S-Parameters: New Look and Similarity

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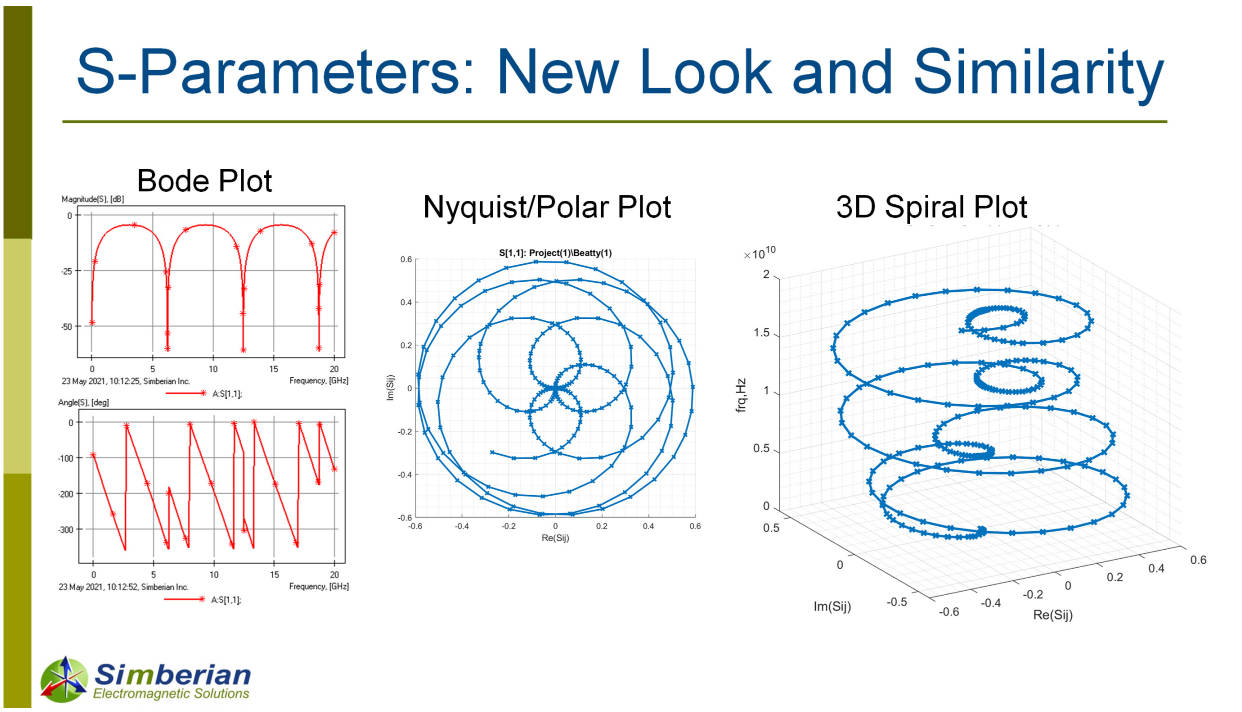
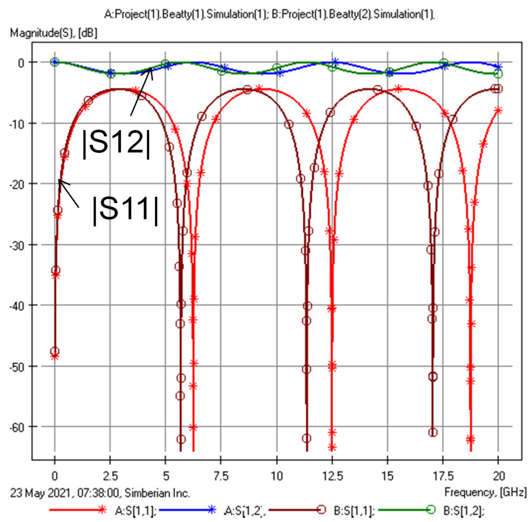
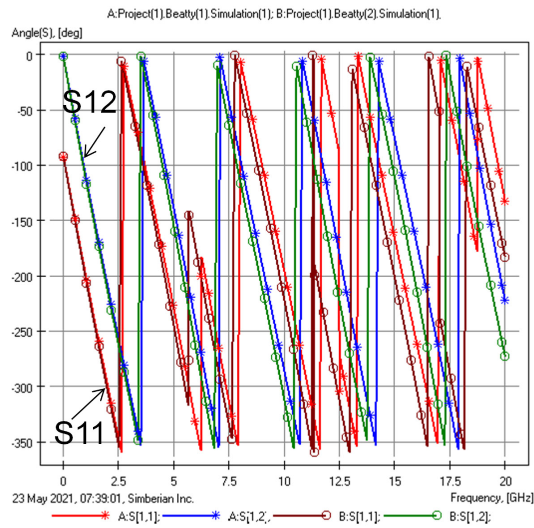


