

# Minimize Aging-Induced Degradation of Performance using $V_{th}$ Assignment and Aging Manipulation on Clock Network

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**Abstract**—Device aging, which causes significant loss on circuit performance and lifetime, has been a primary factor in reliability degradation of nanoscale designs. In this paper, we propose to take advantage of clock skews (i.e., make them useful for aging tolerance) by manipulating these time-varying skews to compensate for the performance degradation of logic networks. We propose two methodologies of clock skew manipulation. First one is based on  $V_{th}$  assignment. The second one is to manipulate the aging behavior of clock branches. The goal is to assign achievable/reasonable clock skews in a circuit by the two approaches, such that its overall performance degradation due to aging can be minimized, that is, the lifespan can be maximized. On average, 25% aging tolerance can be achieved with insignificant design overhead.

## I. INTRODUCTION

The design and manufacturing of semiconductor devices have recently experienced dramatic innovations, at the cost of downgrading reliability of nanoscale integrated circuits (ICs) and system-on-chips (SOCs). The 2013 ITRS [1] projects that the long-term reliability of sub-100nm technology nodes can reach a noteworthy order of  $10^3$  FITs (failures in  $10^9$  hours). Soft errors, thermal and aging effects are some of the major challenges driving reliability-aware IC/SOC design techniques. With the continuous scaling of transistor dimensions, device aging, which causes temporal performance degradation and potential wear-out failure, is becoming increasingly dominant for lifetime reliability concerns because of limited timing margins [2]. Therefore, the need of a verification and optimization flow considering aging effects emerges as a key factor in guaranteeing reliable and sustainable operation over a required lifespan. *Bias temperature instability* (BTI) is known for prevailing over other device aging phenomena, in terms of dependence on the scaling of nanometer technologies. BTI [3] is a MOSFET aging phenomenon that occurs when transistors are stressed under bias (positive or negative, i.e.,  $V_{gs} = \pm V_{dd}$ ) at elevated temperature. As a result of the dissociation of Si-H bonds along the Si-SiO<sub>2</sub> interface, BTI-induced MOSFET aging manifests itself as an increase in the threshold voltage ( $V_{th}$ ) and decrease in the drive current ( $I_{ds}$ ) [4], which in turn lengthen the propagation delays of logic gates/paths. Experiments on MOSFET aging [5] indicate that BTI effects grow exponentially with higher operating temperature and thinner gate oxide. If the thickness of gate oxide shrinks down to 4nm, the circuit performance can be degraded by as much as 15% after 10 years of stress and lifetime will be dominated by BTI [6]. In contrast, when the stress condition is relaxed ( $V_{gs} = 0$ ), the aging mechanism can be recovered partially [7] and the threshold voltage decreases toward the nominal value by more than 75% if the recovery phase lasts sufficiently long [8]. In addition to the aging effect on the logic gates/paths of a circuit, the impact of aging on the clock network should not be ignored. Considering both “the aging of logic networks” and “the aging of clock networks” is essential since unbalanced aging of clock networks can greatly affect circuit performance by inducing clock skews, as a result of non-uniform increases in clock latency from the clock source to

different terminals. Prior work on addressing such clock skews due to aging (i.e., aging-induced clock skews) mainly attempts to balance the aging effects on various clock sub-networks, such that aging-induced clock skews can be minimized [9]–[11]. However, suppressing aging-induced clock skews may be difficult and costly, especially for clock-gated designs where the rate of aging varies from one clock sub-network to another [12].

Then think about the following question: if one has to work hard on (and incur significant overhead for) minimizing aging-induced clock skews but it turns out that there still exist stubborn non-zero skews, why don’t we try to take advantage of them? We do; we propose to intentionally make aging-induced clock skews useful for aging tolerance. More specifically, we compensate for the performance degradation (due to aging) of logic networks by exploring “useful” clock skews, based on the concept of time borrowing. There are two key idea in our framework: (1) The first idea is to manipulate the rates of aging on different clock branches. Note that the rate of aging depends on the stress time, defined as the amount of time during which a PMOS/NMOS transistor is stressed under negative/positive bias. For clock drivers (comprising pairs of inverters), their stress times are proportional to the duty cycle of the clock signal. Therefore, our aging manipulation on clock branches is achieved by changing the duty cycle of a clock waveform delivered to each of the clock branches. (2) The second idea is based on  $V_{th}$  assignment. That is, the threshold voltages of certain clock buffers are replaced with higher value, such that the delay of the clock buffers are lengthened. The two idea are utilized together to implement the concept of timing borrowing in the designs, such that aging-induced performance degradation can be mitigated effectively, with little design penalty.

## II. RELATED WORK AND PAPER CONTRIBUTION

### A. Previous Work on Aging-Aware Optimization

To deal with aging phenomena, traditional design methods adopt guard-banding by adding extra timing margins, which in practice imply over-design and may be expensive. To avoid overly conservatism, the mitigation of aging-induced performance degradation can be formulated as a timing-constrained area minimization problem with consideration of aging effects. Existing aging-aware techniques basically follow this formulation. A novel technology mapper considering signal probabilities for NBTI was developed in [13]. On average, 10% area recovery and 12% power saving are accomplished, as compared to the most pessimistic case assuming static NBTI on all PMOS transistors in the design. The authors of [14] proposed a gate sizing algorithm based on Lagrangian relaxation. An average of 8.7% area penalty is required to ensure reliable operation for 10 years. Other methods related to gate or transistor sizing can be found in [15], [16].

