Passive Compensation For High Performance Inter-Chip Communication *

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Abstract

This paper develops a novel high-speed inter-chip serial signaling scheme with leakage shunt resistors and termination resistors between the signal trace and the ground. For given abstract topology transmission line based on the data for IBM high-end AS/400 system[1] [2], we put termination resistors at the end of receiver and adjust the shunt and termination resistors value to get the optimal distortion-less transmission line. Analytical formulas are derived to predict the worst case jitter and eye-opening based on bitonic step Response Assumption[3]. Our schemes and the other two comparison cases are discussed.

1 Introduction

Ever-decreasing dimension VLSI technology has resulted in higher current density and power dissipation in global interconnects [4]. At packaging level, serial link performance is greatly restricted by signal distortion resulted from various factors such as frequency dependency of the interconnect parameters. In order to make a high speed, low power, low latency transmission line, some classic methods have been proposed to deal with on-chip serial link signaling, such as clocked discharging [5], non-linear transmission line [6] [7], and etc.

Active compensation such as pre-emphasis [8] and equalization [8] has been a popular technique for high performance communication. However, delay and power consumption are two primary concerns.

For passive compensation, M. Hashimoto et al.[9] and M. Flynn et al. [9] fine-tuned the termination resistance at receiver end to maximize the window of the eye diagram for on-chip and off-chip interconnect. Chen et al. [2] adopted distributed shunt resistors to enforce the Heaviside’s distortionless condition.

Our new schemes is inspired by the basic definition in theory of distortional transmission line which states if R/G=L/C, there will be no distortion at the receiver end and the signal propagates at the speed of light. The primary reason for signal distortion over a serial channel is the frequency dependency of attenuation and phase velocity. We reduce both latency and energy for transmission line by shunt and termination resistor insertion. Compared with other methods, the proposed serial link scheme enjoys several advantages. First, there is no direct feedback path from the transmission line network to the source. The transmission lines are linear network and thus the design and optimization involve no active components.

The rest of paper is organized as below: section 2 presents a brief review of transmission line theory and our theoretical analysis to predict eye-opening and jitter values. We present the overall experiment results in Section 3 and conclude the paper in Section 4.

2 Eye-Opening prediction

2.1 Transmission-Line Theory

Transmission-lines are a special class of the more general electromagnetic waveguide. The voltage and current on the transmission line appear in the form of wave propagation which is a function of both propagation distance z and time t. Assuming the per-unit-length series resistance, series inductance, shunt conductance and shunt capacitance are R, L, G and C, respectively, the voltage and current on the transmission line are dictated by the telegrapher’s equations:

\[ \frac{\partial V(z,t)}{\partial z} = -RI(z,t) - L\frac{\partial I(z,t)}{\partial t} \]  
\[ \frac{\partial I(z,t)}{\partial z} = -GV(z,t) - C\frac{\partial V(z,t)}{\partial t} \]  

The general solution to the above telegrapher’s equations can be expressed as:
Figure 1. Scheme with shunt and terminator resistor.

\[ V(z) = V^+(z) + V^-(z) = V_0^+(z)e^{\gamma z} + V_0^-(z)e^{-\gamma z} \]  

where \( V^+(z) \) and \( V^-(z) \) are the waves traveling in \( z^+ \) and \( z^- \) directions, respectively, with propagation constant \( \gamma \):

\[ \gamma = \alpha + j\beta = \sqrt{(R + j\omega L)(G + j\omega C)} \]  

where \( \alpha \) and \( \beta \) correspond to attenuation and phase velocity, and are functions of frequency in general. The characteristic impedance is defined as the ratio of voltage to current at any point of the line:

\[ Z_0 = \frac{V(z)}{I(z)} = \sqrt{\frac{R + j\omega L}{G + j\omega C}} \]  

Depending on the RLGc values and frequency, the transmission line can operate in the RC region, LC region or skin effect region. When an ideal digital pulse train is transmitted over the channel, this frequency dependency of attenuation and phase velocity will result in distortion of the waveform, causing inter-symbol interference (ISI).

