Design insights from electromagnetic analysis: Effects of meshed reference planes on interconnects

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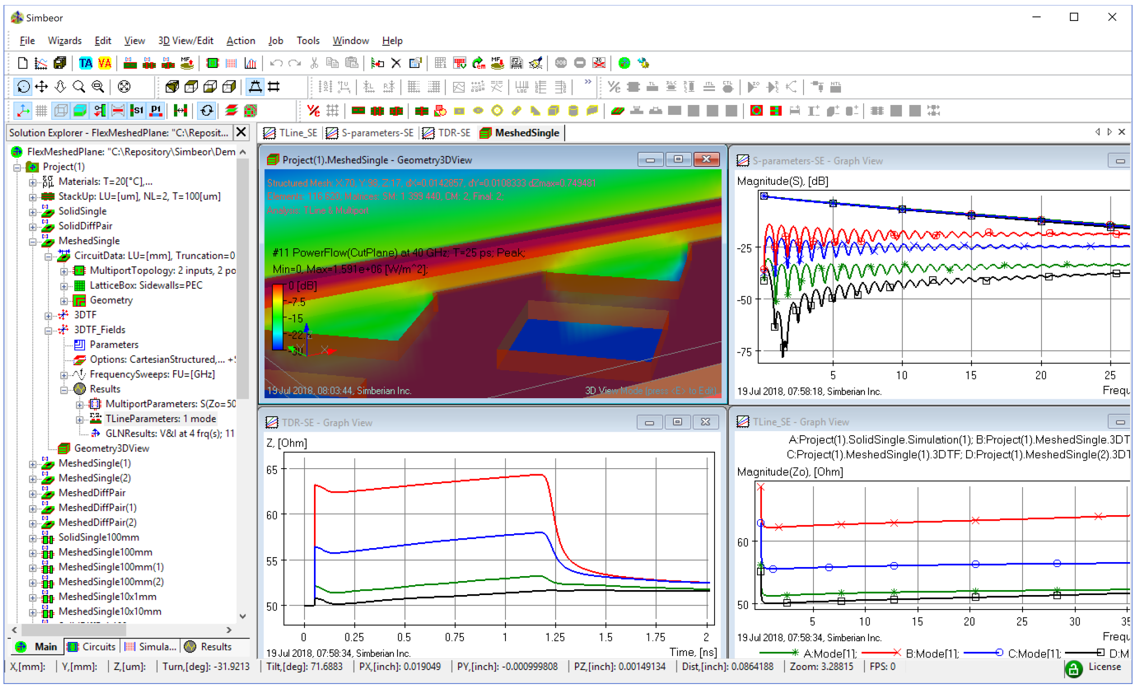

Interconnects in rigid and flexible boards can be formalized and simulated as transmission lines – strip, microstrip, coplanar, single-ended or differential. The number of conductors in such transmission line model is two for single-ended and three for differential lines. **The signal conductors in the electrical model correspond to the interconnect traces and the reference conductors correspond to one or two reference planes.** Static or quasi-static field solvers are usually used to extract modal (impedance, attenuation and phase delay) and per unit length (RLGC) parameters for analysis of data links – as shown in [1] such models may be accurate up to very high frequencies, depending on the geometry and material models. Reference planes in such models are assumed to be solid. That is usually correct assumption for most of the rigid board interconnects (except BGA fields in some cases). Though, **most of the flexible interconnects have meshed or hatched planes – the reference conductors have periodic cut-outs. The question is how to build accurate models for such structures?** It turns out that the traces over conductors with the periodic cut-outs can be effectively simulated as **periodic structures** – that requires 3D electromagnetic analysis of a small segment instead of the analysis of cross-section or analysis of a complete link. Similar to the regular transmission lines, periodic structures can be characterized with per unit length impedance and admittance and the modal parameters - attenuation, phase delay, characteristic impedance [2], [3]. That is very convenient for building models for interconnects with arbitrary length. This paper shows what we can learn from such analysis using a particular example. **Simbeor software is selected for the analysis of interconnects with meshed planes because of it has unique capability to extract modal and per unit length parameters for periodic structures (traces with periodic discontinuities in general).**

