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Dk & Df ALGEBRAIC MODEL v2.05

(NOTE: changes from v2.04 revolve around adding 1 connector application/functionality and extending to 30G)

Let’s take a look…

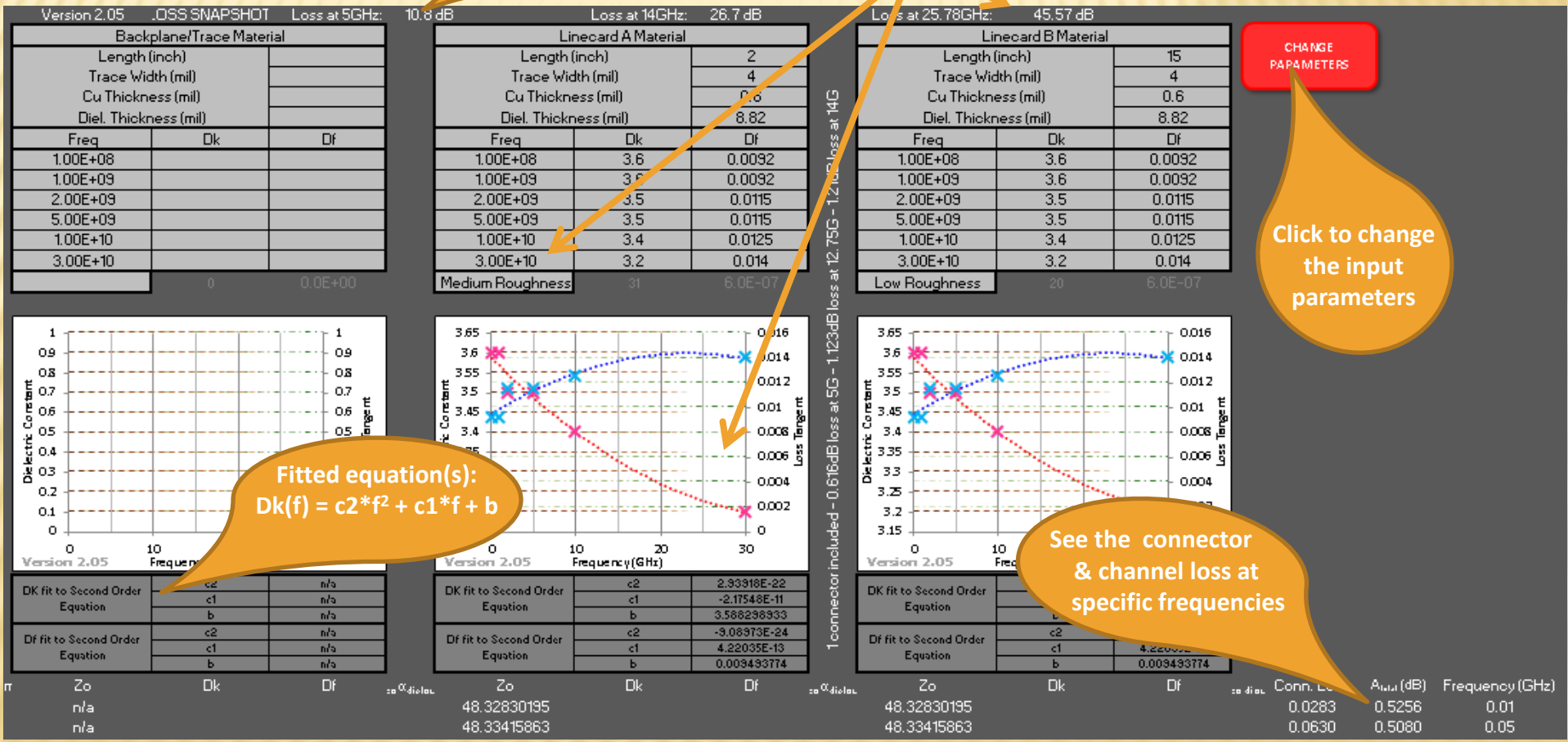
WHAT YOU WILL SEE

NOTE: The Change Parameter window is a visual basic macro. If you save the file to your computer, be sure to select the Maco-Enabled file type.