Aforementioned methods focus on mitigating the aging of logic networks only. There are some work [9]–[11] addressing the aging

problem of clock networks. Methodology of [9] is also based on  $V_{th}$  assignment for clock buffers. Authors of [10] and [11] explore the use of alternative clock gating cells for clock-gated designs. On the other hand, two new clock gating cells were presented in [12] to balance the delay degradation of clock signal propagation, which reduces aging-induced clock skews between ungated and gated clock branches. The above work [9]–[12] aim to minimize aging-induced clock skew instead of making it useful (i.e., assign specific clock skews in the designs to mitigate the aging-induced performance degradation).

### B. Paper Contribution

In this paper, we propose an optimization framework for aging tolerance. Our proposed framework reassigns the threshold voltage of clock buffers and manipulates the rates of aging on different clock branches, which is achieved by changing the duty cycle of a clock waveform delivered to each of the clock branches. The contributions and advantages of this work are threefold:

- **Exploration of aging-induced clock skews for aging tolerance:** Existing work on addressing aging-induced clock skews mainly attempts to minimize the skews. This paper presents the first work on exploring “useful” clock skews (i.e., making them useful) for aging tolerance\*.
- **Problem formulation based on Boolean satisfiability and optimal solutions:** The proposed formulation of making clock skew useful is transformed into a Boolean satisfiability (SAT) problem, and its optimal solution can be efficiently found by a SAT solver such as MiniSat.
- **Low design overhead and little design modification:** Restrained by the synthesized clock tree whose topology and structure are basically determined, our post-CTS (clock tree synthesis) framework does not involve aggressive modification and thus does not incur significant design overhead.

### III. MOTIVATING EXAMPLE

In this section, we use two illustrative examples to demonstrate the idea of making clock skew useful, based on the design in Figure 1(a). The first example is only based on the aging manipulation of clock network, by changing the duty cycle of clock waveform, which is delivered to terminals/flip-flops. The second example is both based on aging manipulation and  $V_{th}$  assignment. Consider the circuit in Figure 1(a) where  $FF_X$ ,  $FF_Y$  and  $FF_Z$  are three edge-triggered flip-flops, and  $L_{XY}$  and  $L_{YZ}$  are the corresponding in-between logic networks. Other notations to be used later are listed in Figure 1(b).

For each pair of flip-flops (e.g.,  $FF_i$  and  $FF_j$ ) between which there exists at least one logic path from  $FF_i$  to  $FF_j$ , the following setup-time (Equation (1)) and hold-time (Equation (2)) constraints need to be satisfied:

$$C_i + T_{cq} + D_{ij} + T_{su} < C_j + T_c \quad (1)$$

$$C_i + T_{cq} + d_{ij} < C_j + T_h = \quad (2)$$

\*We do not minimize “absolute” performance degradation by directly mitigating the aging of logic networks; instead, we minimize “effective” performance degradation by  $V_{th}$  assignment and manipulation of aging rates on clock networks. Furthermore, the aging of logic network is tolerated based on timing borrowing, as a result of newly-designated clock skews in designs, which is achieved by  $V_{th}$  assignment and aging manipulation on clock networks. Of course, one can mitigate the logic’s aging itself by using existing techniques [13]–[16] before applying the proposed framework. This is however beyond the scope of this work and thus not particularly addressed in this paper.

Assume that, at year 10,  $D_{ij}$  is degraded by 15%, and both  $T_{cq}$  and  $T_{su}$  increase by 20%. By using the predictive model presented in [8], [17], we can accurately derive the aging of  $C_i$  and  $C_j$  due to the regularity and predictability of a typical clock waveform of 50% duty cycle. In the process technology used (TSMC 45nm GP standard cell series),  $C_i$  and  $C_j$  are degraded by 13% under 10-year BTI, i.e.,  $C_i$  and  $C_j$  become 1.13X larger.

To be aging-aware for the example circuit in Figure 1(a), we have to consider aforementioned aging factors in the setup-time constraints on  $L_{XY}$  and  $L_{YZ}$ :

$$L_{XY}: \mathbf{1.13}C_X + 1.2T_{cq} + 1.15D_{XY} + 1.2T_{su} < \mathbf{1.13}C_Y + T_c \quad (3)$$

$$L_{YZ}: \mathbf{1.13}C_Y + 1.2T_{cq} + 1.15D_{YZ} + 1.2T_{su} < \mathbf{1.13}C_Z + T_c \quad (4)$$

where  $C_X = C_Y = C_Z = 100$ ,  $T_{cq} = 8$ ,  $T_{su} = 2$ ,  $D_{XY} = 90$  and  $D_{YZ} = 80$ , as shown in Figure 1(a).

By re-arranging Equations (3) and (4):

$$L_{XY}: T_c > 115.5$$

$$L_{YZ}: T_c > 104$$

Therefore, the clock period needs to be larger than 115.5 (dominated by  $L_{XY}$ ) to ensure no setup-time violation over a required lifespan of 10 years. For brevity, we omit the discussion on hold-time constraints, which in our work are actually formulated to ensure no existence of racing due to short paths.

#### A. Example 1: Aging Manipulation on Clock Network

To minimize required  $T_c$  under aging, we use *duty-cycle converter* (DCC) to manipulate the aging rates of clock branches. We insert one 20% DCC at the input of buffer 1, and another 80% DCC at the input of buffer 2. The 20% (80%) DCC can decrease (increase) the stress times of downstream clock buffers by converting the clock duty cycle to 20% (80%), from a typical duty cycle of 50%. Therefore, 20% DCC can mitigate/decelerate the aging of  $C_X$  and 80% DCC can aggravate/accelerate the aging of  $C_Y$ . In the case of no DCC,  $C_X$  and  $C_Y$  are degraded by 13% under 10-year BTI in TSMC 45nm GP standard cell series, while 20% and 80% DCCs will degrade  $C_X$  and  $C_Y$  by 9% and 16%, respectively, assuming that the clock paths from the clock source to  $FF_X$  and  $FF_Y$  are disjoint.

