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A Low-overhead Fault tolerant Technique for TSV-based Interconnects in 3D-IC Systems

Abderazek Ben Abdallah, Khanh N. Dang, and Yuichi Okuyama
Adaptive Systems Labratory
Graduate School of Computer Science and Engineering
The University of Aizu, Aizu-Wakamatsu 965-8580, Japan
Email: benab@u-aizu.ac.jp
Website: http://adaptive.u-aizu.ac.jp

Outlines

- **Era of Multicore Computing & 3D-IC Integration**
- **TSV-cluster Defects Recovery in Highly Reliable 3D-NoC**
- **Design Evaluation and Analysis**
- **Concluding Remarks**

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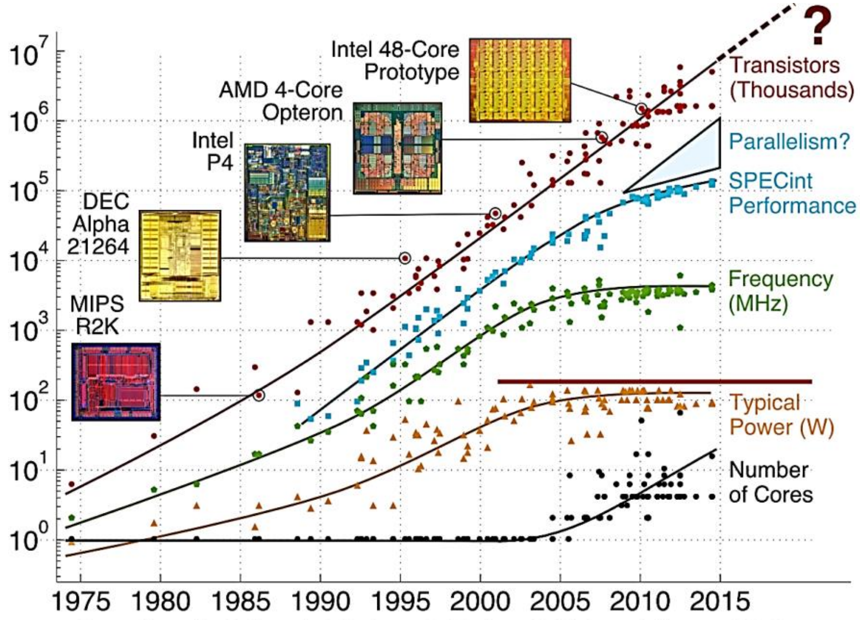
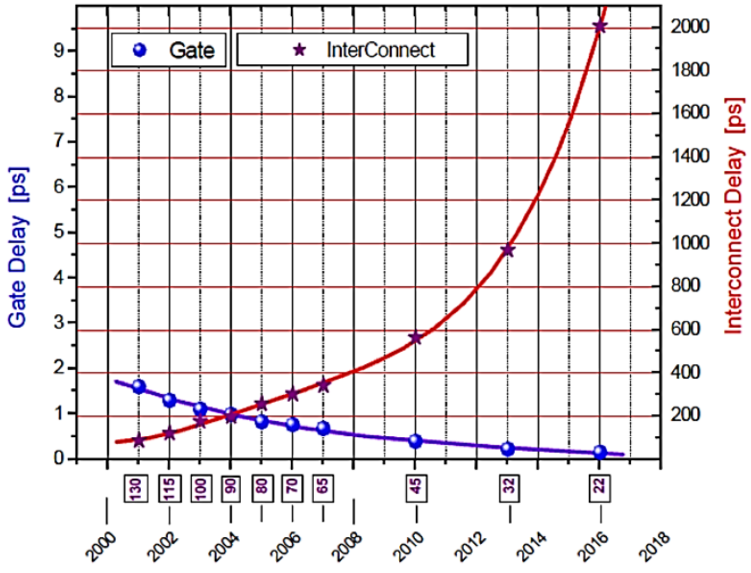
Era of Multi/Many-core processing

Constant increase of the number of cores → multi/many-core processing [Batten2014].



Data collected by M. Horowitz, F. Labonte, O. Shacham, K. Olukotun, L. Hammond, C. Batten

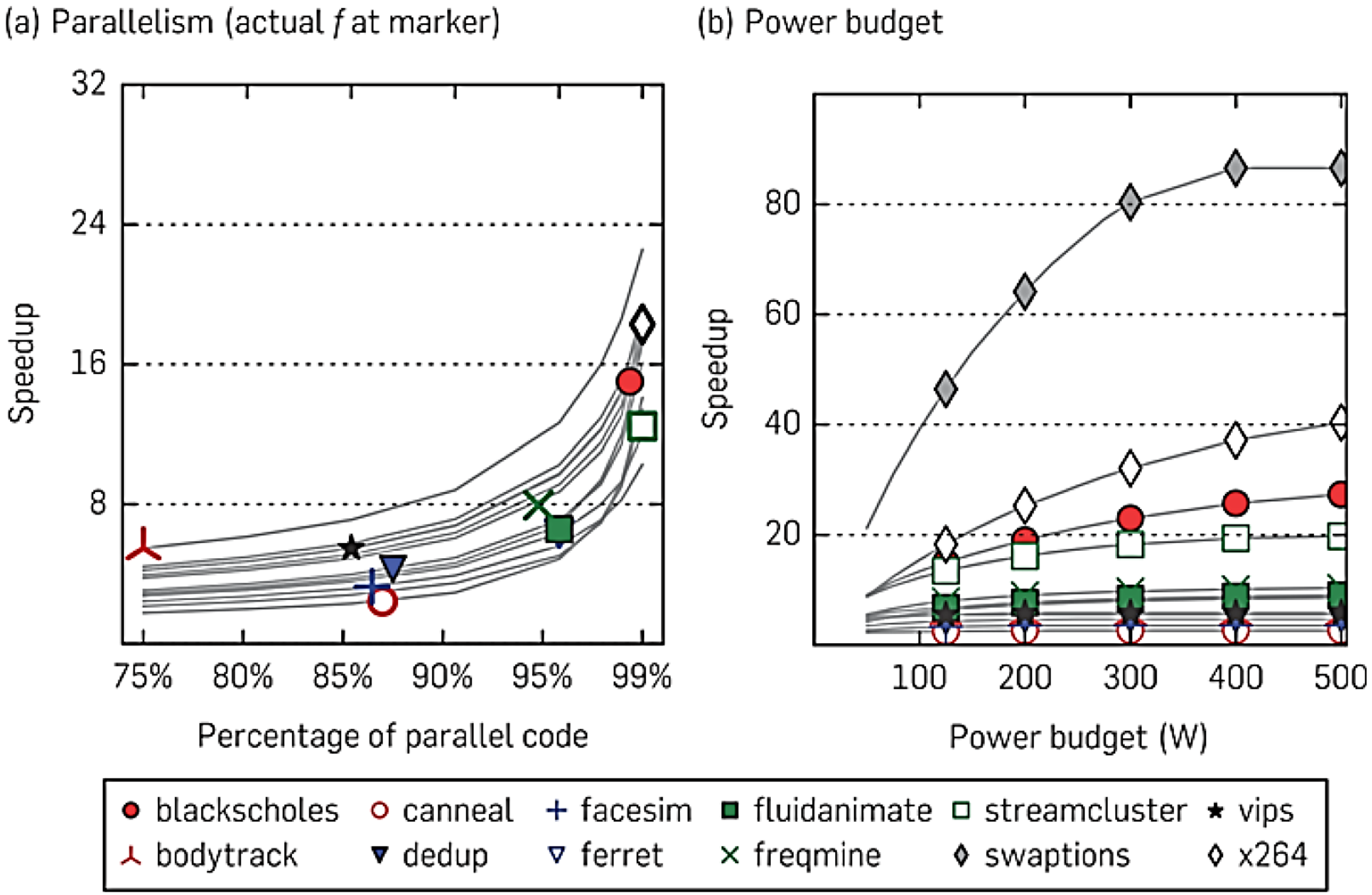
Interconnect delay becomes the major challenge [El-Moursy2005].



To keep up with demands on computational power, we need to:

- Increase parallelism.
- Provide an efficient and low-power interconnect infrastructure to achieve better scalability, bandwidth, and reliability.

