112 Gbps
In and Out of Package Challenges
Design insights from electromagnetic analysis

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Package and PCB scales in symbol time for 112 Gbps PAM4

Package: ~20 symbols in interconnects

PCB: ~100 symbols in interconnects

112 Gbps PAM4, symbol 17.857 ps, good package

12.5 cm of strip line on Meg7

25 cm of strip line on Meg7 (computed with data for actual material)

Can we do better?

What we have on PCB today will eventually happen at the package (20 bits on PCB were at about 14 Gbps NRZ)
Bandwidth for 112 Gbps NRZ and PAM4

What should be the bandwidth for electromagnetic analysis of interconnects? 28 GHz? 56 GHz? 84 GHz? 112 GHz?...140? – it should be defined with numerical experiment and correlation with measurements. See simple case study at Simberian AN #2018_02, “Moving from 28 Gbps NRZ to 56 Gbps PAM4”, www.simberian.com ...
## Package and PCB scales in wavelengths

**Package** (~10 WL @ 28 GHz, ~40 WL @ 112 GHz)

**PCB** (~50*WL @ 28 GHz, ~200*WL @ 112 GHz)

<table>
<thead>
<tr>
<th>Frequency [GHz]</th>
<th>WL [mm], Air</th>
<th>WL [mm]</th>
<th>WL/2 [mm]</th>
<th>WL/4 [mm]</th>
<th>WL/8 [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>14</td>
<td>21.414</td>
<td>15.142</td>
<td>7.571</td>
<td>3.785</td>
<td>1.893</td>
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<tr>
<td>28</td>
<td>10.707</td>
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<td>3.785</td>
<td>1.893</td>
<td>0.946</td>
</tr>
<tr>
<td>56</td>
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<td>1.893</td>
<td>0.946</td>
<td>0.473</td>
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<tr>
<td>84</td>
<td>3.569</td>
<td>2.524</td>
<td>1.262</td>
<td>0.631</td>
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<tr>
<td>112</td>
<td>2.677</td>
<td>1.893</td>
<td>0.946</td>
<td>0.473</td>
<td>0.237</td>
</tr>
</tbody>
</table>

**Design Limits:**
- WL/2 - cutoff for SIW formed by via fences;
- WL/4 - resonances, via localization (pass/fail);
- WL/8 – via fence localization (bandgap structures if not possible);

**WL** is wavelength in dielectric

\[
\lambda = \frac{c}{f \cdot \sqrt{\varepsilon_r}}
\]

*1 mm = 39.37008 mil
1 mil = 0.0254 mm

We are deep into microwave and mm-wave territory

**Waveguide Domain ruled by the Electromagnetic Analysis!**
Electromagnetic Analysis of Interconnects:
Problem dimension and formulation

1D models or transmission line models – Telegrapher’s equations
Modal or per unit length parameters for the Telegrapher’s equations (Z, Y) are computed with static or quasi-static field solver (2D problems for Laplace’s equations) or an electromagnetic fields solver (3D problems for Maxwell’s equations)
Lines with coupling, multimodal waveguides, periodic structures can be accurately modeled

2D models or transmission plane models - 2D Telegrapher’s equations (Maxwell’s equations for 2D TE problems)
Component to model power delivery processes in parallel plane PDNs
See more at Y. Shlepnev, ACES 2006, EPEPS 2012

3D models or 3D full-wave models - everything described and solved with Maxwell's equations without any simplifications for 3D geometries or field components
Analysis of discontinuities such as via-holes, connectors or any type of transitions between uniform traces
Analysis of SI, PI or SI+PI with 3D models is possible with some tools, but may be not practical due to enormous complexity and accuracy issues
**Electromagnetic Analysis of Interconnects:**

**Hybrid models**

1D+3D: Hybrid de-compositional analysis with transmission line models for traces (1D) and 3D models for discontinuities or transitions

The best technique for the serial interconnects under the localization condition (Y. Shlepnev, EMC 2013)

This approach usually works for PCB and packaging problems with relatively long traces, but may fail if trace segments are too short - complete 3D analysis is required in this case.

1D+2D: Hybrid analysis with transmission line models (1D) and the transmission plane models (2D) coupled at the via-holes (more at Y. Shlepnev, ACES 2006)

Such models are usually used to simulate SI + PI - even the whole board simulation is possible in many tools based on this technique, popular for solving un-localized problems.

Though, the accuracy is severely limited due to via-hole models simplifications.

1D+2D+3D: Hybrid analysis with transmission line models (1D), transmission plane models (2D) with the coupling between two modeled simulated with 3D analysis

Advantage - fast algorithms of 1D+2D and accuracy of 3D at the discontinuities

Needed only in case if there is substantial coupling between 3D (via for instance) and 2D (PDN) models - case of non-localized vias, when energy from SI go to PI and the other way around.

If you forced to use this approach, the alternative is to fix design – enforce the localization and simplify the problem back to 1D+3D.
Accuracy of 1D+3D de-compositional analysis

- Accuracy depends on proper **localization of every single element in the link**
  - Difficult in package and almost impossible on PCB for bandwidth of 112 Gbps signal
- **Broadband dielectric and conductor roughness models** are identified (with GMS-parameters or SPP Light)
  - About time to start doing it for packages, very important for PCB – models must be statistical (see more A. Manukovsky, Y. Shlepnev, DesignCon 2019)
- **Manufactured geometry adjustments** are identified
  - May be less important for packages, very important for PCB – models must be statistical
- **Electromagnetic solvers are formally validated with measurements** using systematic approach (“sink or swim” for instance)
  - This is not just getting the analysis matching the measurements by any means – see more at M. Marin, Y. Shlepnev, DesignCon 2018, EMC 2018
  - There are no data on solvers that are formally validated for 112 Gbps signal bandwidth (so far variations in geometry and materials technically prohibit this)
- Other considerations: Ports consistency and de-embedding, boundary conditions,...
Only localized structures must be used to design PCB/Packaging interconnects – design only with predictable structures!

Not localized == not predictable!  
Predictable, conditionally localized, single-mode!

- Stripline
- Microstrip
- Via + stitching via(s) somewhere
  - “Fenced” Stripline
  - CBCPW
  - Localized Vias
  - If not possible - use of bandgap structures for localization
Conclusion

• Understand the electromagnetic solver technology limitations by systematic validation over the target bandwidth (applicable to system-level simulators too)

• Define the target bandwidth by numerical experiment with identified material models, correlated with measurements

• Design only predictable localized interconnects with the identified material models and manufacturing adjustments and properly validated solvers!