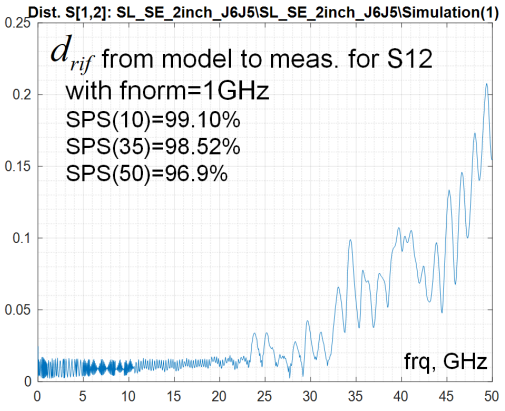




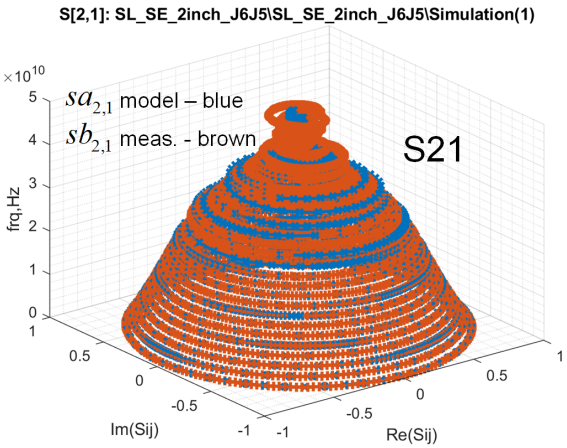


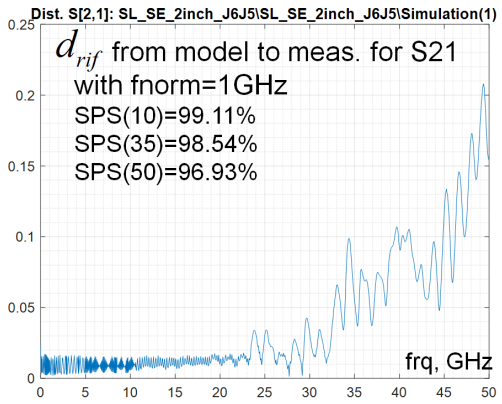






© 2021 Simberian, Inc. • www.simberian.com





For illustrative purpose, a frequency point sa^k and the distance $d_{rif}\left(sa^k, sb\right)$ defined by (3) are also shown on the spiral plot for S11. Technically, it is the minimal distance from one of the blue points to a point on the brown curve. It can be also defined as the smallest distance directly to the brown curve, if interpolation is allowed. Note that the corresponding point on the brown curve sb^m may be not necessarily at the same frequency as sa^k. If the sampling is collocated and the curves are very close, two points are at the same frequency, if the normalization frequency is sufficiently small. However, if there are two resonances at slightly different frequencies (two spiral loops shifted along the frequency axis), the distance between two different frequency points on those loops may be smaller than the distance at the same frequency point with sufficiently large normalization frequency. It allows comparison of S-parameters with similar features such as sharp resonances.

Dependency of the distance $d_{rif}\left(sa^k, sb\right)$ from all points in the model data set to the closest point in the measurement data set versus frequency are also plotted above (right plots) for all elements of S-matrix of 2-inch segment. We can see that the distance is growing with the frequency for all elements as expected (model deviates from the measurement at higher frequencies). SPS values (6) computed with bandwidth 10 GHz (SPP(10)) 35 GHz (SPP(35)) and 50 GHz (SPP(50)) are also shown on the plots. We can see that the SPS measure decreases with the increase of bandwidth – it is consistent with our observation of the similarity.

