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Methods for TSVs placement in 3D Network-on-chip

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Outline

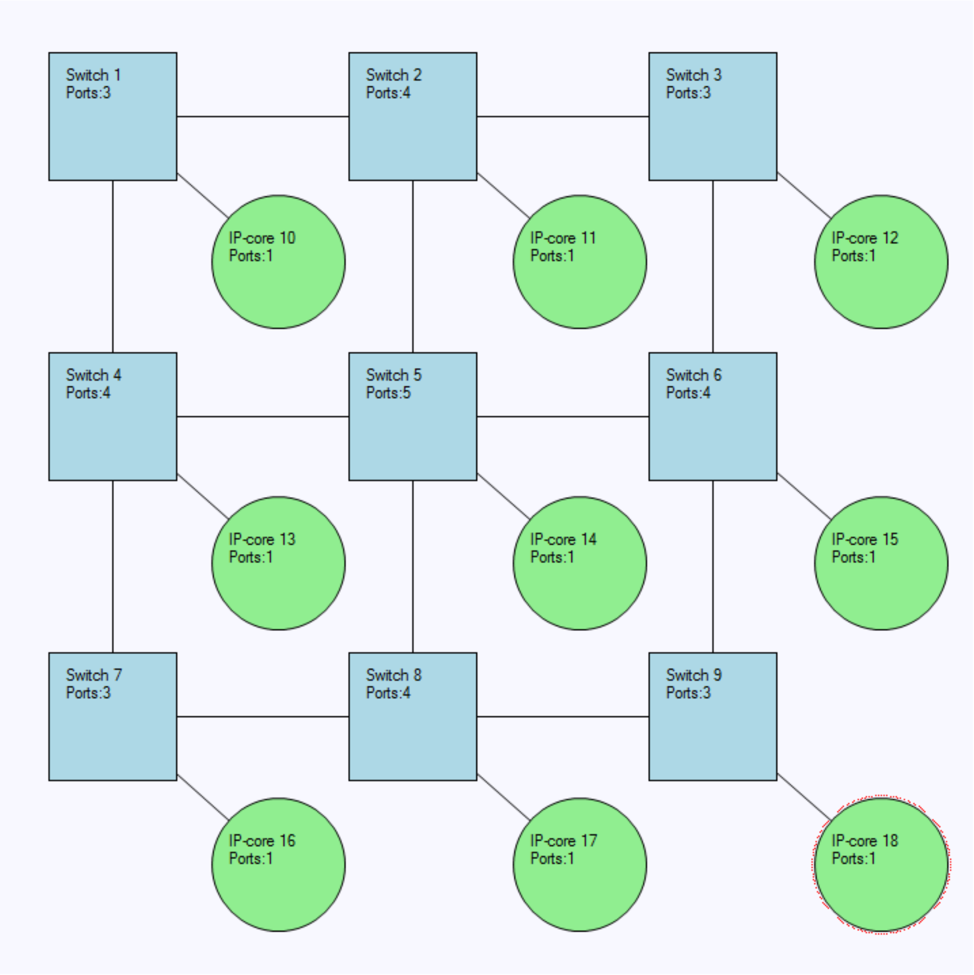
1. Introduction
2. Problems of 3D NoC design
3. Placement TSV nodes on the dies with the **same** topologies
4. Placement TSV nodes on the dies with the **different** topologies

Network-on-Chip

Network-on-Chip (NoC) – a communication subsystem between intellectual property (IP) cores in the System-on-Chip (SoC)

NoC includes:

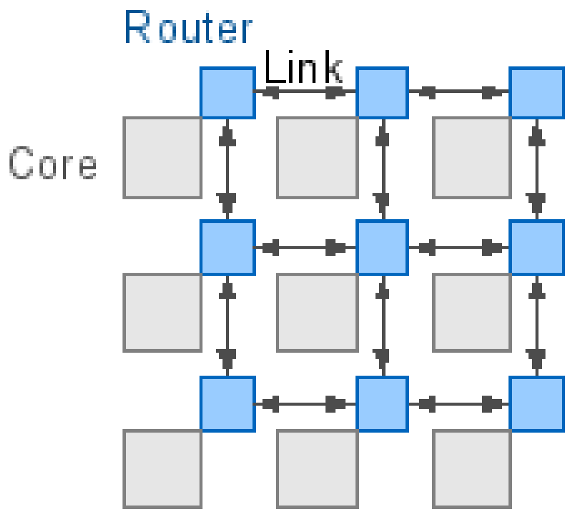
- Terminal nodes (IP cores)
- Switch nodes
- Interconnect

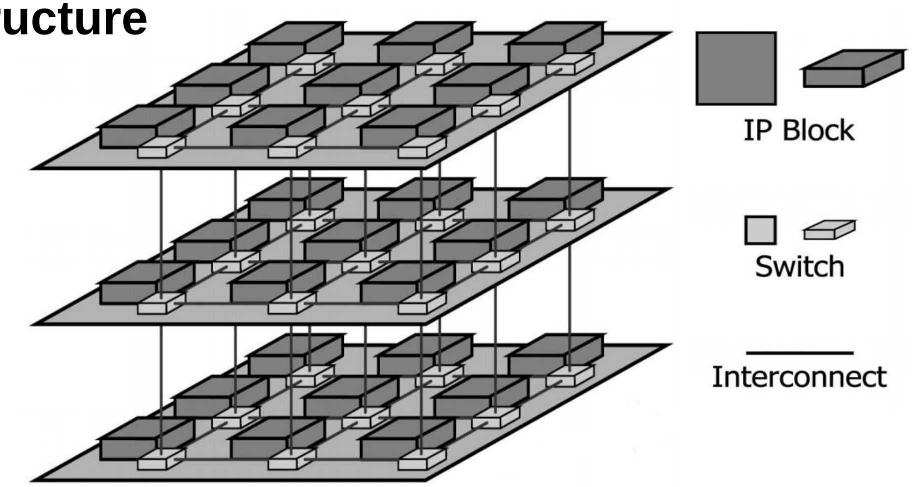


Difference between 2D and 3D NoC

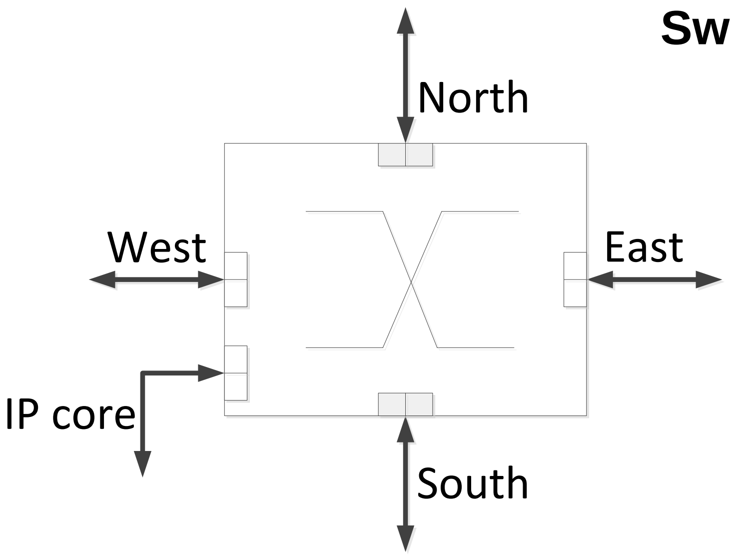
2D	3D

NoC structure

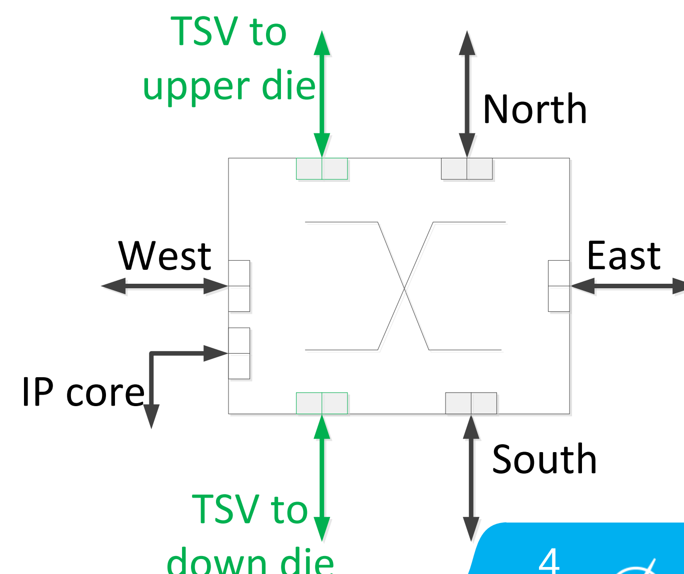




Switch Structure



TSV - Through-Silicon-Via



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Problems of 3D NoC design

Modern 3D NoC development is complex task

Developer has to solve different problems:

- IP blocks placement on the die
- Energy consumption limitation
- System performance improvement
- **Organization of vertical links between dies in the 3D stack (TSV placement)**

