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ANALYTICAL DELAY METRIC FOR ON-CHIP RLCG INTERCONNECT FOR GENERALISED INPUT

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ABSTRACT

In this paper we have put forward an analytical model, which could accurately capture the on chip interconnect delay. As we move onto higher frequency range, of the order of GHz, the effects of shunt conductance cannot be ignored, as it provides a measure of the possible leakage. Due to this reason, we have derived our on-chip interconnect delay metric considering distributed RLCG segments, rather than sticking to the conventional RLC and RC. We develop a novel analytical model based on the first few moments of the interconnect transfer function when the input is generalised signal. Delay estimate using our first moment based analytical model is within 3% of SPICE-computed delay, and model based on first two moments is within 2% of SPICE, across a wide range of interconnects parameter values.

Keywords: Delay Calculation; RLCG Interconnect; Moment Matching; Generalised Input;

I. INTRODUCTION

Modelling of on chip interconnects using transmission line theory has received a great and increasing interest over the last couple of decades and is still a challenging problem. One of the holy grails of design is to achieve timing closure in a single pass of design simply put, this implies that the design should meet its specifications without iteration. Developing accurate methods for timing is, therefore, a vital part of ensuring fast timing closure in interconnects [1-2] as the interconnect delay are playing more important than the gate delay. Hence, it is desirable to derive accurate and effective delay estimation electrical models for interconnects .Elmore delay is widely used but it do not consider the rise time of the signals. The behaviour of the on-chip interconnect may be modelled using resistor, capacitor and inductor , either as lumped or distributed models depending on the need of frequency and type of input signal. At relatively lower frequency, interconnect may be modeled as distributed RC segments [3-4]. At extremely higher frequencies inductance play a role in calculation of interconnect delay to account for effect such as undershoot, overshoot and ringing, the interconnect is modeled as distributed RLC network [5-6] and the correctness in performance estimation of interconnect eventually got improved. . Resistance (due to the skin effect) and conductance (due to dielectric absorption) are in fact dependent on the frequency. Both effects result in increased attenuation at higher frequencies thus the effect of G at higher frequency cannot be ignored in many practical situations especially in the very high frequency domain used in the present VLSI design [7].

Now it is necessary to consider the effect of inductance and conductance & to prepare a model by taking this frequency of operation. So, many works are done for the delay estimation using RLCG modeling of interconnects, but all these consider the input either as ramp or step[8-13].We want to generalize our input so we take input as generalised (exp x^n) but to the best of our knowledge there is no such analytical explicit delay estimation models proposed which is based on the first few central moments for generalised input.

We have proposed an analytical model for the delay estimation taking generalised input for the on-chip interconnect for different high frequency mode of operations considering the conductance (G) effect.

II.BASIC THEORY

For a simple input source terminated transmission line we can write the transfer function as:

$$H(s) = \frac{V_O(s)}{V_i(s)} = \frac{1}{sCt(R_s\cosh(\gamma d) + Z_o\sinh(\gamma d)) + (R_s/Z_o)\sinh(\gamma d) + \cosh(\gamma d)} \quad (1)$$

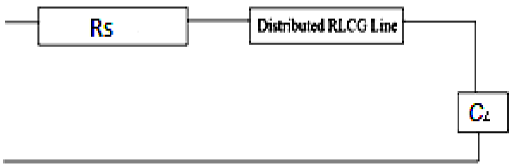

Figure1: Two-Port model of a distributed RLCG line with resistive and inductive source impedance and capacitive load impedance

where $\gamma = \sqrt{(R+sL)(G+sC)}$ is the propagation constant and $Z_o = \sqrt{(R+sL)/(G+sC)}$ is the characteristic impedance of the line. R, L, C and G are the per-unit-length resistance, inductance, and capacitance of the transmission line, respectively. *d* is the length of the line. The series resistance is given by, $R_s = R_{dr} + R_{ter}$ where R_{dr} is the driver resistance and R_{ter} the additional termination resistance. We assume that at the given frequency of interest, the dielectric loss and conductance values are negligibly small. The driver resistance is assumed to be linear. Now the RLCG interconnect can be considered as either lossless or lossy.