Note that the SPS measure will depend on the normalization frequency – this is the only parameter of the similarity measure. It basically defines the scale and vicinity of each point along the frequency axis. To avoid sensitivity to sampling, the normalization frequency should be greater than the step frequency in set *SB* (measured data with equidistant frequency sweep). To investigate the effect of normalization, let's first build a model with exactly the same frequency sampling as the measured data. It is 5000 points from 10 MHz to 50 GHz. The similarity values for each element of S-matrix (columns SPP11-SPP22) with different normalization frequencies shown in the first column are shown in the next table (computed for 35 GHz bandwidth):

fnorm	SPP11	SPP12	SPP21	SPP22	SPP
1 MHz	92.5219	97.5969	97.6797	90.5733	90.5733
10 MHz	92.5219	97.5969	97.6797	90.5733	90.5733
100 MHz	92.5219	97.5969	97.6797	90.5733	90.5733
1 GHz	92.8275	98.3235	98.344	91.1202	91.1202

The last column shows the final similarity value SPP for the whole matrix. We can see that SPP does not depend much on the sampling in this case and the similarity increases only with 1 GHz normalization

frequency. Now, let's use adaptive frequency sweep for the model with just 1525 points from 10 MHz to 50 GHz and maximal deviation of points from linear approximation 0.01 (adaptivity tolerance in Simbeor). The similarity values for each element of S-matrix with different normalization are listed in the next table (computed with 35 GHz bandwidth):

fnorm	SPP11	SPP12	SPP21	SPP22	SPP
1 MHz	0	0	0	0	0
10 MHz	73.0803	74.6885	74.7012	72.457	72.457
100 MHz	92.6053	96.4737	96.5211	91.3543	91.3543
1 GHz	93.7131	98.5223	98.5417	92.5639	92.5639

There is no similarity (SPP=0) if the normalization frequency is too small (smaller than the frequency step) and the similarity at 1 GHz is much closer to the equidistant case. In this case, the frequency step in measured data was 10 MHz and selection of the normalization frequency within 100 MHz to 1 GHz produces practically the same results. 1 GHz normalization frequency and adaptive frequency sampling in the model were used for all examples here.

Finally, values of SPS are computed with Simbeor SDK for all test structures on CMP-28 validation platform [6] and are shown in the next table for 3 different comparison bandwidths – 10 GHz, 35 GHz and 50 GHz for single-ended S-parameters (SPP_SE) and for the mixed-mode S-parameters (SPS_MM):

