

Technology-Aware 3D Placement with ILP-Based Region Planning for Soft Modules

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Outline

- ❑ Introduction
- ❑ Problem Formulation
- ❑ Methodology
- ❑ ILP-Based Region Planning for Soft Modules
- ❑ Experimental Results
- ❑ Conclusion



Introduction



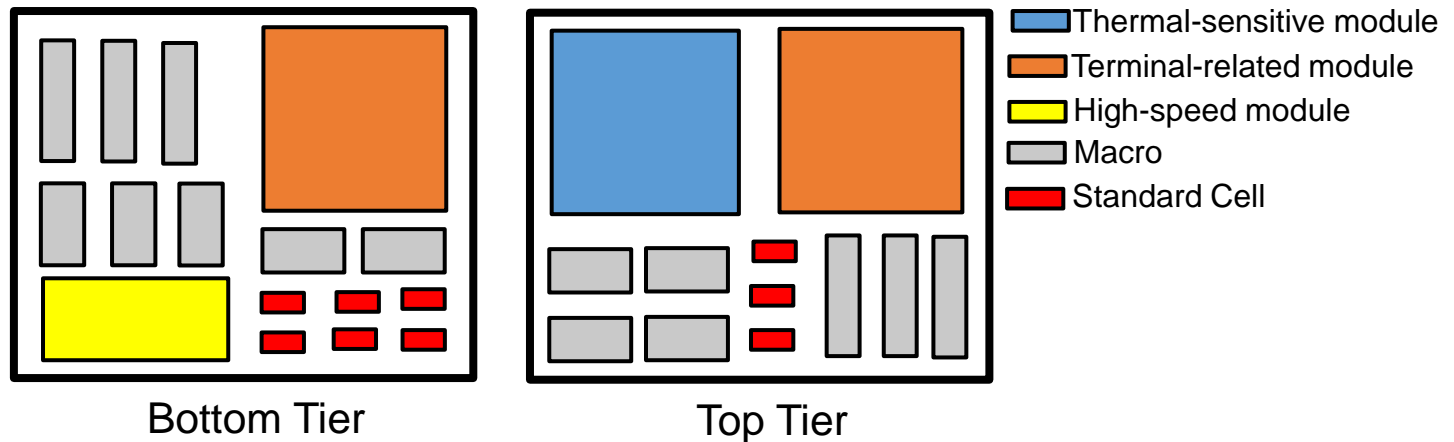
3D IC: Opportunities and Challenges

- ❑ 3D IC enables integration beyond traditional scaling limits
 - Vertical stacking shortens interconnects
 - Improves density and heterogeneous integration
- ❑ However, it introduces several challenges
 - Thermal hotspots due to limited heat dissipation
 - Increased interconnect complexity & routing congestion
 - Heterogeneous integration further complicates 3D placement
 - Analog/digital isolation
 - Voltage/noise domain partitioning
 - Cross-node spatial planning



Need for Spatial Regulation in 3D Placement

- ❑ 3D placement requires controlled spatial grouping of instance clusters
 - Thermal-sensitive modules → cooler regions
 - Terminal-related modules → cross-tier alignment
 - Different performance/power domains → spatial separation



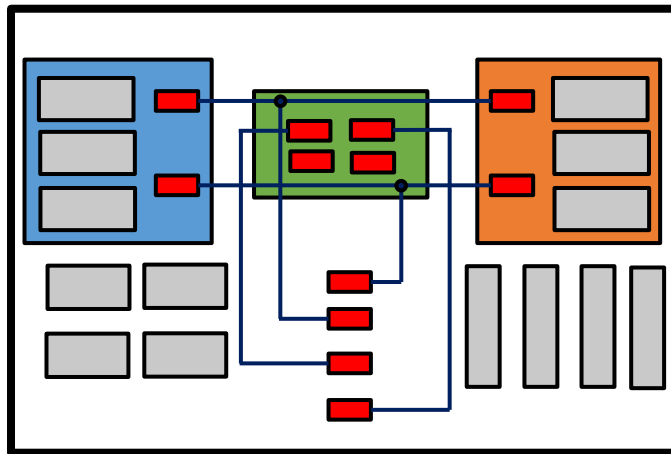
Limitation of Traditional Fence Regions

- ❑ Predefined fence regions limit placement adaptability
 - Region boundaries predefined during floorplanning
 - Shape, size, and location remain static
 - Cannot adapt to dynamically evolving placement conditions and constraints
 - Restricts optimization flexibility and solution quality

