Cell-Flex Metrics for Designing Optimal Standard Cell Layout With Enhanced Cell Layout Flexibility

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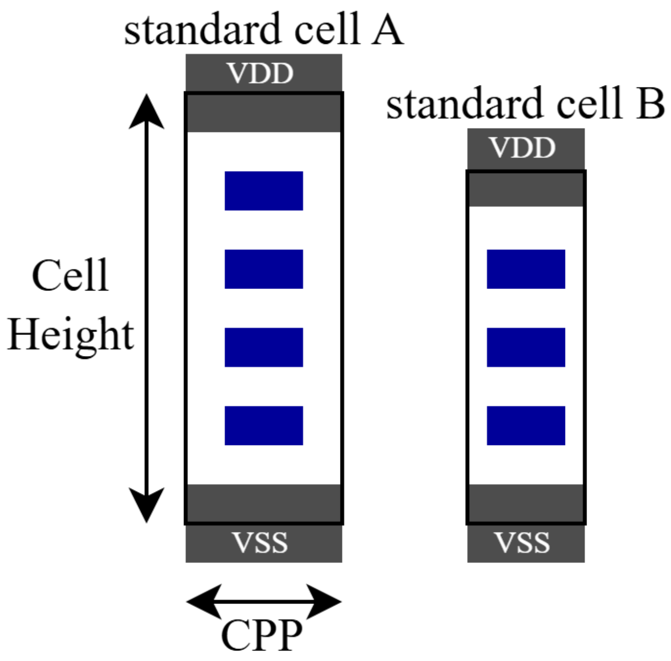
Introduction

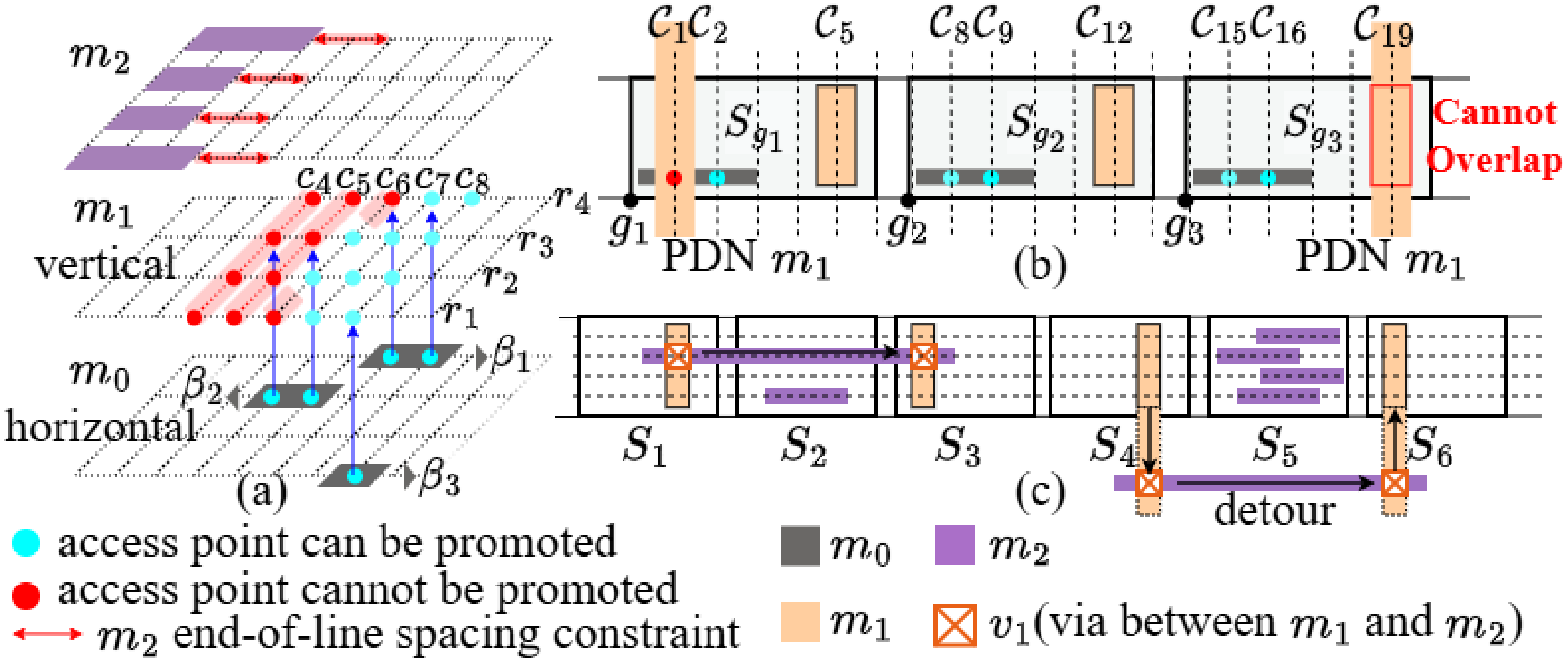
- Area gains achieved at the cell level (Logic Scaling) do not always translate into block area scaling due to three factors.
  - Limitations in routing resources
  - Pin density increase
  - Complexity of the Power Delivery Network (PDN)



$$\text{Logic Scaling} = \frac{\text{standard cell B}}{\text{standard cell A}} \neq \frac{\text{Block Area B}}{\text{Block Area A}}$$

