Doctoral Dissertation Final Review

Development of On-Chip Communication Fault-Resilient Adaptive Architectures and Algorithms for 3D-IC Technologies

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Era of Multi/Many-core processing

Constant increase of the number of cores → *multi/many-core processing*.

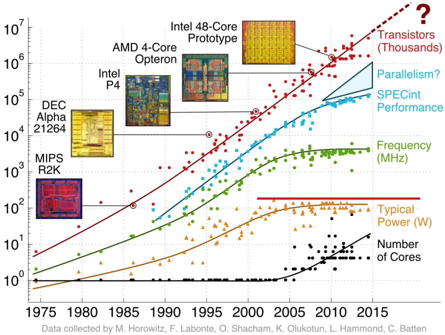


Figure 1: Integrated Circuit Scaling [1].

Interconnect delay becomes the major challenge.

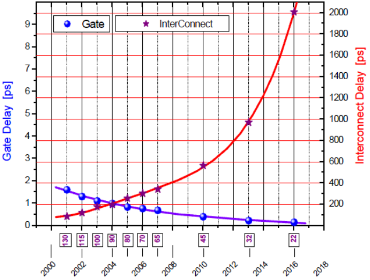


Figure 2: Gate and interconnect delay overtime [2].

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 Multi/Many-core systems

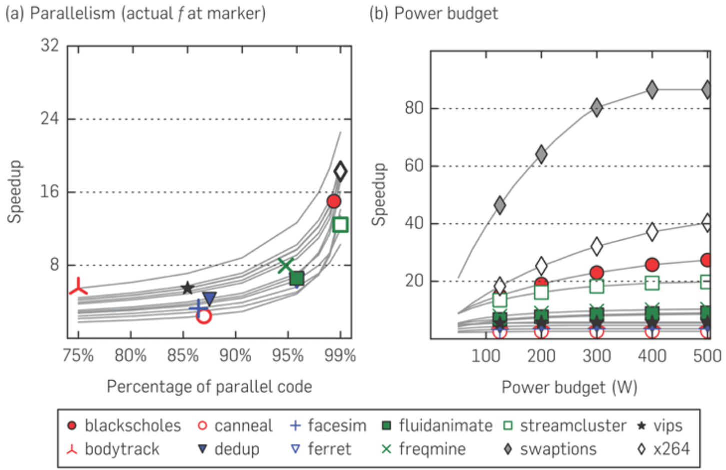


Figure 3: Challenge on *parallelism* and *power budget* on application speedup at 8nm [3].

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.

3D Integration Technology

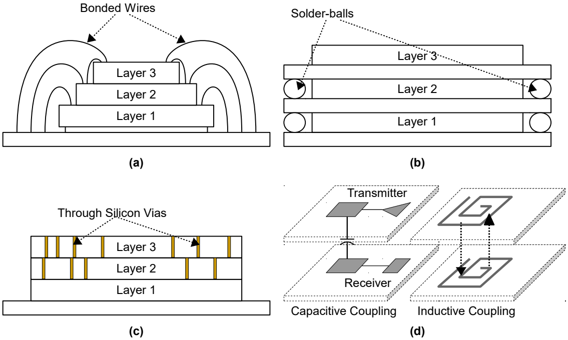


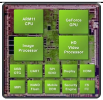
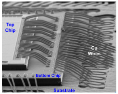
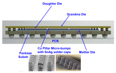
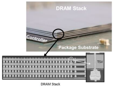
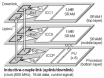
Figure 4: 3D Integration technologies: (a) Wire bonding; (b) Solder balls; (c) Through Silicon Vias (TSVs); (d) Wireless stacking.

Table 1: Performance and power: 3D vs 2D architecture [4].

# 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%	-	-	-	-

Comparison of 3D technologies

Table 2: 3D and 2D Technologies comparison.

Technology	2D SoC	Wire bonding	Solder balls	TSVs	Wireless stacking
					
Integration Capacity	low	high	high	very high	very high
Bandwidth	high	high	medium	very high	very low
Interconnect density	medium	low	low	very high	high
Yield	medium	medium	medium	considerable	N/A
Cost	very low	high	low	very high	N/A
Power Consumption	medium	low	low	very low	N/A

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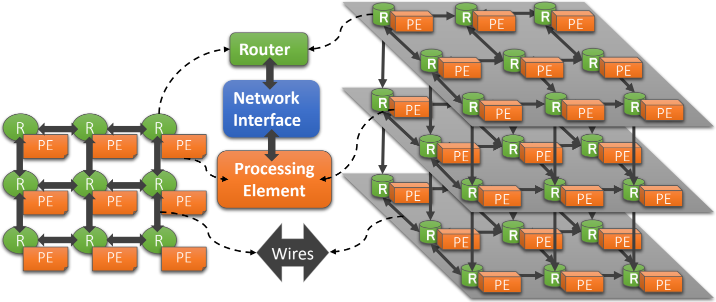
On-Chip Communication Network



2D Mesh Network-on-Chip

3D Mesh Network-on-Chip

Network-on-Chips is an on-chip communication infrastructure:

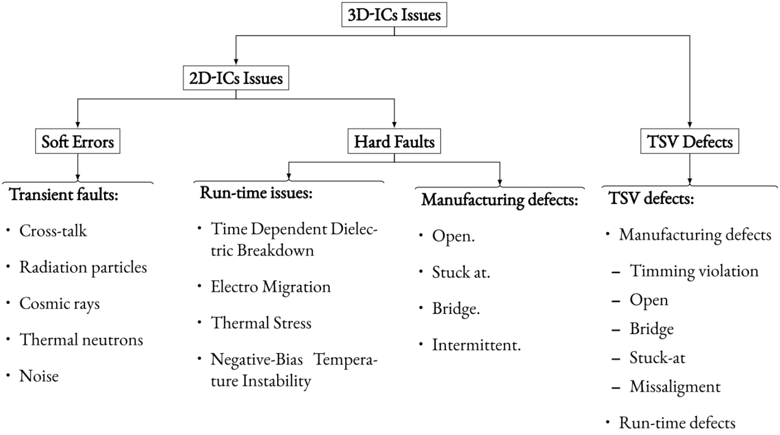
- *Processing Elements* (PEs) are attached to *routers* via *Network Interfaces* (NIs).
- *Network* is established from a set of *routers* in a specific form (topology, size, flit-width) and transaction protocols (node to node, end to end).
- Data (message/packet/flit) transmissions between PEs are handled by *routing* inside the network.

3D Network-on-Chip

- Among the existed interconnect infrastructure (e.g. Bus, Point-to-Point), **Network-on-Chips** have offered benefits on *parallelism*, *scalability* and *resource usability*.
- **3D integration** is considered as the future of ICs that can improve the *performance*, reduce the *footprint*, decrease the *power consumption*, and offer *multiple technologies integration*.
- By using **Network-on-Chips** on *3D integration*[1], we obtain *3D-Network-on-Chips* (3D-NoCs) that inherits the benefits from the both technologies.
- Recently, NoCs are widely used for multi/many core processing. Therefor, **3D-NoCs** will be the future paradigm of multi/many core processing 3D-ICs.
- *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**.

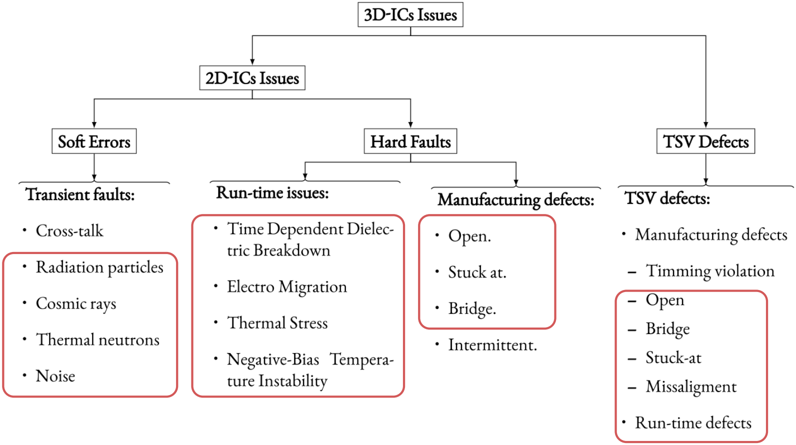
[1] TSVs handle the vertical wires between routers.

Fault/Error Types of 3D-ICs/3D-NoCs



Beside the benefits, TSV-based 3D-ICs also have challenges on reliability. Especially, the *high defect rates* of TSVs are problematic. *Thermal removal difficulty* and *stress issues* also accelerate the fault rates.

Fault/Error Types of 3D-ICs/3D-NoCs



Beside the benefits, TSV-based 3D-ICs also have challenges on reliability. Espec

Thermal remova

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rates.

There are the fault/error types the proposed design can handle.

TSV-based Reliability Issues

- The defect rate is considerably high which also reduces the yield rate.
- Spare (redundancy) is required at the current technology.
- Hot-spots are observed in 3D-ICs which negatively impacts on the Mean Time To Failure of the system.
- The difference of thermal expansion coefficient between materials also creates stress issues.

Table 3: TSV Defect Rate Summary[7].

Work	TSV Pitch	Defect Rate	# TSV	Yield w/o Spare
IBM’05	$0.4\mu m$	13.9E-6	1k-10k	95% 98%
IMEC’06	$10\mu m$	40.0E-6	10k	67%
HRI’07	-	9.75E-6	100k	68%
HRI’09	-	7.95E-6	100k	$\geq$90%
SAMSUNG’09	-	0.63%	300	15%

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Research Motivation

1. Future TSV-based 3D-ICs need fault-tolerances in order to deal with their reliability issues.
2. As considered as the backbone of future 3D-ICs, 3D-NoCs also need fault-tolerance methods to ensure the reliability of their communications.
3. There are numerous number of fault-tolerance works on: *soft errors*, *hard faults*, and *TSV defects*; however, there is also a need of a comprehensive work that can handle all type of faults.
4. Beside *fault recovery*, *fault detection and diagnosis* are also important aspects of fault resilience. Handling faults on-line also help reduce the threat giving by the occurred faults.
5. To quickly assess the system reliability, there is a need for a fast and simple reliability assessment method.

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Goals and Contributions(1/3)

This dissertation provides a set of on-chip communication fault-resilient adaptive architectures and algorithms for 3D-NoC IC technologies. The following are the dissertation's contributions.

❶ An Efficient Reliability Assessment Model for Early Design Stages

To provide a solution that help designers assess the reliability of NoCs system in the early design stages by using mathematical model.

Goals and Contributions(2/3)

❷ A highly reliable comprehensive soft-errors and hard-faults resilient architectures, algorithms, and design methodologies

To provide a comprehensive fault-tolerance method that can handle both soft errors and hard faults. Moreover, a *detection, diagnosis and recovery* scheme is also proposed to help in on-line fault/error handling.

Goals and Contributions(3/3)

❸ A scalable cluster-TSV defect tolerance for vertical connections

Because the cluster-defect is a critical issue that cannot be efficiently dealt by using redundancies, this dissertation proposes a cluster-TSV defect tolerance for 3D-NoCs. Instead of using redundancies, a highly efficient management method is used to maintain the vertical connection. In addition, several algorithms and architectures are added to significantly enhance the reliability of the vertical connections.

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Fault-tolerance

Table 4: Taxonomy of different error recovery protocols and architectures in 3D-NoCs. Classification: A: architecture, S: software and I: integration.

Fault Type	Position/Type	Fault Tolerant Method	Approach
Soft Errors	Data Path	Automatic Re-transmission Request	S
		Error Detecting/Correcting Code	S
	Control Logic	Logic/Latch Hardening	A,I
		Pipeline Redundancy	S
		Monitoring and Correcting model	S
Hard Faults	Routing Technique	Spare wire	A
		Split transmission	A
		Fault-Tolerant routing algorithm	S
	Architecture-based Technique	Hardware Redundancy	A
		Reconfiguration architectures	A
TSV Defects	Redundancy	Shifting	A,I
		Crossbar	A,I
		Network	A,S,I
	Management	Design awareness	I
		Randomly distributed redundancy	A,I

Fault Tolerance Approaches (1/2)

1. **Architecture approach**: adding redundancies or self configuring the system to handle the task of failed module.
   - Example: failed buffer slot isolation[8], router's module triple modular redundancy [9], TSV redundancies [10, 11].
   - **Drawback**: either having high area overhead (redundancy) or degrading the performance (self-configuration).
2. **Software approach**: creating a check-point and roll-back when a fault occurs.
   - Example: pipeline stage redundancy [12].
   - **Drawback**: creating bottleneck by re-executing the failed task.

Fault Tolerance Approaches (2/2)

❸ **Integration approach**: hardening the systems by using protection or improving the reliability of backbone devices.

- Example: TSV placement awareness [13],Logic/Latch Hardening [14].
- **Drawback**: This type of approach leads to a highly complex design process.

❹ **Hybrid approach**: combining multiple approaches to handle the fault.

Reliability Assessment Method

1. **Physical-level**: calculate the reliability using physical characteristic. This method is more suitable for low complexity systems.
2. **System-level simulation**: perform simulation of completed system to find the reliability. Faults are injected to observe the reaction of the system.
3. **Analytical model**: use mathematical models to assess the reliability of the system. This method provides the quickest result.

Notable, work in [15, 16] methods have provided promising solutions for NoCs' reliability assessment; however, they lack the support for fault-tolerant, highly complex, and adaptive systems.

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Reliability Assessment Methodology (1/2)

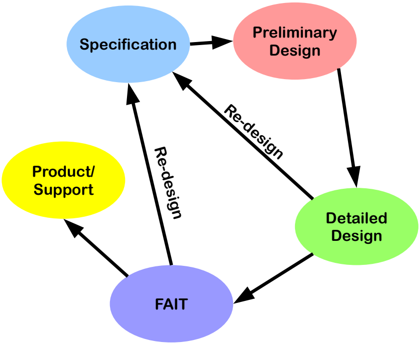


Figure 5: Stages of reliability assessment[2].

- To alleviate the risk of redesign, early assessment is essential, especially the **first three stages**.
- Reliability prediction for NoC systems is still immature.

[2]FAIT:Fabrication, Assembly, Integration and Test

Reliability Assessment Methodology (2/2)

Approach:

- A quantitative factor, which is called as **Reliability Acceleration Factor**, to represent the efficiency of the fault tolerant mechanism.
- A fault assumption to help calculate the failure rate of a system.
- An analytical model to assess the reliability of NoC systems using Markov-state model.

RAF: Reliability Acceleration Factor

RAF (Reliability Acceleration Factor), which represent the efficiency of the applied fault-tolerances, is given by the following equation:

$$\text{RAF} = \frac{\lambda_{original}}{\lambda_{FT}} = \frac{\mathbf{MTTF}_{FT}}{\mathbf{MTTF}_{original}} \geq 1 \qquad (1)$$

Where:

- λ is the fault rate and it is the inverse value of Mean Time to Failure (*MTTF*).
- $\mathbf{MTTF}_{original}$ is the MTTF of the original system.
- $\mathbf{MTTF}_{FT}$ is the MTTF of the fault-tolerant system.

RAF vs λ:

RAF is designed to be independent from technology parameters and operation conditions. It only reflexes the efficiency of the fault-tolerant method.

Fault Rate Assumption

For a system with k components, its fault rate is given by:

$$\lambda_{system} = \frac{1}{\mathbf{MTTF}_{system}} = \sum_{i=1}^{k} f_i \pi_i \lambda_{unit} \tag{2}$$

Where:

- $unit$ is a selected module as a reference for calculation.
- π_i is the fault-rate ratio between the component and the *unit*.
- f_i is the fault-rate ratio after attaching the component to the system.

By using the same *unit*, MTTF of both fault-tolerance and original systems can be obtained. RAF, as the result of a division, will eliminate λ_{unit} to obtain a quantitative value.

Markov-state Model

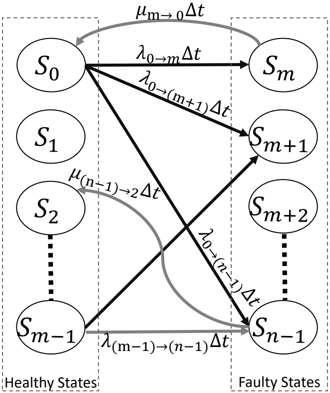


Figure 6: A Markov-state reliability model for an *n* states system with *m* non-faulty states.

Mean Time To Failure (MTTF) calculation as follows:

$$\textbf{MTTF} = \int_{t=0}^{\infty} R(t) = \lim_{s\to 0}(R^*(s)) \qquad (3)$$

where $R(t)$ is the reliability function and $R^*(s)$ is its Laplace form.
Assume a system has n states of failure/healthy. $\mathbb{H}$ is the set of healthy states. $\mathbb{F}$ is the set of failed states.

$$R^*(s) = P(\mathbb{H}) = \sum_{S_i\in\mathbb{H}} P(S_i) \qquad (4)$$

By calculating the probability of each state (in Laplace domain), we can obtain the MTTF value.

Markov-state Model (cnt.)

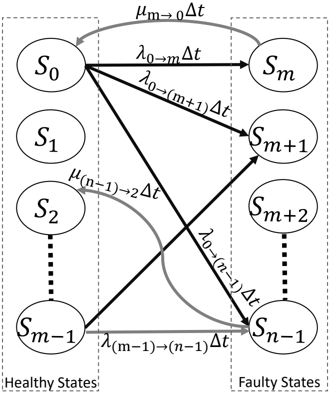


Figure 7: A Markov-state reliability model for an *m* states system with *n* non-faulty states.

Inside a Markov-state model, the transitions between states are indicated with:

- **Fault-rate of a sub-module** (λ): when a sub-module is failed, the state of the system may change to another state.
- **Repair-rate of a sub-module** (μ): when a sub-module is repaired, the state of the system may change to another state.

Reliability Assessment Methodology

Dividing:

1. A Network-on-Chip consists of N_R routers.
2. A router is divided into several modules.

Conquering:

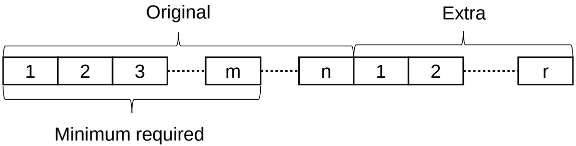
1. For each module of a router, analyze it using one of the following model:
   - *Model 0*: non fault-tolerant module - use the fault assumption (Eq. 2).
   - *Model 1*: spare or reconfiguration module.
   - *Model 2*: fault reduced module.
   - *Model 3*: module with fault-tolerance support.

Merging:

1. A router reliability is obtained by *Router Merging*.
2. A network reliability is obtained by *Network Merging*.

Model 1: spare/reconfiguration

This strategy handles faults using spare modules or by reconfiguring.



- Module has n separate identical parts.
- Module can function with at least m parts.
- Extra r spare parts are added in the design stage.
- f is the number of parts that are faulty in a state.

Lemma 1: The RAF values can be calculated as follows:

$$\text{RAF}_{conv.} = \frac{\textbf{MTTF}_{FT}}{\textbf{MTTF}_{original}} = \Sigma_{i=m}^{n+r} \frac{n}{i} = 1 + \Sigma_{i=m}^{n-1} \frac{n}{i} + \Sigma_{i=n+1}^{n+r} \frac{n}{i} \tag{5}$$

Model 2: fault reduced

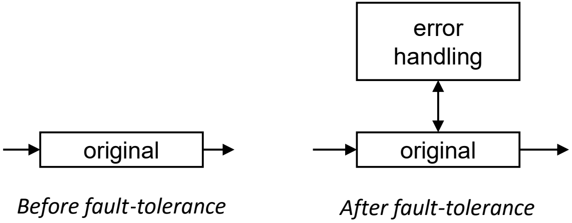
- For helping the platform being compatible with other reliability assessments, this model can integrate them together.
- With a fault reduction value f_{FT} given by the other technique, the new fault rate is obtained by Eq. 6.

$$\lambda_{FT} = f_{FT}\lambda_{original} \tag{6}$$

The RAF value can be obtained by:

$$\mathrm{RAF}_{FT} = 1/f_{FT} \tag{7}$$

Model 3: module with fault-tolerance



Because the fault-tolerance technique may require additional modules for checking and correcting faults. These correction modules also add fault-rates.