Design Challenges of Manycore systems



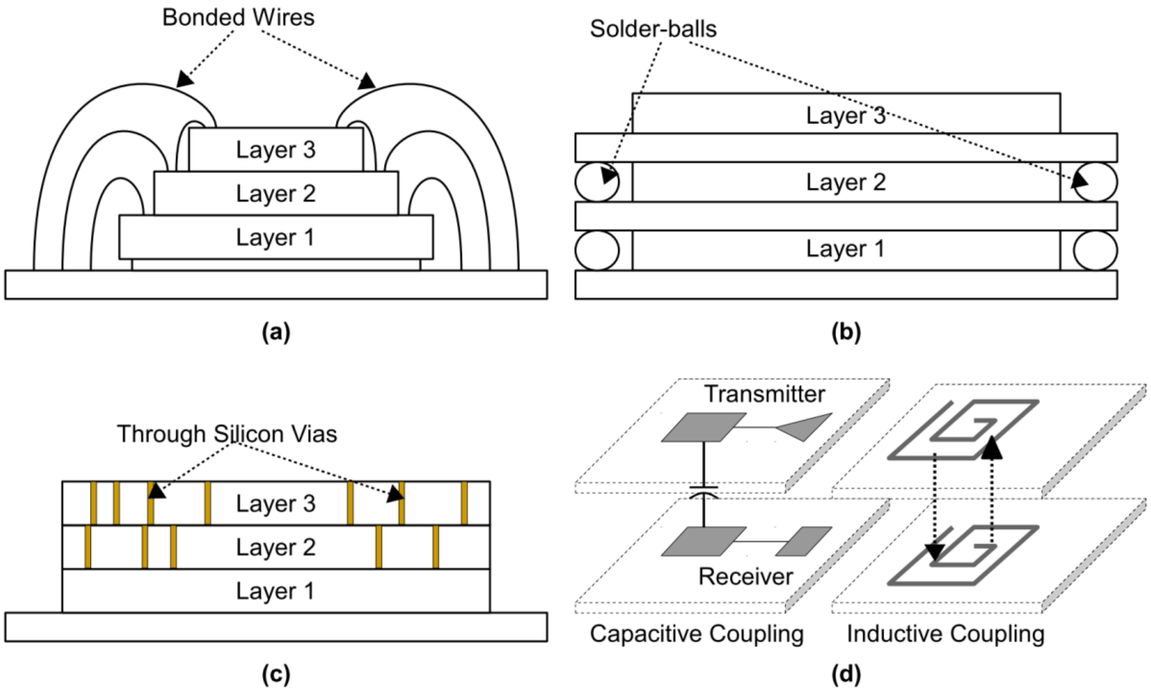
Challenge on parallelism and power budget on application speedup at 8nm [Esmaeilzadeh2013].

Emerging Interconnect Paradigms

- **RF/Wireless**: Replacing on-chip wires by integrated on-chip antennas to communicate with electromagnetic waves, in free space or guided medium.
- **Carbone Nanotube**: Using of carbon-based interconnect to replace the Cu/low-k technology.
- **Photonic**: Using photon instead of electron to transfer data.
- **Network-on-Chips**: Electronic networks were designed on a chip to allow parallel data transmission.
- **3D Integration**: Stacking multiple layers to obtain smaller footprints and shorter intra-layers interconnects.

Achraf Ben Ahmed, Tsutomu Yoshinaga, Abderazek Ben Abdallah, "Scalable Photonic Networks-on-Chip Architecture Based on a Novel Wavelength-Shifting Mechanism", ***IEEE Transactions on Emerging Topics in Computing***, 2017 (in press). DOI: 10.1109/TETC.2017.2737016

3D Integration Technology

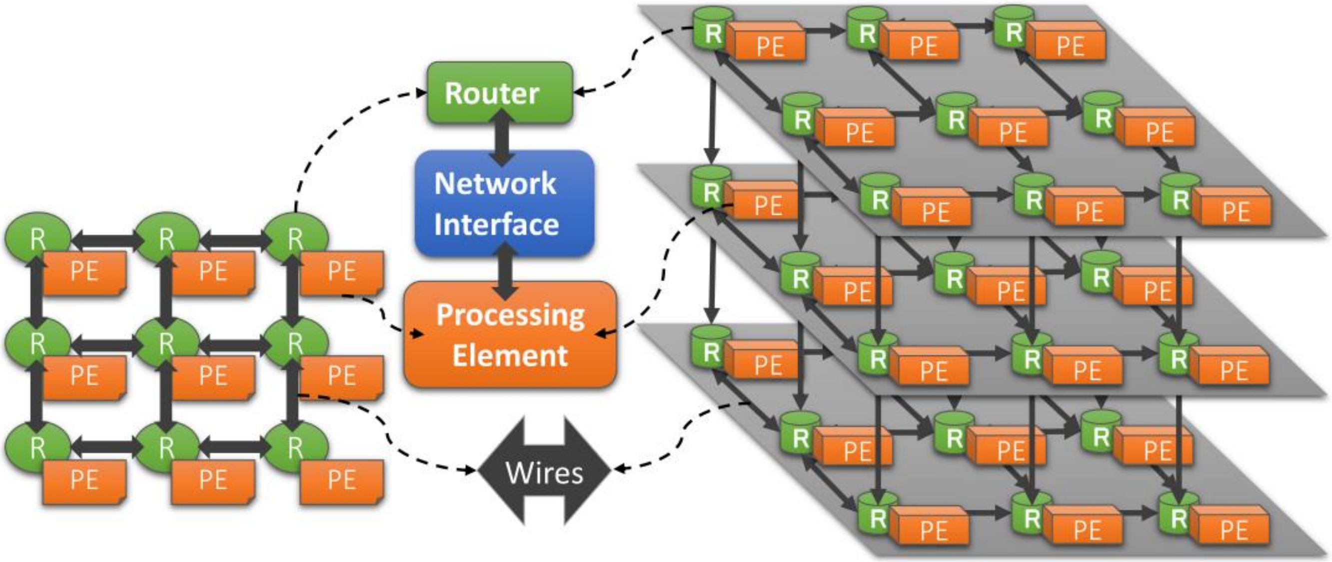


3D Integration technologies: (a) Wire bonding; (b) Solder balls; (c) Through Silicon Vias (TSVs); (d) Wireless stacking.

# of input bits	Kogge-Stone Adder		Log shifter 16		Log shifter 32	
	16-bits				32-bits	
	Delay	Power	Delay	Power	Delay	Power
2 planes	-20.23%	-8%	-13.4%	-6.5%	-28.4%	-8%
3 planes	-23.60%	-15%	-	-	-	-
4 planes	-32.70%	-22%	-	-	-	-

3D vs 2D Integration: Power consumption and Performance [Vaidyanathan2007].

Network-on-Chip



2D Mesh Network-on-Chip

3D Mesh Network-on-Chip

- Processing Elements are attached to routers via Network Interfaces.
- Network is established from a set of routers in a specific form and transaction protocols.
- Data transmissions between PEs are handled by routing inside the network.

3D Network-on-Chip (3D-NoC)

- Among the existing interconnect infrastructure (e.g. Bus, Point-to-Point), Network-on-Chip offers high parallelism, scalability, and high resource usability.
- 3D-IC integration is considered as the future of ICs and can improve the performance, reduce the footprint, decrease the power consumption, and allows multiple technologies integration.
- 3D-NoC inherits the benefits of both 2D and 3D-IC technologies.
- However, due to the vulnerability of deep sub-micron devices and the high defect rate of TSVs, 3D-NoCs are predicted to encounter the reliability challenge.