Problem Statement

- We considered this issue caused by lack of Cell Layout Flexibility (**Cell-Flex**).
  - (a) Pin Access Flexibility (PAF)
  - (b) Cell Placement Flexibility (CPF)
  - (c) Track Utilization Flexibility (TUF)

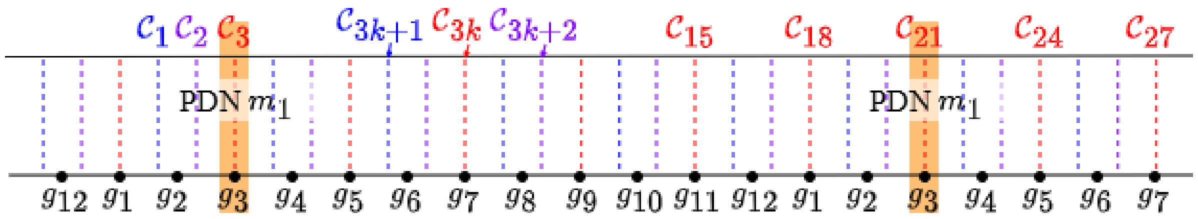


Contribution

- **Cell-Flex Metric for evaluating Cell Layout Flexibility.**
  - We introduce Cell-Flex metrics, which include Cell Placement Flexibility (CPF), Pin Access Flexibility (PAF), and Track Utilization Flexibility (TUF). These metrics assess cell layout quality and the impact of cell layout on block designs.
- **Cell-Flex Oriented Cell Layout for Block Area Reduction.**
  - We regenerate the cell layout, with Cell-Flex metrics as objectives. By improving Cell-Flex, block area can be reduced without increasing Design Rule Violations(DRVs).
- **Cell-Flex Features for DRV prediction.**
  - We develop a Machine Learning (ML) model using Kolmogorov–Arnold Networks (KAN) for DRV prediction, demonstrating the superior predictive capability of our metrics with high accuracy and F1 scores.

Cell Placement Flexibility (CPF)

- **CPF quantifies how much a cell can be freely assigned** during placement and routing, influenced by the PDN configuration.
- Generally, PDN metals are placed periodically.
  - How to avoid potential PDN location by using this nature.



Our paper's assumption for PDN configuration, repeated every 18 metal columns and 12 cpp grids.

Definition 1. The *CPF* of a cell S placed in g_m is defined by the following formula:

$$CPF_{S_{g_m}} = fpc(g_m, 0) + \sum_{cpp_s=1}^{\frac{\text{PDN period}}{2}} \left(\frac{fpc(g_m, cpp_s)}{dp(cpp_s) \times ap(cpp_s)} \right)$$

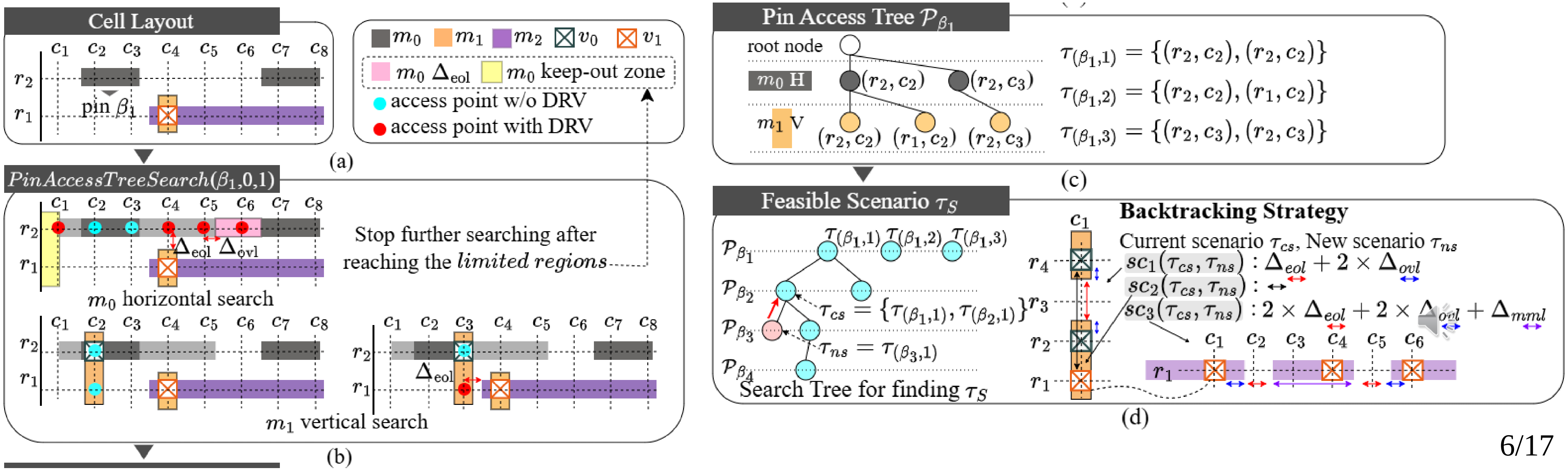
where:

- cpp_s represents the number of contact poly pitch(CPP) shifts.
- $fpc(g_m, cpp_s)$ represents the feasible placement cases, considering a shift of cpp_s to the left and right from g_m.
- $dp(cpp_s) = 1 + cpp_s$ defines the distance penalty factor.
- $ap(cpp_s) = \begin{cases} \frac{\text{cell height}}{\text{single height}} \times cpp_s & \text{if } cpp_s \leq \text{cell width}, \\ \frac{\text{cell height}}{\text{single height}} \times \text{cell width} & \text{otherwise}, \end{cases}$

  determines the area penalty based on cpp_s.