Assuming RLGc themselves are constant. Suppose that we follow Heaviside’s condition [10].

\[ \frac{R}{G} = \frac{L}{C} \]  

We can obtain frequency-independent attenuation and phase velocity across the whole spectrum. Equation (4) and (6) are reduced to

\[ \gamma = \sqrt{(R + j\omega L)(G + j\omega C)} = \frac{R}{Z_0} + j\omega \sqrt{LC} \]  

\[ Z_0 = \sqrt{\frac{L}{C}} \]  

For inter-chip application, R, L, G, C are frequency dependent because of the skin effect and proximity effect. However, we demonstrate that by inserting shunt and termination resistors we can improve the eye-diagram.

Table 1 presents all definitions and terms used in this paper.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Connotation</th>
</tr>
</thead>
<tbody>
<tr>
<td>( R )</td>
<td>Serial resistance per unit length, in ( \Omega ) per meter</td>
</tr>
<tr>
<td>( L )</td>
<td>Serial self loop inductance per unit length, in ( \mu H ) per meter</td>
</tr>
<tr>
<td>( G )</td>
<td>Shunt conductance per unit length, in ( \mu S ) per meter</td>
</tr>
<tr>
<td>( V )</td>
<td>Input voltage value</td>
</tr>
<tr>
<td>( V_{\text{max}} )</td>
<td>Maximum voltage of the step response</td>
</tr>
<tr>
<td>( V_{\text{sat}} )</td>
<td>Final saturation voltage of the step response</td>
</tr>
<tr>
<td>( V_{\text{atten}} )</td>
<td>Voltage after attenuation</td>
</tr>
<tr>
<td>( V_1 )</td>
<td>Voltage value in period time ( T )</td>
</tr>
<tr>
<td>( H(s) )</td>
<td>Transfer function</td>
</tr>
<tr>
<td>( Z_0 )</td>
<td>Characteristic impedance</td>
</tr>
<tr>
<td>( I )</td>
<td>Input current value</td>
</tr>
<tr>
<td>( r_s, r_t )</td>
<td>Shunt and terminator resistors</td>
</tr>
<tr>
<td>( f_i )</td>
<td>Input frequency</td>
</tr>
<tr>
<td>( f_s )</td>
<td>Transmission line impedance value</td>
</tr>
<tr>
<td>( \alpha )</td>
<td>Attenuation constant</td>
</tr>
<tr>
<td>( \beta )</td>
<td>Phase constant</td>
</tr>
</tbody>
</table>

Table 1. Index table for definitions and terms.

### 2.2 Bitonic Step Response Assumption

We use bitonic function to model the step input response. Due to the wave nature of transmission line, signals undergo multiple reflections if perfect termination is not provided. As a result, the output step response will fluctuate before it settles down to the saturation voltage. However, for lossy transmission lines such as on-chip and MCM interconnect, the reflected wave will diminish to a negligible amount after two round trips. Thus, the output step response usually appears to be bitonic [3].

**Definition 2.1** A step response is defined to be bitonic if it monotonically increases to its peak voltage and then monotonically decreases to its saturation voltage.

For a generic bitonic step response, we characterize the generic bitonic step response \( s(t) \) with five pivotal points:

\[ V_1 = V(T) \]

\[ V_{\text{max}} = V(T_0) = \text{maximum voltage of the step response} \]

\[ V_{\text{sat}} = \text{final saturation voltage of the step response} \]

(9)

**Lemma 2.2** Both worst case eye-diagram and jitter values can be predicted by \( V_{\text{sat}}, V_1, \) and \( V_{\text{max}} \) [3].

The worst-case eye-opening is then bounded by

\[ V_{\text{eye}} = V_{\text{top}} - V_{\text{bottom}} = V_{\text{sat}} - 2(V_{\text{max}} - V_1) \]  

(10)

The worst-case jitter is bounded by:

\[ \Delta t = \max \{ t^2 \} - \max \{ t_1 \} \]

(11)
To determine the jitter, we will first extract the fastest rising edge, which will cross the threshold voltage \( V_{sat}/2 \) earliest at \( t_1 \). The slowest rising edge will cross the threshold voltage latest at \( t_2 \). And the worst-case jitter is bounded by \( \Delta t = t_2 - t_1 \). Since the eye-diagram is symmetric with regard to its falling edge and rising edge, considering only rising edge is sufficient.

