V-GR: 3D Global Routing with Via Minimization and Multi-Strategy Rip-up and Rerouting

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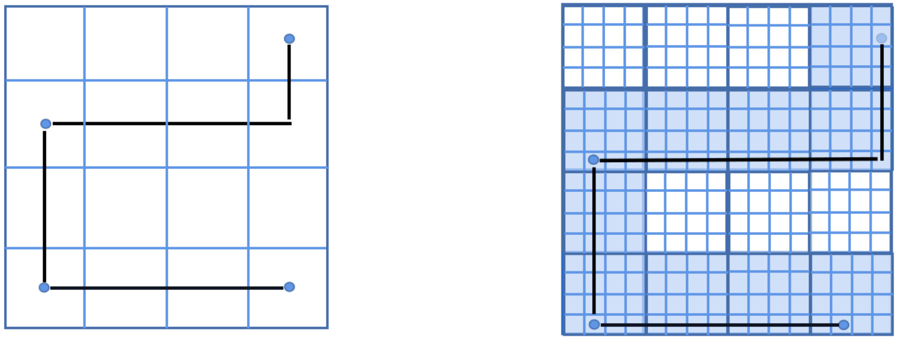
Global Routing and Detailed Routing

Routing

Global routing

Nets are routed on a coarse-grained grid, and the routing location is determined while minimizing wire lengths, vias, and overflows.

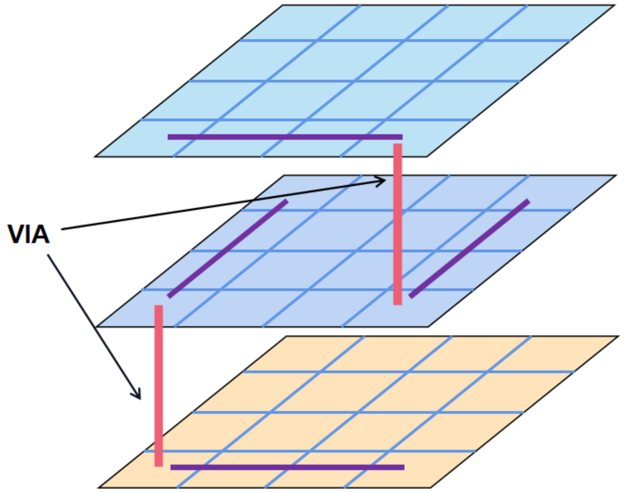


Detailed routing

Detailed routing uses the routing scheme determined by the global routing as a routing guide to obtain specific routing paths.

Global Routing and Detailed Routing

Vias: provide connections for segments between different layers.



1. A large number of vias reduces manufacturing yields, leads to degraded circuit performance, and increases the area required for interconnections.

2. DFM (Design for Manufacturability) in physical design has strict requirements for vias. And satisfying DFM is necessary for physical design.

[1] Y. Xu, Y. Zhang, and C. Chu, “FastRoute 4.0: Global router with efficient via minimization,” in Proceedings of IEEE/ACM Asia and South Pacific Design Automation Conference, 2009, pp. 576–581.

Global Routing

Global routing：

Given a grid and a set of nets consisting of pins, find a routing scheme for each net that connects all pins to minimize the total overflow： $\min \sum_{e \in E} of_e$,

Minimizing the wire length and minimizing the number of vias are also important goals for global routing optimization.

