Improving Power Supply Induced Jitter Simulation Accuracy

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Ku(t) & Kd(t) Modification (An Example)

Modify Ku(t), Kd(t) as a function of **time averaged** power rail voltage Vcc(t); introduce correction coefficient A and B as a function of **time**

$$K_u(t) = K_{u0}(t) + B_u(t)\cdot\left[\frac{\int_0^t V_{cc}(\tau)d\tau}{t} - V_{cc0}\right] + A_u(t)\left[\frac{\int_0^t V_{cc}(\tau)d\tau}{t} - V_{cc0}\right]^2$$

$$K_d(t) = K_{d0}(t) + B_d(t)\cdot\left[\frac{\int_0^t V_{cc}(\tau)d\tau}{t} - V_{cc0}\right] + A_d(t)\left[\frac{\int_0^t V_{cc}(\tau)d\tau}{t} - V_{cc0}\right]^2$$

Eqns are modified based on Curtis Clark's comments

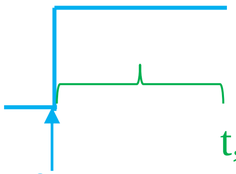
Ku, Kd under nominal Vcc (typical)

Linear fitting coefficient

Quadratic fitting coefficient

Average value of Vcc(t)

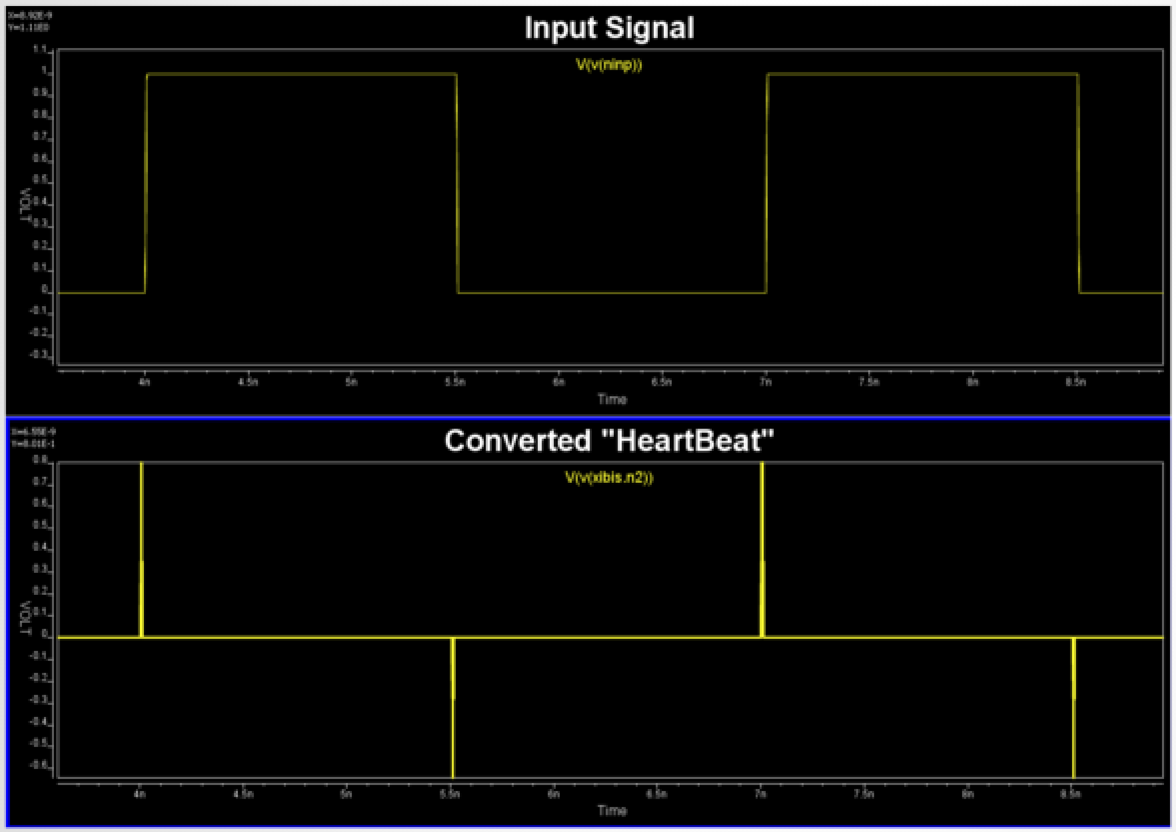
Previous method on modification of Ku, Kd does not consider the time averaged effect;
Source: Behavioral modeling of jitter due to power supply noise for input/output buffers (US Patent 9842177B1)



