ISPD 2024

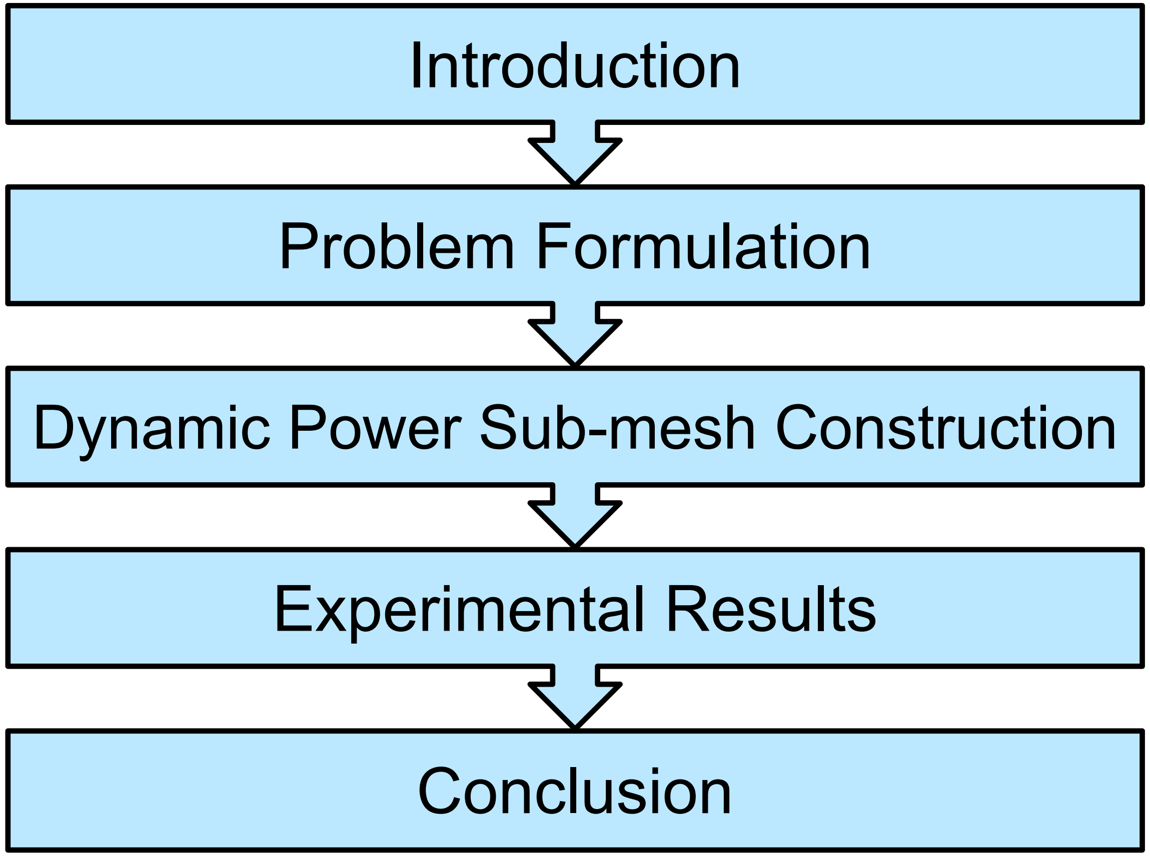
Power Sub-Mesh Construction in Multiple Power Domain Design with IR Drop and Routability Optimization

Chien-Pang Lu[1] Iris Hui-Ru Jiang[2] Chun-Ching Peng[1] Mohd Razha Mohd Mawardi[1] Uber Alessandro[1]

intel[1]

國立臺灣大學 National Taiwan University[2]

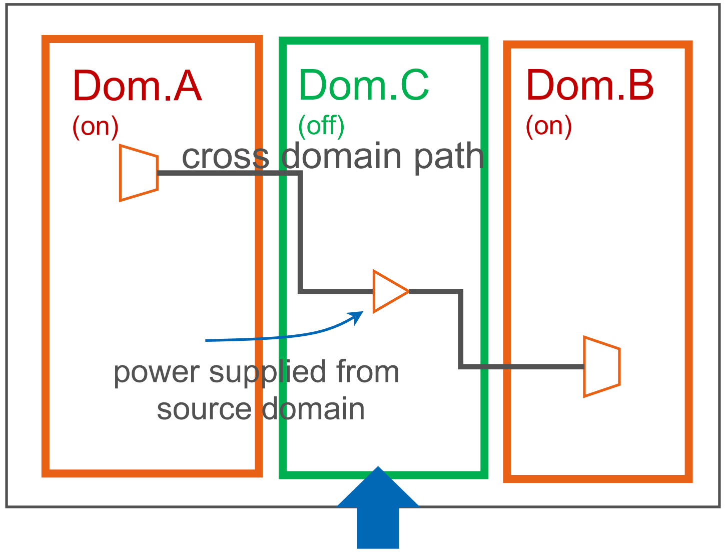
Outline


Introduction
Problem Formulation
Dynamic Power Sub-mesh Construction
Experimental Results
Conclusion

