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FTHOE: a Hamiltonian-driven fault-tolerant routing algorithm for wafer-scale interconnection networks

Key words: Wafer-scale system; Fault-tolerant; Hamiltonian path; Odd–even turn model; Load balancing

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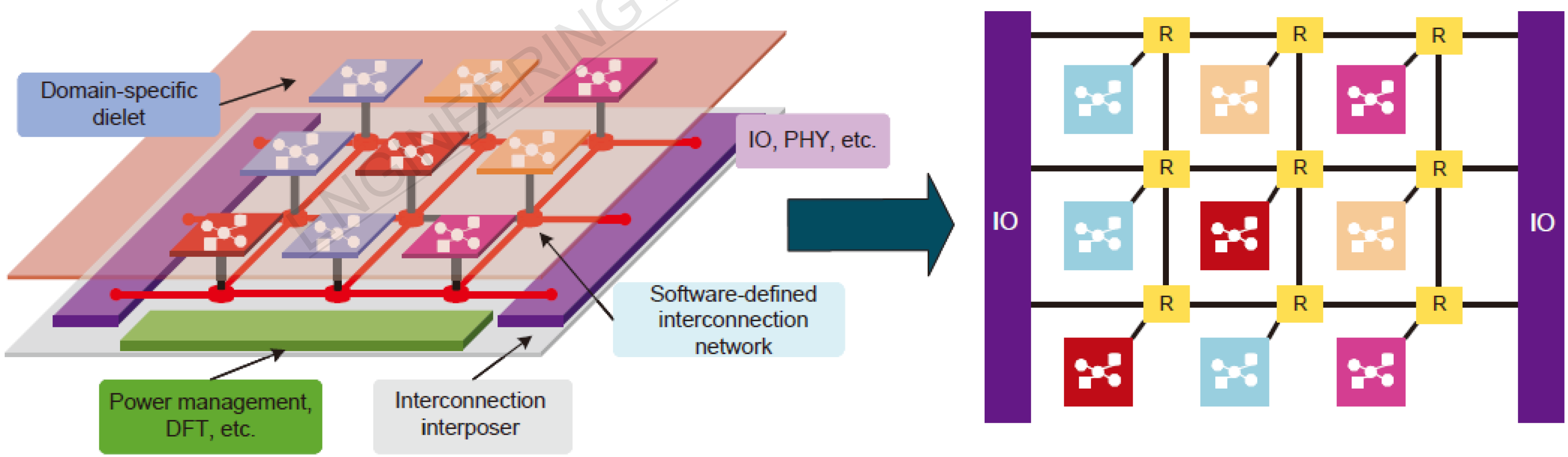
Research background

Large-scale wafer systems face significant communication challenges due to inevitable hardware faults.

- Wafer-scale systems integrate thousands of processing elements on a single wafer, enabling extremely high computing capabilities.
- However, manufacturing defects inevitably introduce faulty nodes and links, posing serious challenges to on-chip communication.
- Efficient and fault-tolerant routing is therefore critical.

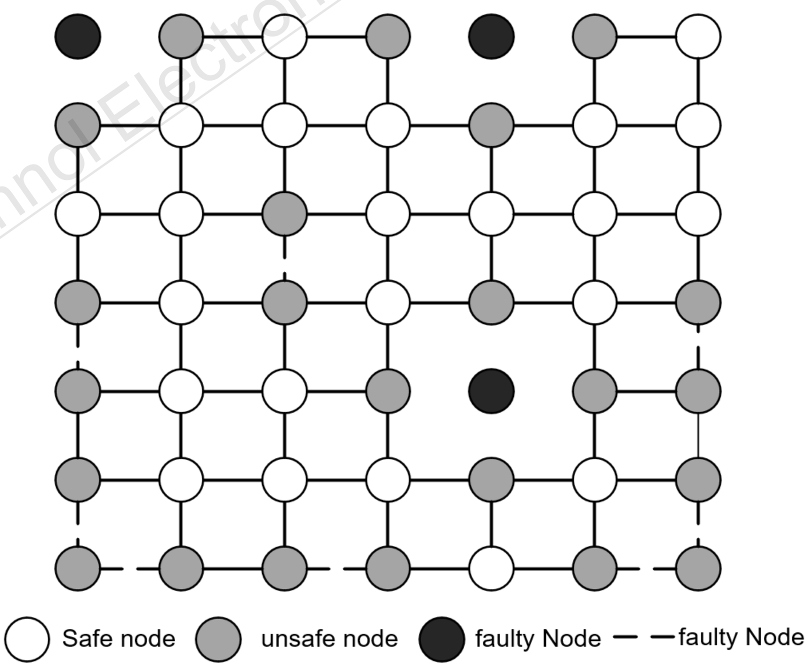


Research problem

Existing routing methods struggle to achieve both fault-tolerance and low routing complexity

Many conventional routing algorithms are designed for fault-free networks.