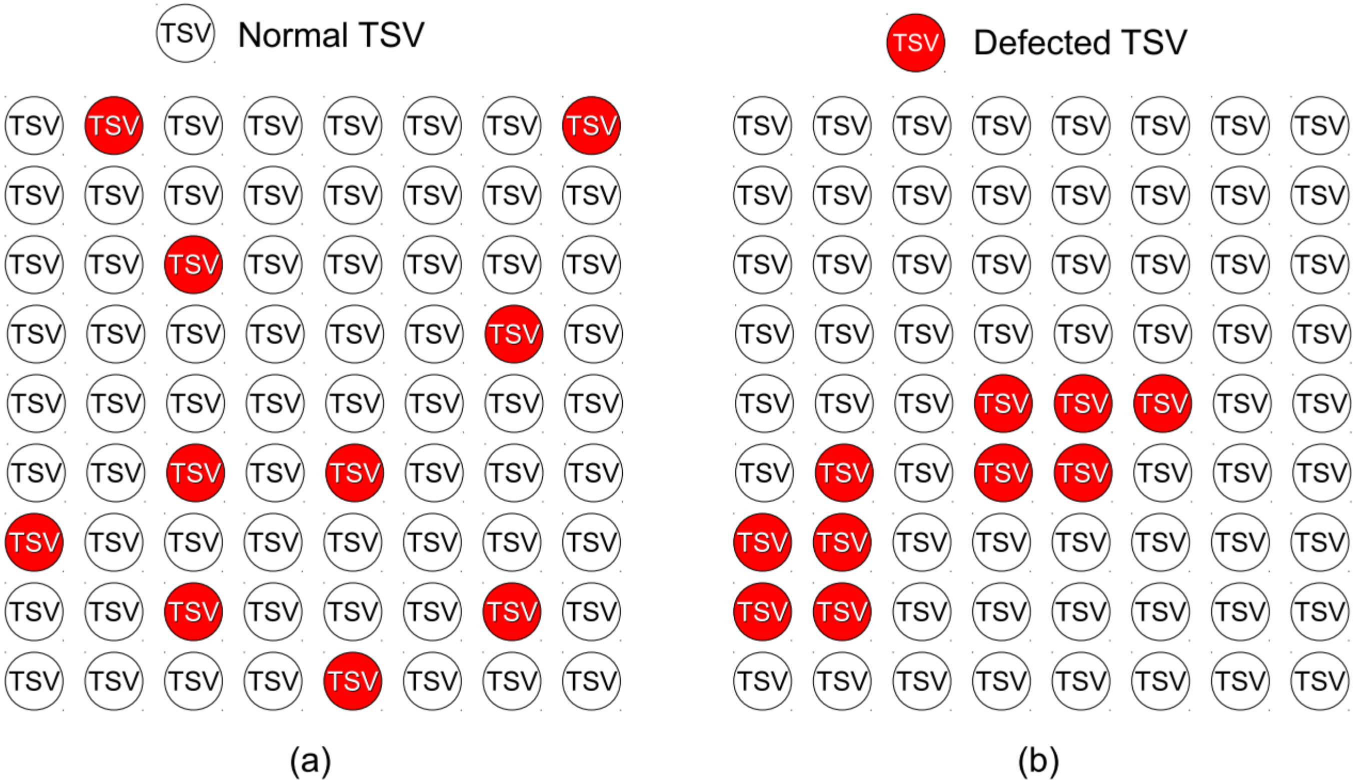
TSV Reliability Issue

- The defect rate of TSVs is considerably high which negatively impacts the overall yield.
- In addition, due to the nature difficulties on thermal removal and the stress issue, 3D-ICs may be corrupted during operation.

Work	**TSV Pitch**	**Defect Rate**	**Number of TSV**	**Yield w/o Spare**
IBM’05	0.4μm	1.39×10^{-6}	1K-10K	95%-98%
IMEC’06	10μm	40.0×10^{-6}	10K	67%
HRI’07	-	9.75×10^{-6}	100K	68%
HRI’09	-	7.95×10^{-6}	100K	≥90%
SAMSUNG’09	-	0.63%	300	15%

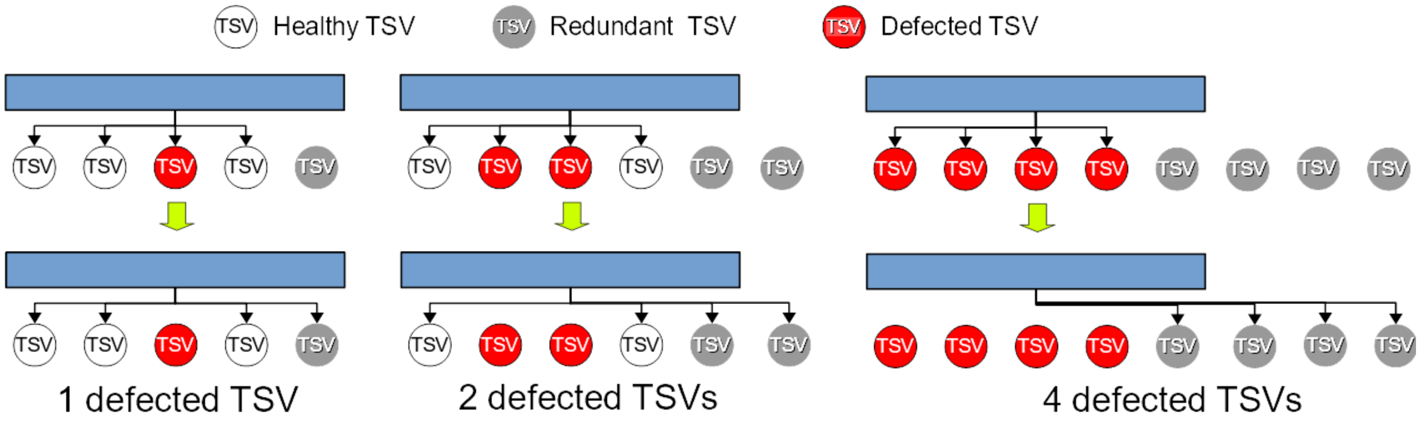
Several implementation TSV with the defect rate and the impact on yield rate [Jiang2013].

TSV Defect Distributions



Two major TSV defect distribution: (a) Random defect; (b) Cluster defect [Zhao2011, Jiang2013].

TSV Fault Recovery with Redundancy



Using redundancy to recover the TSV defect.

- Using redundancies with any configuration encounter major problems:
  - ✓The number of redundancies has to be larger than defected TSV. Because it cannot be changed after fabrication, designers need to carefully investigate the defect rate [Zhao2011, Jiang2013].
  - ✓With the cluster defect, defect groups demand a lot of redundancies while the other may not need any redundancy.
- On the other hand, 3D-NoCs is observed to not always fully utilize its vertical links (TSV-based connections) [Hwang2011].

This Work Contribution

- This paper presents a highly scalable and low-overhead TSV management supported by an adaptive TSV recovery algorithm for 3D-NoC systems.

- We aim to maintain a graceful performance for 3DNoCs without the need for redundant links or employing routing algorithms

- This is different from existing techniques which rely on correcting the TSV defects by using redundancy or employing routing algorithms → costly area and power consumption penalties.

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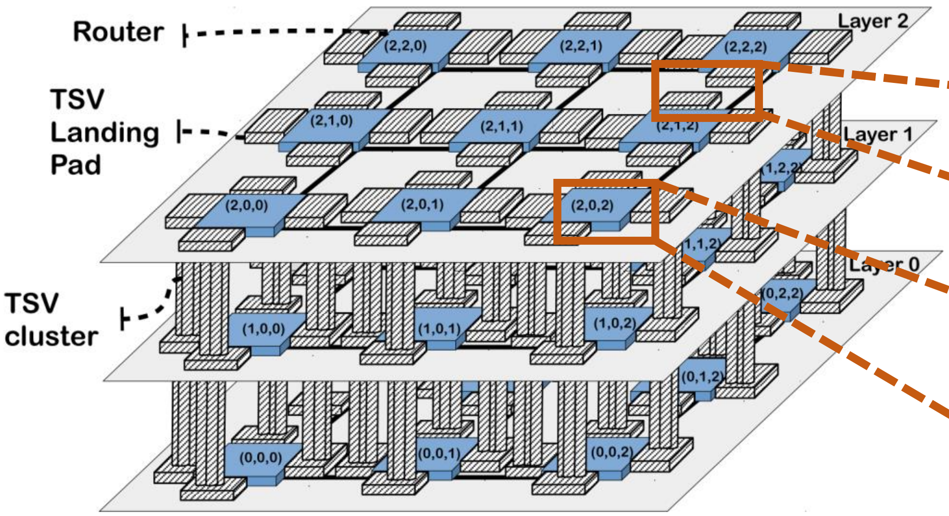
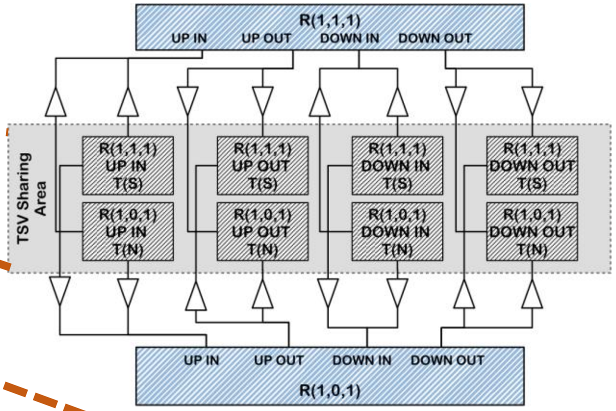
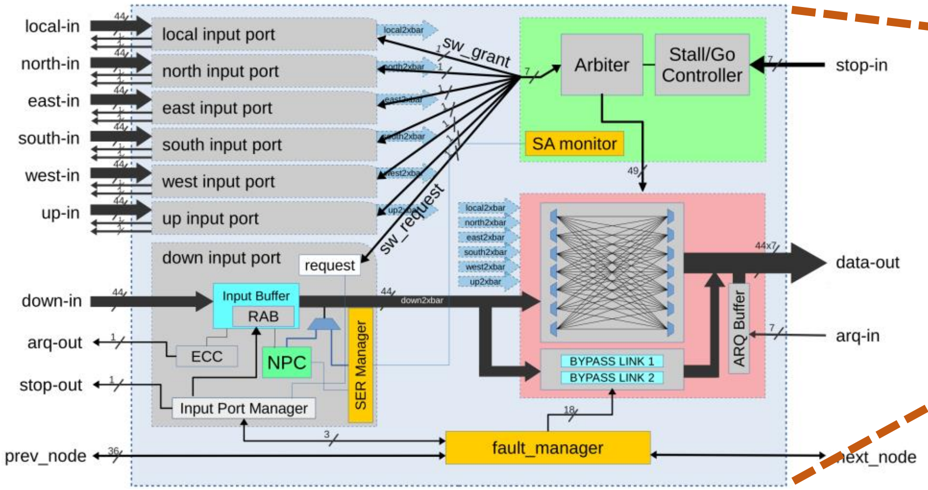
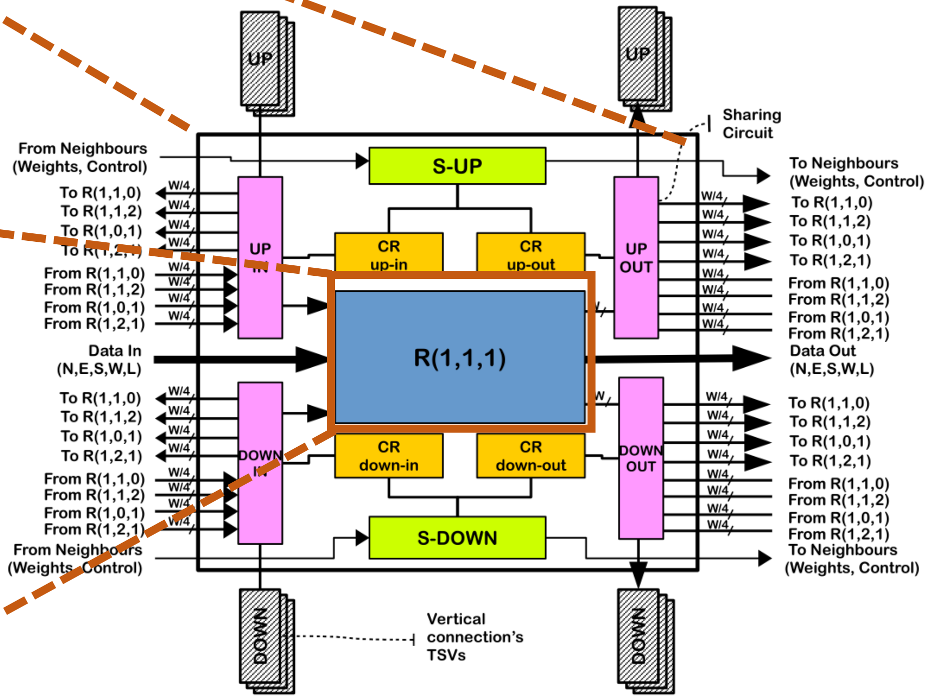
TSV-cluster Defects Recovery Mechanism