Advanced Node: Feedthrough Cell 2^{nd} Power Pin Routing Issue

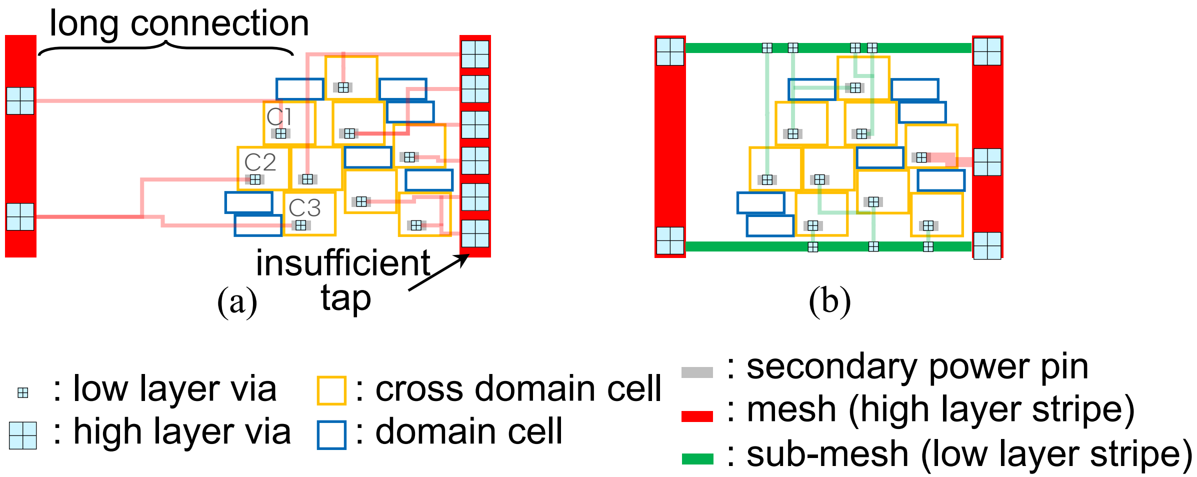
- Cross domain power supply: feedthrough interconnect

Multiple domain design



Two power mesh structures:
1. local domain supply
2. feedthrough domain supply`

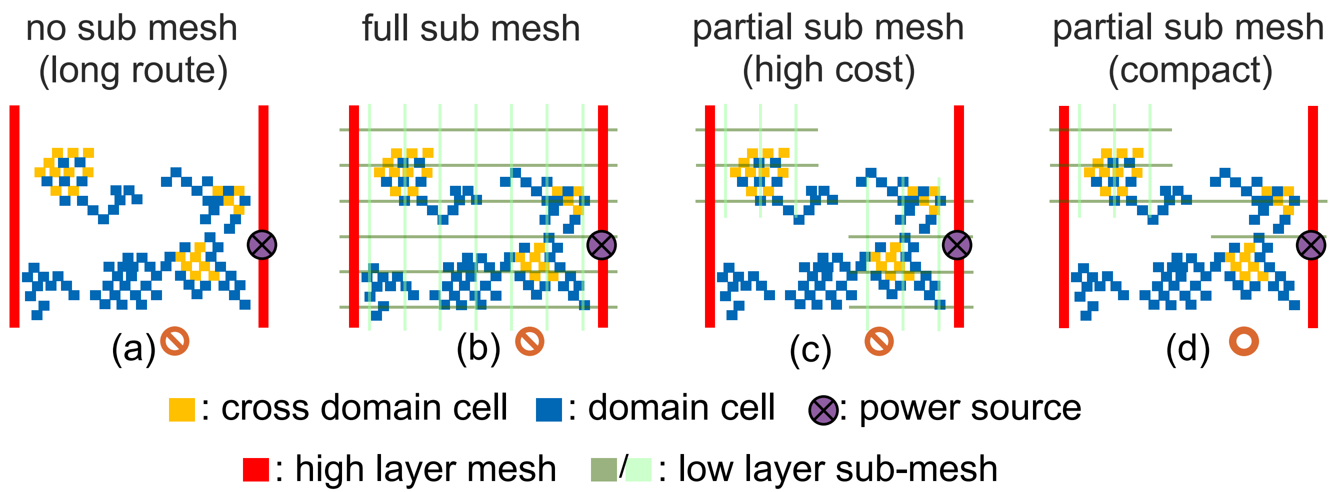
Cross domain cell, 2^{nd} power IR and routing issue in multiple power domain at advanced process node



Higher metal layer, larger via layer ⟹
add lower metal layer stripe for insufficient tap issue

Power Sub-mesh Construction

- Reduce IR drop and routing overhead
  - Partial sub-mesh to satisfy voltage drop constraint and save routing resource



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Best Cost Sub-mesh IR drop & Routing Problem

- Given
  - A timing-driven placed and clock-routed multiple power domains design
  - A set of cross-domain cells and corresponding power sources
  - Primary power mesh and signal routing distributions

- Goal
  - Construct power sub-meshes such that the IR drop constraints on cross-domain cells are satisfied, the design rule violations on signal routing are minimized without timing degradation