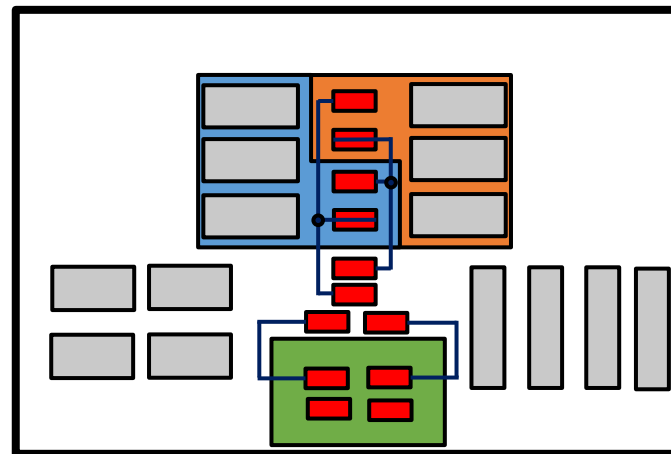


Hierarchy Constraint (Proposed)

- We introduce a hierarchy constraint that preserves structural grouping while allowing flexible region geometry
 - Groups designated instances into a “soft module”
 - Maintains structural hierarchy
 - Region geometry (shape, size, location) is determined during placement
 - Jointly optimized with placement



Fence Region Constraint



Hierarchy Constraint

- Region1
- Region2
- Region3
- Macro
- Cell



Problem Formulation



Problem Formulation

□ Given

- Mixed-size 2-tier design (heterogeneous technologies)
- Netlist with standard cells and macros
- Physical constraints (utilization, spacing, terminals)
- Soft module specification (grouped instance sets)

□ Objective

- $Score = W_{btm} + W_{top} + c_{term} \times |V_{term}|$

□ Key Constraints

- No overlap & row alignment
- Tier assignment for instances
- Utilization and terminal constraints
- Hierarchy constraint



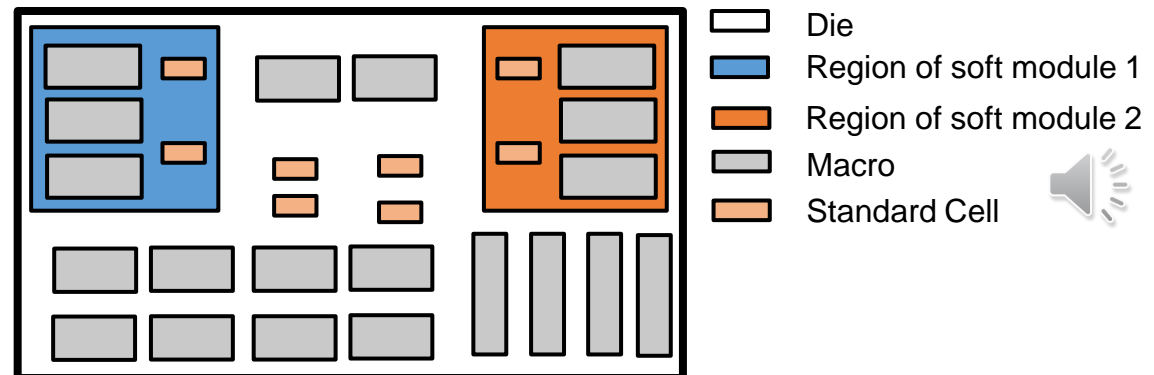
Hierarchy Constraint

□ Definition

- A **soft module** groups designated instances
- All grouped instances must
 - Be placed on the same tier
 - Stay inside the module region
- Free instances cannot enter module regions