- **Deterministic routing (e.g., XY routing) cannot bypass faults**
- **Some fault-tolerant methods introduce high routing complexity**
- **Maintaining both deadlock freedom and high performance remains challenging**



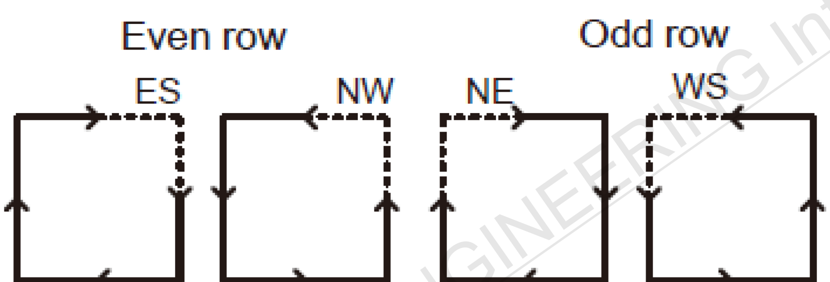
How can we design an efficient fault-tolerant routing algorithm for wafer-scale networks?

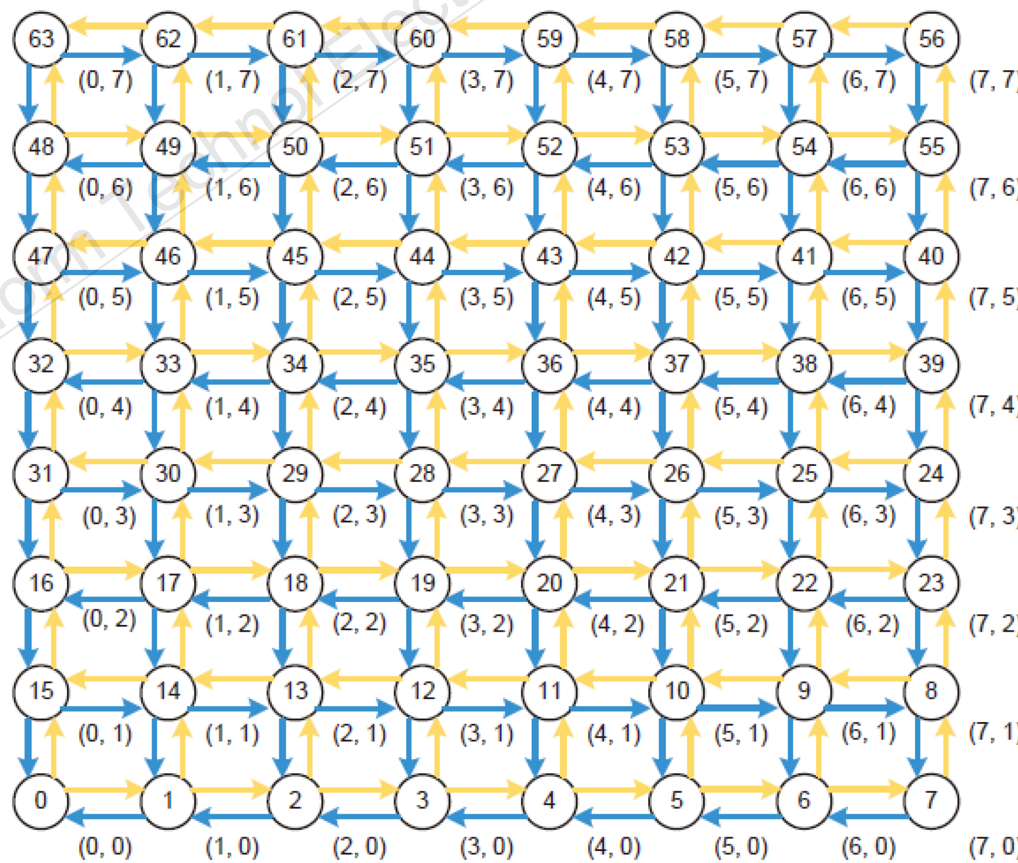
Core Idea of FTHOE

FTHOE is a Hamiltonian-guided fault-tolerant routing algorithm.

It combines the advantages of:

- Hamiltonian path ordering
- Odd–even routing rules





This design ensures deadlock freedom while enabling adaptive fault avoidance.