Electromagnetic waves in traces over plane with periodic cut outs

In general, periodic structure is made of repetition of a unit cell in one, two or three dimensions. For instance, Fig.1 provides a simple example of the periodic repetition of a rectangular cut-out in transmission line reference plane (example from demo-videos #2017_02 and 2017_03). The cut-outs are repeated in 2 dimensions, but for the wave propagating along the trace it is essentially a one-dimensional periodic structure (it becomes 2D for leaky mode investigation). Though, to extract per unit length and modal parameters of such structure, 3D electromagnetic analysis is needed due to the non-TEM structure of the waves propagating along the traces.

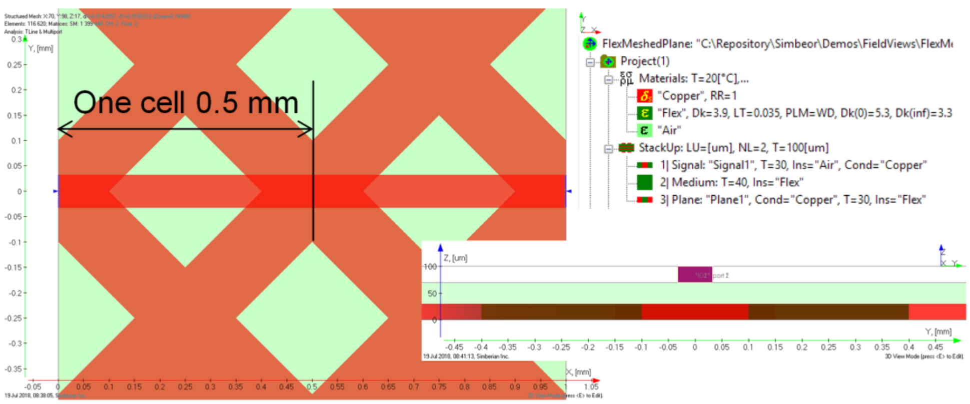

Fig. 1. Trace over meshed plane as periodic structure – geometry of two cells are needed for analysis in Simbeor software, to extract modal and per unit length parameters.

Most of the transmission lines in PCB or packaging interconnects have so called quasi-TEM waves with the electric and magnetic fields mostly perpendicular or transverse to the propagation direction. Parameters of such transmission lines can be accurately approximated with the analysis of a single cross-section in a 2D field solver. **With the cut-outs in the reference plane, the waves become non-TEM and not even quasi-TEM due to presence of the longitudinal components in the electric and magnetic fields** – the electric field above the cut-outs are shown in Fig. 2. We can clearly see the "non-transverse" nature of the electric field in the areas of angles in the reference conductors.