From Figure 3, the worst-case jitter is bounded by:

\[
\Delta t = \max\{t_2\} - \max\{t_1\} \quad (12)
\]

and can be solved:

\[
P = (V_{\max} - V_{\text{eye}})/2 \quad (13)
\]

\[
\text{Jitter} = \frac{PT}{E_{\text{eye}}} \quad (14)
\]

### 2.3 Passive Compensation

We derive analytical formulation of three primary components \( V_{sat}, V_{out} \) and \( V_{\max} \) for our schemes and the other two comparison cases. We use the following function for the analysis [10]:

\[
V_{\text{atten}}(f) = V_{\text{in}}e^{-\alpha(f)t} \quad (15)
\]

\[
V_1 = V_{\text{atten}}(f = \frac{1}{2T}) = \frac{2Z_t}{Z_0 + Z_t} \quad (16)
\]

\[
V_{\max} = V_{\text{atten}}(f \to 0) = \frac{2Z_t}{Z_0 + Z_t} \quad (17)
\]

\[
V_{\text{sat}} = V_{\text{out in DC path}} \quad (18)
\]

where \( Z_t \) is the termination impedance at the receiver.

We discuss the three cases (1) \( Z_t \) is real and bounded, \( G = \infty \), (2) \( Z_t = \infty \), \( G \) is bounded, and (3) \( Z_t \) and \( G \) are real and bounded.

- **T-line with resistive termination**

  We set a resistor as the terminator \( Z_t = R_t \).

  \[
  \alpha \approx \frac{1}{2} \left( R(f) \sqrt{\frac{C}{L}} \right) \quad (19)
  \]

  Put equation (16) to (18) into equation (10) and (13), we can derive the worst-case jitter and eye:

  \[
  V_{\text{sat}} = V_{\text{atten}}(f = 0) \frac{R_t}{R_w + R_t} \quad (20)
  \]

  where \( R_w \) is the total line resistance at DC.

- **T-line with shunt resistors**

  From equation (20), (21) and \( Z_t = \infty \), we have:

  \[
  \alpha \approx \frac{1}{2} \left( R(f)/Z_0 + GZ_0 \right) \quad (21)
  \]

  From Telegrapher’s equation (1) (3) with DC path, we derive \( V_{\text{sat}} \):

  \[
  V_{\text{sat}} = V_s \left[ \frac{2}{e^{-\sqrt{RG}} + e^{\sqrt{RG}}} \right] \quad (22)
  \]

- **T-line with shunt and terminator resistors**

  Since \( Z_t = R_t \), we have

  \[
  \alpha \approx \frac{1}{2} \left( R(f)/Z_0 + GZ_0 \right) \quad (23)
  \]

  From Telegrapher’s equation (1) to (3) with DC path, we derive \( V_{\text{sat}} \):

  \[
  V_{\text{sat}} = V_s \left[ \frac{2R_t}{(R_t - \sqrt{RG})e^{-\sqrt{RG}} + (R_t + \sqrt{RG})e^{\sqrt{RG}}} \right] \quad (24)
  \]
Table 2: Jitter and eye-opening with R- terminator only.

