Unified approach to interconnect conductor surface roughness modelling

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***Abstract*—Commonalities of five conductor roughness models are analysed and unified form of roughness correction coefficient (RCC) is suggested in the paper. It is shown that Hammerstad, Huray, Groiss, Hemispherical and Bushminskiy roughness correction coefficients can be written in the following unified form K=1+(RF-1)*F(SR), where RF is roughness factor that has meaning of maximal possible increase of losses with frequency due to the conductor roughness. F is a frequency-dependent function describing transition from zero at lower frequencies to one at higher frequencies (roughness transition function). It is shown that the unified RCC can be used in multi-level additive form for surfaces with two or more dominant discontinuity sizes or in multi-level multiplicative form for surfaces with fractal type discontinuities. Measurements on a test board are used to identify and compare all five RCCs.**

I. Introduction

During the manufacturing of laminates and printed circuit boards (PCBs) copper foil is treated, to increase surface roughness and improve adhesion to dielectrics and avoid delamination. At the same time, the copper roughness can substantially increase signal losses in interconnects [1]. Electrical modeling of conductor roughness is important for accurate prediction of signal degradation effects.

The effect of roughness is the subject of ongoing research – overview can be found in [2], [3]. Direct electromagnetic analysis of rough copper surface is simply out of question. The rough surface can be simulated with an "effective" material layer [4]. There is less uncertainty in the conductor to dielectric boundary definition in this approach – the boundary is replaced with a transitional layer with "effective" properties. On the other hand, the model has too many parameters that are not readily available and is difficult to identify [5]. More practical approach for the roughness modelling is based on the estimation of increase in attenuation with the frequency due to conductor surface roughness expressed as a roughness correction coefficient (RCC). It is usually a formula with one or more parameters in addition to frequency. With a static or quasi-static field solver used for the analysis of t-line cross-section, RCC can be applied to the internal impedance part of the total p.u.l. impedance of the transmission line [1], [2]. More accurate approach is to apply RCC to the conductor interior impedance operator as suggested in [2], [3] – such model properly accounts for the surface current distribution and allows different roughness model parameters on different surfaces of the same conductor.

The first roughness correction coefficient was suggested by Hammerstad and Jensen in [6] (Hammerstad model). It was derived for conductor surface with 60-degree triangular bumps and because of that has limit on the expected growth of attenuation. To overcome this limit, modified Hammerstad RCC with two parameters was recently introduced in [2] (formula in [2] has typo that is corrected in [3]). Another RCC is derived from solution for plane wave diffraction on a conductive hemisphere [7] (Hemispherical model). Estimate of the power loss on multiple conductive spheres was used in [8] to derive equation known as the Huray snowball model. Causal version of Huray model was suggested in [13]. Measurement of the quality factor of the cavity resonators is used in [9] to obtain another formula for RCC with one parameter known as the Groiss model. Less known two-parameter RCC was derived in [10] from measurement of attenuation in microstrip lines (Bushminskiy model). Power spectral density of the rough surface can be also used to compute the power absorption enhancement function [14] that can be used for roughness modeling similar to RCC.

In this paper we express five commonly used RCCs in the same unified form, to simplify the description and identification and to show possible existing models extensions that follow from the unification.

II. Unified Roughness Correction Coefficient

Five roughness correction coefficients (RCC) discussed in the introduction section can be expressed in the following unified form:

$$K_{ri} = 1 + \left(RF_i - 1\right) \cdot F\left(SR_i, \delta_s\right) \tag{1}$$

In general, it describes multiplicative increase of conductor absorption with frequency as a transition from 1 at lower frequencies (or zero frequency) to maximal value defined by the roughness factor parameter *RF*. *RF* can be greater than or equal to 1. Function *F* describes transition from zero at low frequencies to the unit at high frequencies. Parameter *SR* is a size of a surface model basic element – bump size or ball radius. δ_s is skin depth defined as follows:

$$\delta_s = \left(\pi \cdot f \cdot \mu \cdot \sigma\right)^{-1/2} \tag{2}$$

Metric parameter *SR* defines onset frequency of skin-effect on a rough surface. Index *i* in (1) and other formulas designates the level discussed in the multi-level model section.

The roughness transition function *F* for the modified Hammerstad model [2], [3] can be expressed as follows:

$$F_h\left(\Delta_i, \delta_s\right) = \frac{2}{\pi} \cdot \arctan\left[1.4\left(\frac{\Delta_i}{\delta_s}\right)^2\right] \tag{3}$$

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Parameter Δ_i is a roughness bump size and usually defined as the root mean square of the peak-to-valley distance on the rough surface. Though, it may be simply treated as a fitting parameter that defines frequency of the onset of the skin-effect on a rough surface. Use of (3) and setting *RF=2* in (1) produces regular Hammerstad-Jensen model with the RCC limited by 2 [6]. With the roughness factor parameter *RF* in (1) and *Fh* defined as (3) the model is known as the modified Hammerstad RCC [2], [3].