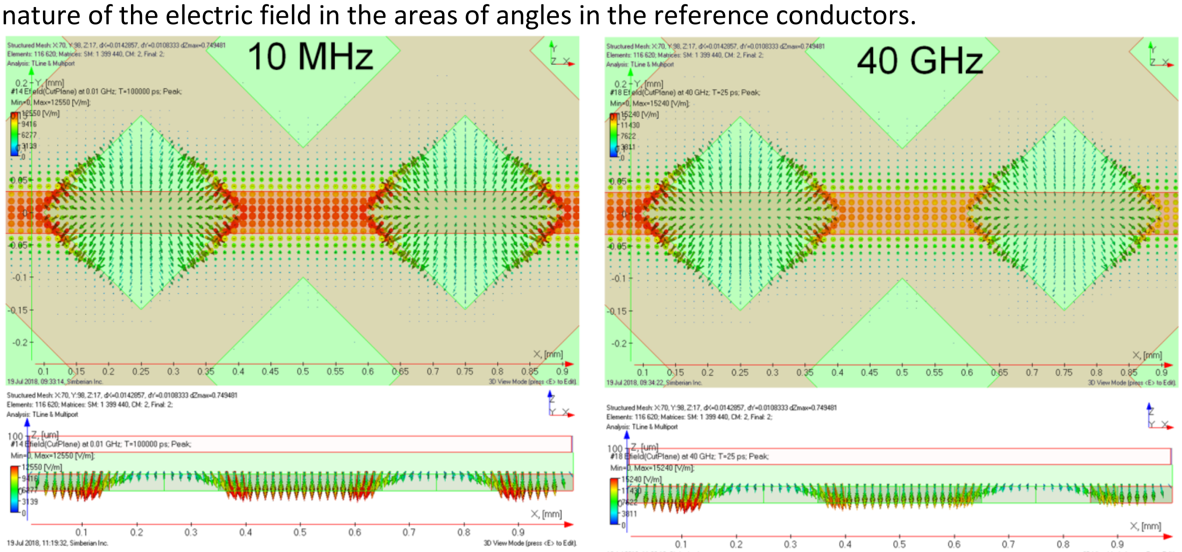

Fig. 2. Peak values of electric field intensity in plane with z-coordinate 35 um (right above the cut-outs).

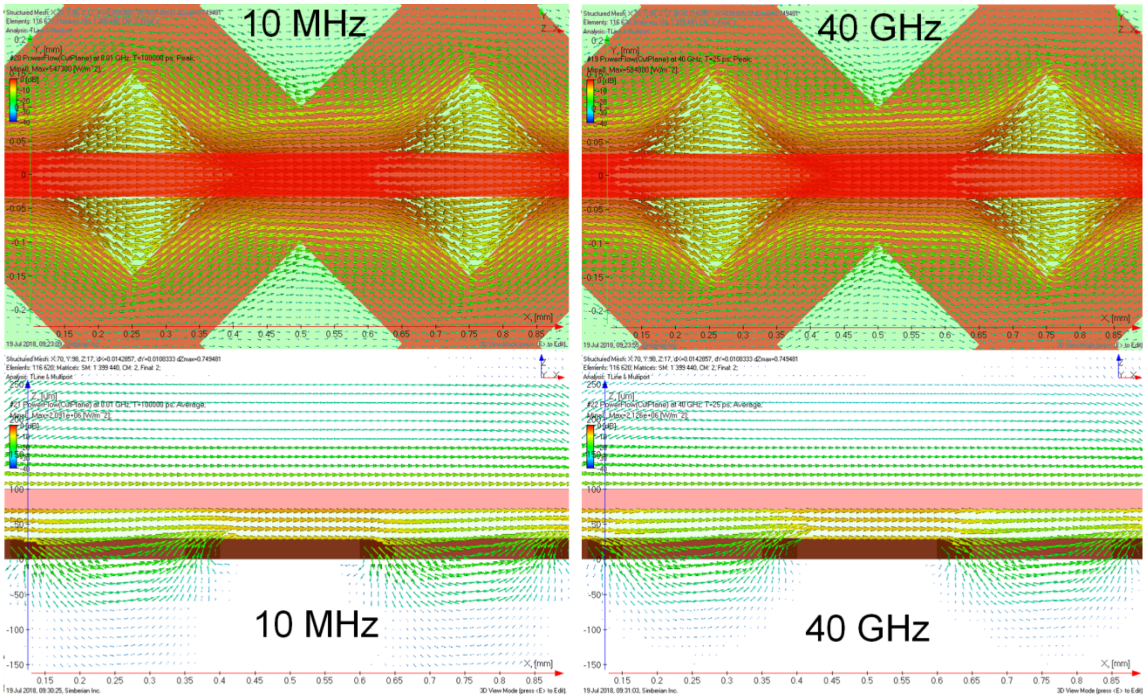

Fig. 3. Peak values of power flow density in plane with z-coordinate 35 um (top) and in plane along the trace.