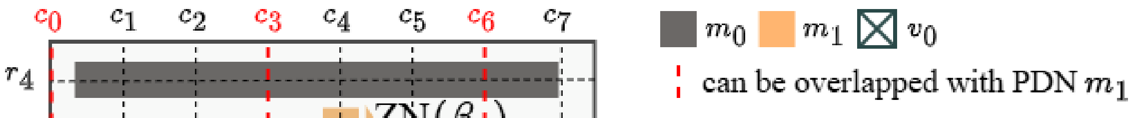
Pin Access Flexibility (PAF) - 1

- **PAF implies the number of feasible routing scenarios** for a standard cell layout, considering DRs, cell architecture, internal routing blockages, PDN metals, and pin interference.
- Our algorithm produces a pin access tree through a modified breadth-first search algorithm.



Pin Access Flexibility (PAF) - 2

- Routing Scenario calculation.
  - τ_S : the set of feasible scenarios for the cell.
  - It can be also affected by PDN.



Placement grid	$\|\tau_S\|$
g_1, g_{12}	432
g_2, g_{11}	0
g_3~g_{10}	672

- PAF Definition.

Definition 2. The Pin Access Flexibility (*PAF*) for a given cell S placed in g_m is calculated as:

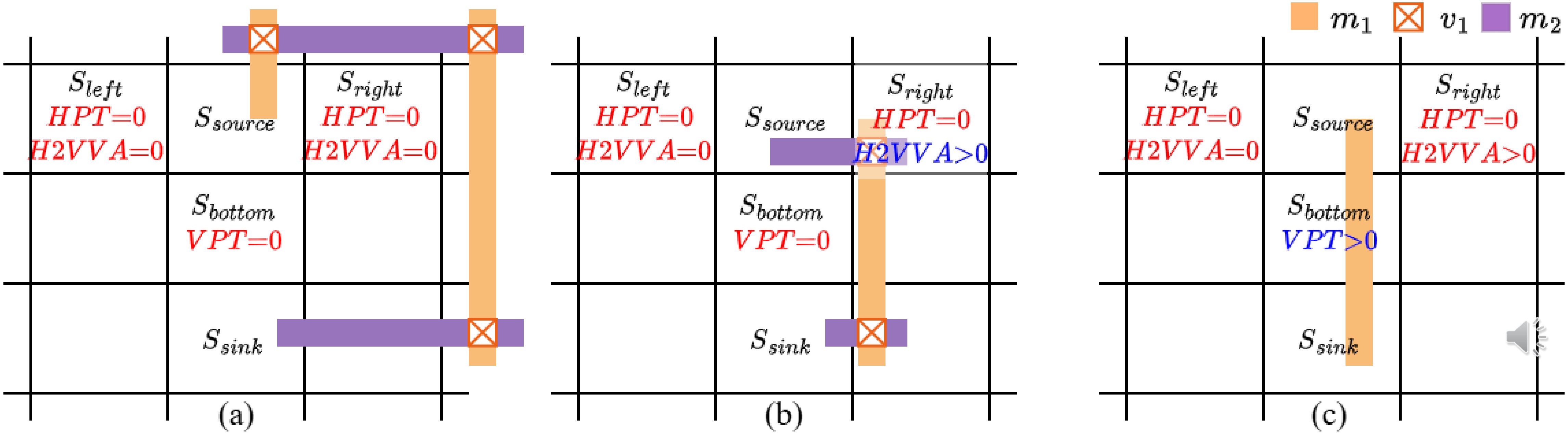
$$PAF_{S_{g_m}} = |\tau_{S_{g_m}}|^{\frac{1}{\#\text{pins}(S)}},$$

where $|\tau_{S_{g_m}}|$ represents the number of elements in $\tau_{S_{g_m}}$ and #pins(S) represents the number of pins in cell S.

  - Since τ_S depends on a cell's pin count, we normalize PAF by applying a factor of function that represents the number of pins.

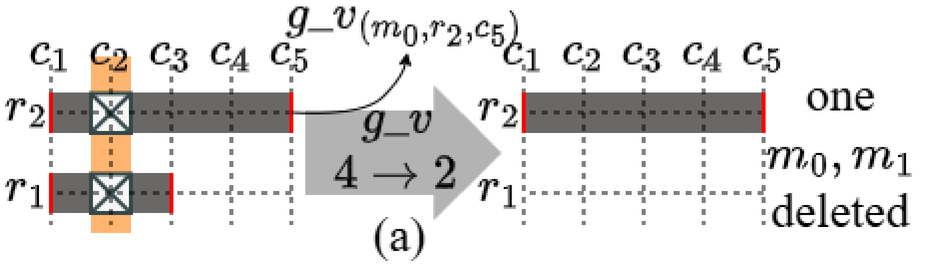
Track Utilization Flexibility (TUF)

- **TUF indicates how many metal tracks and via locations** within a cell can be used for routing at the block level.
- The TUF is classified into two features based on how the empty tracks within a cell can be utilized : **Passing Tracks(PT)** and **Via Availability(VA)**.



