A Hybrid ECO Detailed Placement Flow for Improved Reduction of Dynamic IR Drop

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ABSTRACT
With advanced semiconductor technology progressing well into sub-7nm scale, voltage drop has become an increasingly challenging issue. As a result, there has been extensive research focused on predicting and mitigating dynamic IR drops, leading to the development of IR drop engineering change order (ECO) flows – often integrated with modern commercial EDA tools. However, these tools encounter QoR limitations while mitigating IR drop. To address this, we propose a hybrid ECO detailed placement approach that is integrated with existing commercial EDA flows, to mitigate excessive peak current demands within power and ground rails. Our proposed hybrid approach effectively optimizes peak current levels within a specified “clip” – complementing and enhancing commercial EDA dynamic IR-driven ECO detailed placements. In particular, we: (i) order instances in a netlist in decreasing order of worst voltage drop; (ii) extract a clip around each instance; and (iii) solve an integer linear programming (ILP) problem to optimize instance placements. Our approach optimizes dynamic voltage drops (DVD) across ten designs by up to 15.3% compared to original conventional flows, with similar timing quality and 55.1% less runtime.

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1 INTRODUCTION
As technology nodes scale down, IR drop becomes a critical, blocking step in design signoff. Below 7nm, high-end silicon designs, particularly those with aggressive clock targets, tend to consume more power and occupy more area. For correct timing analysis and closure of these designs, dynamic IR drop simulations are performed and a timing derate factor is then applied to all instances affected by IR drops. Notably, as dynamic IR drop increases, the timing derate factor increases, potentially leading to slower timing (fmax) – or greater power and area (from up sizing) – in the design outcome [16]. Therefore, to optimize power, performance, area and cost (PPAC) in these advanced designs, it is crucial to effectively mitigate dynamic IR drops.

To tackle the challenge of dynamic IR drop mitigation, designers often strengthen the power delivery network (PDN) to supply additional current with lower resistance to instances with the worst IR drops. However, this method is not always viable for high-end designs. The PDN consumes routing resources, and adding more PDN can fail when there is a shortage of these resources [16]. Another strategy is to consider static IR drop during various stages (power-driven placement, clock tree synthesis (CTS), routing) of the physical design flow. However, there can be significant discrepancies between static and dynamic IR drop, as illustrated in Figure 1. Static IR drop models cannot fully capture the complexities and transient characteristics of dynamic IR drops, risking both underestimations and overdesign before the layout is final.

An alternative approach to mitigate dynamic IR drop involves applying detailed placement using an ECO flow in a post-route opt (PRO) stage. [7] proposes an ECO detailed placement method to address dynamic IR drop at the PRO stage. Their approach employs two integer-linear programming (ILP)-based strategies: (i) adjusting the y-axis placement to minimize the peak current waveforms for power and ground rails, and (ii) minimizing x-displacement within each row. However, the approach can potentially lead to suboptimal solutions since the x and y coordinates are not optimized concurrently. Commercial tool flows (an example is [12]) offer dynamic IR drop-driven ECO detailed placement features. However, current tools only imperfectly mitigate dynamic IR drop, leaving quality of results (QoR) on the table. With this as motivation, we propose a hybrid ECO detailed placement approach that integrates an ILP-based detailed placer with a commercial EDA tool, and effectively mitigates peak current demands within power and ground rails. Our contributions are summarized as follows.
• We propose an ILP-based detailed placer that can be used at the post-route opt (PRO) stage. Our approach uses a hybrid ECO methodology that further optimizes IR drops beyond the capabilities of traditional ECO detailed placement flows.
• To achieve scalability, we extract “clips” and formulate an integer linear programming (ILP) problem to minimize cell displacement and maximum peak currents for each power and ground rail. In contrast to [7], our method concurrently optimizes both $x$ and $y$ coordinates within a clip.
• Our proposed approach is designed to complement and integrate seamlessly with existing ECO detailed placement flows of commercial EDA tools. This compatibility makes it particularly valuable in addressing real-world design challenges.
• Experimental results show that our hybrid approach achieves up to 15.3% reduction in DVD compared to conventional flows, with similar timing quality and 55.1% less runtime.1

This paper is organized as follows. Section 2 reviews related works. Section 3 discusses a linearity assumption for the demand current waveform. Section 4 explains our hybrid ECO detailed placement approach, and Section 5 gives details of our ILP formulation. Section 6 presents experimental results and Section 7 concludes our paper.