Implementation in Open-Source Spice (Ngspice)

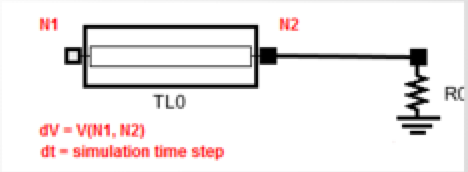
Implementation in Ngspice (Modify based on current ibis2spice algorithm)

1. Ku0, Kd0, Bu, Au, Bd, Ad calculated offline from rising/falling waveforms
2. From input switching edge dv/dt, judging rising or falling



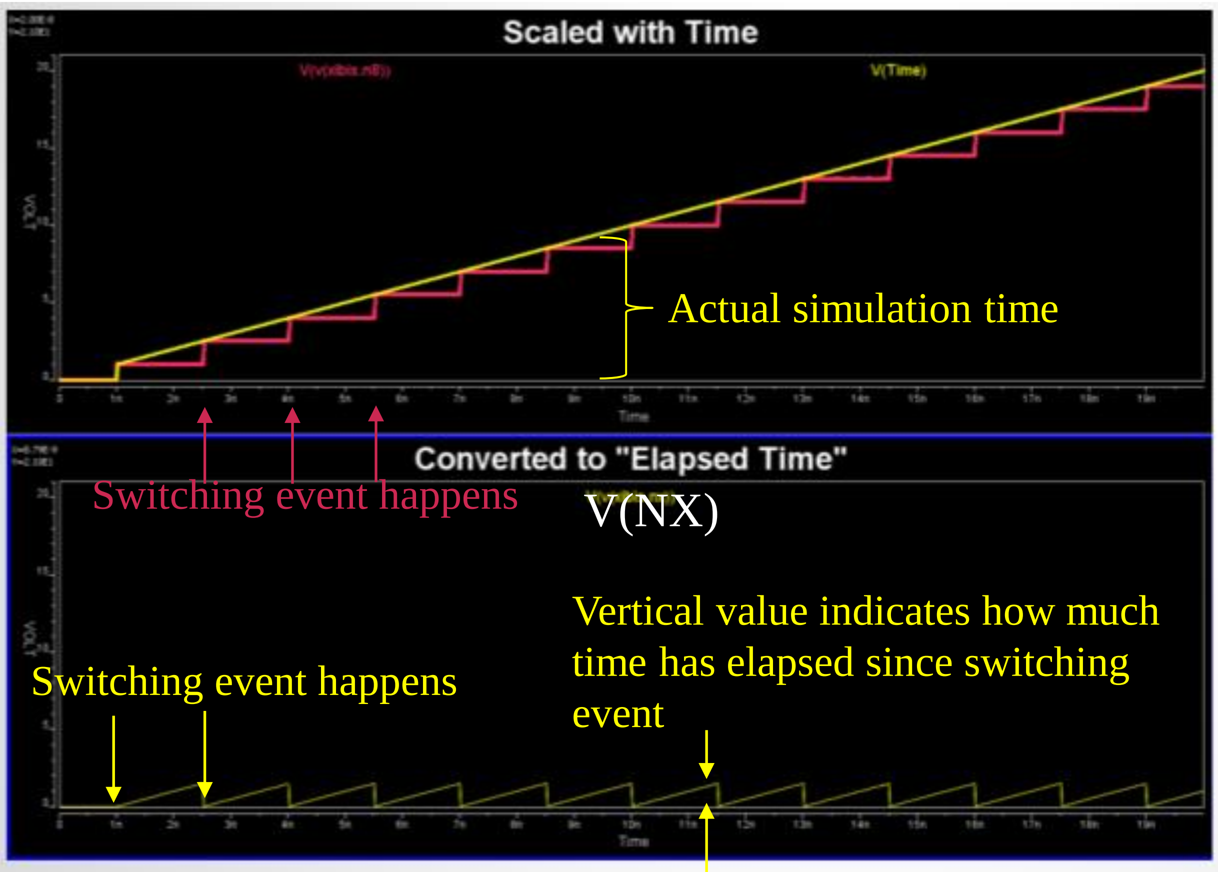
Source:
http://www.spisim.com/blog/ibis2spice_p1/
http://www.spisim.com/blog/ibis2spice_p2/