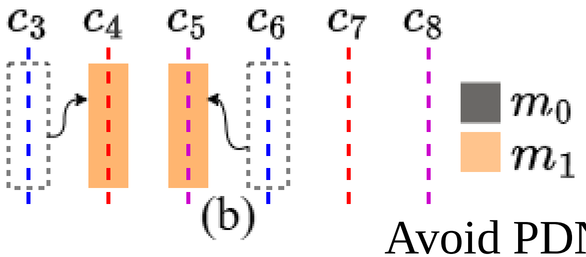
Cell Library Regeneration

- To demonstrate the effectiveness of Cell-Flex metrics in standard cell design, we enhanced the PROBE3.0 4-Track 2-fin library based on Cell-Flex metrics.



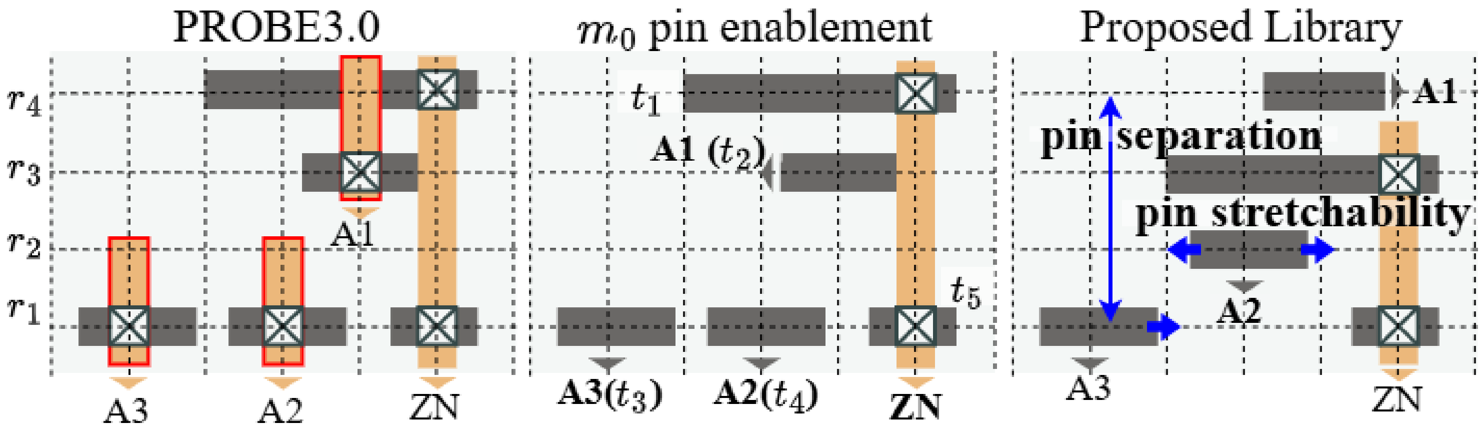
$$\text{minimize} \sum_{g\_v \in GV} g\_v(m_0, r, c)$$