Consider the new aging factors (due to effects of various clock duty cycles) in the setup-time constraints on  $L_{XY}$  and  $L_{YZ}$ :

$$L_{XY}: \mathbf{1.09}C_X + 1.2T_{cq} + 1.15D_{XY} + 1.2T_{su} < \mathbf{1.16}C_Y + T_c \quad (5)$$

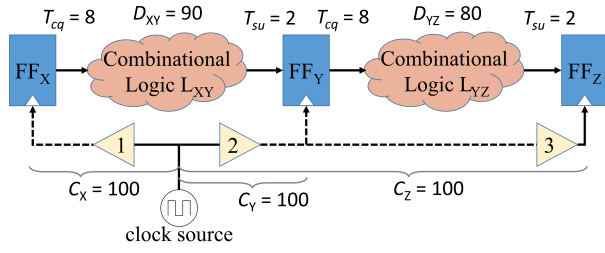
$$L_{YZ}: \mathbf{1.16}C_Y + 1.2T_{cq} + 1.15D_{YZ} + 1.2T_{su} < \mathbf{1.16}C_Z + T_c \quad (6)$$

By re-arranging Equations (7) and (8):

$$L_{XY}: T_c > 108.5$$

$$L_{YZ}: T_c > 104$$

As it can be seen, we can reduce the required  $T_c$  from 115.5 to 108.5 (dominated by  $L_{XY}$  still), by adding two DCCs in the existing synthesized clock tree to create aging-induced clock skews. The skew for  $L_{XY}$  (between  $FF_X$  and  $FF_Y$ ), quantified as  $1.16C_Y$  minus  $1.09C_X$ , is useful/beneficial and accounts for the reduction of required  $T_c$ . A certain level of aging tolerance is thus achieved because aging-induced performance degradation of  $D_{XY}$  (plus  $T_{cq}$  and  $T_{su}$  actually) can be tolerated, by exploring such useful aging-induced clock skews.



(a) Example

Symbol	Description
$FF_i$	Edge-triggered flip-flop, e.g., $i \in \{X, Y, Z, \dots\}$
$L_{ij}$	Corresponding in-between logic network, e.g., $i, j \in \{X, Y, Z, \dots\}$
$T_c$	Clock period
$C_i$	Clock arrival time to flip-flop $i$ ( $FF_i$ )
$D_{ij}/d_{ij}$	Longest/shortest path delay of $L_{ij}$
$T_{cq}$	Clock-to-output delay
$T_{su}/T_h$	Setup/hold time

(b) Notations

Figure 1. Illustrative example and notations for the proposed framework based on DCC deployment/insertion

### B. Example 2: $V_{th}$ Assignment and Aging Manipulation on Clock Network

In the example, the two approaches,  $V_{th}$  assignment and aging manipulation, are both applied to further optimize/reduce required  $T_c$ . We let the DCC deployment same with that in the first example, i.e., 20% DCC and 80% DCC are inserted at the inputs of buffer 1 and buffer 2, respectively. Moreover, a *technology leader* is inserted at the input of buffer 2. Here, *technology leader* denotes that, the technology of downstream (toward terminals/flip-flops) clock buffers are replaced with new technology, such that the  $V_{th}$  of the buffers are changed. Note that, the so-called downstream clock buffers are those between technology leader and terminals/flip-flops. For instance, when one technology leader is inserted at the input of buffer 2, the downstream buffers are those in the intervals from buffer 2 to  $FF_X$  and to  $FF_Y$ , which also include buffer 2 and buffer 3, but exclude flip-flops. Therefore, we can find that, for the clock buffers, which are in the intervals from buffer 2 to  $FF_X$  and to  $FF_Y$ , their technology is replaced with the new counterpart. Note that, in the example, we consider one type of new technology: HTV (High Threshold Voltage or High- $V_{th}$ ) technology. Thus, the associated technology leader is named *HTV leader*, which assigns high- $V_{th}$  to the downstream clock buffers. To include the aging rates of HTV buffers (clock buffers with high- $V_{th}$ ) in the setup-time constraint, we assume that, the fresh delay of HTV buffer is 1.2X longer than that of nominal buffer, and aging rates of HTV buffer, with the duty cycle of 20%, 40%, 50% and 80%, are 0.5%, 4.1%, 5.4% and 8.2%, respectively. Note that, the aging rates of HTV buffer are lower than those of nominal buffer, because the higher/lower  $V_{th}$  leads to lower/higher aging rates. Consider the new aging factors in the setup-time constraints on  $L_{XY}$  and  $L_{YZ}$ :

$$L_{XY}: 1.09C_X + 1.2T_{cq} + 1.15D_{XY} + 1.2T_{su} < (1.2+0.08)C_Y + T_c \quad (7)$$

$$L_{YZ}: (1.2+0.08)C_Y + 1.2T_{cq} + 1.15D_{YZ} + 1.2T_{su} < (1.2+0.08)C_Z + T_c \quad (8)$$

By re-arranging Equations (7) and (8):

$$L_{XY}: T_c > 96.5$$

$$L_{YZ}: T_c > 104$$

Apparently, the required  $T_c$  is further reduced/optimized from 108.5 to 104 (dominated by  $L_{YZ}$  rather than  $L_{XY}$  in the first example), by inserting two DCCs and one HTV leader in the existing synthesized clock network. Note that, there exists a difference between DCC and HTV leader. DCC is a physical gate; however, HTV leader is conceptually an imaginary location, from which we begin manipulating the technology of clock buffers toward flip-flops. As it can be seen, when the two approaches,  $V_{th}$  assignment and aging manipulation (by DCC insertion), are applied together in the second

example, the skew for  $L_{XY}$ , which equals  $1.28C_Y$  minus  $1.09C_X$ , is larger than that in the first example. Therefore, the new skew for  $L_{XY}$  is more useful/beneficial and accounts for the better optimization of required  $T_c$ . Additionally, when it comes to the timing-borrowing mechanism of the two examples, there exists a difference: 1) The timing-borrowing mechanism, in the first example, is achieved by the aging-induced clock skew, caused by manipulating the duty-cycle delivered to flip-flops. 2) In the second example, the timing-borrowing mechanism is based on aging-induced clock skew and *tech-induced* clock skew, which is caused by manipulating the technology of clock buffers, i.e., re-assign the  $V_{th}$  of clock buffers.