TSV placement problems

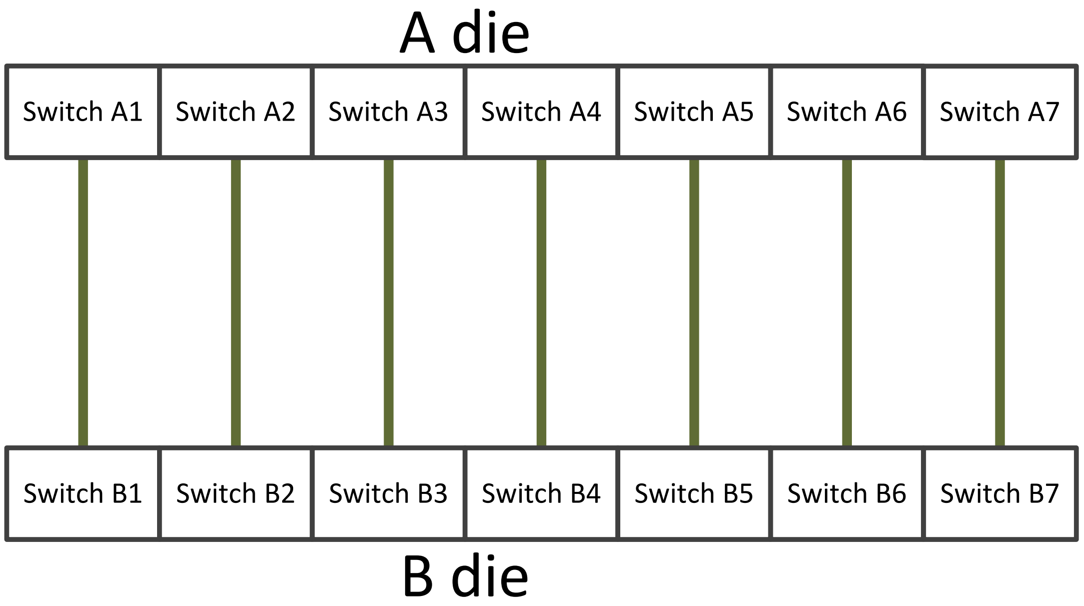
TSV placement problems

- **TSVs heat dissipation**

Design problems

TSV placement problems

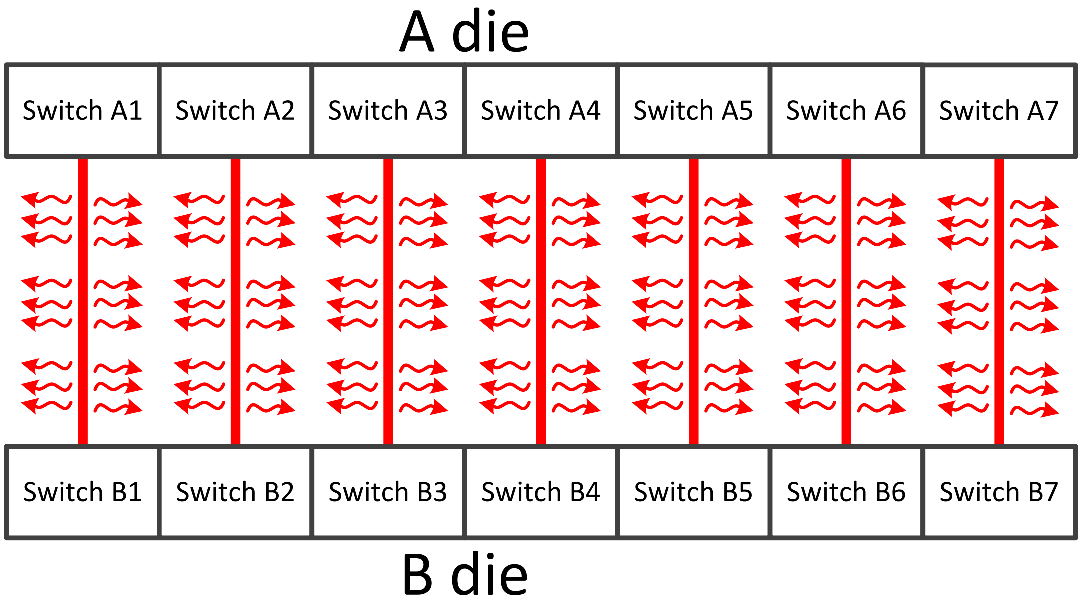
- **TSVs heat dissipation**



TSV placement problems

- **TSVs heat dissipation**

Problem:
Overheating at full connection dies

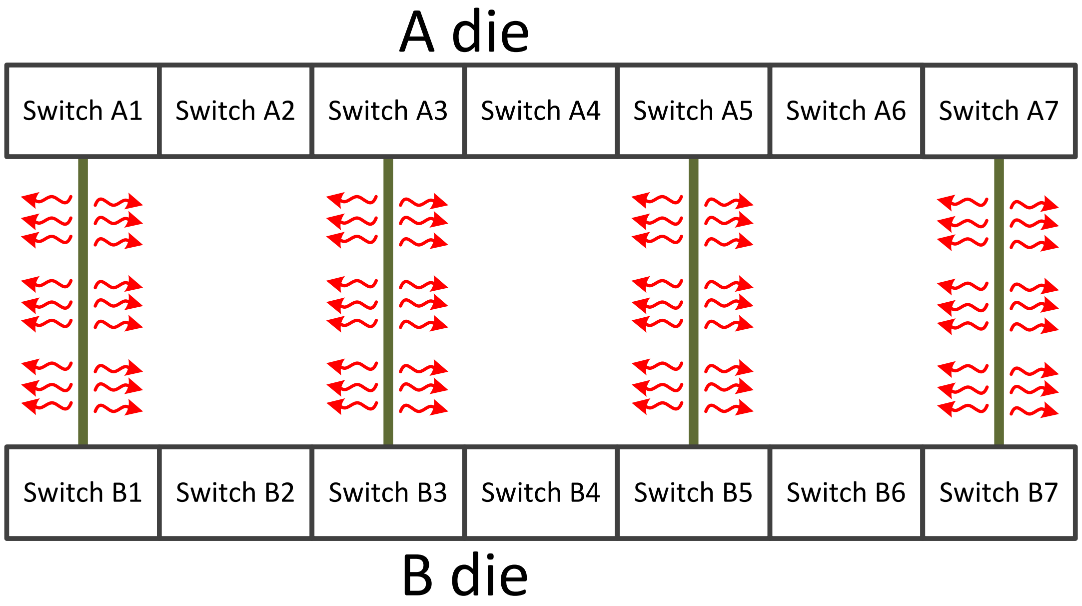


TSV placement problems

- **TSVs heat dissipation**

Problem:
Overheating at full connection dies

Solution:
Partial dies connection



TSV placement problems

- **TSVs heat dissipation**

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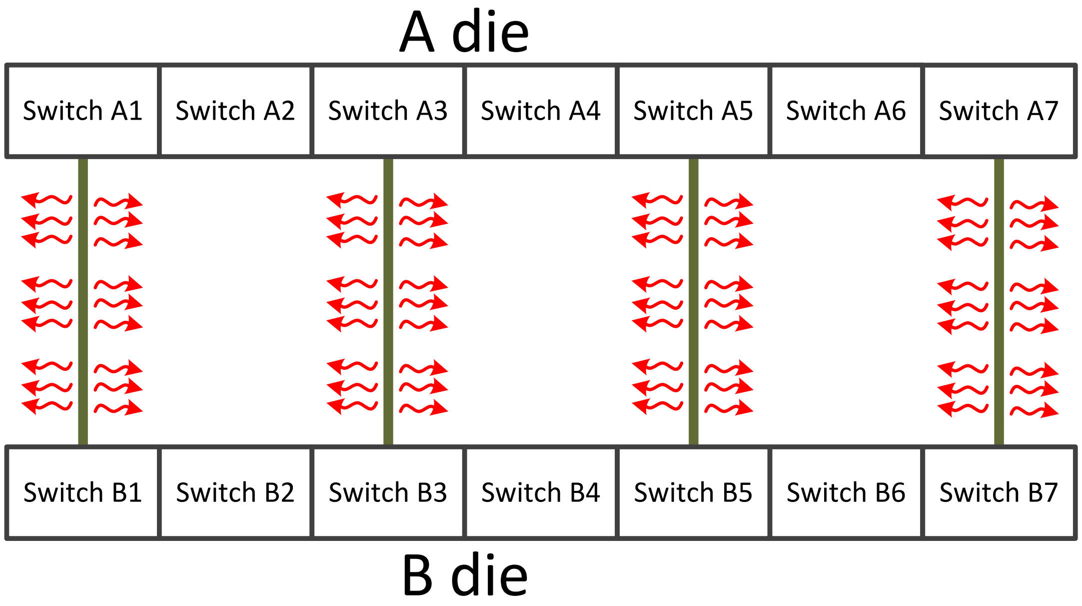

- **Bottleneck in data transfer from die to die**

TSV placement problems

- **TSVs heat dissipation**

  Problem:
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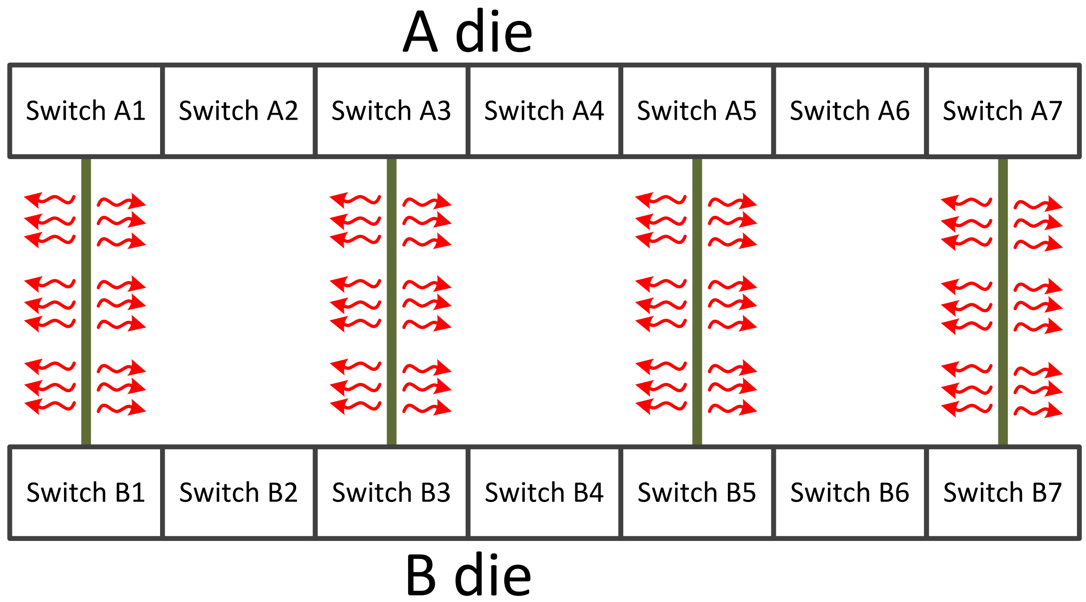
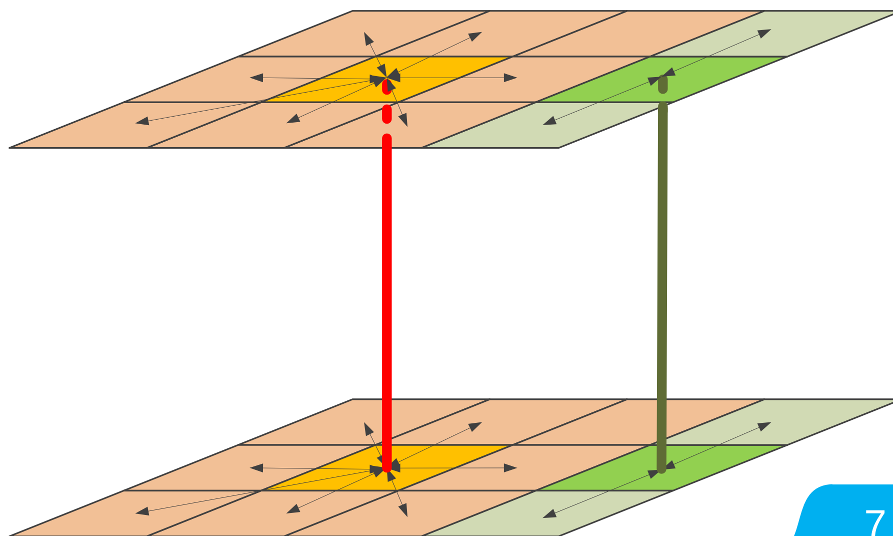
  Solution:
  Partial dies connection



- **Bottleneck in data transfer from die to die**

  Problem:
  Some TSVs are overloaded
  Some TSVs are underloaded



Design problems

TSV placement problems

- **TSVs heat dissipation**

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Overheating at full connection dies

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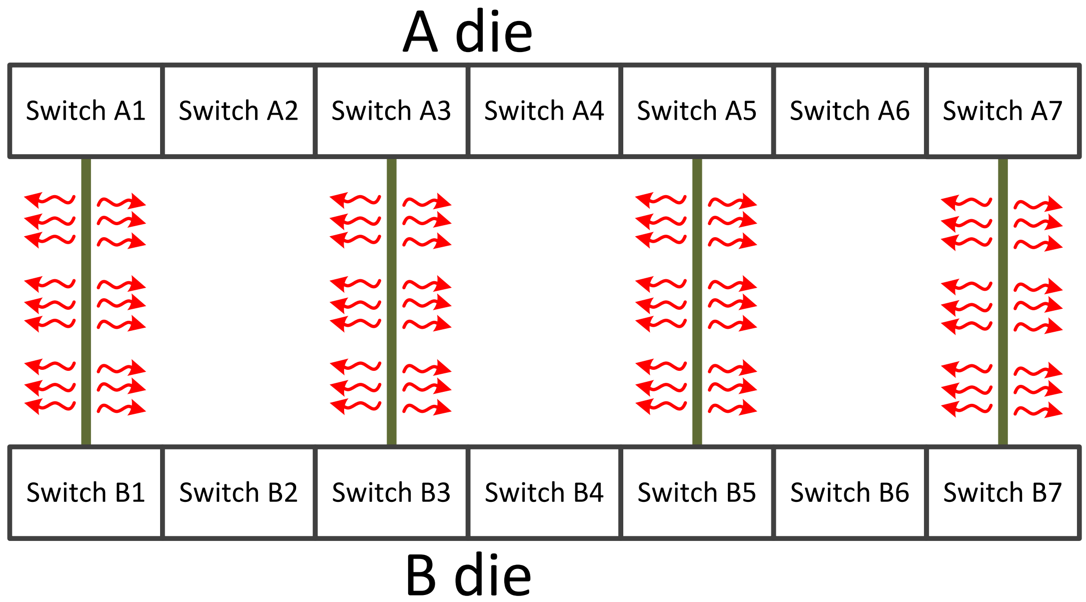
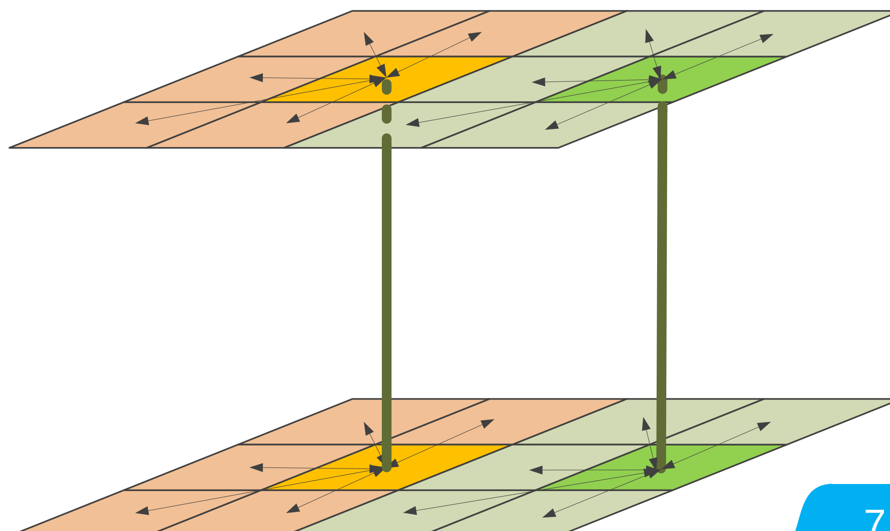