2 RELATED WORKS

Placing instances to mitigate IR drop is known to be an NP-hard problem [3]. Hence, various heuristics have been proposed in the literature. We discuss two categories of previous works: IR drop prediction and IR drop optimization.

**IR drop prediction.** [6] proposes an XGBoost-based machine learning model to predict the static IR drop at each power node in a design. This avoids rerunning the IR drop tool for incremental changes in the placement or PDN. [4] proposes an XGBoost-based machine learning model to predict dynamic IR drop, thus speeding up dynamic IR drop analysis in each ECO iteration. [11] improves upon the work of [4] by proposing a CNN-based machine learning model to predict dynamic IR drop. Compared to previous approaches, the authors preprocess design dependent information before it is fed to the ML model. A recent work [7] improves upon [6], [4] and [11], and predicts both static and dynamic IR drop. The authors use feature engineering and introduce a Random Forest (RF)-based regression model for IR drop prediction.

**IR drop optimization.** [8] proposes an IR drop-aware global placer, which considers the worst voltage drop across all cells in the design. The authors approximate this voltage drop with a log-sum-exp function and integrate it with other placement objectives (wavelength, congestion and timing) in the APlace placer [9]. [3] improves upon [8] by introducing power spreading forces in the analytical placement framework of NTUPlace3 [2]. The power spreading forces push cells with voltage drop violations to new locations that improve the voltage drop. [1] proposes an IR drop mitigation approach that is applicable at theCTS stage. The authors decompose the peak current minimization problem into many smaller subproblems. Solving each subproblem reduces the local peak current of each via-stack in the on-chip PDN. By greedily scheduling useful skews from unused timing slacks, the authors demonstrate that their approach can substantially reduce peak IR drop and peak current. [5] proposes a dynamic programming based detailed placer that maximizes power staple insertions to reduce IR drop. The authors show that their approach can achieve significant reductions in IR drop with similar WNS when compared to a standard flow. [7] proposes a machine learning (ML)-based IR drop-aware detailed placer that uses predicted IR drop hotspots to guide cell movements. The authors show that their approach can reduce IR drop without timing degradation.

3 LINEARITY OF THE DEMAND CURRENT WAVEFORM

[7] introduces the concept of minimizing the maximum peak current values using detailed placement. Following [7], in this work, we assume that after moving an instance by one row either upward or downward, the total demand current waveform [3] seen by power and ground rails remains unchanged. Figure 2 illustrates the overarching concept of current linearity in this context. The figure is divided into the following parts for clarity.

- Parts (a), (b) and (c) show examples of current waveforms measured at VDD pin of instances 1, 2 and 3, respectively. In these examples, instances 1 and 2 reach their peak currents, denoted as $m$, at timestamp $t_1$. Instance 3 reaches its peak current, denoted as $n$, at a later timestamp $t_2$. Here, we assume that $m < n < 2m$ and $t_1 < t_2$.
- Part (d) shows an example of placed instances. In this placement, instances 1 and 2 are connected to the VDD1 power rail, and instance 3 is connected to the VDD2 power rail.
- Part (e) shows a scenario prior to any cell movement. Here the VDD1 rail has a combined maximum demand peak current of $2m$ at timestamp $t_1$. This is due to the accumulation of currents from instances 1 and 2. Meanwhile, the VDD2 rail
shows a maximum demand peak current of \( n \) at timestamp \( t_2 \), solely attributed to instance 3.

