A Superior Delay Estimation Model for VLSI Interconnect in Current Mode Signaling

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Abstract—Today’s VLSI networks demands for high speed. And in this work the compact form mathematical model for current mode signalling in VLSI interconnects is presented. RLC interconnect line is modelled using characteristic impedance of transmission line and inductive effect. The on-chip inductance effect is dominant. First order transfer function is designed using finite difference equation, Laplace transform and by applying the boundary conditions at the source and load termination. It has been observed that the dominant pole determines system response and delay in the proposed model. The novel proposed current mode model shows superior performance as compared to voltage mode signalling. Analysis shows that current mode signalling in VLSI interconnects provides 2.8 times better delay performance than voltage mode. Secondly the damping factor of a lumped RLC circuit is shown to be a useful figure of merit.

Keywords—Current Mode, Voltage Mode, VLSI Interconnect.

I. INTRODUCTION

MODERN deep sub-micron system on chip (SoC) designs, interconnects play a dominant role in determining circuit performance and reliability. As the die size of CMOS integrated circuits continues to increase and feature sizes decrease, the performance of high speed VLSI circuits is primarily limited by the interconnect delay. Traditionally, voltage mode repeaters inserted in the long interconnects have been used to reduce the delays in signal transmission. However, there is a limit to the performance improvement that can be obtained with repeater insertion in deep submicron designs in terms of power and delay [1], [2]. Current mode signaling has been explored as an alternative for data transmission over repeater inserted interconnects [3]-[5]. In this technique, it is approximated that input resistance ($R_{in}$) seen by the modulated signal at the receiver end is very low (ideal value $R_{in}$ = 0) compared to voltage mode signaling where $R_{in}$ is very high (ideally $R_{in}$ = $\infty$), the same concept is already used to speed up SRAM CMOS circuits [6]. In [7] Schmid, has given that researchers can explicitly apply the current mode approach. The current mode approach is an alternative way of designing analog integrated circuits (ICs) and not a tool to classify circuits. Tabrizi [8] has used an efficient approach to optimize the power and delay of the global interconnects. The low swing method is optimized and used for various lengths of global interconnect. Again, [9] has proposed two accurate and efficient approaches to optimize the power and delay of global interconnects in VLSI ICs. The conventional buffer insertion and low swing methods are modified for delay and power optimizations of various length of global interconnect. Non-equidistance buffer insertion and current mode driver and receiver techniques are addressed with smart optimization procedure. Maekawa has proposed [10] solution for on-chip pulsed-current-mode transmission line interconnector (PTLI) with a stacked-switch transmitter that does not consume static power and generates return-to-zero (RZ) codes. Dave [11] has proposed that the current mode signaling is an energy efficient technique for data transmission. It is found experimentally that 6mm long link (on-chip interconnects) offers 22% improvement in delay with 81% lower energy consumption at 0.62Gbps over the voltage mode scheme. Kancharapu [12] has proposed low power low skew current mode based clock distribution network and proposed receiver consumes 35% less power than that of state of the art current mode receiver. A closed-form RC model for current mode interconnects has been derived using first order moment approximation and boundary condition matching [14], [15]. Transmission line model for delay formulation is also exploited in [16]. However, as system requirements push for the use of wider low resistance line, the inductance become increasingly dominant under fast transitions in GHz frequency range. In this case a RC delay model in [14] results in an error more than 20% compared to HSPICE simulations when operating in inductance dominated regions. But this aspect is important for current mode interconnects and therefore has been attempted in the present research work. An RLC interconnect line needs to be approximated as a RC line model using inductance-resistance equivalent model. This helps in mitigating the estimated error in [14] for GHz frequency range. Due to this the overall system performance gets improved in terms of speed.

The rest of the paper is organized as follows. In Section II inductance equivalent resistance concept is discussed. In Section III the proposed analytical model and mathematical formulation is presented for resistive load termination and damping factor is considered for accuracy. Results and their discussion are presented in Section IV. Finally conclusions are drawn in Section V.

II. INDUCTANCE-RESISTANCE EQUIVALENT MODEL

The current mode interconnect delay expression is derived through two main steps namely, (A) absorbing the line inductance into effective resistance and (B) using transfer
function Laplace operator approach and by applying boundary conditions at source and load end of line.

The line inductance is converted into an effective resistance. In case of RC interconnects, the equivalent line resistance is "\( R_s + R_T \)". However, when inductive effect is dominant the equivalent resistance equals "\( R_T + 0.65R_s + 0.36Z_o \)" where the factors 0.65 and 0.36 reflect the shielding effect of inductance [13]. For delay computation the 1st order transfer function dominant pole is evaluated, because the dominant pole decides the delay of a distributed network. Thus the equivalent resistance is given as

\[
R = 0.65R_s + 0.36Z_o + R_T \tag{1}
\]

where \( R_s \) is the source resistance and \( Z_o \) is the characteristic impedance \( Z_o = \sqrt{L_T/C_T} \) and \( R_T, C_T \) and \( L_T \) represents total line resistance, capacitance and inductance discussed in Table I for any length of line.