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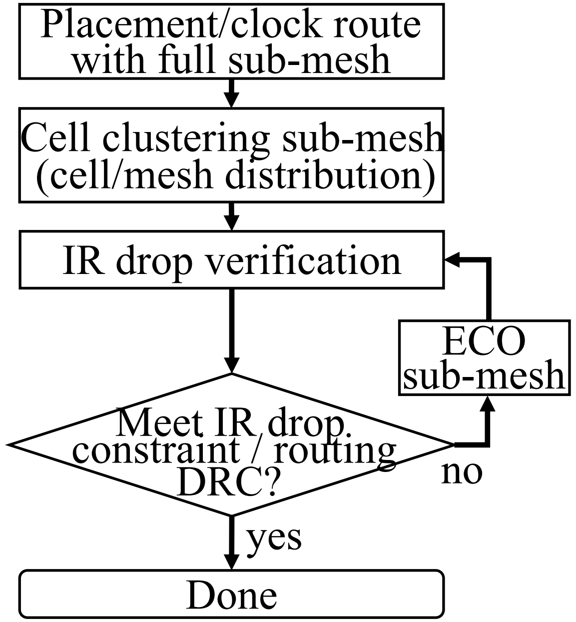
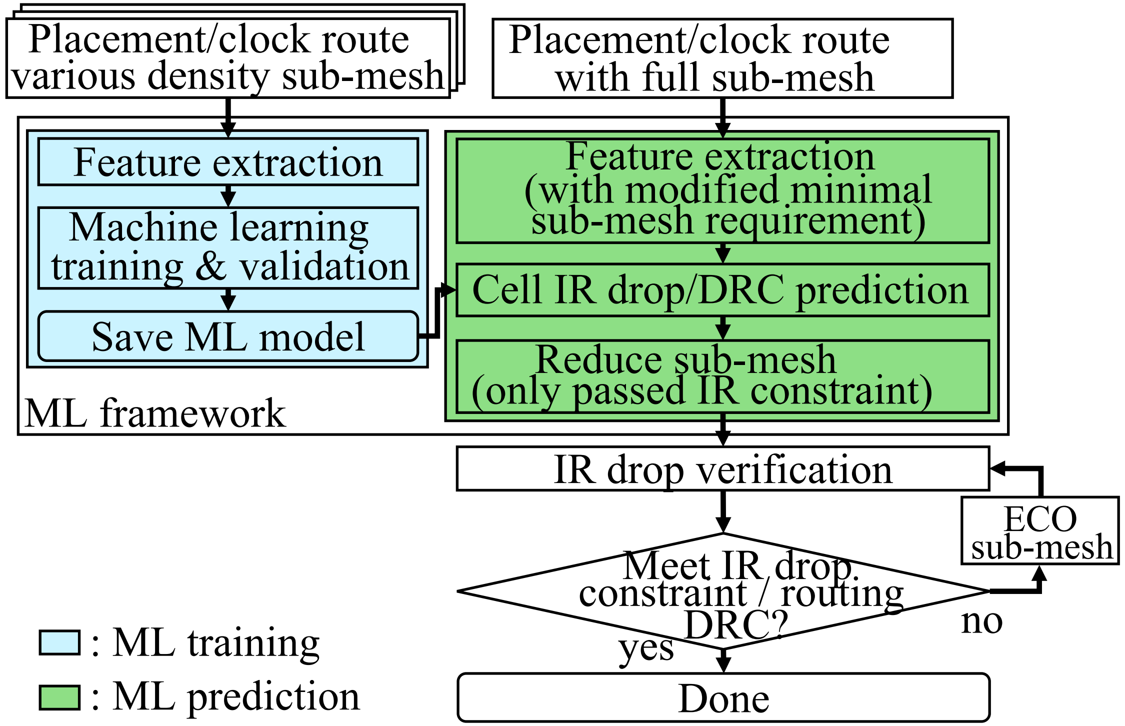
Traditional & ML Dynamic Power Mesh IR Drop Analysis Flow

Traditional
Dynamic Sub-mesh Flow



(a)

Machine learning
Dynamic Sub-mesh Flow



(b)

Feature Selection/Extraction

- Three categories: physical, power and timing features
  - Total 46 features for each target cell
  - Target: IR drop, DRC prediction

Physical	Power	Timing	Features	Description
✓R			SMD_j	Sub-mesh power/ground metal density on layer j over a grid.
✓R			RMD_j	Primary mesh power/ground metal density on layer j over a grid.
✓C			SD_j	Signal routing density on layer j over a grid.
✓R			CA	Area of target cell.
		✓	CL	Loading of target cell (i.e. total output loading).
		✓	CP	Clock period of target cell (extracted from timing report).
	✓		$NNAD$	Area density of neighboring cells (supplied by the same constant power on N-well) over a grid.
	✓		$NSAD$	Area density of neighboring cells (supplied by the same power on their secondary power pins) over a grid.
✓C			$NNLD$	Loading density of neighboring cells (supplied by the same constant power on N-well) over a grid.
✓C			$NSLD$	Loading density of neighboring cells (supplied by the same power on their secondary power pins) over a grid.
	✓		$PGSD$	The distance from target cell to power/ground source.
	✓		PGD	The distance from target cell to indirect power source (power gating cell, level shifter).