- Part (f) depicts the scenario after cell movement. The VDD1 rail now shows a maximum demand peak current of \( m \) at timestamp \( t_1 \) because only instance 1 remains on this rail. On the other hand, the VDD2 rail still has a maximum demand peak current of \( n \) at timestamp \( t_2 \). This is due to the accumulation of currents from instances 2 and 3. Notably, the maximum peak current on the VDD2 rail remains the same as before \( (n) \), since the peak currents of instances 2 and 3 occur at different timestamps \( (t_1 \) and \( t_2 \), respectively).

Our proposed detailed placement methodology is based on the above concepts, and focuses on minimizing the peak demand current over all power and ground rails. Cell moves during the detailed placement are limited to enable an assumption of current linearity.

### 4 PROPOSED METHODS

In this section, we introduce our hybrid ECO detailed placement flow (Figure 3). We first define three terminologies.

- **Clip:** A clip is a window of layout extracted from the original layout of a netlist.
- **PDN zone:** A PDN zone is a region that is formed by adjacent power and ground connections on the bottom metal layer.
- **Clip overlap violations:** Clip overlap violations refer to geometric overlaps between multiple clips. More details are presented in the later subsection.

**Overall flow of our hybrid ECO detailed placer.** The details of our proposed hybrid detailed placement flow are given in Algorithm 1. Our flow comprises two steps: (i) ILP-based detailed placement optimization and (ii) commercial ECO detailed placement. Our flow starts by measuring the dynamic IR drop at every cell instance (Line 1). We next determine the filtered instance set \( FN \) according to the input DVD threshold \( Th \), and effective DVD [13] of all instances (Line 2). We also define the clips set \( C \) and PDN zones set \( P \) to avoid clip overlap violations as shown in Figure 5 (Lines 3–4). If an instance \( i \) in the routed layout has a DVD hotspot, i.e., \( i \) has greater effective DVD than the input DVD threshold \( Th \), we generate a clip \( C \) at the DVD hotspot, using \( i \)'s location and \( c \)'s dimensions, \( cw \) and \( ch \) (Line 7). If \( c \) does not have clip overlap violations, we update the clip set \( C \) (Lines 8–9). After all clips are generated, we run the ILP-based ECO DP with inputs \( maxDisp \) and \( RL \) (Lines 12–15); details are given in Section 5 below. We run ECO route to restore routing correctness following the relocation of instances by the ILP-based ECO DP (Line 16). To further improve the dynamic IR drop, we run the commercial ECO DP on the ILP-generated solution (Line 17).

**Algorithm 1:** Our Proposed Hybrid Detailed Placer

```
Input: Instance set \( N \) after RouteOpt stage of P&R, DVD threshold \( Th \), clip width \( cw \), clip height \( ch \), max displacement \( maxDisp \), max row limit \( RL \)
Output: IR drop-mitigated placements
1: Run dynamic IR drop simulation with DVD threshold \( Th \)
2: Define filtered instance set \( FN \) \( \leftarrow i \in N \) if effective DVD of \( i \geq Th \)
3: Define clips set \( C \) \( \leftarrow \phi \)
4: Define PDN zones set \( P \) from layout
5: // Create clip set \( C \) from \( FN \)
6: for \( i \in FN \) do
7: Generate clip \( c \), centered at \( i \) with dimensions \( (cw, ch) \)
8: if \( c \) does not have clip overlap violations using \( C \) and \( P \) then
9: Insert \( c \) to \( C \)
10: end if
11: end for
12: for \( c \in C \) do
13: Create ILP formulation of \( c \) with \( maxDisp \), \( RL \) and solve
14: Update instance locations from \( c \)
15: end for
16: Run ECO Route
17: Continue commercial IR drop-aware detailed placement
```

**Clip and PDN zones extraction.** [10] extracts clips for better scalability of the ILP solver. We adopt a similar idea. We extract a clip around any instance that violates the target Dynamic Voltage Drop (DVD) threshold. Figure 4 gives an illustration: (a) shows a heatmap from dynamic IR drop simulation of the mpeg2_top design; (b) shows an extracted clip from the red square in (a); and (c) shows how we define three PDN zones. In Figures 4(a) and (c), it is observed that the voltage drops across various PDN zones are independent of each other. This is due to the vertical PDN stripes (depicted in orange in Figure 4(a)), that are responsible for establishing the power and ground connections. Therefore, we only consider the \( y \)-axis overlap when the clips lie within the same PDN zone.