□ Region Properties

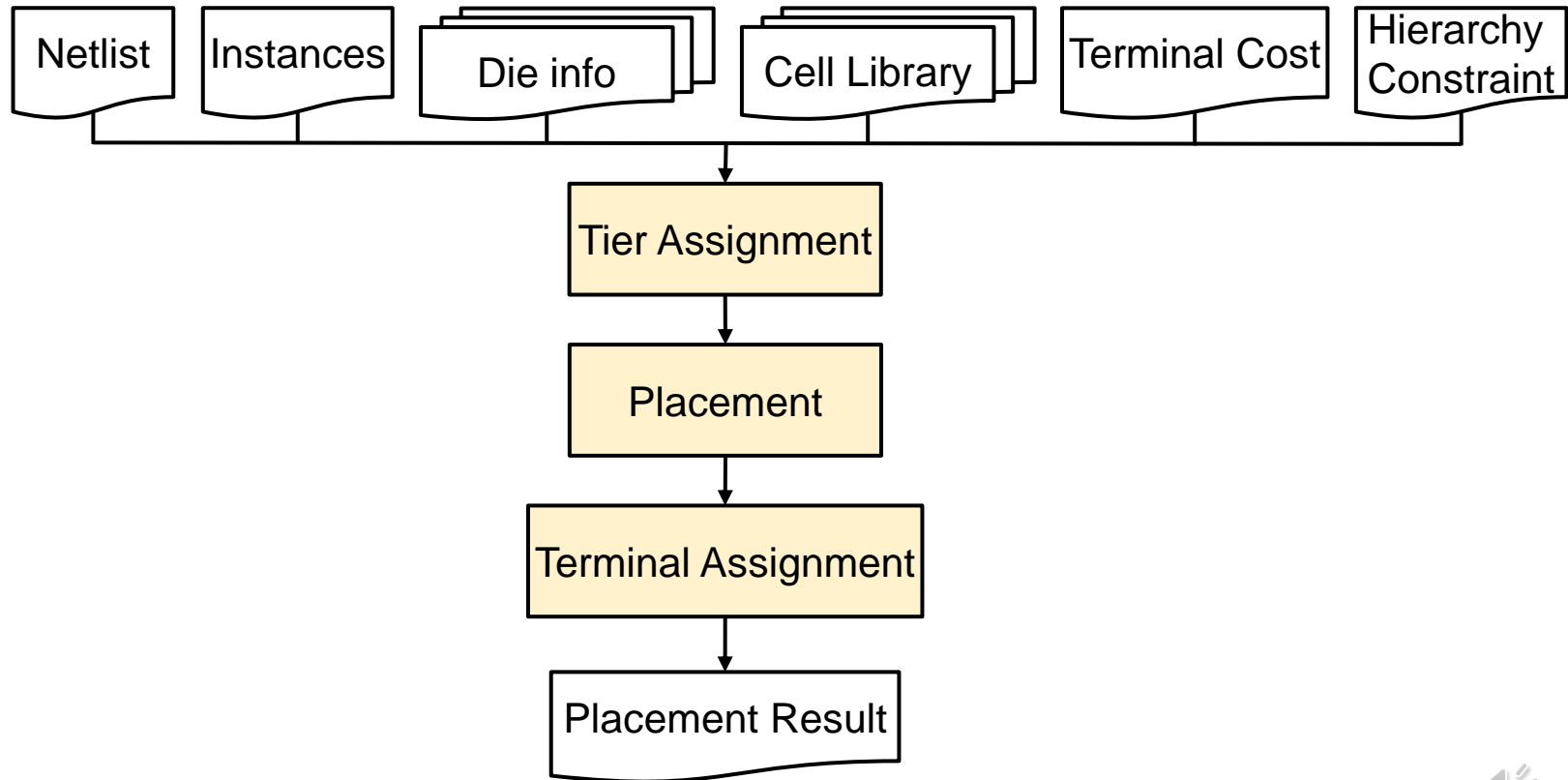
- Each soft module can be placed on either tier
- Region shape: rectangular or L-shaped



Methodology



Methodology Overview



Technology-Aware Tier Assignment

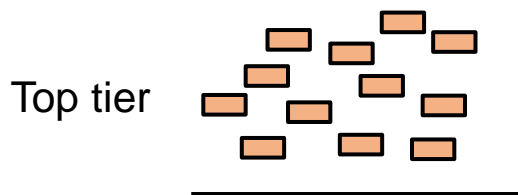
❑ Hypergraph Partitioning

- Hypergraph partitioning via **KaHyPar**
- Soft modules contracted as super-nodes

❑ **Issue:** Technology-aware imbalance

- Cross-tier technology differences cause size imbalance
- KaHyPar is not technology-aware
- Leads to pseudo-balanced partitions

❑ Solution: Iterative refinement for technology-aware balancing



PS First technology-aware partition

Bottom tier

KaHyPar

- blocks V_i are roughly equal-sized:

$$c(V_i) \leq (1 + \epsilon) \left\lceil \frac{c(V)}{k} \right\rceil$$

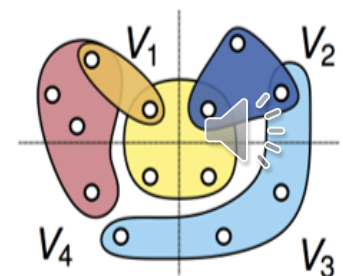
imbalance parameter

- objective function is minimized:

cut-net:
 $\sum_{e \in \text{cut}} \omega(e) = 3$

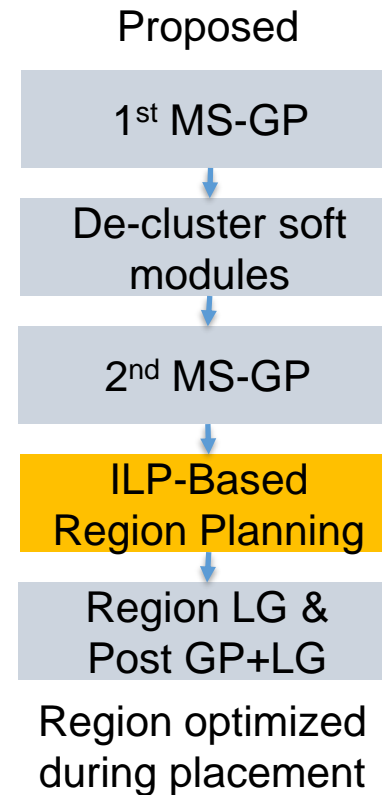
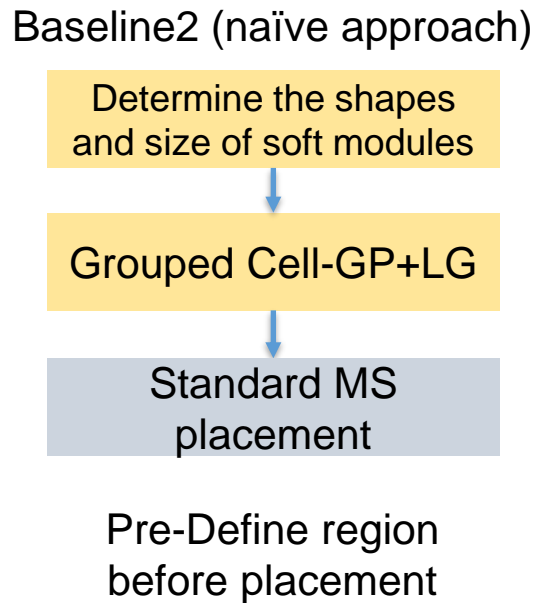
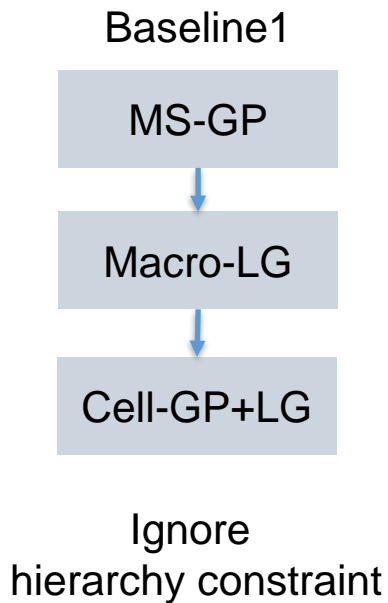
connectivity:
 $\sum_{e \in \text{cut}} (\lambda - 1) \omega(e) = 6$

blocks connected by net e



Source: <https://github.com/kahypar/kahypar?tab=readme-ov-file>

Comparison of Placement Flows



MS: Mixed Size
GP: Global Placement
LG: Legalization



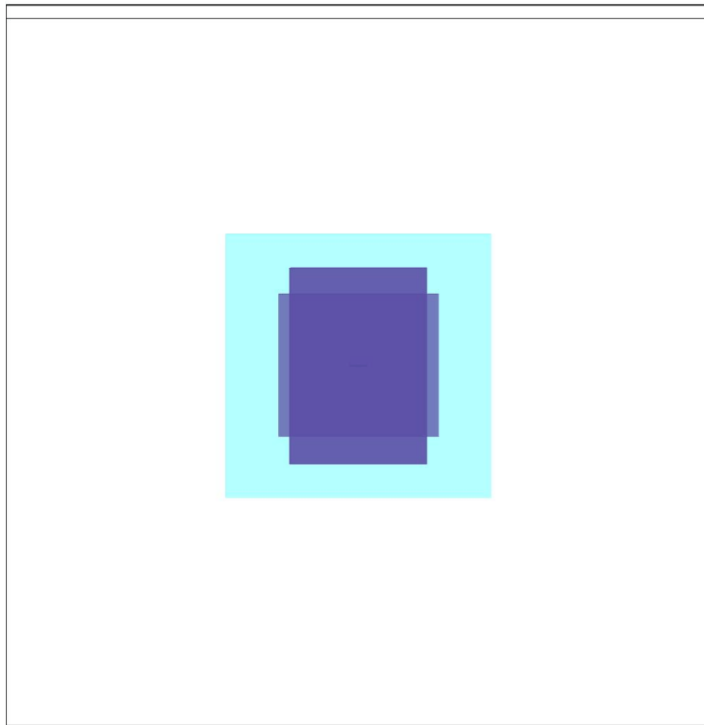
1st MS-GP



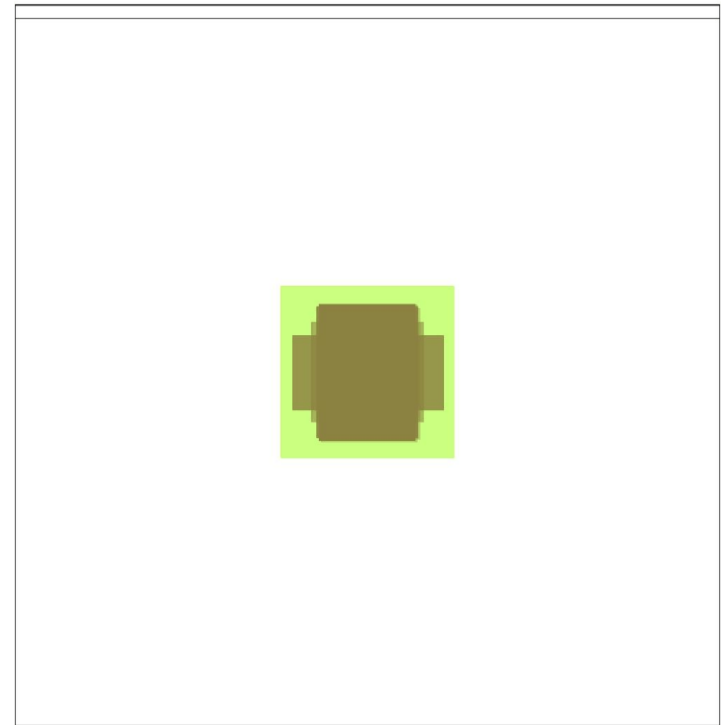
2nd MS-GP

Feature	B1	B2	Proposed
Hierarchy Aware	✗	✓	✓
Region Flexible	✗	✗	✓
Joint Optimization	✗	✗	✓