Use a transmission line to realize the differentiation



Implementation (Cont.)

3. Record elapsed time since every switching event



Source:
http://www.spisim.com/blog/ibis2spice_p1/
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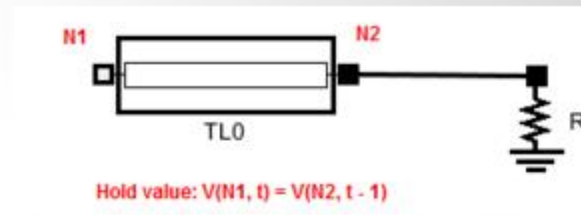


The level hold (latch) realized with an ideal transmission line

t - value hold

Implementation (Cont.)

4. Implement the time averaged Vcc

```
* INPUT CONTROL
BN NINX 0 V= ((V(NINP) > 0.5) & (V(NENB) > 0.5))? 1.0 : 0.0

* CONTROL LOGIC
BI NI 0 V=(V(NINX) - 0.5)
B2 N2 0 V=V(NI, N9) * 8
B3 N3 0 V=abs(V(N2))
B4 N4 0 V=(V(N3) > 0.5)? 1 : -1
B5 N5 0 V=V(N4) > 0? TIME * 1E9: 0
B6 N6 0 V=V(N4) > 0? V(N5) : V(N8)
B7 NX 0 V=(V(N6) >= 1.0)? TIME * 1E9 - V(N8) : 0.0
B8 NT1 0 V=(V(NX) > 0.01)? (V(NVCC)*0.001-1.8*0.001+V(NTD)) : 0.0
B9 NT 0 V=(V(NX) > 0.01)? V(NT1)/V(NX) : 0.0

* DELAY ELEMENT: Td value must match time-step
T1 N6 0 N8 0 Z0=50 Td=1p
T2 NI 0 N9 0 Z0=50 Td=1p
T3 NT1 0 NTD 0 Z0=50 Td=1p
R1 N8 0 50
R2 N9 0 50
R3 NTD 0 50
```

Vcc

Vcc0

V(NT1) store the summation of Vcc voltage since start of switching

Realized by:
Vcc+V(NTD)

V(NX) time elapsed since the switching

V(NT) is the time averaging of Vcc

$$\frac{\int_0^t V_{cc}(\tau)d\tau}{t}$$

Implementation (Cont.)

5. Implement the modified Ku, Kd as B source

V(1,2) is V(NX), time elapsed since switching event;
V(3,4) is the Ku or Kd value
V(5) is the time averaged Vcc

Original Ku implementation: Ku0(t)

```
* KU COEF RISE
.SUBCKT driver_TYP_KU_R 3 4 1 2
B1 3 4 V =
+ (V(1,2) < 0.000000E0)? 0.000000E0:
+ (V(1,2) < 3.622352E-3)? 1.287944E1 * V(1,2) + 0.000000E0:
+ (V(1,2) < 7.244704E-3)? -7.295161E-5 * V(1,2) + 4.665411E-2:
```

