Useful Skew Design Flow: How To?

Wai-Shing Luk

Fudan University

2017-11-16

Useful Skew Design: Why vs. Why Not

Why not

- Need more engineer training.
- Balanced clock-tree is more difficult to build.
- Don't know how to handle process variation, multi-corner multi-mode, ..., etc.

Why

If you do it correctly,

- spend less time for struggling timing issues.
- obtain better chip performance or yield.

Clock Arrival Time vs. Clock Skew

- Clock signal runs periodically.
- Thus, absolute clock arrival time u_i is not so important.
- Instead, the skew $y_{ij} = u_j - u_i$ is more important in this scenario.

Useful Skew Design vs. Zero-Skew Design

- "Critical cycle" instead of "critical path".
- "Negative cycle" instead of "negative slack".
- If there is a negative cycle, it means that there is no positive slack solution no matter how to schedule.
- Others are pretty much the same.
- Same design principle:
    - Always tackle the most critical one first!

Linear Programming vs. Network Flow Formulation

- Linear programming formulation
  - can handle more complex constraints
- Network flow formulation
  - usually more efficient
  - return the most critical cycle as a bonus.
  - can handle quantized buffer delay (???)
- Anyway, timing analysis is much more time-consuming than the optimization solving.

Target Skew vs. Actual Skew

Don't mess up these two concepts:

- Target skew:
  - the skew we want to achieve in the scheduling stage.
  - Usually deterministic (we schedule a meeting at 10:00, rather than 10:00 $\pm$ 34 minutes, right?)
- Actual skew
  - the skew that the clock tree actually generates.
  - Can be formulated as a random variable.

Background Knowledge

A Simple Case

To warm up, let us start with a simple case:

- Assume equal path delay variations.
- Single-corner.
- Before a clock tree is built.
- No adjustable delay buffer (ADB).

Network

Definition (Network)

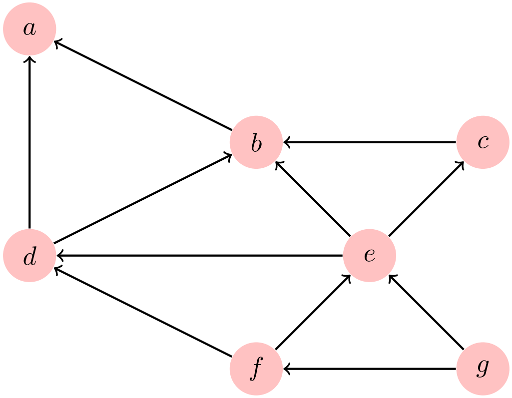
A *network* is a collection of finite-dimensional vector spaces of *nodes* and *edges/arcs*:

- $V = \{v_1, v_2, \cdots, v_N\}$, where $|V| = N$
- $E = \{e_1, e_2, e_3, \cdots, e_M\}$ where $|E| = M$

which satisfies 2 requirements:

1. The boundary of each edge is comprised of the union of nodes
2. The intersection of any edges is either empty or a boundary node of both edges.

Example:



Orientation

Definition (Orientation):

An *orientation* of an edge is an ordering of its boundary node (s, t), where

- s is called a source/initial node
- t is called a target/terminal node

Definition (Coherent):

Two orientations to be the same is called *coherent*

Node-edge Incidence Matrix

Definition (Incidence Matrix):

A $N \times M$ matrix A^T is a node-edge incidence matrix with entries:

$$A(i,j) = \begin{cases} +1 & \text{if } e_i \text{ starts at node } v_j \text{ ,} \\ -1 & \text{if } e_i \text{ ends at node } v_j \text{ ,} \\ 0 & \text{otherwise .} \end{cases}$$

Example:

$$A^T = \begin{bmatrix} 0 & -1 & 1 & 1 & 0 \\ 1 & 1 & 0 & -1 & -1 \\ -1 & 0 & -1 & 0 & 1 \end{bmatrix}$$

Timing Constraint

- Setup time constraint

$$y_{skew}(i,f) \leq T_{CP} - D_{if} - T_{setup} = u_{if}$$

While this constraint destroyed, cycle time violation (zero clocking) occurs.

- Hold time constraint

$$y_{skew}(i,f) \geq T_{hold} - d_{if} = l_{if}$$

While this constraint destroyed, race condition (double clocking) occurs.