Model	Measurement	SPS_SE 10 GHz	SPS_SE 35 GHz	SPS_SE 50 GHz	SPS_MM 10 GHz	SPS_MM 35 GHz	SPS_MM 50 GHz
SL_SE_2inch_J6J5	cmp28_strpl_2in_50ohm_p1J6_p2J5_s2p	97.1513	92.5639	84.677	n/a	n/a	n/a
SL_SE_8inch_J7J8	cmp28_strpl_8inch_p1J7_p2J8_s2p	97.8176	91.8262	80.9387	n/a	n/a	n/a
SL_SE_Beatty_25Ohm_J28J27	cmp28_strpl_Beatty_25ohm_p1J28_p2J27_s2p	98.3164	91.7525	81.1544	n/a	n/a	n/a
SL_SE_Resonator_J23J24	cmp28_strpl_resonator_p1J23_p2J24_s2p	98.5621	92.8552	82.7012	n/a	n/a	n/a
SL_SE_Via_Capacitive_J18J17	cmp28_strpl_via_capacitive_p1J18_p2J17_s2p	94.9476	91.1739	82.8437	n/a	n/a	n/a
SL_SE_Via_Backdrilled_J14J13	cmp28_strpl_via_backdrilled_p1J14_p2J13_s2p	97.1172	90.8311	82.0804	n/a	n/a	n/a
SL_SE_2inch_Capacitive_J9J10	cmp28_strpl_2in_Capacitive_p1J10_p2J09_s2p	97.7805	93.0992	87.3275	n/a	n/a	n/a
SL_SE_2inch_Inductive_J11_J12	cmp28_strpl_2in_Inductive_p1J12_p2J11_s2p	97.8352	93.8351	87.8757	n/a	n/a	n/a
SL_DF_2inch	cmp28_strpl_diff_2inch_J39J40J35J36_s4p	95.9985	91.087	83.0354	96.0773	91.2115	83.5488
SL_DF_6inch	cmp28_strpl_diff_6inch_J47J48J43J44_s4p	96.8208	93.0776	85.1746	96.6165	93.2208	85.3854
MS_SE_2in_J1_J2	cmp28_mstrp_2in_p1J1_p2J2	97.9111	94.7303	91.8845	n/a	n/a	n/a
MS_SE_8in_J4_J3	cmp28_mstrp_8inch_p1J4_p2J3	97.6372	95.3771	91.645	n/a	n/a	n/a
MS_SE_Beatty_25Ohm_J25_J26	cmp28_mstrp_Beatty_25ohm_p1J25_p2J26	96.5268	93.3182	89.9407	n/a	n/a	n/a
MS_SE_Resonator_J21_J22	cmp28_mstrp_resonator_p1J21_p2J22	98.0708	94.1929	90.5811	n/a	n/a	n/a
MS_SE_GND_Voids_J74_J75	cmp28_gnd_voids_p1J74_p2J75	97.6512	88.4187	83.5582	n/a	n/a	n/a
MS_SE_GraduateCoplanar_J70_J69	cmp28_graduate_coplanar_p1J70_p2J69	97.6924	94.4118	91.4621	n/a	n/a	n/a
MS_SE_Via_Inductive_J15_J16	cmp28_mstrp_via_inductive_p1J15_p2J16	96.6664	93.596	90.0153	n/a	n/a	n/a
MS_SE_Via_Capasitive_J19_J20	cmp28_mstrp_via_capacitive_p1J19_p2J20	96.5088	93.969	90.1057	n/a	n/a	n/a
MS_SE_Via_Pathology_J65_J66	cmp28_via_pathology_p1J65_p2J66	97.2525	91.9582	88.486	n/a	n/a	n/a
MS_DF_2inch	cmp28_mstrp_diff_2inch_J38J37J34J33	95.4645	93.3429	90.407	95.2326	93.3716	90.771
MS_DF_6inch	cmp28_mstrp_diff_6inch_J46J45J42J41	95.5751	93.9318	90.9123	95.63	93.9971	91.0086
MS_DF_GND_Cutout	cmp28_mstrp_diff_gnd_cutout_J59J60J55J56	94.4506	91.4807	88.7113	94.488	89.9057	87.5165
MS_DF_Vias	cmp28_mstrp_diff_vias_J49J50J51J52	95.6808	91.6811	88.4878	95.6215	89.4264	86.7044

"n/a" means that the structure is single-ended and does not have the mixed-mode S-parameters. We can see that there is much better similarity at lower frequencies (10 GHz column) and it degrades with larger bandwidths (35 and 50 GHz columns). Note that some structures have lower SPP – MS_SE_GND_Voids_J74_J75 for instance – this is because of the loss of localization. Complete Kit with all data and plots can be downloaded for further comparisons.

Matlab script similarity_CMP28.m used here for the analysis to measurement similarity evaluation is available in Simbeor SDK.