Bandwidth required for signal integrity analysis of PCB and packaging interconnects is growing with the increase of data rates. **Evaluation of model accuracy requires validation with the measurements – this is a necessary element of successful design process with data rates above 10 Gbps.** A systematic approach to the analysis to measurement validation was 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"). The process needs formal approach and possibility of automation. 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 formal single-number S-parameters similarity (SPS) measure is introduced in [4]. A new look at S-parameters in 3D Real-Imaginary-Frequency (RIF) space enabled application of the image recognition technique to computation of similarity between 2 sets of S-parameters. This article is just a brief introduction into how SPS is defined with some practical examples – more details are available in [4]. 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.

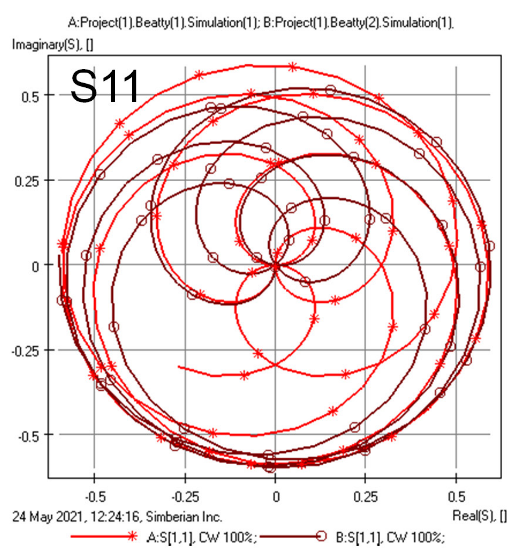
S-parameters are usually a set of S-matrices computed or measured at a number of frequency points. Each element of the matrix or S-parameter is a set of complex numbers at the frequency points. They can be plotted as magnitude and angle (Bode plot) as illustrated below for reflection and transmission parameters for two simple Beatty resonators:

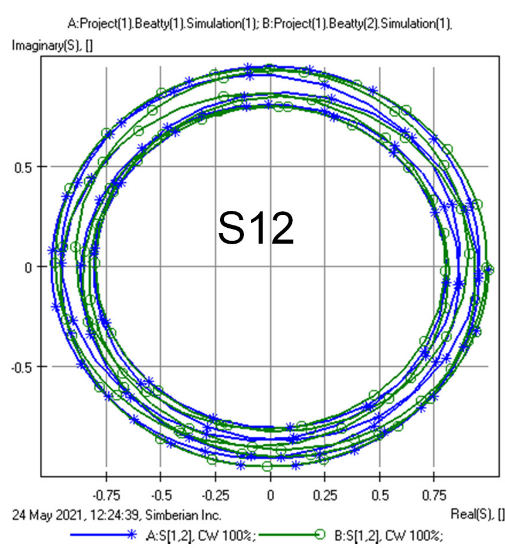




We can observe some shift of resonances in two structures, but it is difficult to make any conclusion on the angles – they are close at lower frequencies, but then deviate from each other. The jumps can be un-wrapped, but it is not always straightforward for measured data.