Animation of Proposed Placement Flow



Bottom

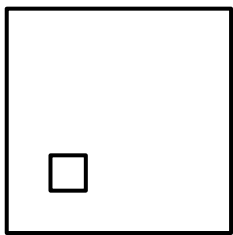


Top

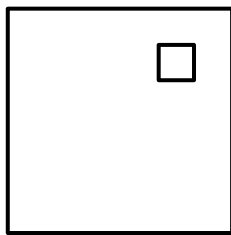


Terminal Assignment

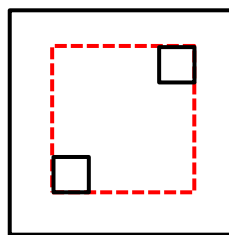
- ❑ Compute an optimal region for each cross-tier net
- ❑ Partition placement area into legal bin grids
 - 1 bin = 1 terminal
- ❑ Assign terminals via bipartite matching
 - Ensures spacing legality and avoids wirelength overhead



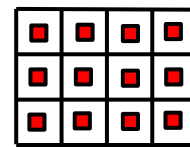
Bottom tier



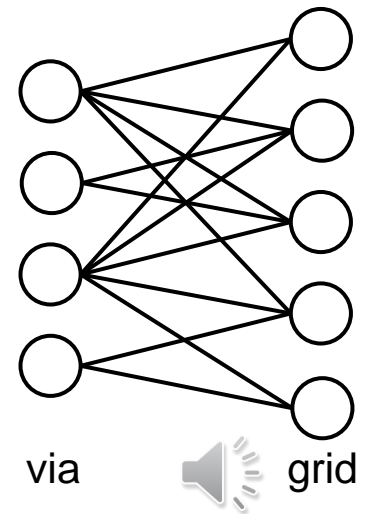
Top tier



Optimal region



Predefined grids

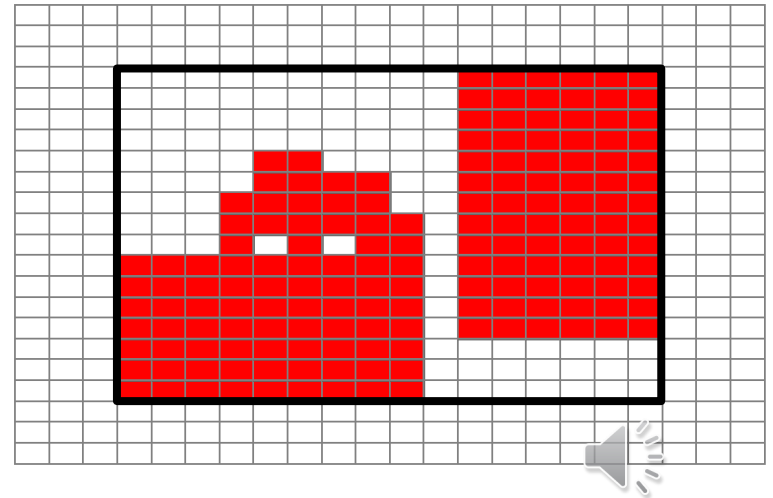
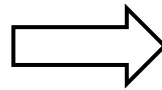
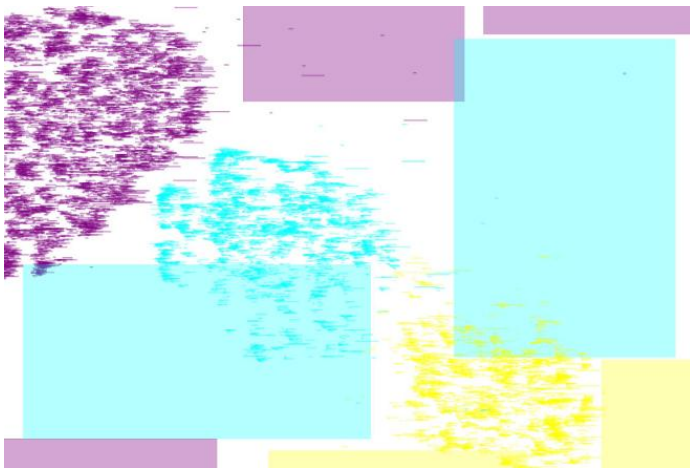