II.1 Lossy Interconnect

For a Lossy transmission line shown in Figure 1, the central moments are given by following equation

$$\left.\begin{aligned} \mu_2 &= \frac{a_1 + b_1 + c_1 + d_1}{\phi_1} \\ \mu_3 &= \frac{a_2 + b_2 + c_2 + d_2 + \kappa_2}{\phi_2} \end{aligned}\right\} \quad (2)$$

where

$$a_1 = R_S^3\left(17C^2G - 9RC^2G - C^3G\right)$$

$$b_1 = R_S^2\left(-\frac{58}{3}RC^2G - 3C^2 - 2RC^2\right)$$

$$c_1 = R_S\left(-\frac{4}{3}RC^2 - \frac{25}{3}CLG\right)$$

$$d_1 = -\left(LC + 3RLGC\right)$$

$$\phi_1 = \left(1 + \frac{9}{2}RG + 9R_SG\right)$$

$$a_2 = R_S^4\left(82C^3G + 66RC^3G\right)$$

$$b_2 = R_S^3\left(14C^3RG + 14C^3 + C^2RG + 6RC^3\right)$$

$$c_2 = R_S^2\left(4RC^3 - 25C^2GL + 21RC^2LG\right)$$

$$d_2 = R_S\left(-3LC^2 - 37RC^2LG + \frac{3}{2}RLC^2\right)$$

$$\kappa_2 = \left(-\frac{5}{2}RLC^2 - 3L^2GC\right)$$

$$\phi_2 = \left(1 + \frac{17}{2}RG + 17R_SG\right)$$

R, L,C and G are the per-unit-length resistance, inductance, and capacitance of the transmission line, respectively

II.2 Lossless Interconnect

For a transmission line without load and without loss driven by a step input, the optimal termination resistance is R_s=Z_0. With this termination, the output signal is delayed version of the input step, which is delayed by the time-of flight along the line, and is given by, $T_f = \sqrt{LC}d$. Minimizing the central moments the ideal impulse response can be still obtained . For the lossless line in Figure 2, the transfer function is given by [14-15],

$$H(s) = \frac{1}{(R_s/Z_o)\sinh(\gamma d) + \cosh(\gamma d)} \quad (3)$$

where γ and Z_0 are the propagation constant and the characteristic impedance, respectively and are defined as, $\gamma = s\sqrt{LC}$ and $Z_o = \sqrt{L/C}$. For the equation (3) the second and third central moments of the impulse response are symbolically given as follows:

$$\left.\begin{aligned} \mu_2 &= -CLd^2 - 3R_s{}^2C^2d^2 \\ \mu_3 &= -3R_sC^2Ld^3 + 14R_s{}^3C^3d^3 \end{aligned}\right\} \quad (4)$$

Above equations can be obtained by putting R=0 and G=0 in equation (2).

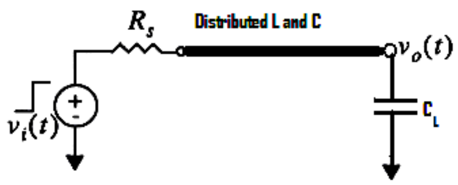

Figure 2: Lossless transmission line

Solving for $\mu_2 = 0$ from (4) yields $i\sqrt{L/3C}$ and $-i\sqrt{L/3C}$ as roots.

Again solving $\mu_3 = 0$ from (4) yields $0, \sqrt{3L/14C}$ and $-\sqrt{3L/14C}$ as roots.

R_s = Z_0, approximately is the solution considering positive root. Then, the transfer function given as,

$$H(s) = \frac{1}{\sinh(\gamma d) + \cosh(\gamma d)} = e^{-sT_f} \quad (5)$$

where $T_f = \sqrt{LC}d$ is the time of flight. Now the output of transmission line ideally is as follows

$$v_o(t) = v_i(t - T_f) \quad (6)$$

From (6), it can be inferred that the ideal impulse response for a lossless transmission line is symmetric and localized (zero dispersion) about its mean, $\mu = \sqrt{LC}d$. Conversely, forcing the impulse response to be symmetric and localized about the mean ensures critical damping.

So from (6) we can write the following equation:

$$V_o(s) = V_i(s)e^{-sT_f} \quad (7)$$

In case of generalised input,

$$v_i(t) = V_{DD}x^n(t) \quad (8)$$

$$v_i(s) = \frac{V_{DD}n!}{s^{-n-1}} \quad (9)$$

Substituting (9) in (7) we get,

$$V_i(s) = \frac{V_{DD}n!}{s^{-n-1}}e^{-sTf} \quad (10)$$

Taking inverse Laplace transform of (10)

$$V'o(t) = nV_{DD}(t - T_f)^n u(t - T_f) \quad (11)$$

For calculation of the time delay we take $V_0(s) = 0.5V_{DD}$ at time $t = T_D$ and hence substituting in (11) , we have,

$$0.5V_{DD} = nV_{DD}(T_D - T_f)^n u(t - T_f) \quad (12)$$

$$0.5 = n(T_D - T_f)^n \quad (13)$$

$$\frac{(0.5)^{1/n}}{n} = T_D - T_f \quad (14)$$

So for $t \geq T_f$ the T_D is given as,

$$T_D = T_f + \frac{(0.5)^{1/n}}{n} \quad (15)$$

The above equation (15) is our proposed closed form expression for delay for lossless transmission line RLCG interconnects system.