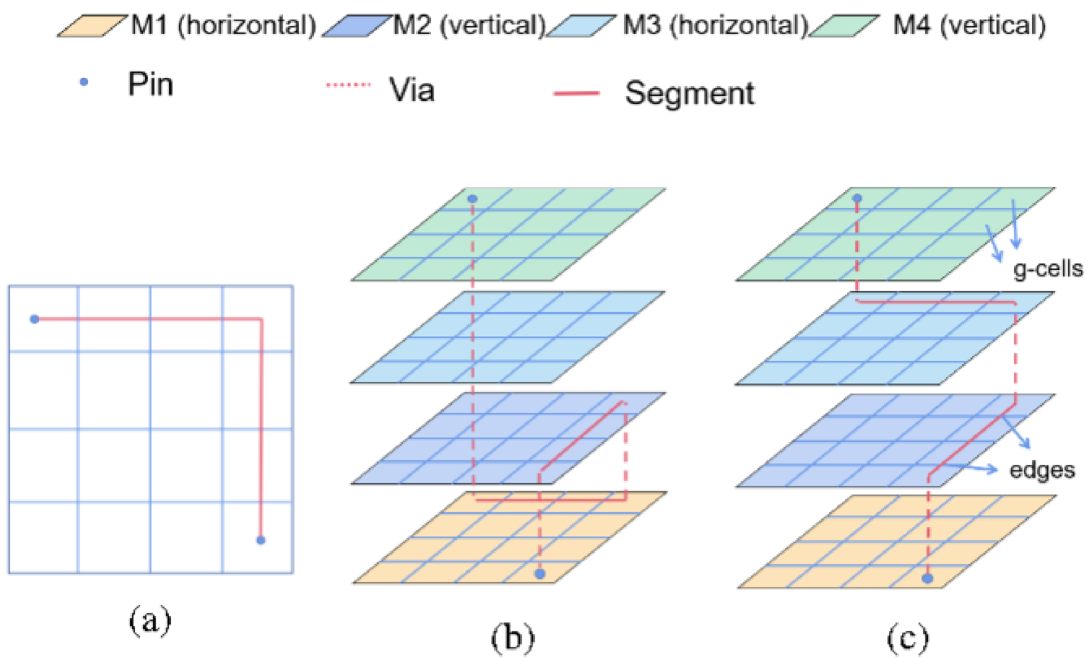


Fig. 1: Two 3D global routing results with the same 2D routing path.

Global Routing Strategy

2DRouting+layer assignment

Router：NTHU-Route 2.0 [Chang et al., 2010] , SPRoute 2.0 [He et al., 2010] , NCTU-GR 2.0 [Liu et al., 2013] and FastRoute 4.0 [Xu et al., 2009].

Advantages ：Fast

Disadvantages：Only the number of bend points is available before layer assignment, and the ability to obtain accurate via information is not available.