ILP-Based Region Planning for Soft Modules



Pre-Processing

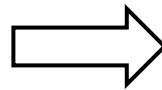
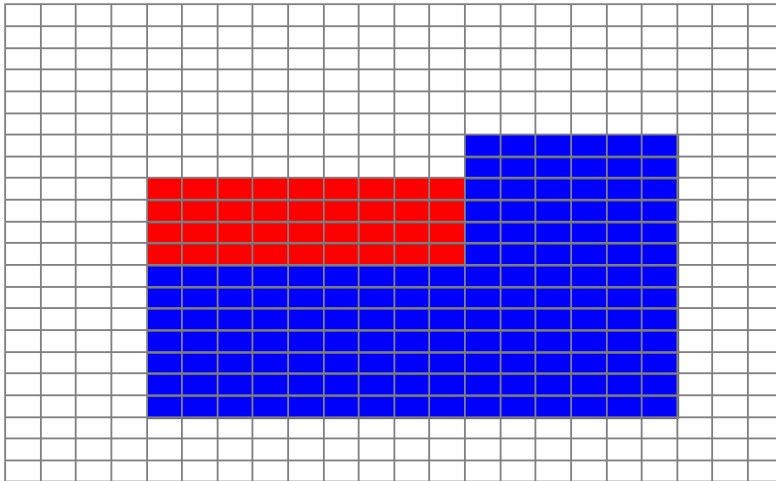
1. Grid-based region discretization (e.g. 16×16)
2. Feasibility filtering (utilization $> 50\%$ or macro overlap)
3. Boundary slack reservation
 - Ensure a feasible solution



Our Goal

- ❑ Select a grid set that
 - Covers all grouped instances
 - Minimizes perturbation to global placement
 - Shape constraint: rectangular or L-shaped

 Macro
 Cell



ILP Variables for a Grid (i, j)

□ Input / Output

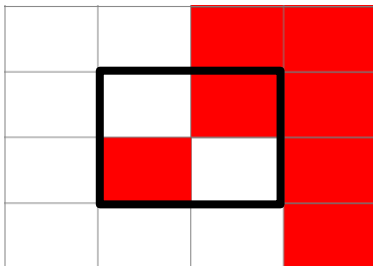
- $x_{(i,j)} \in \{0, 1\}$: Input grid (Given)
- $y_{(i,j)} \in \{0, 1\}$: Selected output grid

□ Difference Indicator

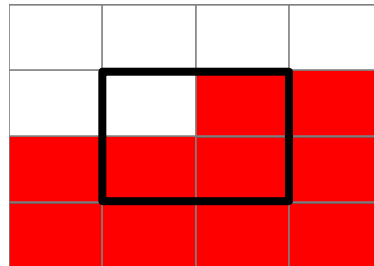
- $d_{(i,j)} = x_{(i,j)} \oplus y_{(i,j)}$

□ Shape-Related Indicators (2×2 local pattern)

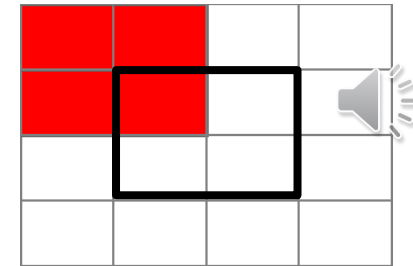
- Check neighborhood (16 configurations)
 - Illegal: 2, Concave: 4, Convex: 4, Others: no constraint
- $illegal_{(i,j)}, concave_{(i,j)}, convex_{(i,j)} \in \{0, 1\}$
- Exactly one configuration per 2×2 block



Illegal(2 types)



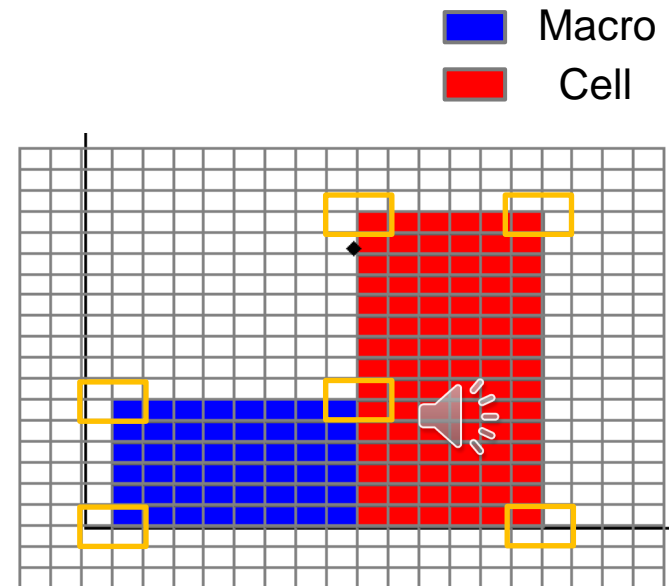
Concave(4 types)



Convex(4 types)