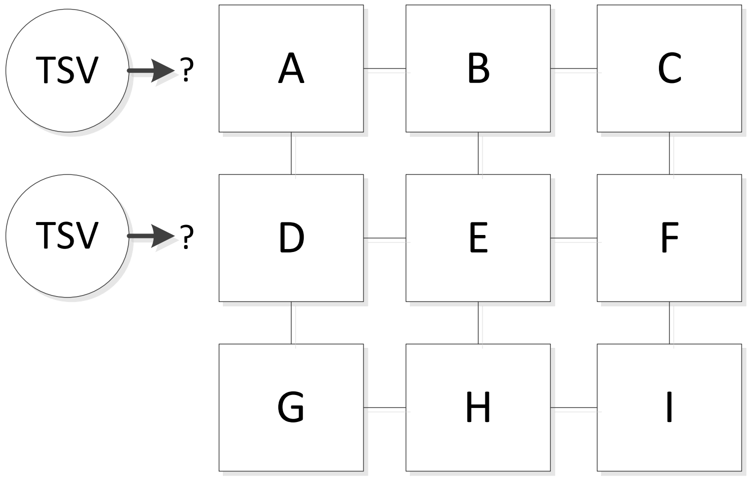
- **Bottleneck in data transfer from die to die**

Problem:
Some TSVs are overloaded
Some TSVs are underloaded

Solution:
The uniform attachment of nodes to each TSV



P – median problem in 3D NoC design



- The problem of placement specific nodes (P nodes), such that for each pair of nodes the Chebyshev distance is not less than H and the number of attached nodes should be near equal among regions
- **Chebyshev distance** (H) is the maximal absolute componentwise difference

$$H(\vec{x},\vec{y}) = \max_{1 \le i \le n} |x_i - y_i|$$

- **Necessary condition**: $V = V_P \cup V_{Att}$, where V_P - set of medians,
  V_{Att} - set of attached nodes,
  V - set of all nodes in the graph

P – median problem in 3D NoC design

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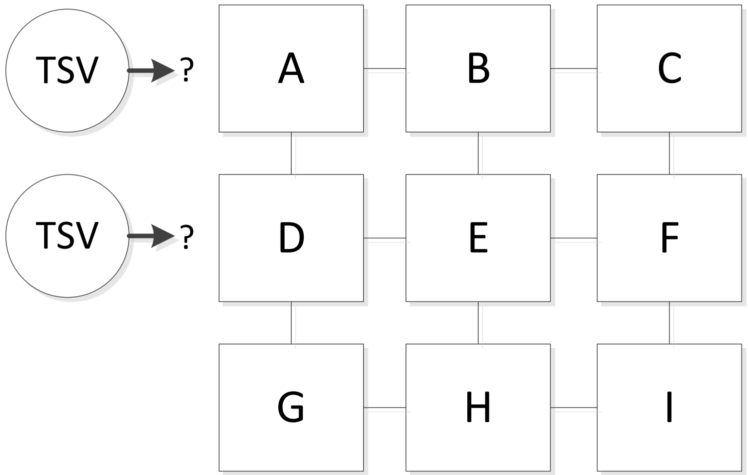

- **Chebyshev distance** (H) is the maximal absolute componentwise difference

$$H(\vec{x},\vec{y}) = \max_{1 \le i \le n} |x_i - y_i|$$

	1	2	**3**	4	5	6	7
1	4	4	4	4	4	4	4
2	3	3	3	3	3	3	4
3	2	2	2	2	2	3	4
4	2	1	1	1	2	3	4
5	2	1	TSV	1	2	3	4
6	2	1	1	1	2	3	4
7	2	2	2	2	2	3	4

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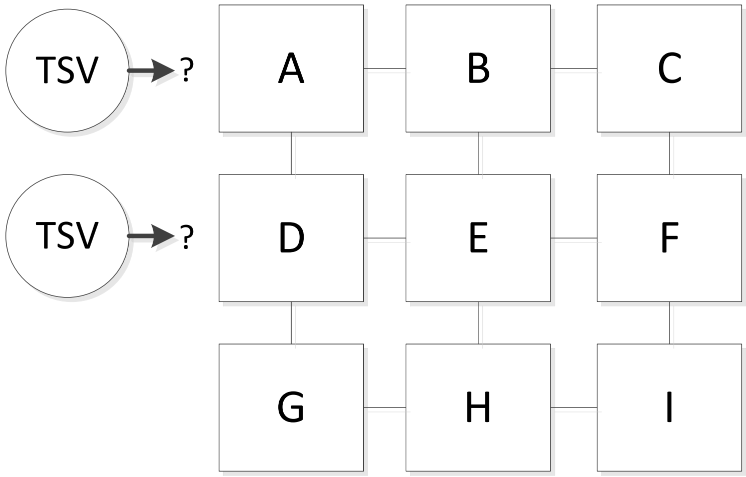

- **Chebyshev distance** (H) is the maximal absolute componentwise difference

$$H(\vec{x}, \vec{y}) = \max_{1 \le i \le n} |x_i - y_i|$$

H=3

	1	2	**3**	4	5	6	7
1	4	4	4	4	4	4	4
2	3	3	3	3	3	3	4
3	2	2	2	2	2	3	4
4	2	1	1	1	2	3	4
5	2	1	TSV	1	2	3	4
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Same topologies

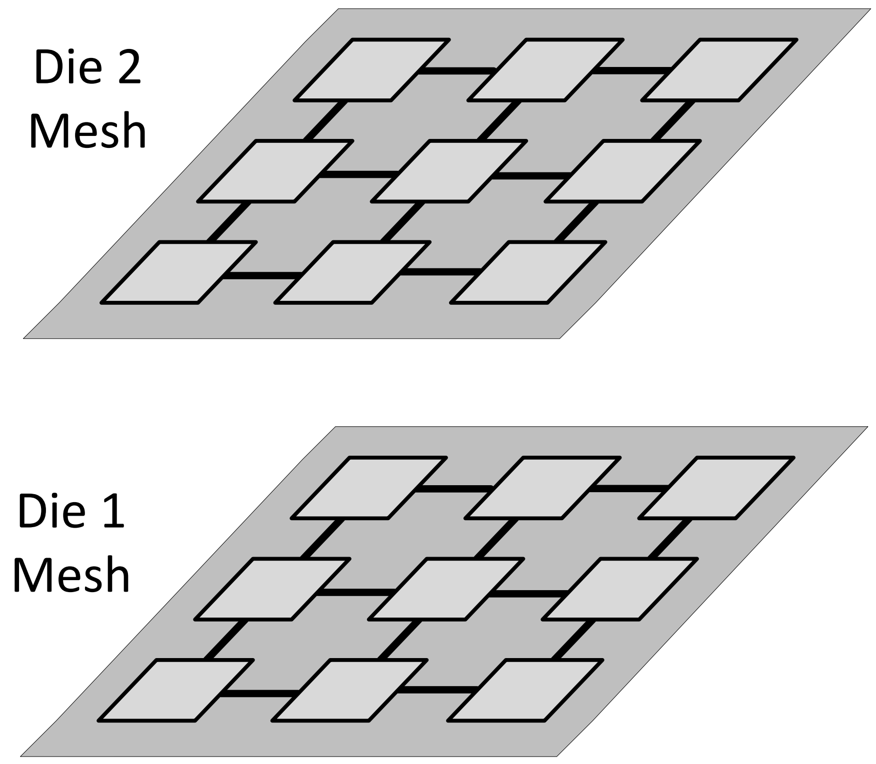
Placement TSV nodes on the dies with the same topologies

Problem: Find the location of P TSVs on the die

Goal: Connect the dies in 3D stack without overheating and to provide the maximal uniform loading of connections between the dies

Input data:
- Topology
- Number of TSVs (P)
- Distance between TSVs (H)

Output data:
- Set of solutions with locations of P TSVs



Same topologies

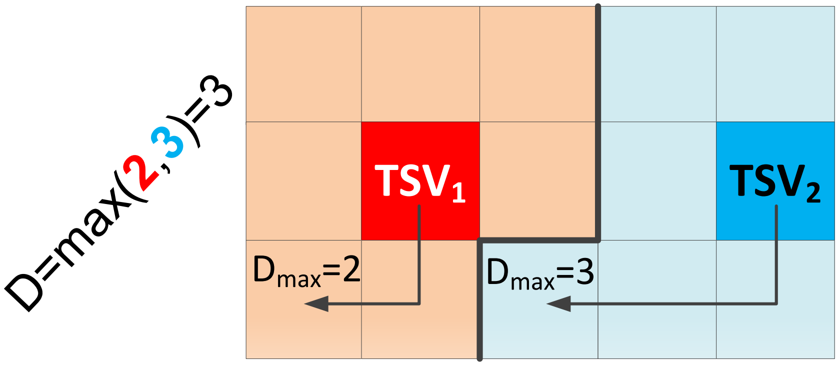
Criteria for choosing best solution on the die

The following criteria are applied when we choose best solution on the die:

- **Distance** [D, hops] – the maximal distance between TSV node and the farthest node in it's **flat** region among all TSV nodes:

$$D=max_{i=1}^{P}\left(max_{v_i}\, d(m_i, v_i)\right)$$

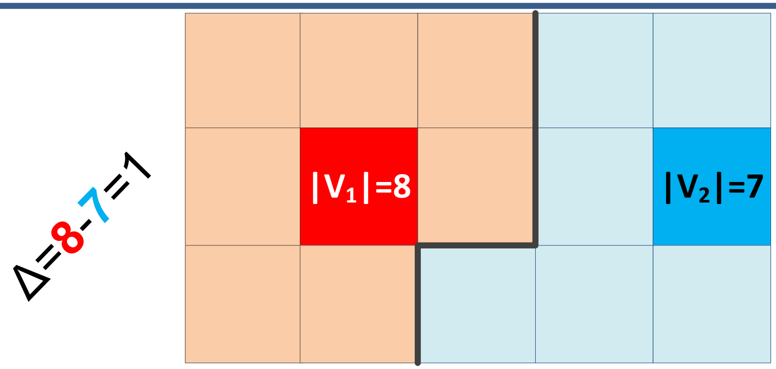
Where
d(.) – shortest distance between two nodes
P – the number of TSVs
v_i – node in i^{th} flat region
m_i – TSV node in i^{th} flat region



- **Difference of TSVs load** [Δ, Number nodes] – maximal absolute difference of nodes count among all pairs of **flat** regions:

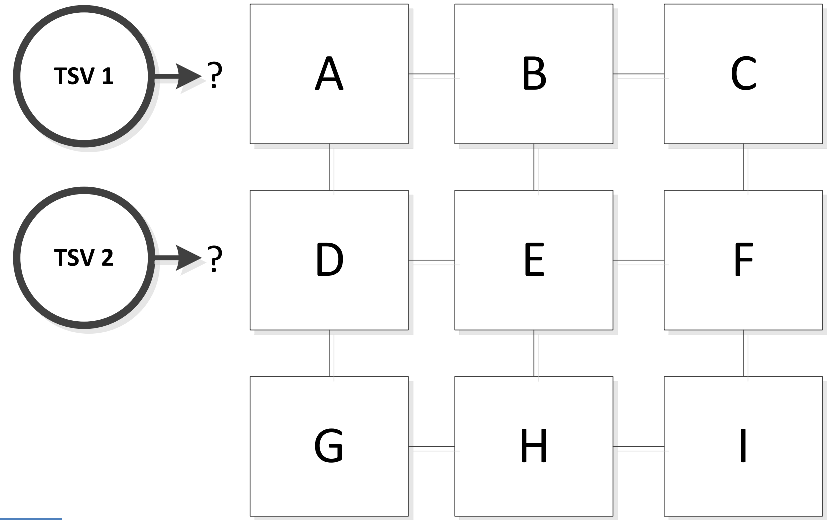
$$\Delta = max_{i \neq j}\left|n_i - n_j\right|,$$

Where
n_i=$|V_i|$, n_j=$|V_j|$
V_i,V_j – set of nodes in i^{th} and j^{th} flat region correspondingly



Placement algorithm (1/4)

It is necessary to place two TSVs (P = 2) in a 3x3 NoC with Mesh topology, and achieve a minimal distance from the TSV node to other nodes, achieve the maximal uniform attachment of nodes.