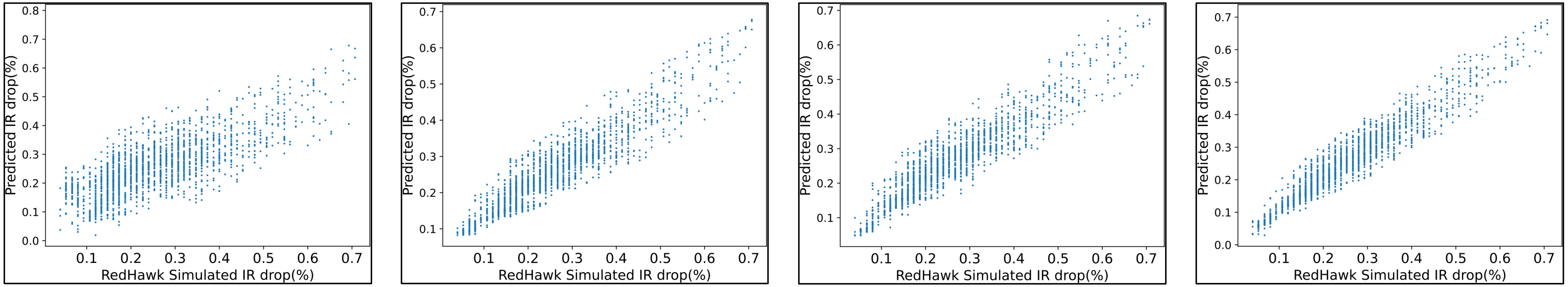
*R: resistance related features; C: congestion related features.

Machine Learning Model Comparison

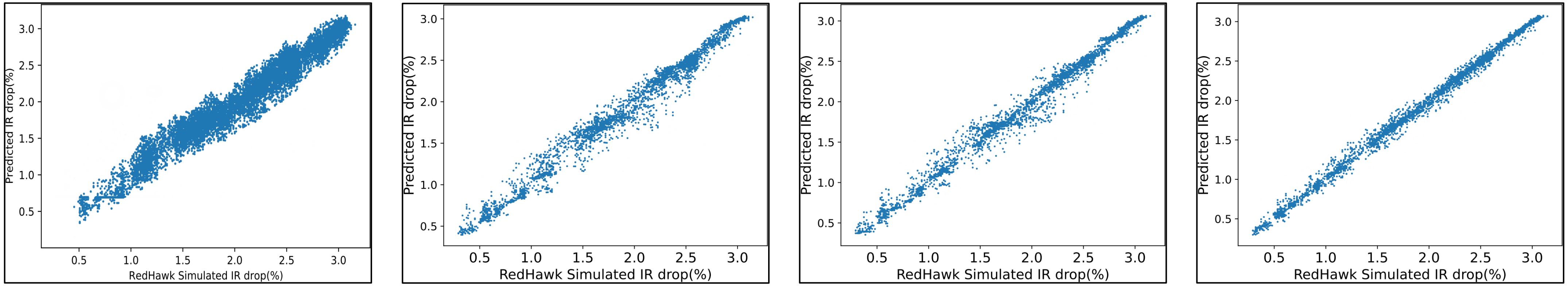
- 4 models: Extra Trees, MLP(ANN), Random Forest, XGBoost

Direct: cross-domain cell with direct supply
Indirect: cross-domain cell with indirect supply

Training and validation set with 80:20



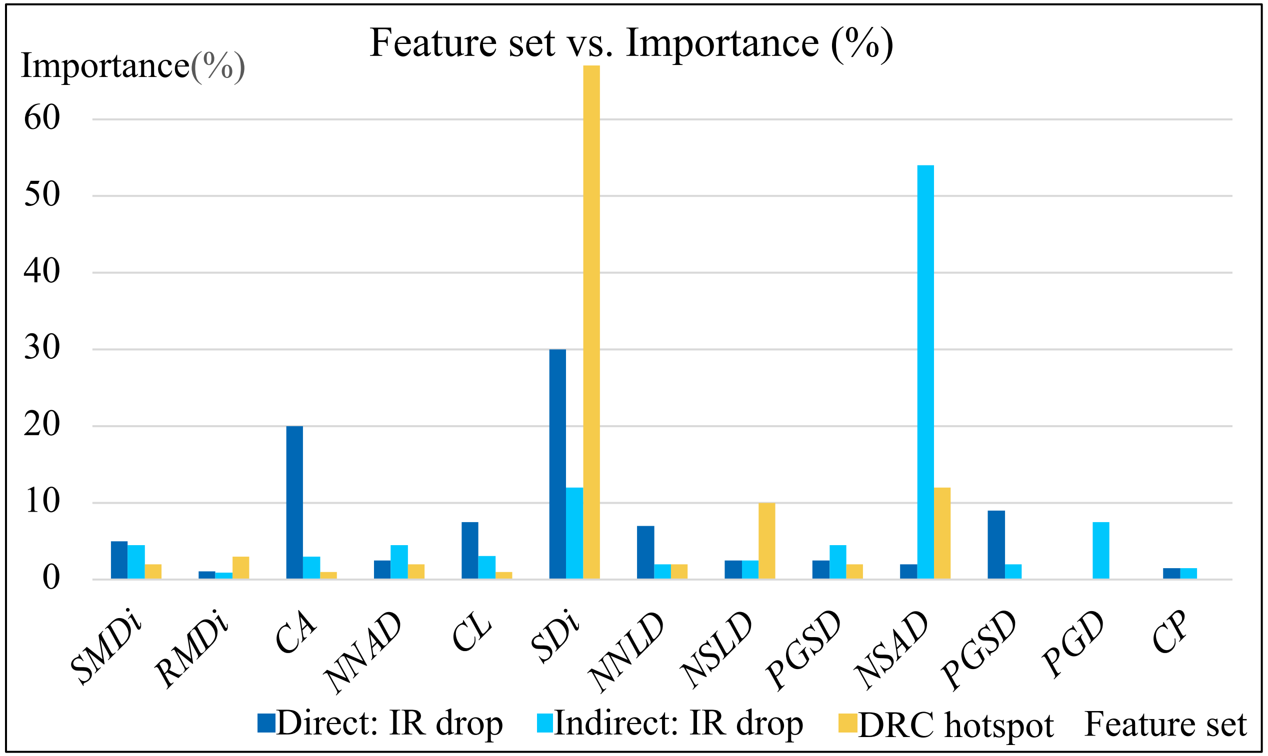
(a) Direct: predicted by Extra Trees (b) Direct: predicted by MLP (c) Direct: predicted by Random Forest (d) Direct: predicted by XGBoost