Reduce Geometric variables to maximizing TUF

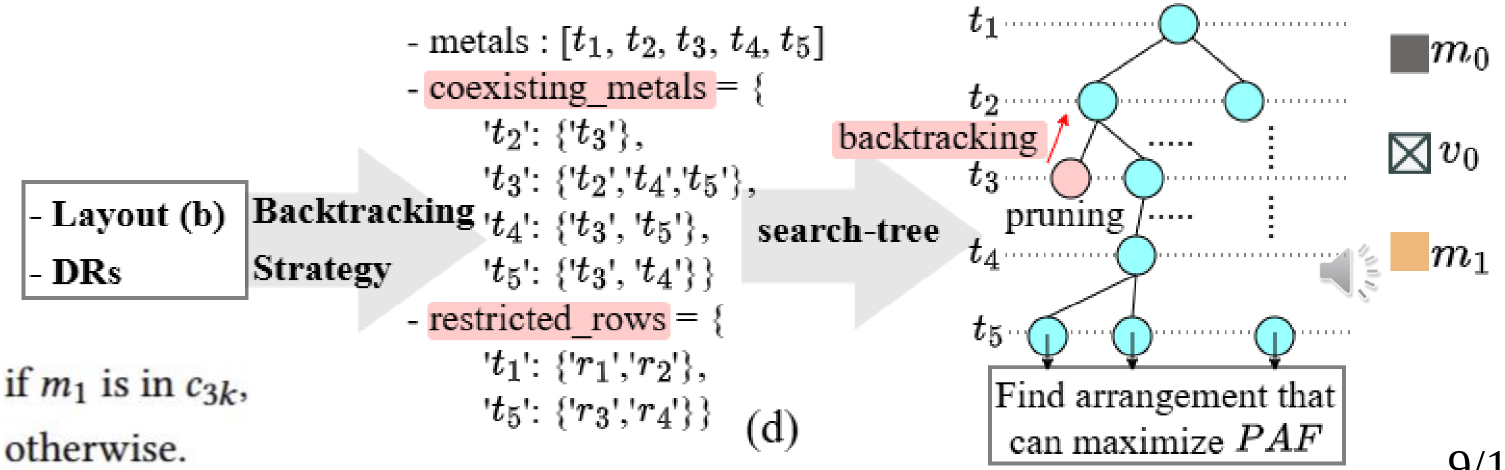


Avoid PDN track for maximizing CPF

$$\text{minimize} \sum_{k=0}^{\lfloor \frac{c_{max}}{3} \rfloor} x_{c_{3k}}^{m_1}, \text{ where } k \in \mathbb{Z} \text{ and } x_{c_{3k}}^{m_1} = \begin{cases} 1 & \text{if } m_1 \text{ is in } c_{3k}, \\ 0 & \text{otherwise.} \end{cases}$$



(a) $PAF = 2.43$ (b) $PAF = 2.94$ (+0.51) (c) $PAF = 5.87$ **(+3.44)**



(d)

Cell-Flex Comparison

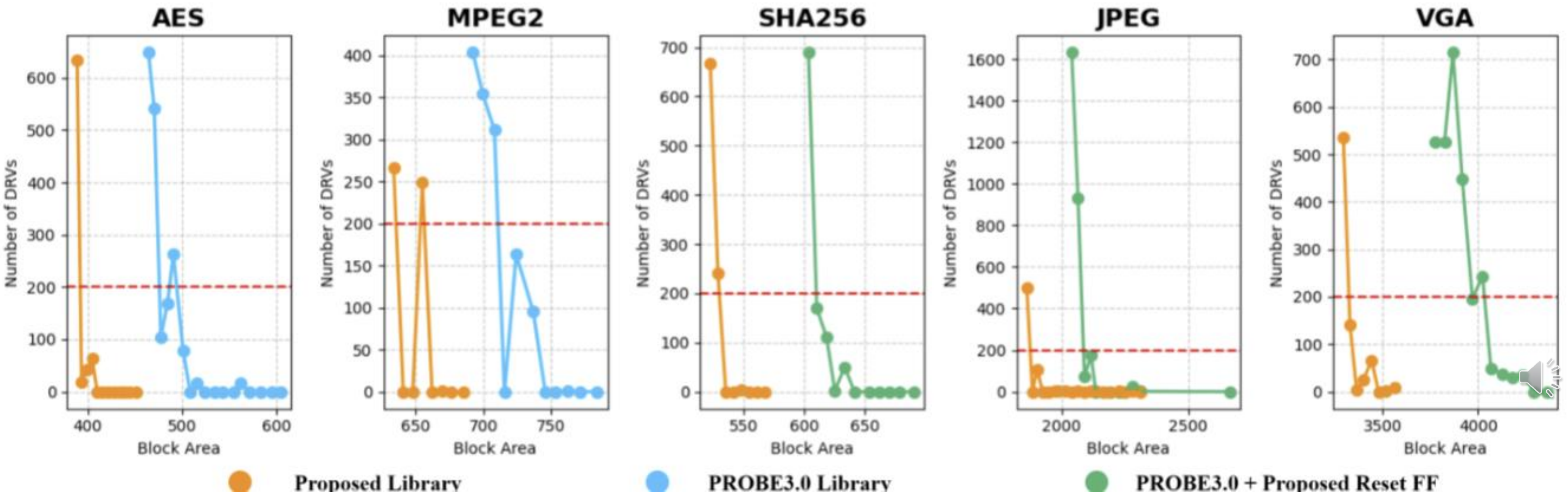
- Cell-Flex enhancement compared to PROBE 3.0.

Table 3: Comparison of the X1 cell's layout quality between PROBE3.0 and the proposed library in terms of *Cell-Flex* and RPA metrics.

