Practical Method for Modeling Conductor Surface Roughness Using Close Packing of Equal Spheres

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Outline

- Overview
- Conductor loss
- Copper foil fabrication
- Modeling roughness
- Hexagonal Close-packing of Equal Spheres Model
- Practical method to determine rough conductor loss
- Case study
Failure To Model Roughness Can Ruin You Day

With just -3.5dB delta
@12.5 GHz => ½ the eye height with rough copper

Simulated with Keysight ADS

25Gb/s
Current distribution at DC is uniform through cross-sectional area of conductor.
DC Resistance

DC resistance is proportional to resistivity and inversely proportional to the cross sectional area.

\[ R_{DC\_cond} = \frac{\rho}{t \times w} \, \Omega / m \]

\[ \rho = \text{Bulk resistivity of the material in } \Omega \cdot \text{m} \]
Skin Effect

Above ~10MHz current flows mainly along “skin” of the conductor
Skin depth ($\delta$) is effective thickness where AC current flows.
Skin Depth vs Frequency

\[ \delta = \sqrt{\frac{1}{\pi f \mu_0 \sigma}} \]

\( \mu_0 = \) Permeability of free space in H/m
\( \sigma = \) Conductivity in S/m.

Skin depth inversely proportional to \( \sqrt{f} \)
AC Resistance

\[ R_{AC\_cond} \approx \frac{\rho}{2\delta \times w} \, \Omega / m \]

Reduced cross-sectional area causes AC resistance to increase proportional to \( \sqrt{f} \)
Current Distribution Microstrip

High frequency currents concentrated mostly along surface facing reference plane due to proximity effect
Current Distribution Stripline

Symmetrical

Asymmetrical
Return Current Distribution

Return current on respective reference plane ≈ +/-3H from signal conductor center
AC Resistance Microstrip

\[ R_{AC\_microstrip} = R_{AC\_trace} + R_{AC\_ref} \]

\[
R_{AC\_microstrip} (f) = \sqrt{\frac{\pi \mu_0 f \rho}{w}} \left[ 0.94 + 0.132 \frac{w}{H} - 0.0062 \left( \frac{w}{H} \right)^2 \left( \frac{1}{\pi} + \frac{1}{\pi^2} \ln \frac{4\pi w}{t} \right) + \frac{w}{H} \left( \frac{w}{H} + 5.8 + 0.03 \left( \frac{H}{w} \right) \right) \right] \Omega/m \; ; \text{when} \; 0.5 \leq \frac{w}{H} \leq 10
\]

Reference [1]
1. Determine $R_{AC\_microstrip1}$
2. Determine $R_{AC\_microstrip2}$
3. Combine both in parallel

$$R_{AC\_stripline}(f) = \frac{(R_{AC\_microstrip1}(f))(R_{AC\_microstrip2}(f))}{(R_{AC\_microstrip1}(f))+(R_{AC\_microstrip2}(f))} \Omega/m$$

4. Determine Insertion Loss:

$$IL_{smooth}(f) = -20 \log_{10} e\left(\frac{R_{AC\_stripline}(f)}{Z_0(f)}\right) \text{dB/m}$$
Conductor Loss Model Validation

\[ IL_{\text{smooth}}(f) = -20 \log_{10} \left( R_{\text{AC-stripline}}(f) \right) \frac{1}{Z_0(f)} \text{ dB/m} \]

**VS**

**Excellent correlation!**
No such thing as a perfectly smooth PCB conductor surface

Roughness is always applied to promote adhesion to the dielectric material
Copper Foil Manufacturing Processes

Rolled

Smotherer

VS

Electro-deposited (ED)

Lower Cost
Rolled Copper Foil Fabrication Process

- Copper bar fed through a series of progressively smaller rollers to achieve final thickness
- Roller smoothness determines final smoothness of foil
Electrodeposited Copper Foil Fabrication Process

- Drum speed controls foil thickness
- Matte side always rougher than drum side
## Common Roughness Profiles