Routing mechanism

FTHOE classifies packet transmission directions into **eight categories**: **EN, WN, ES, WS, E, W, N**, and **S**. For each direction, candidate output ports are selected according to a routing policy table.

Table 2 Port-priority rules of FTHOE under different direction classes

Direction class	State condition	P1	P2	Suboptimal path
EN	Odd ∧ SameRow	E/N	N/E	W (S if necessary)
	Odd ∧ no SameRow	N	E	When E is unavailable, S
	Even ∧ $y_c \neq y_d - 1$	E/N	N/E	S
	Even ∧ $y_c = y_d - 1$	E	N/A	S
WN	Odd ∧ $y_c \neq y_d - 1$	W/N	N/W	S
	Odd ∧ $y_c = y_d - 1$	W	N/A	S
	Even ∧ SameRow	W/N	N/W	S
	Even ∧ no SameRow	N	W	S
ES	Odd	E/S	S/E	W
	Even ∧ SameRow	E/S	S/E	W
	Even ∧ no SameRow	S	E	W
WS	Odd ∧ SameRow	W/S	S/W	E
	Odd ∧ no SameRow	S	W	E
	Even	W/S	S/W	N
E	–	E	N/A	S (again N)
W	–	W	N/A	S (again N)
S	Odd	S	N/A	E (again W)
	Even	S	N/A	W (again E)
N	Odd	N	N/A	E (again W)
	Even	N	N/A	W (again E)

– indicates that no specific state condition is required; N/A: not available

Experimental setup

The performance of FTHOE is evaluated using extensive simulations in the gem5/Garnet environment.

Parameter	Setting
Simulator	gem5 with Ruby Garnet
Network topology	2D mesh, 8×8, 16×16, 32×32
Routing algorithms	FTHOE, OFTR, LBFT
Injection rate	0–0.20 flits/(node·cycle), step 0.01
Data VC buffer depth	4 flits per data VC
Control VC buffer depth	1 flit per control VC
latency	Router 1 cycle / Link 1 cycle
Warm-up period	10 000 cycles
Measurement period	50 000 cycles
Traffic patterns	Uniform, transpose, bit-reverse, hotspot
Evaluation metrics	latency, throughput, energy efficiency, and load balancing.

Simulation results

Simulation results show that FTHOE consistently achieves lower latency across different traffic loads. The saturation throughput is improved compared with existing routing algorithms. This demonstrates the efficiency of the proposed routing strategy.

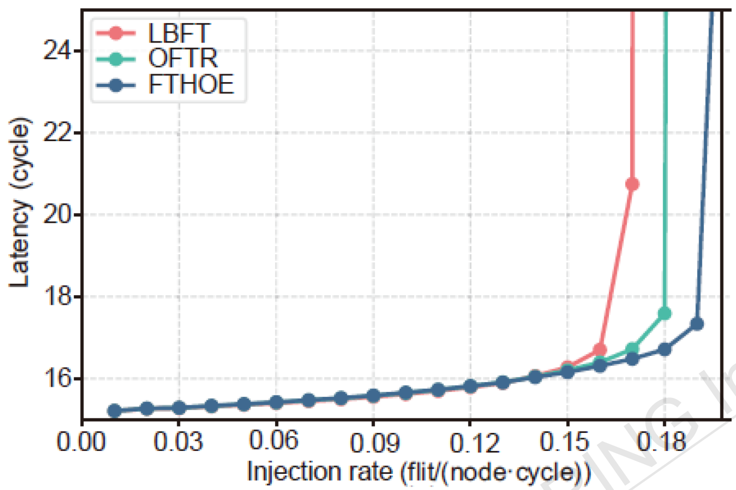


Fig. 9 Average network latency under fault-free conditions

Table 4 Saturated delivered throughput under various scenarios

Algorithm	Throughput (flit/(node·cycle))					
	Uniform			Hotspot		
	Fault-free	1 link	1 node	Fault-free	1 link	1 node
LBFT	0.1703	0.1677	0.1462	0.1507	0.1377	0.1099
OFTR	0.1851	0.1698	0.1547	0.1587	0.1475	0.1399
FTHOE	0.1970	0.1797	0.1644	0.1821	0.1562	0.1507

All values are averaged over 20 independent runs. 1 link: single-link fault; 1 node: single-node fault

Table 5 Saturated delivered throughput under mixed faults (K links+L nodes)

Algorithm	Throughput (flit/(node·cycle))					
	Uniform			Hotspot		
	$K=L=1$	$K=L=2$	$K=L=4$	$K=L=1$	$K=L=2$	$K=L=4$
LBFT	0.1455	0.1354	0.1029	0.1081	0.1030	0.0843
OFTR	0.1541	0.1450	0.1122	0.1366	0.1124	0.0844
FTHOE	0.1627	0.1538	0.1216	0.1453	0.1220	0.0931

All values are averaged over 20 independent runs

Load balancing

FTHOE improves traffic load balancing, reducing congestion and communication energy consumption. FTHOE achieves better traffic distribution across the network:

- Improved load balancing among routers
- Reduced traffic congestion around hotspots
- Lower communication energy per flit

These improvements lead to higher overall network efficiency.