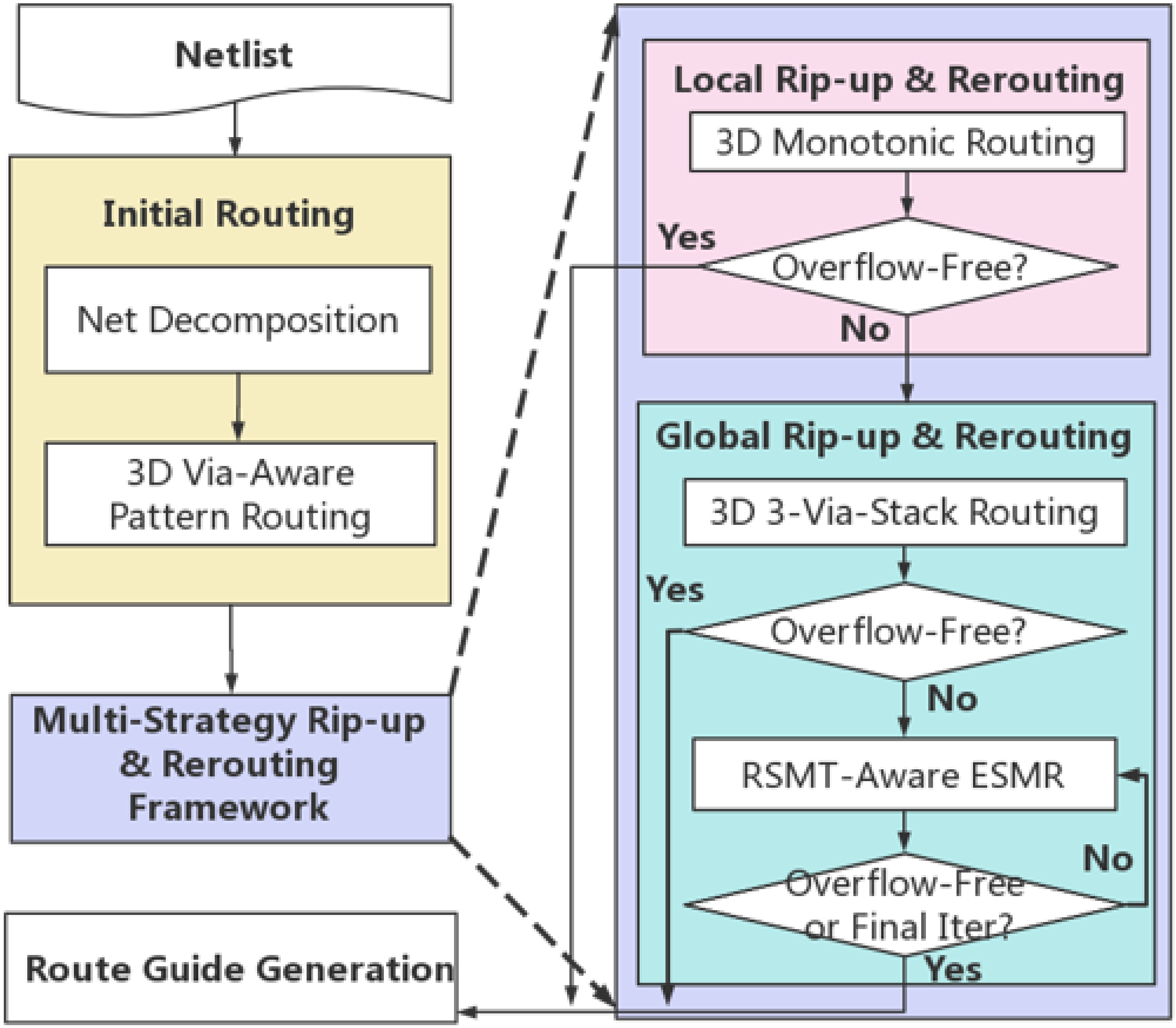
3D Routing

Router：FGR [Roy et al., 2008]，GRIP[Wu et al., 2009]，MGR[Xu etal., 2011]，CUGR[Liu et al. 2020]

Advantages ：Ability to overcome problems with 2D strategies and better quality of solutions

Disadvantages：slow.

V-GR Global Routing Flow



Modified Via-Aware Routing Cost Function

Modified Via-Aware Routing Cost Function：

Rectangular Uniform wire Density (RUDY) is used in routability prediction, in which the wire density is defined as the wire length per unit area of its bounding-box. We use the length of the RSMT estimate the wire density:

$$wd_n(u,v) = \begin{cases} \frac{rl}{area}, & (u,v) \in bdb(n); \\ 0, & (u,v) \notin bdb(n), \end{cases}$$

An edge with higher wire density consumes more capacity. When the capacity of edge is exhausted, the tendency is to use the corresponding edges of other layers, which leads to an increase in the number of vias. We consider the effect of wire density on via and make improvements to the via cost:

$$cost_v(u,u') = uvc \times (1 + \lg(u) + \lg(u')$$

$$cost_v(u,u') = \frac{\gamma \times uvc \times (1 + \lg(u) + \lg(u'))}{(1.0 + \exp(wd_N(u) + wd_N(u'))^{-1}},$$

Multi-Strategy Rip-up and Rerouting Framework

Local rip-up and rerouting

After initial routing, 3D monotonic routing is used within the bounding box of net to reduce the number of vias and overflow without increasing the wire length.

Global rip-up and rerouting

The 3D 3-via-stack routing and the RSMT-Aware ESMR are used globally to rip-up and reoute congested net while ensuring the least possible growth in wire lengths and number of vias.