The roughness transition function for Huray snowball model [8] can be expressed as follows:

$$F_{hur}\left(r_i,\delta_s\right)=\left(1+\frac{\delta_s}{r_i}+\frac{\delta_s^2}{2r_i^2}\right)^{-1} \tag{4}$$

The first parameter r_i is the ball radius in this case. As in the case of the Hammerstad model, it can be simply a parameter that approximately defines onset frequency of the absorption growth due to the conductor surface roughness. With the transition function (4), the roughness factor in formula (1) is related to the original Huray snowball model as follows (see definition of the parameters in [8]):

$$RF_i=1+\frac{3}{2}\frac{N_i\cdot 4\pi\cdot r_i^2}{A_{hex}} \tag{5}$$

The roughness factor can be also computed from or converted to the Hall-Huray surface ratio (*sr*) with the following formulas:

$$RF_i=1+\frac{3}{2}\cdot sr_i;\ \ sr_i=\frac{2}{3}\cdot\left(RF_i-1\right)$$

Huray model was modified in [13] to make it complex and causal as follows (Huray-Bracken model):

$$F_{hur}\left(r_i,\delta_s\right)=\left(1+\left(1-j\right)\frac{\delta_s}{2r_i}\right)^{-1} \tag{6}$$

Formula (6) produces exactly the same increase in the losses as the original Huray model (4) when substituted into (1). However, it predicts larger growth of the internal inductance.

The roughness transition function for the Groiss model [9] can be expressed as follows:

$$F_g\left(\Delta_i,\delta_s\right)=\exp\left[-\left(\frac{\delta_s}{2\cdot\Delta_i}\right)^{1.6}\right] \tag{7}$$

Parameter Δ_i has the same meaning as in the modified Hammerstad model (3). Also similar to the Hammerstad model, use of roughness function (7) in (1) and setting *RF*=2 produces Groiss model suggested in [9] exactly. The RCC is limited by 2 in this case. The model (1) with roughness function defined by (7) with arbitrary *RF* parameter can be called modified Groiss RCC, similar to the modified Hammerstad RCC. As the modified Hammerstad, the modified Groiss model has two parameters that give it more flexibility for the PCB and packaging interconnect problems.

The roughness transition function for hemispherical model [7] can be expressed as follows:

$$F_{hs}\left(r_i,\delta_s\right)=\frac{2}{\pi^2 r_i^2\mu f\delta_s}\cdot\left|\mathrm{Re}\left[\eta\frac{3\pi}{4k^2}\left(\alpha(1)+\beta(1)\right)\right]\right|-\frac{1}{2}$$

$$F_{hs}\left(r_i,\delta_s\right)=\begin{vmatrix}0\ if\ F_{hs}\left(r_i,\delta_s\right)<0\\ F_{hs}\left(r_i,\delta_s\right)\ otherwise\end{vmatrix} \tag{8}$$

All parameters of formula (8) are defined exactly in the original model [7]. In particular, parameter r_i is the hemisphere radius that can be simply treated as a parameter that defines the onset of skin-effect on the rough surface. With the hemispherical transition function, the roughness factor in formula (1) is related to parameters in the original hemispherical model [7] as follows:

$$RF_i=1+2\pi\cdot r_i^2\big/Atile_i \tag{9}$$

Unlike all other four RCCs, the hemispherical RCC is not a smooth function of frequency and the RCC grows above *RF* at very high frequencies when the formula assumptions become not valid (well above of PCB interconnect bandwidth of interest). The maximal value of the roughness factor is also limited by $1+\pi/2$ due to the limit on the hemisphere size relative to the tile size. Though, this limit is usually not enforced and the model is used as the fitting formula.

Another roughness correction coefficient was obtained in [10] by fitting experimental data for microstrip lines with the hyperbolic tangent function (Bushminskiy model). It was uses in Simbeor software since 2008 and also known as Simbeor original model. The transition function for Bushminskiy model can be expressed as follows:

$$F_{so}\left(\Delta_i,\delta_s\right)=\tanh\left[\frac{\Delta_i}{1.8\cdot\delta_s}\right] \tag{10}$$

Parameter Δ_i has the same meaning as in the modified Hammerstad model (3).

The transition functions for all RCCs are compared in Fig. 1.

