Fence-Region-Aware Mixed-Height Standard Cell Legalization

SangGi Do
Design Enablement Team
Samsung Electronics
Hwaseong, Korea
sanggi.do@samsung.com

Mingyu Woo
Electrical & Computer Engineering
UCSD
California, U.S.
mwoo@eng.ucsd.edu

Seokhyeong Kang
Electrical Engineering
POSTECH
Pohang, Korea
shkang@postech.ac.kr

ABSTRACT

We propose a fence-region-aware mixed-height standard cell legalization that can optimize the placement of standard cells that have more than a two row height in various shapes of the fence region. The algorithm consists of pre-legalization and mixed-height standard cell legalization steps to prioritize cell legalization; then a quality refinement step that uses simulated annealing reduces the displacement. Our proposed method achieved 63% improvement in the average quality score and 72% improvement in average runtime, compared to the winners of the ICCAD-2017 contest.

CCS CONCEPTS

• **Hardware → Physical design (EDA)**; **Placement**;

KEYWORDS

Mixed-Height Standard Cell; Detailed Placement; Legalization

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1 INTRODUCTION

The standard cell method is an efficient and effective approach to integrated circuit design. This method encapsulates the large-scale integration (transistor level) into an abstract logic representation (gate level). This encapsulation decreases the physical design complexity for electronic design automation (EDA). However, in advanced technology nodes, the designs are so complex that conventional standard cells have reached a limit of routability. Thus, a multi-deck standard cell that occupies multiple rows has been proposed for the new technology nodes. This technique can reduce internal wire congestion, shrink the standard cell area, reduce power consumption, and increase optimality of cell assignment compared with the conventional single-deck design. However, this multi-deck design is not yet widely used because it impairs cell legalization.

Cell legalization is the process of ensuring that the circuit design emplaces cells appropriately and in the allotted space. In the standard cell design flow, cell legalization has become difficult because of complicated design rules and design utilization at advanced technology nodes [1]. Furthermore, multi-deck standard cell structure increases the physical design complexity of legalization exponentially.

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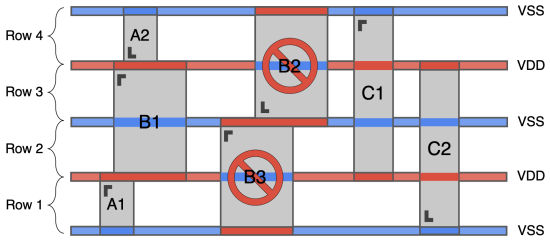

Figure 1: An example of multi-deck standard cell power alignment. Red bars: Power (VDD); blue: ground (VSS); A1, A2: single row height cells; B1, B2, B3: double row height cells; C1, C2: triple row height cells. B2 and B3 violate power alignment.

The most important characteristic of the conventional standard cell is that every standard cell has the same height; this strategy greatly simplifies design a chip by EDA methods. However, the multi-deck standard cell has various cell heights and causes problems with power alignment and vertical overlap. The power alignment problem (Fig. 1) for multi-deck standard cells occurs because multi-deck standard cells cannot be flipped to align power.

Vertical overlap is also a problem. The multi-deck standard cells occupy several rows, and therefore can overlap both horizontally and vertically. The fence region further aggravates the legalization problem. In advanced System-on-Chip technology obstacles, such as 3D-IC with Through Silicon Via(TSV), complicate the area in which standard cells can be placed [2]. Thus, the importance of the fence region-aware legalization increases.

Several multi-deck standard cell legalization methods have been proposed recently; they can be categorized as (i) heuristic and (ii) analytic approaches. Heuristic approaches [3, 4] can solve the legalization problem quickly, but cannot guarantee an optimal solution. Analytic methods [5, 6] convert the legalization problem into other well-known problems which can be solved using existing solvers.