A 3D-NoC router architecture

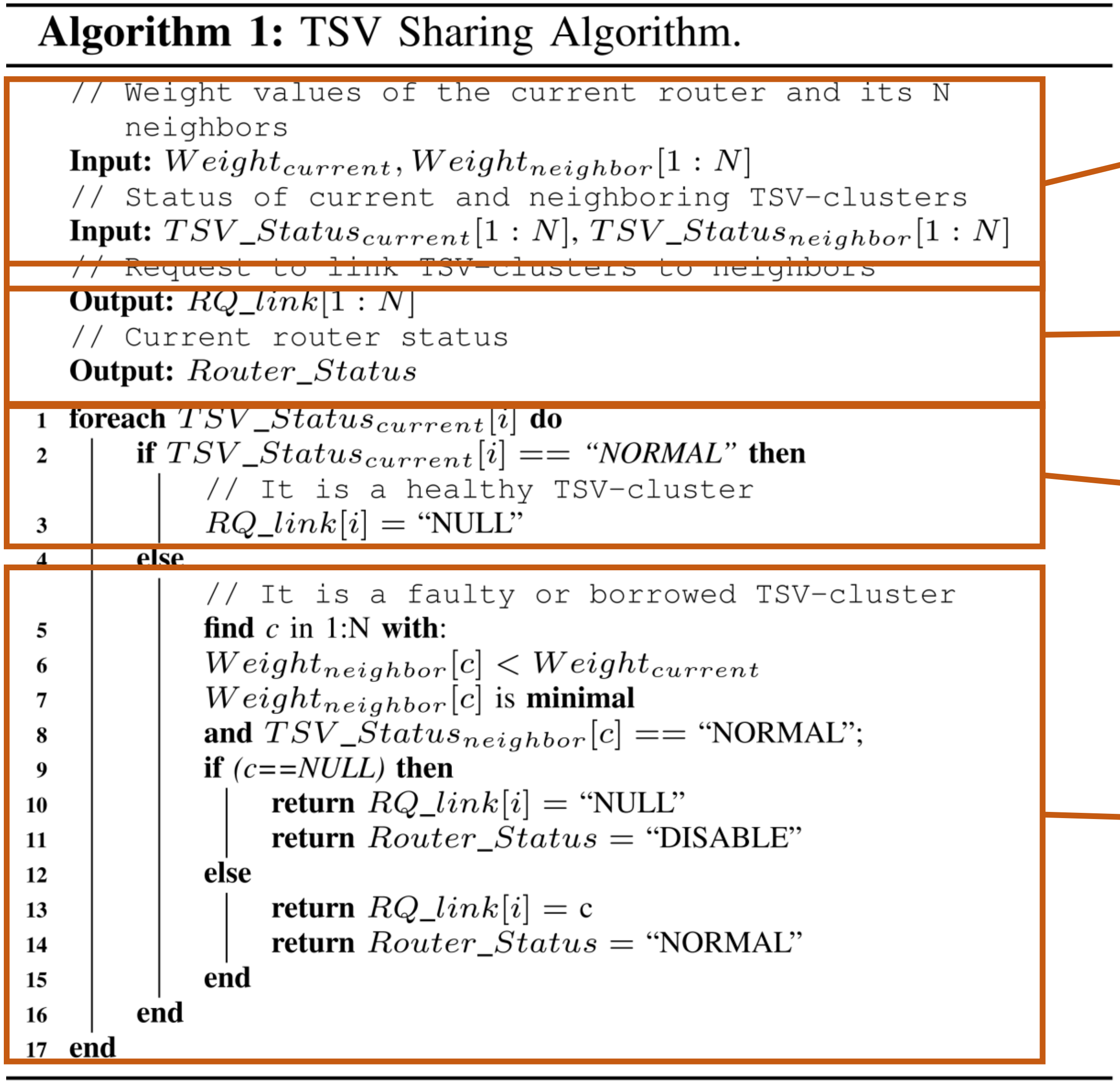
Wrapped router architecture

Khanh N. Dang, Akram Ben Ahmed, Yuichi Okuyama, and Abderazek Ben Abdallah, "Scalable Design Methodology and Online Algorithm for TSV-cluster Defects Recovery in Highly Reliable 3D-NoC Systems", ***IEEE Transactions on Emerging Topics in Computing***, 2017 (in press). DOI: 10.1109/TETC.2017.2762407

TSV-cluster Defects Recovery Mechanism

- Instead of grouping TSVs of a router in a same region, we divide them in four clusters.
- Inside a layer, a router has ability to access its own 4 clusters, and its 4 neighboring clusters (North, East, South, West).
  - The accessibility is controlled by arbiter using tristate gates.
  - Router having defected clusters tries to borrow neighboring clusters.
- Every router has a weight:
  - Higher weight router can borrow lower weight router.
  - Weight values are decided based on traffic or importance of the vertical connection.
- There is no redundant TSV → reduce the area cost.
- An extended version of this work can be found in [Dang2017].