III. MATHEMATICAL MODEL FORMULATION

A. Problem Definition

In this work a bit line delay is modeled when a read operation performed on CMOS SRAM. Current mode signaling technique is exploited for fast access/transfer of information to data line of any microprocessor/microcontroller. For current mode signaling a system consist of a driver circuitry, interconnect line and followed by receiver circuitry having a decoding unit. The problem targeted in this work detailed in Fig. 1(a).

For constant current

\[
I(x, t) - I(x + \Delta x, t) = -\frac{1}{R}\frac{\partial V(x, t)}{\partial t}
\]

For \( \Delta x \to 0 \)

\[
I(x, t) = -\frac{1}{R}\frac{\partial V(x, t)}{\partial t}
\]

For constant voltage

\[
I(x, t) - I(x + \Delta x, t) = c\Delta x \frac{\partial V(x, t)}{\partial t}
\]

Fig. 1 (a) Analogue for the proposed problem (when SRAM transmit a signal on bit line)

For constant current voltage on the line the differential equations representation is used, where voltage \( V(x, t) \) and \( V((x + \Delta x), t) \) and current \( I(x, t) \) and \( I((x + \Delta x), t) \) are represented at the source and load ends at \( x = 0 \) and \( x = d \) (length of line) respectively. Fig. 2 shows the equivalent distributed rc interconnect model. Here \( R \) represent unit length equivalent resistance and \( C \) represent unit length capacitance of the interconnect.

For constant current

\[
\frac{V(x, t) - V(x + \Delta x, t)}{R \Delta x} = I(x, t)
\]
For $\Delta x \to 0$

$$\frac{\partial^2 V(x,t)}{\partial x^2} = -c \frac{\partial V(x,t)}{\partial t} \tag{3}$$

Substituting (2) into (3), reduces to

$$\frac{\partial^2 \hat{V}(x,t)}{\partial x^2} = r c \frac{\partial \hat{V}(x,t)}{\partial t} \tag{4}$$

s-domain representation of (4) is

$$\frac{\partial^2 \hat{V}(x,s)}{\partial x^2} - r cs \hat{V}(x,s) = 0 \tag{5}$$

Fig. 2 Equivalent $rc$ interconnect line model

Fig. 3 Interconnect line model as a distributed line

Fig. 3 gives the $rc$ distributed model of an interconnect line. $V_{in}(t)$ is the time varying input signal, and $R_S$ is a source resistance with $R_L$ resistive load. $r, \Delta x$ and $c, \Delta x$ represent small increments in the value of unit length resistance and capacitance down the interconnect line. The solution of partial differential equation (5) in terms of voltage and current on the line is given by

$$V(x,s) = A_{11} \sinh(\sqrt{rc}x) + B_{11} \cosh(\sqrt{rc}x) \tag{6}$$

$$I(x,s) = -\frac{1}{\sqrt{r}} \left[ A_{11} \cosh(\sqrt{rc}x) + B_{11} \sinh(\sqrt{rc}x) \right] \tag{7}$$

Applying the boundary conditions on (6) and (7), $A_{11}, B_{11}$ with $R_L$ as resistive load termination are obtained. And the boundary conditions are:

$$V_{in}(s) = V(x=0,s) + I(x=0,s)R_S$$

$$V(x=d,s) = I(x=d,s)R_L$$

$$A_{11} = -\frac{V_{in}(s)[\cosh(\sqrt{rc}d)] + \frac{r}{\sqrt{r}} R_L \sinh(\sqrt{rc}d)}{(\sqrt{rc}R_LR_S + 1) \sinh(\sqrt{rc}d) + \sqrt{r} (R_L + R_S) \cosh(\sqrt{rc}d)}$$

$$B_{11} = \frac{V_{in}(s)[\sinh(\sqrt{rc}d)] + \frac{r}{\sqrt{r}} R_L \cosh(\sqrt{rc}d)}{(\sqrt{rc}R_LR_S + 1) \sinh(\sqrt{rc}d) + \sqrt{r} (R_L + R_S) \cosh(\sqrt{rc}d)}$$

On calculation (6) and (7) can be reproduced as (8):

$$\frac{V(x=d,s)}{V_{in}(s)} = \frac{\frac{r}{\sqrt{r}} R_L}{(\sqrt{rc}R_LR_S + 1) \sinh(\sqrt{rc}d) + \sqrt{r} (R_L + R_S) \cosh(\sqrt{rc}d)} \tag{8}$$