1. Building a matrix of shortest distances.

	A	B	C	D	E	F	G	H	I
A	0	1	2	1	2	3	2	3	4
B	1	0	1	2	1	2	3	2	3
C	2	1	0	3	2	1	4	3	2
D	1	2	3	0	1	2	1	2	3
E	2	1	2	1	0	1	2	1	2
F	3	2	1	2	1	0	3	2	1
G	2	3	4	1	2	3	0	1	2
H	3	2	3	2	1	2	1	0	1
I	4	3	2	3	2	1	2	1	0

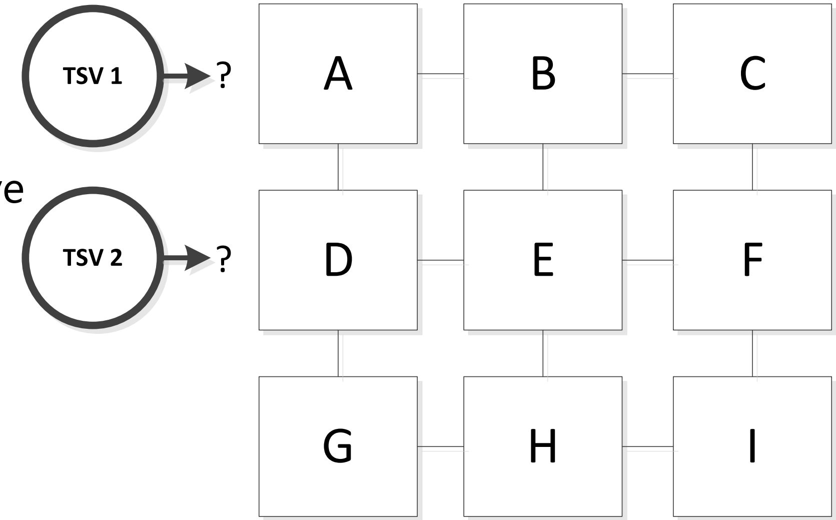
Input data:

- Mesh 3x3
- P=2

Placement algorithm (2/4)

2. Sort the matrix of shortest distances by ascending distance. The index shows the distance from median to nodes in the row.

3. We choose two rows (since P=2) and remove from these rows median nodes. In this step, median nodes are H and B



A	A_0	B_1	D_1	C_2	E_2	G_2	F_3	H_3	I_4
B	B_0	A_1	C_1	E_1	D_2	F_2	H_2	G_3	I_3
C	C_0	B_1	F_1	A_2	E_2	I_2	D_3	H_3	G_4
D	D_0	A_1	E_1	G_1	B_2	F_2	H_2	C_3	I_3
E	E_0	B_1	D_1	F_1	H_1	A_2	C_2	G_2	I_2
F	F_0	C_1	E_1	I_1	B_2	D_2	H_2	A_3	G_3
G	G_0	D_1	H_1	A_2	E_2	I_2	B_3	F_3	C_4
H	H_0	E_1	G_1	I_1	B_2	D_2	F_2	A_3	C_3
I	I_0	F_1	H_1	C_2	E_2	G_2	B_3	D_3	A_4

Same topologies

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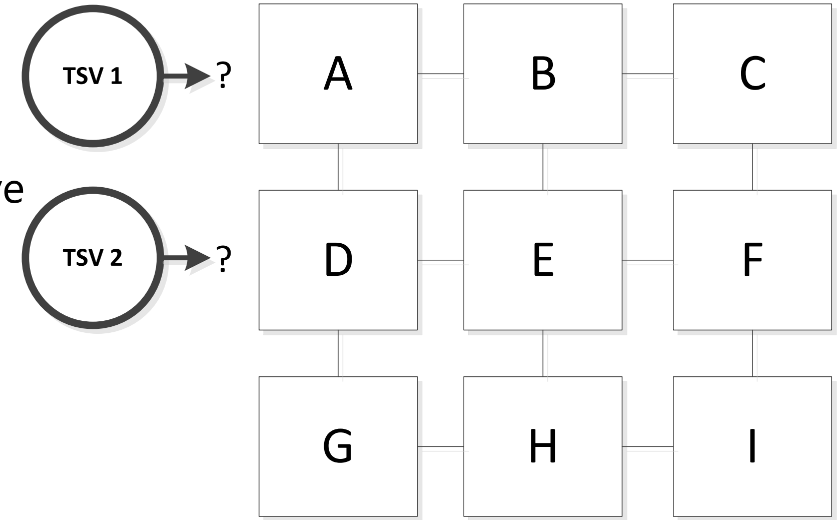

Potential medians

A	A_0	B_1	D_1	C_2	E_2	G_2	F_3	H_3	I_4
B	B_0	A_1	C_1	E_1	D_2	F_2	H_2	G_3	I_3
C	C_0	B_1	F_1	A_2	E_2	I_2	D_3	H_3	G_4
D	D_0	A_1	E_1	G_1	B_2	F_2	H_2	C_3	I_3
E	E_0	B_1	D_1	F_1	H_1	A_2	C_2	G_2	I_2
F	F_0	C_1	E_1	I_1	B_2	D_2	H_2	A_3	G_3
G	G_0	D_1	H_1	A_2	E_2	I_2	B_3	F_3	C_4
H	H_0	E_1	G_1	I_1	B_2	D_2	F_2	A_3	C_3
I	I_0	F_1	H_1	C_2	E_2	G_2	B_3	D_3	A_4

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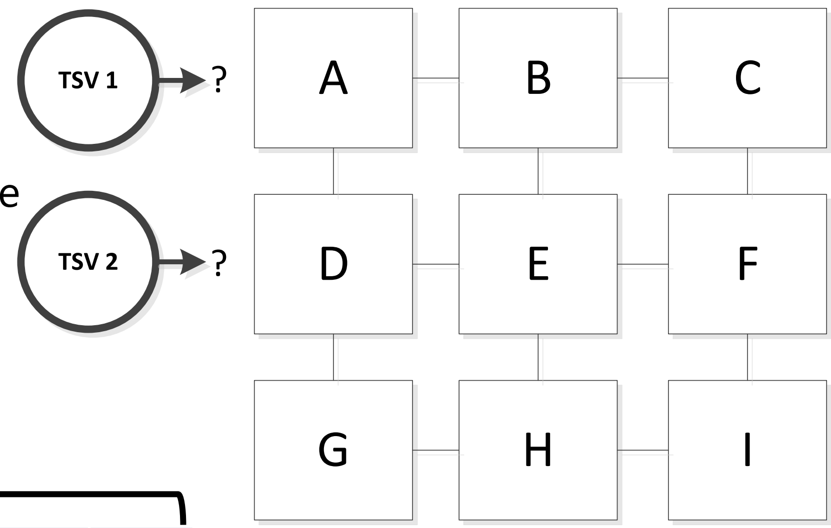

Potential medians | Attachable nodes

A	A_0	B_1	D_1	C_2	E_2	G_2	F_3	H_3	I_4
B	B_0	A_1	C_1	E_1	D_2	F_2	H_2	G_3	I_3
C	C_0	B_1	F_1	A_2	E_2	I_2	D_3	H_3	G_4
D	D_0	A_1	E_1	G_1	B_2	F_2	H_2	C_3	I_3
E	E_0	B_1	D_1	F_1	H_1	A_2	C_2	G_2	I_2
F	F_0	C_1	E_1	I_1	B_2	D_2	H_2	A_3	G_3
G	G_0	D_1	H_1	A_2	E_2	I_2	B_3	F_3	C_4
H	H_0	E_1	G_1	I_1	B_2	D_2	F_2	A_3	C_3
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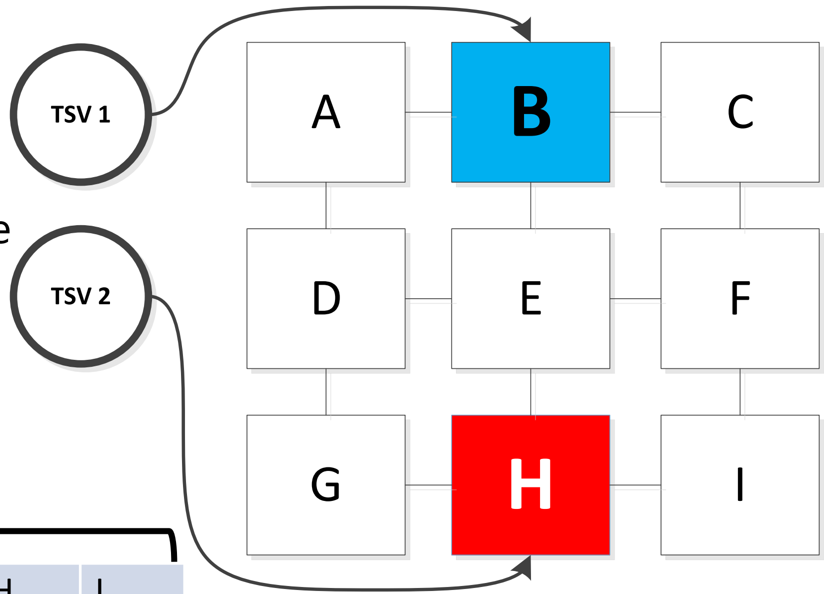

Potential medians | Attachable nodes

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C	C_0	B_1	F_1	A_2	E_2	I_2	D_3	H_3	G_4
D	D_0	A_1	E_1	G_1	B_2	F_2	H_2	C_3	I_3
E	E_0	B_1	D_1	F_1	H_1	A_2	C_2	G_2	I_2
F	F_0	C_1	E_1	I_1	B_2	D_2	H_2	A_3	G_3
G	G_0	D_1	H_1	A_2	E_2	I_2	B_3	F_3	C_4
H	H_0	E_1	G_1	I_1	B_2	D_2	F_2	A_3	C_3
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Same topologies

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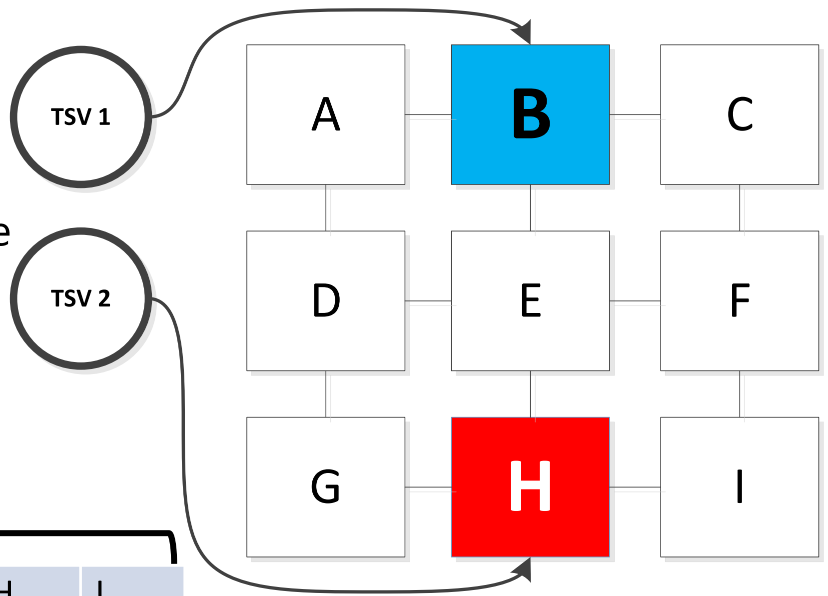


Potential medians | Attachable nodes

A	A_0	B_1	D_1	C_2	E_2	G_2	F_3	H_3	I_4
B	~~B_0~~	A_1	C_1	E_1	D_2	F_2	~~H_2~~	G_3	I_3
C	C_0	B_1	F_1	A_2	E_2	I_2	D_3	H_3	G_4
D	D_0	A_1	E_1	G_1	B_2	F_2	H_2	C_3	I_3
E	E_0	B_1	D_1	F_1	H_1	A_2	C_2	G_2	I_2
F	F_0	C_1	E_1	I_1	B_2	D_2	H_2	A_3	G_3
G	G_0	D_1	H_1	A_2	E_2	I_2	B_3	F_3	C_4
H	~~H_0~~	E_1	G_1	I_1	~~B_2~~	D_2	F_2	A_3	C_3
I	I_0	F_1	H_1	C_2	E_2	G_2	B_3	D_3	A_4

Same topologies

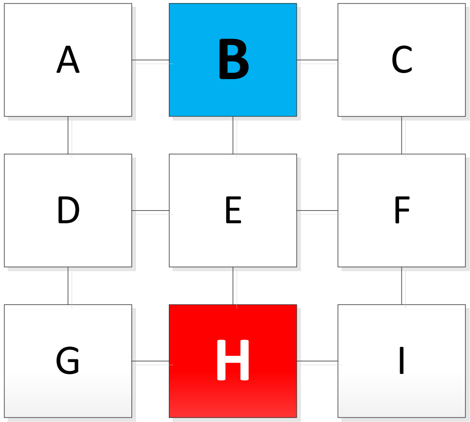
Placement algorithm (3/4)

4. We derive a new table that contains attachable nodes, medians, to which they are attached and the distance to them in ascending order.