TSV Sharing Algorithm



Algorithm 1: TSV Sharing Algorithm.

```
// Weight values of the current router and its N neighbors
Input: $Weight_{current}, Weight_{neighbor}[1:N]$
// Status of current and neighboring TSV-clusters
Input: $TSV\_Status_{current}[1:N], TSV\_Status_{neighbor}[1:N]$
// Request to link TSV-clusters to neighbors
Output: $RQ\_link[1:N]$
// Current router status
Output: $Router\_Status$
foreach $TSV\_Status_{current}[i]$ do
    if $TSV\_Status_{current}[i]$ == "NORMAL" then
        // It is a healthy TSV-cluster
        $RQ\_link[i]$ = "NULL"
    else
        // It is a faulty or borrowed TSV-cluster
        find $c$ in 1:N with:
        $Weight_{neighbor}[c] < Weight_{current}$
        $Weight_{neighbor}[c]$ is minimal
        and $TSV\_Status_{neighbor}[c]$ == "NORMAL";
        if ($c$==NULL) then
            return $RQ\_link[i]$ = "NULL"
            return $Router\_Status$ = "DISABLE"
        else
            return $RQ\_link[i]$ = c
            return $Router\_Status$ = "NORMAL"
        end
    end
end
```

Inputs of the algorithm are the weight of routers and the status of TSV cluster

Output of the algorithm are the request signal and the status of router

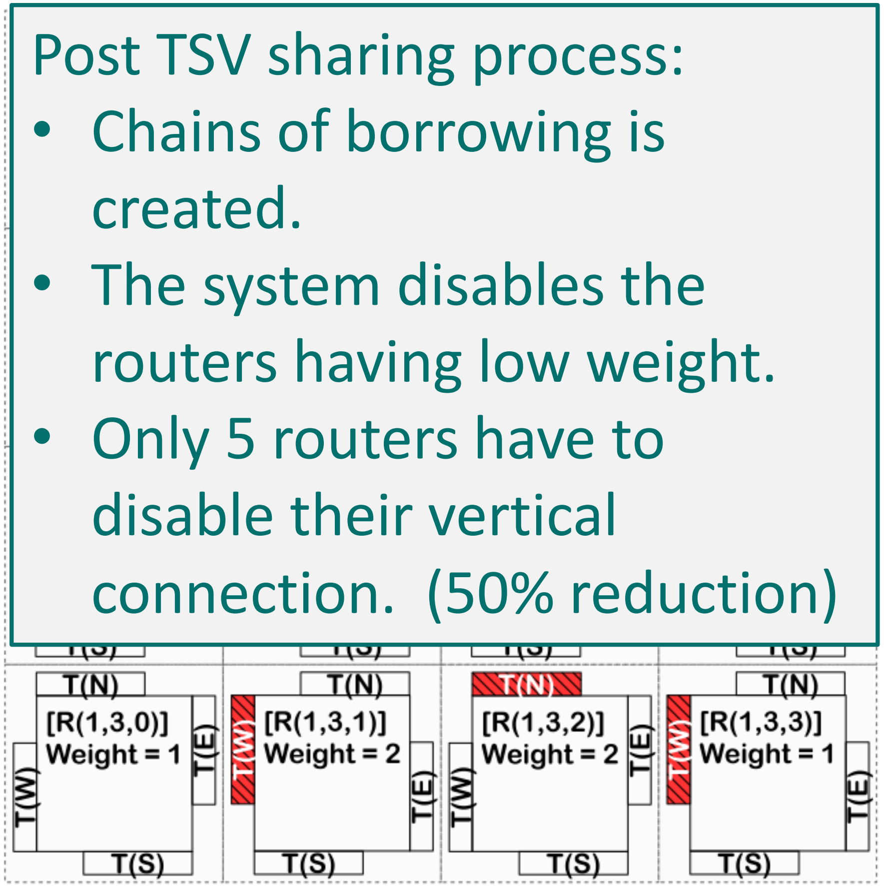
If all TSV clusters is healthy, do nothing

If there is defected/borrowed cluster, find the healthy candidate with the lowest weight.
If there is an candidate, send the request. Otherwise, the vertical connection is disabled.

Example of TSV sharing

Post TSV sharing process:

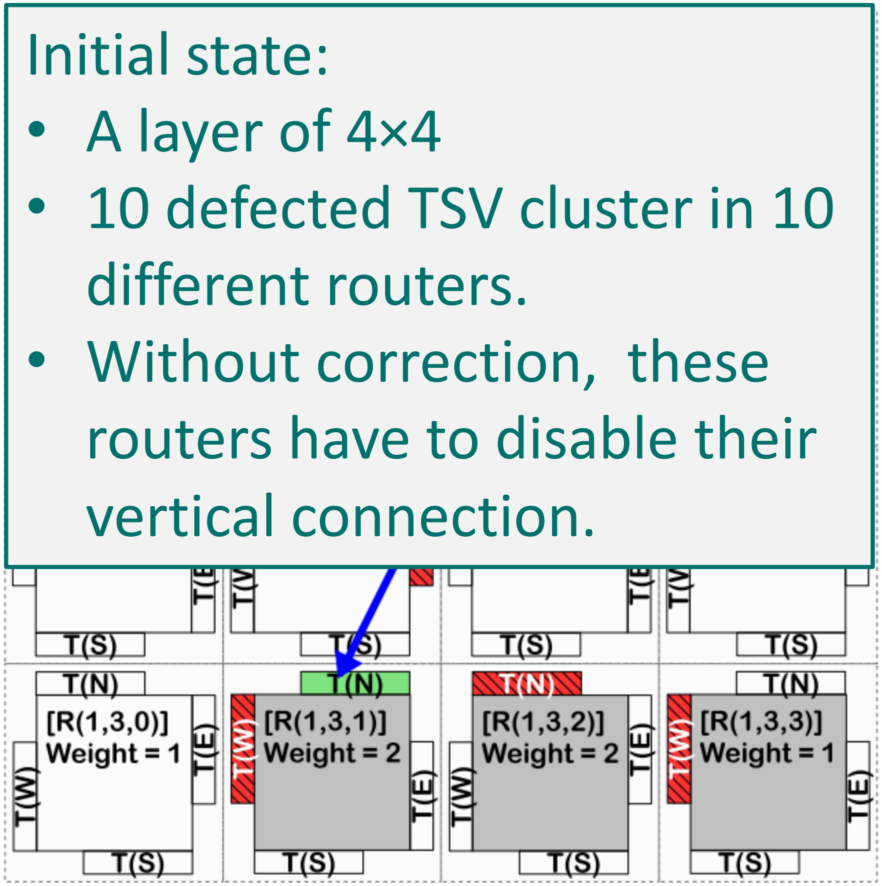
- Chains of borrowing is created.
- The system disables the routers having low weight.
- Only 5 routers have to disable their vertical connection. (50% reduction)



Initial state

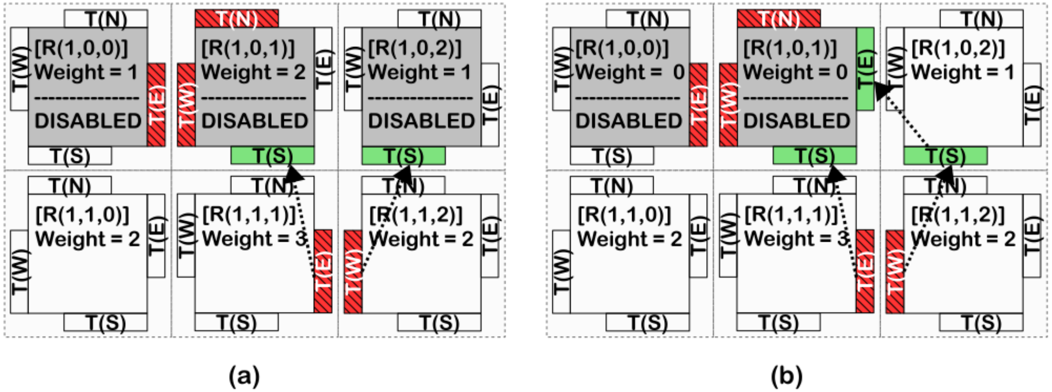
Initial state:

- A layer of 4×4
- 10 defected TSV cluster in 10 different routers.
- Without correction, these routers have to disable their vertical connection.



After the sharing algorithm

Optimizing the TSV Sharing: Weight adjustment



Weight adjustment: (a) before; (b) after.

- **Weight adjustment**: reduce the weight of disabled routers to help lower weight router be able to borrow clusters.
- **Serialization:** because no redundancy is used, there some router having less than 4 clusters.
  - To maintain the connectivity, we use Serialization (2:1 or 4:1).
- **Fault-tolerant routing:** if a router has no available TSV cluster, the packet to the corresponding connection is re-routed by using a fault-tolerant routing algorithm.