EvR-1 Validation Platform: "Sink or swim" approach [1] was validated with EvR-1 platform first introduced in [7] and later used in [2]. The last step of the approach is to simulate every single structure on the validation platform with identified material models and manufacturing adjustments, but without any "calibration", "tuning" or "tweaking" and observe the correlation. Comparing to CMP-28, the board stackup was closer to more realistic production cases and manufactured with less precision typical for

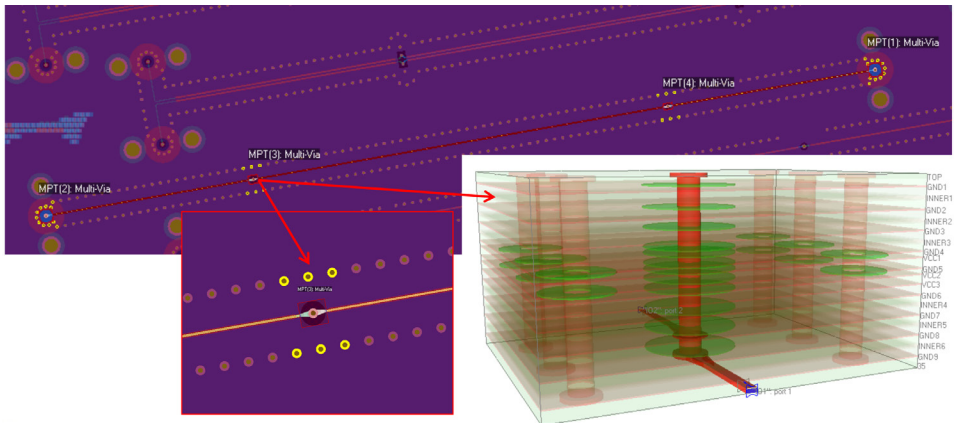
mass-production (see details in [7]). After the analysis and visual comparisons of S-parameters and TDRs, reports like that were created [2]:

Structure	IL [GHz] SE & MM	RL [GHz] SE & MM	FEXT & NEXT [GHz]	TDR (Ω) ~ SE / MM	Eye (30 Gbps, diff.)	Notes
INNER1 5cm 10cm	 25 25	 15 15	 30	 1 / 2 1 / 2	 1% EH & EW	There is uncertainty in the epoxy filling after the backdrilling, the launches is more inductive then predicted. DM/CM phase delay correlate up to 25GHz.
INNER2 5cm 10cm	 30 30	 25 25	 30	 1 / 2 1 / 2	 1% EH & EW	Trace width seems to be 95um instead of 99um. Launch more inductive then predicted, PCB trace width variation. DM/CM phase delay correlate up 30 GHz.
INNER3 5cm 10cm	 30 30	 30 30	 30	 1 / 2 1 / 2	 3.6% EH, 1% EW	Core/prepreg dielectric models – layered anisotropy. Resonance frequency little lower than predicted. Launches have long stubs (not backdrilled).
INNER6 5cm 10cm	 30 30	 10-15 10-15	 30 30	 1 / 3 2 / 4	 2% EH, 1% EW	Differences in RL expected due to geometry differences Mode conversions in measurements up to -30dB DM/CM phase delay correlation ~ 30GHz Impedance variations, launch mismatch, loss of localization.

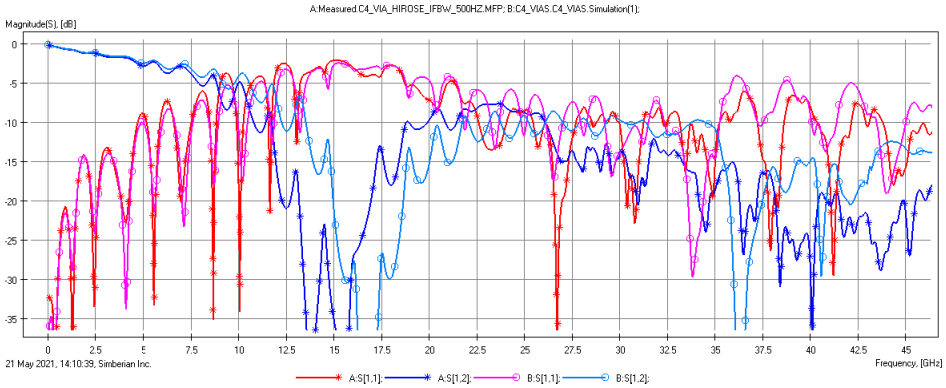
It is informative, but definitely not suitable for the automated analysis to measurement validation. Now we can do it with the new SPS measure automatically computed with Simbeor SDK. The results are shown in the table below:

Model	Measurement	SPS_SE 10 GHz	SPS_SE 30 GHz	SPS_SE 50 GHz	SPS_MM 10 GHz	SPS_MM 30 GHz	SPS_MM 50 GHz
bottom_5cm	BOTTOM_5CM_2_4MM	96.8794	93.8748	91.0964	96.8487	94.3083	91.0312
bottom_10cm	BOTTOM_10CM_2_4MM	97.3225	93.3726	89.9538	97.2836	94.2057	90.4303
c1_vias	C1_2_4MM	96.5812	89.8957	87.6369	96.4881	84.5651	83.0403
c2_vias	C2_2_4MM	97.7527	94.1594	92.0496	97.5927	93.5917	91.1854
c3_vias	C3_2_4MM	96.6935	90.4189	89.9007	96.4762	88.1249	88.883
C4_VIAS	C4_VIA_HIROSE_IFBW_500HZ	91.8131	81.6629	80.329	n/a	n/a	n/a
C5_VIAS	C5_VIA_HIROSE_IFBW_500HZ	93.6226	80.9815	76.027	n/a	n/a	n/a
INNER6_5cm	INNER6_5CM_2_4MM	97.9282	95.2488	93.5004	98.1915	96.1638	93.0851
INNER6_10cm	INNER6_10CM_2_4MM	98.0079	96.2949	94.3676	98.0913	96.8311	92.9737
F1_AC0402	F1_2_4MM	95.6116	89.9624	88.5524	93.5732	87.0771	85.2955
F2_AC0201	F2_2_4MM	95.4258	87.1843	87.8359	93.8553	82.6032	83.0044
F3_DecapShorted	F3_2_4MM	96.6008	88.994	86.8609	96.1133	85.2825	84.8707
G1	G1_2_4MM	97.58	94.7692	92.4024	96.3346	92.5155	91.5084
G2	G2_2_4MM	97.5394	96.027	94.4308	97.2923	96.1297	94.1932
D2_Beatty6	D2_BEATTY_25OHM_INNER6	97.6913	95.5578	92.1797	n/a	n/a	n/a
E1_MeanderStraight	E1_Meander_10cm_Hirose_co	91.9887	80.8534	75.3068	n/a	n/a	n/a
NNER1_5cm	INNER1_5CM_2_4MM	98.3749	95.226	90.7426	98.4463	95.8208	91.1003
INNER1_10cm	INNER1_10CM_2_4MM	98.272	94.9564	90.6877	98.4756	95.7491	90.8221
INNER2_5cm	INNER2_5CM_2_4MM	97.7826	94.7072	92.4632	97.9628	95.1115	91.8582
INNER2_10cm	INNER2_10CM_2_4MM	97.5838	95.8042	94.5077	97.92	96.3239	93.2927
INNNER3_5cm	INNER3_5CM_2_4MM	98.0741	95.856	95.0785	98.2038	96.0933	95.0072
INNNER3_10cm	INNER3_10CM_2_4MM	97.6933	96.6618	95.6197	97.9462	96.93	95.3461
D1_BEATTY	D1_BEATTY_25OHM_INNER1	96.7996	91.9662	90.3091	n/a	n/a	n/a