II.3 Lossless Interconnect Considering Mutual Inductance

In order to calculate the exact time delay in two parallel RLCG line, we consider the mutual inductance between two inductors as M. Figure 3, shows two highly coupled transmission line system.

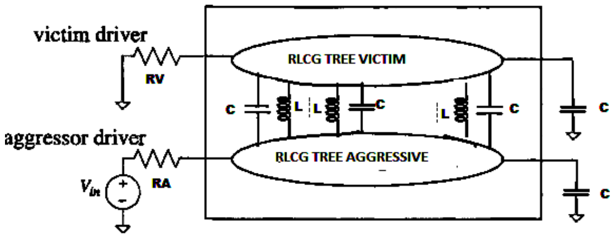

Figure 3: Highly coupled transmission line

1) Mutual Inductance

The mutual inductance of two coupled inductances L_1 and L_2 is given by

$$M = E_{2m} / \left(\frac{di_1}{dt}\right) \quad (16)$$

$$M = E_{1m} / \left(\frac{di_2}{dt}\right) \quad (17)$$

The mutually induced voltages E_{1m} and E_{2m}, then

$$M = \left(\frac{E_{2m}}{E_{1s}}\right) * L_1 \quad (18)$$

$$M = \left(\frac{E_{1m}}{E_{2s}}\right) * L_2 \quad (19)$$

Combining equations (18) and (19) we get,

$$M = \sqrt{\frac{E_{1m}E_{2m}}{E_{1s}E_{2s}}} * \sqrt{L_1L_2} = k_M (L_1L_2)^{1/2} \quad (20)$$

where k_M is the mutual coupling coefficient of the two inductances L_1 and L_2. If the coupling between the two inductances L_1 and L_2 is perfect, then the mutual inductance M is:

$$M = (L_1L_2)^{1/2} \quad (21)$$

III. PROPOSED DELAY MODEL

III.1 Calculation of Delay for Even Mode

From (1) and for a simple input source terminated transmission line, we can write the transfer function as,

$$\left.\begin{aligned} H(s) &= \frac{V_O(s)}{V_i(s)} \\ &= \frac{1}{sC_L(R_s\cosh(\gamma_e d) + Z_{oe}\sinh(\gamma_e d)) + (R_s/Z_{oe})\sinh(\gamma_e d) + \cosh(\gamma_e d)} \end{aligned}\right\} \quad (22)$$

where is the $\gamma_e = \sqrt{(R + s(L+M))(G + sC)}$ is the propagation constant for even mode and $Z_{oe} = \sqrt{(R + s(L+M))/(G + sC)}$ is the characteristic impedance for even mode of the line. R, L, M, C and G are the per-unit-length resistance, inductance, mutual inductance capacitance and conductance parameters of the transmission line, respectively, d is the length of the line. The series resistance is given by $R_s = R_{dr} + R_{ter}$ where R_{dr} is the driver resistance and R_{ter} the termination resistance. We assume that the dielectric loss and hence the conductance, G to be negligibly small. The driver resistance is assumed to be linear. For a no loss load free transmission line with a step input, the optimal termination resistance is $R_s=Z_{oe}$. The time of flight for the above termination , is given by

$$T_{fe} = \sqrt{(L+M)C}d \tag{23}$$

The following discussion shows that this ideal response is indeed obtained when the central moments of the impulse response are minimized. For the lossless line in Fig.2, the transfer function is given by,

$$H(s) = \frac{1}{(R_s / Z_{oe})\sinh(\gamma_e d) + \cosh(\gamma_e d)} \tag{24}$$

where $\gamma_e = s\sqrt{(L+M)C}$ and $Z_{oe} = \sqrt{(L+M)/C}$. For the equation (24) , the II and III central moments of the impulse response are given as follows:

$$\left.\begin{aligned} \mu_2 &= -C(L+M)d^2 - 3R_s^2C^2d^2 \\ \mu_3 &= -3R_sC^2(L+M)d^3 + 14R_s^3C^3d^3 \end{aligned}\right\} \tag{25}$$