Model 3: module with fault-tolerance

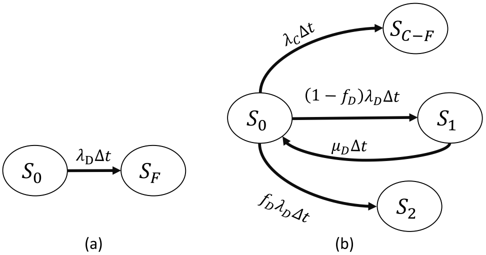


Figure 8: A simplified Markov-state reliability model for (a) the original system; (b) the fault-tolerant (FT) system.

Lemma 2: The RAF value can be then expressed as:

$$\mathrm{RAF}_{FT} = f_D + \frac{\lambda_C}{\lambda_D} \quad (8)$$

Where

- λ_D is the fault-rate of the original system (D).
- λ_C is the fault-rate of the repair module of the FT system.
- f_D is the fault reducing value by applying the fault-tolerance mechanism.

Reliability Assessment Methodology

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Merging:

1. A router reliability is obtained by *Router Merging*.
2. A network reliability is obtained by *Network Merging*.

Merging

Router

The fault rate of a router is summarized from its own N sub-modules (M_i):

$$\lambda_{router} = \sum_{i=1}^{N} f_{M_i} \lambda_{M_i} \tag{9}$$

Network

The fault rate of a network is summarized from three parts: (1) the local connection (router-PE), (2) the routing paths inside network and (3) other modules inside routers:

$$\lambda_{network} = \lambda_{local} + \lambda_{transmitting-path} + \lambda_{others} \tag{10}$$

Network Merging

Three main parts of network are:

- $\lambda_{local} = N_R \times (2\lambda_{1-channel} + \lambda_{input-buffer})$ is the fault-rate of all local connections.
- $\lambda_{transmitting-path} = \lambda_{RTR} \times N_{RTR}$. λ_{RTR} is the fault-rate of all router-to-router (RTR) connections. N_{RTR} is the number of used RTR connections.
- λ_{others} is given by the fault-rates of other parts (non-routing parts) of routers.

Reliability of transmitting path

- A router-to-router (RTR) connection consists of: an input buffer, a crossbar link and an intra-router channel[3].
- For transmitting path reliability, we use the *k-failure* [18] model: a router is disconnected at the presence of *k* failures[4].
- For 3D-NoCs, we the *k* value depends on the position of the router and the efficiency of the fault-tolerant algorithm.[5].

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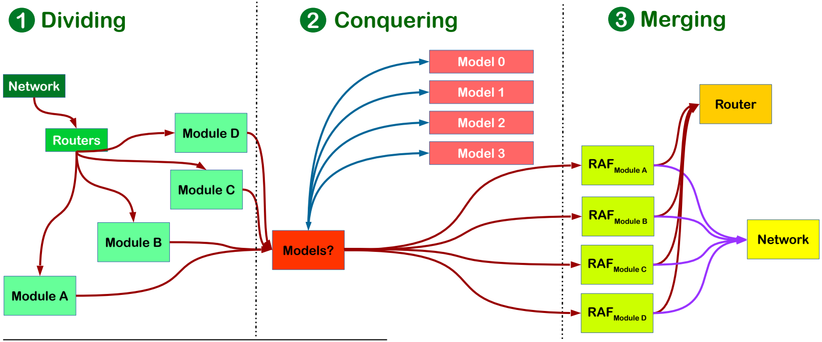
[3] The control logic is counted as other modules in the network equation (Eq. 10).

[4] Note: Not only the *k-failure* model, any reliability network assessment can be applied to obtain the $\lambda_{transmitting-path}$.

[5] Conner routers: k=3, middle routers: k= 6

Reliability Assessment Methodology



Related conference paper

1. **Khanh N. Dang**, Michael Meyer, Yuichi Okuyama and Abderazek Ben Abdallah, "Reliability Assessment and Quantitative Evaluation of Soft-Error Resilient 3D Network-on-Chip Systems", The IEEE 25th Asian Test Symposium (ATS), pp. 161-166, Hiroshima, Japan, November 21-24, 2016. **[MAJOR]**

Related paper under second re-revision

1. **Khanh N. Dang**, Akram Ben Ahmed, Xuan-Tu Tran, Yuichi Okuyama and Abderazek Ben Abdallah, "A Comprehensive Reliability Assessment of Fault-Resilient Network-on-Chip Using Analytical Model", IEEE Transactions on Very Large Scale Integration Systems, *(Under Minor Revision)*. **[MAJOR], Submitted on February 1, 2017.**

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Soft Error Hard Fault Tolerant Architectures and Algorithms (1/4)

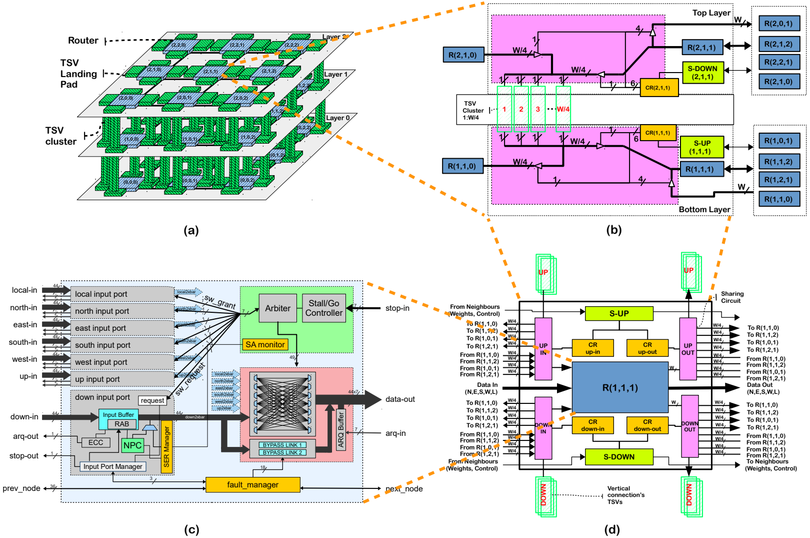


Figure 9: System architecture: (a) 3D NoC, (b) Interface between two routers from adjacent layers; (c) Router architecture; and (d) The wrapped router.

Fault Assumption

Hard Fault Assumption

- Hard faults only occur in the following positions: *input buffer*, *crossbar* and *inter-router channel*.
- Hard faults are modeled as stuck-at faults where the output values of faulty gates are always ‘0’ or ‘1’.
- This type of faults occurs permanently.

Soft Error Assumption

- Soft errors can occur in data path or in the routing arbitrator (Next Port Computing and Switch Allocator).
- Soft errors are modeled as stuck-at faults where the output values of faulty gates are always ‘0’ or ‘1’.
- This type of faults only occurs in a single clock cycle.

Soft Error Hard Fault Tolerant Architectures and Algorithms (2/4)

Proposed Algorithms and Architecture:

- A soft error resilience method, named as **Pipeline Computation Redundancy** (PCR), to handle soft errors on pipeline stage.
  - Multiple executions to detect and correct soft errors.
  - Since *NextPortComputing*/*SwitchAllocation* are the important part inside the network, we handle soft errors using PCR.
- A **detection, diagnosis and recovery mechanism** (DDRM) for handling the possible faults.
- As a summary, a comprehensive design of 3D-NoC system (3D-FETO) that can handle both soft errors and hard faults.

Related journal paper

- **Khanh N. Dang**, Michael Meyer, Yuichi Okuyama and Abderazek Ben Abdallah, "A Low-overhead Soft-Hard Fault Tolerant Architecture, Design, and Management Scheme for Reliable High-performance Many-core 3D-NoC Systems", The Journal of Supercomputing, pp. 1-25, January 2017.

Soft Error Hard Fault Tolerant Architectures and Algorithms (3/4)

To complete the design, we adopted the following fault-tolerant methods:

- **Error Correction Code**: SECDED (Single Error Correction, Double Error Detection) [20] to protect data path against soft errors.
- **Buffer Slot Fault Tolerance**: Random Access Buffer[21].
- **Crossbar Link Fault Tolerance**: Bypass-Link-on-Demand[21].
- **Intra-router Link Fault Tolerance**: Lookahead-Fault-Tolerant (LAFT) routing algorithm[22].

Soft Error Hard Fault Tolerant Architectures and Algorithms (4/4)

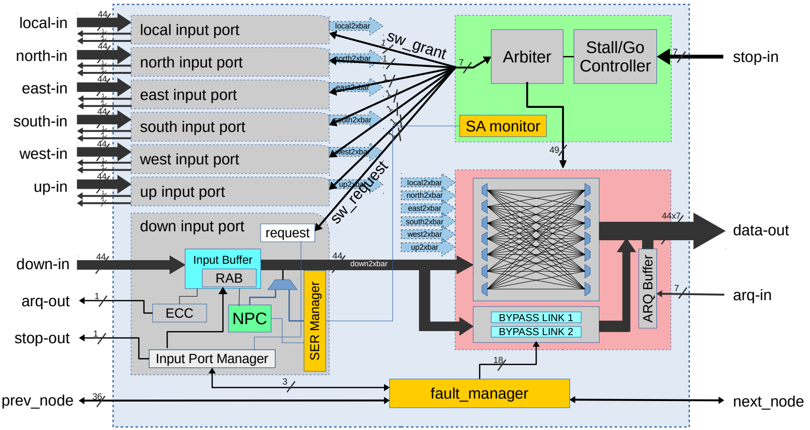
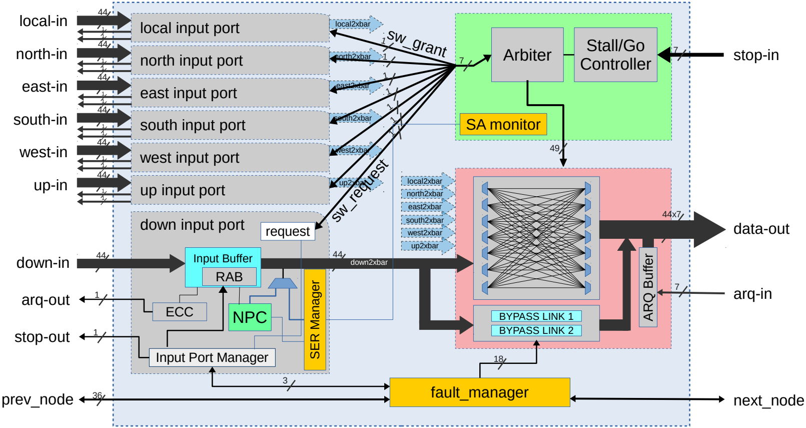


Figure 10: Adaptive 3D-FETO router architecture.

Soft Error Hard Fault Tolerant Architectures and Algorithms (4/4)



This 3D router is designed for 3D Mesh topology. There are three main components: input buffer, switch allocator and crossbar.

Soft Error Hard Fault Tolerant Architectures and Algorithms (4/4)

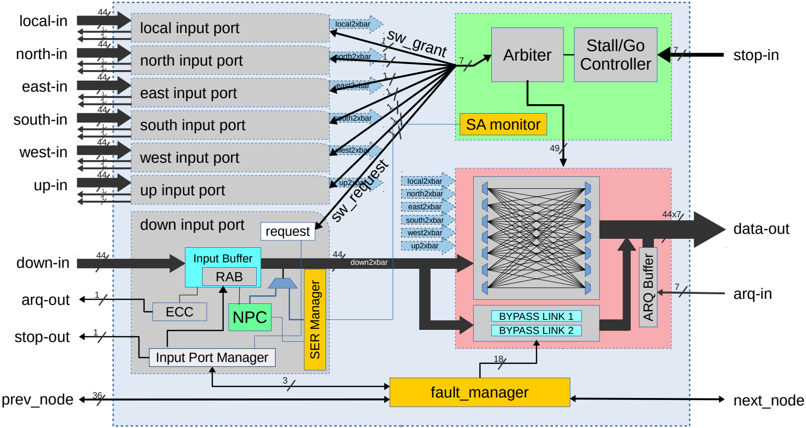
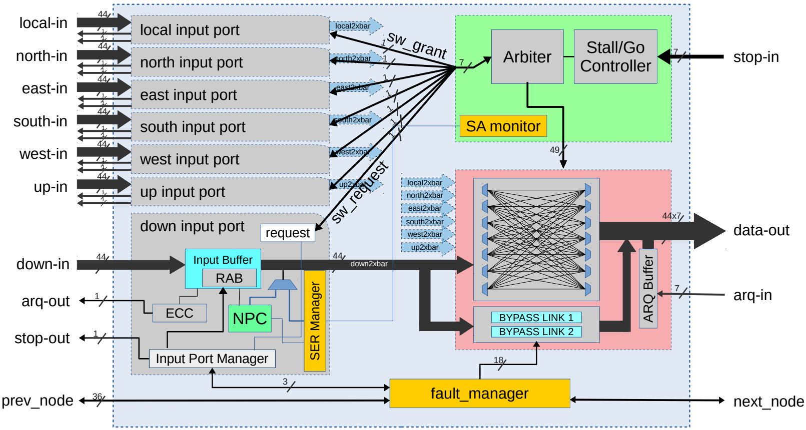


Figure 10: Adaptive 3D-FETO router architecture.

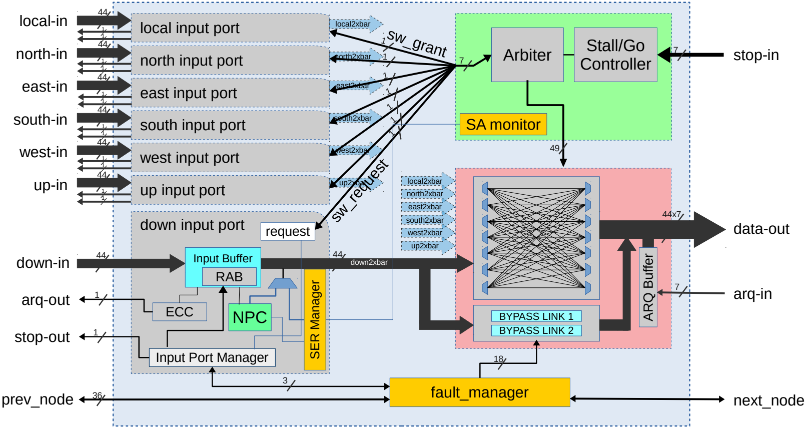
Each router has maximum 7 ports for 7 directions: Up, Down, North, East, South, West, and Local.

Soft Error Hard Fault Tolerant Architectures and Algorithms (4/4)



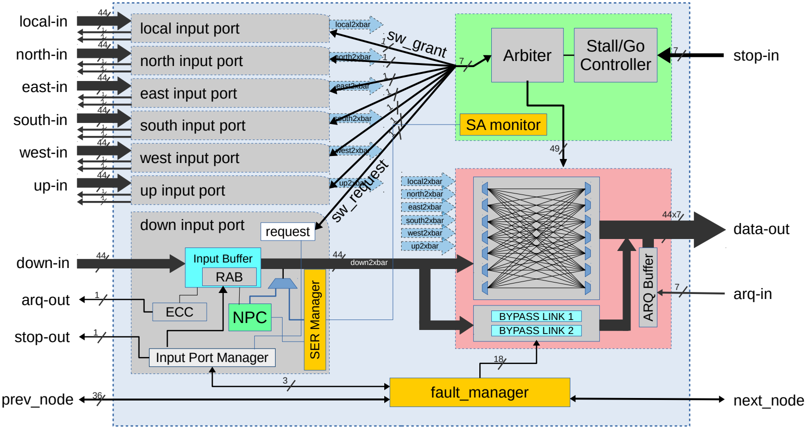
Incoming flits will be stored in input buffer (in *Buffer Writing* stage). After that, its routing information is read and processed by Next Port Computing (NPC) and Switch Allocation (SA). This is *Next Port Computing/Switch Allocation* stage.

Soft Error Hard Fault Tolerant Architectures and Algorithms (4/4)



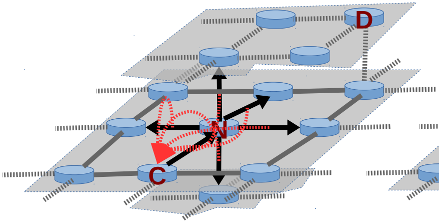
NPC calculates the *next_port* value for the next node, as look-ahead routing. SA receives requests from all input ports and *grants* the transmission to the next node through the crossbar.

Soft Error Hard Fault Tolerant Architectures and Algorithms (4/4)

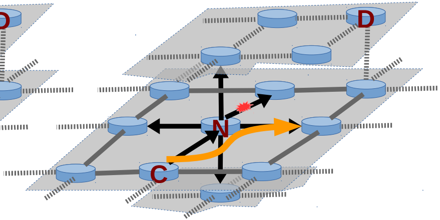


After getting the *grant* from SA and the new *next_port* value from NPC, the flit is forwarded to the next node through crossbar (*Crossbar Traversal* stage).

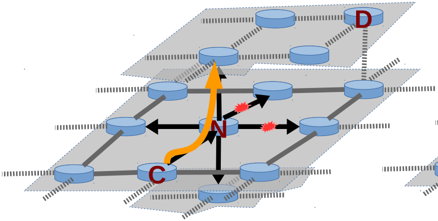
Overview of Hard Fault-Tolerances (1/2)



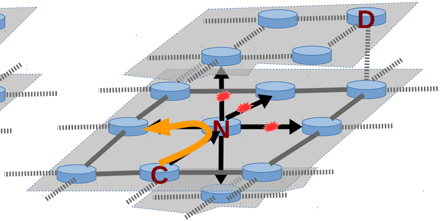
Updating faulty information.



Case1: One faulty link.



Case2: Two faulty links.



Case3: Minimal routing.

Figure 11: Look-Ahead-Fault-Tolerant Algorithm. C, N, and D are *current*, *next* and *destination* nodes, respectively. Black arrows: possible routing directions. Red doted arrows: updating faulty information. Orange arrows: routing decisions.

Overview of Hard Fault-Tolerances (2/2)

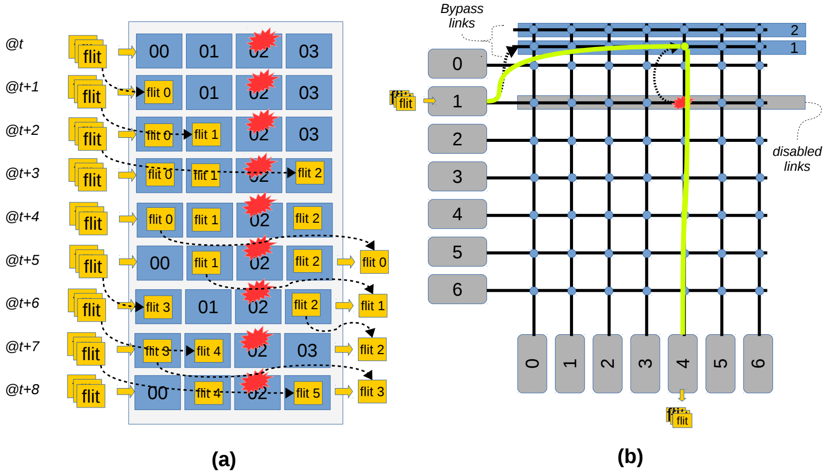


Figure 12: Hard Fault Tolerances: (a) Random Access Buffer; (b) Bypass-link on Demand.

Pipeline Computation Redundancy Algorithm

```
// input flit's data
Input: in_flit
// output flit's data
Output: out_flit

// Write flit's data into buffers
BufferWriting(in_flit)
// Compute first time of NPC and SA
next_port[1] = NextPortComputing(in_flit)
grants[1] = SwitchAllocation(in_flit)

// Compute redundant of NPC and SA
next_port[2] = NextPortComputing(in_flit)
grants[2] = SwitchAllocation(in_flit)

// Compare orginal and redundant to
   detect soft-error
// Soft-error on NPC
if (next_port[1] ≠ next_port[2]) then
    // roll-back and recalculate NPC
    next_port[3] =
     NextPortComputing(in_flit)
    final_next_port =
     MajorityVoting(next_port[1,2,3]);
else
    // No soft-error on NPC
    final_next_port = next_port[1]

// Soft-error on SA
if (grants[1] ≠ grants[2]) then
    // roll-back and recalculate SA
    grants[3] = SwitchAllocation(in_flit)
    final_grants =
     MajorityVoting(grants[1,2,3])
else
    // No soft-error on SA
    final_grants = grants[1]

// After detection and recovery, the
   algorithm finishes with CT
out_flit = CrossbarTraversal(in_flit,
  final_next_port, final_grants);
```

Algorithm 1: Algorithm of Pipeline Computation Redundancy (PCR).