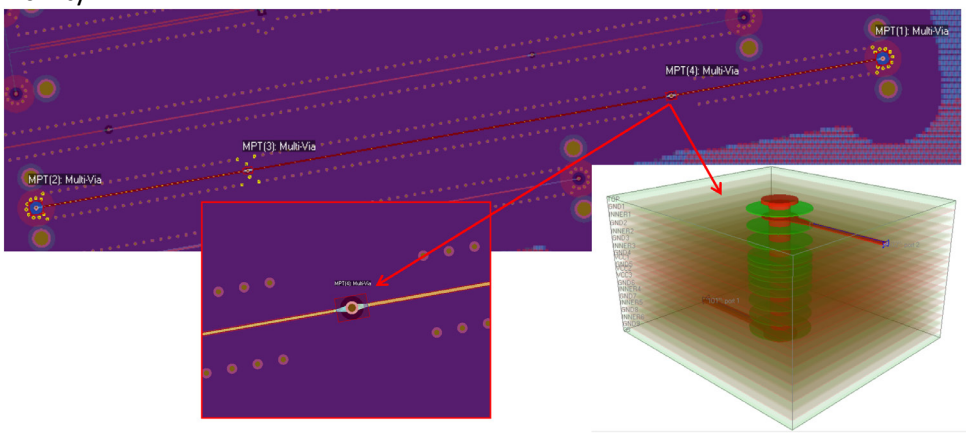
Columns SPS_SE show values of SPS computed with 10 GHz, 30 GHz and 50 GHz bandwidths. Columns SPS_MM show the same values in the mixed-mode space. The launches on EvR-1 loose the localization starting from 30 GHz - the original target for this design was 30 GHz. As with the previous CMP-28 example, the SPP values decrease with the comparison bandwidth increase. Though, some structures have considerably lower SPP values – C4_VIAS and C5_VIAS for instance. If we take a closer look at C4_VIAS, we will see that single-ended link contains vias with the reference vias that are relatively far from the signal via and signal via has very large stub:



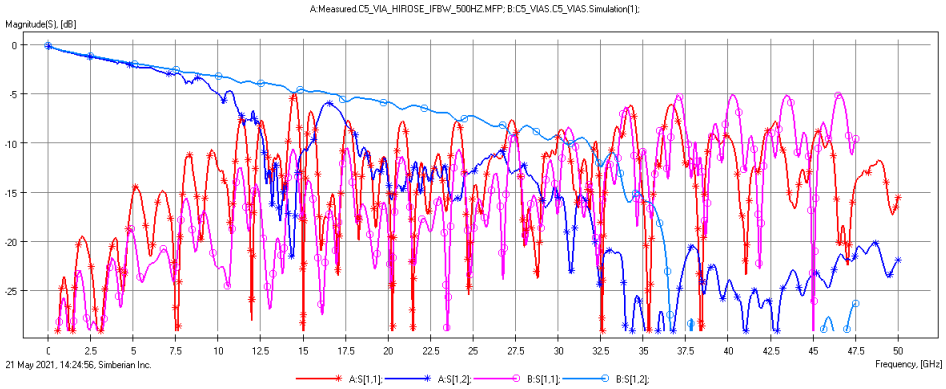
The stub produces large resonance and the reflection parameter does not correlate with the measurements as illustrated below:



Though, the reflection and transmission parameters are still similar (SPP(30)=81.66), but not as similar as in the other cases. Another structure with the low analysis to measurement similarity value C5_VIAS is also single-ended link and has one via with the severe localization problem – no reference vias in the vicinity:

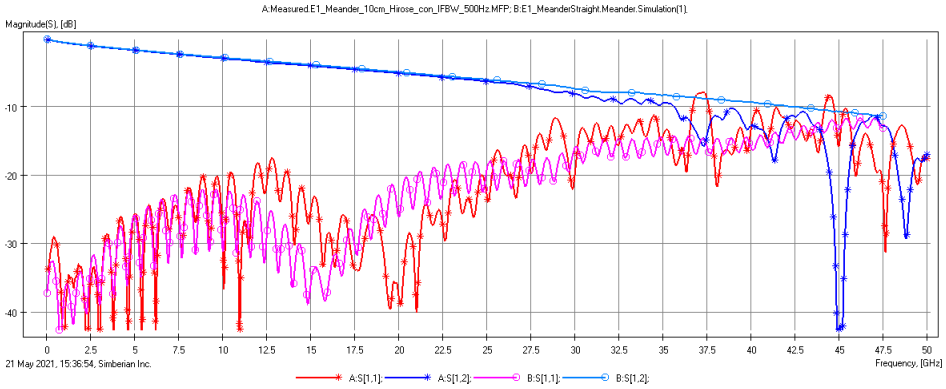


As the result, simulated and measured transmission and reflection parameters do not correlate well as illustrated below:

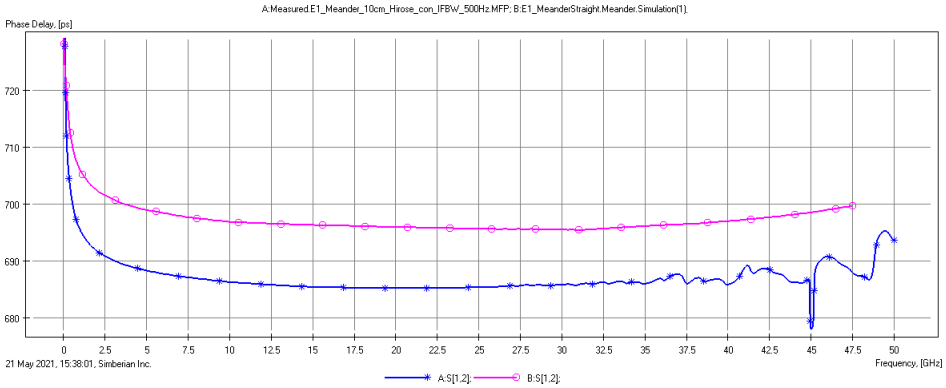


And corresponding similarity measures are relaively small – the structure is unpredictable at frequencies above 5-6 GHz.

Another structure with the hidden problem is E1_MeanderStraight with SPS(30)=80.85% – if we look at the magnitudes of the reflection and transmission parameters, they look normal:



However, the problem is hidden in the difference of phase delays:



About 10 ps difference in the delay in the transmission parameters reduced SPS measure. The similarity measure allows quick detection and correction of the problems like that. In this case, the effective length of the meandering line was not properly defined in the model. After correcting the problem the similarity measure increased to SPS(30)=95.47%.

Matlab script similarity_EvR1.m used here for the analysis to measurement similarity evaluation is available in Simbeor SDK. Complete EvR-1 Kit is available https://drive.google.com/drive/folders/1Rm-QpROluiQ_fsIfpetCt8hu8PtfZfkz?usp=sharing

Possible SPS Applications: SPS measure can be used for all types of S-parameter analysis that involves finding similarity and data mining. For instance, finding measurements for a particular model or the other way around. By comparing all models in solution 8_StripSingle(1) from CMP-28 Kit with all loaded

measurements we can see that SPS values are the highest for the structures that model is created for as shown next:

Model\Meas	'cmp28_strpl_2in_50ohm_p1J6_p2J5_s2p'	'cmp28_strpl_8inch_p1J7_p2J8_s2p'	'cmp28_strpl_Beatty_25ohm_p1J28_p2J27_s2p'	'cmp28_strpl_resonator_p1J23_p2J24_s2p'
SL_SE_2inch_J6J5	92.4394	63.4563	61.6764	48.7333
SL_SE_8inch_J7J8	46.7434	91.8262	62.2733	58.5501
SL_SE_Beatty_25Ohm_J28J27	54.1567	73.3791	91.7525	58.1063
SL_SE_Resonator_J23J24	47.8512	59.0499	57.4813	92.8552

Also we can see that SPS are way below 80% for the structures that do not have much in common. Another possible application is to find port mapping between the model and measured data. For instance, if we assume that measurement for EvR-1 4-port structure BOTTOM_5CM_2_4MM has the same port numeration as the model bottom_5cm has, we will get the following SPS values for each element of the S-matrix (SPS(30)=34.24%):