<table>
<thead>
<tr>
<th>Profile</th>
<th>Specification</th>
<th>Other Names</th>
</tr>
</thead>
<tbody>
<tr>
<td>IPC Standard Profile</td>
<td>No min/max spec</td>
<td></td>
</tr>
<tr>
<td>IPC Very Low Profile (VLP)</td>
<td>&lt; 5.2 μm max</td>
<td>Other names: HVLP, VSP</td>
</tr>
<tr>
<td>Ultra Low Profile (ULP) Class</td>
<td>- No IPC spec</td>
<td>- Typically &lt; 2 μm max</td>
</tr>
</tbody>
</table>

SEM Photos Courtesy [6]
Electro-deposited Copper Foil Nodulation Treatment

Drum Side Untreated

Matte Side Untreated

Untreated Foil

Drum Side

Matte Side

Nodulation Treatment

Drum Side

Matte Side

Matte Side Treated

Drum Side Treated

SEM Photos Courtesy [2]
Measuring Surface Roughness

Profilometers are often used to measure surface roughness
Optical Profilometer

- 3D Scan Profile
- Faster
- More reliable
- More accurate
Average Roughness Parameter

- Average roughness \((R_a)\) typically specified for drum side on data sheet
- \(R_a = \text{Arithmetic average of the absolute values of deviations } Y_i\)

\[
R_a = \frac{1}{N} \sum_{i=1}^{N} |Y_i|
\]
Ten-point Mean Roughness Parameter

- Ten-point mean roughness ($R_z$) typically specified for matte side on data sheet

- $R_z = \text{Sum of the average of the five highest peaks and the five lowest valleys over the sample length}$

$$R_z = \frac{1}{5} \sum_{i=1}^{5} |Y_{Pi}| + \frac{1}{5} \sum_{i=1}^{5} |Y_{Vi}|$$
Modeling Copper Roughness
Hamerstad & Jenson Model

- Assumes 2D corrugated surface
- Based on mathematical fit to S.P. Morgan Power Loss Data (1948)
- Lose accuracy above 5GHz for rough copper

\[
K_{HJ} = \frac{P_{\text{rough}}}{P_{\text{flat}}} = 1 + \frac{2}{\pi} \arctan(1.4 \left(\frac{\Delta}{\delta}\right)^2)
\]

\[\Delta = \text{RMS tooth height in meters}\]
Modified Hamerstad & Jenson Model

- $SF = \text{scaling factor representing the ratio of the length of the rough surface } (L_{\text{rough}}) \text{ to the spatial length } (L_{\text{spatial}}) - \text{Ref [2]}$

- Impractical from first principles perspective – $L_{\text{rough}}$ not published in data sheets

$$K_{\text{HJM}} = \frac{P_{\text{rough}}}{P_{\text{flat}}} = 1 + \frac{2}{\pi} \arctan \left( 1.4 \left( \frac{\Delta}{\delta} \right)^2 \right) \times (SF - 1)$$
Huray “snowball” Model

\[ K_{SRH}(f) = \frac{P_{rough}}{P_{flat}} = \frac{A_{matte}}{A_{flat}} + \sum_{i=1}^{j} \left( \frac{N_i \times 4\pi a_i^2}{A_{flat}} \right) \left( 1 + \frac{\delta(f)}{a_i} + \frac{\delta^2(f)}{2a_i^2} \right)^{-1} \]

\( \frac{A_{matte}}{A_{flat}} \) = relative area of the matte base compared to a flat surface

\( a_i \) = radius of the copper sphere (snowball) of the \( i^{th} \) size, in meters

\( \frac{N_i}{A_{flat}} \) = number of copper spheres of the \( i^{th} \) size per unit flat area in sq. meters

\( \delta(f) \) = skin-depth, as a function of frequency, in meters

Reference [2]
Huray Model Prior Art

Assumes stacked “snowballs” arranged in hexagonal lattice

11 spheres min; 38 spheres max of radius 1μm to fit within hex tile area and height of 5.8μm

Fit equation parameters to measured data
Design Feedback Method*

Benefits:
- Practical
- Accurate

Issues:
- Expertise Required
- Time
- Money

*Reference [2]
Hexagonal Close-packing of Equal Spheres (HCPES) Model
Why Bother?