Library	PROBE3.0 [10]							Proposed Library						
Metric	*PAF*	*CPF*	*VPTA*	*HPTA*	*V2HVA*	*H2VVA*	RPA [17]	*PAF*	*CPF*	*VPTA*	*HPTA*	*V2HVA*	*H2VVA*	RPA
AND2_X1	2.75	2.24	2	4	10	28	1.78	6.03	2.68	4	4	16	28	3.00
AOI21_X1	2.43	2.24	1	4	6	28	1.42	4.21	2.68	4	4	16	28	1.33
AOI22_X1	1.80	1.78	1	4	7	36	1.27	3.01	2.67	5	4	20	36	1.25
BUF_X1	2.89	2.29	1	4	5	20	2.00	2.89	2.74	2	4	8	20	1.00
DFFHQN_X1	0.00	0.44	6	0	29	45	1.33	2.51	2.22	12	1	48	54	1.50
DFFRNQ_X1	0.00	0.00	3	0	22	48	1.67	1.72	2.22	12	0	48	35	1.00
INV_X1	3.46	2.95	0	4	1	12	2.00	3.46	2.95	1	4	4	12	1.00
LHQ_X1	1.10	0.89	6	3	27	73	2.33	2.20	1.78	8	3	32	71	1.00
MUX2_X1	1.94	1.78	3	3	14	47	2.25	4.18	2.22	7	3	28	51	2.50
NAND2_X1	0.00	2.29	1	4	5	20	1.78	3.11	2.29	2	4	8	20	2.00
NAND3_X1	2.43	2.24	1	4	7	28	1.42	5.87	2.68	4	4	16	28	1.78
NAND4_X1	0.00	1.78	2	4	10	36	1.60	4.17	2.22	5	4	20	36	1.50
NOR2_X1	2.40	2.29	0	4	1	20	1.33	3.11	2.29	2	4	8	20	2.00
NOR3_X1	2.43	2.24	1	4	6	28	1.42	5.87	2.68	4	4	16	28	2.00
NOR4_X1	1.95	1.78	1	4	8	36	1.40	4.18	2.22	5	4	20	36	1.75
OAI21_X1	2.43	2.24	1	4	5	28	1.42	4.21	2.68	4	4	16	28	1.33
OAI22_X1	1.80	1.78	1	4	6	36	1.27	3.01	2.67	5	4	20	36	1.25
OR2_X1	2.75	2.24	2	4	10	28	1.78	6.03	2.68	4	4	16	28	3.00
OR3_X1	2.15	1.78	2	4	10	36	1.67	4.09	2.22	4	4	16	36	1.44
XOR2_X1	1.21	1.78	3	3	13	35	1.50	3.01	2.67	4	3	16	33	4.00
X1 AVG	1.71	1.85	1.90	3.48	10.10	33.52	1.66	3.88	2.48	4.86	3.52	19.43	33.33	1.77

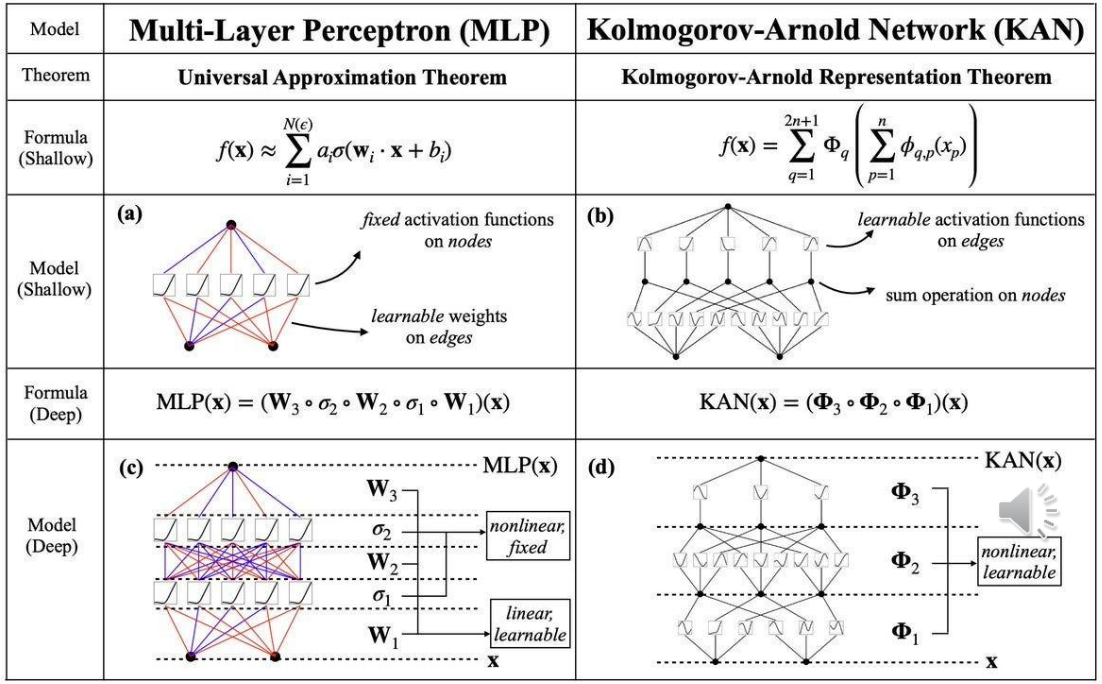
Block-Level Experiments

- Across five block designs, we can reduce the block area by **13.2%**.
  - We set the # of DRVs threshold as 200 for a valid block area.
- This result is aligned with the overall trends observed in evaluating the Cell-Flex metrics between two libraries.



ML-Driven Design Rule Violation(DRV) Prediction

- To validate the relationship between our metrics and DRV emerging location, **we propose a cell-oriented ML model** that leverages Cell-Flex values extracted from the layout as key features for DRV prediction.
- We utilize the **Kolmogorov–Arnold Networks (KAN)** as our modeling framework.
  - Because it models complex and non-linear relationships between features.
  - KAN expresses any multivariate continuous function as a superposition of continuous functions of a single variable and addition, allowing for non-linear and learnable activation functions.