Attachable nodes	A	C	E	G	I	D	F	A	C	G	I
Medians	B	B	B,H	H	H	B,H	B,H	H	H	B	B
Distance	1	1	1	1	1	2	2	3	3	3	3

5. We select connection to p-median with the minimal distance for each node. From the resulting table you can uniquely identify nodes that can be attached to only one median.

Attachable nodes	A	C	E	G	I	D	F	A	C	G	I
Medians	B	B	B,H	H	H	B,H	B,H	H	H	B	B
Distance	1	1	1	1	1	2	2	3	3	3	3



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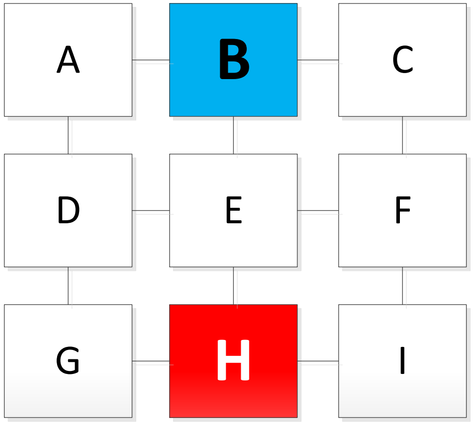
Distance	1	1	1	1	1	2	2	3	3	3	3



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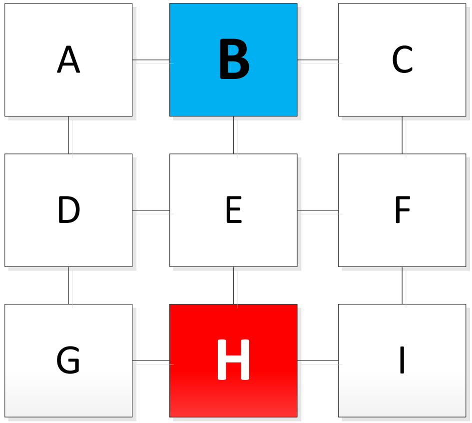
Attachable nodes	A	C	E	G	I	D	F
Medians	B	B	B,H	H	H	B,H	B,H
Distance	1	1	1	1	1	2	2



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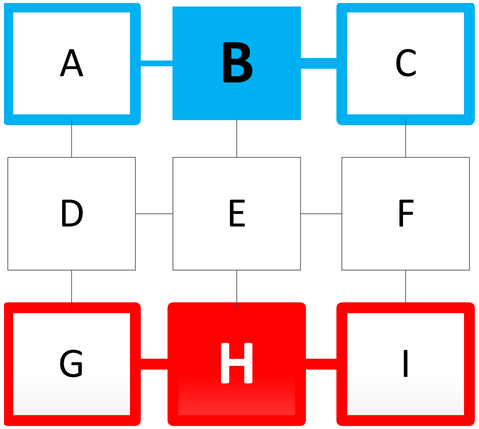
Medians	B	B	B,H	H	H	B,H	B,H	H	H	B	B
Distance	1	1	1	1	1	2	2	3	3	3	3

5. We select connection to p-median with the minimal distance for each node. From the resulting table you can uniquely identify nodes that can be attached to only one median.

Attachable nodes	A	C	E	G	I	D	F
Medians	B	B	B,H	H	H	B,H	B,H
Distance	1	1	1	1	1	2	2



Same topologies

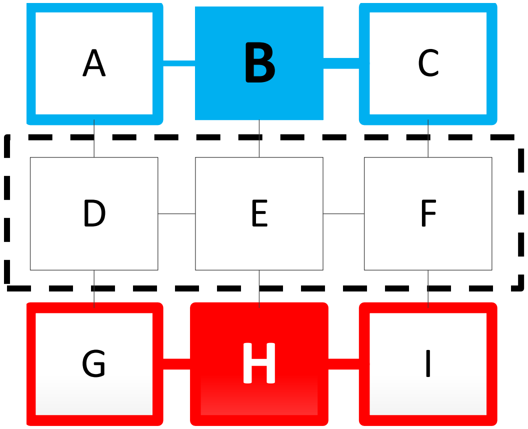
Placement algorithm (3/4)

4. We derive a new table that contains attachable nodes, medians, to which they are attached and the distance to them in ascending order.

Attachable nodes	A	C	E	G	I	D	F	A	C	G	I
Medians	B	B	B,H	H	H	B,H	B,H	H	H	B	B
Distance	1	1	1	1	1	2	2	3	3	3	3

5. We select connection to p-median with the minimal distance for each node. From the resulting table you can uniquely identify nodes that can be attached to only one median.

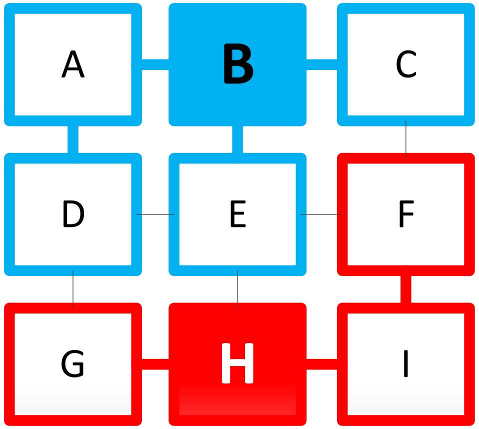
Attachable nodes	E	D	F
Medians	B,H	B,H	B,H
Distance	1	2	2



Placement algorithm (4/4)

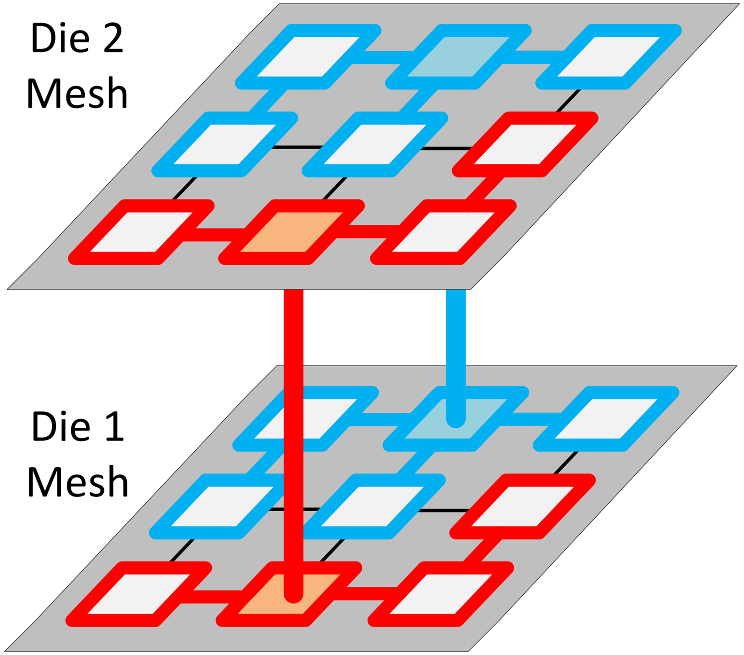
6. Distribute remaining nodes on the medians with the maximal uniformly attachment

Attachable nodes	E	D	F
Medians	B,H	B,H	B,H
Distance	1	2	2



Solution checking:

- $V_P \cup V_{Att} = V$
- $H=2$
- $D=\max(d(V_P, V_{Att})) = 2$ hops
- $\Delta=1$ node



Outline

1. Introduction
2. Problems of 3D NoC design
3. Placement TSV nodes on the dies with the **same** topologies
4. Placement TSV nodes on the dies with the **different** topologies

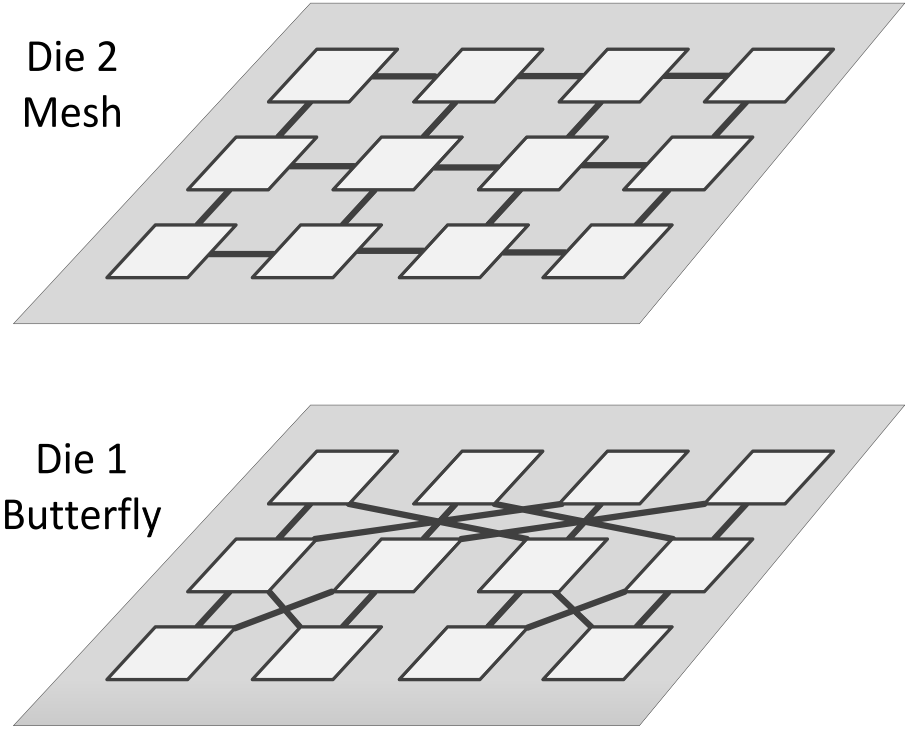
Placement TSV nodes on the dies with the different topologies

Problem: Find the location of p TSVs for dies with different topologies

Goal: Connect the dies in 3D stack without overheating and to provide the maximal uniform loading of connections between the dies

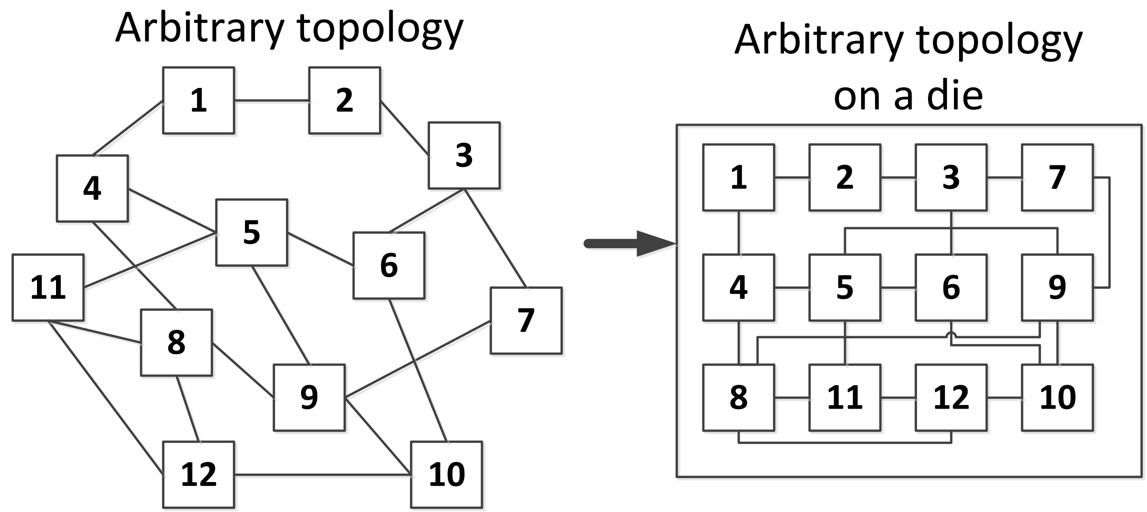
Input data:
- Topologies
- Number of TSVs (p)
- Distance between TSVs (H)