Solving for $\mu_2 = 0$ from equation (25) yields $i\sqrt{(L+M)/3C}$ and $-i\sqrt{(L+M)/3C}$ as roots. Again solving $\mu_3 = 0$ from equation (25) yields 0, $\sqrt{3(L+M)/14C}$ and $-\sqrt{3(L+M)/14C}$ as roots. The positive root provides the solution $R_s = Z_{oe}$, approximately Then, the transfer function given as,

$$H(s) = \frac{1}{\sinh(\gamma_e d) + \cosh(\gamma_e d)} = e^{-sT_{fe}} \tag{26}$$

where, $T_{fe} = \sqrt{(L+M)C}d$ is the time of flight. Then it can be easily shown that this transfer function provides the output delayed by time of flight as:

$$v_o(t) = v_i(t - T_{fe}) \tag{27}$$

So from equation (27) we can write the following equation:

$$V_o(s) = V_i(s)e^{-sT_{fe}} \tag{28}$$

In case of generalised input

$$v_i(t) = V_{DD}x^n(t) \tag{29}$$

$$V_i(s) = \frac{V_{DD}n!}{s^{-n-1}} \tag{30}$$

Substituting (30) in (28) we get,

$$V_i(s) = \frac{V_{DD}n!}{s^{-n-1}}e^{-sTfe} \tag{31}$$

Taking inverse Laplace transform of (31)

$$V'o(t) = nV_{DD}(t - T_{fe})^n u(t - T_{fe}) \tag{32}$$

For the calculation of the time delay we take $V_0(s) = 0.5V_{DD}$ at time $t=T_D$ and hence substituting in (32), we have,

So for $t \ge T_{fe}$, T_D is given as,

$$0.5V_{DD} = nV_{DD}(T_D - T_{fe})^n u(t - T_{fe}) \tag{33}$$

$$0.5 = n(T_D - T_{fe})^n \tag{34}$$

$$\frac{(0.5)^{1/n}}{n} = T_D - T_{fe} \tag{35}$$

$$T_D = T_{fe} + \frac{(0.5)^{1/n}}{n} \tag{36}$$

The above equation (36) is our proposed closed form expression for delay for lossless transmission line RLCG tree circuit in even mode and with mutual inductance for generalized input.

III.2 Calculation of the Delay in Odd Mode

Again from equation (1) for a simple input source terminated transmission line we can write the transfer function as,

$$\left.\begin{aligned} H(s) &= \frac{V_O(s)}{V_i(s)} \\ &= \frac{1}{sC_L(R_s\cosh(\gamma_o d) + Z_{oo}\sinh(\gamma_o d)) + (R_s / Z_{oo})\sinh(\gamma_o d) + \cosh(\gamma_o d)} \end{aligned}\right\} \tag{37}$$

where, $\gamma_o = \sqrt{(R + s(L-M))(G + sC)}$ is the propagation constant and $Z_{oo} = \sqrt{(R + s(L-M))/(G + sC)}$ is the characteristic impedance for odd mode of the line, respectively R, L, M, C and G are the per-unit-length resistance, inductance, mutual inductance capacitance and conductance parameters of the transmission line, respectively, d is the length of the line, and the series resistance is given by $R_s = R_{dr} + R_{ter}$. Where R_{dr} is the driver resistance and R_{ter} the termination resistance. We assume the dielectric loss and hence the shunt conductance, *G* to be negligibly small. The driver resistance is assumed to be linear. For load free no loss transmission line driven by a step input, the optimal termination resistance is $R_s=Z_{oo}$. With this termination, the ideal signal is the input step delayed by the time-of flight along the line, is given by, $T_{fo} = \sqrt{(L-M)C}d$. So, minimizing the central moments the ideal response is still obtained. For the lossless line in Figure 2, the transfer function is given by,

$$H(s) = \frac{1}{(R_s / Z_{oo})\sinh(\gamma_o d) + \cosh(\gamma_o d)} \tag{38}$$

where $\gamma_o = s\sqrt{(L-M)C}$ is the propagation constant and $Z_{oo} = \sqrt{(L-M)/C}$ is the characteristic impedance for equation (38), the II and III central moments of the impulse response are given as:

$$\left.\begin{aligned}\mu_2 &= -(L-M)d^2 - 3R_s^{\,2}C^2d^2\\ \mu_3 &= -3R_sC^2(L-M)d^3 + 14R_s^{\,3}C^3d^3\end{aligned}\right\} \quad (39)$$