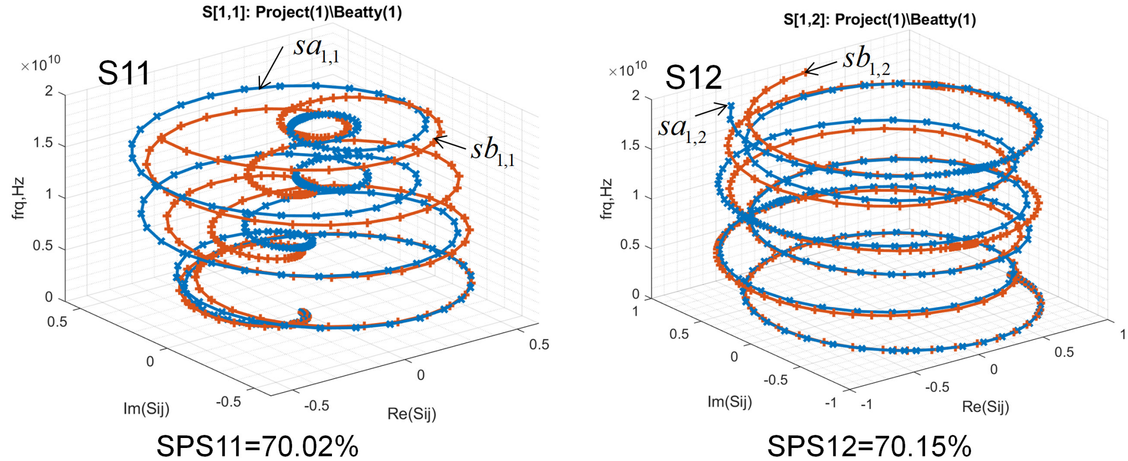
Another possible way to visualize S-parameters is to use Nyquist or polar plots – simply plot real value of S-parameter vs. imaginary at each frequency point and connect the points as the frequency increases. A vector from 0 to each frequency point gives magnitude and angle of the corresponding S-parameter at that frequency. The same reflection and transmission parameters shown above on the Bode plots are shown below on the polar plots:



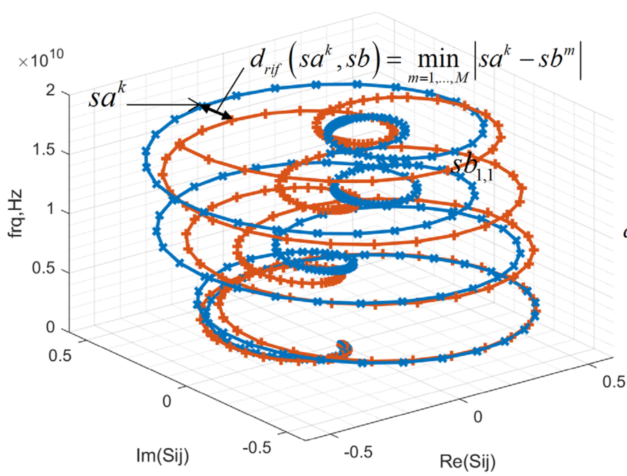


Such plots are even more confusing and less usable for the comparison purpose.

What if we plot the real and imaginary parts in 3D with the frequency as additional or Z-axis? We will get 3D spiral plots as shown below for the same set of S-parameters for 2 Beatty resonators:



The plots do not have intersections as the polar plots and no jumps of angles as on Bode plots. The visual comparison is still difficult, but we can apply an image recognition technique to measure the similarity of the data sets. In particular, Modified Hausdorff Distance (MHD) can be used to measure the distance between the two data sets (S-parameters of 2 Beatty resonators in this case):



MHD for S-Matrix Element *i,j*

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

MHD for S-Matrix *NxN*:

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

S-Parameters Similarity Metrics:

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

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

S-parameters similarity (SPS) measure with span from 0 (no similarity) to 100% (identical structures) can be introduces with the MHD computed for each element of matrix and for the whole matrix as shown on the picture above. **Very easy and straightforward – it is just a few lines of code in Matlab as shown in [4].**

As a practical case let's evaluate all models with all measurements for CMP-28 validation platform [5] from Wild River Technology (https://www.wildrivertech.com/). Values of SPS are computed with Simbeor SDK for all test structures on CMP-28 validation platform 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. Simulation was done with de-compositional analysis in Simbeor software and measurements are provided by WRT. The models are measurements are used from CMP-28 Simbeor Kit Rev. 4 with all data available at https://drive.google.com/drive/folders/0B6jLiKYCgxAnbFE0WFRmamxvLVE?usp=sharing.

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 and experiments. See more in [4].

"Sink or swim" approach [1] was validated with EvR-1 platform first introduced in [6] 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. Results of the visual analysis in provided in [2]. 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

Further analysis of this data is provided in [4]. Complete EvR-1 Kit is available https://drive.google.com/drive/folders/1Rm-QpROluiQ_fsIfpetCt8hu8PtfZfkz?usp=sharing

References:

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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.
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6. 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.