<table>
<thead>
<tr>
<th>R (Ω)</th>
<th>80</th>
<th>90</th>
<th>100</th>
<th>110</th>
<th>120</th>
<th>130</th>
<th>140</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jitter (ps)</td>
<td>7.52</td>
<td>4.46</td>
<td>3.91</td>
<td>3.87</td>
<td>3.49</td>
<td>3.09</td>
<td>2.73</td>
</tr>
<tr>
<td>( V_{\text{eye}} ) (V)</td>
<td>0.55</td>
<td>0.57</td>
<td>0.56</td>
<td>0.57</td>
<td>0.58</td>
<td>0.58</td>
<td>0.57</td>
</tr>
<tr>
<td>( V_{\text{max}} )</td>
<td>0.685</td>
<td>0.704</td>
<td>0.784</td>
<td>0.8</td>
<td>0.82</td>
<td>0.86</td>
<td>0.88</td>
</tr>
<tr>
<td>( V_{\text{p}} )</td>
<td>0.64</td>
<td>0.65</td>
<td>0.67</td>
<td>0.69</td>
<td>0.71</td>
<td>0.73</td>
<td>0.73</td>
</tr>
<tr>
<td>( V_{\text{sh}} )</td>
<td>0.61</td>
<td>0.63</td>
<td>0.66</td>
<td>0.68</td>
<td>0.71</td>
<td>0.71</td>
<td>0.73</td>
</tr>
<tr>
<td>( V_{\text{E}} ) (V)</td>
<td>19.7</td>
<td>20.7</td>
<td>21.7</td>
<td>21.8</td>
<td>22.1</td>
<td>21.9</td>
<td>21.8</td>
</tr>
<tr>
<td>( V_{\text{E}} ) (V)</td>
<td>0.52</td>
<td>0.53</td>
<td>0.52</td>
<td>0.54</td>
<td>0.59</td>
<td>0.58</td>
<td>0.59</td>
</tr>
<tr>
<td>( V_{\text{max}} )</td>
<td>0.73</td>
<td>0.77</td>
<td>0.81</td>
<td>0.84</td>
<td>0.87</td>
<td>0.90</td>
<td>0.92</td>
</tr>
<tr>
<td>( V_{\text{p}} )</td>
<td>0.48</td>
<td>0.51</td>
<td>0.53</td>
<td>0.55</td>
<td>0.57</td>
<td>0.59</td>
<td>0.60</td>
</tr>
<tr>
<td>( V_{\text{sh}} )</td>
<td>0.62</td>
<td>0.66</td>
<td>0.69</td>
<td>0.72</td>
<td>0.74</td>
<td>0.77</td>
<td>0.79</td>
</tr>
<tr>
<td>( Jitter^E ) (ps)</td>
<td>3.94</td>
<td>4.18</td>
<td>4.39</td>
<td>4.59</td>
<td>4.77</td>
<td>4.96</td>
<td>5.1</td>
</tr>
<tr>
<td>( E_{\text{eye}} ) (V)</td>
<td>0.40</td>
<td>0.42</td>
<td>0.43</td>
<td>0.44</td>
<td>0.45</td>
<td>0.45</td>
<td>0.46</td>
</tr>
</tbody>
</table>

Table 2. Jitter and eye-opening with R-terminator only.

3.1 Transmission Line with Resistive Terminator

Table 2 depicts the eye diagram of the transmission line with resistive terminator. The first row lists the termination resistance ranging from 70 to 140Ω. The next three section of rows describe the simulation results on the eye diagram, the step input response, and the eye diagram derived from the step input response. Jitter^E, \( V_{\text{eye}} \). The last two groups display the predicted step input response and the predicted eye diagram, Jitter^E, \( V_{\text{eye}} \).

The eye diagram estimated by the step input response matches the simulated results. The estimated eye height \( V_{\text{eye}} \) is almost the same as the simulated result. The estimated jitter follows the trend of the simulation results by a factor of 2.2-3.1.

For the analytical formula, the saturate voltage \( V_{\text{p}} \) matches the simulation result. The maximum voltage \( V_{\text{max}} \) deviates from the simulation result by only 7%. The rise voltage \( V_{\text{r}} \) looks different from the simulation result. However, after multiplying by a factor 1.3, the revised rising voltage \( V_{\text{r}} \) fits the simulation result with an error smaller than 3%. Thus, we use the revised rising voltage \( V_{\text{r}} \) to predicted eye height \( V_{\text{eye}} \) and jitter Jitter^E.

3.2 Transmission Line with Shunt Resistors

Table 3.4 lists the result of transmission line with shunt resistors. The top two rows describes the shunt resistance per centimeter. The eye height \( V_{\text{eye}} \) derived from step input response deviates from the simulation result by up to 15%. The jitter Jitter^E derived from step input response differs from the simulation result by a factor ranging from 1.9 to 3.

For the analytical formula, the saturate voltage \( V_{\text{p}} \) matches the simulation result. The maximum voltage \( V_{\text{p}} \) deviates from the simulation result by only 1.8%. After multiplying by a factor 1.3, the revised rising voltage \( V_{\text{r}} \) fits the simulation result with an error smaller than 5%.