Local Rip-Up and Rerouting

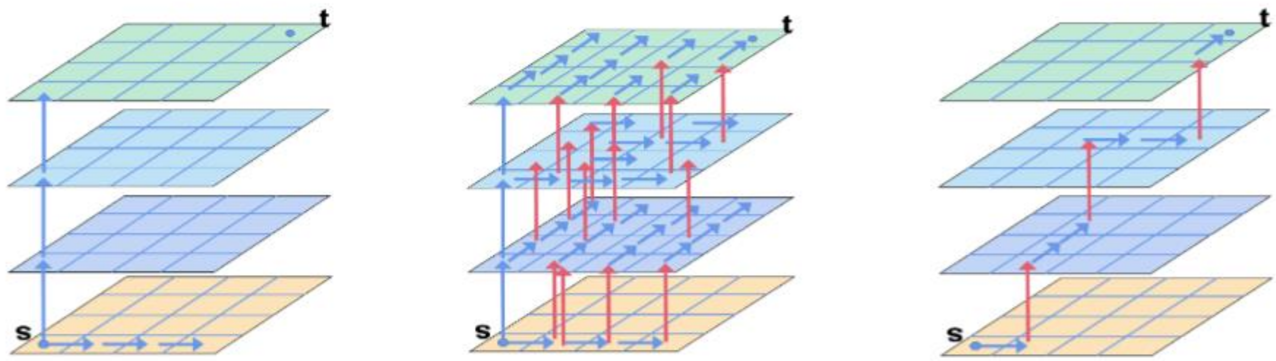
3D monotonic routing:

After initial routing, there are still many overflow nets to deal with. We propose a 3D monotonic routing, aiming to reduce overflow and minimize the number of vias without increasing the wire length.

The algorithm is executed inside the bounding box of net and requires that the next path node found must **satisfy a decreasing or constant 3D Manhattan distance** during the routing process.

The edge costs in this paper are consistent with the CUGR definition of edge costs:

$$cost_w(u, v) = wl(u, v) + eo(u, v) \times \lg(u, v)$$



(a) (b) (c)

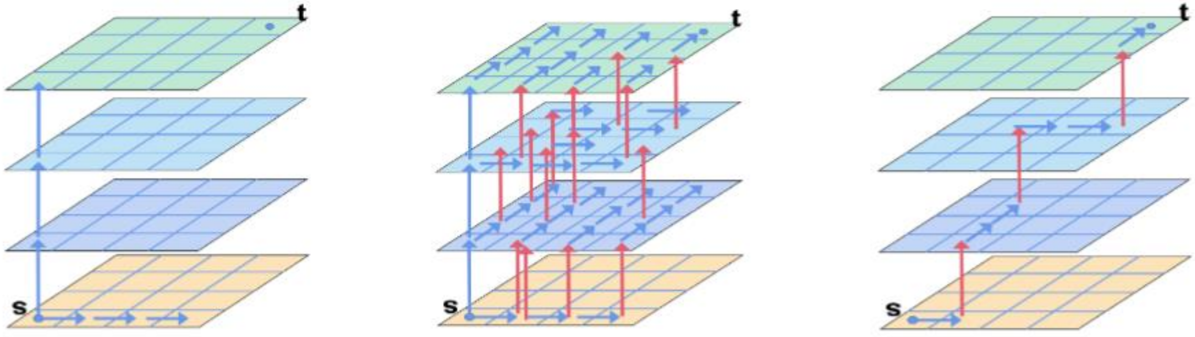
Local Rip-Up and Rerouting

3D monotonic routing：

cost(u,v): the cost of an edge or via (u,v).
d(u): The minimum cost from the source to u.
prev(u): The predecessor node of node u.

procedure：
step 1. Calculate d(u) for nodes with the same x or y or z coordinates as the source point.
step 2. The idea of dynamic programming is used to calculate d(u) .
step 3. Search prev(u) from the sink until the source .

The algorithm complexity is O(|B|) and B is the size of the 3D bounding box.



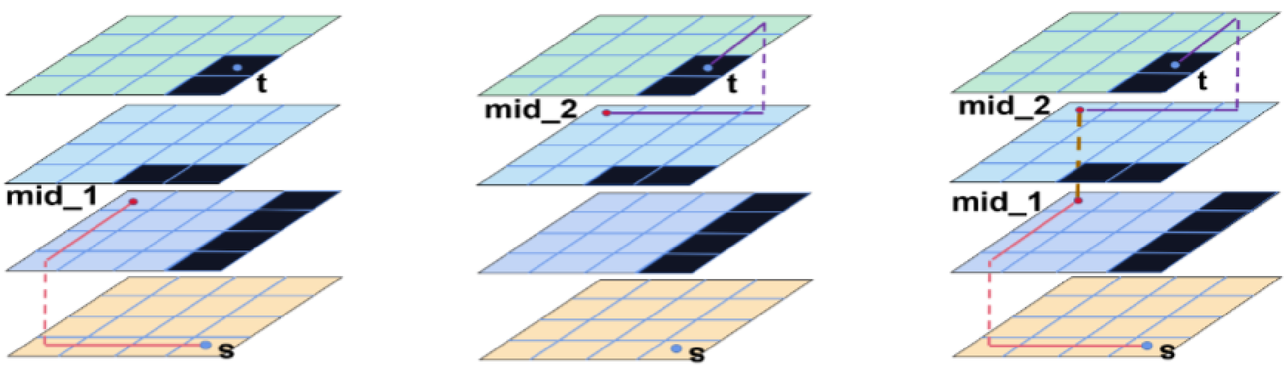
(a) (b) (c)