In this paper, we propose a multi-deck standard cell legalization method that is aware of fence regions and uses metaheuristic optimization. The proposed method uses multi-stage legalization to achieve a near-optimal solution while maintaining a global placement result. To preserve the global placement result, our proposed method minimizes both maximum cell displacement and total cell displacement. The main contributions of this work are:

- Our proposed method can legalize mixed-height standard cells on a complex fence region.
- Our method achieves a higher quality score and a lower runtime than the top ranked results under the ICCAD-2017 contest benchmarks.
- Our binary has compatibility with *Innovus* and the source code is published as an open source through the *GitHub* [7].

The rest of this paper is organized as follows. Section II briefly explains previous cell legalization studies and their limitations. Section III introduces our proposed method, fence-region-aware multi-deck standard cell legalization. Section IV provides experimental results, evaluation metric and analysis. Section V summarizes the results and concludes the paper.

2 RELATED WORKS

Standard cell legalization is an important problem in the placement procedure of physical circuit design. The placement procedure is divided into global placement and detailed placement. Global placement optimizes wire-length, routability, power and other factors, but ignores legalization. Detailed placement legalizes the results of global placement. The objective of standard cell legalization is to align the standard cells and remove overlaps to fit the design rules, while maintaining the global placement result.

Legalization is essential for the physical design, so various legalization methods have been proposed [8, 9]. They can be divided into heuristic and analytic approaches. The heuristic approach seeks optimal solutions by trial-and-error. This can achieve a solution in a practical time, but does not guarantee an optimal solution. The analytic approach builds mathematical models by applying objective functions and seeks the globally-optimal solution. The analytic approach guarantees the optimal solution if the fence region is simple, but not when it is complex (Fig. 2).

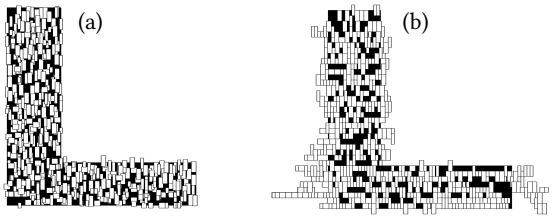

Figure 2: Examples of LCP based multi-deck standard cell legalization. (a) global placement result with a fence region. (b) faulty legalization result obtained using a Linear Complementary Problem with a fence region.

2.1 Single-deck Standard Cell Legalization

Single-deck standard cell legalization considers the case in which every standard cell has the same height. This problem is much easier than multi-deck standard cell legalization. Because of the high complexity of solving analytical models, heuristic approaches are common for standard cell legalization problems. Tetris [8] and Abacus [9] have been widely utilized for single-deck standard cell legalization.

2.2 Multi-deck Standard Cell Legalization

Multi-deck standard cell legalization problem is much more complex than single-deck standard cell legalization, because moving a multi-deck cell affects several placement rows concurrently. Thus, heuristic approaches were tried first: Wang et al. [4] extends Abacus, and Lin et al. [10] uses dynamic programming.

However, recent studies use analytic approaches. Hung et al. [6] uses dynamic programming with refinement based on Linear Programming (LP). Chen et al. [5] converts the legalization problem to a Linear Complementarity Problem (LCP). The state-of-the-art is LCP-based legalization. However, this approach is not an effective solution when the fence region exists (Fig. 2b). LCP-based legalization does not consider vertical cell movement, so a significant number of standard cells can violate the fence region. This limitation is exacerbated when space utilization is high.

3 PROPOSED ALGORITHM

For the multi-deck legalization, we propose a multi-stage algorithm that consists of three procedures (Fig. 3): pre-legalization, multi-deck standard cell legalization, and quality refinement. The pre-legalization and multi-deck legalization steps prioritize cell legalization; the quality refinement focuses on reducing displacement. First, the pre-legalization step arranges region violation cells

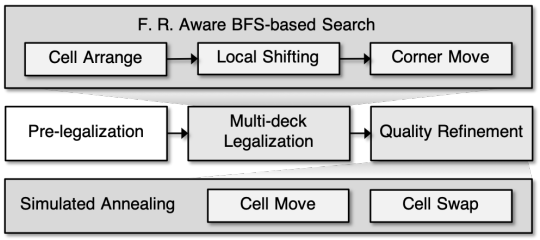

Figure 3: Overall flow of our proposed algorithm.

that global placement has put outside of the fence region. Then the multi-deck standard cell legalization step legalizes remaining cells in three small steps; cell arrangement, local cell shifting, and corner weight move. Finally, the quality refinement step uses simulated annealing to reduce the displacement.