Timing Constraint Graph

- Create a graph (network) by
  - replacing the hold time constraint with an *h-edge* with cost $-(T_{hold} - d_{ij})$ from FF_i to FF_j, and
  - replacing the setup time constraint with an s-edge with cost $T_{CP} - D_{ij} - T_{setup}$ from FF_j to FF_i.
- Two sets of constraints stemming from clock skew definition:
  - The sum of skews for paths having the same starting and ending flip-flop to be the same;
  - The sum of clock skews of all cycles to be zero

Timing Constraint Graph (TCG)

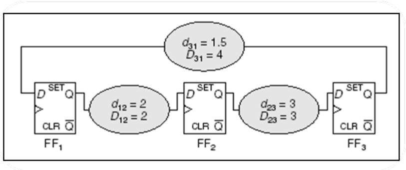


Figure 1: Example circuit

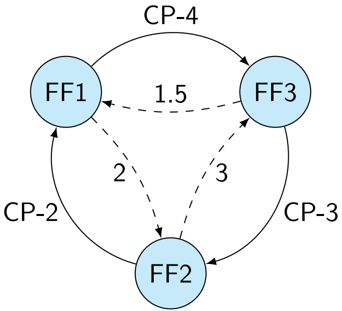


Figure 2: Timing Constraint Graph (Assume $T_{\text{setup}} = T_{hold} = 0$)

First Thing First

Meet all timing constraints

- Find y in $\{y \in \mathbb{R}^n \mid y \leq d, A\,u = y\}$
- How to solve:
  1. Find a negative cycle, fix it.
  2. Iterate until no negative cycle is found.
- Bellman-Ford algorithm (and its variants are publicly available):
  - Strongly suggest "Lazy Evaluation":
    - Don't do full timing analysis on the whole timing graph at the beginning!
    - Instead, perform timing analysis only when the algorithm needs.
  - Stop immediately whenever a negative cycle is detected.

Delay Padding (DP)

- Delay padding is a technique that fixes the timing issue by intentionally **solely** "increasing" delays.
- Usually formulated as:
  - Find p, y in $\{p, y \in \mathbb{R}^n \mid y \leq d + p, A\, u = y, p \geq 0\}$
- If the objective is to minimize the sum of p, then the problem is the dual of the standard *min-cost flow* problem, which can be solved efficiently by the *network simplex* algorithm (publicly available).
- Beautiful right?

Delay Padding (cont'd)

- No, the above formulation is not practical.
- In modern design, “inserting” a delay may mean swapping a faster cell with a slower cell from the cell library. Thus, no need to minimize the sum of p.
- More importantly, it may not be possible to find a position to insert delay for some delay paths.
- Some papers consider only allowing insert delays to the max-delay path only. Some papers consider only allowing insert delays to both the max- and min-delay paths together only. None of them are perfect.

Delay Padding (cont'd)

- My suggestion. Instead of calculating the necessary $p's$ and then look for the suitable position to insert, it is easier (and more flexible) to determine the position first and then calculate the suitable values.
- It can be achieved by modifying the timing graph and solve a feasibility problem. Easy enough!
- Quantized delay can be handled too (???).

Four possible ways to insert delay

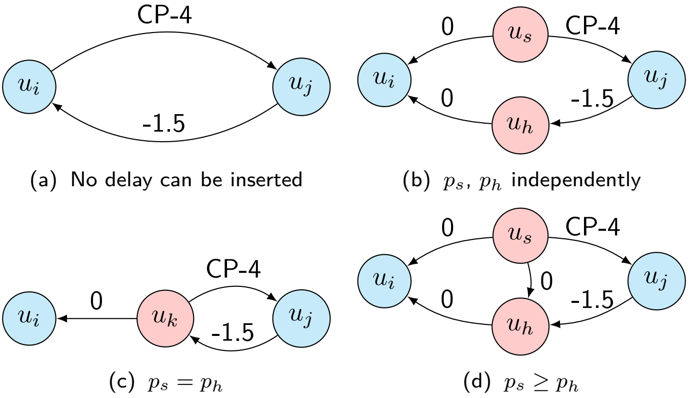


Figure 3:

Delay Padding (cont'd)

- If there exists a negative cycle in the modified timing graph, it implies that the timing problem cannot be fixed by simply the delay padding technique.
  - Then, try decrease D_{ij}, or increase T_{CP}
- Be aware of the min-delay path is still the min-delay path after a certain amount of delay is inserted (how???).