✓ Helps make informed decision sooner - “Sometimes an OK answer NOW! is more important than a good answer late” – Eric Bogatin

✓ Fast simulation time - Practical for what-if spreadsheet analysis

✓ Minimal expertise required

✓ Useful to sanitize CAD tools

✓ Useful to gain intuition on what to expect with measurements and help determine root cause of differences
HCPES Model

- Similar to Huray Model
- Based on close-packing of 11 equal sized spheres
- Does not require SEM analysis to determine stack height ($H_{RMS}$) or hexagonal tile area

Reference [5]
HCPES Correction Factor

\[ K_{\text{HCPES}}(f) \approx \frac{P_{\text{rough}}}{P_{\text{flat}}} \approx 1 + 66 \left( \frac{\pi r^2}{A_{\text{Hex}}} \right) \left( 1 + \frac{\delta(f)}{r} + \frac{\delta^2(f)}{2r^2} \right) \]

- Assumes nodule treatment applied to perfect flat surface
- Sphere radius and hex tile area determined solely on published roughness parameters from manufacturer’s data sheet
HCPES lattice structure loosely resembles the actual SEM photo

SEM Photo Courtesy [3]
HCPES Model Scalability

Lattice structure scales inversely to the square of the height.
HCPES Model Anatomy

- Total of 11 equal sized spheres
- \( H_{\text{RMS}} \) = height of 2 tetrahedrons plus 2 sphere radii
- Hexagonal tile perimeter surrounds 7 base spheres exactly
Determine Height of Single Tetrahedron
1. Determine DE

Given:
✓ Each side of the tetrahedron = 2r
✓ \( DE = \frac{2}{3} DF \)

Using Pythagorean theorem:
\[
DE = \frac{2}{3} \sqrt{DB^2 - BF^2}
\]
\[
= \frac{2}{3} \sqrt{(2r)^2 - (r)^2}
\]
\[
= \frac{2}{3} r \sqrt{3}
\]
2. Determine Height (AE)

Therefore:

\[ AE = \sqrt{AD^2 - DE^2} \]

\[ = \sqrt{(2r)^2 - \left(\frac{2}{3}r\sqrt{3}\right)^2} \]

\[ = \frac{2}{3}r\sqrt{6} \]
Determine HCPES Sphere Radius

Since $H_{RMS} = \text{height of 2 tetrahedrons} + \text{sphere dia.}$

$$H_{RMS} = 2AE + 2r$$

$$= 2r \left( \frac{2}{3} \sqrt{6} + 1 \right)$$

Therefore sphere radius is:

$$r = \frac{H_{RMS}}{2 \left( \frac{2}{3} \sqrt{6} + 1 \right)}$$
Determine Hexagonal Tile Area

A_{Hex} = 6 \times \text{area of equilateral triangle ADG}

\[
A_{Hex} = 6 \left( DF \times AF \right)
= 6 \left( r \left( \frac{1}{\sqrt{3}} + 1 \right) \times r \sqrt{3} \left( \frac{1}{\sqrt{3}} + 1 \right) \right)
= 6r^2 \sqrt{3} \left( \frac{1}{\sqrt{3}} + 1 \right)^2
\]
Method to Determine Rough Conductor Loss
Stripline Geometry with Surface Roughness Example

Typically:
- Must consider roughness of each side when determining AC resistance
- Matte sides bonded to core
- Drum sides bonded to prepreg
- Drum sides roughened with oxide or etch treatment prior to lamination
Dual Triangular Sawtooth Profile (DTSP) Model

Used to approximate RMS height of matte and drum side

\[
H_{\text{RMS}_a} \approx \frac{R_a}{2\sqrt{3}} \\
H_{\text{RMS}_z} \approx \frac{R_z}{2\sqrt{3}}
\]
1. Determine RMS Tooth Height of Matte and Drum Sides

\[ H_{RMS\_drum} \approx \frac{R_a}{2\sqrt{3}} \]

\[ H_{RMS\_matte} \approx \frac{R_z}{2\sqrt{3}} \]