Modified Ku implementation

```
* KU COEF RISE
.SUBCKT driver_TYP_KU_R 3 4 1 2 5
B1 3 4 V =
+ (V(1,2) < 0.000000E0)? 0.000000E0:
+ (V(1,2) < 0.0036223520000000)? 12.8794400000000007 * V(1,2) + 0.0000000000000000
+ (V(1,2) < 0.0072447040000000)? -0.0000729516100000 * V(1,2) + 0.0466541100000000
```

Ku0(t)

```
+ (0.0000251111959497 * V(1,2) + -0.1034584500000000) * V(5) + (0.0039680452540881 * V(1,2) + -7.5443674999999999) * V(5) * V(5) :
+ (0.0002022823036612 * V(1,2) + -0.1034590917761164) * V(5) + (0.0091645843101826 * V(1,2) + -7.5443863236936428) * V(5) * V(5) :
```

Bu(t) Au(t)

B source in Ngspice to store tabulated data

5.1 Bxxxx: Nonlinear dependent source (ASRC)

5.1.1 Syntax and usage

General form:

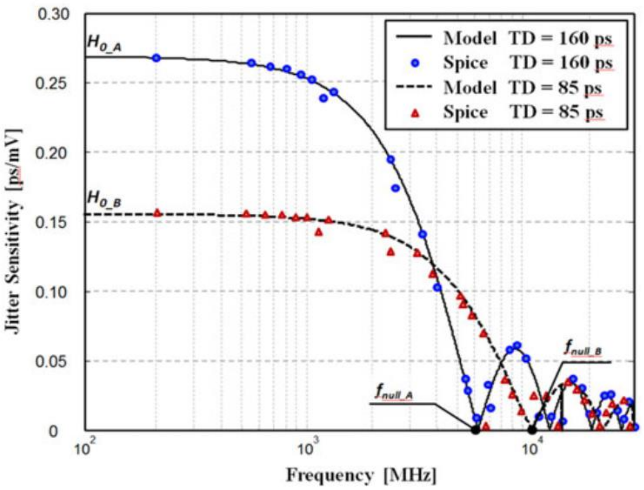
```
BXXXXXXX n+ n- <i=expr> <v=expr> <tc1=value> <tc2=value>
+ <temp=value> <dtemp=value>
```

Examples:

```
B1 0 1 I=cos(v(1))+sin(v(2))
B2 0 1 V=ln(cos(log(v(1,2)^2)))-v(3)^4+v(2)^v(1)
B3 3 4 I=17
B4 3 4 V=exp(pi^i(vdd))
B5 2 0 V = V(1) < {Vlow} ? {Vlow} : V(1) > {Vhigh} ? {Vhigh} : V(1)
```

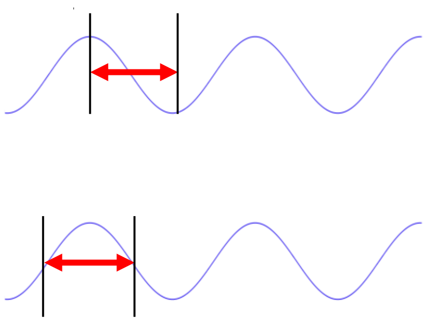
Discussion - Why Propagation Delay Needed?

1) Different propagation delay, different breaking frequency



Y. Shim and D. Oh, System Level Modeling of Timing Margin Loss Due to Dynamic Supply Noise for High-Speed Clock Forwarding Interface, TEMC, 2016

2) Just a jitter sensitivity number (ps/mV) is not enough



- Jitter could be different even for the same frequency power noise
- Muti-tone power noise case

Discussion – typ/min/max variation

Comments from the previous meeting

- Rising/falling waveforms may not have the same t=0 reference across typ/mix/max variants.