LOOK & FEEL

v2.05: Graphs, loss snapshot, and material entries now go to 30G

Quick preview of select frequencies



NOTE: The Change Parameter window is a visual basic macro. If you are having issues opening this window, consider Microsoft button > Excel Options > Trust Center > Trust Center Settings > Macro Settings

LOOK & FEEL

Enter Parameters for the Material

Setup | Backplane | Line Card

Trace Only, no connectors

Backplane w/ 2 Connectors, 1 material

Backplane w/ 2 Connectors, different materials

Linecard w/ 1 Connector

You have 4 input options; Feel free to return and select a different option if you change your mind.

Here's what you'll see...

Enter Parameters for the Material

Setup | Backplane | Line Card

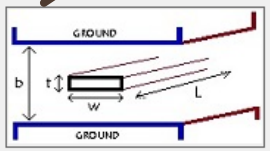
All fields must be completed.
Backplane/Trace Material:

	Dk (real)	Df
100M	3.67	0.0039
1G	3.65	0.004
2G	3.59	0.0043
5G	3.576	0.0049
10G	3.3494	0.0055
20G	3	0.0065

Want to auto-fill? Meg6 | -13SI | Imp FR4

Copy Mat. to Linecard

CU Roughness: Low Med High



If applicable, the same b, L, w and t format is used for linecard material entries

b, Dielectric Thickness (mils): 16 w, Trace Width (mils):

L, Trace Length (inches): 20 t, Cu Thickness (mils):

Include 2 connectors

Since you selected Trace Only, please select OK to get your loss calculations.

OK Clear

Enter Parameters for the Material

Line Card

All fields must be completed.
Line/Daughter Card #1 Material:

	Dk (real)	Df
	3.6	0.0092
	3.6	0.0092
	3.5	0.0115
	3.5	0.0115
	3.4	0.0125
	3.2	0.014

Want to auto-fill? Meg6 | -13SI | Imp FR4

ughness: Low Med High

ness (mils): 12.9 w, Trace Width (mils): 6

h (inches): 2 t, Cu Thickness (mils): 0.6

Enter Parameters for the Material

Setup | Backplane | Line Card

All fields must be completed.
Line/Daughter Card A Material:

	Dk (real)	Df
100M	3.6	0.0092
1G	3.6	0.0092
2G	3.5	0.0115
5G	3.5	0.0115
10G	3.4	0.0125
30G	3.2	0.014

Want to auto-fill? Meg6 | -13SI | Imp FR4

CU Roughness: Low Med High

b, Dielectric Thickness (mils): 8.82 w, Trace Width (mils): 4

L, Trace Length (inches): 2 t, Cu Thickness (mils): 0.6

Line/Daughter Card B Material:

Use same as LC #1

	Dk (real)	Df
100M	3.6	0.0092
1G	3.6	0.0092
2G	3.5	0.0115
5G	3.5	0.0115
10G	3.4	0.0125
30G	3.2	0.014

Want to auto-fill? Meg6 | -13SI | Imp FR4

CU Roughness: Low Med High

b, Dielectric Thickness (mils): 8.82 w, Trace Width (mils): 4

L, Trace Length (inches): 15 t, Cu Thickness (mils): 0.6

OK Clear

v2.05: added "Linecard w/ 1 Connector"

LOOK & FEEL

Enter Parameters for the Material

Setup | Backplane | Line Card

1) Select your configuration

Single Trace Only

Backplane w/ 2 Connectors, 1 Material

Backplane w/ 2 Connectors, Different Mate

Enter Parameters for the Material

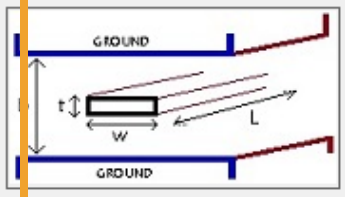
Setup | Backplane

All fields must be completed. Material: | Trace | Want to auto-fill?

	Dk (real)	Df	
100M	3.6	0.0092	Meg6
1G	3.6	0.0092	-13SI
2G	3.5	0.0115	Imp FR4
5G	3.5	0.0115	Copy Mat. to
10G	3.4	0.0125	
30G	3.2	0.014	

CU Roughness: Low | Med | High

2) Enter material & parameters



If applicable, the same b, L, w, and t format is used for linecard material entries.

b, Dielectric Thickness (mils): 16 | w, Trace Width (mils): 8

L, Trace Length (inches): 1 | t, Cu Thickness (mils): 0.6

Since you selected Trace Only, please select OK to get your loss calculations.