Shape-Constrained Modeling

- ❑ Boundary condition
 - $y_{(i,j)} = 0, \forall i, j \in \{0, Grids - 1\}$ (boundary grids)
- ❑ Area preservation
 - $\sum_{(i,j) \in P} x_{(i,j)} \leq \sum_{(i,j) \in P} y_{(i,j)}$
- ❑ Local Encoding (2x2)
 - Illegal / Concave / Convex indicators
 - Exactly one configuration per block
- ❑ Shape enforcement for soft module
 - $\sum_{(i,j) \in P} illegal_{(i,j)} = 0$
 - $\sum_{(i,j) \in P} concave_{(i,j)} \leq 1$
 - $4 \leq \sum_{(i,j) \in P} convex_{(i,j)} \leq 5$
 - Guarantees rectangular or L-shaped region



Macro Placement within a Soft Module

□ Macro Placement Variables

- m_k be the k -th macro, $m_k \in M$
- X_k, Y_k : decision variables representing the location of m_k
- $p_{u,v}, q_{u,v} \in \{0,1\}$: Relative position encoding of m_u and m_v
- W_k, H_k : Width and Height of m_k
- GW, GH : Width and Height of the grid map
- $m_{k(i,j)} \in \{0,1\}$: if m_k is placed at (i,j) , $m_{k(i,j)} = 1$

□ Constraint for unique placement

- $\sum_{(i,j) \in P} m_{k(i,j)} = 1$

□ Big-M non-overlap constraints

- Binary variables $(p_{u,v}, q_{u,v})$ encode 4 relative positions for each macro pair



Macro-to-Grid Coupling

□ If $m_k(i,j) = 1$

– Macro occupies: $[x = i, i + W_k - 1], [y = j, j + H_k - 1]$

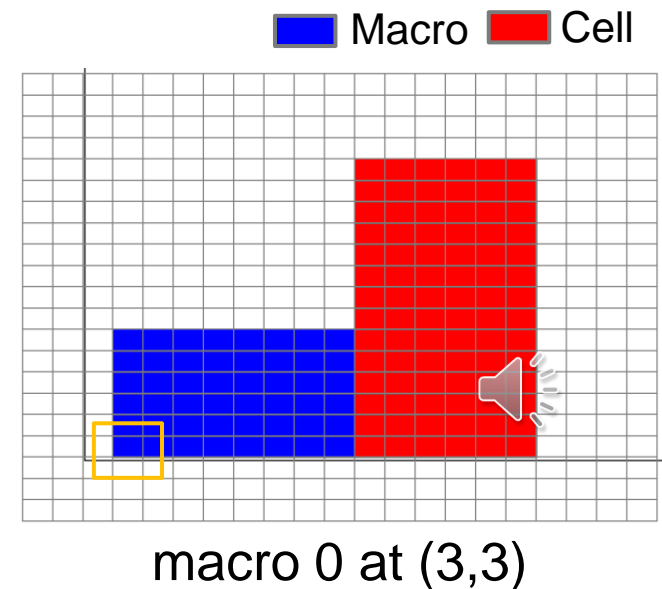
– $\Rightarrow X_k = i, Y_k = j$

– $\Rightarrow i + W_k \leq GW, j + H_k \leq GH$

– $\Rightarrow \sum_{x=i}^{i+W_k-1} \sum_{y=j}^{j+H_k-1} y_{(x,y)} = W_k \times H_k$

- Forces all grids under macro to be selected since $y_{(x,y)} \in \{0,1\}$

E.g. $m_0(3,3) = 1, W_0 = 8, H_0 = 6$
 $\Rightarrow m_0$ at $(3,3), \sum(y_{(3,3)} \sim y_{(10,8)}) = 48$



Linear Approximation of Region Area

□ Naïve formulation

- $\sum y_{(i,j)}$
- Accurately models region area
- Large solution space \rightarrow time-consuming

□ Our linear approximation, linearizable and much more efficient

- $range_w = \max_k(X_k + W_k) - \min_k(X_k)$
- $range_h = \max_k(Y_k + H_k) - \min_k(Y_k)$



Objective Function

- ❑ Goal of Region Planning
 - Maximize area utilization
 - Preserve original placement distribution
- ❑ To achieve these goals, the objective integrates three cost components
 - Cell distribution pattern difference (XOR-based)
 - Placement stability
 - Region compactness
- ❑ Final Objective
 - X'_k, Y'_k : Original location of m_k

$$\min \alpha \sum_{(i,j) \in P} d_{(i,j)} + \beta \sum_{k \in M} (|X_k - X'_k| + |Y_k - Y'_k|) + \gamma (range_w + range_h)$$



Experimental Results



Experimental Setup

❑ Benchmark

- 2023 ICCAD Contest at Problem B: 3D Placement with Macros
- 7 testcases
- Up to **740K** cells, **34** macros, and **3** soft modules

❑ Preprocessing

- KaHyPar for k-way partitioning
- Selected partitions form **soft modules**
- Hierarchy constraint applied to selected groups