*Use Micro-etch Roughness for Drum Side*
2. Determine HCPES Matte & Drum Correction Factors

\[ r_{\text{matte}} = \frac{H_{\text{RMS, matte}}}{2 \left( \frac{2}{3} \sqrt{6} + 1 \right)} \]

\[ A_{\text{Hex, matte}} = 6 \left( r_{\text{matte}} \right)^2 \sqrt{3} \left( \frac{1}{\sqrt{3}} + 1 \right)^2 \]

\[ K_{\text{HCPES, matte}} (f) \approx 1 + 66 \left( \frac{\pi \left( r_{\text{matte}} \right)^2}{A_{\text{Hex, matte}}} \right) \left( \frac{1 + \delta(f)}{r_{\text{matte}}} + \frac{\delta^2(f)}{2 \left( r_{\text{matte}} \right)^2} \right) \]

\[ r_{\text{drum}} = \frac{H_{\text{RMS, drum}}}{2 \left( \frac{2}{3} \sqrt{6} + 1 \right)} \]

\[ A_{\text{Hex, drum}} = 6 \left( r_{\text{drum}} \right)^2 \sqrt{3} \left( \frac{1}{\sqrt{3}} + 1 \right)^2 \]

\[ K_{\text{HCPES, drum}} (f) \approx 1 + 66 \left( \frac{\pi \left( r_{\text{drum}} \right)^2}{A_{\text{Hex, drum}}} \right) \left( \frac{1 + \delta(f)}{r_{\text{drum}}} + \frac{\delta^2(f)}{2 \left( r_{\text{drum}} \right)^2} \right) \]
3. Determine AC Resistances of Each Surface

$$R_{AC_{\text{ret-2}}} (f) = \sqrt{\pi \mu_f \rho \frac{w_2}{H_2}} \left( \frac{w_2}{H_2} + 5.8 + 0.03 \left( \frac{H_2}{w_2} \right) \right) \Omega/m$$

$$R_{AC_{\text{ret-2}}} (f) = \sqrt{\pi \mu_f \rho \frac{w_2}{H_2}} \left( 0.94 + 0.132 \frac{w_2}{H_2} - 0.0062 \left( \frac{w_2}{H_2} \right)^2 \right) \Omega/m$$

$$R_{AC_{\text{ret-1}}} (f) = \sqrt{\pi \mu_f \rho \frac{w_1}{H_1}} \left( \frac{w_1}{H_1} + 5.8 + 0.03 \left( \frac{H_1}{w_1} \right) \right) \Omega/m$$

$$R_{AC_{\text{ret-1}}} (f) = \sqrt{\pi \mu_f \rho \frac{w_1}{H_1}} \left( 0.94 + 0.132 \frac{w_1}{H_1} - 0.0062 \left( \frac{w_1}{H_1} \right)^2 \right) \Omega/m$$

* when $0.5 \leq \frac{w_n}{H_n} \leq 10$

Reference [1]
4. Determine Stripline Rough Conductor Loss

\[
R_{AC\_drum}(f) = K_{HCPES\_drum}(f) \left[ R_{AC\_w2}(f) + R_{AC\_ref2}(f) \right] \, \Omega/m
\]

\[
R_{AC\_matte}(f) = K_{HCPES\_matte}(f) \left[ R_{AC\_w1}(f) + R_{AC\_ref1}(f) \right] \, \Omega/m
\]

\[
R_{AC\_strip\_rough}(f) = \frac{R_{AC\_matte}(f)}{R_{AC\_drum}(f)} \left[ \frac{R_{AC\_matte}(f)}{R_{AC\_drum}(f)} + R_{AC\_drum}(f) \right] \, \Omega/m
\]

\[
IL_{\text{rough}}(f) = -20 \log_{10} \left( \frac{R_{AC\_strip\_rough}(f)}{Z_o(f)} \right) \, \text{dB/m}
\]
Case Study
Test Platform

Case 1
Megtron-6 HVLP Cu

Case 2
N4000-13EP VLP Cu

12 Layer test boards designed, built and tested by Molex Inc., courtesy of David Dunham

Generalized Modal S-parameters (GMS) data courtesy Scott McMorrow, Teraspeed Consulting Group

Generalized Modal S-parameters (GMS) data courtesy Yuriy Shlepnev, Simberian Software Corp