Let $\sqrt{rc}d = u$

This leads to

$$\frac{V(x=d,s)}{V_{in}(s)} = \left( \frac{1}{1 + \frac{r}{\sqrt{r}} R_L R_S} \right) \sinh(u) + \frac{r}{\sqrt{r}} R_S \cosh(u)$$

Rewriting (8) as:

$$f(u) = \left( \frac{a}{u} + bu \right) \left( \frac{e^u - e^{-u}}{2} \right) + c \left( e^{\alpha u} - e^{-\alpha u} \right) \tag{10}$$

where,

$$a = \frac{rd}{R_L}, \quad b = \frac{R_S}{R_L}, \quad c = \left( 1 + \frac{R_S}{R_L} \right)$$

On simplifying (10), it gives:

$$f(u) = 1/2[e^{u} + bu + c] + (c - bu - \frac{a}{u})e^{-u} \tag{11}$$

By solving (11), $f(u)$ finally reduces to

$$f(u) = (a + c) + \left( b + \frac{c}{u} + \frac{a}{u^2} \right) u^2 + \left( \frac{b}{u^3} + \frac{c}{u^4} + \frac{a}{u^5} \right) u^4 + \left( \frac{b}{u^6} + \frac{c}{u^7} + \frac{a}{u^8} \right) u^6 + \cdots$$

Substituting the value of $u = \sqrt{rc}d$; $cd = C_L$, Total effective capacitance of interconnect line of length $d$, $rd = R_L$, Total effective resistance of interconnect line of length $d$, and (12) becomes:

$$f(u) = (a + c) + \left( b + \frac{c}{u} + \frac{a}{u^2} \right) C_L R_S + \left( \frac{b}{u^3} + \frac{c}{u^4} + \frac{a}{u^5} \right) (C_L R_S)^2 s^2 + \left( \frac{b}{u^6} + \frac{c}{u^7} + \frac{a}{u^8} \right) (C_L R_S)^3 s^3 + \cdots$$

(13)

Thereby the distributed network is further approximated to a first order transfer function as shown below where $\alpha_1$ is the dominant pole that determines the delay of the line.

$$\frac{V(x=d,s)}{V_{in}(s)} = \frac{1}{(a+c)+(b+c/a)\alpha_1 R_S} \tag{14}$$

First order transfer function is equivalent to

$$\frac{V(x=d,s)}{V_{in}(s)} = \frac{R_L}{s+\alpha_1} \tag{15}$$
Finally, system response is converted into time domain and gives:

\[ V(x = d, t) = \frac{V_{dc}}{a+e} \left[1 - e^{-\alpha t}\right] u(t) \]  

(16)

Hence the delay time is computed as:

\[ \tau_d = \frac{1}{a_i} \left(\frac{b+c}{a+c}\right) L_i R_i \]  

(17)

Substituting the values of \( a, b, \) and \( c \), (17) reduces to:

\[ \tau_d = \frac{\rho_a^{\frac{1}{2}} \left(\frac{1}{\rho_a^{\frac{1}{2}}}\right)^{\frac{1}{2}}}{\frac{v}{2}} \left(\frac{1}{\rho_a^{\frac{1}{2}}}\right)^{\frac{1}{2}} L_i R_i \]  

(18)

B. Damping Factor

For current mode signalling, a lumped system model can be used for the approximate evaluation of the line inductance effect. This analysis of an RLC transmission line is compared to the analysis of a lumped RLC circuit [21].

The interconnect is modelled as a lumped RLC circuit with \( R, L, \) and \( C \) as shown in Fig. 4.

![Lumped RLC circuit model of an Interconnect line](image)

Fig. 4 Lumped RLC circuit model of an Interconnect line

The poles of the circuit are

\[ P_{1,2} = \omega_0 \left(\frac{1}{2} \pm \sqrt{\left(\frac{1}{2}\right)^2 - 1}\right) \]  

(19)

and the damping factor \( \xi \) is

\[ \xi = \frac{R d}{2 \sqrt{L}} \]  

(20)

As (19) implies, if \( \xi \) is greater than one, the poles are real and the effect of the inductance on the circuit is small. The greater the value of \( \xi \), the more accurate the model becomes.

On the other hand, as \( \xi \) become less than one, the poles become complex and oscillation occurs. In that case, the inductance cannot be neglected. This relationship is physically intuitive, since \( \xi \) represents the degree of attenuation the wave suffers as it propagates a distance equal to the length of the line. As this attenuation increases, the effect of the reflections decrease and the RC model becomes more accurate. Therefore \( \xi \) is a useful figure of merit that anticipates the importance of considering in a particular interconnect line.