Each cut-out is a discontinuity that distorts the electric and magnetic fields. As the result, the power flows not along the trace, as in the cases or transmission lines with the solid planes, but "deviates" in the horizontal as well as in the vertical directions as illustrated in Fig. 3 (learn the basics of the fields visualization from webinar #7). The power flow density actually depicts where the energy of the signal propagate – it is very useful tool to investigate the field localization [4]. **The cut-outs below or close to the trace also prevent the return currents from flowing straight along the traces** as it is shown in Fig. 4.

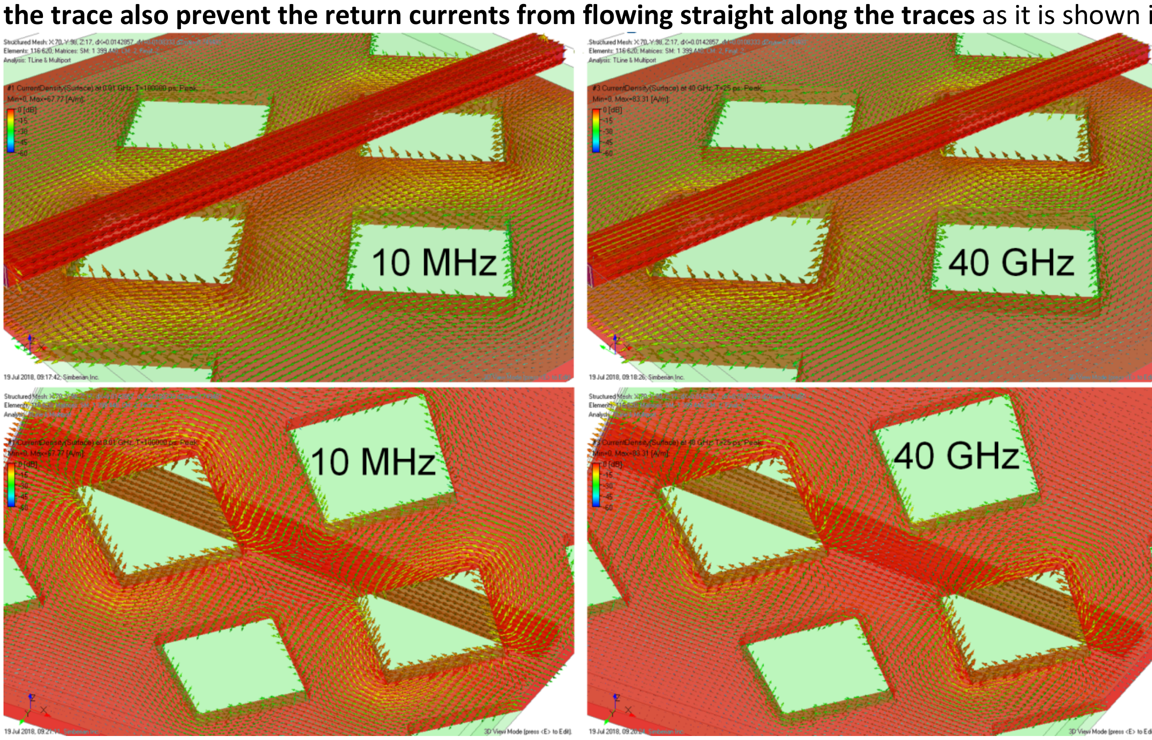

Fig. 4. Peak values of the surface current flow density on strips and below (top) and on the opposite side (bottom).