OK | Clear

Enter Parameters for the Material

Setup | Input

All fields must be completed. Material Definition (w, b, t, & L specific to each card): | Want to auto-fill?

	Dk (real)	Df	
100M	3.6	0.0092	Meg6
1G	3.6	0.0092	-13SI
2G	3.5	0.0115	Imp FR4
5G	3.5	0.0115	
10G	3.4	0.0125	
30G	3.2	0.014	

CU Roughness: Low | Med | High

Backplane Design:

b, Dielectric Thickness (mils): 16 | w, Trace Width (mils): 8

L, Trace Length (inches): 1 | t, Cu Thickness (mils): 0.6

Include 2 connectors

Line Card A Design:

b, Dielectric Thickness (mils): | w, Trace Width (mils):

L, Trace Length (inches): 0 | t, Cu Thickness (mils):

Line Card B Design:

b, Dielectric Thickness (mils): | w, Trace Width (mils):

L, Trace Length (inches): 0 | t, Cu Thickness (mils):

3) Must have all entries filled in, then click OK

OK | Clear

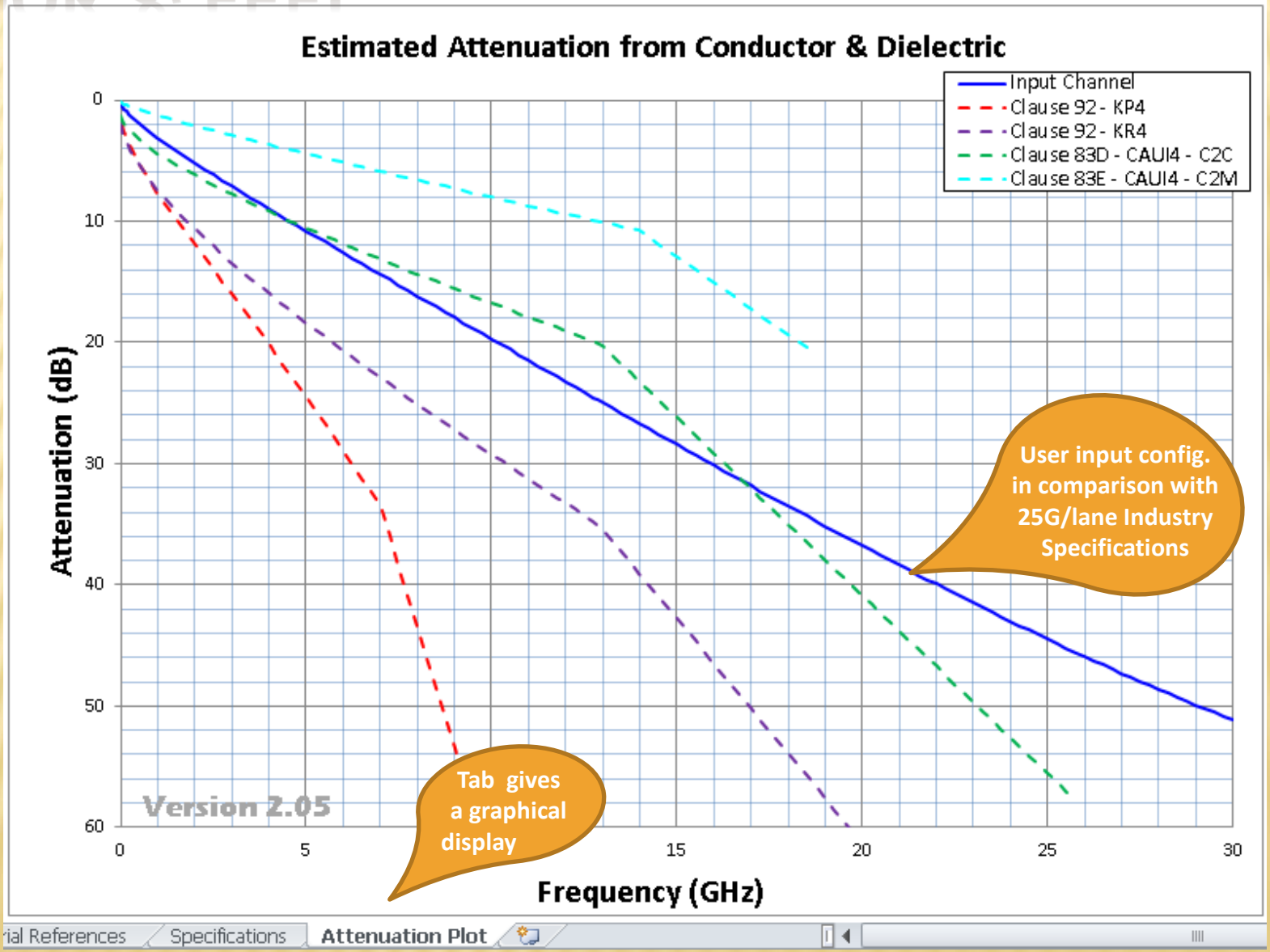
Frequency (GHz) 10 15 20

c2	3.64774E-23
c1	-2.02392E-11
b	3.591963577
c2	-1.15209E-23
c1	4.54439E-13
b	0.009448676

v2.05: changed 6th frequency point from 20G to 30G

v2.05: removed 10G KR curve… added 100G generation curves: C2C, C2M, KR4, and KP4

LOOK & FEEL



Behind the Scenes…

EQUATIONS AND REFERENCES OF MODEL

FREQUENCY DEPENDENCE

Unchanged from v2.01

- 6 input frequency points for Dk and Df
- Fit Dk and Df to second order equations
  - Coefficients shown on sheet
  - Graphical representation shown on sheet
- Note that frequency dependence fit is only approximated to 20G, therefore, loss approximations should only be considered to 20G
- Z_0 is calculated with Dk (or ε_r) at a given frequency; a similar technique is used in loss calculations

DK & DF SECOND ORDER EQUATIONS

Unchanged from v2.01