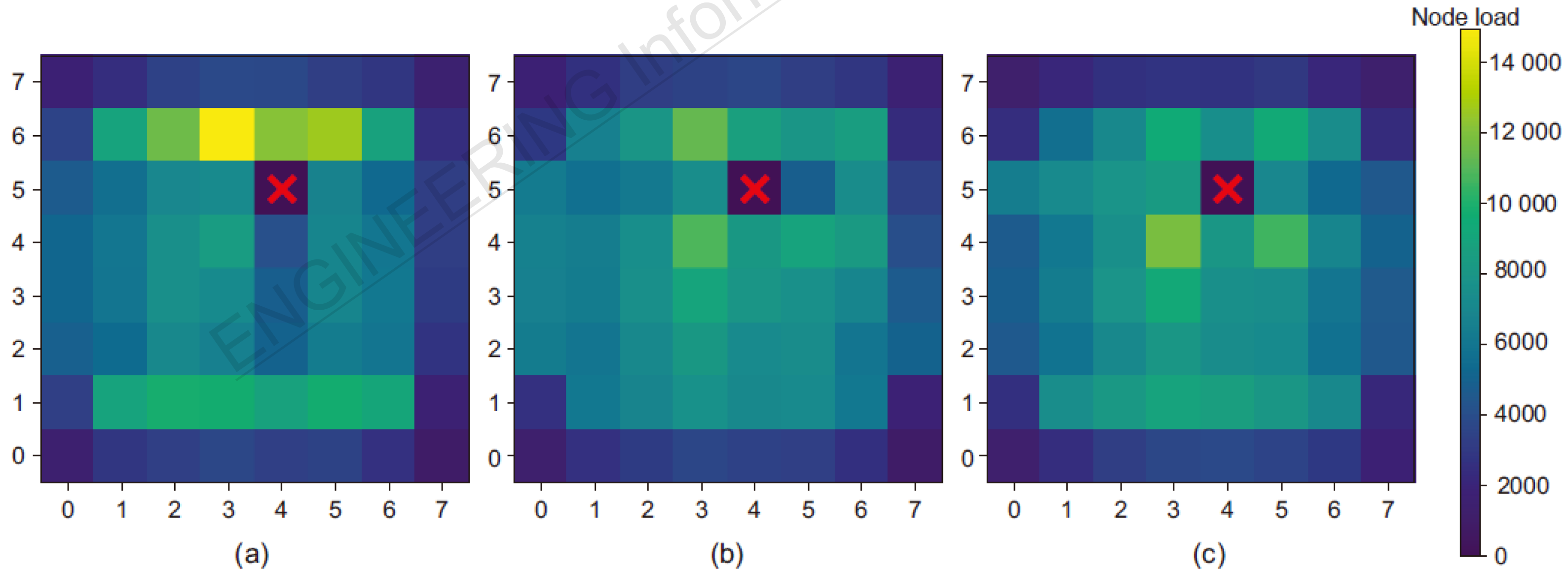


Fig. 14 Comparison of heatmaps for three algorithms under a hotspot traffic pattern: (a) LBFT; (b) OFTR; (c) FTHOE. The horizontal and vertical coordinates indicate the position of the node in the network

Contributions

FTHOE enables efficient, reliable, and scalable communication in fault-prone wafer-scale interconnection networks. The main contributions of this paper are as follows:

- Proposed FTHOE, a Hamiltonian-driven fault-tolerant routing algorithm for wafer-scale interconnection networks
- Introduced a local fault-aware port-priority mechanism for adaptive detouring
- Achieved better load balancing and path diversity under fault conditions
- Demonstrated lower latency and higher throughput with minimal hardware overhead

Qinrang Liu is a Professor at Fudan University. His research interests include software-defined wafer-scale systems, next-generation computer architecture, cyberspace security, and intelligent information processing.

Shuaikang Hou is currently pursuing his Ph.D. degree in Information and Communication Engineering at the Information Engineering University. His research focuses on wafer-scale interconnection networks and fault-tolerant routing algorithms.