3.1 Pre-legalization

During the placement stage, hierarchical design has sub-modules; their physical regions can be assigned using EDA tools. Benchmarks from the ICCAD-2017 contest contain various numbers of fence regions [1]. The pre-legalization step (Fig. 4) only legalizes cells that violate a fence region. Displacement of these cells can cause the maximum cell displacement, so we consider them first to minimize the maximum cell displacement. The positions of pre-legalized cells are fixed to preserve the maximum cell displacement quality during the subsequent multi-stage legalization process. The cells that violate regions shrink into or stretch out to the fence region.

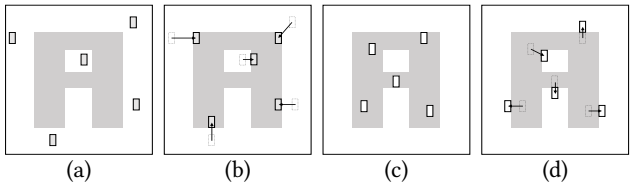

Figure 4: Examples of pre-legalization. (a) Region-violation cells that are outside the fence region. (b) shrink into the region. (c) Region-violation cells that are inside the fence region. (d) stretch out to the region. Gray cells must be within the A-shaped fence region, and white cells must be placed outside of it.

3.2 Multi-deck Standard Cell Legalization

Multi-deck standard cell legalization consists of three steps: cell arrangement, local cell shifting, and corner weight move. This algorithm finds a nearest available position for the multi-deck standard cell. When the search algorithm cannot find an available position, the local cell shifting algorithm tries to insert the multi-deck standard cell by shifting peripheral cells. When this local cell shifting cannot find an available position, the corner weight move algorithm is required. Legalization complexity of large cells is higher than small cells, so the algorithm sort all cells in descending order of size. Using the sorted result, cell arrangement, local cell shifting, and corner weight move strategies are conducted sequentially.

3.2.1 Fence-Region-Aware BFS. Fence-region-aware BFS (FRA-BFS; Algorithm 1) is a core algorithm of the proposed multi-deck standard cell legalization method, and is used in all steps of multi-deck legalization. The concept of the search algorithm comes from previous detailed placement algorithm [11]. Our search algorithm can find a nearest available position by considering moves in both the x- and y directions by using a 2-D grid structure; this ability is an improvement of previous methods, which can only consider movement in the x direction [4–6, 10].

ALGORITHM 1: Fence-Region-Aware BFS

input : $C \leftarrow$ Target cell, $P_{(x,y)} \leftarrow$ Search point coordinates
output: $T_{(x,y)} \leftarrow$ Nearest Available Position

```
1  Define A as available position array.
2  Define G as 2-D grid of circuit by rows and sites.
3  Define G'(s) as a set of encapsulated square region which distance is s from P(x,y).
   (Initial s is zero.)
4  while A is empty do
5      if s is larger than L or out of boundary then
6          return false.
7      end
8      Construct G'(s).
9      for each square region in G'(s) do
10         if square region has an available position for C then
11             Push the available position into A.
12         end
13     end
14     if A is not empty then
15         Find nearest available point T(x,y) from A.
16         return T(x,y).
17     end
18     Increase the search distance s.
19 end
```

FRA-BFS takes target cell C as an input, generates coordinates $P_{(x,y)}$ of the search point, and find the nearest available position $T_{(x,y)}$. For the physical layout, the row height is larger than the site width. Thus, we have constructed the encapsulated square grid G_0 which consists of multiple sites (Lines 2-3). For each square in G_0, we select a single available position and put it into an available position array (Lines 10-12). G_0 has fewer available positions compared to a 2-D grid G, so the runtime of FRA-BFS can be reduced. The procedure searches the surrounding area from center to the boundary of G_0 until the nearest available position is found (Lines 4-19). In the loop, the search distance is increased when no position is available (Line 18). If the search boundary exceeds the search limit L, the procedure stops searching (Lines 5-7). The search limit L is empirically defined by a displacement constraint. If this constraint is not specified, L is the larger of die width and die height.