- Second order approximation is created using the LINEST function. This function essentially fits a 2nd order polynomial to the 6 frequency points given; resulting in

$$D_k = c_2 * f^2 + c_1 * f + b$$

- Function as implemented in the spreadsheet:

LINEST(C8:C13,B8:B13^[1,2])

Y Values (Dk entered points)

X Values (Freq. associated w/ entered points)

Exponents of X; Creating a second order equation.

- See Excel HELP for more details on LINEST function. Methodology verified against "add trend line" within plot.

CHARACTERISTIC IMPEDANCE[2, EQU 4-5]

$$Z_0 = \frac{94.15}{\sqrt{\varepsilon_r}\left(\frac{\frac{w}{b}}{\frac{1-t}{b}} + \frac{c_f^{'}}{0.0885\varepsilon_r}\right)} \; ohms$$

$$c_f^{'} = \frac{0.0885\varepsilon_r}{\pi}\left\{\frac{2}{1-\frac{t}{b}}\log_e\left(\frac{1}{1-\frac{t}{b}}+1\right) - \left(\frac{1}{1-\frac{t}{b}}-1\right)\log_e\left(\frac{1}{\left(1-\frac{t}{b}\right)^2}-1\right)\right\}$$

ε_r = relative dielectric constant (at a given frequency)

b = plate spacing (mil)

w = trace width (mil)

t = trace thickness (mil)

$c_f^{'}$ = fringing capacitance (μf/cm) * assuming semi - infinite plate between two infinite ground planes, but good approximation for w/(b - t) ≥ 0.35

Unchanged from v1.01

ATTENUATION IN LOSSY LINES

Unchanged from v1.01

- Attenuation per length[1, EQN 9-54]:

$$\alpha_n = \sqrt{\frac{1}{2}\left[\sqrt{\left(R_L^2 + \omega^2 L_L^2\right)\left(G_L^2 + \omega^2 C_L^2\right)} - \omega^2 L_L C_L + R_L G_L\right]} \text{ nepers/length}$$

- Using a low-loss approximation[1, EQN 9-55]: (surface roughness ignored)

$$\alpha_n = \frac{1}{2}\left(\frac{R_L}{Z_0} + G_L Z_0\right) \text{ nepers/length}$$