As we can see, the currents in the strip are pretty much the same as expected in cases with the solid planes. However, the cut-outs destruct the return current flow – it has to bypass the cutouts. **Also the currents flow on the opposite side of the meshed plane!** As we will see, that may cause unwanted coupling to the traces "shielded" by the meshed planes. **All those effects must be simulated to design predictable interconnects.**

Characteristic impedance

Now let's get back to the basics and take a look at the characteristic impedance of the dominant mode in the periodic structure formed by the trace over meshed plane. Any deviation from the link target impedance can cause the increase of the reflection losses in interconnect link. With stackup defined in Fig. 1, 65 um wide trace over the solid reference plane gives about 51 Ohm transmission line impedance at 1 GHz as illustrated in Fig. 5 (green lines). Relatively large cut-outs in the reference plane right below the strips increases the impedance to about 62 Ohm (red lines in Fig. 5) – it may cause the design failure due to excessive reflection losses or due to possible resonances in the system with non-uniform impedance links. This is the worst case scenario for this size of the cut-outs. The trace may be shifted to have more metal below the trace, to provide better path for the return current. This shift reduces the impedance down to 55.5 Ohm (blue lines in Fig. 5). The deficiency of the reference conductor area reduces the capacitance and increases the inductance of the periodic structure. In reality, without control of the trace position over the cutouts, one should expect the impedance variations from 55.5 to 62 Ohm in this case. Can we get it back down to 50 Ohm? Yes, but, unfortunately, only for a particular position of the trace. For instance, if we increase the trace width to 100 um, it is going to be about 50 Ohm if it goes directly over the cut-outs in the reference planes (black lines in Fig. 5). The impedance will decrease substantially, if the trace is shifted. **In general, all possible scenarios must be simulated.**

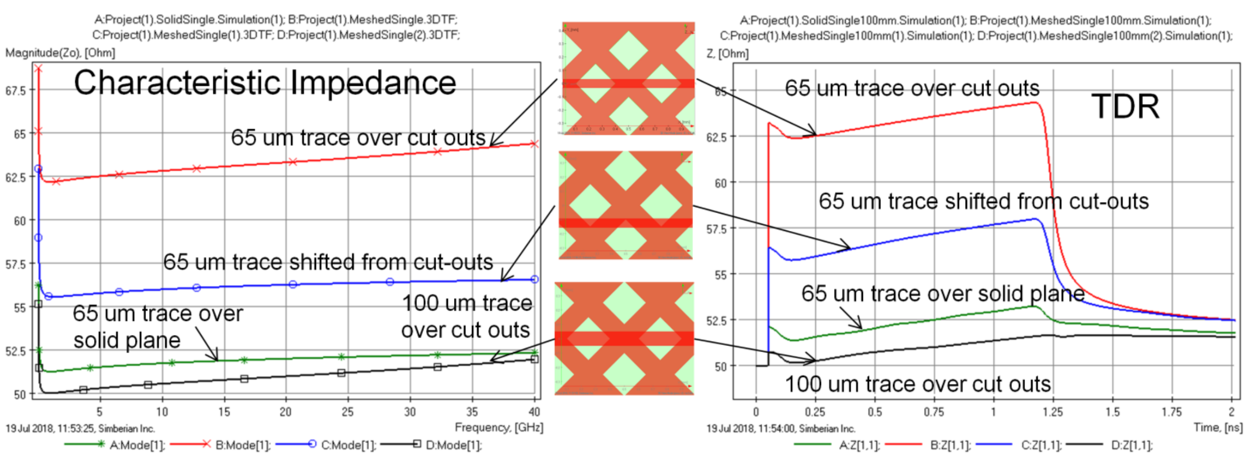

Fig. 5. Characteristic impedance for traces over solid and meshed plane (left) and corresponding TDR of 10 cm trace segment.