Photos courtesy [2]
### Board Parameters From Data Sheets and Design

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Case 1 Megtron-6</th>
<th>Case 2 N4000-13EP</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Dk$</td>
<td>3.62 @50GHz</td>
<td>3.6-3.7 @10GHz[i]</td>
</tr>
<tr>
<td>$Df$</td>
<td>0.006 @ 50GHz</td>
<td>0.008-0.009 @ 10GHz[ii]</td>
</tr>
<tr>
<td>$R_z$ HVLP</td>
<td>1.50 $\mu$m</td>
<td>-</td>
</tr>
<tr>
<td>$R_z$ VLP</td>
<td>-</td>
<td>2.50 $\mu$m</td>
</tr>
<tr>
<td>$R_a$ w/Micro-etch [iii]</td>
<td>1.44 $\mu$m</td>
<td>1.44 $\mu$m</td>
</tr>
<tr>
<td>Trace Thickness, $t$</td>
<td>15.23 $\mu$m</td>
<td>15.23 $\mu$m</td>
</tr>
<tr>
<td>Trace Widths $w_1, w_2$</td>
<td>251 $\mu$m, 236 $\mu$m</td>
<td>251 $\mu$m, 236 $\mu$m</td>
</tr>
<tr>
<td>Dielectric Heights, $H_1, H_2$</td>
<td>249 $\mu$m, 231 $\mu$m</td>
<td>249 $\mu$m, 231 $\mu$m</td>
</tr>
<tr>
<td>GMS trace length</td>
<td>10.15 cm (4.00 in)</td>
<td>10.15 cm (4.00 in)</td>
</tr>
<tr>
<td>$Zo(fo)$ ohms [iv]</td>
<td>52.29 @ 50GHz</td>
<td>52.07 @ 10GHz</td>
</tr>
</tbody>
</table>

[i] $Dk$ = 3.65 used  
[ii] $Df$ = 0.0085 used  
[iii] CO-BRA BOND® SM is an example of a hydrogen peroxide/sulfuric acid micro-etch treatment often used by PCB fabricators to improve the adhesion of copper surface to dielectric materials.  
[iv] $Zo(fo)$ = Characteristic impedance determined by 2D field solver at frequency $fo$
Determining Total Insertion Loss

\[
IL_{Total}(f) = IL_{dielectric}(f) + IL_{cond\_rough}(f)
\]

**Keysight ADS**

- Svensson/Djordjevic wideband Debye model used to ensure causality for dielectric loss
- Conductivity parameter set to a value much greater than the normal conductivity of copper ensures the conductor is lossless for the simulation
Simulation Correlation Results

Excellent correlation!
Model Comparisons

\[ K_{HJ} = \frac{P_{\text{rough}}}{P_{\text{flat}}} = 1 + \frac{2}{\pi} \arctan \left( 1.4 \left( \frac{\Delta}{\delta} \right)^2 \right) \]

\[ K_{HJM} = \frac{P_{\text{rough}}}{P_{\text{flat}}} = 1 + \frac{2}{\pi} \arctan \left( 1.4 \left( \frac{\Delta}{\delta} \right)^2 \right) \times (SF - 1) \]

Tuned SF=1.65

\[ K_{HCPES} (f) \approx \frac{P_{\text{rough}}}{P_{\text{flat}}} \approx 1 + 66 \left( \frac{\pi v^2}{A_{\text{Hex}}} \right) \left( 1 + \frac{\delta(f)}{r} + \frac{\delta^2(f)}{2r^2} \right) \]
Correction Factor Comparisons ($R_a = 1.44 \mu m; R_z = 2.5 \mu m$)
Summary and Conclusions

1. Using the concept of hexagonal close-packing of equal spheres, a novel method to accurately calculate sphere size and hexagonal tile area was devised for use in the Huray model.

2. By using published roughness parameters and dielectric properties from manufacturers’ data sheets, we show the need for further SEM analysis or experimental curve fitting, may no longer be required for preliminary design and analysis.

3. HCPES model looks promising as a practical alternative to previous modeling methods.
Ongoing Research

Test the HCPES model to see how well this method applies to other material and copper roughness
References


Thank You!