![Figure 3: Conventional ECO DP flow and our hybrid DP flow.](image)

![Figure 4: Illustration of clip and PDN zones from mpeg2_top. (a) Heatmap of dynamic IR drop with PDN; (b) an extracted clip from the red square in (a); and (c) PDN zones defined in (a).](image)
Clip overlap violations. During clip generation, it is crucial that there are no overlaps between the clips. Overlaps along the y-axis can disrupt the optimization process for peak currents during the detailed placement. Figure 5 presents an example. Figure 5(a) shows a clip overlap violation scenario where clip D overlaps with clips B and C along the y-axis. Figure 5(b) demonstrates a scenario without any clip overlap violations. Despite clip D overlapping along the y-axis with clips A and B, and B and C, there are no overlaps between the clips. Overlaps along the x-axis with clips A and B, clips A and C, and clips B and C are situated in different PDN zones. We see that taking PDN zones into account enables generation and processing of more clips, which can lead to more effective reduction of IR drop.

5 PROPOSED ILP FORMULATION

We now describe our Integer Linear Programming (ILP) formulation, adapted from [10]. Table 1 presents definitions of all terminologies, where Var denotes a variable and Const refers to a constant value. Table 2 defines the various sets used in the ILP formulation. Our ILP optimizes

\[
\min OBJ = α \cdot OBJ_{\text{ird}} + β \cdot OBJ_{\text{disp}} \quad (α \gg β)
\]

where \(OBJ_{\text{ird}}\) denotes the objective function related to IR drop mitigation, and \(OBJ_{\text{disp}}\) denotes the objective function related to the displacement of instances during ECO detailed placement. \(α\) and \(β\) denote the weights between IR drop and displacement, respectively, as shown in Equation 1. Our goal is to effectively mitigate the IR drop while simultaneously minimizing the perturbation caused during the detailed placement process. To accomplish this, we assign a higher value to \(α\) compared to \(β\) \((α \gg β)\). We now explain the two components of our ILP objective function in more details.

5.1 IR Drop Mitigation

The objective of mitigating the IR drop is to minimize the maximum peak current across every power rail \((I^P)\) and ground rail \((I^G)\) (Equation 2).

\[
OBJ_{\text{ird}} = I^P + I^G
\]

\[
i^P_p = B^P_{pt} + \sum_{i \in N \land k \in V^P_{pi}} \lambda^k \cdot W^P_{ki} \leq I^P \quad \forall p \in P, \forall t \in T
\]

\[
i^G_g = B^G_{gt} + \sum_{i \in N \land k \in V^G_{gi}} \lambda^k \cdot W^G_{ki} \leq I^G \quad \forall g \in G, \forall t \in T
\]

The expected current value within the \(p^{th}\) power rail at timestamp \(t\) \((i^P_p)\) is defined in Equation 3. \(B^P_{pt}\) represents the background noise within the \(p^{th}\) power rail at timestamp \(t\). The term \(\sum_i W^P_{ki}\) indicates the sum of all current values contributed by the instances attached to the \(p^{th}\) power rail at the same timestamp. The expected current value for a ground rail at a given timestamp is defined similarly (Equation 4).

5.2 Cell Displacement Minimization

The objective of minimizing the total displacement during ECO detailed placement in the post-route opt (PRO) stage is captured in Equation 5.

\[
OBJ_{\text{disp}} = \sum_{i \in N \land k \in K_i} d^k_i \cdot \lambda^k_i
\]

\[
\sum_{i \in N \land k \in K_i} r^k_i \cdot \lambda^k_i \leq RL
\]

Minimizing total displacement during the PRO stage is beneficial for the following reasons:

- **Reduced ECO routing runtime:** Minimizing cell disturbance avoids excessive cell movements that can potentially lead to increased ECO routing runtime.
- **Stability in optimization results:** Excessive cell movement can also lead to divergent or less predictable results, after optimization by commercial tools. Keeping cell displacement to a minimum helps ensure more reliable optimization outcomes.