One may note that *clock skew scheduling* (CSS) [18], which derives unequal delays for all clock branches prior to *clock tree synthesis* (CTS), can also optimize a circuit for aging tolerance. However, the optimization potential of general CSS is limited since it is difficult to precisely implement a wide range of clock delays during [19].

In contrast, post-CTS clock skew scheduling based on buffer insertion is another option. We will demonstrate that, if buffer insertion is employed to match our optimization results based on DCC insertion, the number of inserted buffers is usually much larger than the number of inserted DCCs. Also, as described later in Section IV-D, the overhead of a single DCC can be diminished by integrating a DCC with its downstream buffer, which further reveals the cost effectiveness of our proposed DCC-based framework.

### C. Aging Prediction Model

Before discussing the proposed framework, we briefly introduce the aging (BTI degradation) model for logic gates/networks [8], [17] used in our paper. This model enables us to analyze the long-term behavior of BTI-induced MOSFET degradation, with both aging and recovery mechanisms taken into account. First, the degradation of threshold voltage at a given time  $t$  can be predicted as:

$$\Delta V_{th} = \left( \frac{\sqrt{K_v^2 \cdot T_{clk} \cdot \alpha}}{1 - \beta_t^{1/2n}} \right)^{2n} \quad (9)$$

where  $K_v$  is a function of temperature, electrical field, and carrier concentration,  $\alpha$  is the stress probability, and  $n$  is the time exponential constant, 0.2 for the used technology. The detailed explanation of each parameter can be found in [8].

Next, the authors of [17] simplify this predictive model to be:

$$\Delta V_{th} = b \cdot \alpha^n \cdot t^n = b \cdot (\alpha \cdot t)^n \quad (10)$$

where  $b = 3.9 \times 10^{-3} V \cdot s^{-1/5}$ .

Finally, the rising/falling propagation delay of a gate through the degraded P-type/N-type MOSFET can be derived as a first-order approximation:

$$\tau'_p = \tau_p + a \cdot (\alpha \cdot t)^n \quad (11)$$

where  $\tau_p$  is the intrinsic delay of the gate without BTI degradation and  $a$  is a constant.

We apply Equation (11) to calculate the delay of each gate under BTI, and further estimate the performance of a logic circuit. The coefficient  $a$  in Equation (11) for each gate type and each input pin is extracted by fitting HSPICE simulation results in 45nm, Predictive Technology Model (PTM). The simplified long-term model successfully predicts the MOSFET degradation, with less than 5% loss of accuracy against cycle-by-cycle simulations [8].

#### IV. PROPOSED FRAMEWORK (MAUI) BASED ON BOOLEAN SATISFIABILITY (SAT)

There exist two basic idea in the proposed framework for aging tolerance. The two idea are based on time-borrowing, so as to mitigate the aging-induced performance degradation of logic network. The first idea is based on aging manipulation by inserting *duty-cycle converters* (DCCs) in the existing clock tree. The second idea is based on  $V_{th}$  assignment of clock buffers by inserting the technology leaders in the clock tree. This way, we can intentionally create aging-induced and tech-induced clock skews, which can compensate for the performance degradation of the logic circuit based on time borrowing. We formulate the problem using Boolean satisfiability (SAT) and thanks to the efficiency of existing SAT solvers, the optimal solution can be obtained efficiently. The end result of this formulation is the locations (in the existing clock tree) of DCCs and technology leaders such that, when aging-induced and tech-induced clock skews are considered, the required clock period of the given circuit under  $n$ -year BTI is minimized. The clock period can be minimized since the performance degradation of the logic circuit is “tolerated” as a result of useful (aging-induced and tech-induced) clock skews. The minimum required clock period thus implies maximum level of aging tolerance. Note that, as mentioned in III-B, we re-assign  $V_{th}$  of clock buffers, based on the insertion of technology leader\*, from which we begin assigning new- $V_{th}$  to the downstream† clock buffers toward flip-flops.

The overall flow of our framework is depicted in Figure 2, where a binary search for the minimum clock period ( $T_c$ ) is involved. Formulated based on SAT, the key of our framework is to represent the problem in *conjunctive normal form* (CNF). A CNF representation is a conjunction of one or more clauses, where each clause is a disjunction of one or more Boolean variables. In the sequel, Section IV-A explains how the proposed problem of DCC and technology leader deployment/insertion is encoded by Boolean variables. Section IV-B and Section IV-C describe three major components, DCC constraints, HTV leader constraint and timing constraints, for our SAT-based formulation and how they are translated into legal SAT formula, i.e., CNF representation.

##### A. Encoding for DCC and HTV leader Deployment

The problem of DCC deployment/insertion needs to be encoded into Boolean representation before being transformed into a SAT-based formulation. Assume that a total of  $N$  types of DCCs can be chosen. Including the DCC-free case where no DCC is inserted,

\*Technology leader is an imaginary location instead of a physical gate such as DCC. It indicates the location where we begin assigning new- $V_{th}$  to clock buffers toward flip-flops, but exclude flip-flops (i.e., the  $V_{th}$  of flip-flops will not be re-assigned to new counterpart).