IV. RESULTS AND DISCUSSION

The various results obtained are presented in this section. Their implications are also given. In order to verify the analytical results, simulations of the RLC line modeled in Fig. 3 i.e. \( rc \) line are performed. Using PTM parameters for interconnects in 180nm technology node, the results are evaluated for 2mm to 10mm length of global interconnect [15]. For proposed model validation the parameters used are detailed in Tables I and II. Table I gives the computation of inductance effect into equivalent resistance and the change in unit length resistance is also detailed. \( R_S = 2.5k \) is used in the analyses. Different results are computed from the analytical model by using MATLAB (7.80) [18]. Furthermore the results are verified by SPICE simulations [20]. Analyses show that the proposed delay model is in close agreement to the simulation results. The various case studies which validate the proposed model are presented in this section.

| Case 1: | In Fig. 5 the delay variation with interconnect length for current mode signaling with \( (R_C = 0) \) i.e. ideally load resistance must be zero is shown. This result is computed by proposed analytically model (18) for current mode interconnect. The results of the proposed model are compared with existing current model in literature [15]. It is concluded that the proposed model shows speed improvement when compared to that in [15]. With variation in the length of interconnect the detailed results are shown in Table III. This improvement in delay factor is because moment approximation method is used in [15] while the proposed model overcomes the approximation.

| Case 2: | For voltage mode ideally load is terminated by infinite resistance (\( R_L = \infty \)) which is practically not possible. The value of \( R_L \) has been approximated in range 1kΩ to 5kΩ for voltage mode signaling. Delay value for voltage mode signaling is detailed in Table IV. Delay variation with interconnect length for \( R_L = 200 \) to 5kΩ is shown in Fig. 6 andnd respectively. From these figures it is inferred that for larger values of load resistance, the system response goes sluggish. Therefore, system demands for smaller values of load impedance for quicker response.

| Case 3: | In Fig. 7 the delays obtained by voltage and current mode system are compared. It is found that current mode signaling is far better than voltage mode signaling for data
transmission over longer interconnects is detailed in Table V. It is completely high speed data transmission system. Longer interconnect lengths for instance 10 mm current mode (CM) system gives 14.68 times lesser delay than voltage mode at RL= 5kΩ.

**Case 4:** For R_L = R_T = R_I, total line resistance. The delay is almost three time the current mode value (R_L=0). It is still less than voltage mode signaling. This is according to results shown in Fig. 8. At 10mm interconnect length it is found that at R_L = R_T, the delay is 0.8012ns, which is 2.77 times the proposed current mode system at R_L = 0 where delay is 0.288ns.

**Case 5:**: Fig. 9 shows the variation of delay with load resistance as a variable. It is found that increase in the value of load, makes the system slower. It means that only for smaller value of impedance the system will respond faster. A comparative analysis of the proposed mathematical model and SPICE simulation results is carried for RLC interconnects and shown in Fig. 10. The value of N for distributed network is taken 1001 [17]. The simulation results deviate from the proposed model by 0.01%, 3.57%, 4.38%, 5.61% and 6.44% for 2mm, 4mm, 6mm, 8mm, and 10mm lengths of interconnect line respectively. The average error is 3.96% between the proposed model and the SPICE simulations. This shows fairly good agreement between the two.

V. CONCLUSION

In this paper a novel analytical delay model for current mode signaling is developed and presented. By using this proposed model dominant pole is computed from the first order system function. It is analyzed for different current mode circuit parameters to determine the nature of current mode circuits. It is also observed that with the increase in the length of interconnect the simulation results deviate from the proposed model by 3.96%. For load resistance equal to total equivalent resistance of RLC lines the system delay is still smaller than voltage mode signalling. The delay at R_L=0 is 2.8 times lesser than the current mode delay at R_L = R_T. Finally, it is concluded that the use of current mode techniques can lead to significant speed enhancement in long VLSI interconnects. This proposed current mode technique can significantly impact chip access times and architecture trade-offs for future fast CMOS SRAM design. Current mode signal receivers can be used to significantly reduce the line delays in CMOS VLSI chips. Secondly, figure of merit have been developed that determine the relative accuracy of a R_{teff}C_T model of on-chip interconnects. The derived expression along with accuracy analysis can serve as a convenient tool for delay estimation with minimal computation during design.

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<tr>
<th>Length (mm)</th>
<th>Delay (ns)</th>
<th>Analytical Delay (ns)</th>
<th>Simulation Delay (ns)</th>
<th>% Decrease in delay value of Col. 3 compared to Col. 2. (ns)</th>
<th>% of Relative error Analytical v/s Simulation</th>
<th>Delay (ns) at R_L = R_T</th>
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<td>0.017</td>
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![Fig. 5 Delay comparison between proposed and existing model](image-url)

![Fig. 6 Delay variations for Voltage mode with interconnect length](image-url)
Fig. 10 Analytical versus simulation results for delay variation with interconnect length

Fig. 9 Delay variation with load resistance for CM signalling

Fig. 8 Delay versus interconnect length when load impedance equal to line impedance

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