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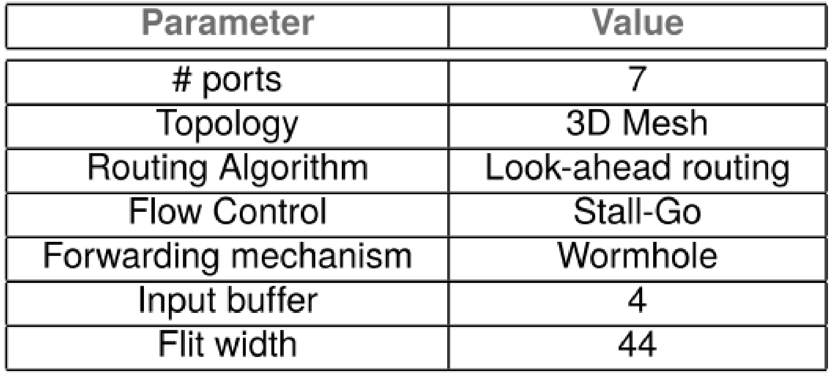
Evaluation Methodology

Platform:

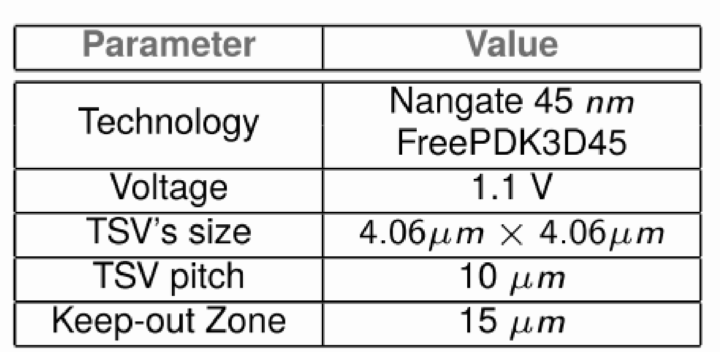
- Verilog HDL
- Synopsys Design Compiler
- Cadence Innovus

Evaluation:

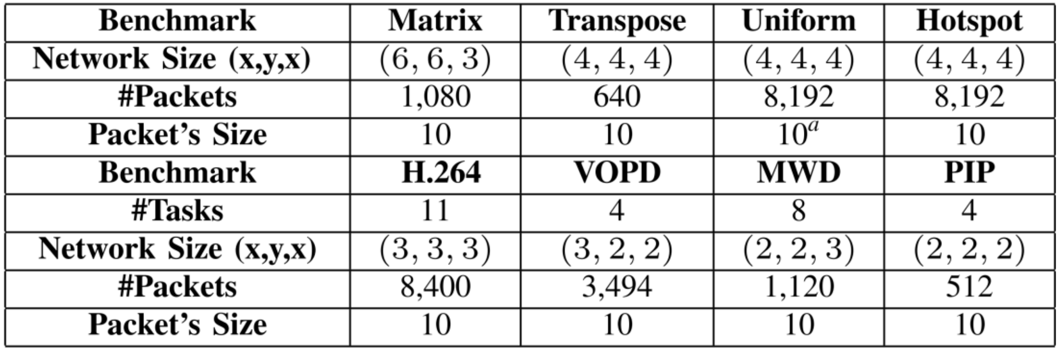
- Reliability
- Performance (latency, throughput



Parameter	Value
# ports	7
Topology	3D Mesh
Routing Algorithm	Look-ahead routing
Flow Control	Stall-Go
Forwarding mechanism	Wormhole
Input buffer	4
Flit width	44

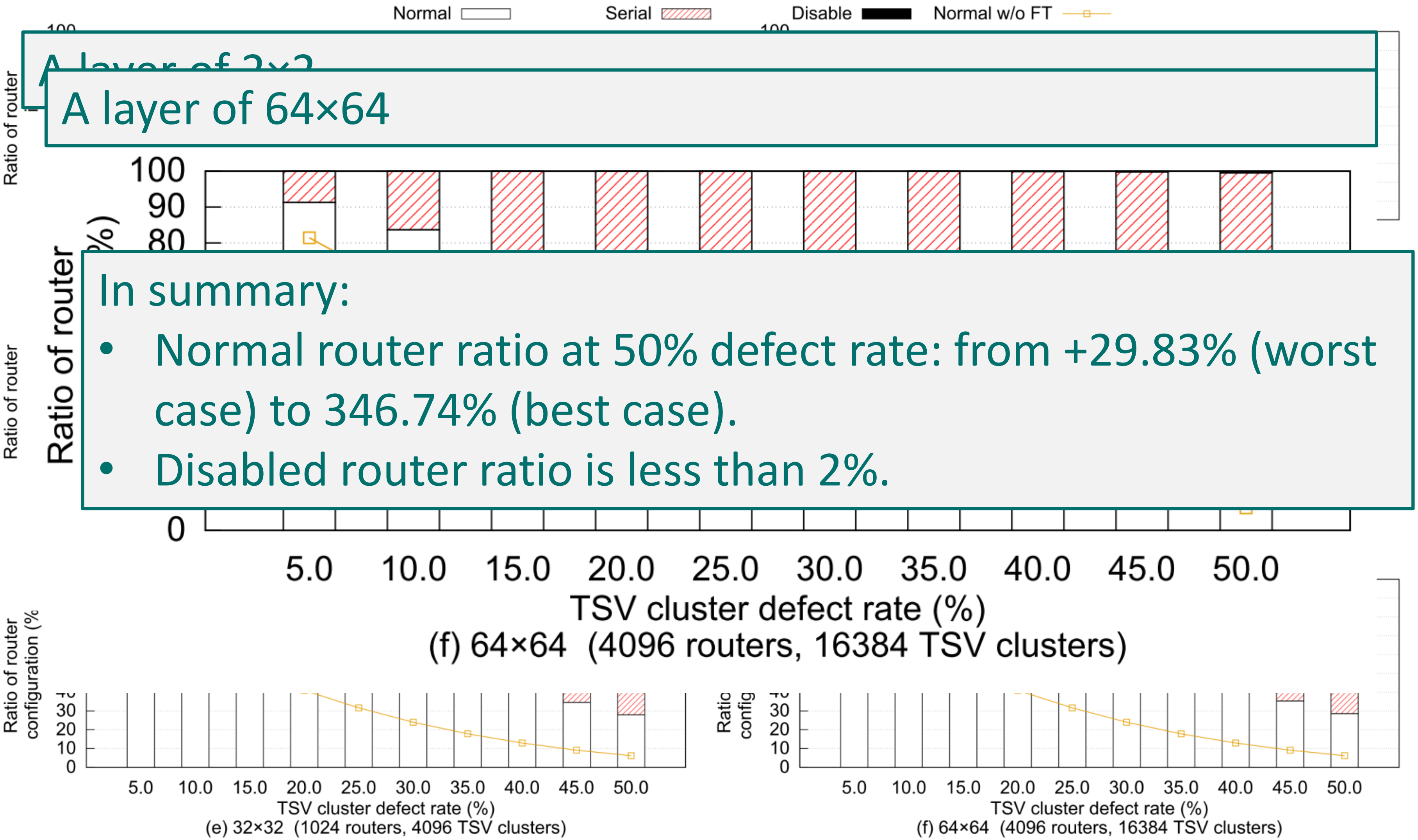


Parameter	Value
Technology	Nangate 45 *nm* FreePDK3D45
Voltage	1.1 V
TSV's size	$4.06\mu m \times 4.06\mu m$
TSV pitch	10 μm
Keep-out Zone	15 μm



Benchmark	**Matrix**	**Transpose**	**Uniform**	**Hotspot**
Network Size (x,y,x)	$(6, 6, 3)$	$(4, 4, 4)$	$(4, 4, 4)$	$(4, 4, 4)$
#Packets	1,080	640	8,192	8,192
Packet's Size	10	10	10^a	10
Benchmark	**H.264**	**VOPD**	**MWD**	**PIP**
#Tasks	11	4	8	4
Network Size (x,y,x)	$(3, 3, 3)$	$(3, 2, 2)$	$(2, 2, 3)$	$(2, 2, 2)$
#Packets	8,400	3,494	1,120	512
Packet's Size	10	10	10	10

Reliability Evaluation



A layer of 2×2

A layer of 64×64

(f) 64×64 (4096 routers, 16384 TSV clusters)