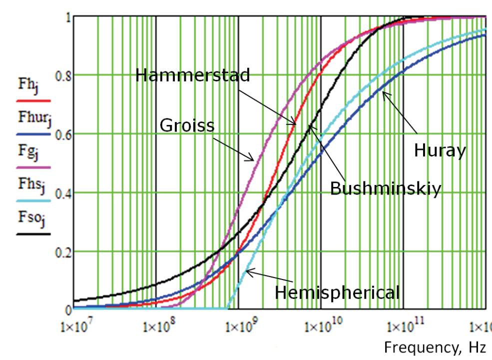

Fig. 1. Comparison of the roughness transition functions: $\Delta=1\mu$ for Bushminskiy, Hammerstad and Groiss models, $r=1\mu$ for Huray snowball and $r=2\mu$ for Hemispherical models.

III. Multi-Level Extensions of RCC

The unified RCC (1) can be further generalized for two types of the surfaces. If surface contains two levels of the discontinuities as shown in Fig. 2 (top), the overall RCC can be expressed in the additive form as follows:

$$K_{ar}=1+\sum_i\left(RF_i-1\right)\cdot F\left(SR_i,\delta_s\right) \tag{11}$$

If the conductor surface has fractal-type structure as shown in Fig. 2 (bottom), the overall RCC can be expressed in the multiplicative form as follows:

$$K_{mr} = \prod_i \left[1 + \left(RF_i - 1 \right) \cdot F\left(SR_i, \delta_s \right) \right] \qquad (12)$$

Note that use of the products of some RCCs for multi-level surfaces was first suggested in [11] and sum was used in [8]. Any roughness transition function (3), (4), (6), (7), (8), (10) or mixture of different functions F can be used in either additive (11) or multiplicative (12) form (depends on dominant shapes for each level).

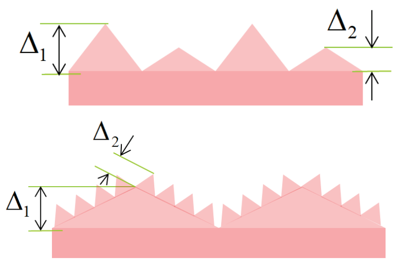

Fig. 2. Example of surface with two levels of triangular bumps at the same base level (top, additive absorption) and fractal-type surface with two levels of triangular bumps (bottom, multiplicative absorption).

IV. Identification Example

To compare different RCCs or roughness transition functions, we identify the roughness model parameters with the measured S-parameters provided by Wild River Technology for CMP-28 channel modelling platform made with Isola FR-408HR dielectric and VLP copper. GMS-parameters of strip line segment are used for the model identification [12]. First, conductor is set to smooth and dielectric model was identified as the Wideband Debye model [12] by matching modelled and measured GMS transmission phase delay from 10 MHz to 35 GHz and GMS insertion loss (IL) from 10 MHz to 3 GHz. The dielectric model parameters are Dk=3.81 and LT=0.0011 @ 1 GHz, that is close to the published by the manufacturer. Next, the conductor roughness model parameters are identified by matching GMS IL from 3 GHz to 35 GHz. *RF* and *SR* parameters for all five identified models are shown in Table 1. Minimization of RMS error with pattern search algorithm in Simbeor software was used to identify all roughness models. The maximal per inch deviations of the measured and computed GMS-parameters at frequencies from 10 MHz to 35 GHz are also shown in the Table 1. MHRCC stands for modified Hammerstad model – equations (1) and (3); HRCC is for Huray model – equations (1) and (4); MGRCC is for the modified Groiss model – equations (1) and (7); HSRCC is for Hemispherical RCC – equations (1) and (8); and BRCC is for the Bushminskiy model – equations (1) and (10). All roughness models are 1-level. The best accuracy in this particular case was achieved with the modified Groiss model (MGRCC). Addition of another level to all models decreases the magnitude error about 2 times. The phase delay is practically not affected by the real RCCs. Note that if causal model (6) is used, the identified Dk of dielectric model becomes smaller.

V. Conclusion

Commonality of five roughness models have been analysed and a unified RCC formula with 2 parameters per roughness level has been suggested. It simplifies the process of the roughness parameters description and identification. It is shown that the unified RCC can be used in multi-level additive form for surfaces with two or more dominant discontinuity sizes or in multi-level multiplicative form for surfaces with fractal type discontinuities. Use of five RCCs has been illustrated with a practical PCB interconnect example.

Table 1. Parameters for five RCCs identified for CMP-28 platform and maximal per inch difference of measured and modelled GMS-parameters magnitude and phase delay (10 MHz to 35 GHz).

RCC	RF	SR, um	Max |S| diff. per inch	Max PD diff. per inch, ps
MHRCC	2.595	0.313	1.52e-3	0.238
HRCC	7.846	0.123	1.78e-3	0.239
MGRCC	2.759	0.216	1.23e-3	0.238
HSRCC	3.97	0.563	2.73e-3	0.255
BRCC	2.40	0.362	2.9e-3	0.221

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