†The downstream clock buffers are those between imaginary technology leader and flip-flops. We use the adjective “downstream” to describe the clock buffers, based on the direction that clock signal pass toward (i.e., clock signal is generated from clock source, passes through clock buffers, and finally arrives at flip-flops).

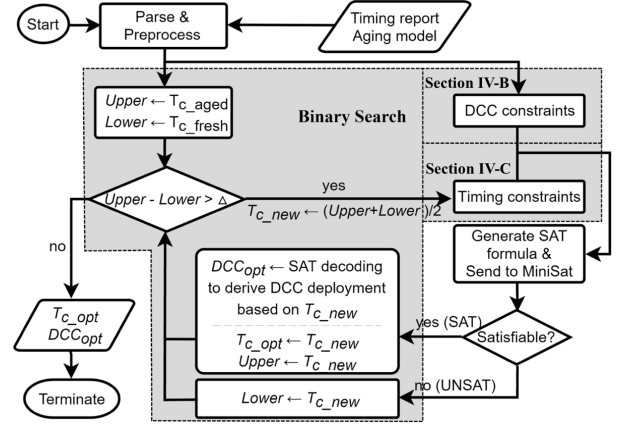


Figure 2. The overall flow of MAUI

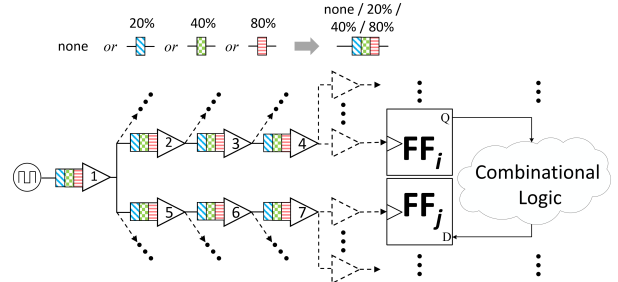


Figure 3. Generalized DCC insertion for a target pair of flip-flops

there are  $(N + 1)$  possibilities of DCC insertion for each clock buffer. Furthermore, we also assume that a total of  $M$  types of technology leaders can be chosen. Including the nominal case where no technology leader is inserted, there are  $(M + 1)$  possibilities of technology leader insertion for each clock buffer. Note that, when a DCC/technology leader is inserted, it is inserted at the input of a buffer. We denote a clock buffer by  $p$  ( $1 \leq p \leq P$ ) where  $P$  is the number of buffers. For each buffer, Boolean variables  $B_{p,q}$  ( $1 \leq p \leq P, 1 \leq q \leq Q = \lceil \lg(N + 1)(M + 1) \rceil$ ) are introduced where  $\{B_{p,1}, B_{p,2}, \dots, B_{p,Q}\}$  encode the aforementioned  $(N + 1)(M + 1)$  possibilities of DCC insertion at the input of buffer  $p$ .

Without loss of generality, we assume  $N = 3$ , and  $M = 1$ . Thus, there are 3 types of DCCs, which are assumed to be 20%, 40%, and 80% DCCs, as shown in Figure 3. In addition, there is 1 type of technology leader, which is assumed to be a HTV leader. Therefore, three Boolean variables are used for encoding eight possibilities of DCC and technology leader insertion at the input of any buffer. The eight possibilities can be encoded as follows:

Leader type	DCC type	$\{B_{p,3}, B_{p,2}, B_{p,1}\}$
(1) Nominal $V_{th}$	None	$\{0, 0, 0\}$
(2) Nominal $V_{th}$	20%	$\{0, 0, 1\}$
(3) Nominal $V_{th}$	40%	$\{0, 1, 0\}$
(4) Nominal $V_{th}$	80%	$\{0, 1, 1\}$
(5) HTV	None	$\{1, 0, 0\}$
(6) HTV	20%	$\{1, 0, 1\}$
(7) HTV	40%	$\{1, 1, 0\}$
(8) HTV	80%	$\{1, 1, 1\}$

For example, in Figure 4(b), a 20% DCC and an 80% DCC are

inserted at buffer 3 and buffer 5, respectively. Therefore,  $\{B_{3,2}, B_{3,1}\} = \{0, 1\}$ ,  $\{B_{5,2}, B_{5,1}\} = \{1, 1\}$ , and  $\{B_{p,2}, B_{p,1}\} = \{0, 0\}$  for  $p = 1, 2, 4, 6$  or  $7$ .

The 20% DCC will mitigate the aging of buffer 3 and its downstream buffers, while the 80% DCC will aggravate the aging of buffer 5 and its downstream buffers. It can be found that, if a DCC is deployed deep in the clock tree (i.e., close to the flip-flops), the number of buffers affected is limited and thus the overall impact of aging mitigation/aggravation on  $C_i/C_j$  may be insignificant, which diminishes the benefit from deploying DCCs for aging tolerance. To avoid this phenomenon, we set a rule of prohibiting DCC deployment at a clock tree level larger/deeper than a specified boundary. This rule also greatly reduces the complexity of our SAT-based formulation because a significant fraction of buffers are excluded from being considered for DCC deployment. For example, in Figure 3, those dashed buffers and their downstream buffers are excluded.

### B. DCC Constraints and Corresponding Clauses

Figure 3 shows a generalized example of DCC insertion for a pair of flip-flops ( $FF_i$  and  $FF_j$ ) where there exist aging-critical paths from  $FF_i$  to  $FF_j$ . A path is defined as an aging-critical path if, in the presence of aging, it is possible to determine the clock period of the circuit. Every pair of flip-flops between which there exist aging-critical paths needs to be considered and here, we use this generalized example to illustrate our SAT-based formulation.