Solving for $\mu_2 = 0$ from equation (39) yields $i\sqrt{(L-M)/3C}$ and $-i\sqrt{(L-M)/3C}$ as roots. Again solving $\mu_3 = 0$ from equation (49) yields 0, $\sqrt{3(L-M)/14C}$ and $-\sqrt{3(L-M)/14C}$ as roots. The positive root provides the solution R_s = Z_{0o}, Then, the transfer function may be expressed as,

$$H(s) = \frac{1}{\sinh(\gamma_o d) + \cosh(\gamma_o d)} = e^{-sT_{f_o}} \quad (40)$$

where $T_{f_o} = \sqrt{(L-M)C}d$ is the time-of-flight. Then it is easy to show that this transfer function provides the desired ideal waveform at the output of the transmission line is

$$v_o(t) = v_i(t - T_{f_o}) \quad (41)$$

So from (41), we can write the following equation:

$$V_o(s) = V_i(s)e^{-sT_{f_o}} \quad (42)$$

In case of arbitrary input,

$$v_i(t) = V_{DD}x^n(t) \quad (43)$$

$$V_i(s) = \frac{V_{DD}n!}{s^{-n-1}} \quad (44)$$

Substituting (42) in (44) we get,

$$V_i(s) = \frac{V_{DD}n!}{s^{-n-1}}e^{-sTfo} \quad (45)$$

Taking inverse Laplace transform of equation (45)

$$V'o(t) = nV_{DD}(t - T_{fo})^n u(t - T_{fo}) \quad (46)$$

In order to calculate the time delay we take $V_0(s)$ = $0.5V_{DD}$ at time t = T_D and hence putting in equation (46), we have,

$$0.5V_{DD} = nV_{DD}(T_D - T_{foo})^n u(t - T_{foo}) \quad (47)$$

$$0.5 = n(T_D - T_{fo})^n \quad (48)$$

$$(0.5)^{1/n} = n(T_D - T_{fo}) \quad (49)$$

$$\frac{(0.5)^{1/n}}{n} = T_D - T_{fo} \quad (50)$$

$$T_D = T_{fo} + \frac{(0.5)^{1/n}}{n} \quad (51)$$

So for $t \geq T_{fo}$ the T_D is given as,

$$T_D = T_{fo} + \frac{(0.5)^{1/n}}{n} \quad (52)$$

The above equation (52) is our proposed closed form expression for delay for lossless transmission line RLCG tree circuit in Odd mode and with mutual inductance for generalized input.

IV SIMULATION RESULTS AND DISCUSSION

Only capacitive coupling is considered in research and reduction techniques earlier. But, inductive crosstalk plays a major part and it should be included in case of very high frequencies (GHz) scale coupling noise analysis. The configuration of circuit for simulation is shown in Figure 4. The high-speed interconnect system consist of two coupled interconnect lines and ground and the length of the lines is d =10 mm.
The extracted values [16] for the parameters R, L, C, and G are given in Table 1.

TABLE 1:. EXTRACTED VALUES OF R, L, C, G

Parameter(s)	Value/m
Resistance(R)	120 kΩ/m
Inductance(L)	270 nH/m
Conductance(G)	15 pS/m
Capacitance(C)	240 pF/m
Mutual Inductance(M)	54 nH/m

For very high frequencies as in GHz scale, inductive effect plays a major role therefore it should be considered for complete delay analysis. The configuration of circuit for simulation is shown in Figure 4

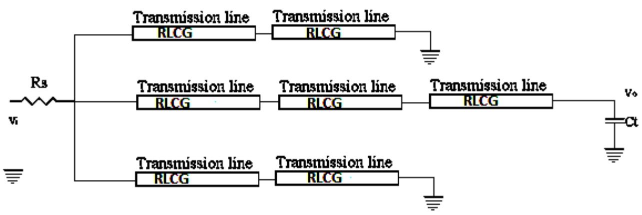

Figure 4: An RLCG tree example

TABLE 2: COMPARISON OF THEORETICAL AND SIMULATED RESULT FOR DELAY TIME

Value of *n*	Value of load Capacitance C_L (pF)	Proposed value of τ_D (ns)	SPICE value of τ_D (ns)
1	80	3.21	3.10
1	210	3.29	2.98
1	140	2.76	2.59
2	70	2.31	2.17
2	40	0.62	1.98
2	60	0.83	1.62
3	30	0.69	1.21
3	60	0.91	0.87
3	90	1.42	0.92
4	40	0.86	0.89
4	80	1.53	1.62
4	120	1.78	1.83

Theoretical and experimental results for delay are given in Table 2,From this we concluded that as the order of the input & load capacitance increases the accuracy of the delay time decreases.