Variation Issue

Yield-driven Clock Skew Scheduling

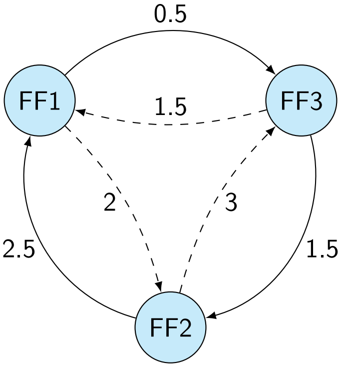
- Assume all timing issues are fixed.
- Now, how to schedule the arrival times to maximize yield?
- According to the critical-first principle, we seek for the most critical cycle first.
- The problem can be formulated as:
  - $\max\{\beta \in \mathbb{R} \mid y \le d - \beta, A\,u = y\}$.
- It is equivalent to the *minimum mean cycle* problem, which can be solved efficiently by for example *Howard's algorithm* (publicly available).

Minimum Balancing Algorithm

- Then we evenly distribute the slack on this cycle.
- To continue the next most critical cycle, we contract the first one into a "super vertex" and repeat the process.
- The process stops when the timing graph remains only a single vertex.
- The overall method is known as *minimum balancing* (MB) algorithm in the literature.

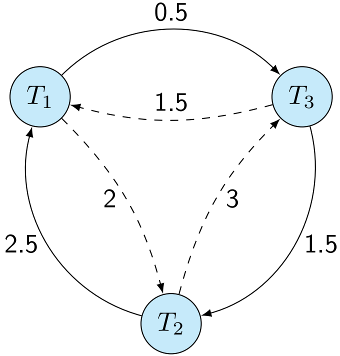
Example: Most timing-critical cycle

The most vulnerable timing constraint



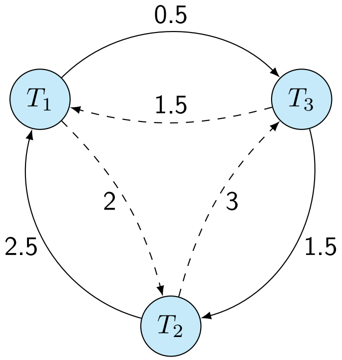
Example: Distribute the slack

- Distribute the slack evenly along the most timing-critical cycle.



Example: Distribute the slack

- Distribute the slack evenly along the most timing-critical cycle.



$-1.5 \leq T_3 - T_1 \leq 0.5$

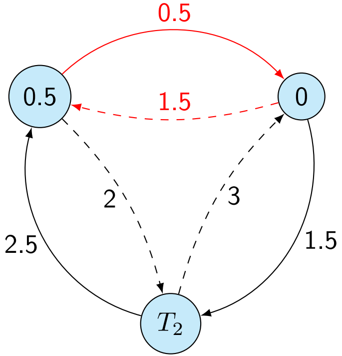
$\Downarrow$

$T_3 - T_1 = -0.5$ **evenly**

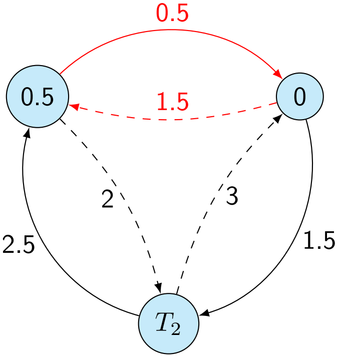
$\Downarrow$ *$T_3 = 0$*

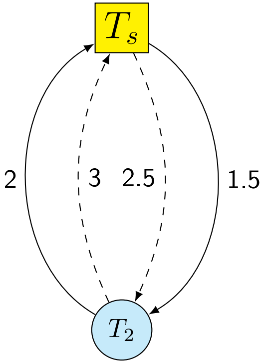
$T_1 = 0.5 \quad T_3 = 0$

- To determine the optimal slacks and skews for the rest of the graph, we replace the critical cycle with a super vertex.

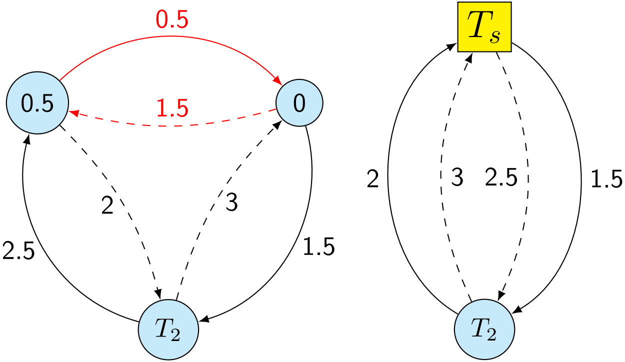


- To determine the optimal slacks and skews for the rest of the graph, we replace the critical cycle with a super vertex.





- To determine the optimal slacks and skews for the rest of the graph, we replace the critical cycle with a super vertex.