(e) Indirect: predicted by Extra Trees (f) Indirect: predicted by MLP (g) Indirect: predicted by Random Forest (h) Indirect: predicted by XGBoost

Feature/Target Relation

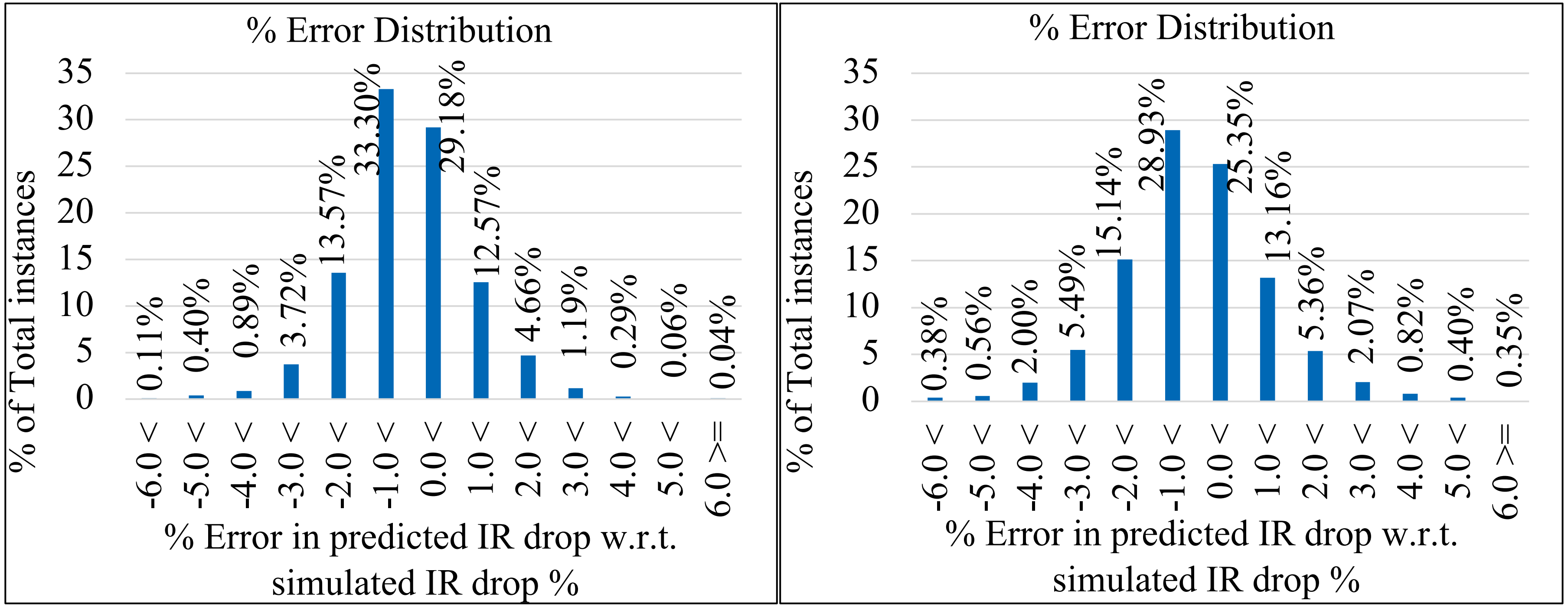
- XGBoost: importance of each feature on direct/indirect and DRC hotspots



Parameters	Explanation
SMD_i	Sub-mesh P/G metal density of i layer of a grid unit.
RMD_i	Regular mesh P/G metal density of i layer of a grid unit.
SD_i	Signal route density of i layer of a grid unit.
CA	Target cell area.
CL	Target cell loading, sum of all outpin loading.
CP	Target cell clock period, extracted from timing report.
$NNAD$	Neighbor cell (supplied by the same constant power on n-well) area density of a grid unit.
$NSAD$	Neighbor cell (supplied by the same power on secondary power pin) area density of a grid unit.
$NNLD$	Neighbor cell (supplied by the same constant power on n-well) loading density of a grid unit.
$NSLD$	Neighbor cell(supplied by the same power on secondary power pin) loading density of a grid unit.
$PGSD$	Power/ground source distance (to target cell).
PGD	Power gating cell, MTCMOS, distance (to target cell).