Output data:
- Set of solutions with locations of p TSVs



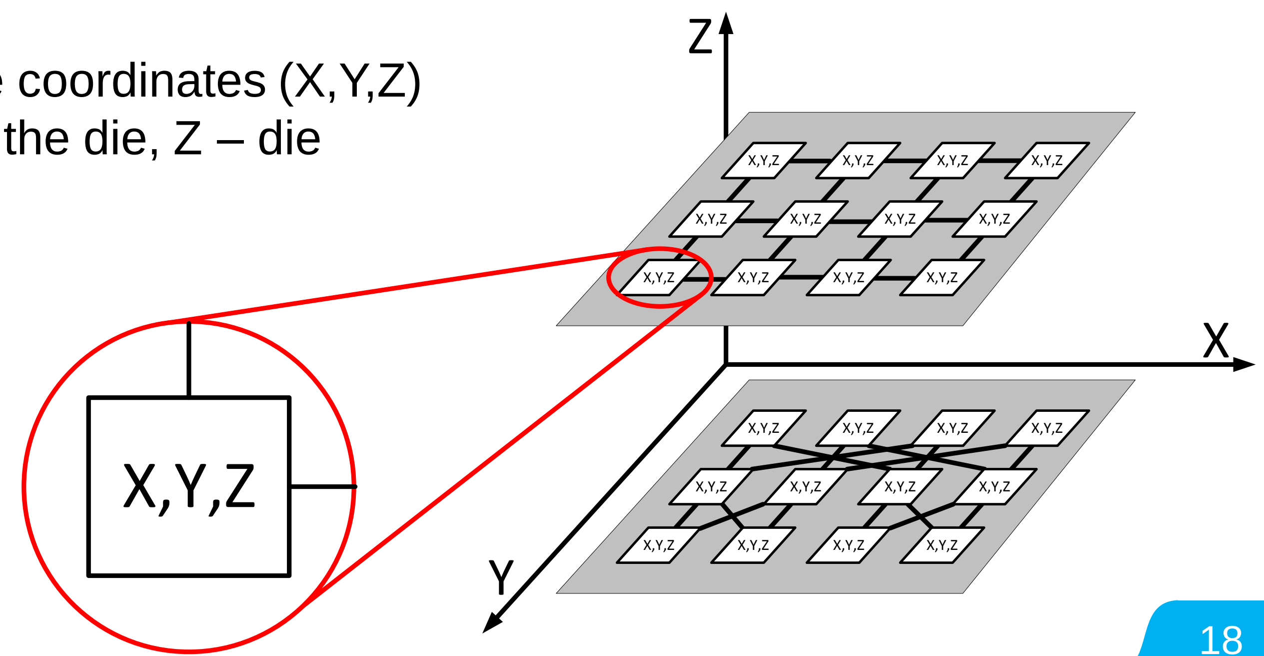
Network placement on the die

- Nodes must form a matrix



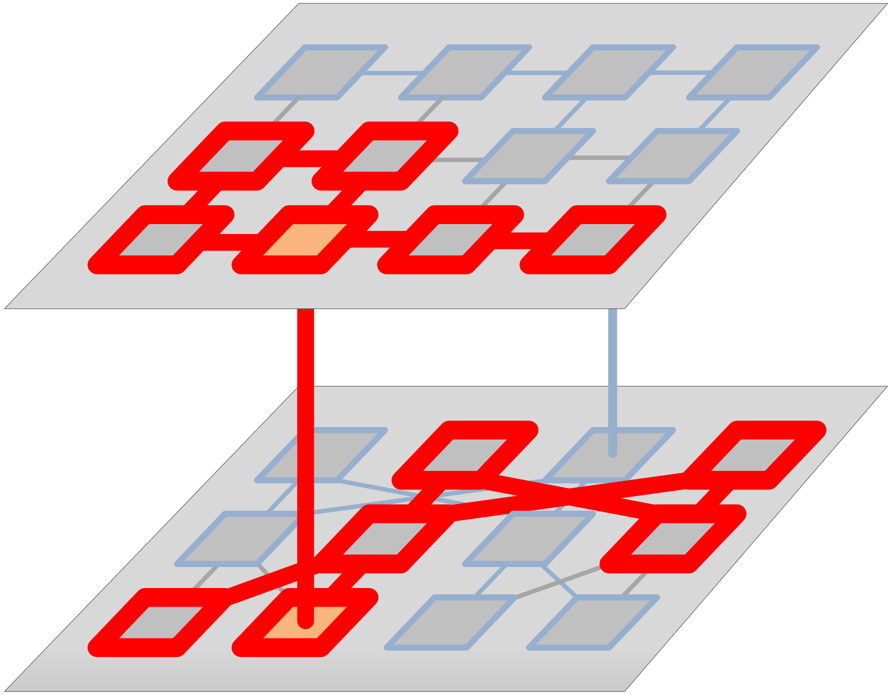
- Each node has three coordinates (X,Y,Z)

Where X,Y- location on the die, Z – die number

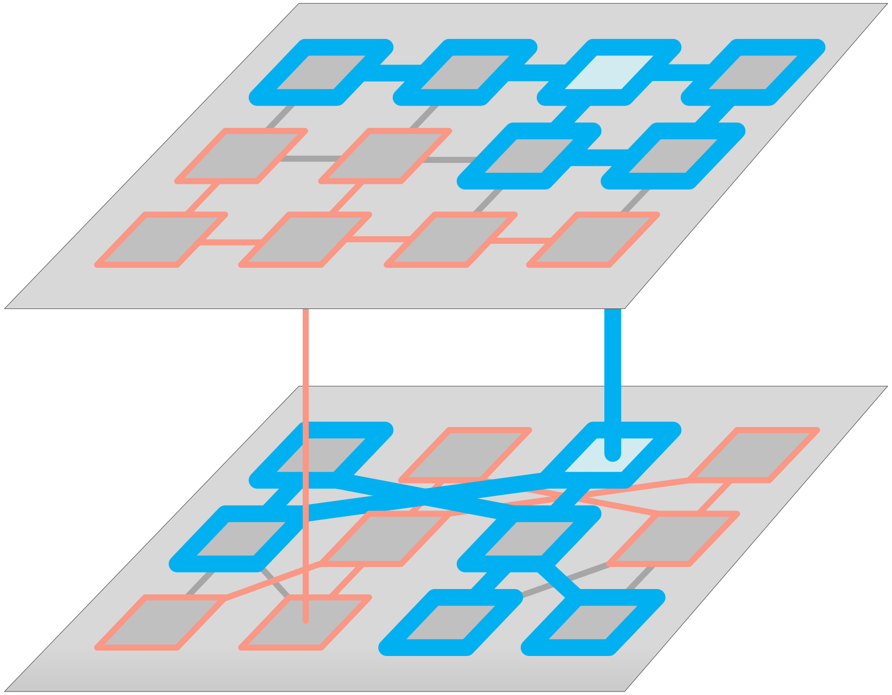


Vertical regions

Vertical region - subgraph of the entire network, which consists of one node with TSV and nodes attached to it on each die



Red vertical region



Blue vertical region

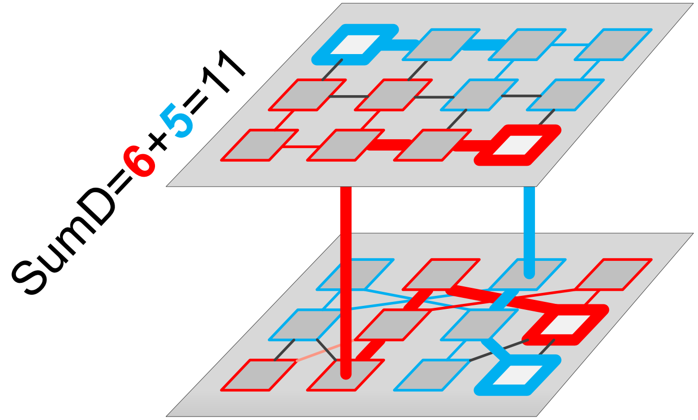
Criteria for choosing best solution for full system

The following criteria are applied when we choose best solution for full system:

- **Sum of diameters** [SumD, hops] – the sum of diameters of all **vertical** regions:

$$\mathrm{SumD}=\sum_{i=1}^{P}\max_{v_i,w_i} d(v_i,w_i)$$

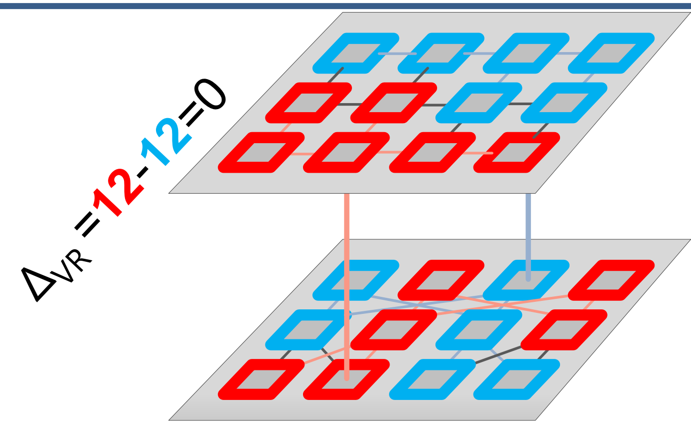
Where
d(.) – shortest distance between two nodes
v_i, w_i – nodes in i-th vertical region
P – the number of TSVs



- **Difference of TSVs load** [Δ_{VR}, Number nodes] - maximal absolute difference of nodes count among all pairs of **vertical** regions:

$$\Delta_{VR} = \max_{i\neq j}|n_i - n_j|,$$

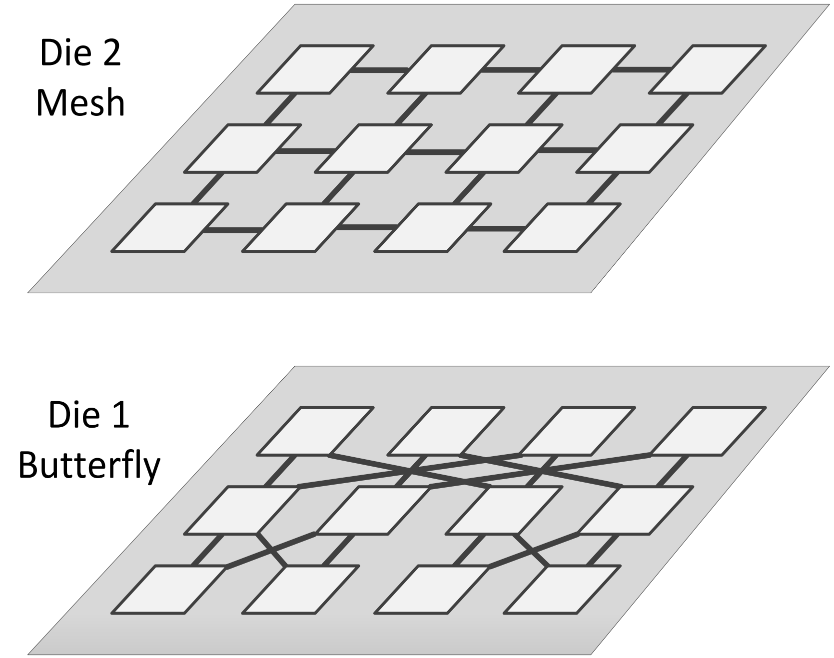
Where
$n_i=|V_i|$, $n_j=|V_j|$
V_i,V_j – set of nodes in i-th and j-th vertical region correspondingly

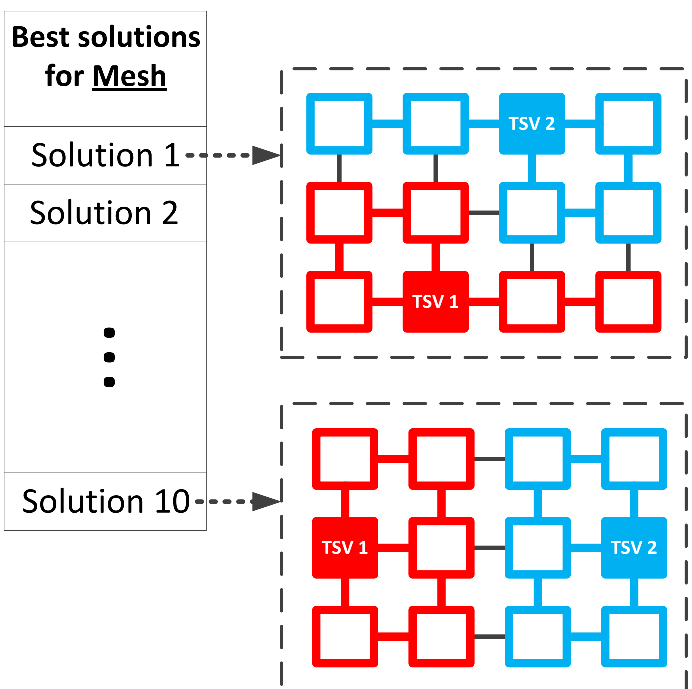


Placement algorithm (1/4)

It is necessary to place two TSVs (p = 2) in a 3x4 NoC for 2 dies with Mesh and Butterfly topology correspondently, and achieve minimal diameter and minimal load difference of vertical regions.