Pipeline Computation Redundancy Timeline

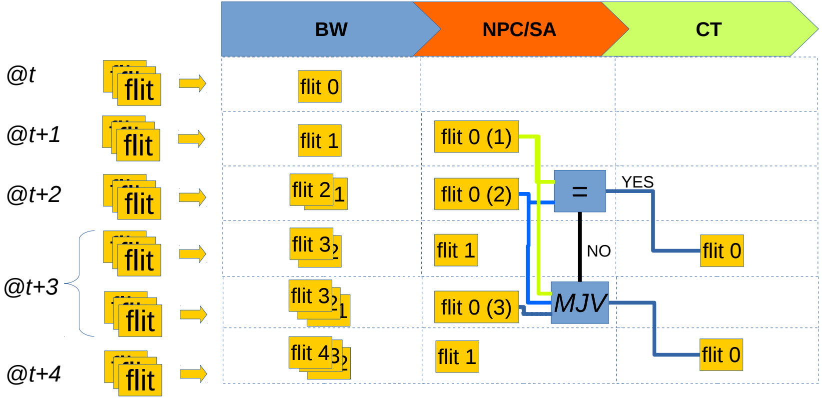


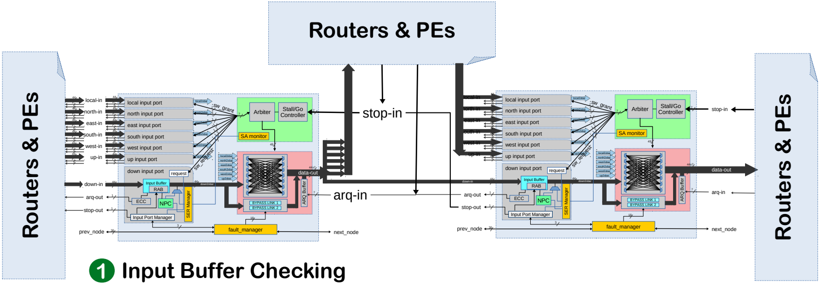
Figure 13: Pipeline Computation Redundancy (PCR).

Detection, Diagnosis and Recovery Mechanism Algorithm

```
// Automatic Retransmission Request
Input: transmitting_flit
// Transmitted Buffer Position
Input: buffer_position
// Control signal to all Fault-Tolerance
   modules
Output: RAB_control, BLoD_control,
        LAFT_control
// Transmit the flit, get the ECC's feedback
Transmit(transmitting_flit);
ECC_result = ECC-Decoder(transmitting_flit);
// DETECTION PHASE:
if ECC_result == ARQ then
    // Automatic Retransmission Request
    increase(ARQ_counter);
    ARQ(transmitting_flit);
else
    // The transmitted flit is non faulty
    Finish;
// Check the number of consecutive ARQs
if (ARQ_counter == 2) then
    // There is a permanent fault
    // Jump to DIAGNOSIS-RECOVERY PHASE
// DIAGNOSIS-RECOVERY PHASE:
// Start with Input Buffer Checking
Buffer_Failure ←
  Buffer_Checking(buffer_position);
if (Buffer_Failure == Yes) then
    // Random Access Buffer is received the
       position to handle.
    RAB_Control = buffer_position;
    Finish;
else
    // The buffer slot is non faulty.
    // Move to Crossbar Checking: using a
       Bypass-Link.
    BLoD_control = enable;
    // Get the ECC's feedback and detect with
       ARQ counter.
    if (ARQ_counter == 2) then
        // BLoD cannot fix the fault, the link
           is failed.
        BLoD_control = release;
        // The LAFT routing algorithm handles
           the faulty link.
        LAFT_control = faulty;
        Finish;
    else
        // BLoD already fixed the failure, the
           recovery step is finished.
        Finish;
```

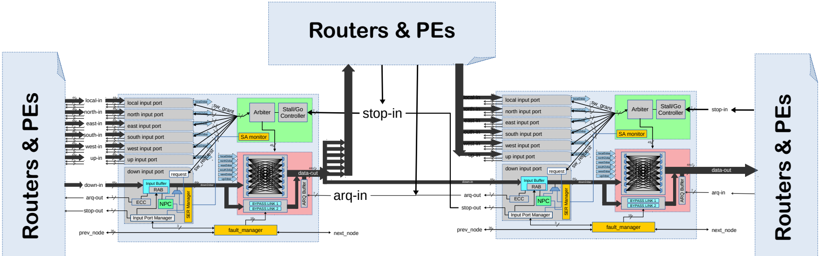
Algorithm 2: Fault Detection, Diagnosis and Recovery.

Detection, Diagnosis and Recovery Mechanism



1. **Input Buffer Checking**
2. **Configure BLoD**
3. **Fault-Tolerant Routing**

Detection, Diagnosis and Recovery Mechanism



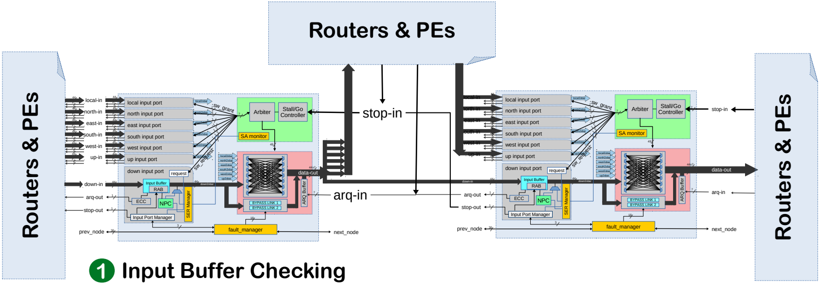
1. Input Buffer Checking
2. Configure BLoD
3. Fault-Tolerant Routing

Detection:

If there are two consecutive ARQ signals (Double-ARQs), it could be a hard fault instead of soft error. DDRM starts monitoring the communication (Diagnosis stage).

Assumption: A soft error, which typically occur in 1 clock cycle, can be recovered by ECC with the help of ARQ. However, a hard fault will demand infinite ARQs which can be detected by Double-ARQs.

Detection, Diagnosis and Recovery Mechanism



1 **Input Buffer Checking**

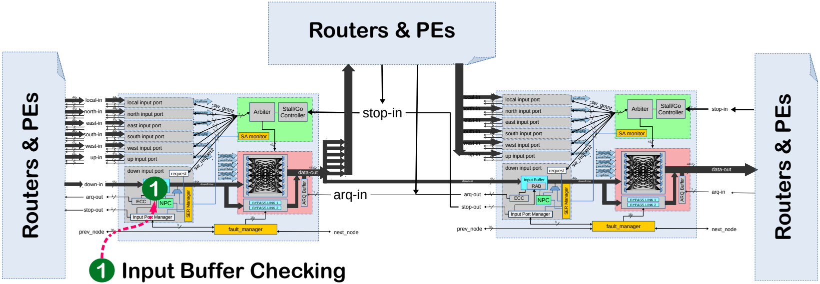
2 **Configure BLoD**

3 **Fault-Tolerant Routing**

Diagnosis:

DDRM exams the ARQ to find the position of hard fault (1: input buffer, 2: crossbar, or 3: intra-router channel).

Detection, Diagnosis and Recovery Mechanism

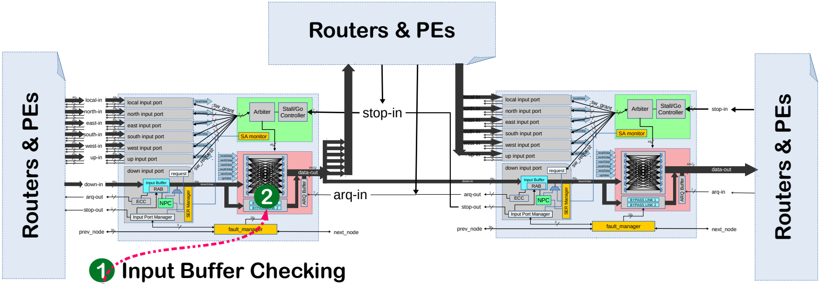


1. **Input Buffer Checking**
2. **Configure BLoD**
3. **Fault-Tolerant Routing**

Diagnosis: 1 - input buffer

- If the Double-ARQs repeats at *the same buffer slot*, this buffer slot if faulty.
- If the Double-ARQs repeats *the all buffer slots*, the following transmitting path (crossbar, inter-router channel) is faulty. Move to *Configure BLoD*.

Detection, Diagnosis and Recovery Mechanism



1 Input Buffer Checking

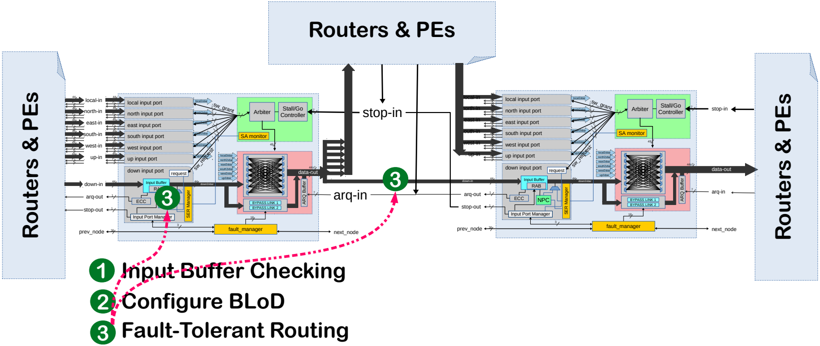
2 Configure BLoD

3 Fault-Tolerant Routing

Diagnosis: 2 - Configure BLoD

- The router uses an alternative bypass link (assumed being healthy) instead of the original link (input port - output port).
- If the Double-ARQs repeats even with the bypass link, the inter-router channel is faulty. Move to *Fault-Tolerant Routing*.
- If non *Double-ARQs* repeats, its mean BLoD correct the crossbar failure.

Detection, Diagnosis and Recovery Mechanism

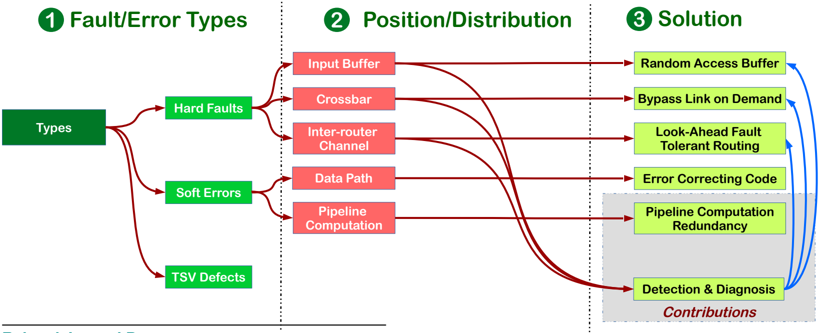


Diagnosis: ❸ - Fault-Tolerant Routing

- The channel failure information is updated to avoid it in the routing process.

Recovery: depend on the position of the fault, the *fault-manager* module send signals to the corresponded fault-tolerant module.

Soft Error Hard Fault Tolerant Architectures and Algorithms



Related Journal Paper

- **Khanh N. Dang**, Michael Meyer, Yuichi Okuyama and Abderazek Ben Abdallah, "A Low-overhead Soft-Hard Fault Tolerant Architecture, Design, and Management Scheme for Reliable High-performance Many-core 3D-NoC Systems", The Journal of Supercomputing, pp. 1-25, January 2017.

Related Conference Paper

- **Khanh N. Dang**, Michael Meyer, Yuichi Okuyama and Abderazek Ben Abdallah, "Reliability Assessment and Quantitative Evaluation of Soft-Error Resilient 3D Network-on-Chip Systems", The IEEE 25th Asian Test Symposium (ATS), pp. 161-166, Hiroshima, Japan, November 21-24, 2016. **[MAJOR]**
- **Khanh N. Dang**, Yuichi Okuyama, and Abderazek Ben Abdallah, "Soft-error resilient network-on-chip for safety-critical applications", *The 2016 International Conference on IC Design and Technology (ICICDT)*, pp. 1-4, Ho Chi Minh City, Vietnam, June 27-29, 2016. **[MAJOR]**
- **Khanh N. Dang**, Michael Meyer, Yuichi Okuyama, Abderazek Ben Abdallah, and Xuan-Tu Tran, "Soft-error resilient 3d network-on-chip router", *The 2015 IEEE 7th International Conference on Awareness Science and Technology (iCAST)*, pp. 84-90 Qinhuangdao, China, September 22-24, 2015. **[MAJOR]**

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Scalable Cluster-TSV Defect Tolerance (1/5)

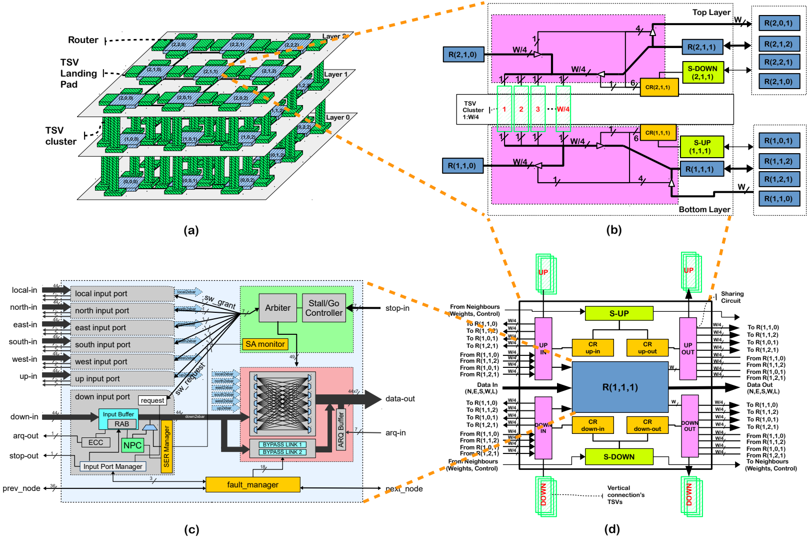

Figure 14: System architecture: (a) 3D NoC, (b) Interface between two routers from adjacent layers; (c) Router architecture; and (d) The wrapped router.

Scalable Cluster-TSV Defect Tolerance (2/5)

Approach:

- A method to organize the TSVs in 3D-NoC systems to handle the cluster defect[6].
- A cluster-TSV defect recovery method without adding TSV redundancies.
- An adaptive online algorithm to handle the cluster-TSV defect.

Related under review paper

- **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, *(Under Review)*. **[MAJOR], Submitted on March 1, 2017.**

[6] In fact, in this design, ECC code can handle random failed TSVs.

Fault Assumption

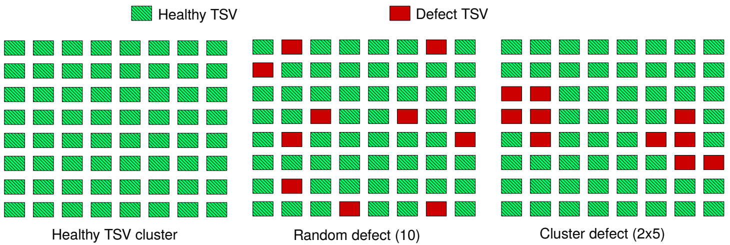

Figure 15: TSV fault assumption.

- This work only focuses on cluster defect. No random defects are considered.
- Detection is assumed to be done by a dedicated module[7].

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[7] *DDRM* module can help detect the fault occurence; however, it does not support the diagnosis phase.

Scalable Cluster-TSV Defect Tolerance (3/5)

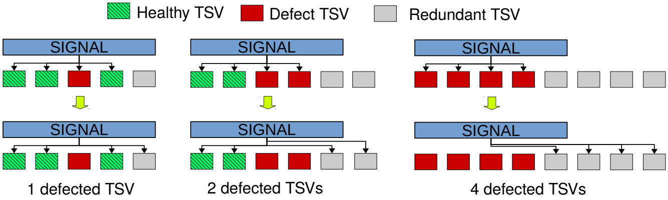


Figure 16: Conventional TSV fault-tolerant method.

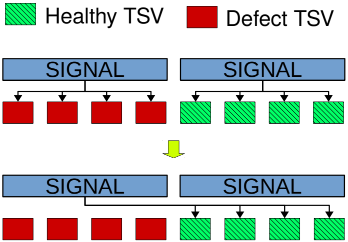


Figure 17: The proposed technique.

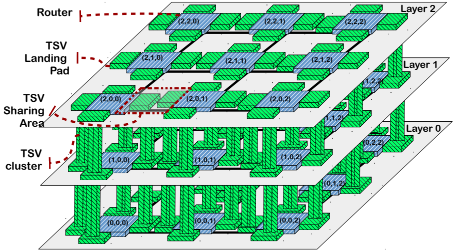


Figure 18: Simplified block diagram of the proposed system with configuration $3 \times 3 \times 3$.

Scalable Cluster-TSV Defect Tolerance (4/5)

Placement of shared TSV clusters

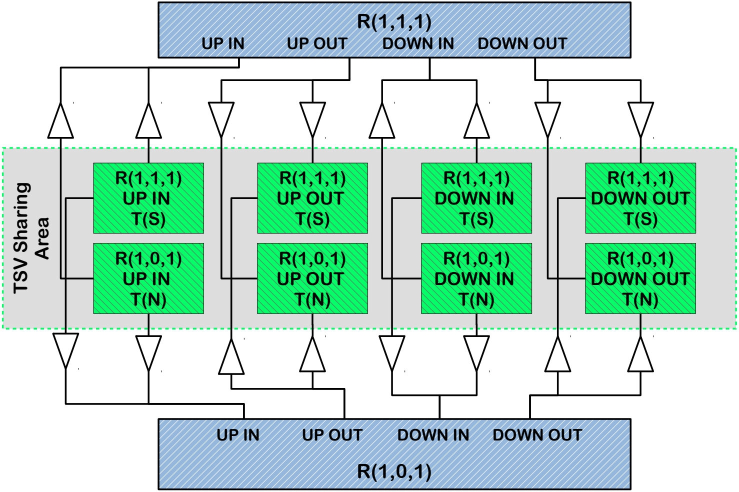


Figure 19: TSV sharing area placement and connectivity between two neighboring routers.

Scalable Cluster-TSV Defect Tolerance (4/5)

Placement of shared TSV clusters

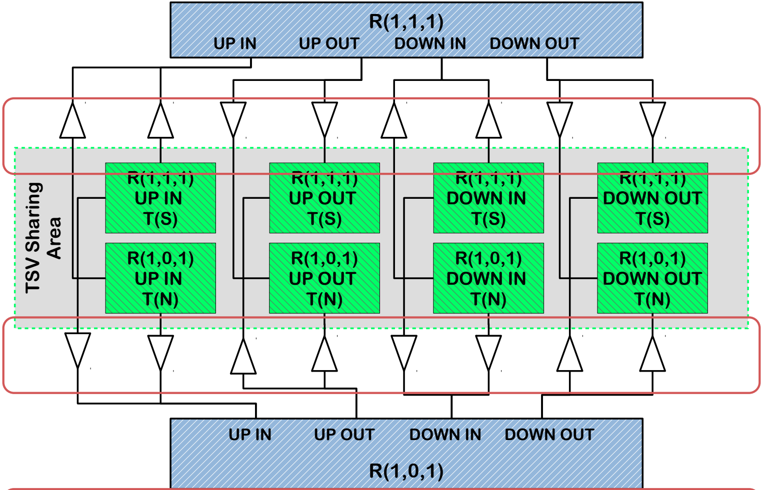


Fig
rou

Tri-state gates are used to allow the accessibility of a router to a TSV cluster.