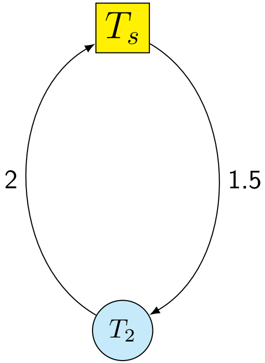


$T_1 - T_2 \leq 2.5$
$T_2 - T_1 \leq 2$

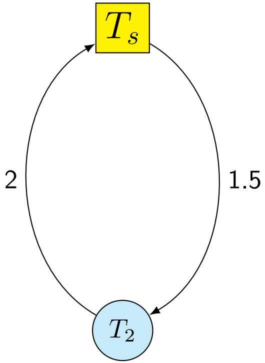
$(0.5+T_s) - T_2 \leq 2.5$
$T_2 - (0.5+T_s) \leq 2$

$T_s - T_2 \leq 2$
$T_2 - T_s \leq 2.5$

Repeat the process iteratively



Repeat the process iteratively



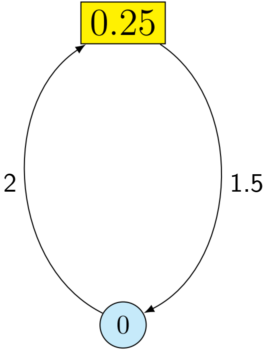
$-2 \leq T_2 - T_s \leq 1.5$

$T_2 - T_s = -0.25$ **evenly**

$T_2 = 0$

$T_2 = 0 \quad T_s = 0.25$

Repeat the process iteratively



$$-2 \le T_2 - T_s \le 1.5$$

$$\Downarrow$$

$$T_2 - T_s = -0.25$$ **evenly**

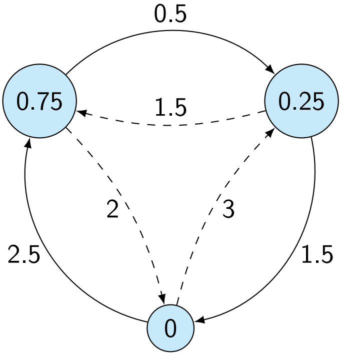
$$\Downarrow \; T_2 = 0$$

$$T_2 = 0 \quad T_s = 0.25$$

Final result

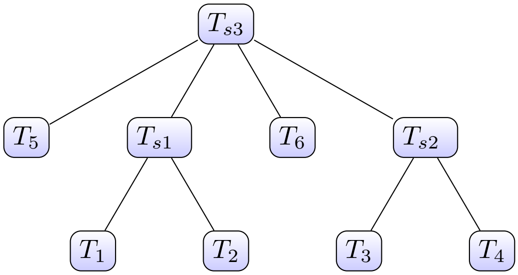
- $\text{Skew}_{12} = 0.75$
- $\text{Skew}_{23} = \text{-}0.25$
- $\text{Skew}_{31} = \text{-}0.5$
- $\text{Slack}_{12} = 1.75$
- $\text{Slack}_{23} = 1.75$
- $\text{Slack}_{31} = 1$

where $\text{Slack}_{ij} = \text{CP - D}_{ij} \text{ - T}_{\text{setup}} \text{ - Skew}_{ij}$



What the MB algorithm really give us?

- The MB algorithm not only give us the scheduling solution, but also a tree-topology that represents the order of “criticality”!



Clock-tree Synthesis and Placement

- I strongly suggest that the topology of the clock-tree precisely follows the order of "criticality"!
  - since the lower branch of clock-tree has smaller skew variation.
- I also suggest that the placer should follow the topology of the clock-tree:
  - Physically place the registers of the same branch together.
  - The locality implies stronger correlation of variations and implies even smaller skew variation due to the cancellation effect.
  - Note that the current SSTA does not provide the correlation information, so this is the best you can do!

Second Example: Yield-driven Clock Skew Scheduling

- Now assume that SSTA (or STA+OCV, POCV, AOCV) is performed.
- Let ($\bar{d}$, s) be the (mean, variance) of $\mathbf{d}$
- The most critical cycle can be obtained by solving:
  - $\max\{\beta \in \mathbb{R} \mid y \leq \bar{d} - \beta s, A\,u = y\}$
- It is equivalent to the minimum cost-to-time ratio cycle problem, which can be solved efficiently by for example Howard's algorithm (publicly available).
- Gaussian distribution is assumed. For arbitary distribution, see my DAC'08 paper.

What About the Correlation?