1. Find set of the best flat solutions for die using the previous algorithm

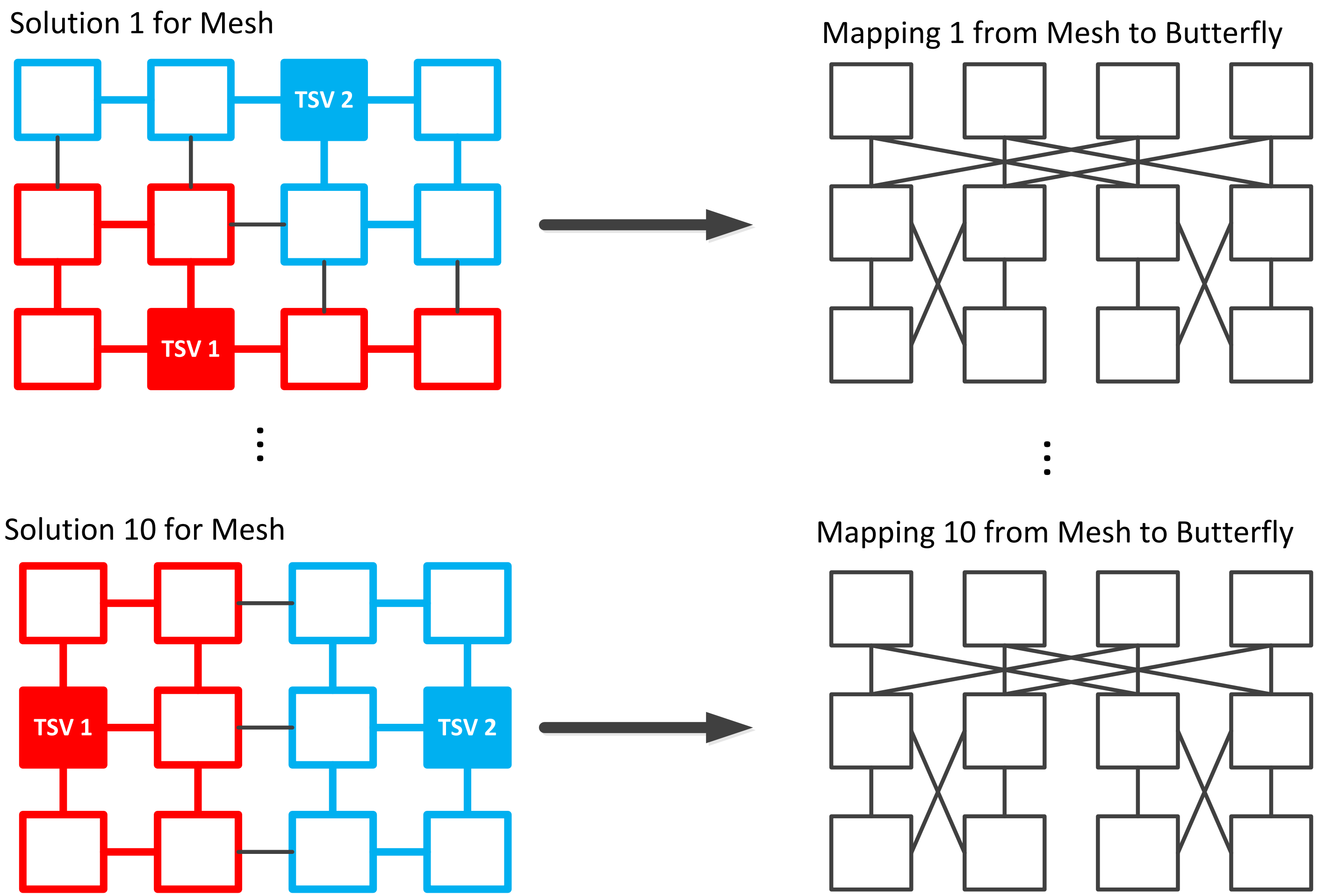




Different topologies

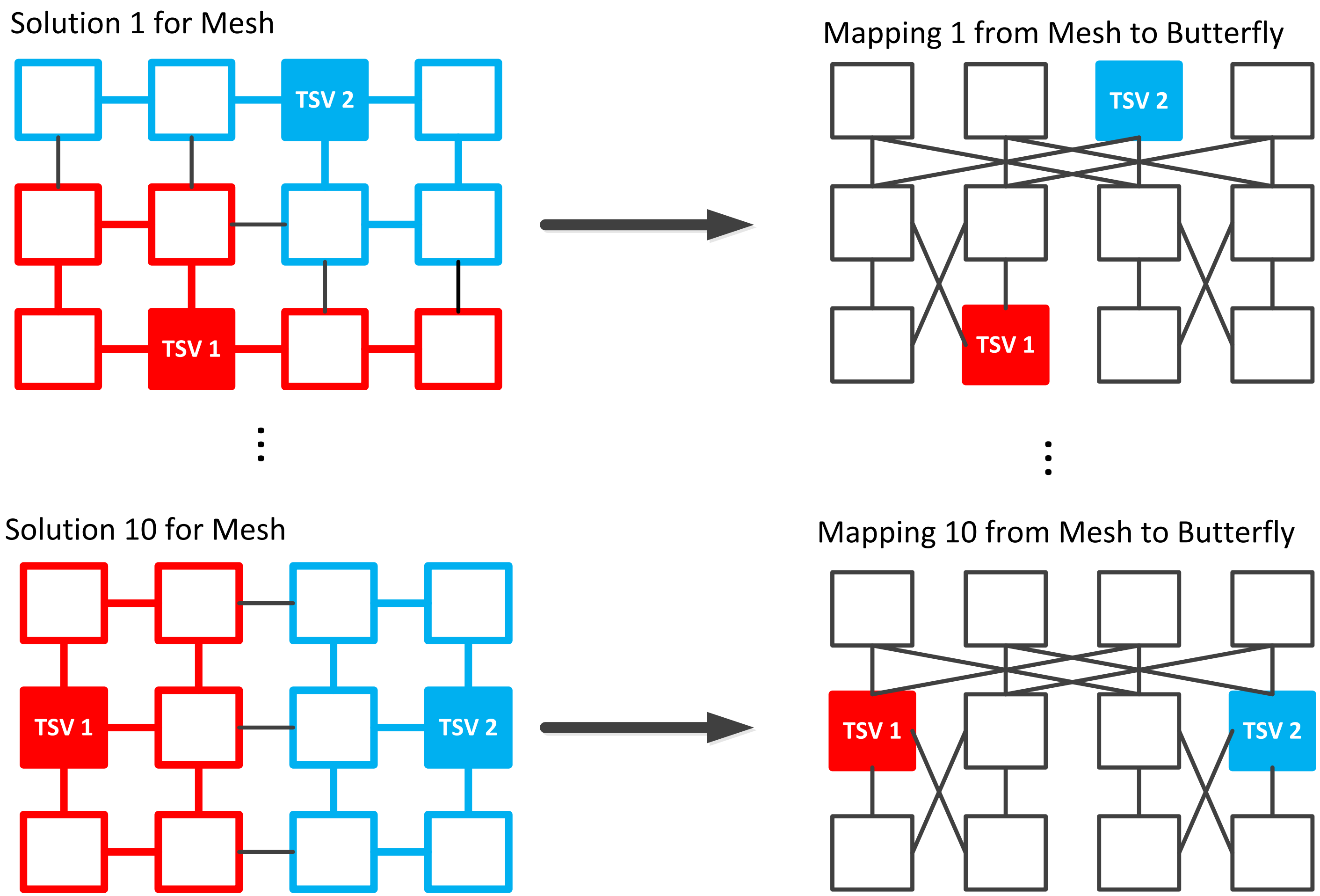
Placement algorithm (2/4)

2. Mapping each flat solution from the current die to other dies. Create vertical regions for each solution



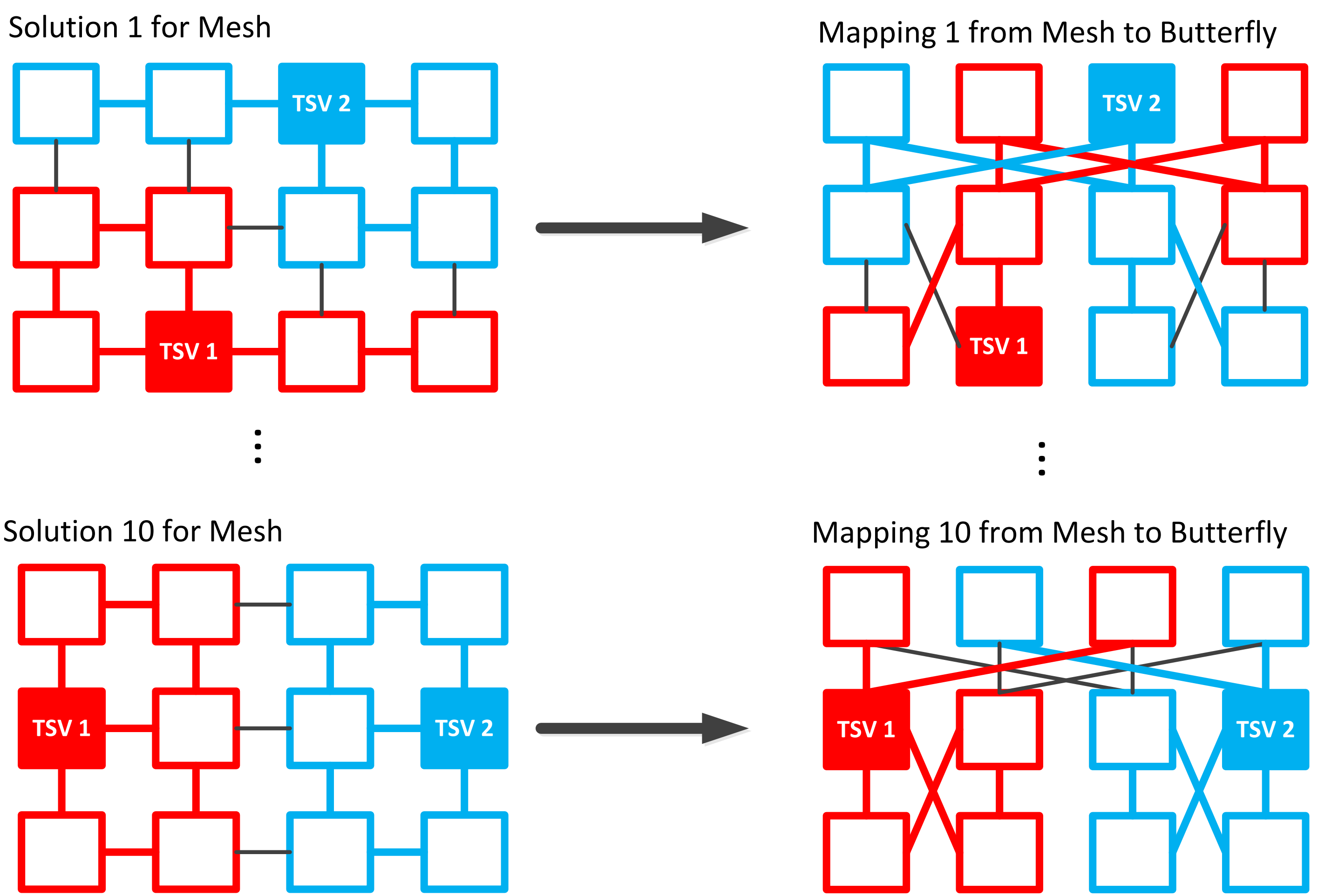
Placement algorithm (2/4)

2. Mapping each flat solution from the current die to other dies. Create vertical regions for each solution



Placement algorithm (2/4)