Global Rip-Up and Rerouting

3D 3-via-stack routing:

Completes the connection of two pins with up to a 3-via-stack. It has a greater ability to reduce congestion compared to 3-D pattern routing. In addition, it has the advantage of generating fewer vias and is faster compared to 3D monotonic routing and 3D maze routing.

3D 3-via-stack path consists of three parts: Two 3D L-paths and a via-stack, such as s -> mid_1, mid_2 -> t, and mid_1 -> mid_2.



(a) (b) (c)

Effectiveness of 3D Monotonic Routing and 3D 3-Via-Stack Routing

Effect Comparison:

The first set of experiments used: 3D monotonic routing, 3D 3-via-stack routing and RSMT-aware ESMR after initial routing.
The second set of experiments used: the RSMT-aware ESMR after initial routing.

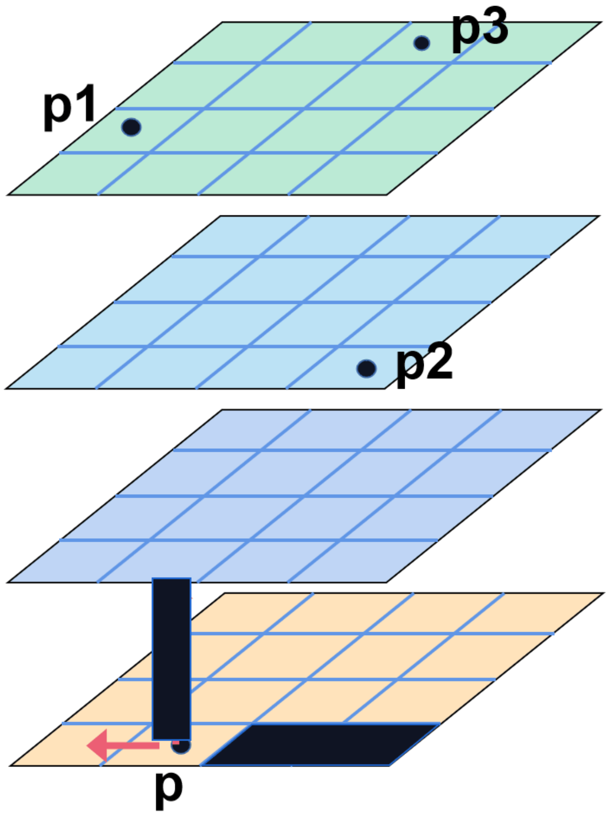
Benchmarks	Ours without the Algorithms			Ours with the Algorithms		
	Wire Length	#Via	Overflow	Wire Length	#Via	Overflow
18test5	**27019100**	816721	0	27029600	**761579**	0
18test5m	**27329100**	804629	**3216**	27343000	**759084**	3221
18test8	**64225300**	2062620	0	64235200	**1895530**	0
18test8m	**63155300**	1970615	5593	63195000	**1855570**	**5500**
18test10	**66635400**	2194560	0	66720800	**2019910**	0
18test10m	**69689400**	2117990	1495	69695800	**1979430**	**645**
19test7	**118296000**	3218160	0	118377000	**3041740**	0
19test7m	**106591000**	3234286	4318	106508000	3034040	**3989**
19test8	181935000	5594214	0	**181836000**	**5213620**	0
19test8m	**179116000**	5553435	6986	179229000	**5263920**	**6551**
19test9	273311000	9126440	60	**273237000**	**8617980**	**0**
19test9m	**271199000**	9438193	**3689**	271278000	**8853840**	3782
Avg.	**120708466**	3844321	2113	120723700	**3608020**	**1974**
Norm.	**99.9%**	106.5%	107.1%	100%	**100%**	**100%**

The table shows that using 3D monotonic routing and 3D 3-via-stack routing was able to reduce vias by 6.5%, and overflow by 7.1%.