In Figure 3, buffers 1 – 7 are candidate locations for DCC insertion and according to the encoding scheme explained in Section IV-A, two Boolean variables are introduced for each of the seven buffers to encode four possibilities of DCC insertion. Considering all seven buffers, there are a total of  $16,384 (= 4^7)$  possibilities, just for this pair of flip-flops. This makes the formulation based on SAT intractable due to clause explosion. Therefore, we set up the following constraint on DCC insertion:

#### DCC constraint: At most one DCC on a single clock path (from the clock source to one of the flip-flops)

In order to ensure no more than one DCC on any clock path, we can use the Boolean variables introduced for DCC insertion, i.e.,  $B_{p,q}$  ( $1 \leq p \leq P, 1 \leq q \leq Q = \lceil \lg(N+1) \rceil$ ), to generate some clauses which suppress the occurrence of having two DCCs on a clock path. Consider buffer 2 (encoded by  $\{B_{2,2}, B_{2,1}\}$ ) and buffer 3 (encoded by  $\{B_{3,2}, B_{3,1}\}$ ) in Figure 3. If there is a DCC at buffer 2 (i.e.,  $\{B_{2,2}, B_{2,1}\} \neq \{0, 0\}$ ), then there must no DCC at buffer 3 (i.e.,  $\{B_{3,2}, B_{3,1}\} \equiv \{0, 0\}$ ), and vice versa. The constraint can be formally written as:

$$(\{B_{2,2}, B_{2,1}\} \equiv \{0, 0\}) \vee (\{B_{3,2}, B_{3,1}\} \equiv \{0, 0\})$$

Next, it can be translated into 4 CNF clauses:

$$(\neg B_{2,1} \vee \neg B_{3,1}) \wedge (\neg B_{2,1} \vee \neg B_{3,2}) \wedge (\neg B_{2,2} \vee \neg B_{3,1}) \wedge (\neg B_{2,2} \vee \neg B_{3,2})$$

Any pair of buffers along a single clock path should be constrained in this way. Among buffers 1 – 7 in Figure 3, there are 12 pairs:  $\langle 1, 2 \rangle, \langle 1, 3 \rangle, \langle 1, 4 \rangle, \langle 1, 5 \rangle, \langle 1, 6 \rangle, \langle 1, 7 \rangle, \langle 2, 3 \rangle, \langle 2, 4 \rangle, \langle 3, 4 \rangle, \langle 5, 6 \rangle, \langle 5, 7 \rangle, \langle 6, 7 \rangle$ . Each pair translates to 4 clauses and a total of 48 clauses will be generated accordingly.

With DCC constraints and corresponding clauses, we can drastically reduce the possibilities of DCC insertion to be formulated. In the above example where 48 clauses associated with DCC constraints are generated, the number of possibilities drops from 16,384 to 103. In the next subsection, we describe what the 103 possibilities are and how they are translated into the final CNF representation.

### C. Timing Constraints and Corresponding Clauses

Given a pair of flip-flops, if there exists one logic path between them, the timing (i.e. setup-time and hold-time) constraints must be met based on the inequalities (1) and (2). Different types of DCCs reveal different aging influence on clock latency. Consider the lifespan specification of 10 years in Figure 4(b): the delay of each clock buffer is changed after 10 years. The clock latency of  $FF_i$  (i.e.,  $C_i$ ) is the sum of clock buffer delays from clock source to  $FF_i$ :

$$C_i = \tau_1 + \tau_2 + \tau_3 + \tau_4 + \dots \text{ and}$$

$$C_j = \tau_1 + \tau_5 + \tau_6 + \tau_7 + \dots, \text{ where } \tau_k \text{ is the delay of buffer } k.$$

Consider aging effects on  $C_i$  and  $C_j$ :

$$C_{i\_aged} = 1.13 \times (\tau_1 + \tau_2) + 1.09 \times (\tau_3 + \tau_4 + \dots) \text{ and}$$

$$C_{j\_aged} = 1.13 \times \tau_1 + 1.16 \times (\tau_5 + \tau_6 + \tau_7 + \dots), \text{ where } C_{i\_aged} \text{ and } C_{j\_aged} \text{ denote aged } C_i \text{ and } C_j, \text{ respectively.}$$

Next, we apply Equations (1) and (2) to check whether timing constraints will be violated under this DCC deployment.

#### Timing constraint: No existence of timing violation

Given one clock period  $T_c$  derived by binary search, one aging-critical path, and its associated clock network, all possible DCC deployments can be classified into 3 classes according to the number of DCCs used. Furthermore, due to the aforementioned DCC constraints, the SAT solver will only output a DCC deployment where there does not exist more than one DCC along any clock path. Thus, in the following discussion, the deployment with more than one DCC along a single clock path can be ignored. In each class, if the DCC deployment causes a timing violation within 10 years (i.e., the lifespan specification), then the deployment will be transformed into CNF clauses, such that the solver will not output the deployment as results. Here, we explain the generation of CNF clauses by using the example in Figure 4.

##### **Class 1:** No DCC is inserted on either clock path

Consider the situation that no DCC is inserted at buffers 1 – 7. If it causes a timing violation along the aging-critical path within 10 years, then the Boolean representation of the deployment,

$$(\{B_{1,2}, B_{1,1}\} \equiv \{0, 0\}) \wedge (\{B_{2,2}, B_{2,1}\} \equiv \{0, 0\}) \wedge \dots \wedge (\{B_{7,2}, B_{7,1}\} \equiv \{0, 0\}),$$

equivalent to the following CNF clause:

$$(B_{1,2} \vee B_{1,1} \vee B_{2,2} \vee B_{2,1} \vee \dots \vee B_{7,2} \vee B_{7,1}),$$

should be generated such that the solver will not output the corresponding deployment in the result if the CNF is satisfiable. In this case, a total of 1 CNF clause is generated.