Routing Complexity (Distributed Heat) Calculation

- The entire block region is divided into $W \times H$ grid of GCells, each sized at 21 times the CPP and 7 times the cell height.
- We define the heat of a $g_{j,k}$, $H^F_{j,k}$, which represents routing complexity, as follows:

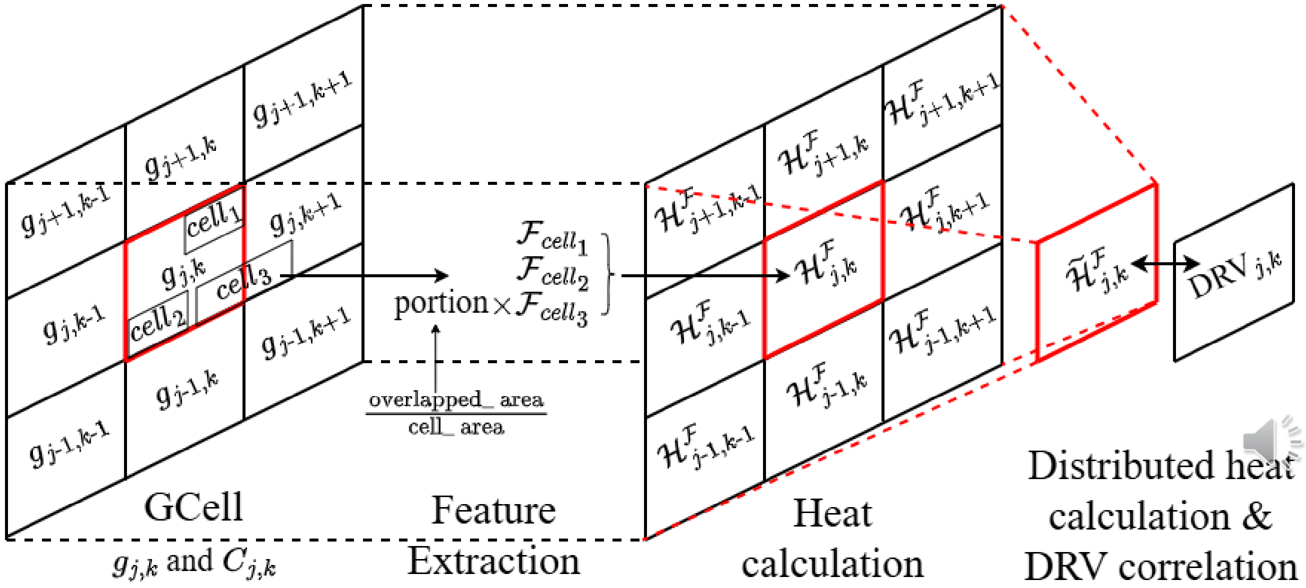
$$\mathcal{H}^{\mathcal{F}}_{j,k} = \sum_{c \in C_{j,k}} (\mathcal{F}_{max} - \mathcal{F}_c),$$

F is a feature and $C_{j,k}$ is the collection of cells that overlap with $g_{j,k}$.

- Distributed heat calculation.

$$\widetilde{\mathcal{H}}^{\mathcal{F}}_{j,k} = \sum_{m=j-1}^{j+1} \sum_{n=k-1}^{k+1} \mathrm{w}_{m,n} \cdot \mathcal{H}^{\mathcal{F}}_{m,n},$$

$$\mathrm{w}_{m,n} = \begin{cases} 0.5 & \text{if } m = j \text{ and } n = k, \\ 0.5 \times \frac{1}{8} & \text{otherwise.} \end{cases}$$



Prediction Performance

- Evaluation Metric :

$$\text{Accuracy} = \frac{TP + TN}{TP + TN + FP + FN},$$

$$\text{F1 score} = 2 \cdot \frac{\text{Precision} \times \text{Recall}}{\text{Precision} + \text{Recall}},$$

where:

$$\text{Precision} = \frac{TP}{TP + FP}, \quad \text{Recall} = \frac{TP}{TP + FN}.$$

- Comparison of DRV prediction performance on training and testing sets regarding F1 score and Accuracy across different feature combinations.

Dataset		Training set (80%)						Testing set (20%)					
Metric	feature combination	AES	MPEG2	SHA256	JPEG	VGA	ALL§	AES	MPEG2	SHA256	JPEG	VGA	ALL§
F1 score	Grid†	0.67	0.34	0.39	0.60	0.40	0.52	0.67	0.35	0.39	0.60	0.40	0.52
	Grid† + RPA	0.73	0.51	0.39	0.64	0.40	0.52	0.73	0.52	0.39	0.65	0.40	0.52
	Grid† + *PAF*	0.74	0.70	0.40	0.69	0.77	0.69	0.74	0.71	0.40	0.69	0.77	0.69
	Grid† + *Cell-Flex*‡	**0.76**	**0.86**	**0.59**	**0.74**	**0.83**	**0.78**	**0.75**	**0.86**	**0.57**	**0.73**	**0.83**	**0.78**
Accuracy	Grid†	0.72	0.52	0.64	0.72	0.67	0.65	0.73	0.53	0.64	0.72	0.67	0.65
	Grid† + RPA	0.75	0.57	0.64	0.75	0.67	0.66	0.76	0.58	0.64	0.75	0.67	0.65
	Grid† + *PAF*	0.76	0.70	0.64	0.77	0.79	0.71	0.77	0.71	0.64	0.77	0.80	0.71
	Grid† + *Cell-Flex*‡	**0.77**	**0.86**	**0.68**	**0.80**	**0.83**	**0.79**	**0.77**	**0.86**	**0.67**	**0.79**	**0.82**	**0.79**