Error Distribution

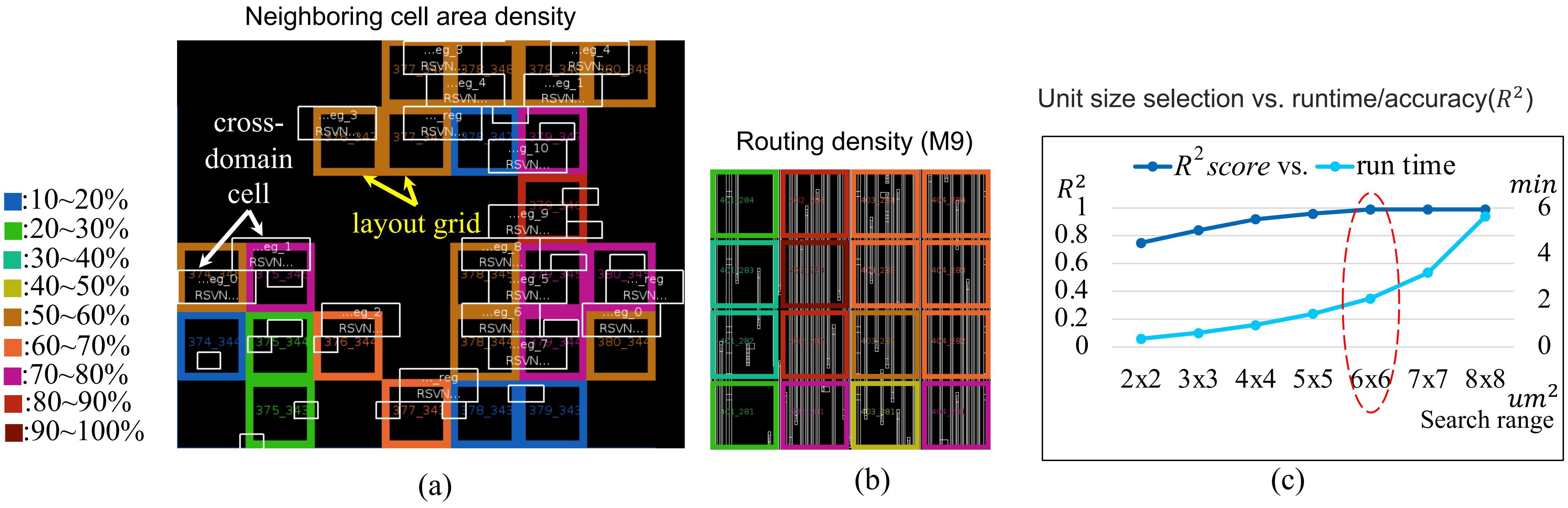
- XGBoost: cross-domain cell with direct and indirect supply



(a) Direct (b) Indirect

Unit Size Selection for Sub-meshes

- Runtime and accuracy trade-off



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Experimental Setting

- Setting:
  - Language: C++, Tcl and Python 3.7.4
  - Platform: Xeon Linux workstation with 3.2GHz CPU and 512GB memory
  - EDA tools: Synopsys Fusion Compiler

- Benchmark statistics

Circuit	# of Instances	# of Domains	Area (um2)	# of Nets	# of D.S. Instances	# of I.D.S. Instances	Period (ns)
ckt1	940329	2	258567	4167119	10000	17921	0.312
ckt2	620610	2	937054	875909	31708	1629	0.312
ckt3	557635	4	365361	13060997	5438	9609	0.312
ckt4	1075600	2	328038	1651630	3414	11695	0.312
ckt5	225094	6	322605	367503	2204	4819	0.5

Comparison

- None: no sub-mesh
- Full: full sub-mesh
- GR-aware: global route aware
- Ours ML: machine learning

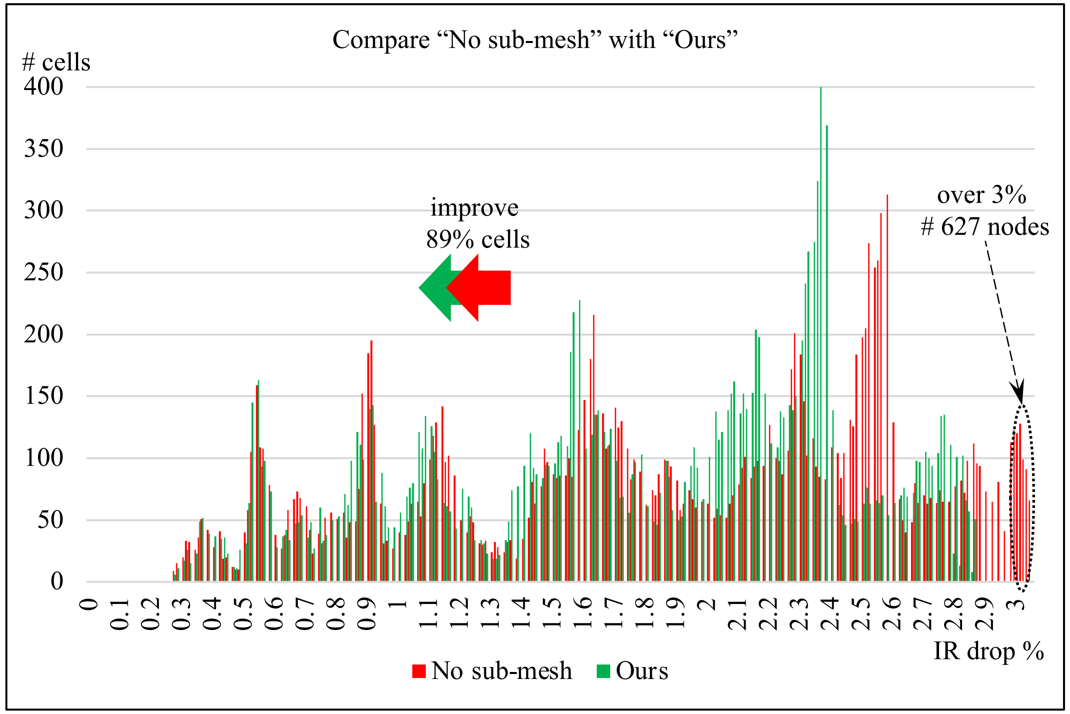
- Detailed routing results:

CKT	Method	S-mesh length (M8/M9 um)	S-mesh coverage% (D.C./I.D.C.)	Direct IR % (max/avg)	Indirect IR % (max/avg)	IR improved cells %	# of over 3% IR cells	# of DRCs	Runtime (sec)
ckt1	None	0	0.0/0.0	1.641/0.313	3.052/1.819	89.32	627	56	-
	Full	314459	100.0/100.0	1.275/0.300	2.991/1.801	2.26	0	43	15
	GR-aware	29308	87.4/94.4	1.405/0.306	2.991/1.804	9.23	0	40	193
	Ours: ML*	130501	0.2/94.5	1.640/0.313	2.987/1.799	-	0	20	198
ckt2	None	0	0.0/0.0	2.280/0.422	3.096/0.818	93.50	32	182	-
	Full	1955527	100.0/100.0	1.720/0.406	3.004/0.786	0.07	2	52	8
	GR-aware	1682633	82.5/89.9	1.735/0.420	3.010/0.803	5.48	2	41	218
	Ours: ML*	1243836	29.8/95.2	1.782/0.420	2.979/0.800	-	0	16	206
ckt3	None	0	0.0/0.0	0.990/0.187	1.604/0.538	13.59	0	197	-
	Full	79325	100.0/100.0	0.987/0.181	1.600/0.545	0	0	163	10
	GR-aware	69382	80.9/77.5	0.987/0.184	1.600/0.545	3.68	0	109	392
	Ours: ML*	41121	16.3/99.2	0.996/0.183	1.600/0.545	-	0	60	401
ckt4	None	0	0.0/0.0	0.907/0.050	1.000/0.332	98.44	0	446	-
	Full	912931	100.0/100.0	0.890/0.049	0.733/0.293	0	0	83	18
	GR-aware	698389	78.2/74.5	0.890/0.049	0.733/0.299	5.71	0	85	212
	Ours: ML*	294302	3.5/99.8	0.893/0.050	0.734/0.299	-	0	33	207
ckt5	None	0	0.0/0.0	0.827/0.108	3.080/1.081	26.96	97	41	-
	Full	173684	100.0/100.0	0.772/0.103	2.792/1.065	22.21	0	58	8
	GR-aware	146283	85.2/81.5	0.793/0.105	2.842/1.071	14.23	0	58	163
	Ours: ML*	62425	1.1/51.6	0.812/0.110	2.740/1.071	-	0	33	167
Ratio	None	0	0	1.177/1.039	1.063/1.020	13.113	378.000	1.817	-
	Full	1.000	1.000	1.000/1.000	1.000/1.000	1.000	1.000	1.000	1.000
	GR-aware	0.841	0.828/0.835	1.029/1.024	1.004/1.007	1.561	1.000	0.834	19.966
	Ours: ML*	0.515	0.101/0.880	1.084/1.035	0.992/1.004	-	0	0.406	19.983