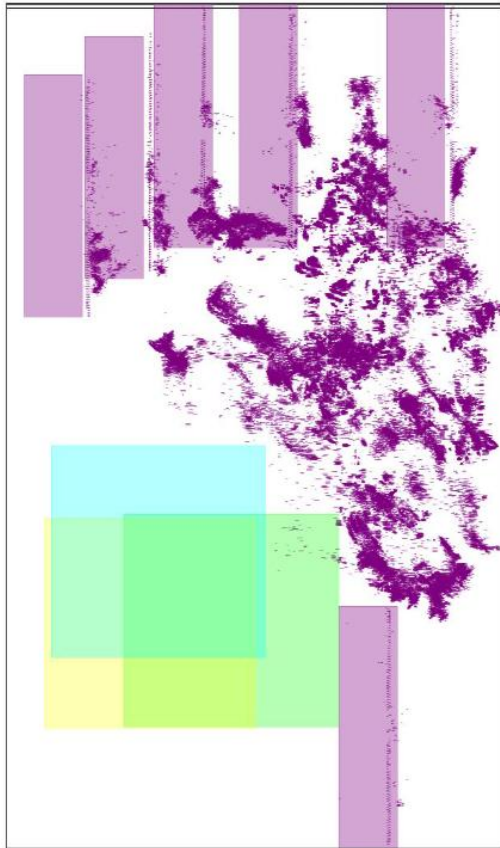


Experimental Result

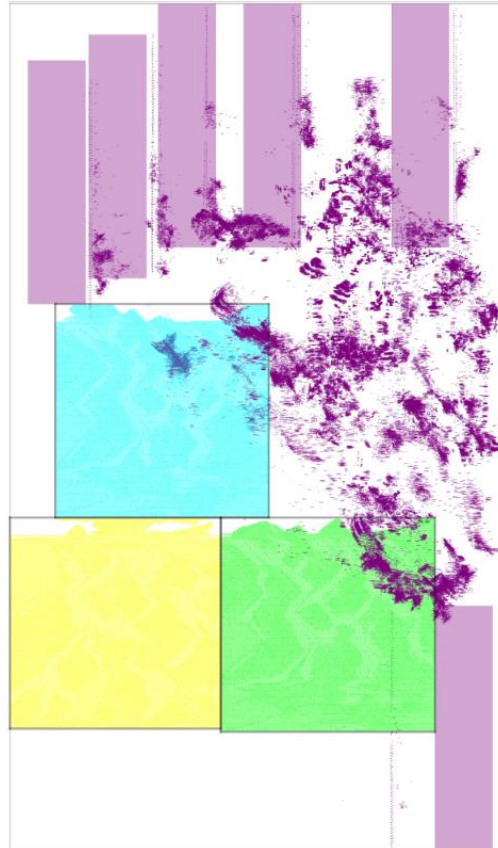
- ❑ Compared to Naïve approach
 - 21% cost reduction
 - 26% runtime reduction
- ❑ Compared to Baseline placer (no region constraint)
 - Only 5% cost penalty



Result for Case4h-Pre-Defined



MS-GP

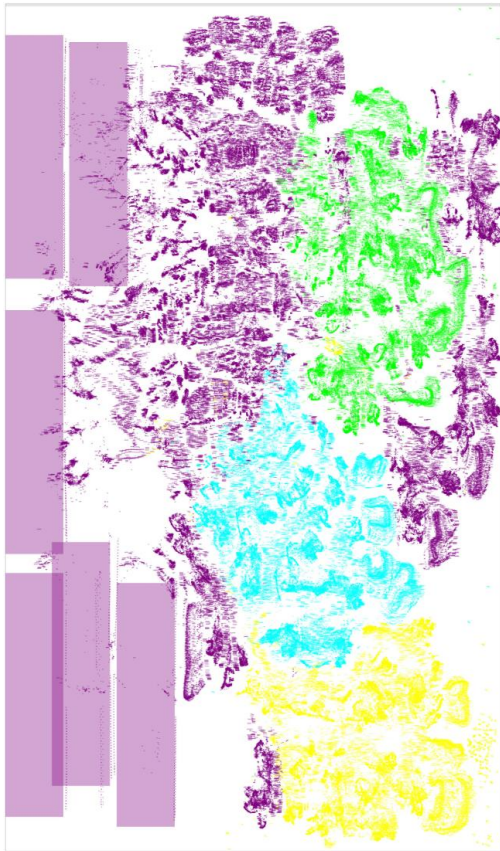


Macro LG



Final Placement

Result for Case4h-Proposed



2nd MS-GP



Region Planning
& Legalize macro



Final Placement

Conclusion



Conclusion

❑ Contributions

- A multistage framework for hierarchy-aware 3D placement
- ILP-based region planning for soft modules

❑ Key Results

- **21% cost reduction** over naïve approach
- Only **5% cost penalty** vs baseline placer