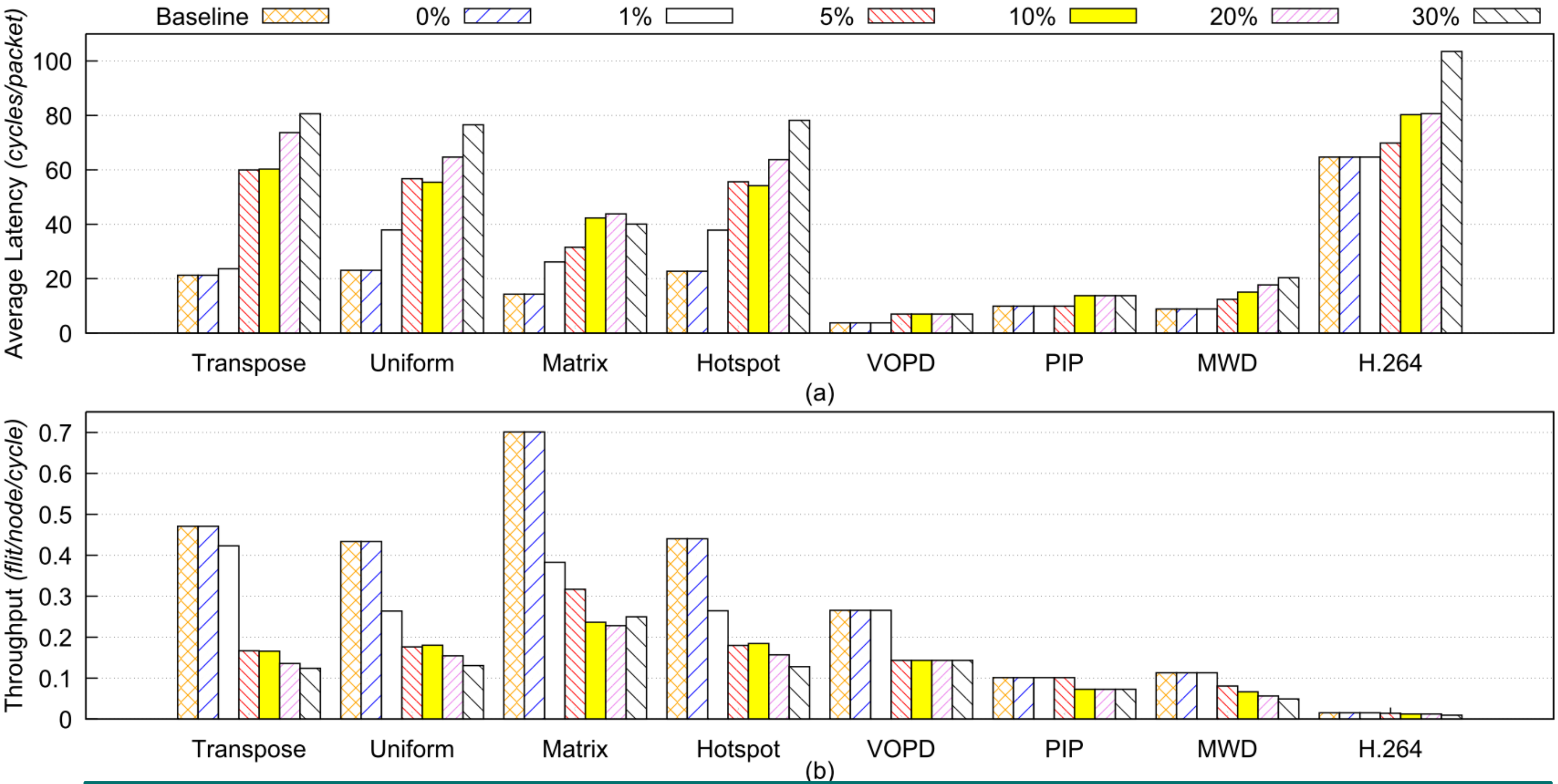
(e) 32×32 (1024 routers, 4096 TSV clusters)

(f) 64×64 (4096 routers, 16384 TSV clusters)

In summary:

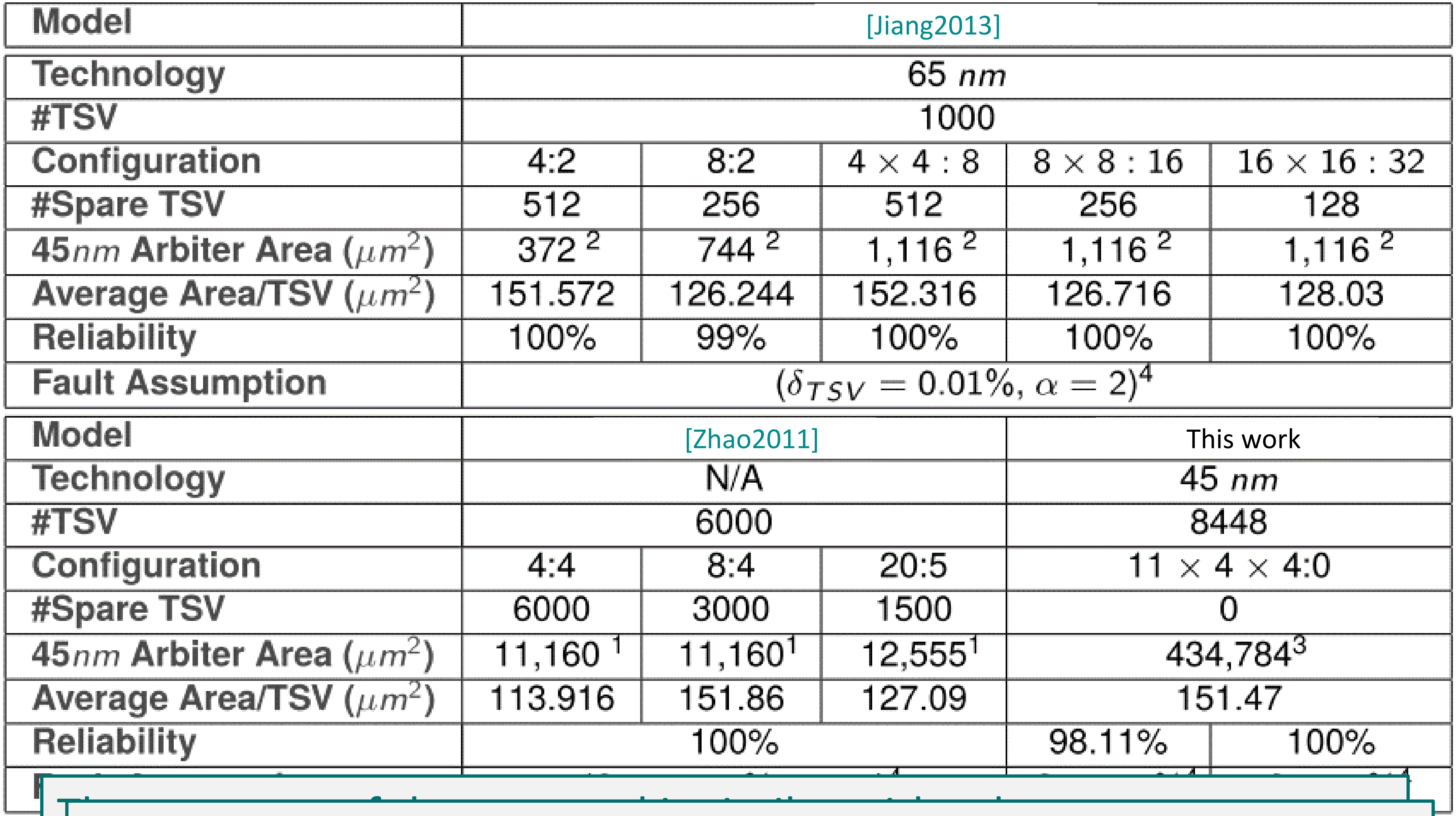
- Normal router ratio at 50% defect rate: from +29.83% (worst case) to 346.74% (best case).
- Disabled router ratio is less than 2%.

Performance Evaluation



In the synthetic benchmarks, the impact is still high, however, the system still be able to work under very high defect rate.

Comparison

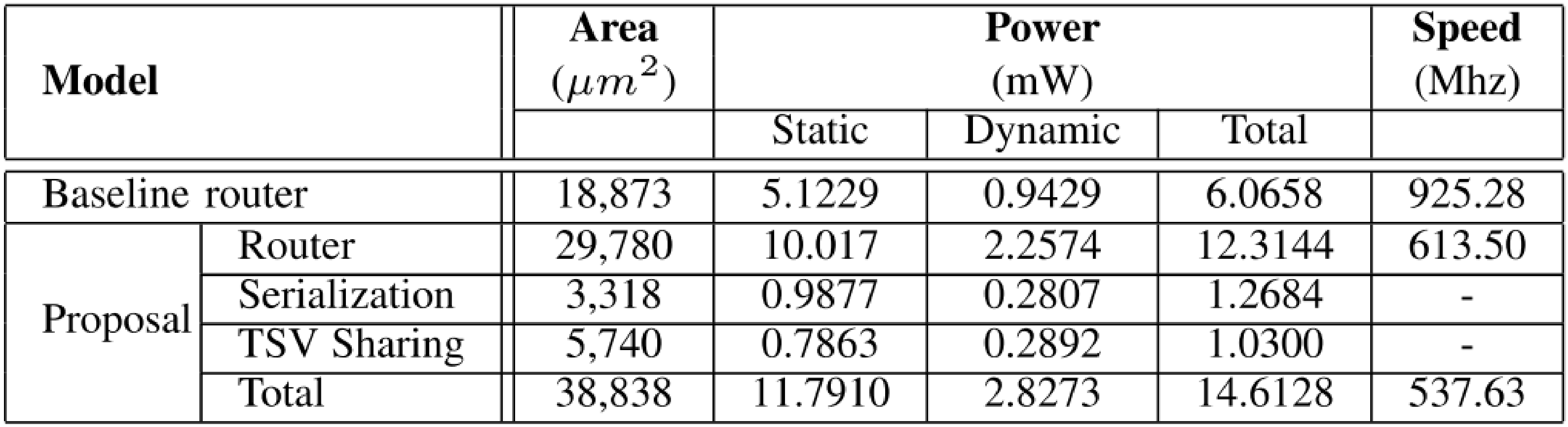


Model	[Jiang2013]				
Technology	65 nm				
#TSV	1000				
Configuration	4:2	8:2	$4 \times 4:8$	$8 \times 8:16$	$16 \times 16:32$
#Spare TSV	512	256	512	256	128
45nm Arbiter Area (μm^2)	372 [2]	744 [2]	1,116 [2]	1,116 [2]	1,116 [2]
Average Area/TSV (μm^2)	151.572	126.244	152.316	126.716	128.03
Reliability	100%	99%	100%	100%	100%
Fault Assumption	$(\delta_{TSV} = 0.01\%, \alpha = 2)^4$				