- typ/min/max variations represent process and temperature, not just voltage

➔ Using typ/min/max variations for PSIJ simulation seems to be challenging

➔ Only voltage variation needs to be included

➔ Propagation delay + jitter sensitivity @DC

New Keyword

[XYZ] | this keyword provides information on power supply induced jitter and additional internal path delay

| Parameter	typ	min	max
dt/dv	0.166	NA	NA
int_path_delay	0.20e-9	0.19e-9	0.21e-9

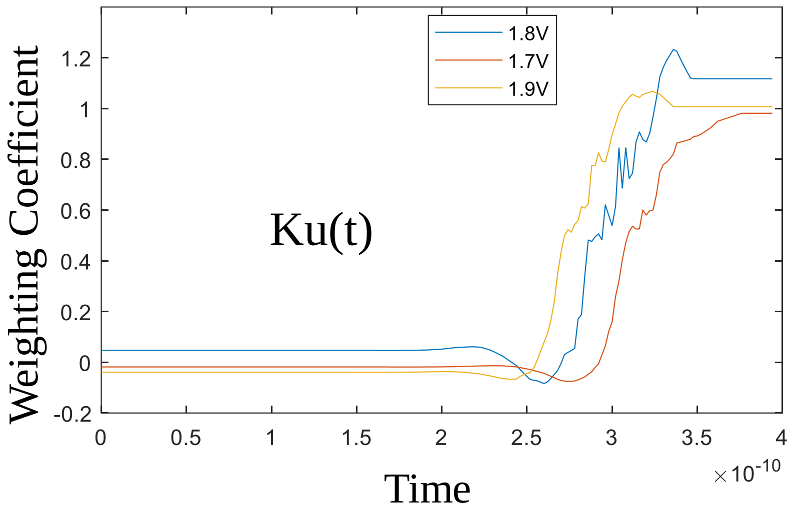
dt/dv: jitter sensitivity at DC (seconds/volt) for the entire path (internal path + buffer)

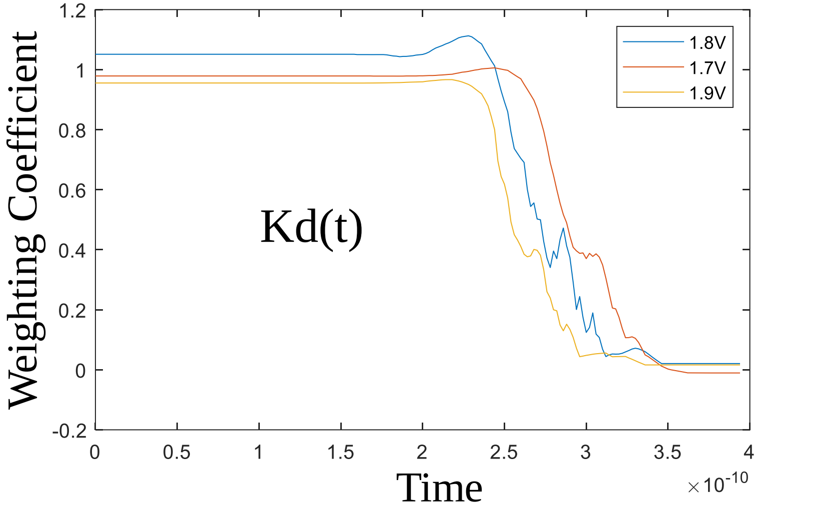
Internal path delay: delay to be added to Ku(t)/Kd(t)

[Initial Delay] could replace this with an appropriate time 0.

Extracted Ku(t) and Kd(t)

- How the modified Ku(t), Kd(t) account for Vcc(t) caused delay change





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$$K_d(t) = K_{d0}(t) + B_d(t) \cdot \left[\frac{\int_0^t V_{cc}(\tau)d\tau}{t} - V_{cc0} \right] + A_d(t) \left[\frac{\int_0^t V_{cc}(\tau)d\tau}{t} - V_{cc0} \right]^2$$

1. At each time point, use Ku, Kd under three cases => B(t), A(t);

2. B(t), A(t) can account for the delay change due to Vcc(t) noise;

3. The total effect of Vcc(t) during the time range of propagation delay is considered by the time-averaged Vcc(t)