Scalable Cluster-TSV Defect Tolerance (4/5)

Placement of shared TSV clusters

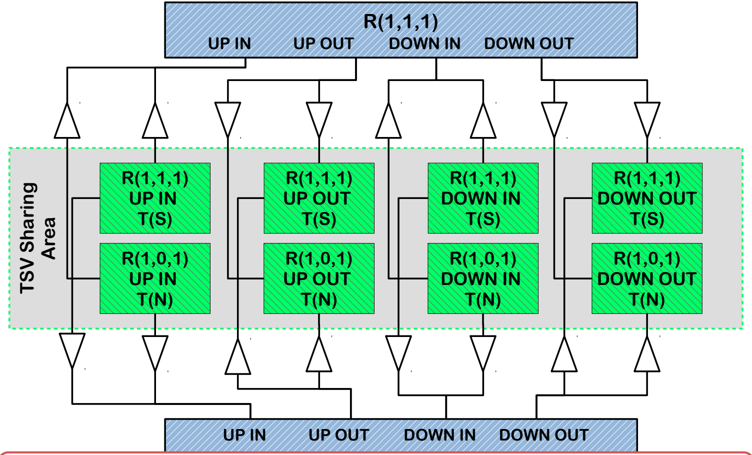
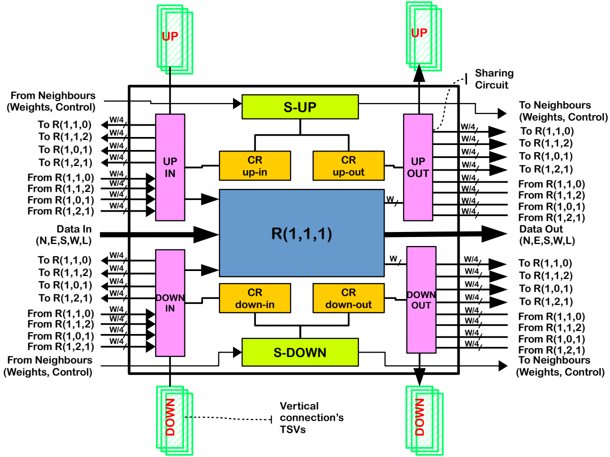


Fig
rou

A router has four ports using TSV clusters: UP IN, UP OUT, DOWN IN and DOWN OUT. They can be eliminated if there is no upper/lower layer.

Scalable Cluster-TSV Defect Tolerance (5/5)

Router Architecture



The TSV Router wrapper fault-tolerance architecture. *S-UP* and *S-DOWN* are the sharing arbitrators which manage the proposed mechanism. *CR* stands for configuration register and *W* is the flit width.

Inter-Layer Connection

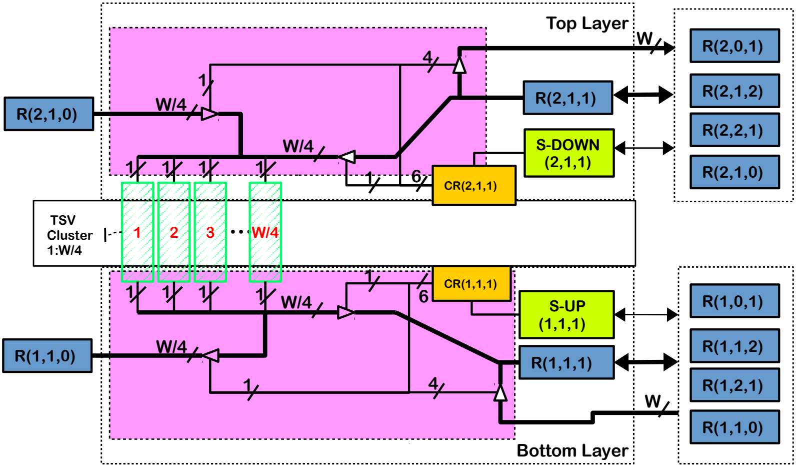
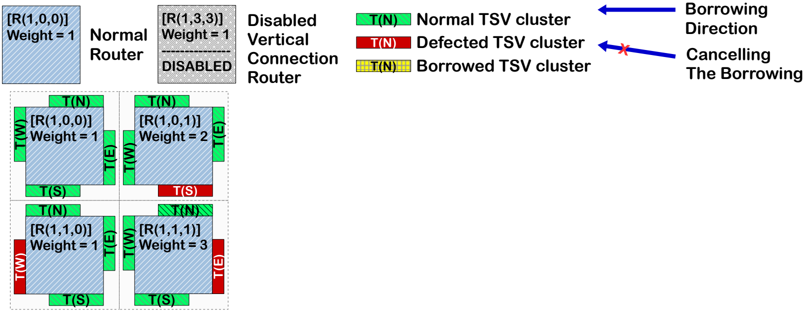


Figure 20: Cluster-TSV connection between two layers.

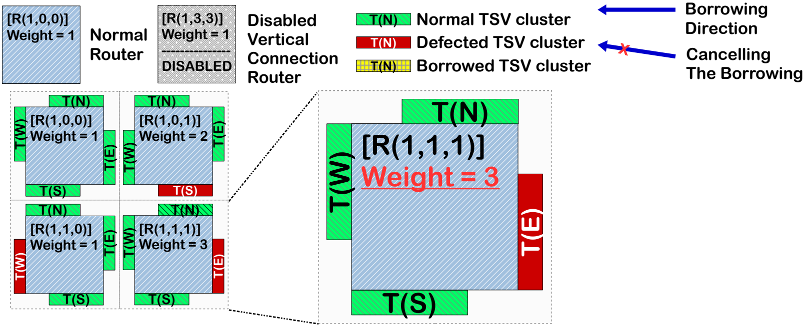
```
// Weight values of the current router and its N neighbors
Input: Weight_current, Weight_neighbor[1 : N]
// Status of current and neighboring TSV-clusters
Input: TSV_Status_current[1 : N], TSV_Status_neighbor[1 : N]
// Request to link TSV-clusters to neighbors
Output: RQ_link[1 : N]
// Current router 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"
```

Algorithm 3: TSV Sharing Algorithm.

TSV Sharing Algorithm



TSV Sharing Algorithm

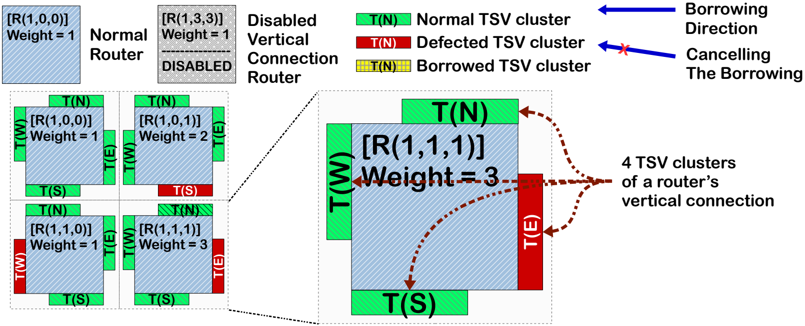


- Every router is assigned a weight value.

Note: The weight values can be generated based on traffic of the vertical connection of the router. In this dissertation, we generate higher weights for the middle routers and lower weights for the border routers:

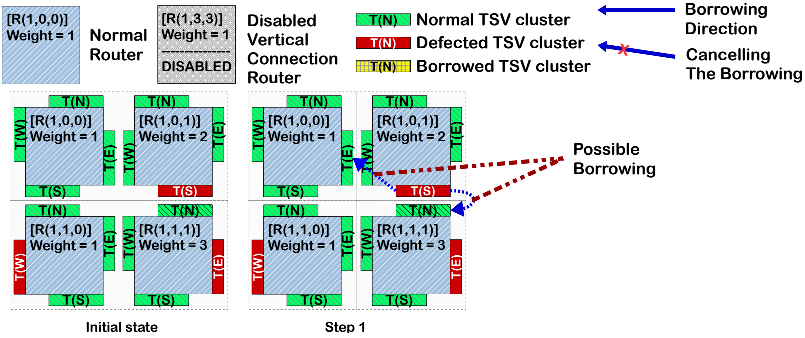
$$\text{Weight}_{\text{router}}(x, y) = \min(x, \text{cols} - x) + \min(y, \text{rows} - y) + 1 \qquad (11)$$

TSV Sharing Algorithm



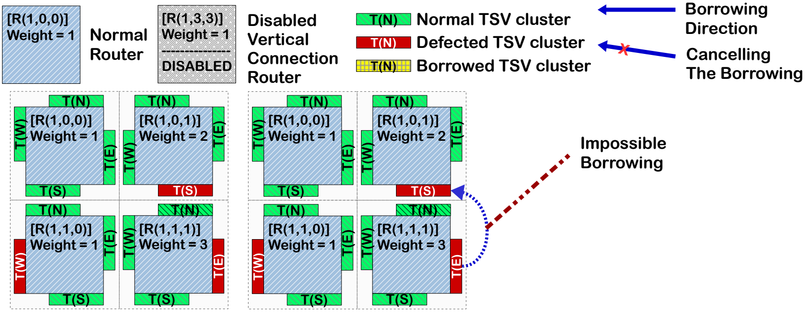
- Every router is assigned a weight value.
- TSVs of a router are organized in four clusters around it.

TSV Sharing Algorithm



- Every router is assigned a weight value.
- TSVs of a router are organized in four clusters around it.
- Each router having defected/borrowed TSV cluster (red/yellow) can borrow from one of its neighbors.

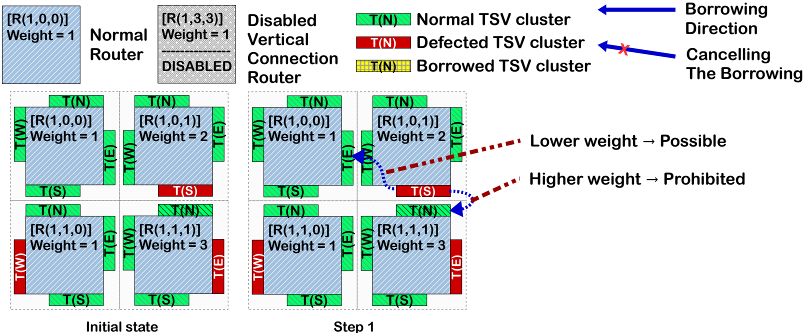
TSV Sharing Algorithm



Initial state Step 1

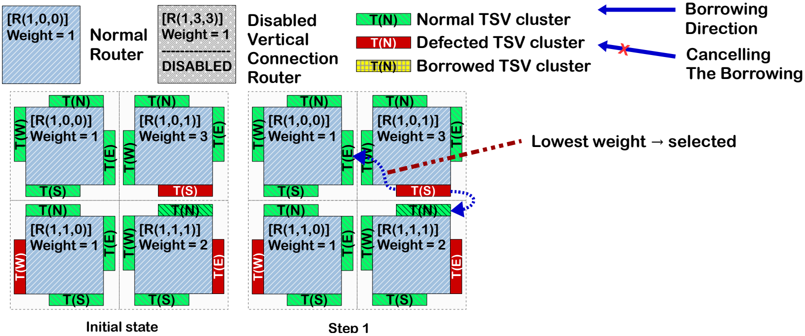
- Every router is assigned a weight value.
- TSVs of a router are organized in four clusters around it.
- Each router having defected/borrowed TSV cluster (red/yellow) can borrow from one of its neighbors.
- The borrowed cluster must be healthy.

TSV Sharing Algorithm



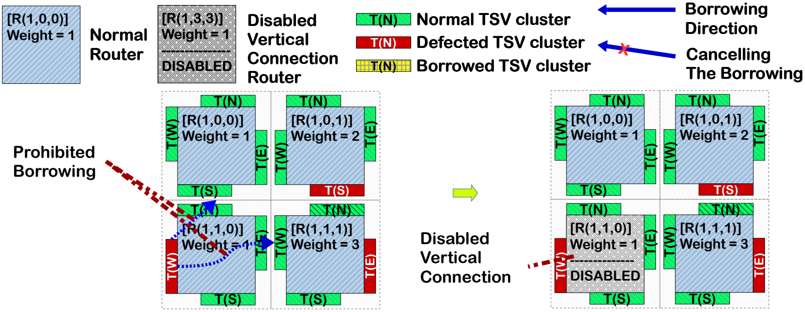
- Every router is assigned a weight value.
- TSVs of a router are organized in four clusters around it.
- Each router having defected/borrowed TSV cluster (red/yellow) can borrow from one of its neighbors.
- The borrowed cluster must be healthy.
- The borrowed cluster must belong to the router having lower weight than the current router.

TSV Sharing Algorithm



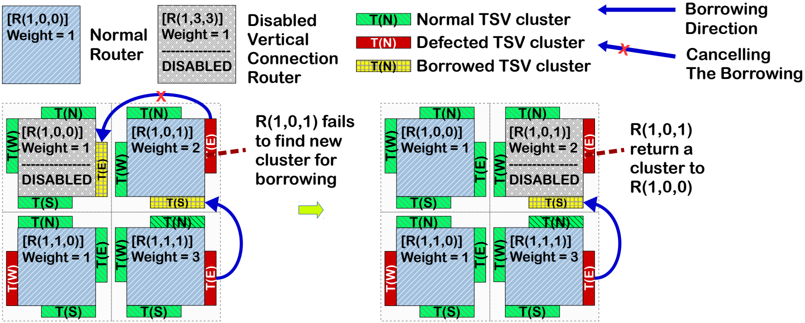
- Every router is assigned a weight value.
- TSVs of a router are organized in four clusters around it.
- Each router having defected/borrowed TSV cluster (red/yellow) can borrow from one of its neighbors.
- The borrowed cluster must be healthy.
- The borrowed cluster must belong to the router having lower weight than the current router.
- The borrowed router must have the lowest weight than all possible candidates.

TSV Sharing Algorithm



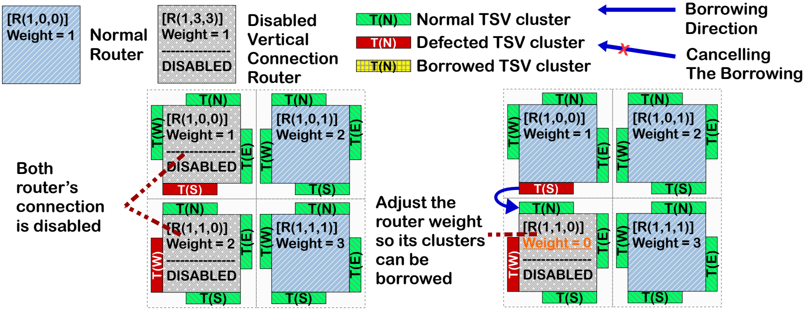
- Every router is assigned a weight value.
- TSVs of a router are organized in four clusters around it.
- Each router having defected/borrowed TSV cluster (red/yellow) can borrow from one of its neighbors.
- The borrowed cluster must be healthy.
- The borrowed cluster must belong to the router having lower weight than the current router.
- The borrowed router must have the lowest weight than all possible candidates.
- If a router fails to find a cluster to maintain its connection, its vertical connection is disabled.

TSV Sharing Algorithm: Optimization



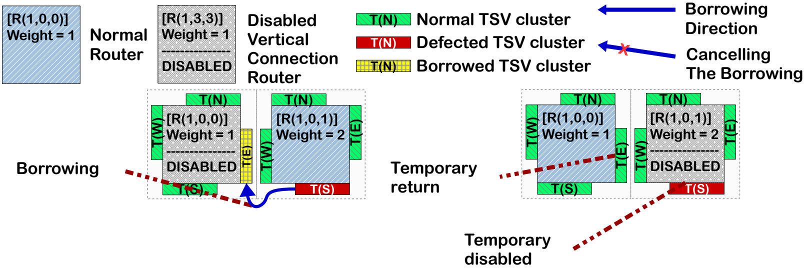
- New disabled router will return its borrowing cluster.

TSV Sharing Algorithm: Optimization



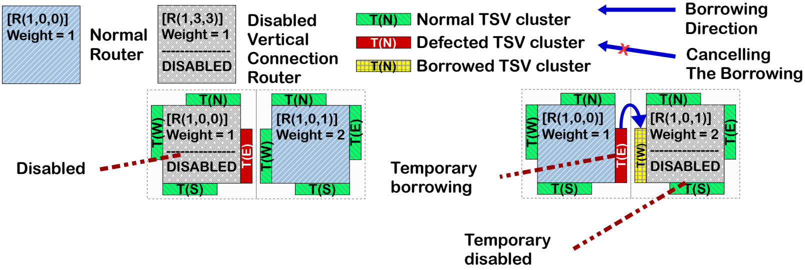
- New disabled router will return its borrowing cluster.
- Disabled router's weights are considered to be adjusted. This helps lower weight routers can gain their operations.

TSV Sharing Algorithm: Optimization



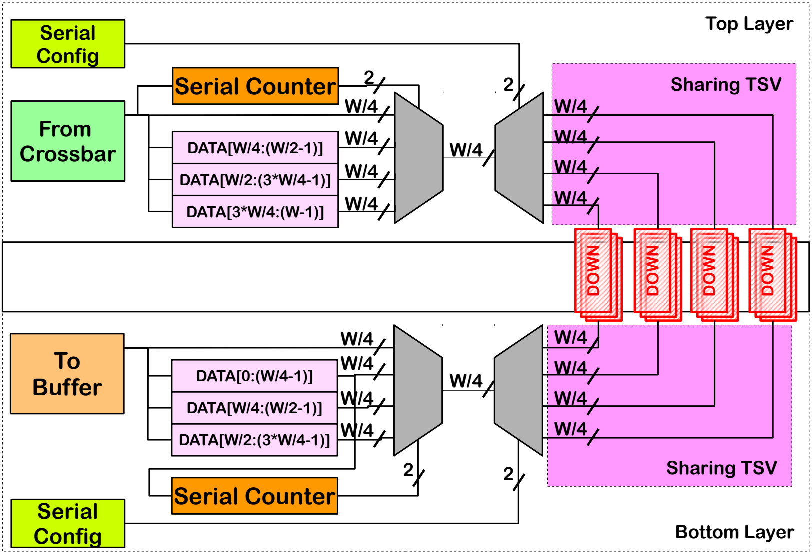
- New disabled router will return its borrowing cluster.
- Disabled router's weights are considered to be adjusted. This helps lower weight routers can gain their operations.
- **Virtual TSV:** Even being disabled, router can temporarily borrow a cluster to transmit data. *Case 1: return the cluster to its origin.*

TSV Sharing Algorithm: Optimization



- New disabled router will return its borrowing cluster.
- Disabled router's weights are considered to be adjusted. This helps lower weight routers can gain their operations.
- **Virtual TSV:** Even being disabled, router can temporarily borrow a cluster to transmit data. *Case 2: borrow from a higher weight router.*

TSV Sharing Algorithm: Optimization



- **Serialization:** When it is impossible to have 4 clusters, serialization technique is adopted to maintain the connection.

TSV Sharing Algorithm Example

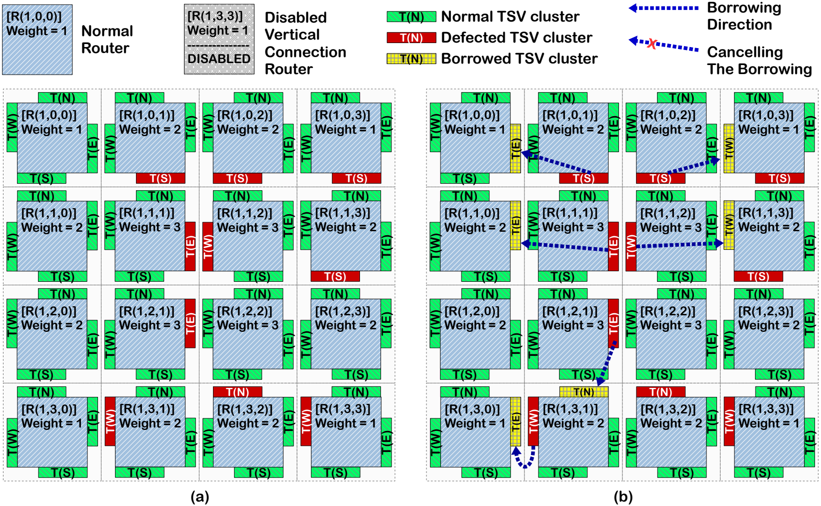


Figure (a): a layer with 10 defected TSV clusters. Figure (b): the routers having defect clusters start to find a replacement. The arrows show the borrowing direction.

TSV Sharing Algorithm Example (cnt.)