3.2.2 Cell Arrangement. Cell arrangement is the first strategy that moves a cell into the nearest available position from the global placement result. The displacement is the distance between the initial and legalized position, so we should minimize the cell displacement. With the global placement result, we perform FRA-BFS during the cell-arrangement procedure. FRA-BFS has search limits, so it may not find an available position; in that case, the local cell shifting procedure is required.

3.2.3 Local Cell Shifting. Shifting a single cell can cause significant cell movements. To solve this problem, the local-cell-shifting algorithm sets a region and rearranges peripheral cells by using the FRA-BFS algorithm. First, a region clip is generated by the size of target cell P (Fig. 5a). The region clip defines the peripheral cells and disallowed area, which is generated from a cell that is partially within the region clip (Fig. 5b). After overlapping cells are collected, peripheral cells are ready for local cell shifting (Fig. 5c). Next, target cell A is placed appropriately and peripheral cells are placed (Fig. 5d). We sort the peripheral cells in descending order of size.

3.2.4 Corner Weight Move. This is the final legalization strategy. The failure of cell arrangement and local cell shifting means that the area is densely occupied, so the possible legalization strategy is to minimize the distance between peripheral cells. The corner weight move divides the fence region into four sub-regions, and then in each sub-region the corner weight move shift the cells toward the corner. Cells are moved in ascending order of their distance from the corner. This strategy is effective when the fence regions are densely occupied.

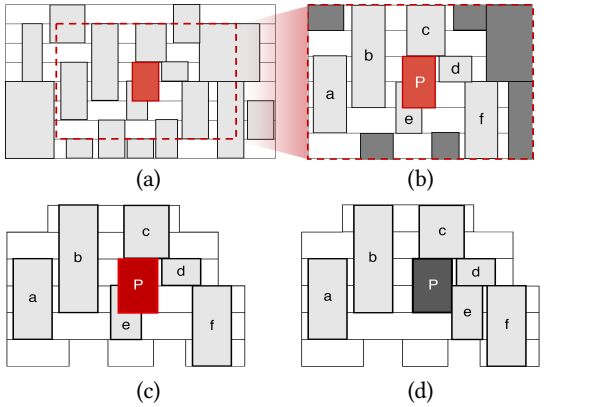

Figure 5: Example local cell shifting. (a) Region clip is defined by selected cell P. (b) Cell area that is cut off by the region clip is treated as a disallowed area (dark grey), and cells (a to f) within the selected region are treated as movable cells. (c) The initial state is generated by region selection. (d) The peripheral cells are rearranged.

3.3 Quality Refinement

After the multi-deck standard cell legalization step, we optimize the results further in a quality-refinement stage. We optimize the results by applying a simulated annealing technique. Cell moving and cell swapping optimize maximum and total displacements during the simulated annealing iterations. These movements and swaps do not affect the legality of results.

3.3.1 Cell Move. Cell movement can improve the displacement quality. If the displacement penalty of target cell is less than the threshold value, we move the target cell. This movement might increase the cell displacement. From the previous cell move, another cell movement decreases the cell displacement. These two cell movements combine to decrease both the total displacement and the maximum displacement. The displacement threshold is proportional to the width of core site and inverse proportional to the number of iteration steps.

3.3.2 Cell Swap. Cell swap can also improve the displacement quality. The principle of cell swap is the same as the previous cell move. However, to ensure that the maintaining legalized result is retained, we can only swap same-sized cells. By swapping two identically-sized cells, both the total and the maximum displacement are decreased. This cell swapping is effective when the utilization is high, because cell swapping can optimize the displacement quality without changing the layout placement.