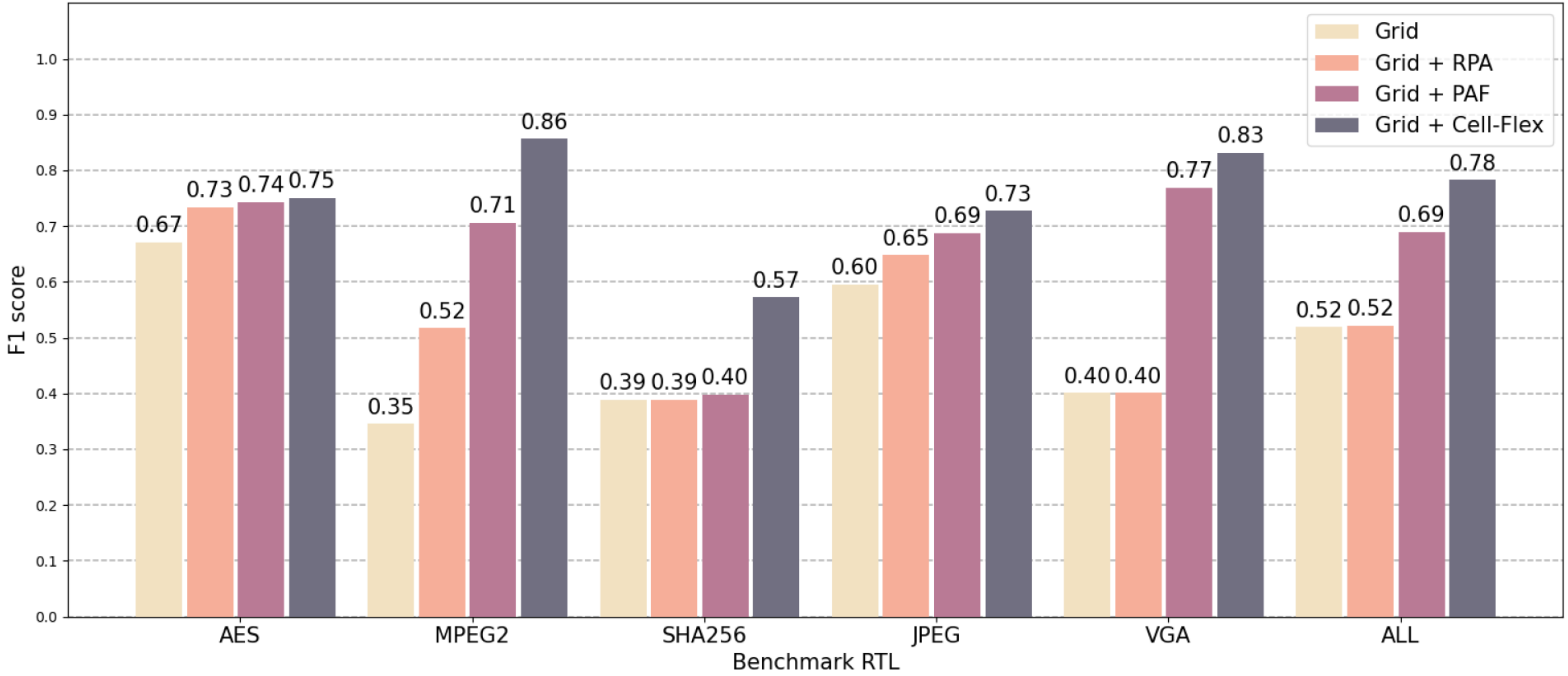
† Grid feature set includes total pin count within each GCell and the total occupied cell area in each GCell.

‡ *Cell-Flex* feature set includes *PAF*, along with *CPF* and *TUF*, where *TUF* consists of four features: *HPTA*, *VPTA*, *H2VVA* and *V2HVA*.

§ ALL refers to the dataset that combines block design data from all five RTLs: AES, MPEG2, SHA256, JPEG, and VGA.

Prediction Performance

- The entire set of Cell-Flex metrics as features **enables sophisticated prediction** of DRV occurrences.



Conclusion

- We introduced the Cell-Flex metrics, including **PAF, CPF, and TUF**.
  - They reflect how well P&R tools can leverage standard cells in placement and routing to optimize block designs.
- We integrate Cell-Flex metrics into cell layout generation and successfully improved block designs, achieving a **13.2%** reduction in block area without increasing total DRVs.
- We **prove the correlation** between Cell-Flex features and DRV occurrences by developing an ML-driven DRV prediction model using KAN.
  - F1 score enhancement shows how Cell-Flex metrics can capture the impact of a cell's placement and routing performance.

Future Work

- Comparison of ML models with other techniques.
  - e.g., KAN vs. MLP for DRV prediction: Which performs better?
  - Comparison with DRV prediction models from other papers.
- New feature generation representing pin inaccessibility (derived from PAF).
- Integrating Cell-Flex metrics into cell layout automation more systematically.

Thanks!

Q&A