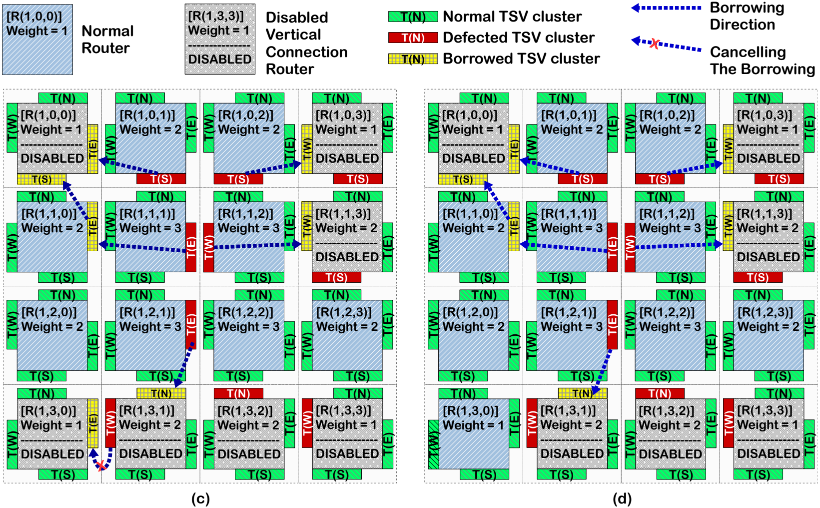
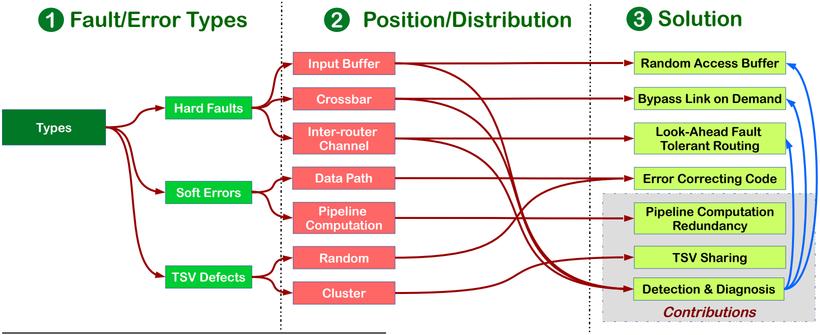


Figure (c): The routers having borrowed clusters also start to find a replacement. If a router is borrowing a cluster and is later disabled, it returns the borrowed cluster to the owner.

Figure (d): The final configuration.

Scalable Cluster-TSV Defect Tolerance



Under review paper

- **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, *(Under Review)*. **[MAJOR], Submitted on March 1, 2017.**

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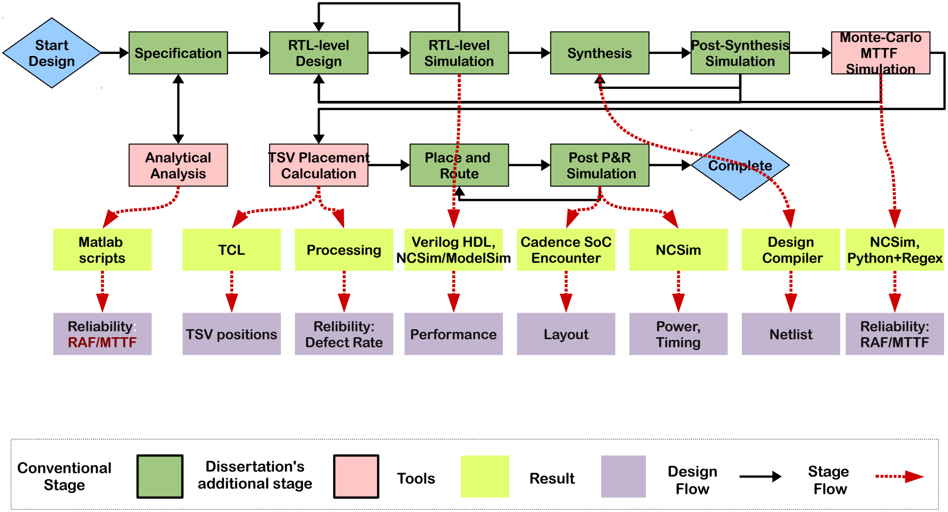
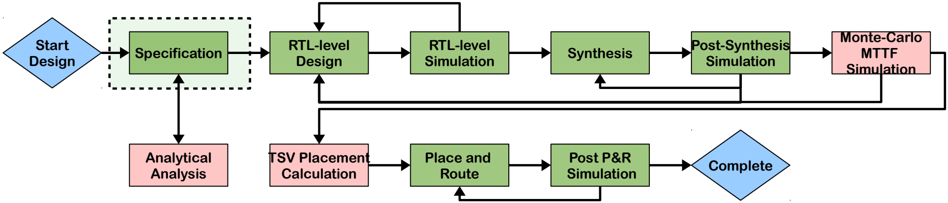
Evaluation Methodology



Evaluation Methodology



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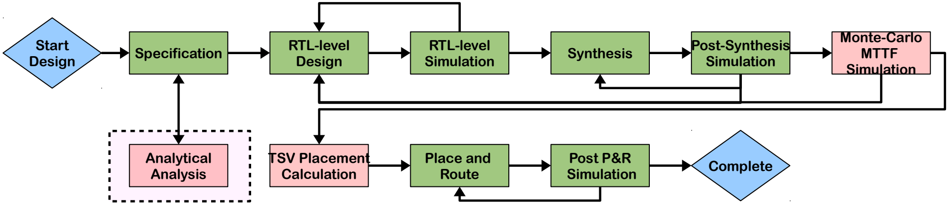

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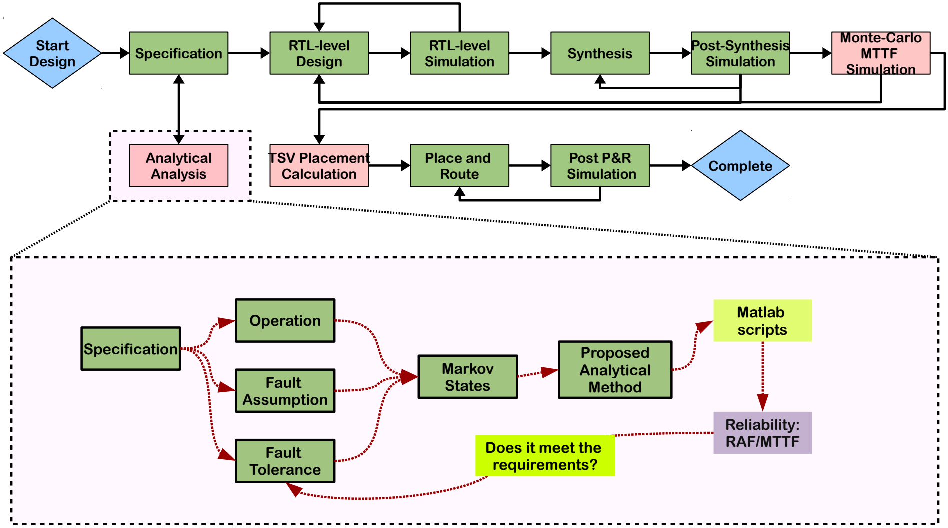

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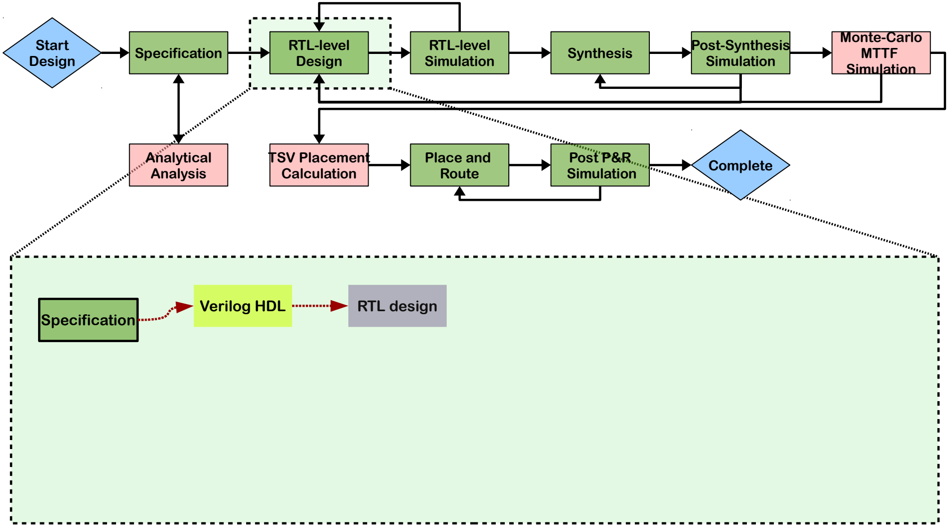

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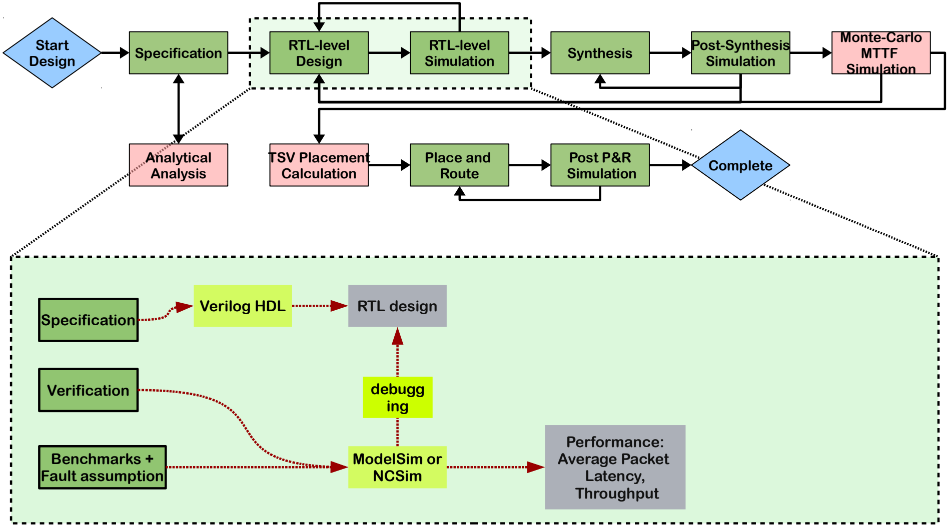

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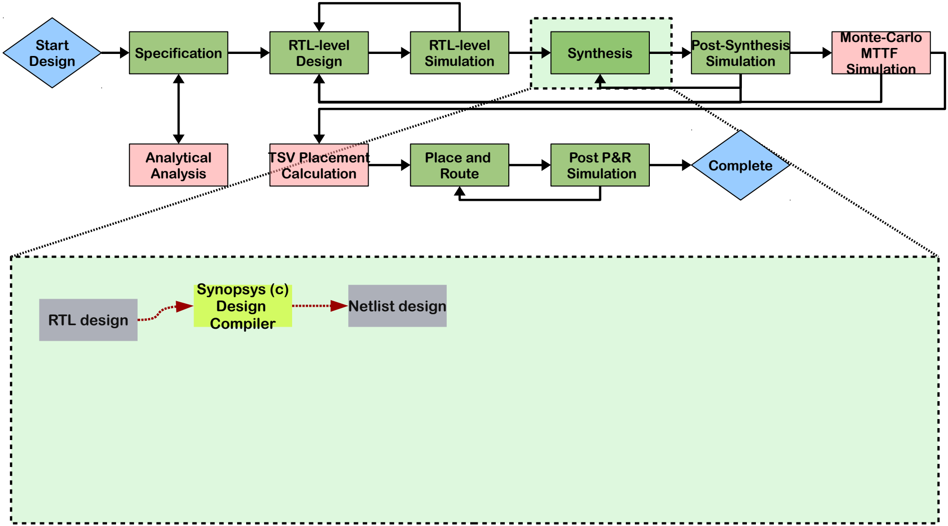

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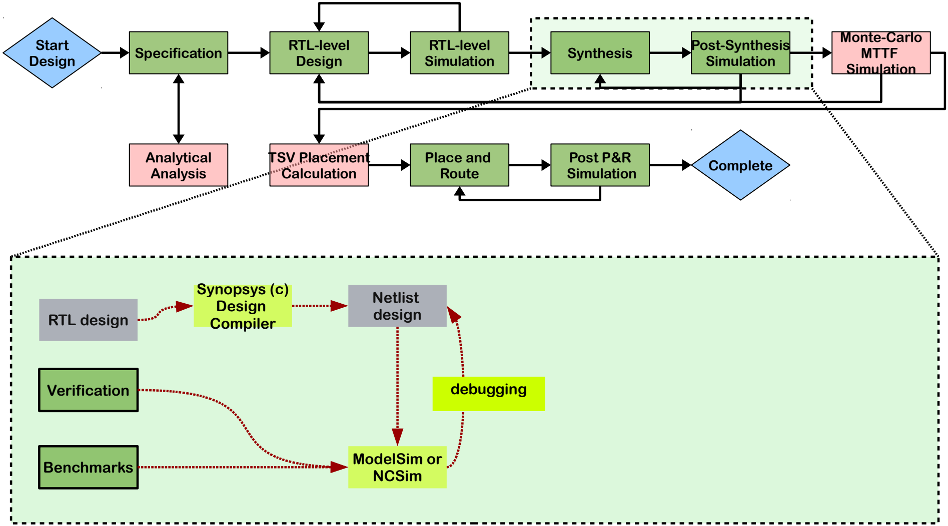
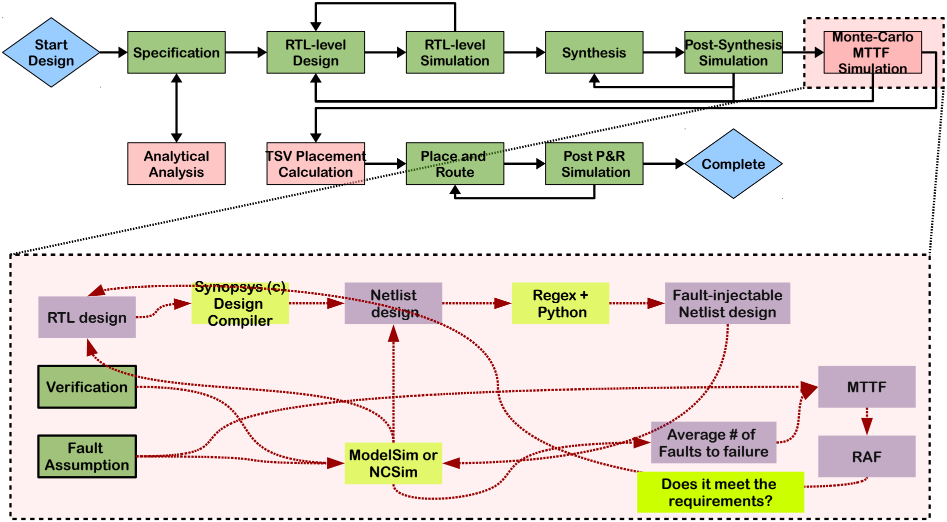


Evaluation Methodology



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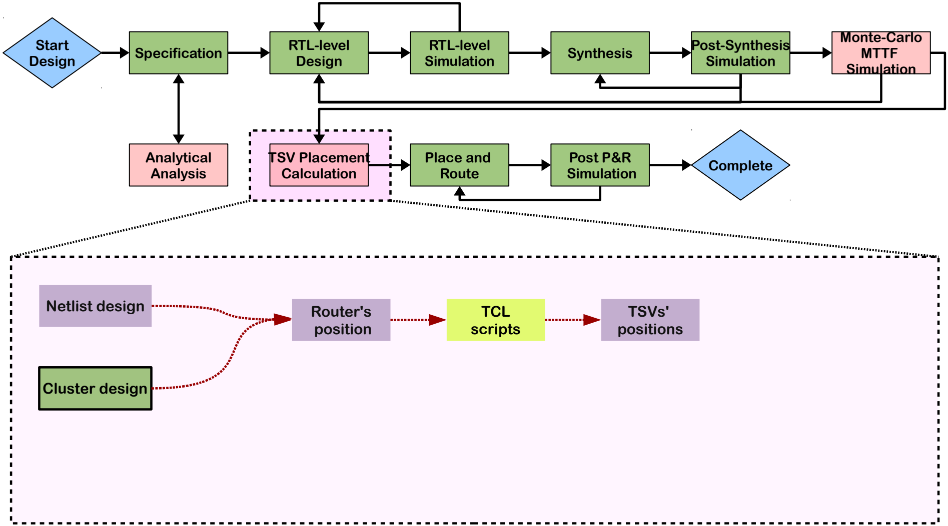

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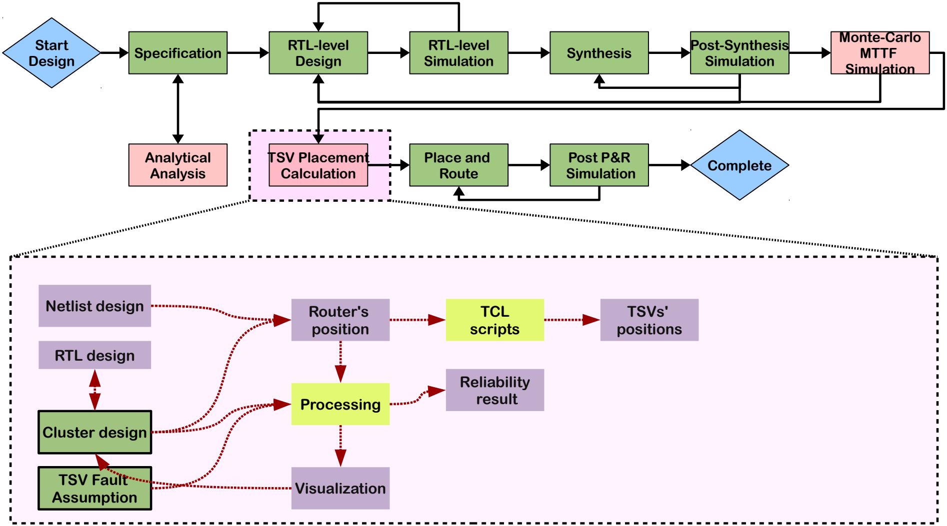

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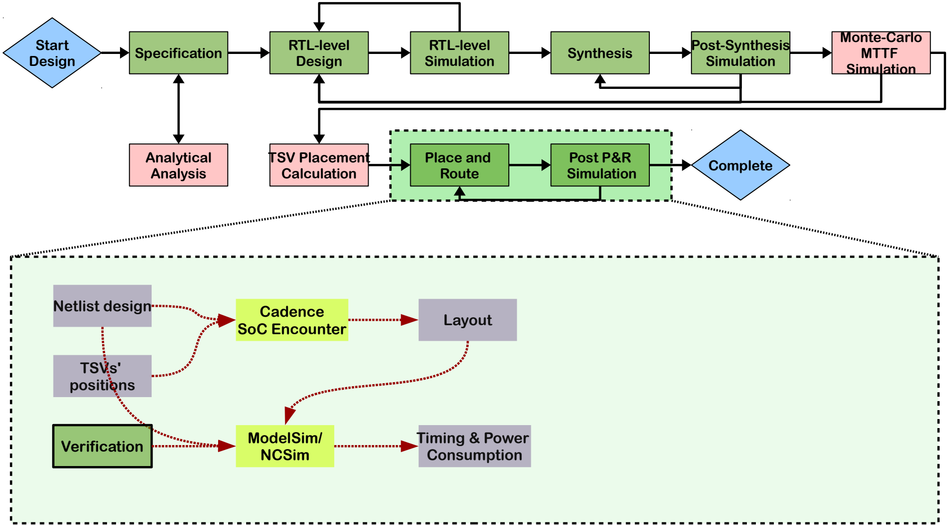


Evaluation Configuration and Assumption

Table 5: Technology parameters.

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

Fault-rate of hard faults:

- Percentage of routers having faults.
- There is no local link is failed.

Fault-rate of soft errors:

- For ECC, percentage of ARQ per flit.
- For PCR, percentage of error per executing clock cycle.

Fault-rate of TSV-cluster defects:

- No random defect.
- TSVs randomly fail in clusters.

Table 6: System configurations.

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

Table 7: Simulation configurations.