3.3.3 Simulated Annealing. The simulated annealing is a probabilistic technique to approach the global optimum of a given objective function. In this work, we use total displacement as the objective function. For temperature scheduling, an escape condition is considered as the cell swap and cell move ratio per the total number of cells. For effective legalization between quality and runtime, we set the escape constant k as 0.004 empirically. The optimization process proceeds for each fence region, and the simulated annealing is iterated until the escape function stops it. At each iteration step, the moving cell and swapping cell pairs are selected randomly.

4 EXPERIMENTAL RESULTS

Our experiments and evaluations are based on the ICCAD-2017 contest [1] environment. We built our binary by using C++, and executed it on a 2.2 GHz Intel Xeon workstation with 64 GB of memory, which are similar to the ICCAD-2017 contest environment. We consider 15 benchmarks from the ICCAD-2017 contest (Table 1). We neglect one benchmark that only contains single-deck standard cells and lacks a fence region.

Table 1: Benchmark Information and score comparison with the ICCAD-2017 Contest Winners.

Benchmark	# Cells	Cell type				# F.R.	Max F-Util.	Util.	Team ranked #1		Team ranked #2		Team ranked #3		Ours	
		1xH	2xH	3xH	4xH				S_{total}	Time	S_{total}	Time	S_{total}	Time	S_{total}	Time
des_perf_a_md1	103589	95.66	4.34	0	0	4	72.64	55.11	22.15	14.39	459.27	9.35	10948.43	35.62	9.52	3.85
des_perf_a_md2	103589	96.99	1	1	1	4	75.99	55.92	192.59	17.42	952.05	11.93	283.3	38.19	57.69	3.55
des_perf_b_md1	112679	94.8	5.2	0	0	12	96.2	54.98	0.39	6.59	1.14	10.85	***0.69**	12.08	0.63	3.43
des_perf_b_md2	112679	90.47	6.02	2.01	1.5	12	71.74	64.69	0.81	6.26	1.2	18.01	1.09	12.65	0.82	2.72
edit_dist_1_md1	130661	90.31	6.12	2.04	1.53	0	N/A	67.47	0.88	8.58	1.03	20.6	2.88	14.14	1.9	1.9
edit_dist_a_md2	127414	90.31	6.12	2.04	1.53	1	9.73	59.42	0.76	7.59	1.2	31.5	1.37	14.36	1.03	2.31
edit_dist_a_md3	119626	93.88	2.04	2.04	2.04	1	9.3	57.22	1.18	21.02	30.48	12.1	5.95	39.84	1.18	2.43
fft_2_md2	32281	89.62	6.56	2.18	1.64	0	N/A	83.12	0.78	1.6	1.31	30.64	1.09	4.35	0.9	0.51
fft_a_md2	30625	89.57	6.59	2.19	1.65	0	N/A	32.41	0.77	1.41	0.9	2.5	1.14	3.16	0.78	0.84
fft_a_md3	30625	93.42	2.19	2.19	2.19	0	N/A	31.24	0.6	1.36	0.67	2.45	0.92	2.95	0.62	0.86
pci_bridge32_a_md1	29533	90.39	6.07	2.02	1.52	3	38.67	49.57	1.03	1.43	1.51	2.51	1.66	2.75	1.07	1.28
pci_bridge32_a_md2	29533	85.51	7.08	4.04	3.37	3	62.44	57.72	1.22	4.02	22.78	2.47	4.63	7.21	1.45	1.12
pci_bridge32_b_md1	26134	90.38	6.07	2.02	1.52	3	35.98	28.68	2.07	6.42	1.71	1.83	1.54	8.49	1.18	1.59
pci_bridge32_b_md2	26134	97.97	1.01	1.01	1.01	3	41.67	19.72	14.27	6.35	8.82	1.79	4.48	8.5	3.61	1.68
pci_bridge32_b_md3	26134	94.94	1.01	2.02	2.02	3	62.09	23.98	32.62	3.9	17.95	1.58	40.94	8.39	19.22	2.17
							Avg.		18.14	7.22	100.14	10.67	753.34	14.18	6.77	2.01
							N. Avg.		1	1	5.44	1.48	40.92	1.96	0.37	0.28