V CONCLUSION

In this paper we have proposed an accurate delay analysis approach for distributed RLCG interconnect line under generalised input. We derived the transient response in time domain function of a generalised input. In Table 2 comparative results of our proposed dealy model with spice dealy are given and it our prposed model gives less dealy as the load capacitance is increasing.In future this paper can be modified for any specific input.

References

[1] W. C. Elmore, "The Transient Response Of Damped Linear Networks With Particular Regard To WideBband Amplifiers," Journal of Applied Physics, vol. **19**, .55–63 (1948).

[2] A.B. Kahng, S Muddu , "An Analytical Delay For RLC Interconnects"., IEEE Trans. Computer-Aided Design of Integrated Circuits and Systems, **16,** 1507-151 4 (1997).

[3] C. Alpert , A. Devgan, C. Kashyap, "A Two Moment RC Delay Metric For Performance Optimization", ACM International Symposium on Physical Design, New York (USA) (2000), pp 69-74.

[4] R. Gupta, B. Tutuianu and L. Pileggi, "The Elmore Delay As Bound For RC Trees Generalized Input Signals" , ACM/IEEE Design Automation Conference, New York, USA (1995), pp.364-369.

[5] K. Banerjee, A. Mahrotra, "Analysis Of On-Chip Inductance Effects For Distributed RLC Interconnects", IEEE Transactions on Computer Aided Design of Integrated Circuits and Systems , **21,** 904-915 (2002).

[6] J.V.R. Ravindra, M.B. Srinivas, "Modelling And Analysis Of Crosstalk For Distributed RLC Interconnects Using Difference Model Approach" Proc. 20th Annual Conference on Integrated Circuits and Systems Design, Rio de Janeiro, Bresil (2007), pp. 207-211.

[7] Xiaopeng Ji, Long Ge, Zhiquan Wang, "Analysis Of On-Chip Distributed Interconnects Based On Pade Expansion", Journal of Control Theory and Applications, **7**, 92–96 (2009).

[8] Jun-De Jin, Shawn S.H.Hsu, Tzu-Jin Yeh, M.T.Yang, Sally Liu,"Fully Analytical Modelling Of Cu Interconnects Upto 110GHz". Japanese Journal of Applied Physics, **47,** 2473-2476 (2008).

[9] Hu Zhi Hua, Xu Jie, "State Space Models Of RLCG Interconnect With Super High Order In Time Domain And Its Research," Journal of Electronics and Information Technology**, 31**, 1980-1984 (2009).

[10] R. Kar , V. Maheshwari, D Sengupta , A K Mal, A K Bhattacharjee, "Analytical Delay Model For Distributed On-Chip RLCG Interconnects", International Journal of Embedded Systems and Computer Engineering, **2,** 17-21 (2010).

[11] R. Kar , V. Maheshwari , Md. Maqbool., A K Mal , A K Bhattacharjee. "An Explicit Coupling Aware Delay Model For Distributed On-Chip RLCG Interconnects Using Difference Model Approach", International Journal of Embedded Systems and Computer Engineering, **2,** 39- 44 (2010).

[12] R Kar ,V Maheshwari , A. Choudhary , A Singh, "Modelling of On Chip Global RLCG Interconnect Delay For Step Input". IEEE International Conference on Computer and Communications (ICCC-2010), Allahabad, India, pp ; 318−323.

[13] V.Maheshwari, Hemlata Yadav, R.Kar, D.Mandal, A K Bhattacherjee, "Delay Metric for On-Chip RLCG Interconnects for Ramp Input", Jounal of Electronic Device, **14**, 1122-1127 (2012).

[14] Mustafa Celik, Lawrence Pillegi, Altan Odabasioglu, "IC Interconnect Analysis". Kluwer Academic Press , (2002) .

[15] J. Cong, Z. Pan, L. He, C.K Koh , K Y Khoo, "Interconnect Design For Deep Submicron ICs", International Conference on Computer Aided design (ICCAD), San Jose california, USA, November 1997, 478-485..

[16] C. F. Bermond ,S . Putotet ," Extraction of (R,L,C,G) Interconnect Parameters in 2D Transmission Lines Using Fast and Efficient Numerical Tools", International Conference on Simulation of Semiconductor Processes and Devices (SISPAD 2000), santa Clara CA, USA, pp.87-89.