Parameter/System		Value
Network Size ($x \times y \times z$)	Matrix	$6 \times 6 \times 3$
	Transpose	$4 \times 4 \times 4$
	Uniform	$4 \times 4 \times 4$
	Hotspot 10%	$4 \times 4 \times 4$
	H.264	$3 \times 3 \times 3$
	VPOD	$3 \times 2 \times 2$
	MWD	$2 \times 2 \times 3$
	PIP	$2 \times 2 \times 2$
Total Injected Packets	Matrix	1,080
	Transpose	640
	Uniform	8,192
	Hotspot 10%	8,192
	H.264	8,400
	VPOD	3,494
	MWD	1,120
	PIP	512
Packet's Size	Hotspot 10%	10 flits+10% on hostpot nodes
	Others	10 flits

Reliability Assessment Accuracy Comparison

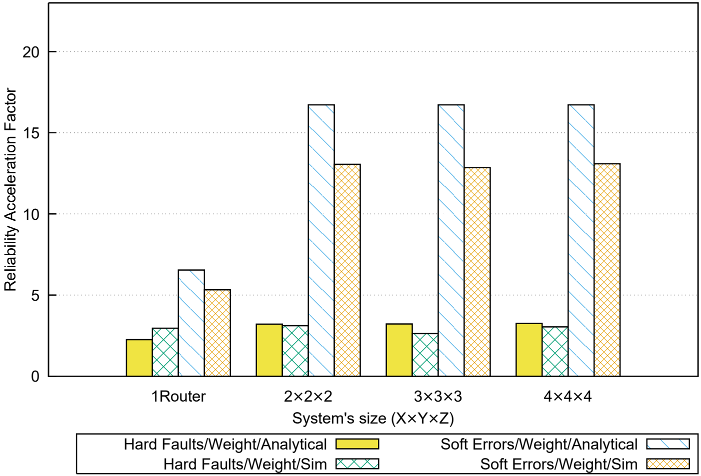


Figure 21: Comparison results between the analytical assessment and the Monte-Carlo MTTF simulation.

Average Packet Latency of realistic benchmarks

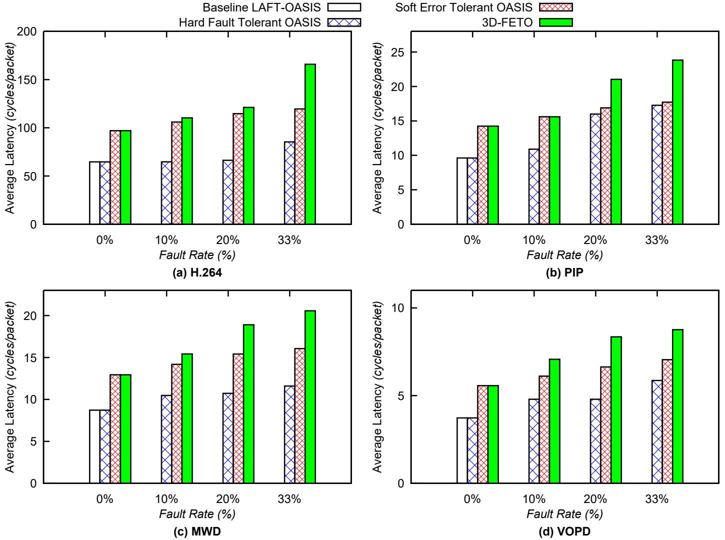
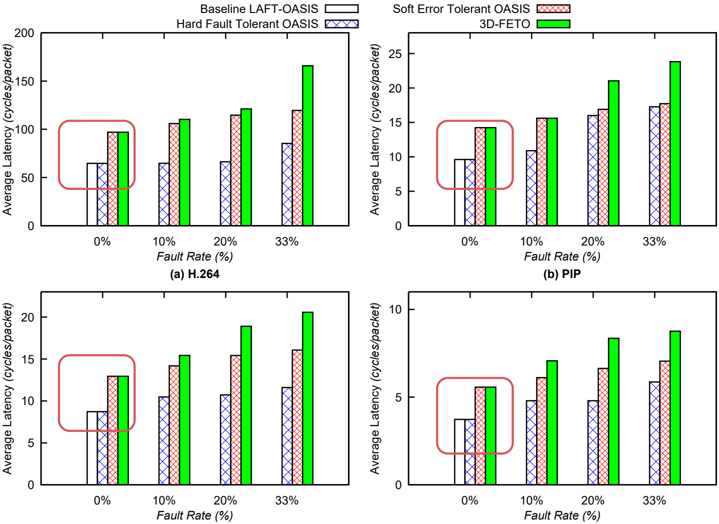


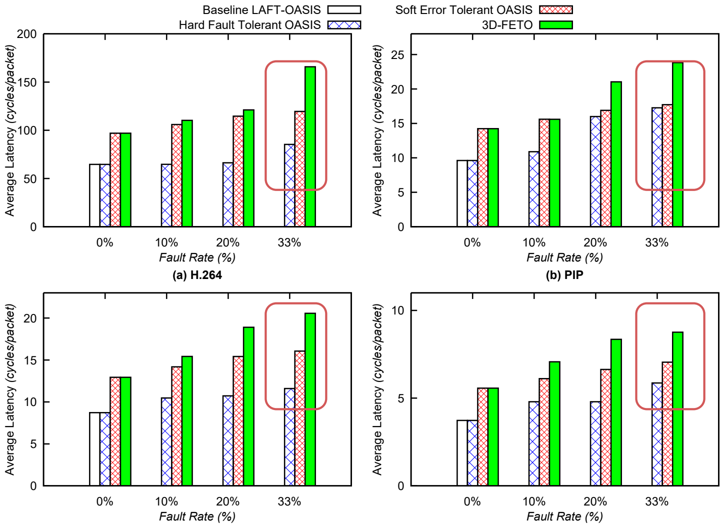
Figure 22: **Average packet latency** evaluation of the *realistic* benchmarks.

Average Packet Latency of realistic benchmarks



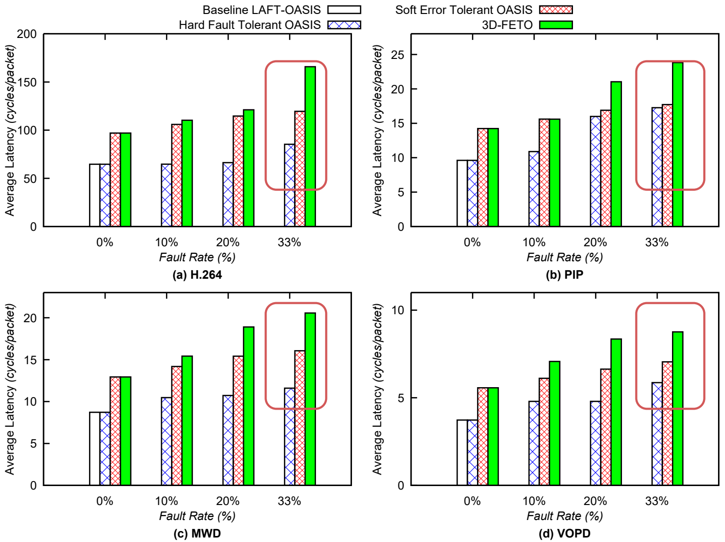
APL at **0%** of error rates, Soft Error Tolerant OASIS $\simeq$ 49.95% + the baseline.

Average Packet Latency of realistic benchmarks



APL at **33%** of error rates, Soft Error Tolerant OASIS $\leq$ 84.92% + the baseline.

Average Packet Latency of realistic benchmarks



APL at **33%** of error rates, 3D-FETO $\leq 2.5\times$ the baseline.

Throughput of synthetic benchmarks

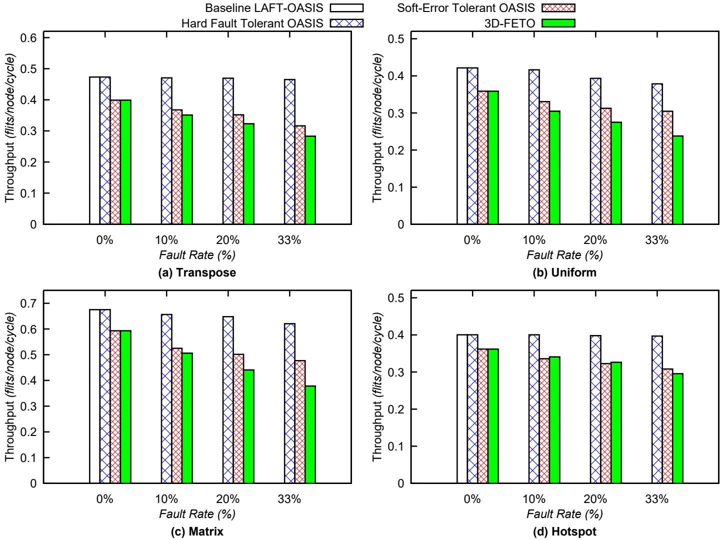
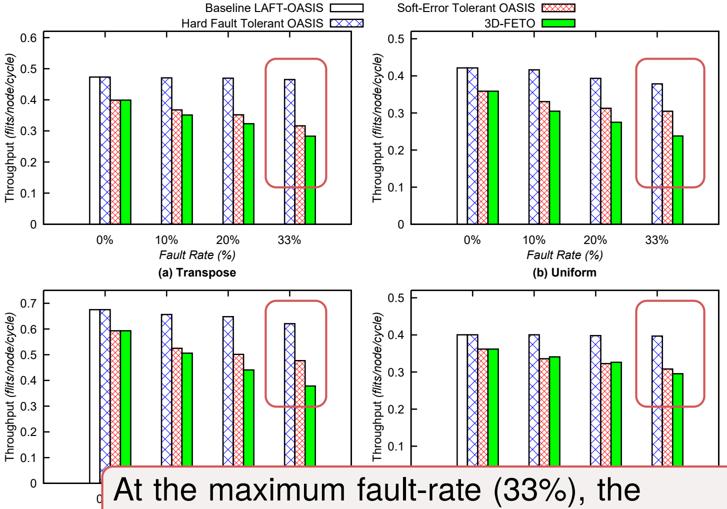


Figure 23: **Throughput** evaluation of the *synthetic* benchmarks.

Throughput of synthetic benchmarks



At the maximum fault-rate (33%), the throughput of 3D-FETO decreases less than 44%.

Figu

Comparison of Soft Error Tolerance

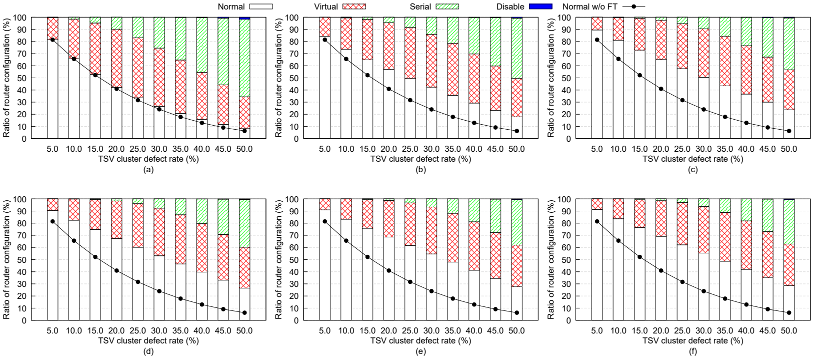
Model	TMR-OASIS[8]	[12]	[23]	PCR
Mechanism	Majority Voting	Monitor	Monitor	Monitor
Area Overhead	204.33%	9%	3% (average)	54.46%
RAF	$\simeq 1.33$	$\simeq 11.11$	$\simeq 1$ (only detection)	1.84
Delay (cycle)	+0	+0 (no fault) +1 (recovery)	0% (only detection)	+1 (redudancy) +2 (recovery)
Fault Coverage	100% of hard faults and soft errors	design specific (7 faults)	design specific (13 faults)	100% soft errors
Reovery method	immediately	re-execution	unsupport	re-execution

Summary:

- Pipeline Computation Redundancy (PCR) coverage the maximum soft errors (100%) under the assumption.
- The RAF value of PCR is smaller than the technique by Yu et al. [12].
- The area overhead of PCR is still smaller than the TMR method.

[8] Triple Modular Redundancy for SA and RC

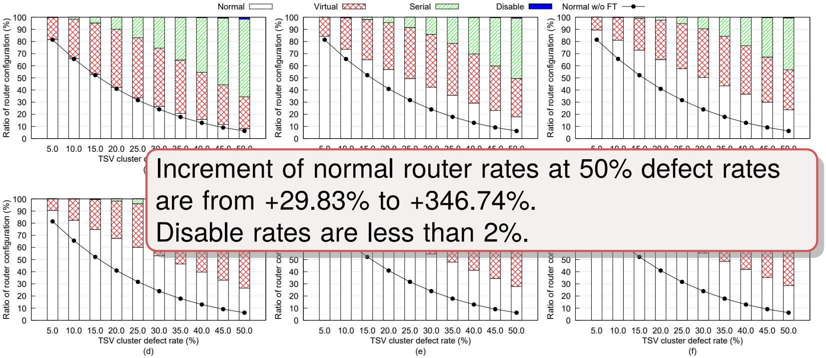
TSV-cluster: Reliability Evaluation



Defect-rate evaluation[9]: (a) Layer size: 2×2 (4 routers, 16 TSV clusters); (b) Layer size: 4×4 (16 routers, 64 TSV clusters); (c) Layer size: 8×8 (64 routers, 256 TSV clusters); (d) Layer size: 16×16 (256 routers, 1024 TSV clusters); (e) Layer size: 32×32 (1024 routers, 4096 TSV clusters); (f) Layer size: 64×64 (4096 routers, 16384 TSV clusters).

[9] We generate 100K cases and calculate the average value.

TSV-cluster: Reliability Evaluation

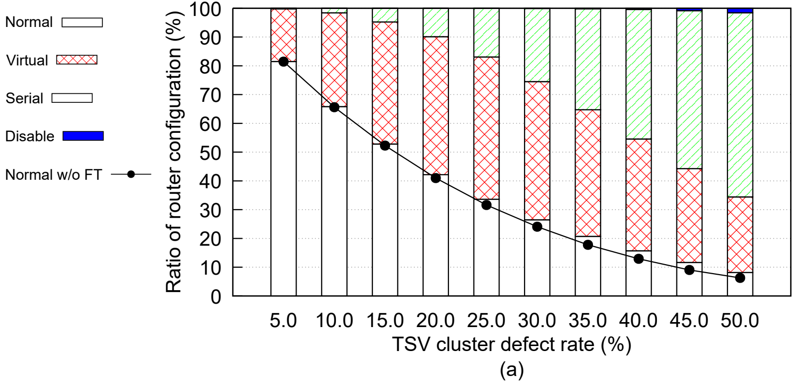


Increment of normal router rates at 50% defect rates are from +29.83% to +346.74%.
Disable rates are less than 2%.

Defect-rate evaluation[9]: (a) Layer size: 2×2 (4 routers, 16 TSV clusters); (b) Layer size: 4×4 (16 routers, 64 TSV clusters); (c) Layer size: 8×8 (64 routers, 256 TSV clusters); (d) Layer size: 16×16 (256 routers, 1024 TSV clusters); (e) Layer size: 32×32 (1024 routers, 4096 TSV clusters); (f) Layer size: 64×64 (4096 routers, 16384 TSV clusters).

[9] We generate 100K cases and calculate the average value.

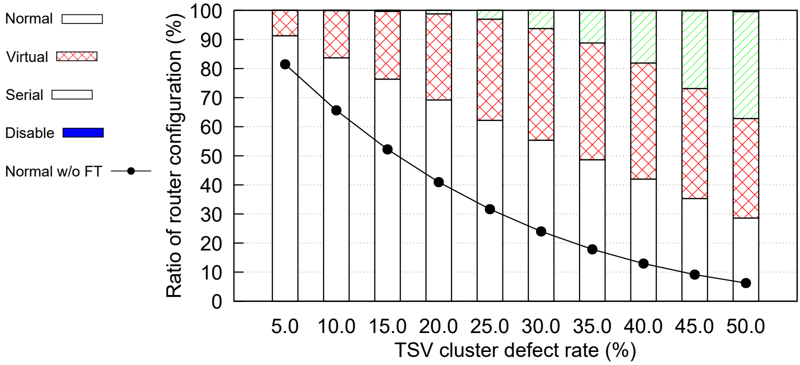
TSV Fault Tolerance Reliability Evaluation (cnt.)



Defect-rate evaluation: (a) *Layer size:* 2×2 (4 routers, 16 TSV clusters).

Normal router rates at 50% defect rates is increased by 29.83%.
Disable rates: 0.23% - 1.57%.

TSV Fault Tolerance Reliability Evaluation (cnt.)



(f)

Defect-rate evaluation: (f) *Layer size:* 64×64 (4096 routers, 16384 TSV clusters).

Normal router rates at 50% defect rates is increased by +257.79%.
Disable rates at 50% defect rates: 0.418%.

TSV Fault Tolerance Performance Evaluation

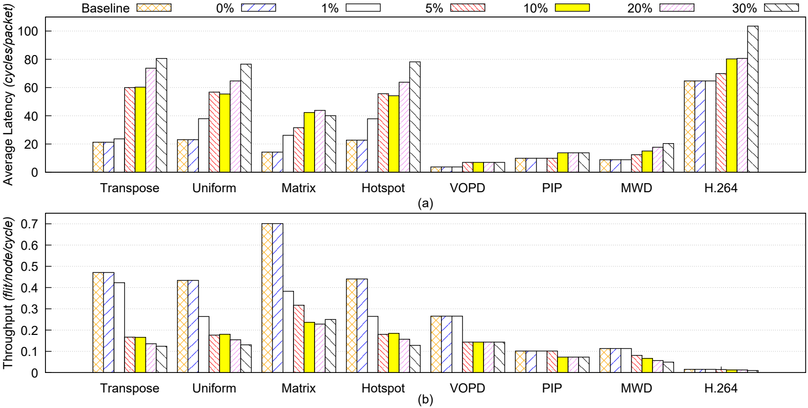


Figure 24: Evaluation result: (a) Average Packet Latency; (b) Throughput.

- Use the same configuration as 3D-FETO.
- Only cluster-TSV defects are randomly injected.

TSV Fault Tolerance Performance Evaluation

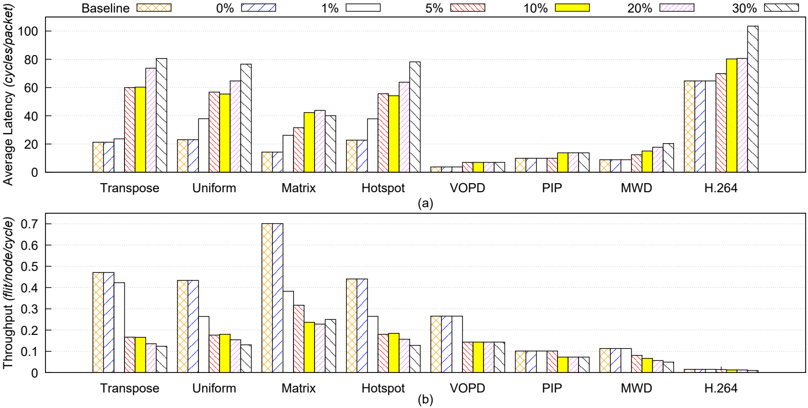


Figure 24: Evaluation result: (a) Average Packet Latency; (b) Throughput.

- Use th
- Only c

There are some benchmarks that even we increase the fault rate, the performance is stable or is lightly degraded. For example: PIP, VOPD, MWD.

TSV Fault Tolerance Performance Evaluation

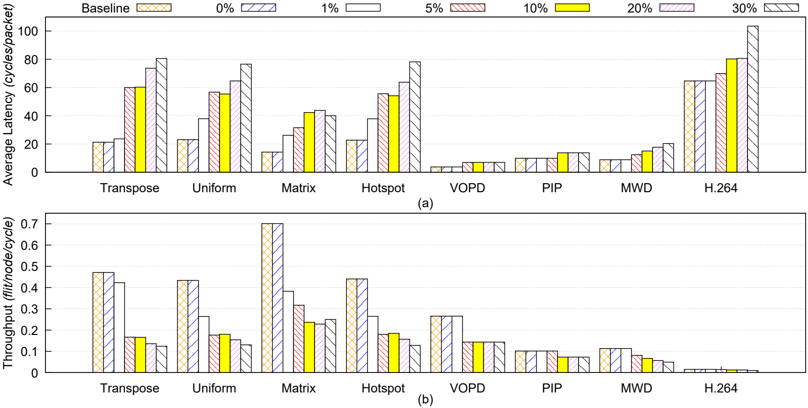


Figure 24: Evaluation result: (a) Average Packet Latency; (b) Throughput.