\[\text{In our experiments, we set } \alpha \text{ and } \beta \text{ to } 10^{12} \text{ and } 1, \text{ respectively. This can be changed if different units are applied.}\]
For each possible placement of instance $i$, represented by the variable $q_i$, there is a unique cell and row displacement value denoted as $d_i^k$ and $r_i^k$, respectively. These values quantify the extent of movement for each cell from its original position. To improve scalability, we use a threshold displacement value $maxDisp$, and generate the $\lambda_i^k$ variables only when the displacement does not exceed the threshold $maxDisp$, i.e., $d_i^k \leq maxDisp$. This constraint reduces the ILP runtime by reducing the total number of variables and constraints in our ILP formulation.\(^5\) To further reduce the detailed placement perturbation and preserve the assumption of demand current linearity, we introduce a row limit, denoted as $RL$. This limit is set to control the total number of row swaps allowed for each clip (Equation 6). Consequently, the total number of instances that can be row-swapped is bounded by $RL \cdot \#Clips$.

5.3 Detailed Placement Baseline

For our ILP-based detailed placement, we adopt the single-cell-placement (SCP) model, which has demonstrated superior performance in comparison to other detailed placement models (S and RQ models) \(^10\).\(^6\) The SCP model comprises multiple variables $\lambda_i^k$ for each instance $i$, corresponding to the total number of possible placements ($|K_i|$). The overall complexity of the model scales as $O(|N|R|Q|)$.

$$\sum_{i \in N} \sum_{k \in K_i} p_{i rq}^k \cdot \lambda_i^k \leq 1 \quad \forall r \in R, \forall q \in Q$$

(7)

$$\sum_{k \in K_i} \lambda_i^k = 1 \quad \forall i \in N$$

(8)

The detailed placement solution must have at most one site occupation for every cell and its associated placement (Equation 7). For each instance $i$, only a single placement must exist as enforced by Equation 8.

6 EXPERIMENTAL RESULTS

We use IBM ILOG CPLEX 12.10 as our ILP solver and run all experiments on a server with an Intel Xeon(R) Gold 6148, 2.40GHz (40 cores) CPU and 256GB memory. We use five testcases: aes_cipher_top, des_perf, jpeg_encoder, mpeg2_top, and vga_enh_top from OpenCores \(^15\). Table 4 shows a summary of the five designs used in our experiments.\(^7\) These are based on the 7nm FinFET technology node. In Table 4, Init FP Util and Target CP denote the initial floorplan utilization and target clock periods, respectively. In our experiments, we use: (i) Synopsys Design Compiler R-2020.09 \(^17\) to synthesize from RTL, (ii) Cadence Innovus v21.11-s130_1 \(^19\) to run the P&R flow (e.g., floorplan, placement, clock tree synthesis, and routing); and (iii) Cadence Voltus v21.14-s111_1 \(^18\) to measure the dynamic IR drop at the PRO stage. We use an unnamed commercial tool for the IR drop-aware ECO detailed placement. We build the power mesh on metal layers M7 to M9, characterized by a width of 1.0$\mu$m, a pitch of 15.5$\mu$m and an offset of 0.05$\mu$m. We set 7ns as the dynamic IR drop timestamp interval. The dimensions of the clip size are set to 1.4$\mu$m by 1.2$\mu$m, with a maximum displacement ($maxDisp$) of 0.25$\mu$m. The parameters $\alpha$ and $\beta$ are set to 10\(^12\) and 1, respectively, and Row Limit (RL) in Equation 6 is set to 5.\(^8\)

6.1 Hybrid ECO DP Results

Table 3 shows a comparison of DVDs on our designs. We compare between: (i) conventional approaches, denoted as $C$ (one commercial ECO DP iteration) and $C+C$ (two commercial ECO DP iterations), and (ii) our proposed approaches, denoted as $O$ (one ILP ECO DP) and $O+C$ (a combination of our approach followed by the commercial method). Our study does not include comparisons with the previous state-of-the-art \(^7\) due to unavailability of their closed-source implementation. \(^5\) adds power staples for mitigating IR drop whereas we perform ECO DP/DR – so we also omit \(^5\) from our comparisons. In most cases, the hybrid $O+C$ approach demonstrates superior performance across three metrics: worst DVD, average DVD of the top 5 worst cases, and average DVD of the top 10 worst cases. In these comparisons, the minimum counts for each category are highlighted in bold across the four ECO DP approaches we consider ($C, C+C, O, O+C$).