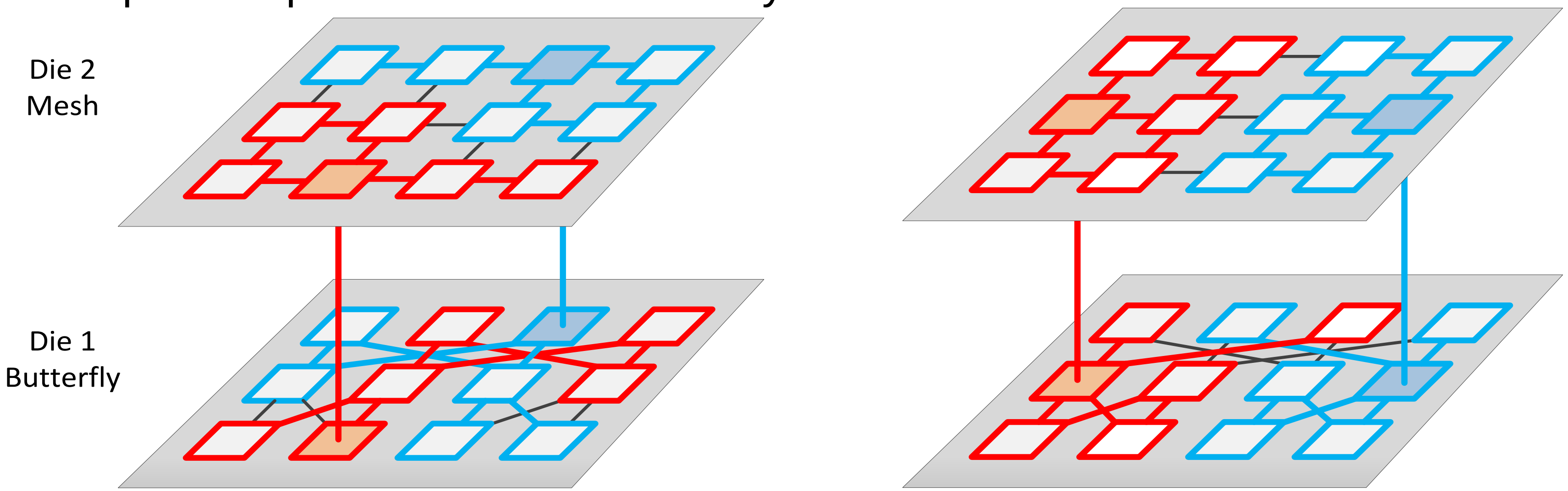
2. Mapping each flat solution from the current die to other dies. Create vertical regions for each solution



Different topologies

Placement algorithm (3/4)

3. Evaluate each resulting solution by the sum diameters of vertical regions and load difference of TSVs
4. Add your resulting solutions to the solutions' set for a full system
5. Repeat Steps1-4 for all dies in the system



Solution checking:

- $V = V_P \cup V_{Att}$
- $H=2$

D_{red}=6 hops
D_{blue}=5 hops
$|V_{red}|$=12 nodes
$|V_{blue}|$=12 nodes

SumD=11
$\Delta_{VR}=0$

D_{red}=5 hops
D_{blue}=5 hops
$|V_{red}|$=12 nodes
$|V_{blue}|$=12 nodes

SumD=10
$\Delta_{VR}=0$

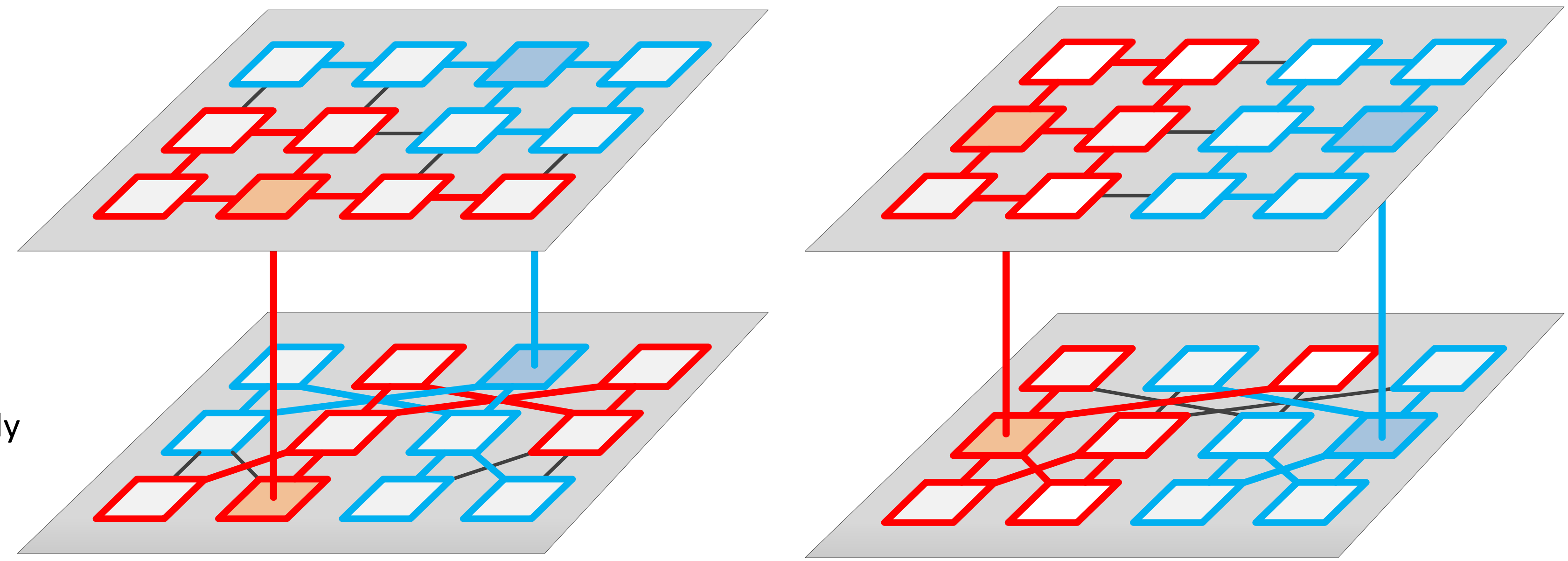
Different topologies

Placement algorithm (4/4)

6. Filter the solutions' set by minimal sum diameters
7. Filter the remaining solutions' set by minimal difference load

Die 2
Mesh

Die 1
Butterfly



D_{red}=6 hops
D_{blue}=5 hops
$|V_{red}|$=12 nodes
$|V_{blue}|$=12 nodes

SumD=11
$\Delta_{VR}=0$

D_{red}=5 hops
D_{blue}=5 hops
$|V_{red}|$=12 nodes
$|V_{blue}|$=12 nodes

SumD=10
$\Delta_{VR}=0$

Placement algorithm (4/4)

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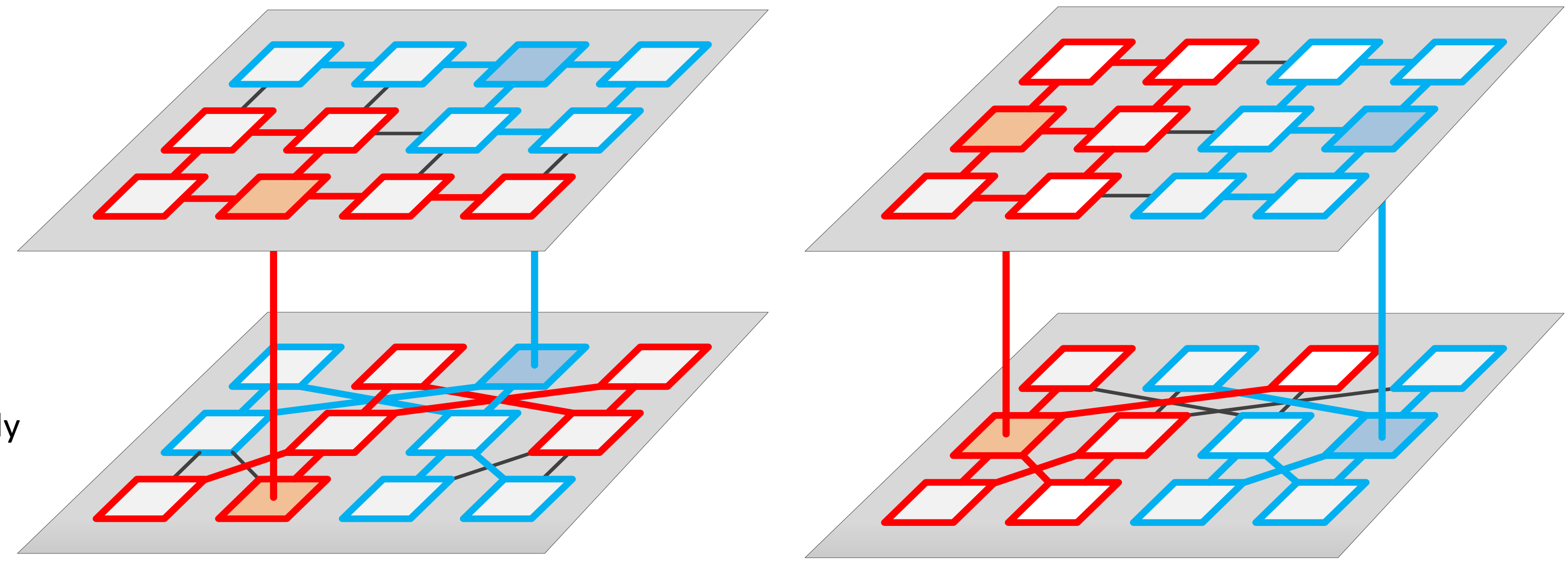

D_{red}=6 hops
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$|V_{red}|$=12 nodes
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SumD=11
$\Delta_{VR}=0$

D_{red}=5 hops
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SumD=10
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Placement algorithm (4/4)

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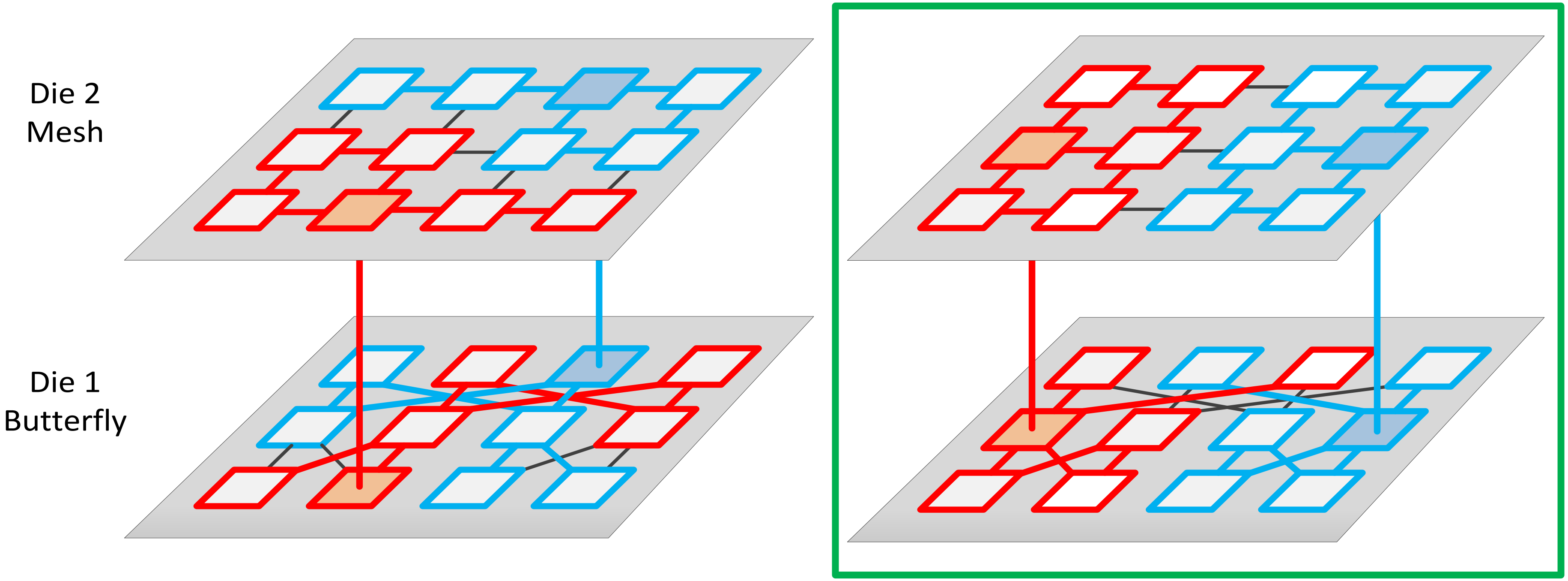

D_{red}=6 hops
D_{blue}=5 hops
$|V_{red}|$=12 nodes
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SumD=11
Δ_{VR}=0

D_{red}=5 hops
D_{blue}=5 hops
$|V_{red}|$=12 nodes
$|V_{blue}|$=12 nodes

SumD=10
Δ_{VR}=0

Conclusion

The aforementioned algorithms solve the following three problems:

- How to place TSV in a 3D NoC?
- How to avoid TSV overheating?
- How to balance the load among TSVs?

	Method for same topologies	Method for different topologies
Applying	Homogeneous systems-on-chip	Heterogeneous systems-on-chip
Count of dies	Without limitations	Time consumption depends on a total die count. $O(n^2)$
Count of nodes on the die	≤ 100	
Count of TSVs	≤ 5	

Thank you for your attention!

Any questions?

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