The impacts on synthetic benchmark is higher than realistic benchmarks. APL at 1% of defect rates: Matrix +83.24% while VOPD, PIP, MWD and H.264 +0%.

- Use th
- Only c

TSV Fault Tolerance Performance Evaluation

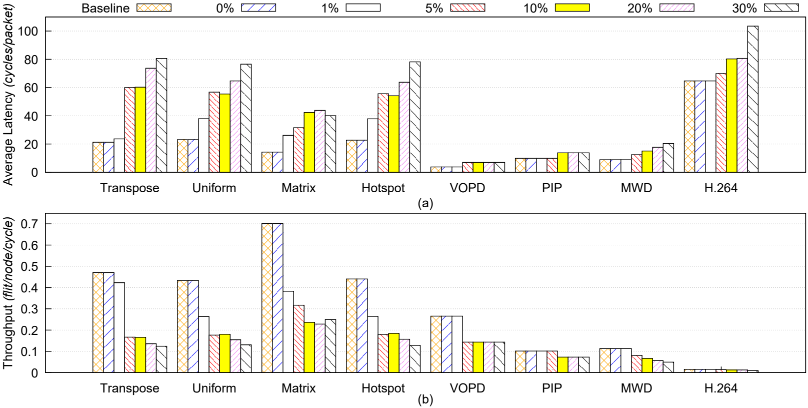


Figure 24: Evaluation result: (a) Average Packet Latency; (b) Throughput.

- Use th
- Only c

APL at 33% of defect rates: the synthetic benchmarks mostly ×3, the realistic traffics less than +129.91% (MWD).

Reliability and Area Cost Comparison of TSV Fault Tolerance

Model	*TSV Network* [10]				
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	*TSV Grouping* [11]			*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%
Fault Assumption	$(\delta_{TSV} = 1\%, \alpha = 2)$ [4]			$\delta_c = 50\%$ [4]	$\delta_c = 1\%$ [4]

[1] The authors use 2:1 multiplexers [11]. For comparison, we use the area cost of multiplexer from Nangate 45nm [24] (MUX2_X1: 0.186μm^2) .

[2] The authors use 1-to-3 multiplexers [10] which consists of two MUX2_X1 multiplexers ($2 \times 0.186 \mu m^2$ [24]).

[3] For fair comparisons, our arbiter only consists of the TSV sharing and serialization modules as shown in Table 9.

[4] δ: defect-rate. α: parameter of Poisson distribution [10, 11]. δ_c: cluster fault rate, δ_{TSV}: TSV fault rate.

Reliability and Area Cost Comparison of TSV Fault Tolerance

Model	TSV Network [10]				
Technology	65 nm				
#TSV	1000				
Configuration	4:2	8:2	$4 \times 4 : 8$	$8 \times 8 : 16$	$16 \times 16 : 32$
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#TSV	6000			8448	
Configuration	4:4	8:4	20:5	$11 \times 4 \times 4{:}0$	
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45nm Arbiter Area (μm^2)	11,160 [1]	11,160[1]	12,555[1]	434,784[3]	
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[1] The authors use 2:1 multiplexers [11]. For comparison, we use the area cost of multiplexer from Nangate 45nm [24]

0.186μm^2 [24]).

as shown in Table 9.

SV fault rate.

The average area of this work is similar with some cases but worse than the best case. However, this work consists of an online arbitration.

Reliability and Area Cost Comparison of TSV Fault Tolerance

Model	*TSV Network* [10]				
Technology	65 nm				
#TSV	1000				
Configuration	4:2	8:2	$4 \times 4 : 8$	$8 \times 8 : 16$	$16 \times 16 : 32$
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Average Area/TSV (μm^2)	151.572	126.244	152.316	126.716	128.03
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Fault Assumption	$(\delta_{TSV} = 0.01\%, \alpha = 2)$ [4]				

Model	*TSV Grouping* [11]			*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]	
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[1] The authors use 2:1 multiplexers [11]. For comparison, we use the area cost of multiplexer from Nangate 45nm [24] (MUX2_X1: 0.186μm^2) .

0.186μm^2 [24]).

as shown in Table 9.

SV fault rate.

In term of number of TSV, this work doesn't requires any redundancies.

Reliability and Area Cost Comparison of TSV Fault Tolerance

Model	*TSV Network* [10]				
Technology	65 nm				
#TSV	1000				
Configuration	4:2	8:2	$4 \times 4 : 8$	$8 \times 8 : 16$	$16 \times 16 : 32$
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[1] The authors use 2:1 multiplexers [11]. For comparison, we use the area cost of multiplexer from Nangate 45nm [24]

0.186μm^2 [24]).

as shown in Table 9.

TSV fault rate.

In term of reliability, this work provide extremely high working rate: 98.11% of routers even with 50% of clusters are defected..

Hardware Design Result (1/2)

Table 8: Design parameters.

Parameter	Value
Technology	Nangate 45 nm FreePDK3D45
Voltage	1.1 V
Chip's size	$865\mu m \times 865\mu m$
TSV's size	$4.06\mu m \times 4.06\mu m$
TSV pitch	10 μm
Keep-out Zone	15 μm

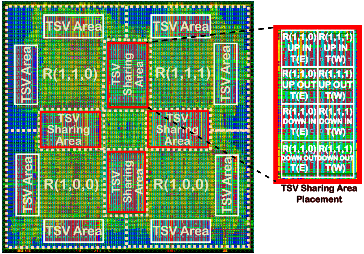

Figure 25: Single layer layout illustrating the TSV sharing areas (red boxes). The layout size is $865\mu m \times 865\mu m$. The sharing TSV area are the red boxes. Each sharing area has 8 clusters for 4 ports and 2 routers.

- Estimated 3D-NoC router layout area: $423.5\mu m \times 423.5\mu m$.
- Estimated 3D-NoC ($X \times Y \times Z$) layout area: Z layers $\times$ $X \times 423.5\mu m \times Y \times 423.5\mu m$
- E.g.: *MWD* ($X = 2$, $Y = 2$, $Z = 3$) needs 3D-NoC with layout of $3 \times 865\mu m \times 865\mu m$

Hardware Design Result (2/2)

Table 9: Hardware complexity of a single router.

Model		Area (μm^2)	Power (mW) Static	Power (mW) Dynamic	Power (mW) Total	Speed (Mhz)
Baseline router [25]		18,873	5.1229	0.9429	6.0658	925.28
3D-FTO [21] router[10]		19,143	6.4280	1.1939	7.6219	909.09
Soft Error Tolerance router[11]		27,457	9.7314	2.6710	12.4024	625.00
3D-FETO router[12]		29,516	10.0819	2.7839	12.8658	613.50
Final router[13]	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

[10] This router consists of RAB, BLoD, and LAFT.

[11] This router consists of ECC and PCR.

[12] This router consists all soft error and hard fault tolerant techniques: RAB, BLoD, LAFT, ECC and PCR.

[13] This router is 3D-FETO with TSV management.

Table of Contents

Discussion and Conclusion

- This dissertation provides a set of on-chip communication fault-resilient adaptive architectures and algorithms for 3D-NoC IC technologies.
- Moreover, a reliability assessment platform is also presented to help designer estimate the reliability of NoC systems.
- Specifically, Pipeline Computation Redundancy is proposed to handle the soft errors on pipeline stage.
- Detection, Diagnosis, and Recovery Mechanism is also present to on-line handle the hard faults.
- A sharing TSV architectures, algorithms and optimization are proposed and provide a high reliability while are still ensuring a graceful degradation in terms of performance, power, speed and area.

Discussion and Conclusion

- The proposed reliability assessment gives a faster estimation without the need of detailed design.
- The soft error hard fault tolerance system suffer about 40% of throughput; however, it ensures an extremely high fault rate (33%).
- TSV sharing provides nearly 99% of working connection and improves from 29% to 340% of fully worked connection.
- The performances of TSV-cluster fault tolerant system are prominent where the realistic traffic patterns show the similar performance even with higher defect rate.

Future Works

- Further research is needed about the **thermal awareness** in terms of design, routing and reliability.
- An in-depth study on **stress issues** is also necessary to understand the potential defects.
- Fault-tolerance also need to be covered in application layers with a cross-layers protocol.

List of publication (1/2)

Refereed Journals

1. **Khanh N. Dang**, Michael Meyer, Yuichi Okuyama and Abderazek Ben Abdallah, “A Low-overhead Soft-Hard Fault Tolerant Architecture, Design, and Management Scheme for Reliable High-performance Many-core 3D-NoC Systems”, *The Journal of Supercomputing*, pp. 1-25, January 2017. **[MAJOR]**

Refereed Refereed International conferences

1. **Khanh N. Dang**, Michael Meyer, Yuichi Okuyama and Abderazek Ben Abdallah, “Reliability Assessment and Quantitative Evaluation of Soft-Error Resilient 3D Network-on-Chip Systems”, The IEEE 25th Asian Test Symposium (ATS), pp. 161-166, Hiroshima, Japan, November 21-24, 2016. **[MAJOR]**
2. **Khanh N. Dang**, Yuichi Okuyama, and Abderazek Ben Abdallah, “Soft-error resilient network-on-chip for safety-critical applications”, *The 2016 International Conference on IC Design and Technology (ICICDT)*, pp. 1-4, Ho Chi Minh City, Vietnam, June 27-29, 2016. **[MAJOR]**
3. **Khanh N. Dang**, Michael Meyer, Yuichi Okuyama, Abderazek Ben Abdallah, and Xuan-Tu Tran, “Soft-error resilient 3d network-on-chip router”, *The 2015 IEEE 7th International Conference on Awareness Science and Technology (iCAST)*, pp. 84-90 Qinhuangdao, China, September 22-24, 2015. **[MAJOR]**

List of publication (2/2)

Under Re-revision

1. **Khanh N. Dang**, Akram Ben Ahmed, Xuan-Tu Tran, Yuichi Okuyama and Abderazek Ben Abdallah, “A Comprehensive Reliability Assessment of Fault-Resilient Network-on-Chip Using Analytical Model”, *IEEE Transactions on Very Large Scale Integration Systems*, **[MAJOR]**, *Submitted on February 1, 2017.*

Under Review

1. **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*. **[MAJOR]**, *Submitted on March 1, 2017.*

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Thank you for your attention!

Backup slides

Optimizations for TSV Sharing

Although TSV sharing significantly enhances the reliability of the vertical connection, there are additional optimizations:

1. **Weight Adjustment**: after finishing the sharing process, there is a chance that a *disabled lower weight* router can borrow a *disabled higher weight router* a cluster to obtain 4 clusters. Therefore, **Weight adjustment** will reduce the weights of the disabled and higher weight routers to optimize.
2. **Virtual TSV**: when a router does not have 4 TSV-clusters, it can *temporarily* borrow one of its neighbors for communication. This only happens when the neighbor is free to be borrowed.
3. **Serialization**: when even borrowing cannot help the router to obtain 4 clusters, it can perform a serialization mode. Instead of 1 flit/clock cycle, it takes 2 or 4 cycles.
4. **Fault-tolerant routing**: at a high fault rate, a router even has no cluster for communication.

Reliability Assessment Configuration

In order to assess the reliability, we first select a random weight where more faults are injected in the protected module. In addition, we extracted the ratio of area cost from hard ware complexity[14].

Table 10: Router's Weight and Gate Ratio.

Module	Submodule	Weight	Gate Ratio
Network	Network	100%	100%
	Routers	70%	100%
	Channels	30%	0%
Router	Router	100%	100%
	Input Buffer	69.72%	7.90%
	Crossbar	8.00%	11.43%
	Switch-Allocator	7.00%	16.97%
	Others	15.28%	63.7%

[14]The used router is 3D-FETO (without TSV fault-tolerance).

```
// 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"
```

Algorithm 4: 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 minir
        and TSV_Status_neighbor[
        if (c==NULL) then
            return RQ_link[i] =
            return Router_Stat
        else
            return RQ_link[i] = c
            return Router_Status = "NORMAL"
```

Initialization: the inputs are the weights and TSV-cluster status of current and neighboring routers.

Algorithm 5: 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 minir
        and TSV_Status_neighbor[
        if (c==NULL) then
            return RQ_link[i] =
            return Router_Stat
        else
            return RQ_link[i] = c
            return Router_Status = "NORMAL"
```

Initialization: the output are the router status and the request signals to neighboring routers.

Algorithm 6: 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 minim
        and TSV_Status_neighbor[
        if (c==NULL) then
            return RQ_link[i] =
            return Router_Statu
        else
            return RQ_link[i] = c
            return Router_Status = "NORMAL"
```

Checking the current TSV status: if all TSV clusters are normal, there is nothing to do.

Algorithm 7: TSV Sharing Algorithm.

```
// Weight values of the current router and its N neighbors
Input: Weight_current, Weight_neighbo
// Status of current and neighb
Input: TSV_Status_current[1 : N], T
// Request to link TSV-clusters
Output: RQ_link[1 : N]
// Current router status
Output: Router_Status
foreach TSV_Status_current[i] do
    if TSV_Status_current[i] == “N
        // It is a healthy TSV
        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”
```

> *Find a replacement for the failed/borrowed clusters*: if there are failed/borrowed TSV clusters , the router finds replacement and sends request signal. If it cannot find, it turns into ‘DISABLE’ mode.

Algorithm 8: TSV Sharing Algorithm.

```
// Weight values of the current router and its N neighbors
Input: Weight_current, Weight_neighbor[1 : N]
```

Conditions:

1. Candidate c should have smaller weight than the current router.
2. Candidate c should have the smallest weight among the possible ones.
3. The TSV cluster from c should be NORMAL.

```
    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"
```

Algorithm 9: TSV Sharing Algorithm.

Overview of PCR

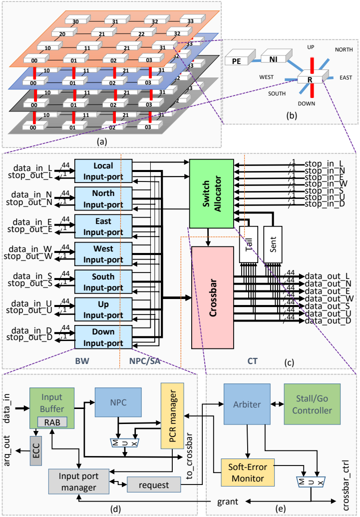


Figure 26: High-level view of the soft-hard error recovery approach: (a) 3D-Mesh based NoC configuration; (b) Tile organization; (c) SHER-3DR router organization; (d) Input-Port; (e) Switch allocation unit.

Speedup of the assessment method

Table 11: Reliability Assessment Speedup.

Evaluated module	A MTTF simulation	Proposed method	Speedup
A router	11 hours	0.090 second	440,000
A $2 \times 2 \times 2$ network	20 hours	0.091 second	791,209
A $3 \times 3 \times 3$ network	2 days	0.092 second	1,878,261
A $4 \times 4 \times 4$ network	3.5 days	0.109 second	2,774,312

Scaling of network reliability

The network reliability doesn't scale up with network size:

- Router vs network: Since router reliability doesn't have the flexibility as inside the network, its reliability is less than the network. E.g. router inside a network can choose an alternative routing path
- The verification of network reliability is uniform, where each node has to send to ever node.
- So, the most critical routing path is actually two neighboring router instead of long routing path.
- Therefore, the fault-tolerant algorithm benefit the reliability but not extremely enhance.

Scaling of network reliability (cnt.)

- We use *k-failure* model to represent that with k failures, a node is disconnected. The k value is either 3 (corner routers), 4(edge routers), 5 (side routers) or 6 (middle routers). There is an improvement while increasing the network size.
- There is a domination of local (router-PE) failure that reduce the overall reliability.

$$\lambda_{RTR} = P_{corner} \times \lambda_{corner} + P_{edge} \times \lambda_{edge} + P_{side} \times \lambda_{side} + P_{middle} \times \lambda_{middle} \quad (11)$$

λ_{corner}, λ_{edge}, λ_{side}, and λ_{middle} are calculated using model 1: m=1, n = k and r= 0. The based element is $\lambda_{conn.}$:

$$\lambda_{conn.} = \lambda_{1-input-buffer} + \lambda_{1-crossbar-link} + \lambda_{1-router-channel} \quad (12)$$

Throughput of realistic benchmarks

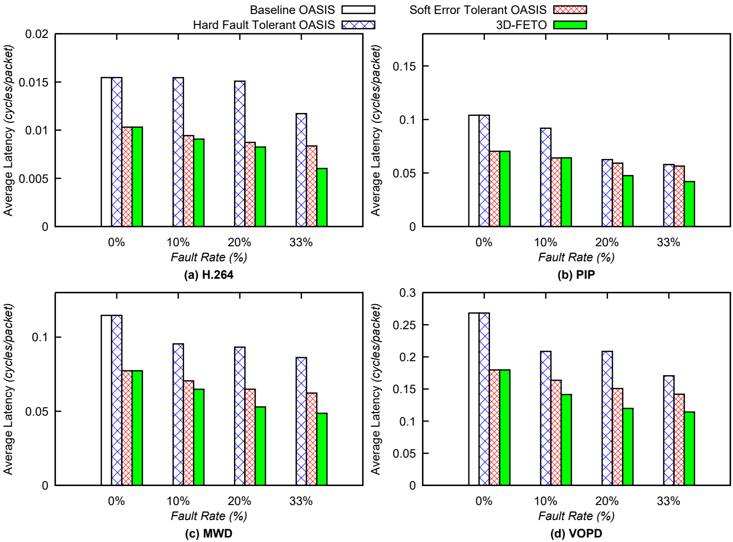


Figure 27: **Throughput** evaluation of the *synthetic* benchmarks.

Reliability Assessment Accuracy Comparison (2)

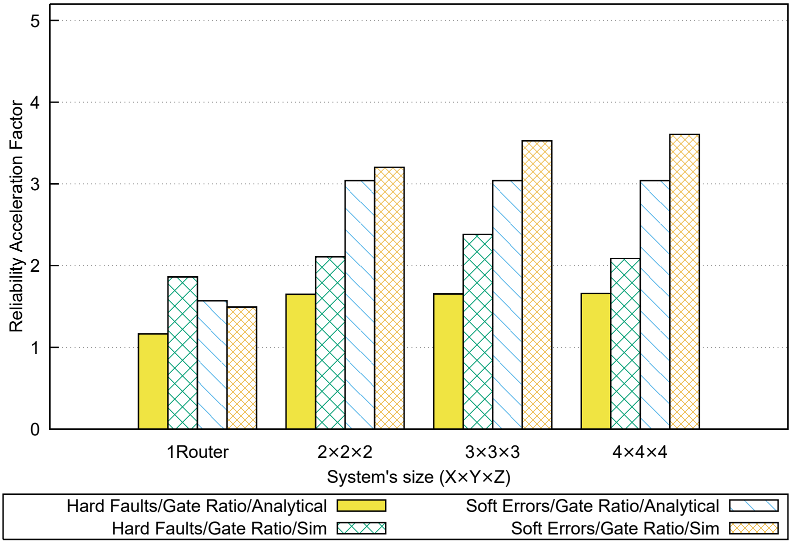


Figure 28: Comparison results between analytical assessment and Monte-Carlo MTTF simulation (cnt.).

Average Packet Latency of synthetic benchmarks

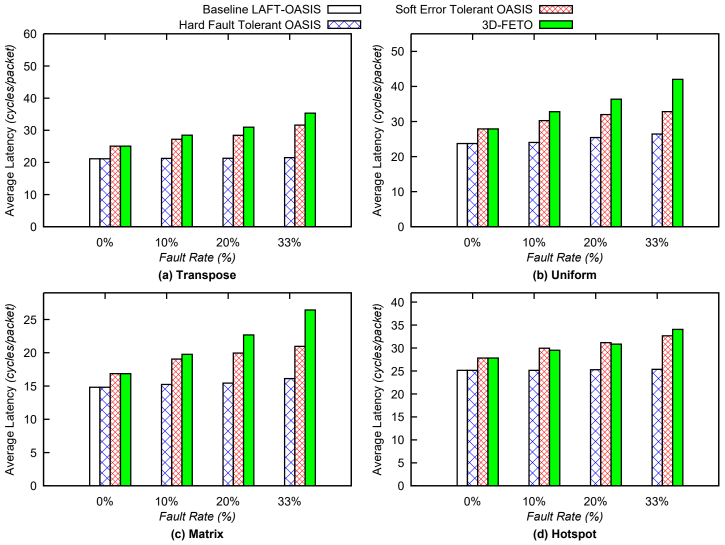


Figure 29: **Average packet latency** evaluation of the *synthetic* benchmarks.

Average Packet Latency of synthetic benchmarks

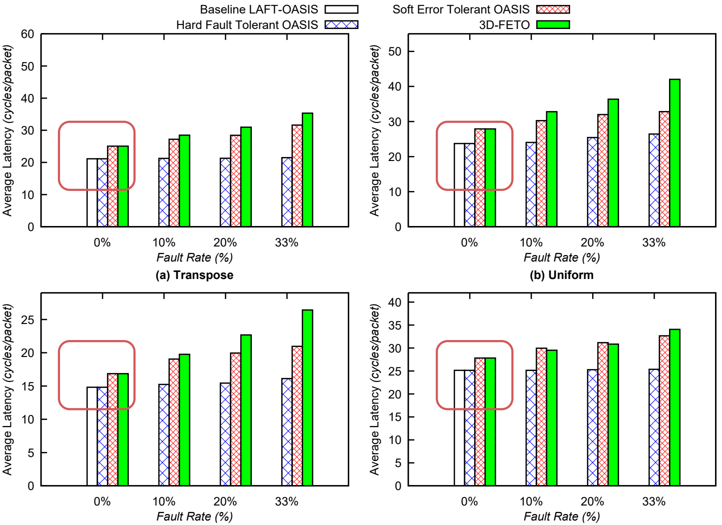


Figure 29: **Ave**

APL at **0%** of error rates, Soft Error Tolerant OASIS $\simeq$ 20% + the baseline.

Average Packet Latency of synthetic benchmarks

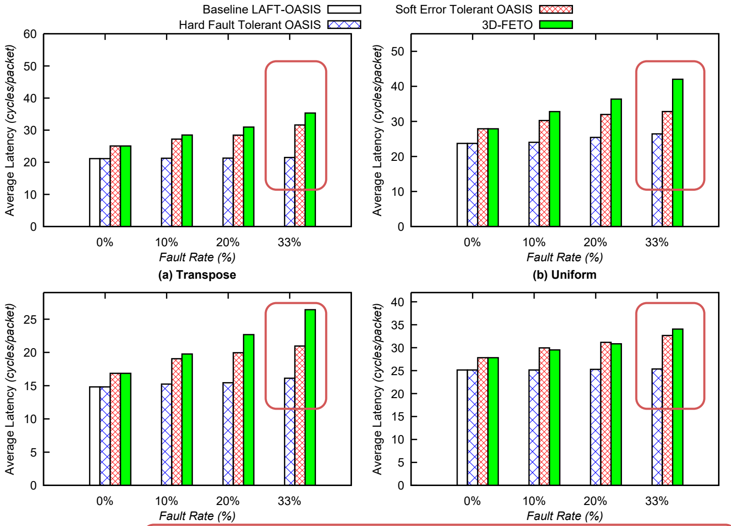


Figure 29: **Ave**

APL at **33%** of error rates, Soft Error Tolerant OASIS $\leq$ 50% + the baseline.

Average Packet Latency of synthetic benchmarks

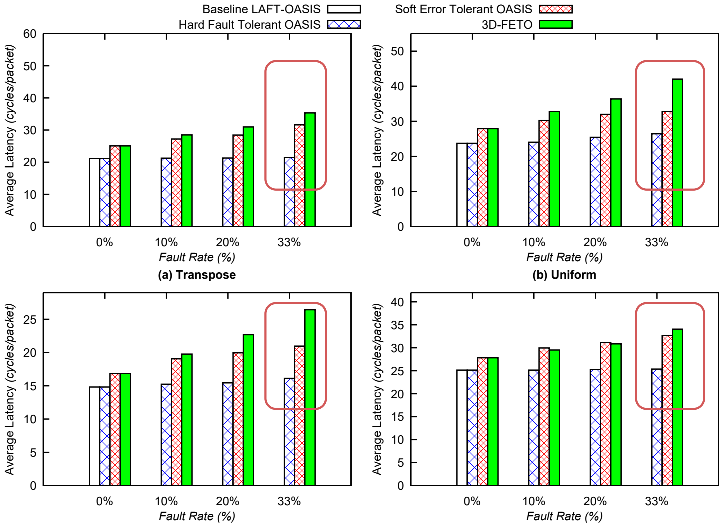


Figure 29: **Ave**

APL at **33%** of error rates, 3D-FETO $\leq$ 79% + the baseline.

Detail of Benchmark

Benchmark	Description	
Transpose	Each node (a,b,c) in a network with (X,Y,Z) sends packets to node (X-a, Y-b, Z-c)	
Uniform	Each node in a network sends packets to all nodes	
Matrix-multiplication	Performs C=A*B. Matrix A is stored in layer-1, is sent to layer-2 which has matrix B. The final values are accumulated in layer-3 as matrix C.	
Hotspot 10%	Each node in a network sends packets to all nodes. X (X=1 or 2 or more) nodes have additional 10% amount of traffic.	
Realistic Traffic Pattern	Generate from task graphs which provide the connections (e.g: node A→B) and the traffic (e.g: 100 packets).	

⇒ The following slides will explain these benchmarks in details.

Transpose algorithm