Attenuation and delay

Another important interconnect design parameters are signal attenuation and delay. Those two parameters are simply derived from the complex propagation constant of a transmission line or periodic structure mode. Attenuation is the energy loss to heat up dielectric (polarization losses) and conductor (conduction losses). The minimal phase delay corresponds to the signal front delay in general. Attenuation in dB/mm and phase delay in ps/mm for different configurations are compared in Fig. 6. Note that attenuation, delay and characteristic impedance depend on the material models used in the analysis. **To have accurate interconnect models, the material models must be either confirmed or**

identified as shown in [1]. Thus, the things we observed on the graphs here cannot be used to draw any design guidelines for any other cases. So, in this particular case, we can observe about 0.01 dB/mm differences in attenuation and about 0.4 ps/mm in phase delay for the investigated structures. This is the case of high loss dielectric. We also neglected the conductor roughness too – this assumption alone can ruin your design [1]. The conductor roughness can be easily accounted for in the simulations, but there were no any numbers to define the model for this case. The outcome of such investigation may be substantially different if dielectric is very low loss and conductor roughness is taken into account. **The point is that all that should be simulated and taken into account.**

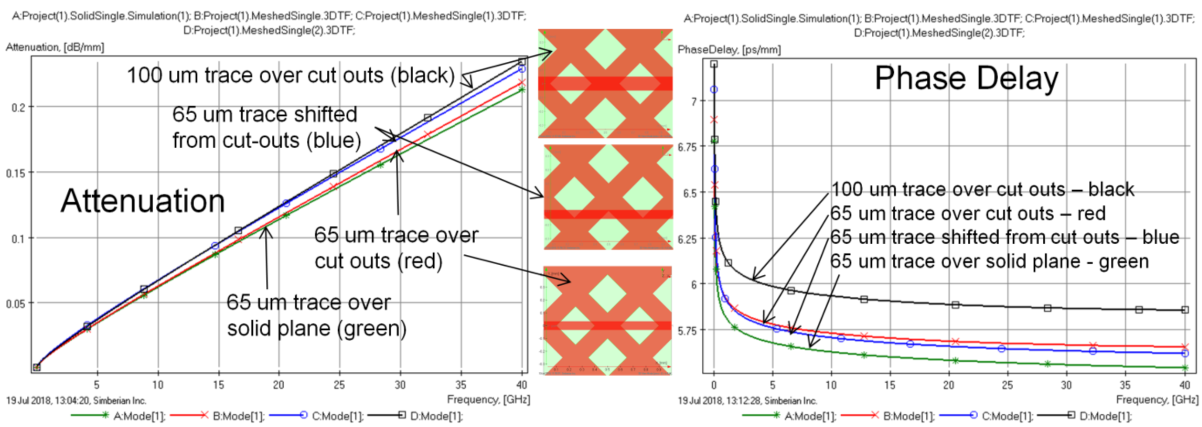

Fig. 6. Attenuation (left) and phase delay (right) for traces over solid and meshed plane.

S-parameters

Scattering or S-parameters and compliance metrics derived from them are getting popular in design of interconnects for digital systems. **S-parameters of a trace segment with the meshed reference plane can be easily computed as soon as the modal and per unit length parameters of the corresponding periodic structure are extracted.** Note that this type analysis is not an approximation – it follows from the physics of the periodic structures [2], [3]. **An alternative to this analysis is simulation of a complete link in a 3D EM solver – it could be very time and resources consuming process, if possible.** Note that most of the flexible interconnects have micron size of the conductors, that brings the onset of the skin-effect into the multi-GHz bandwidth. Thus, simulation of such links requires meshing of the conductor interior, as it is done with Trefftz finite elements in all examples in this paper (Simbeor 3DTF solver).