#F.R.: number of and fence regions; Cell types. 1xH, 2xH, 3xH and 4xH of cell type are the proportions portion of single-deck, double-deck, triple-deck, and quadruple-deck standard cells, respectively;. Max F-Util:. are maximum utilization of fence regions; Util.: utilization of entire benchmark. ***Bold** means given solution is illegal.

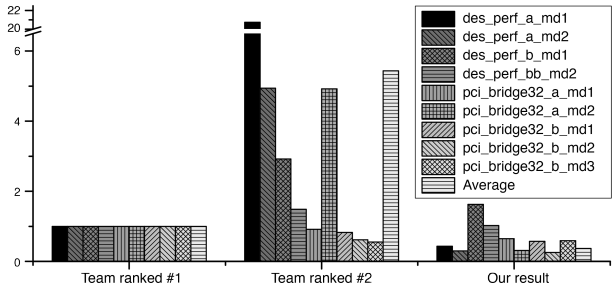

Figure 6: Normalized S_{total} comparison in multiple fence region benchmarks.

4.1 Evaluation

The concept of our evaluation metric is inspired by the ICCAD-2017 contest. Evaluation scoring considered the maximum displacement score(S_{md}), the average displacement score(S_{ad}), and HalfPerimeter Wire Length (HPWL) score(S_{hpwl}). The total score(S_{total}) is the product of these three partial scores. Evaluation scores for top contestants in the ICCAD-2017 contest are calculated from published DEF results on the contest website.

4.2 Results

Our proposed fence region-aware legalization method achieved 63% and 72% improvement in average quality score and average runtime, respectively. We compared our S_{total} and runtime results and those of the ICCAD-2017 contest winners (Table 1, Figs. 6). Runtime analysis of each step of our proposed method demonstrates that File I/O consumed 65.6% of runtime; legalization consumed only 10.9%, and optimization consumed only 23.5%.

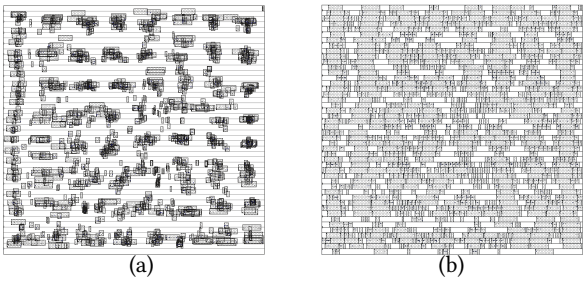

Figure 7: Initial and detailed placement result using spi_top design and TSMC 65*nm* PDK. (a) initial placement result using *Innovus*, and (b) is legalized result using our binary.

4.3 Innovus Compatibility

We check compatibility of our binary [7] with *Cadence Innovus Implementation System*. We use TSMC 65*nm* and ASAP 7*nm*[12] PDK and various open source RTL design such as aes_cipher_top, spi_top, and pci_bridge32. We use *Synopsys Design Compiler* to synthesize netlist and generate initial placement DEF file using *Innovus*. Our binary generates legalized DEF file using initial placement DEF file and LEF file from PDK. Legalized DEF files are verified using *Innovus*. Fig. 7a shows initial placement result of spi_top using TSMC65*nm* PDK and Fig. 7b shows legalized placement result.

5 CONCLUSIONS

We have proposed a fence-region-aware multi-deck standard cell legalization method that uses a multi-stage and metaheuristic optimization. Our work can handle various heights of the multi-deck standard cell, and consider various shapes of fence regions. Our proposed method achieves an effective solution for the multi-deck standard cell legalization. Furthermore, we realize that our simulation binary supports other design and PDK which is out of the ICCAD-2017 contest environment.

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