93.8649 35.9115 34.2403 97.6833
35.9042 94.3134 97.9695 34.3053
34.2412 97.9843 94.7716 35.8398
97.7408 34.3058 35.8304 95.2950

We can see that SPS12, SPS21, SPS13, SPS31, SPS24, SPS42, SPS34 and SPS43 have very low values below 40%. The model has consecutive port numeration – ports 1 and 2 on the left and ports 3 and 4 on the right. But measurements were done with the "through" numeration – ports 1 and 3 on the left and 2 and 4 on the right. With the proper port mapping the SPS for the matrix are as follows (SPS(30)=93.86%):

93.8649 98.1029 97.4252 97.6833
98.1014 94.7709 97.9843 95.8049
97.4376 97.9695 94.3135 98.0679
97.7408 95.8234 98.0640 95.2950

The other types of the port mismatches during the measurements and modeling are also possible, especially in the structures with the number of ports more than 4 (structures with crosstalk).

SPS Tiers: After additional visual inspection of data and explanations of the problems, the following tires for the SPS values are suggested for the broadband interconnect problems:

Good [99,100] - for almost identical S-parameters
Acceptable [90,99) – S-parameters may be considered sufficiently close
Inconclusive [80,90) – additional inspection is required
Bad [0,80) – definitely something went wrong

Conclusion: A new S-parameters similarity measure or pre-metric is introduced in the paper on the base of modified Hausdorff distance applied to elements of S-matrices in 3D real-imaginary-frequency space (RIF space). The metric is simple to implement, computationally straightforward and robust. The technique is intuitive – it is based on comparison of two sets of points in 3D RIF space, that is similar to familiar polar plots. The same approach is used for identification of similarity between two objects in image processing. It is shown that tiers or levels can be introduced for a particular application domain. The approach satisfies 5 basic principles for automated validation method outlined in [3] and may compliment FSV as the fist-pass quick and easy evaluation of S-parameters similarity.
Matlab scripts similarity_CMP28.m and similarity_EvR1.m used for the analysis to measurement similarity evaluation are available in Simbeor SDK.

REFERENCES:

1. Y. Shlepnev, Sink or swim at 28 Gbps, The PCB Design Magazine, October 2014, p. 12-23. - #2014_05 at https://www.simberian.com/AppNotes.php
2. M. Marin, Y. Shlepnev, Systematic approach to PCB interconnects analysis to measurement validation, Proc. of 2018 IEEE Int. Symp. on EMC and SIPI, July 30- August 3, 2018, Long Beach, CA. - #2018_07 at https://www.simberian.com/AppNotes.php
3. A.P. Duffy, G. Zhang, FSV: State of the Art and Current Research Fronts, IEEE Electromagnetic Compatibility Magazine, Volume 9, #3, 2020, p. 55-62.
4. M.-P. Dubuisson, A.K. Jain, A Modified Hausdorff Distance for Object Matching, - Proc. of Int. Conf. on Pattern Recognition, Jerusalem, Israel, 1994, p.566-568.
5. Y. Shlepnev, De-compositional Electromagnetic Analysis of Digital Interconnects, Proc. of IEEE Int. Symp. on EMC (EMC2013), Denver, CO, 2013, p.563-568. - #2013_05 at https://www.simberian.com/AppNotes.php
6. Guide to CMP-28/32 Simbeor Kit, CMP-28 Rev. 4, Sept. 2014.
7. M. Marin, Y. Shlepnev, 40 GHz PCB Interconnect Validation: Expectation vs. Reality, DesignCon2018, January 31, 2018, Santa Clara, CA. - #2018_01 at https://www.simberian.com/AppNotes.php

Revision Notes: Aug. 20, 2021 – YS: similarity measure or pre-metric are more suitable terms.

© 2021 Simberian, Inc. • www.simberian.com