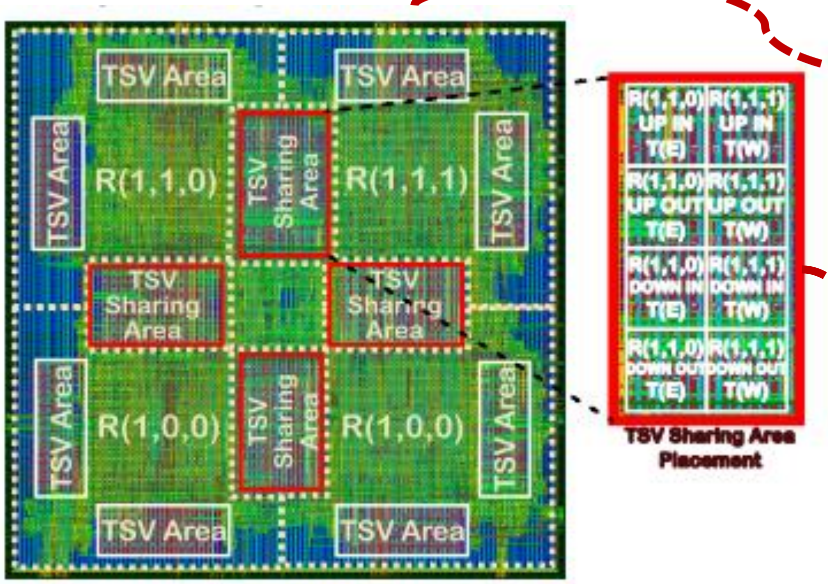
Model	[Zhao2011]			This work	
Technology	N/A			45 nm	
#TSV	6000			8448	
Configuration	4:4	8:4	20:5	$11 \times 4 \times 4:0$	
#Spare TSV	6000	3000	1500	0	
45nm Arbiter Area (μm^2)	11,160 [1]	11,160[1]	12,555[1]	434,784[3]	
Average Area/TSV (μm^2)	113.916	151.86	127.09	151.47	
Reliability	100%			98.11%	100%

Working router rate is extremely high: 98.11% even with 50% of defect rate.

Hardware Design



Model		Area (μm^2)	Power (mW) Static	Dynamic	Total	Speed (Mhz)
Baseline router		18,873	5.1229	0.9429	6.0658	925.28
Proposal	Router	29,780	10.017	2.2574	12.3144	613.50
	Serialization	3,318	0.9877	0.2807	1.2684	-
	TSV Sharing	5,740	0.7863	0.2892	1.0300	-
	Total	38,838	11.7910	2.8273	14.6128	537.63



Single layer layout illustrating the TSV sharing areas (red boxes). The layout size is **865µm × 865µm.**

The sharing TSV area are the red boxes. Each sharing area has 8 clusters for 4 ports and 2 routers.

Khanh N. Dang, Akram Ben Ahmed, Xuan-Tu Tran, Yuichi Okuyama, Abderazek Ben Abdallah, "A Comprehensive Reliability Assessment of Fault-Resilient Network-on-Chip Using Analytical Model", ***IEEE Transactions on Very Large Scale Integration (VLSI) Systems***, Vol. 25, Issue: 11, pp. 3099 – 3112, Nov. 2017. DOI:10.1109/TVLSI.2017.2736004

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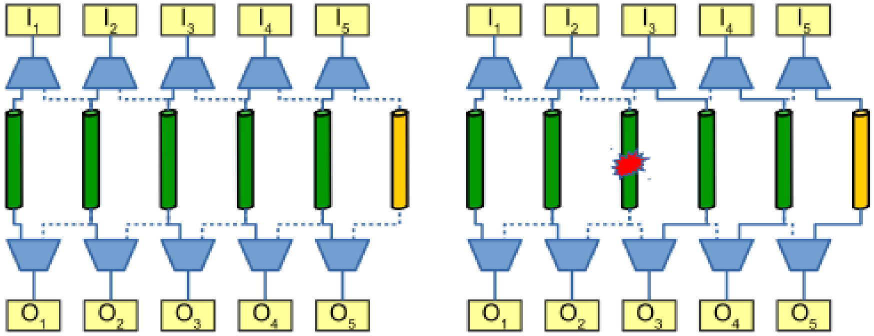
Conclusion

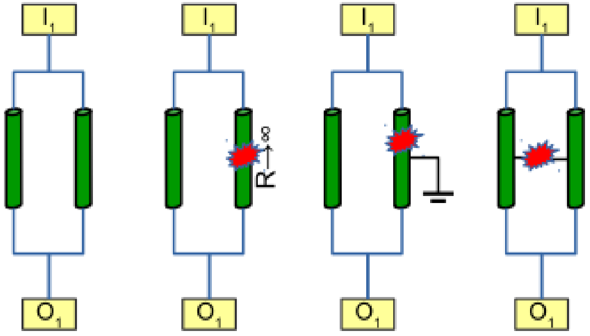
- This paper presented an adaptive and scalable sharing methodology for TSVs in 3D-NoC systems to deal with the TSV-cluster defects.
- The system shows the high reliability that:
  - reach up to 346.74% increase in fully functional routers,
  - less than 2% of router having disabled vertical connection.
- The proposed approach can correctly work with a reasonable degradation in terms of performance even at a 30% of fault-rate.
- Since no TSV redundancy is required, the proposal provides a highly reliability while maintaining an reasonable overhead.

Backup Slides

TSV Random Defect Recovery



Redundancy and Shifting Technology



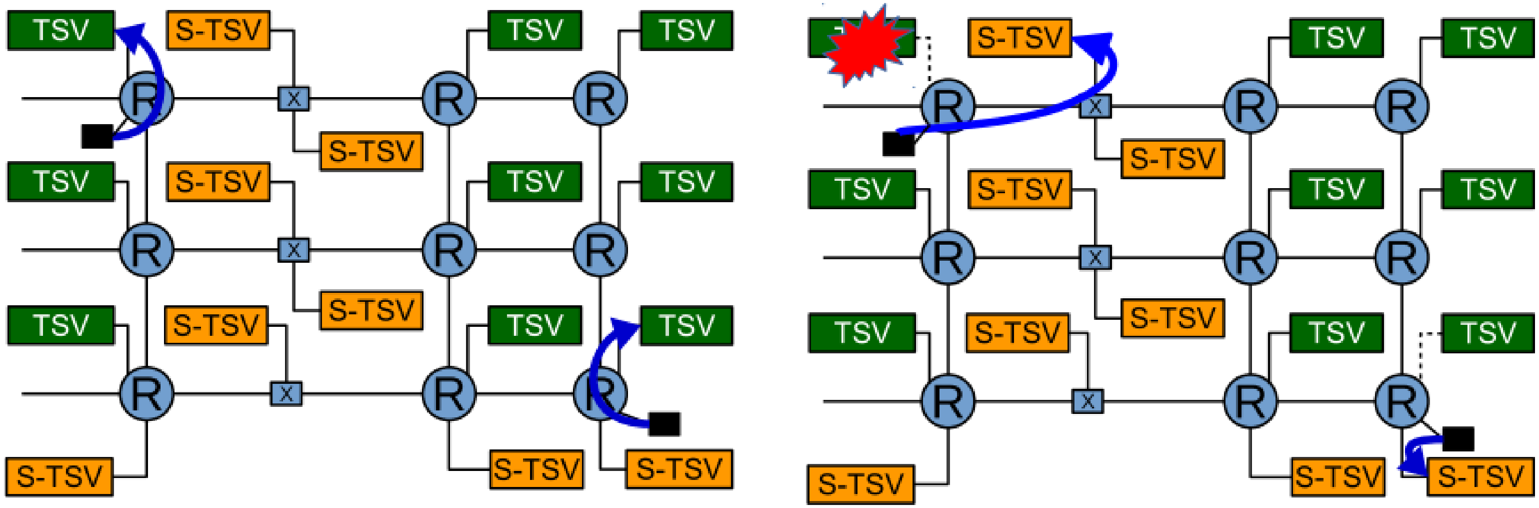
Healthy

Open defect

Stuck-at defect

Bridge defect

Double TSV



Normal case

TSV defect correction

Network-TSV with redundancies