- But we don't typically discuss in nepers…[1, EQN 9-57]

$$10^{\frac{\alpha_{dB}}{20}} = e^{\alpha_n} \qquad \therefore \alpha_{dB} = 20\log_{10} e \times \alpha_n$$

$$\text{for ease of notation: } Y_{n\to dB} = 20\log_{10} e$$

CONDUCTOR LOSS (per inch)

Unchanged from v2.01

$$\alpha_{cond} = \left(Y_{n\rightarrow dB}\right) \times \frac{R_L}{Z_0}$$

α_{cond} = attenuation of amplitude due to conductor loss, in dB/length [1, EQN 9-59]

$Y_{n\rightarrow dB}$ = conversion from nepers to dB

R_L = resistance per length of conductor

Z_0 = characteristic impedance

- Skin effect, ground resistance, and stripline effect are accounted for in resistance[3, EQNs 4.3a-4.10]:
  - R of signal trace & return path (w/skin effect)

$$R_{signal Cu\ skin\ effect} = \frac{\sqrt{\pi\mu\rho f}}{w} \qquad R_{ground Cu\ skin\ effect} = \frac{\sqrt{\pi\mu\rho f}}{6H}$$

  - AC surface resistance for microstrip (or 1 side of a stripline trace)

$$R_{ac\ microstrip} = R_{signal} + R_{ground}$$

CONDUCTOR LOSS (per inch)

Unchanged from v2.02

- Stripline approximation assumes parallel resistance of top and bottom microstrip approximations

$$R_L = \frac{\left[\sqrt{\pi\mu\rho f} * \left(\frac{1}{w} + \frac{1}{6H}\right)\right]^2}{2 * \left[\sqrt{\pi\mu\rho f} * \left(\frac{1}{w} + \frac{1}{6H}\right)\right]}$$

$$\begin{cases} R_L = \text{stripline surface resistance } (\Omega/\text{inch}) \\ w = \text{width of trace (inch)} \\ H = \text{height dielectric from ground to signal (inch)} \\ \mu = \text{permeability of Cu} \approx 4\pi \times 10^{-7} \times 0.999994 \ \frac{\text{H}}{\text{m}} \\ \rho = \text{resistivity of Cu} = \frac{1}{\sigma} = \frac{1}{5.96 \times 10^7} \ \Omega\,\text{m} \\ f = \text{frequency (hertz)} \end{cases}$$

- Conductor loss per inch as entered in the model:

$$\alpha_{cond} = \frac{1}{2} \times (20 \log_{10} e) \times \left(\frac{\left[\sqrt{\pi\mu\rho f} * \left(\frac{1}{w} + \frac{1}{6H}\right)\right]}{2} \right) \times \frac{1}{Z_0}$$

DIELECTRIC LOSS (per inch)

$$\alpha_{diel} = \left(Y_{n\to dB}\right) \times G_L Z_0$$

α_{cond} = attenuation of amplitude due to dielectric loss, in dB/length [1, EQN 9-60]

$Y_{n\to dB}$ = converstion from nepers to dB

G_L = shunt conductance per length from dielectric

Z_0 = characteristic impedance

Unchanged from v1.01

- As developed by Bogatin…

$$G_L = \omega \tan(\delta) C_L$$

$$Z_0 = \frac{\sqrt{\varepsilon_r}}{cC_L}$$

G_L equation [1, EQN 9-19, EQN 9-60]

Z_0 equation [1, EQN 9-67] is used to cancel the capacitance value, the Z_0 value for a given frequency is NOT used

c = speed of light m/s $\therefore$ converstion m $\to$ in. is needed

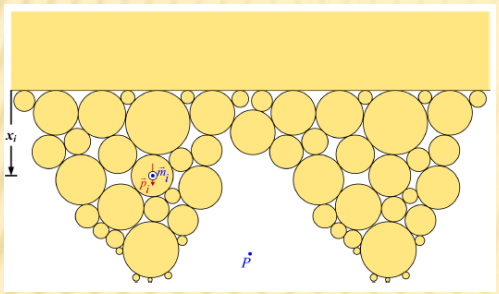
- Dielectric loss per inch as entered in the model:

$$\alpha_{diel} = \frac{1}{2} \times \left(20 \log_{10} e\right) \times \left(2\pi f \times D_f\right) \times \frac{\sqrt{\varepsilon_r}}{299792458 * 39.37}$$

v2.04: Correction made to σ (was 5.69e7 instead of 5.96e7) affecting δ which, in turn, impacted $k_{snowball}$, and thus total loss.