3.3 Transmission Line with Terminator and Shunt Resistors

Table 4 and 5 list the result of transmission line with terminator and shunt resistors. The top two rows describes the termination resistance and the shunt resistance per centimeter. In table 4, we fix the termination resistance at 100Ω and use shunt resistance from 1200Ω to 1800Ω. In table 5, we fix the shunt resistance at 1400Ω and use termination resistance from 80Ω to 140Ω. The eye height \( V_{\text{eye}} \) derived from step input response deviates from the simulation result by up to 3.6%. The jitter Jitter^E derived from step input response differs from the simulation result by a factor ranging from 2.1 to 3.4.

For the analytical formula, the saturate voltage \( V_{\text{p}} \) matches the simulation result. The maximum voltage \( V_{\text{p}} \) deviates from the simulation result by 10%. After multiplying by a factor 1.3, the revised rising voltage \( V_{\text{r}} \) fits the simulation result with an error smaller than 5%.

3.4 Comparison of Four Cases of Transmission Lines

Table 6 reports the comparison of four cases of transmission lines. We add a naked wire without termination and shunt resistance. We choose the best result of each case in terms of the \( V_{\text{eye}} \)/jitter. The line with terminator and shunt resistors has the best \( V_{\text{eye}} \)/jitter = 0.54/4.2 = 0.12. The naked line requires power 4.2mW which is minimal in all four cases. However, after we normalize with the eye height, the naked line has \( P/V_{\text{eye}}^2 = 86.7 \) which is the worst among all.

We present the naked T-line eye-diagram in figure 5. Notice that the jitter value is 66.5ps. Figures 5-8 present the eye diagrams of the four cases in table VI. For the naked
Table 3. Jitter and eye-opening with R-shunt only.

<table>
<thead>
<tr>
<th>R-t (Ω)</th>
<th>100</th>
<th>100</th>
<th>100</th>
<th>100</th>
<th>100</th>
<th>100</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jitter (ps)</td>
<td>5.51</td>
<td>5.56</td>
<td>5.80</td>
<td>5.91</td>
<td>5.82</td>
<td>5.91</td>
</tr>
<tr>
<td>V_{eye} (v)</td>
<td>0.47</td>
<td>0.48</td>
<td>0.48</td>
<td>0.47</td>
<td>0.47</td>
<td>0.47</td>
</tr>
<tr>
<td>V_{max}</td>
<td>0.59</td>
<td>0.61</td>
<td>0.61</td>
<td>0.61</td>
<td>0.61</td>
<td>0.61</td>
</tr>
<tr>
<td>V_{I}</td>
<td>0.54</td>
<td>0.55</td>
<td>0.55</td>
<td>0.55</td>
<td>0.56</td>
<td>0.57</td>
</tr>
<tr>
<td>V_{sat}</td>
<td>0.57</td>
<td>0.57</td>
<td>0.57</td>
<td>0.58</td>
<td>0.59</td>
<td>0.59</td>
</tr>
<tr>
<td>Jitter_{p} (ps)</td>
<td>11.8</td>
<td>14.8</td>
<td>20.5</td>
<td>21.5</td>
<td>19.2</td>
<td>21.2</td>
</tr>
<tr>
<td>E_{eye} (v)</td>
<td>0.47</td>
<td>0.47</td>
<td>0.45</td>
<td>0.46</td>
<td>0.49</td>
<td>0.49</td>
</tr>
<tr>
<td>V_{max}</td>
<td>0.38</td>
<td>0.61</td>
<td>0.64</td>
<td>0.65</td>
<td>0.68</td>
<td>0.69</td>
</tr>
<tr>
<td>V_{I}</td>
<td>0.39</td>
<td>0.41</td>
<td>0.42</td>
<td>0.44</td>
<td>0.45</td>
<td>0.46</td>
</tr>
<tr>
<td>V_{sat}</td>
<td>0.51</td>
<td>0.53</td>
<td>0.55</td>
<td>0.57</td>
<td>0.59</td>
<td>0.60</td>
</tr>
<tr>
<td>Jitter_{p} (ps)</td>
<td>1.6764</td>
<td>1.6166</td>
<td>1.5659</td>
<td>1.5224</td>
<td>1.484</td>
<td>1.451</td>
</tr>
<tr>
<td>E_{eye} (v)</td>
<td>0.477</td>
<td>0.495</td>
<td>0.511</td>
<td>0.526</td>
<td>0.539</td>
<td>0.55</td>
</tr>
</tbody>
</table>

Table 4. Eye-opening and jitter by gradually adjust R-shunt and R-terminator.