Global Rip-Up and Rerouting

RSMT-Aware ESMR:

The main idea of ESMR is that tree edges in a net with completed routing can be reused.



step1. One pin is randomly selected to join the priority queue and the source set, the remaining pins are added to the sink set.

step 2. Take the first node from the priority queue and traverse the neighboring nodes. Perform different operations based on neighboring nodes.

step 3. Add the source point set nodes to the priority queue and repeat step 2 until the sink set is empty.

Global Rip-Up and Rerouting

RSMT-Aware ESMR:

RSMT has a shorter wire length, and combining this property to ESMR proposes the RSMT-Aware ESMR.

Each G-cell that RSMT passes through is labeled, and the cost of the edge varies according to the number of times it is labeled.

$$cost(e) = \begin{cases} wl(e) * \frac{C}{2} + eo(e) \times \lg(e), & \text{e is marked twice;} \\ wl(e) * C + eo(e) \times \lg(e), & \text{e is marked once,} \end{cases}$$

Comparison of the effectiveness of routing solutions produced using different maze algorithms:

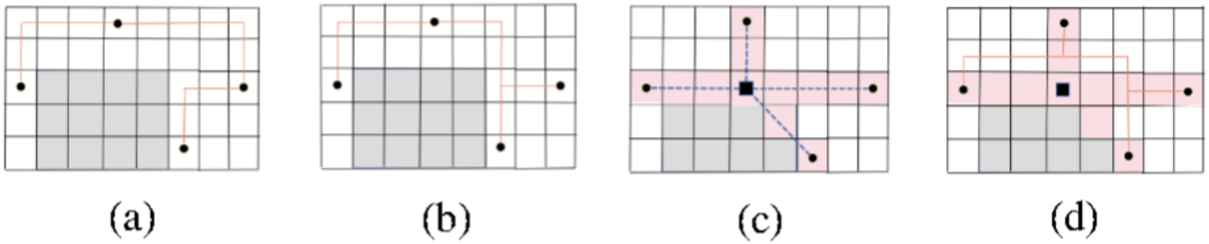


Fig. 6: Comparison of different maze algorithms. (a) Traditional maze routing. (b) ESMR. (c) RMST for Net N. (d) RSMT-aware ESMR.

Effectiveness of RSMT-Aware ESMR

Effect Comparison：

The first set of experiments used: traditional maze routing algorithm.
The second set of experiments used: RSMT-aware ESMR.

Benchmarks	Traditional MR		RSMT-Aware ESMR	
	Wire Length	#Via	Wire Length	#Via
18test5	27326925	766148	**27029600**	**761579**
18test5m	27589087	762879	**27343000**	**759084**
18test8	64819740	1905955	**64235200**	**1895530**
18test8m	63763755	1864840	**63195000**	**1855570**
18test10	67287926	2032231	**66720800**	**2019910**
18test10m	70323062	1989327	**69695800**	**1979430**
19test7	119442393	3056948	**118377000**	**3041740**
19test7m	107466572	3049210	**106508000**	**3034040**
19test8	183472524	5239688	**181836000**	**5213620**
19test8m	180842061	5290239	**179229000**	**5263920**
19test9	275696133	8661069	**273237000**	**8617980**
19test9m	273719502	8898109	**271278000**	**8853840**
Avg.	121812473	3626386	**120723700**	**3608020**
Norm.	100.9%	100.5%	**100%**	**100%**

The table shows that the use of RSMT-aware ESMR was able to reduce the wire length by 0.9% and the via by 0.5%.