SURFACE ROUGHNESS (multiplier)

- Through the snowball method (Huray Model[4, CHAP 6]), surface roughness is approximated as a collection of smaller spheres. *Note image shows non-uniform "snowballs"… model approximates using uniform spheres.



- Applied to trace: $\alpha_{total} = \alpha_{diel} + k_{snowball}\alpha_{cond(smooth)}$
- Surface roughness multiplier as entered in the model:

$$k_{snowball} \approx 1 + \frac{3}{2}\sum_{i=1}^{j} \frac{\left(\frac{N_i 4\pi a_i^2}{A_{flat}}\right)}{\left(1 + \frac{\delta}{a_i} + \frac{\delta^2}{2a_i^2}\right)}$$

a_i = radius of spheres (m)

N_i = number of snowballs of size a_i per A_{flat}

A_{flat} = total area containing stacked snowballs

δ = skin depth (m) …. recall: $\delta = \frac{1}{\sqrt{\pi\mu\sigma f}}$

CONNECTOR LOSS & CHANNEL LOSS

- Attempting to base on 25G technology connectors
- Used connector models from multiple vendors to draw this max* connector loss… used in model:

$$IL_{conn} = 9*10^{-6}*\sqrt{f} - 1.2*10^{-12}*f + 1.6*10^{-21} f^2$$

* Max loss when ignoring majority of ILD. Idea was to create equation that production connectors can beat. Note that this creates additional error in comparing model to measured, however, model should error in pessimistic direction. Connector implementation likely to be changed in future versions.

- Equation gives loss of: 0.6164dB @5G; 1.133dB @12.89G; 1.21dB @14G

- OVERALL CHANNEL LOSS EQUATION: (simple enough, right?)

$$A_{total} = a_{LCA\_total} * L_{LCA} + IL_{conn} + a_{BP\_total} * L_{BP} + IL_{conn} + L_{LCB\_total} * L_{LCB}$$

Unchanged from v2.01

REFERENCES

Unchanged from v2.01

[1] E. Bogatin. *Signal Integrity – Simplified*. Pearson Education, Inc., 2004. ISBN 0-13-066946-6.

[2] S. B. Cohn. “Problems in Strop Transmission Lines.” *IRE Trans. Microwave Theory and Techniques*, Vol. MTT-3, March, 1955, pp 119-126.

[3] S. H. Hall, G.W.Hall, J. A. McCall. High-Speed Digital System Design: A Handbook of Interconnect Theory and Design Practices. John Wiley & Sons, Inc., 2000. ISBN-10 0471360902.

[4] P. G. Huray. The Foundations of Signal Integrity. John Wiley & Sons, Inc., 2010. ISBN-978-0-470-34360-9

TRACKING THE CHANGES

Version	Change
1.01	9/26/2011 – Initial release – second order Dk & Df approximation, track user input channel along with Meg-6 & Improved FR-4 for given length/width/thickness, 3 materials compared to KR limit line.
2.01	12/15/2011 – surface resistance updated to include return path resistance and stripline approximation, Huray model for surface roughness added, “worst-case” connector added, partitioning option added (backplane w/2 daughter cards), KR limit comparison made to attenuation max (instead of IL)
2.02 (a)	1/9/2012 – correction of error found in final multiplication/addition (A_{total})
2.03	2/1/2012 – correction of error found in surface roughness multiplier ($K_{snowball}$) for line cards (matched equation given in the explanation slides), GUI clarified for “Backplane w/ 2 connectors, same material”.
2.05	9/5/2014 - changed 20G entry to 30G for Dk/Df input to give more control to entire curve; Dk second order equation approximation, ignores 100M point to help avoid deep quadratic curve; added functionality of 2 linecard/daughter cards with 1 connector (used same connector loss curve), -13SI, 1G Df changed to 0.0105 (is more realistic, .0115 might have been a typo); changed standard/specification curves to 25G/lane generation; expanded loss equations and plots to 30G