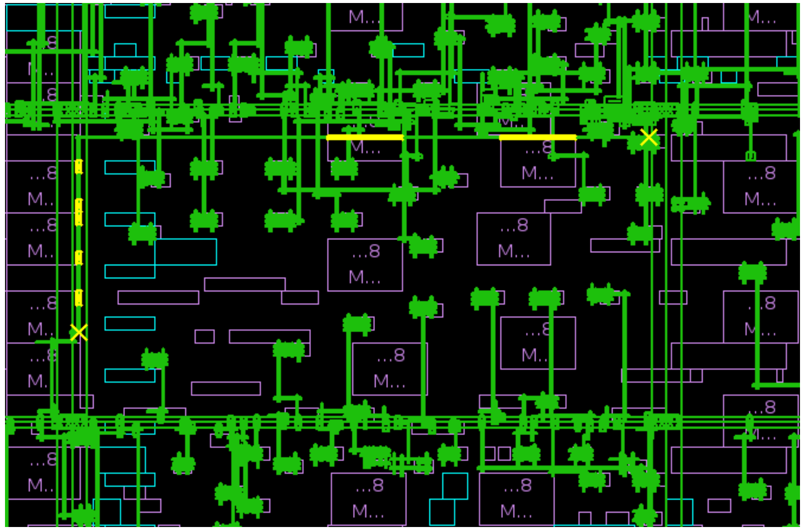
167 ~ 401 seconds

IR Drop Distribution & Short Improvement

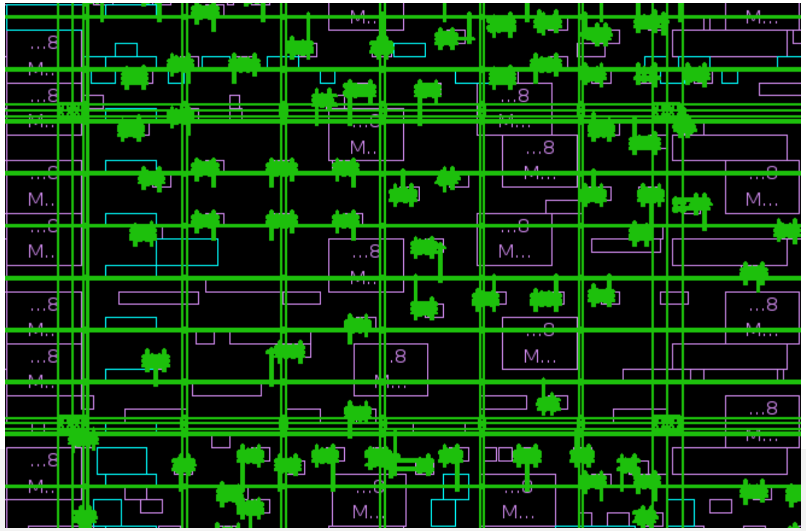
Ckt1, IR drop distribution



Partial layout of ckt3



No sub-mesh,
: 8 shorts



Ours,
: 0 violations

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Conclusion

- Propose a machine learning based power sub-mesh construction methodology
  - Consider physical, power and timing features
  - Capture IR drop and DRC hotspots behaviors

- Five industrial mobile designs with 6nm process

- Routing resource usage, timing QoR are promising after our methodology is applied
  - Vs. full sub-mesh: reduce 49% sub-mesh metal length, 59% DRCs
  - Vs. GR-aware: reduce 33% sub-mesh metal length, 43% DRCs

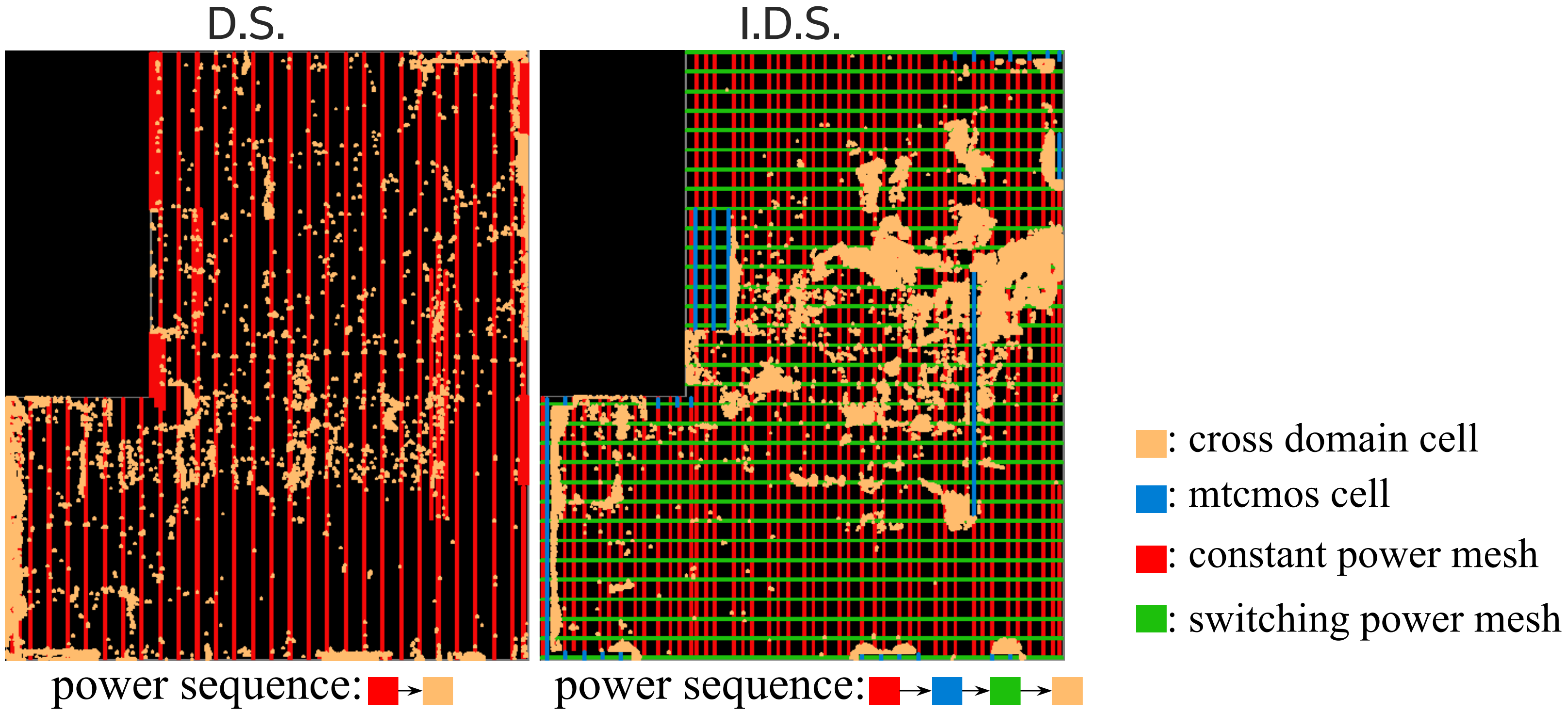
- Extend to dynamic IR drop optimization

Thank you!

Machine learning makes world better

Cross Domain Cell Power Connection

- D.S.(direct power supply cell): power supply source from mesh
- I.D.S.(in-direct power supply cell): power supply source translate from “mtcmos/level shifter”



(a) (b)