Results

GR results

Benchmarks	GR Wire Length		GR #Via		GR Overflow		GR CPU(s)		DR Score	
	CUGR	V-GR	CUGR	V-GR	CUGR	V-GR	CUGR	V-GR	CUGR	V-GR
18test5	**26997000**	27029600	855742	**761579**	0	0	33.6	**25.8**	15609059	**15557607**
18test5m	27915200	**27343000**	802643	**759084**	**3201**	3221	32.0	**29.0**	15902609	**15580356**
18test8	64380000	**64235200**	2174530	**1895530**	0	0	105.5	**95.4**	37831617	**37076170**
18test8m	64697100	**63195000**	1955940	**1855570**	5587	**5500**	122.0	**91.0**	36973756	**36268485**
18test10	66778500	**66720800**	2308290	**2019910**	0	0	123.2	**90.6**	39640768	**39218365**
18test10m	72840100	**69695800**	2200010	**1979430**	1575	**645**	218.0	**109.0**	41514624	**41342376**
19test7	118701000	**118377000**	3124640	**3041740**	0	0	243.2	**236.4**	78239626	**77623552**
19test7m	106977000	**106508000**	3070990	**3034040**	4332	**3989**	221.0	**195.0**	72627528	**71846934**
19test8	181912000	**181836000**	5748110	**5213620**	0	0	208.4	**198.7**	120660152	**119610521**
19test8m	**177674000**	179229000	5599140	**5263920**	7061	**6551**	**388.0**	405.0	118730552	**116784975**
19test9	274113000	**273237000**	9598230	**8617980**	75	**0**	335.5	**284.8**	185445043	**184104089**
19test9m	**267622000**	271278000	9342640	**8853840**	**3652**	3782	455.0	**418.0**	183776050	**180753328**
Avg.	120883908	**120723700**	3898408	**3608020**	2123	**1974**	207.1	**181.5**	78912615	**77980563**
Norm.	100.13%	**100%**	108.05%	**100%**	107.58%	**100%**	114.08%	**100%**	101.20%	**100%**

Results of GR + DR reported by innovus

Benchmarks	Wire Length			#Via			Non-preferred Usage			Design Rule Violations		
	CUGR + Dr. CU 2.0	CUGR + TritonRoute	V-GR + TritonRoute	CUGR + Dr. CU 2.0	CUGR + TritonRoute	V-GR + TritonRoute	CUGR + Dr. CU 2.0	CUGR + TritonRoute	V-GR + TritonRoute	CUGR + Dr. CU 2.0	CUGR + TritonRoute	V-GR + TritonRoute
18test5	13755664	13701011	**13717353**	1854248	1687442	**1614934**	**159196**	306749	225320	335018	**0**	**0**
18test5m	14001665	13891767	**13702732**	1843696	1699774	**1643168**	**120374**	311067	234455	280744	**0**	**0**
18test8	32980410	32778214	**32526979**	4827046	4399240	**4040724**	**254658**	654162	508467	140621	**0**	**0**
18test8m	32407308	32099091	**31651745**	4522450	4112254	**4033852**	**326961**	762411	582889	238783	**0**	**0**
18test10	34054967	33887670	**33874618**	4991064	4617196	**4345714**	**885532**	1135902	998033	662037	**0**	**0**
18test10m	35711640	35370581	**35303348**	4899802	4545166	**4516894**	**1244888**	1541692	1468608	1634185	57183	**53525**
19test7	61002413	60490812	**60272448**	16276308	15155620	**14488772**	**1423304**	2593194	2839479	9779552	**0**	**0**
19test7m	54858539	54237117	**54147005**	16386864	15275220	**14518402**	**1604677**	3115191	3181526	9933662	**0**	**0**
19test8	93471561	**92736584**	92963254	26290792	25323176	**23799936**	**1290976**	2600391	2847331	7466225	**0**	**0**
19test8m	91154538	90262544	**89888979**	25999844	25141952	**23858036**	**899052**	2983055	3037959	8345362	**0**	**0**
19test9	141254192	140047181	**139666849**	42973076	41053404	**39620000**	**2181813**	4169857	4817240	15091717	**0**	**0**
19test9m	138028089	136440857	**135856004**	43195156	41605100	**39795704**	**2474472**	5729092	5101619	15487862	1000	**0**
Avg.	61890082	61328619	**61130942**	16171695	15384628	**14689678**	**1072158**	2158563	2153577	2894823	2423.5	**2229.5**
Norm.	101.24%	100.32%	**100%**	110.09%	104.73%	**100%**	**49.79%**	100.23%	100%	129841.80%	108.70%	**100%**

Thank You !