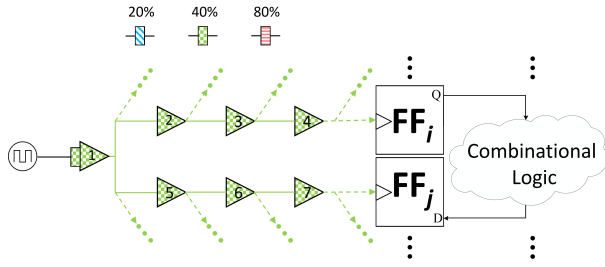
##### **Class 2:** Inserting one DCC

This class can be further classified into 2 sub-classes based on the location of inserted DCCs.

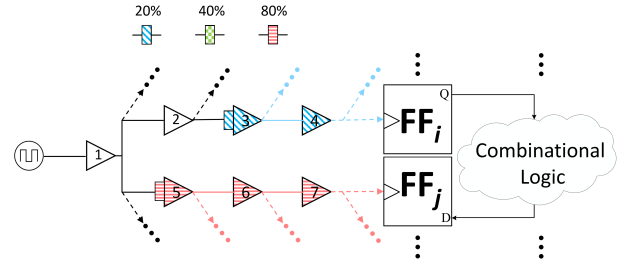
###### *Class 2-1:* Inserting one DCC on the common clock path

In Figure 4, buffer 1 is on the common clock path. Consider the DCC insertion shown in Figure 4(a): if the insertion of a 40% DCC at buffer 1 causes a timing violation within 10 years, then the Boolean representation of the DCC deployment,  $(\{B_{1,2}, B_{1,1}\} \equiv \{1, 0\}) \wedge (\{B_{2,2}, B_{2,1}\} \equiv \{0, 0\}) \wedge \dots \wedge (\{B_{7,2}, B_{7,1}\} \equiv \{0, 0\})$ , equivalent to the following clause:  $(\neg B_{1,2} \vee B_{1,1} \vee B_{2,2} \vee B_{2,1} \vee \dots \vee B_{7,2} \vee B_{7,1})$ , should be generated such that the solver will not output the deployment in the result if the CNF is satisfiable. Given that there are 3 choices of DCCs, a total of 3 CNF clauses will be generated in the worst case.

###### *Class 2-2:* Inserting one DCC on one of the divergent clock paths



(a) Case 2-1: one DCC on the common clock path (e.g., at buffer 1)



(b) Case 2-2: one DCC on one of the divergent clock paths, or class 3: two DCCs, one on each of the divergent clock paths

Figure 4. Examples of DCC insertion

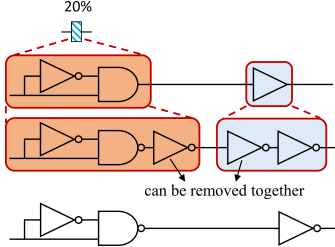


Figure 5. Practical considerations for DCC insertion

This class targets buffers 2, 3, 4, 5, 6, 7. If the insertion of a 20% DCC at buffer 3 causes a timing violation within 10 years, then the Boolean representation of the DCC deployment,  $(\{B_{3,2}, B_{3,1}\} \equiv \{0, 1\}) \wedge (\{B_{1,2}, B_{1,1}\} \equiv \{0, 0\}) \wedge \dots \wedge (\{B_{7,2}, B_{7,1}\} \equiv \{0, 0\})$ , equivalent to the following CNF clause:  $(B_{3,2} \vee \neg B_{3,1} \vee B_{1,2} \vee B_{1,1} \vee B_{2,2} \vee B_{2,1} \vee \dots \vee B_{7,2} \vee B_{7,1})$ , should be generated such that the solver will not output the deployment in the result if the CNF is satisfiable. This class includes 6 candidates: buffers 2, 3, 4, 5, 6, 7, and each has 3 choices of DCCs. Therefore, a total of 18 CNF clauses will be generated in the worst case.

### Class 3: Inserting two DCCs on two clock paths respectively

Given the DCC deployment in Figure 4(b) (a 20% DCC inserted at buffer 3 and a 80% DCC inserted at buffer 5), if it causes a timing violation along the aging-critical path within 10 years, then the Boolean representation of the deployment,  $(\{B_{3,2}, B_{3,1}\} \equiv \{0, 1\}) \wedge (\{B_{5,2}, B_{5,1}\} \equiv \{1, 1\})$ , equivalent to the following CNF clause:  $(B_{3,2} \vee \neg B_{3,1} \vee \neg B_{5,2} \vee \neg B_{5,1})$ , should be generated such that the solver will not output the deployment in the result if the CNF is satisfiable.

Class 3 considers two buffer locations to insert DCCs, one among buffers  $\{2, 3, 4\}$  and the other one among buffers  $\{5, 6, 7\}$ ; thus, there are totally 9 combinations of buffer locations. Each combination includes two buffers and thus 9 possibilities of choosing one specific DCC for each of the two buffers. Therefore, a total of 81 CNF clauses will be generated in the worst case.

Considering all of the above cases, a maximum number of  $1 + 3 + 18 + 81 = 103$  clauses can be derived. This is based on the existence of 48 clauses introduced in Section IV-B.

### D. Practical Considerations

The diagram on the top of Figure 5 shows the primitive design of a DCC, consisting of an inverter and an AND gate. In practice, the AND gate is implemented by a NAND gate feeding an inverter. As

mentioned earlier, when inserting a DCC, it is inserted at the input of a buffer, which is a pair of inverters in practice. Therefore, we can actually use the diagram on the bottom of Figure 5 to realize the insertion of a DCC. More specifically, we use it as a new cell to “replace” a buffer when a DCC is needed. By doing so, the cost of a single DCC can be significantly reduced and not much more expensive than the cost of inserting a buffer for clock skew scheduling.