Our $O+C$ hybrid flow achieves the best results in 17 out of 30 instances\(^9\) for the worst DVD, in 16 instances for the average of the top 5 worst DVDs, and in 15 instances for the average of the top 10 worst DVDs. These results are visually represented in Figure 6, where half of the data points correspond to Table 3. A notable example is the jpeg2 case, under a DVD threshold of 100 mV. Here, our proposed $O+C$ hybrid method achieves a 15.3%\(^10\) better improvement in DVD reduction compared to the conventional ECO DP flow ($C+C$).

6.2 ECO DP Characteristics

Table 5 presents overall characteristics for the ECO detailed placer and our ILP-based DP. We report the total number of moved instances ($\#MInsts$), total displacement ($Disp$), and runtime ($RT$). $\#Clips$ denotes the total number of clips generated during our detailed placement flow. $\#Clips$ denotes the total instances considered during the ILP-based detailed placement, and $\#MInsts$ denotes the total row-swapped moved instances during the ILP-based detailed placement. Given that we set RL to 5 as per Equation 6 in Section 5.2, the count of $\#MInsts$ is strictly bounded by 5 \(^*\) $\#Clips$. Since our method avoids unnecessary cell movements, it results in lower values of $\#MInsts$ and $Disp$ compared to the commercial detailed placement. In terms of runtime, our proposed hybrid methods ($O+C$) achieve an average of 55.1% less runtime compared to two sequential commercial ECO detailed placements ($C+C$). Since our ILP detailed placement does not excessively perturb the placement compared to the conventional method, the hybrid detailed placement can generate better results with small runtime overheads compared

\(^1\)In preliminary experiments, we vary the maxDisp parameter between 0.15$\mu$m and 0.75$\mu$m and measure ILP runtime. These early studies indicate that setting maxDisp $\leq 0.25\mu$m achieves reasonable runtime and QoR.

\(^2\)The S model is known as the site occupation model, and the RQ model refers to the row and column occupation model. Refer to Section 3 of \(^10\) for more details.

\(^3\)We performed studies using a total of ten designs, but for conciseness report on just five here. We make available the remaining results along with runscripts to enable reproduction of our work, in our open-sourced repo \(^14\).

\(^4\)In preliminary experiments, we vary the RL parameter between 1 and 5 and measure the correlation between the expected peak current before DP and the actual measured peak current after the ecoRoute and DP stages. These early studies indicate that the highest correlation is obtained when we set RL to 5.

\(^5\)Tables that we present here show 15 instances = 5 testcases \times 3 thresholds $T$. Results for the other 15 instances are available in \(^14\).

\(^6\)The improvement is calculated as $(value_{baseline} - value_{baseline})$. 
Table 3: DVD QoR comparison between the conventional commercial flow and our flow. \( T_h \) = input DVD threshold. \( C \) = commercial dynamic IR-driven detailed placer. \( O \) = our ILP-based DP. \( C + C \) = running commercial dynamic IR-driven detailed placer two times. \( O + C \) = running our detailed placer followed by commercial dynamic IR-driven detailed placer. Nominal voltage = 650 (mV). To obtain a range of IR drop-violating instances, we sweep \( T_h = 100/80/65 \) (mV). Best results are marked with bold font.

![Table 3](image)
original conventional flow, across ten designs. Our future work aims to develop a new methodology that eliminates the need for hybrid approaches. Reducing the timing perturbation, although challenging, remains another potential direction for improvement. Gaining a new understanding of the commercial ECO detailed placement flow will also be beneficial.

REFERENCES