- In the above formulation, we minimum the maximum possibility of timing violation of each *individual* timing constraint. So only individual delay distribution is needed.
- Yes, the objective function is not the true timing-yield. But it is reasonable, easy to solve, and is the best you can do so far.

Multi-Corner Issue

Meet all timing constraints in Multi-Corner:

- Assume no Adjustable Delay Buffer (ADB)
- Find y in $\{y \in \mathbb{R}^n \mid y \leq d^{(k)}, A\,u = y, \forall k \in [1..K]\}$
- Equivalent to finding y in $\{y \in \mathbb{R}^n \mid y \leq \min_k\{d^{(k)}\}, A\,u = y\}$
- Feasibility problem
- How to solve:
  1. Find a negative cycle, fix it.
  2. Iterate until no negative cycle is found.
- Better avoid fixing the timing issue corner-by-corner. Inducing ping-pong effect.

Delay padding (DP) in Multi-Corner

- The problem CANNOT be formulated as a network flow problem. But still you can solve it by a linear programming formulation.
- Or, decomposite the problem into subproblems for each corner.
- Again use the modified timing graph technique.
- Then, y's are shared variables of subproblems.
- If we solve each subproblem individually, the solution will not agree with each other. Induce *ping-pong effect*.
- Need something to drive the agreement.

Delay Padding (DP) in Multi-Corner (cont'd)

- Follow the idea of *dual decomposition*: If a solution is above the average. then introduce a punishment cost. If a solution is below the average, then introduce a rewarding cost.
- Then, each subproblem is a min-cost potential problem, which can be solved efficiently.
- If some subproblems do not have feasible solutions, it implies that the problem cannot be fixed by simply delay padding.
- The process repeats until all solutions converge. If not, it implies that the problem cannot be fixed by simply delay padding.

Yield-driven Clock Skew Scheduling:

- $\max\{\beta \in \mathbb{R} \mid y \leq d^{(k)} - \beta s, A\,u = y, \forall k \in [1..K]\}$
- More or less the same as in Single Corner.

Clock-Tree Issue

Clock Tree Synthesis (CTS)

- Construct merging location
  - DME algorithm, Elmore delay, buffer insertion
- Some research on *bounded-skew DME algorithm*. But the algorithm is too complicated in my opinion.
- If the previous stage is over-optimized, the clock tree is hard to implement. If it happens, some budgeting techniques should be invoked (engineering issue)
- After a clock tree is constructed, more accurate timing (rather than Elmore delay) can be obtained via timing analysis.

Co-optimization Issue

- After a clock tree is built, we have a clearer picture.
- Should I perform the re-scheduling? And how?
- Some papers suggest adding a factor to the timing constraint, say:

$$1.2u_i - 0.8u_j \leq w_{ij}$$

.

- Then the formulation is not a kind of network-flow, but may still be solvable by linear programming.
- Need to investigate more deeply.

Adjustable Delay Buffer Issue

Adjustable delay buffers in Multi-Mode

- Assume adjustable delay buffers are added solely to the clock tree
- Hence, each mode can have a different set of arrival times.
- Easier for clock skew scheduling, harder for clock-tree synthesis.

Meet timing constraint in Multi-Mode:

- find $y^{(m)}$ in
  $\{y^{(m)} \in \mathbb{R}^n \mid y^{(m)} \leq d^{(m)}, A\,u^{(m)} = y^{(m)}, \forall m \in [1..M]\}$
- Can be done in parallel.
- find a negative cycle, fix it (do not need to know all $d_i^{(m)}$ at the beginning) for every mode in parallel.

Delay Padding (DP) in Multi-mode

- Again use a modified timing graph technique.
- NOT a network flow problem. Use LP, or
- Dual decomposition -> min-cost potential problem for each mode
  - Only p's are shared variables.
  - Initial feasible solution obtained by the single-mode method
    - A negative cycle => problem cannot be fixed by DP
- Not converge => problem cannot be fixed by DP
  - Try decrease D_{ij}, or increase T_{CP}

Yield-driven Clock Skew Scheduling:

- $\max\{\beta \in \mathbb{R} \mid y^{(m)} \leq d^{(m)} - \beta s, A\, u^{(m)} = y^{(m)}, \forall m \in [1..M]\}$
- Pretty much the same as Single-Mode.

Difficulty in ADB Multi-Mode Design

- How to design the clock-tree?
- What is the order of criticality?
- How to determine the minimum range of ADB?

Thank you for your attention!

Backup

```
pandoc -s -t beamer --toc useful_skew.md beamer.yaml \
       -o useful_skew.pdf
```