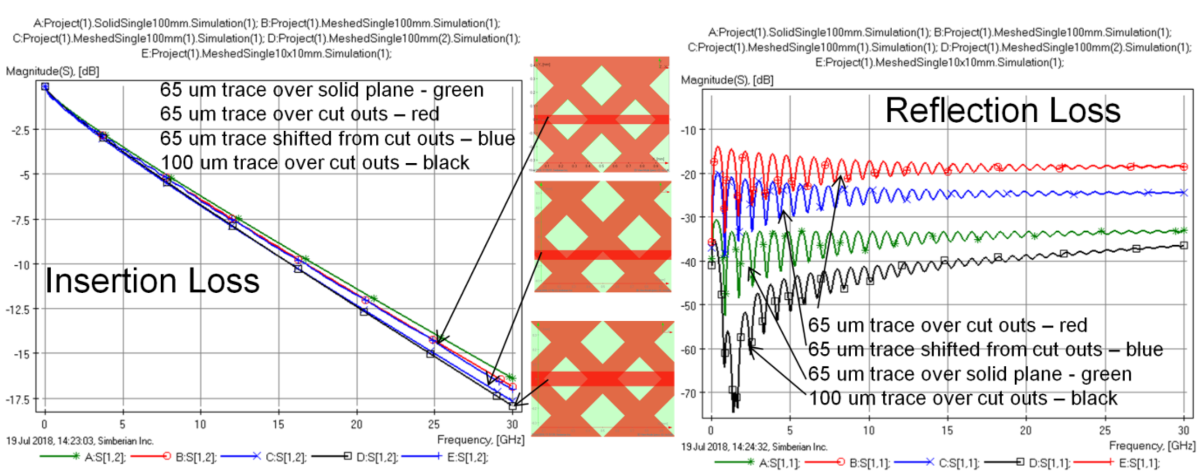

Fig. 7. Insertion loss (left) and reflection loss (right) for 10 cm traces over solid and meshed plane.

As an example, insertion and reflection losses of 10 cm segment of the traces over meshed plane were computed and compared with the trace over the solid reference plane – the results are plotted in Fig. 7. The insertion loss differences are within 1 dB at 20 GHz for the investigated configurations. Though, the reflection losses vary dramatically – this is simply the result of the differences in the characteristic impedances.

Coupling and mode transformations

Finally, what if the meshed plane is used to shield traces on the opposite sides? We can expect almost ideal isolation in case of the solid plane – in other words, the traces can be considered as not coupled with the solid plane. The fields simply do not penetrate through the solid planes at the frequencies with well-developed skin-effect and coupling at lower frequencies below the skin effect does not matter for the signal integrity analysis (interconnects become electrically short). **When we cut the holes, the power flow through the wholes and currents flow on the opposite side of the plane as illustrated in Fig. 3 and Fig. 4.** It can cause crosstalk if another trace gets into that area - this is yet another example of possible violation of the electromagnetic field localization discussed in [4]. However, unlike with the viaholes, this loss of localization effect can be easily simulated. As an example, two traces are simulated – the results are shown in Fig. 8. The traces are located exactly on top of each other. The worst case scenario is with the traces right over the cut-outs. It give the maximal exposure through the holes and, as the result, the maximal coupling. We can observe very significant far end crosstalk (FEXT) (blue line on the left graph in Fig. 8). Such crosstalk can kill the signal with the main spectral harmonic around 8-10 GHz in this particular case – the insertion loss go sharply down as shown on the right graph in Fig. 8 (red curve). It means that the signal harmonics will not get through 10 cm of this interconnect!
Shifting the traces off the cut-outs helps, but not much. With the losses and geometry of interconnects used in this example, the insertion loss null is shifted to about 17 GHz and became wider too. The near end crosstalk (NEXT) is not significant in this case. **This example shows how important to model all possible signal degradation factors.** Looking at just attenuation (Fig. 6) or at the insertion loss in line segment (Fig. 7) may be way too optimistic in this case if the meshed reference plane is used as the common reference for traces on opposite sides. Such scenario would be a disaster for signals with 8 Gbps and higher data rates!