```
// Network
Input: Network(X, Y, Z)
// Amount of data for each communication
Input: D
// Communication set
Output: C = {c_i : (source → destination, amount of data)}
foreach node (a,b,c) in Network(X, Y, Z) do
    add ((a, b, c) → (X − a − 1, Y − b − 1, Z − c − 1), D packets) to C
return C
```

Algorithm 10: Transpose Algorithm.

Uniform algorithm

// Network
Input: $Network(X, Y, Z)$
// Amount of data for each communication
Input: D
// Communication set
Output: $C = \{c_i : (source \rightarrow destination, \text{amount of data})\}$

foreach *node (a,b,c) in* $Network(X, Y, Z)$ **do**
    foreach *node (m,n,p) in* $Network(X, Y, Z)$ **do**
        add $((a, b, c) \rightarrow (m, n, p)$, D packets) **to** C

return C

Algorithm 11: Uniform Algorithm.

Matrix-multiplication algorithm

```
Input: layerA(n, n), layerB(n, n), layerC(n, n),
Input: A(n, n), B(n, n)
Output: C(n, n)
foreach node (i,j) in layerA(n, n) do
    send A(i,j) → layerB(j,i)
foreach node (i,j) in layerB(n, n) do
    receive A(j,i)
    R(i, j) = A(j, i) × B(i, j)
    foreach k in 1:n do
        send R(i,j) → layerC(i,k)
foreach node (i,j) in layerC(n, n) do
    foreach k in 1:n do
        send C(i,j) = C(i,j) + R(k,i)
return C(n, n) from layerC(n, n)
```

Algorithm 12: Matrix-multiplication Algorithm.

Hotspot algorithm

```
// Network
Input: Network(X, Y, Z)
// Amount of data for each communication
Input: D
// Extra percentage of hotspot node
Input: E
// Communication set
Output: C = {c_i : (source → destination, amount of data)}
foreach node (a,b,c) in Network(X, Y, Z) do
    foreach node (m,n,p) in Network(X, Y, Z) do
        if node (m,n,p) is hotspot node then
            add ((a, b, c) → (m, n, p), (D+D*E/100) packets) to C
        else
            add ((a, b, c) → (m, n, p), D packets) to C
return C
```

Algorithm 13: Hotspot Algorithm.

Algorithm of Realistic Benchmark

Input: $Network(X, Y, Z)$

// Communication set

Input: $C = \{c_i : (source \rightarrow destination, D, O)\}$

ProgramCounter = 0;

foreach *node (i,j,k) in* $Network(X, Y, Z)$ **do**

    foreach c_i *in C* **do**

        if $c_i(source) == (i, j, k)$ *and ProgramCounter == O* **then**

            send (i,j,k) $\rightarrow c_i(destination)$ with $c_i(D)$ packets.

        if $c_i(destination) == (i, j, k)$ *and ProgramCounter == O* **then**

            receive $c_i(D)$ packets.

if *all destinations completedly receive their own* $c_i(D)$ *packets* **then**

    ProgramCounter++;

Algorithm 14: Realistic Benchmark Algorithm.

Task mapping (1/5)

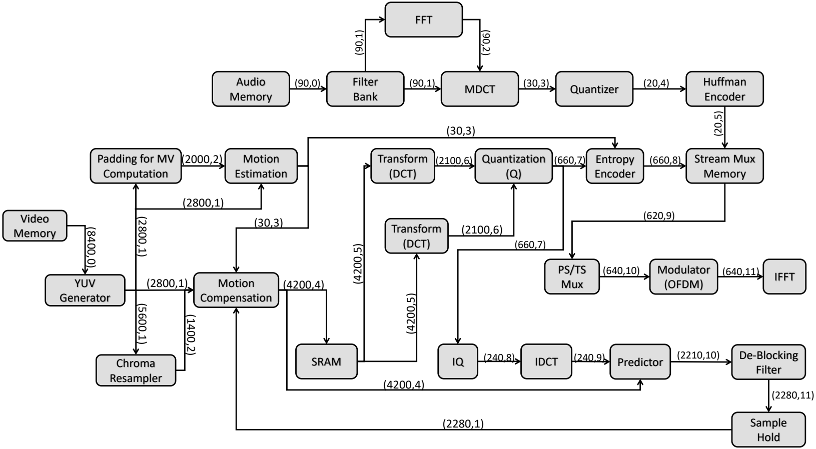


Figure 30: H.264 Task Graph.

Task mapping (2/5)

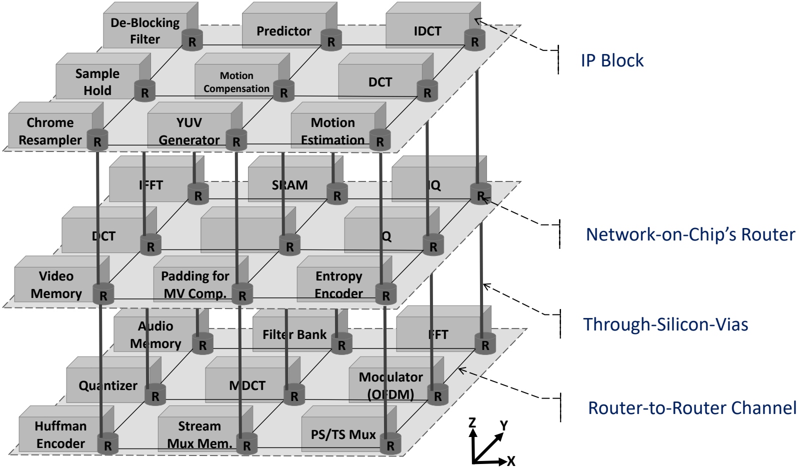


Figure 31: H.264 Task Map.

Task mapping (3/5)

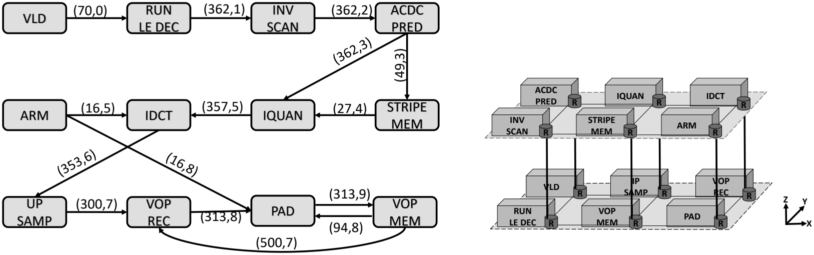


Figure 32: VOPD Task Map.

Task mapping (4/5)

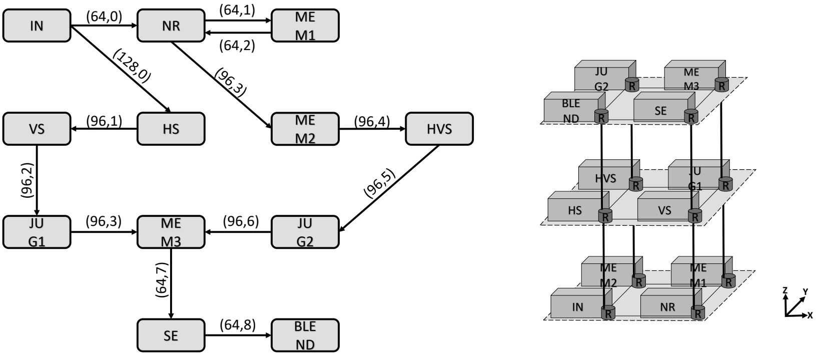


Figure 33: MWD Task Map.

Task mapping (5/5)

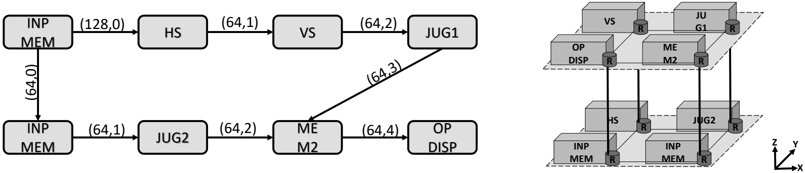


Figure 34: PIP Task Map.

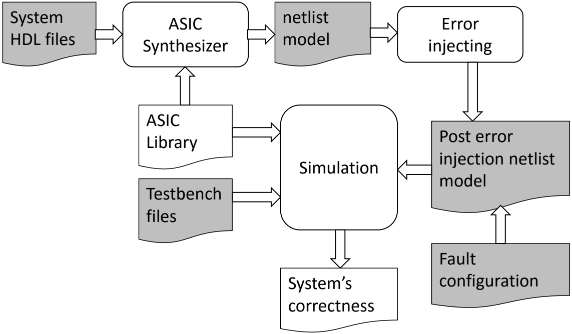


Figure 35: Monte-Carlo setting up flow.

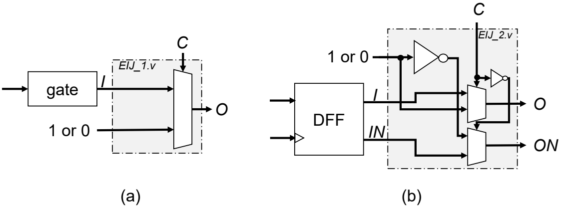


Figure 36: Error Injector architecture (a) Single output gate, (b) Flip-flop with two outputs.

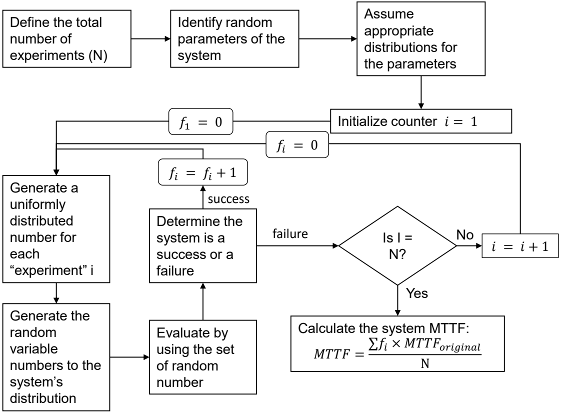


Figure 37: MTTF Monte-Carlo simulation process.

Netlist simulation

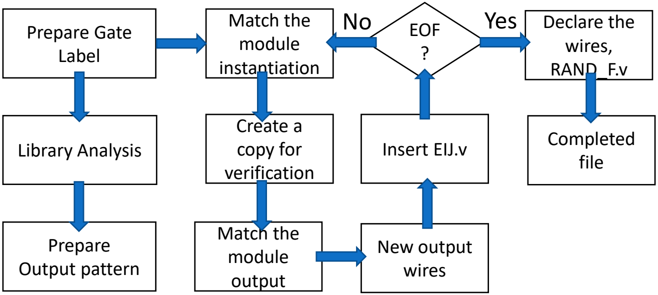


Figure 38: Flow chart of error injector inserting.

Netlist simulation

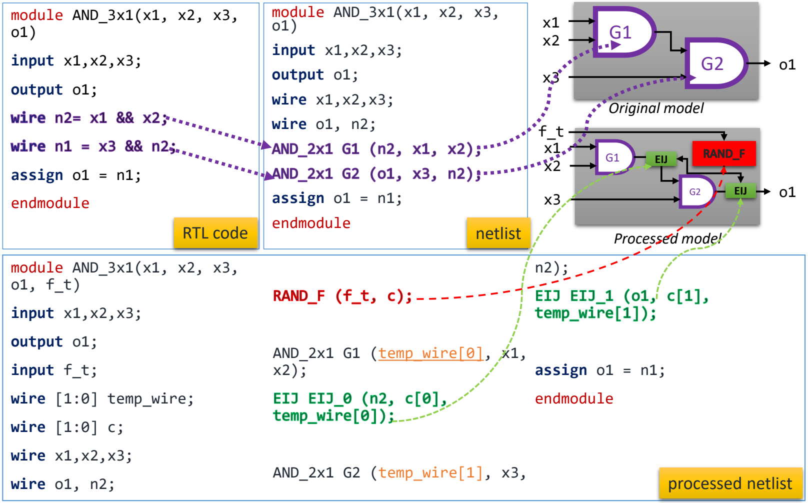
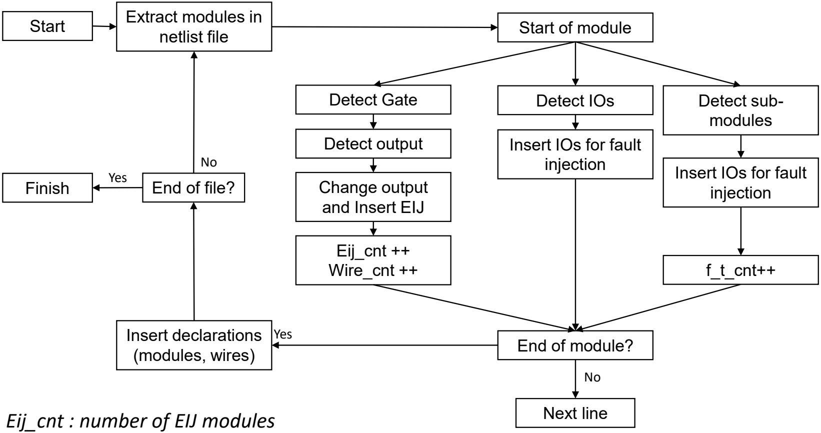


Figure 39: An example of input and output of the netlist processing.

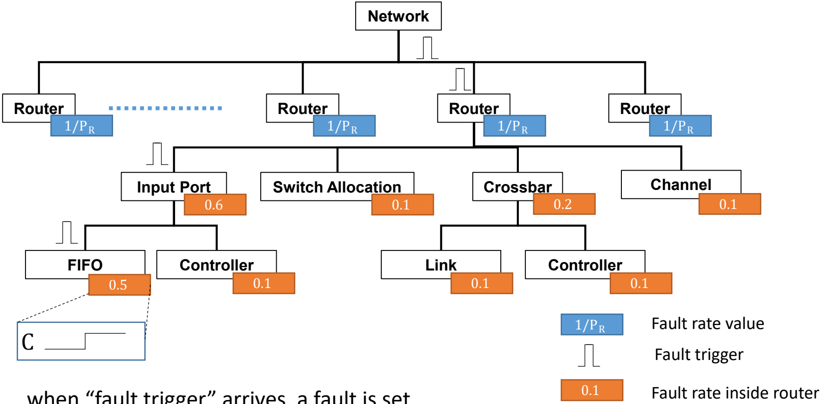
Netlist simulation



Eij_cnt : number of EIJ modules
Wire_cnt: number of temporal wires
f_t_cnt: number of trigger signals

Figure 40: Netlist processing for multiple modules file.

Netlist simulation



when “fault trigger” arrives, a fault is set in a randomized indexed gate.
For example: C =1 makes the corresponded EIJ injects a fault

The values 0.1 are loaded from configuration files.

Figure 41: Fault trigger.