<table>
<thead>
<tr>
<th>R-t (Ω)</th>
<th>100</th>
<th>100</th>
<th>100</th>
<th>100</th>
<th>100</th>
<th>100</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jitter (ps)</td>
<td>4.539</td>
<td>5.266</td>
<td>5.932</td>
<td>6.661</td>
<td>7.144</td>
<td>7.543</td>
</tr>
<tr>
<td>V_{eye} (v)</td>
<td>0.459</td>
<td>0.473</td>
<td>0.482</td>
<td>0.497</td>
<td>0.497</td>
<td>0.451</td>
</tr>
<tr>
<td>V_{max}</td>
<td>0.6</td>
<td>0.6</td>
<td>0.61</td>
<td>0.61</td>
<td>0.61</td>
<td>0.62</td>
</tr>
<tr>
<td>V_{I}</td>
<td>0.55</td>
<td>0.55</td>
<td>0.55</td>
<td>0.55</td>
<td>0.56</td>
<td>0.56</td>
</tr>
<tr>
<td>V_{sat}</td>
<td>0.57</td>
<td>0.57</td>
<td>0.57</td>
<td>0.57</td>
<td>0.57</td>
<td>0.58</td>
</tr>
<tr>
<td>Jitter_{p} (ps)</td>
<td>11.8</td>
<td>14.8</td>
<td>20.5</td>
<td>21.5</td>
<td>22.3</td>
<td>25.8</td>
</tr>
<tr>
<td>E_{eye} (v)</td>
<td>0.47</td>
<td>0.47</td>
<td>0.45</td>
<td>0.45</td>
<td>0.47</td>
<td>0.46</td>
</tr>
<tr>
<td>V_{max}</td>
<td>0.38</td>
<td>0.61</td>
<td>0.63</td>
<td>0.66</td>
<td>0.68</td>
<td>0.69</td>
</tr>
<tr>
<td>V_{I}</td>
<td>0.39</td>
<td>0.41</td>
<td>0.42</td>
<td>0.44</td>
<td>0.45</td>
<td>0.46</td>
</tr>
<tr>
<td>V_{sat}</td>
<td>0.51</td>
<td>0.53</td>
<td>0.55</td>
<td>0.57</td>
<td>0.59</td>
<td>0.60</td>
</tr>
<tr>
<td>Jitter_{p} (ps)</td>
<td>1.345</td>
<td>3.649</td>
<td>3.827</td>
<td>3.99</td>
<td>4.14</td>
<td>4.28</td>
</tr>
<tr>
<td>E_{eye} (v)</td>
<td>0.34</td>
<td>0.35</td>
<td>0.36</td>
<td>0.36</td>
<td>0.37</td>
<td>0.38</td>
</tr>
</tbody>
</table>

Table 5. Optimal solution approach by gradually adjust R-shunt and R-terminator.

transmission line (Fig. 5), no terminators are used. The jitter 66.5ps is more than half the clock cycle 100ps. For the case of the terminator or shunt only, we use termination resistor $R_t = 70\Omega$ and shunt resistor $R_s = 1000\Omega$, respectively. The jitters are 7.4ps and 18.1ps (Figs. 6,7). The composite effect of both shunt resistor ($R_s = 1450\Omega$) and terminator ($R_t = 80\Omega$) reduces the jitter down to 4.2ps with clear trace of the eye diagram (Fig. 8).

4 Conclusion

In this paper, we have developed a transmission line scheme faster yet lower power compare with most existing work. We evenly insert shunt resistor and put termination resistor in the receiver end. The experimental results show that our scheme can tolerate higher frequency and is up to
1.76x and 4.3x faster compared with the existing naked T-line and T-line with R-terminator, and up to 5.6x than only using shunt resistor insertions. Theoretical analysis are also derived to predict the worst case jitter and eye-opening for our schemes and the other two comparison cases based on bitonic step response assumption[3].

Potentially, the proposed technique has applications in designing low-skew clock trees, and our future work includes incorporating transmitter/receiver design and prototype chip fabrication.

Acknowledgments

We would like to acknowledge UC-MICRO fund and IBM Faculty Award. The comments of the anonymous reviewers are appreciated. The authors thank Prof. Wenjian Yu for useful discussion.

References