## V. EXPERIMENTAL RESULTS

The proposed framework for aging tolerance is implemented in C++ and the SAT-based formulation is solved by MiniSat on a 2.83GHz Intel Quad-Core CPU workstation running Linux. The benchmark circuits are chosen from the IWLS’05 and ISCAS’89 suites. The technology used is TSMC 45nm GP standard cell series.

Under 10-year BTI, the aging rates of clock buffers were obtained from HSPICE. The aging rates of clock buffers with duty cycles of 20%, 40%, 50%, and 80% are 8.51%, 12.08%, 13.51%, and 16.41% respectively and the aging rate of logic is obtained by using the predictive model presented in [8], [17] (as in Section III-C).

Table I reports the experimental results and information of each benchmark. Columns two to six show the total number of gates, total numbers of flip-flops, total numbers of clock buffers, numbers of clock buffers formulated into SAT, and maximum level of the clock tree in each benchmark respectively. Column seven demonstrates the fresh clock period that is the circuit delay without aging, denoted by  $T_{c\_fresh}$ . Column eight demonstrates the clock period of the circuit under 10-year aging, denoted by  $T_{c\_aged}$ . Column nine demonstrates the optimum clock period of the circuit under 10-year aging after applying our framework, denoted by  $T_{c\_aged\_opt}$ . A shorter clock period under aging implies better circuit performance and higher level of aging tolerance. The second last column demonstrates the improvement, i.e., the level of aging tolerance which is calculated as:

$$1 - (T_{c\_aged\_opt} - T_{c\_fresh}) / (T_{c\_aged} - T_{c\_fresh})$$

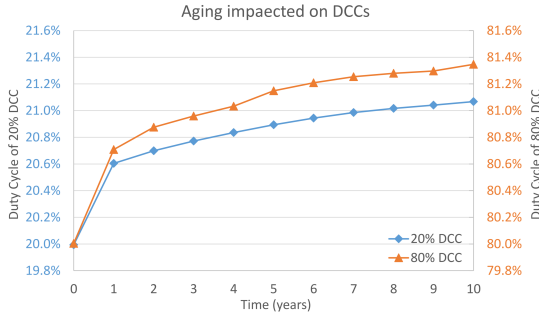
For benchmark *des\_perf*,  $T_{c\_fresh}$  is 773.9ps and  $T_{c\_aged}$  is 897.8ps, which means after 10-year aging the clock period of circuit will increase by 123.9ps. With DCC insertion using the proposed framework, the clock period achieved is 849.9ps, an increment of 76ps against  $T_{c\_fresh}$  (38.66% improvement). As shown in Table I, the improvement ranges from 7.38% to 49.88% and is 25.05% on average. The number of inserted DCCs is between 2 (for benchmark *s38584*) to 17 (for benchmark *des\_perf*), implying very limited degree of circuit modification and insignificant design overhead.

Figure 6 shows the change in the duty cycle of a 20%/80% DCC over 10-year aging. The y axis on the left represents the duty cycle



**Table I**  
RESULTS OF AGING TOLERANCE

Benchmark	# Gates	# FFs	# clock buffers (total)	# clock buffers (formulated)	Max tree level	No aging	10-year aging		Improve (%)	Run time
						$T_{c,fresh}$	$T_{c,aged}$	$T_{c,aged,opt}$		
des_perf	7401	8802	3416	3416	11	773.9	897.8	849.9	38.66%	16.45
leo3mp	526297	108839	26863	4924	10	3016.7	3530.6	3458.5	14.03%	24.89
net_card	561091	97831	33651	7904	12	3367.0	3940.2	3897.9	7.38%	30.69
vga_lcd	101496	17079	5030	4345	10	864.2	1013.7	994.1	13.11%	32.77
s13207	2627	625	186	180	8	776.3	891.7	873.3	15.94%	0.65
s15850	2967	513	100	100	5	1011.1	1165.9	1089.9	49.10%	0.2
s35932	6466	1728	411	411	6	822.1	950.8	886.6	49.88%	1.33
s38417	8422	1564	376	376	6	798.1	933.2	909.8	17.32%	1.46
s38584	6861	1275	627	557	10	731.7	842.5	820.3	20.04%	1.43
AVG.						(ps)	(ps)	(ps)	25.05%	(s)



**Figure 6.** Aging impact on 20%/80% DCC under BTI

of a 20% DCC, and the one on the right represents the duty cycle of an 80% DCC. As it can be seen, the growth in both cases are marginal: 20%  $\rightarrow$  21.07% for a 20% DCC and 80%  $\rightarrow$  81.35% for an 80% DCC, which in turn should not affect the benefit of our proposed framework significantly.

## VI. CONCLUSION AND FUTURE WORK

In this paper, we propose a novel framework, successfully taking advantage of aging-induced clock skews by inserting limited number of DCCs into the clock tree, to enhance circuit aging tolerance. We transform the problem to a Boolean satisfiability formulation which is then solved by using MiniSat. Experiments demonstrate that our framework gains an average of 25.05% aging tolerance via inserting at most 17 DCCs and is experimentally verified to be runtime-efficient.

Process variations (PVs) may shift the delay of each gate, leading to inaccuracy of our optimization results. As indicated in [8], the transistor with a higher (lower) fresh  $V_{th}$  ages at a lower (higher) rate. That is, the variation in  $V_{th}$  can be gradually compensated in the aging process. It is demonstrated in [8] that a PV-induced delay shift of 6.2% can be reduced to 1.6% after 10-year aging. Even though it is not significant compared to the improvement achieved by our work, we plan to consider the impact of PVs in the future so as to make the proposed idea more robust.

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