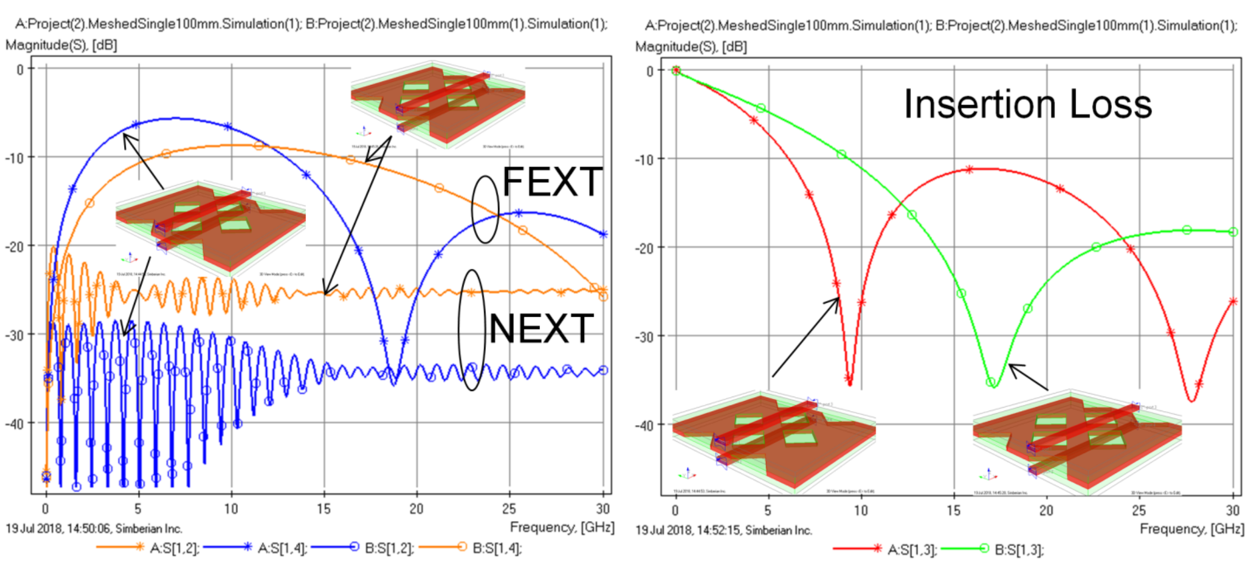

Fig. 8. Near-end (NEXT) and far-end (FEXT) crosstalk (left) and corresponding insertion loss (right) for 10 cm traces over meshed plane for traces over the cutouts and mostly over conductor.

Conclusion
3D electromagnetic analysis of traces over meshed plane is used in this paper to illustrate the following:
1) Traces with the meshed reference planes are actually periodic structures and have to be simulated as the periodic structure with a 3D EM solver.
2) Meshed reference plane has significant effect on the electromagnetic fields, power flow and return current distribution.
3) Meshed planes significantly change the characteristic impedance as well as the reflection and insertion losses.
4) Cut outs may cause significant cross-talk as well as EMI/EMC issues.

Similar observations are valid for a differential case presented in demo-videos demo-videos #2017_02 and 2017_03. In addition to the effects observed in the single-ended case, one can expect differential to common mode conversion if two traces of a differential pair are not aligned with the cut-out in exactly the same way (can be considered as a type of crosstalk). All that must be simulated to design predictable interconnects.

Simbeor 3DTF solver based on Trefftz finite elements was used for all simulations in this paper. It provides high accuracy for structures with the micron size of conductors – the elements in the conductor interior capture low-frequency and high-frequency behavior of the conductors as well as the transition between the two states. **This is very important for interconnects used for high bandwidth memory or packaging applications for instance.** Analysis of each structure takes a few minutes. Note that simulations with the polynomial finite elements may take hours, to solve the problem with proper DC and high frequency asymptotes and comparable accuracy. **See step by step instructions on how to set up analysis of single and coupled traces over meshed planes in app note #2018_04.** Note that Traces in BGA fields, traces with close via fences and some other structures can be also formalized and simulated as the periodic structures – this is an elegant and accurate alternative to the brute force approach of exhaustive 3D EM analysis of a complete link.

References

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