IMPROVED AND EFFICIENT OPTICAL NETWORKS-ON-CHIP ARCHITECTURES AND DESIGNS

Thesis Submitted in Fulfillment for the Requirement of the Degree of

DOCTOR OF PHILOSOPHY

by

KAPIL SHARMA

विद्या तत्व ज्योतिसमः

Department of Computer Science & Engineering and Information Technology

JAYPEE UNIVERSITY OF INFORMATION TECHNOLOGY

Waknaghat, Solan-173234, Himachal Pradesh, INDIA

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SUPERVISOR'S CERTIFICATE

This is to certify that the work in the thesis entitled **"Improved and Efficient Optical Networks-On-Chip Architectures and Designs"** submitted by **Kapil Sharma** is a record of an original research work carried out by him under my supervision and guidance in partial fulfillment of the requirements for the award of the degree of Doctor of Philosophy in Computer Science and Engineering in the Department of Computer Science & Engineering and Information technology, **Jaypee University of Information Technology, Waknaghat, INDIA.** Neither this thesis nor any part of it has been submitted for any degree or academic award elsewhere.

(Signature of Supervisor)

Dr. Vivek Kumar Sehgal

Professor and Head of Department

Department of Computer Science & Engineering and Information Technology

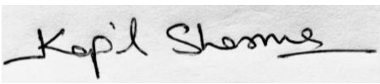
Jaypee University of Information Technology,

Waknaghat -173234, INDIA.

Date: 07-09-2021

DECLARATION BY THE SCHOLAR

I hereby declare that the work reported in the Ph.D. thesis entitled "**Improved and Efficient Optical Networks-On-Chip Architectures and Designs"** submitted at **Jaypee University of Information Technology, Waknaghat, INDIA** is an authentic record of my work carried out under the supervision and guidance of **Prof. (Dr.) Vivek Kumar Sehgal.** I have not submitted this work elsewhere for any other degree or diploma. I am fully responsible for the contents of my Ph.D. thesis.



(Signature of the Scholar)

Kapil Sharma

Department of Computer Science & Engineering and Information Technology

Jaypee University of Information Technology,

Waknaghat -173234, INDIA.

Date: 07-09-2021

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ABSTRACT

Optical Network-on-chip (Optical-NoC) is a promising and emerging on-chip optical interconnect technology to develop energy-efficient and high-performance inter-core communication for many-core processors. By utilizing the silicon interconnects to transmit optical signals, it can achieve ultra-low communicational latency, high bandwidth capacity, and low energy consumption. While several studies have been conducted on designing optical-NoC architecture and routing schemes to support proper communication, most of the existing solutions adopt the methods that were used for electrical interconnects. These solutions limit to achieve the full advantage of optical-NoC communications. Moreover, most of them focus only on their proposed architecture and routing schemes used to perform communication on those architectures. Hence, this thesis shall address the design of an efficient communication scheme for optical-NoC architectures by taking into account the distinctive characteristics and constraints of an optical-NoC.

This thesis examines and studies the problem from a network-level perspective. The design methodology is to deploy optimal routes between PE nodes, with the objective of efficiently utilizing optical waveguide deployment. The novelty is to adopt an optical NoC architecture, which helps to act as a brick-like structure and helps to configure other big optical-NoC architectures. As per routing schemes, two routing algorithms are proposed to fulfill different communication requirements.

To begin with, the photonic integrated circuits (PICs) or optical networks on chip (Optical-NoC) are proposed, which helps to provide a promising solution for on-chip optical communication. Optical-NoCs are providing a better solution with respect to the traditional NoC interconnects which face major challenges such as latency, bandwidth, and energy consumption. Optical-NoCs have the ability to provide low power communication and high data processing at ultra-high speeds. To provide efficient optical communication proper waveguide deployment is one of the major challenges in Optical-NoC architectures. Thus our main focus is to provide an optimal deployment of waveguide among PE nodes. In this architecture, we have used micro-ring resonators (MRRs) which helps to connect each PE node to the main waveguide. These MRRs were used to filter specific optical signals from the main waveguide. Obtained results show the proper working of MRR by filter specific optical signals

from the main waveguide, providing less communicational latency, and used as a brick-like structure to configure other big architectures.

Additionally, Communication among PE nodes plays an important role in overall throughput. In different architectures, different routing algorithms are introduced to perform proper communication. While path reservation criteria were observed as one of the bottlenecks for overall optical transmission. This path reservation criteria also provided many flaws like idle node, path blocking issue, and a deadlock situation. Thus, our main focus is to develop a routing algorithm that employs alternate methods than path reservation criteria for providing communication among PE nodes. Further, the results show proper communication among nodes as well as provides deadlock-free communication. Obtained results show a new qualitative diagram that removes path reservation criteria, provides less hop count, the shortest path between PE nodes and uses less energy consumption while performing optical communication.

Furthermore, In Optical-NoC fault occurrence is one of the major issues due to the delicate nature of Optical-NoC. These components consist of the waveguide, MRR, and other components which are very delicate in nature. A slight change in temperature makes MRRs faulty, which results in the miss delivery of messages and overall system failure. Thus, we have proposed a fault-tolerant routing algorithm that helps to eliminate faulty nodes and achieves the next optimal shortest path between PE nodes to perform optical communication under faulty conditions. This approach helps our proposed optical-NoC to become more reliable as well as provide better performance in terms of fault occurrence. Results show proper communication among nodes under the faulty condition with acceptable availability ratio, algorithm running time, hop count, successful delivery ratio, and energy consumption.

Overall, this work aims to propose an optical-NoC architecture and two routing algorithms that help to maintain and provide efficient optical communication among PE nodes. They have advantages like low design complexity, proper communication power and helps to make the proposed architecture fault-tolerant in nature. These methods may help to achieve high communication power which helps to supports high computation requirements.

LIST OF ACRONYMS

AR	Augmented Reality
ALO	Ant Lion Optimization
AFT	Adaptive Frequency Tuning
BLOCON	Buffer Less Optical-NoC Architecture
CAR	Contention Aware Routing
CGSA	Cataclysm Genetic-based Simulated Annealing
CPU	Central Processing Unit
EVC	Express Virtual Channel
FSR	Free Spectral Range
F	Finesse
FDTD	Finite-Difference Time-Domain
FWHM	Full-Width Half-Maximum
GPU	Graphics Processing Unit
KGD	Known-Good-Dies
LAA	Loss Aware Adaptive
MRR	Micro-Ring Resonator
MILP	Mixed-Integral Linear Programing
MWSR	Multiple Writer and Single Reader
MWMR	Multiple Writer and Multiple Reader
MTBF	Mean Time to Between Failure
MTTR	Mean Time To Repair
NoC	Networks-on-Chip
ORNoC	Optical Ring Network on Chip
OWN	Optical-Wireless Network
OR	Optical Router
PICs	Photonic Integrated Circuits
PE	Processing Elements
PN	p-type and n-type
QoS	Quality of Service

Q-factor	Quality factor
R&D	Research and Development
RAM	Random Access Memory
ROM	Read Only Memory
RF	Radio Frequency
SoC	System-on-Chip
SNR	Signal-to-Noise Ratio
SRMR	Single Writer and Multiple Reader
SWSR	Single Writer and Single Reader
TDM	Time Division Multiplexing
TSV	Through Silicon Via
Wi-Fi	Wireless Fidelity
WDM	Wavelength Division Multiplexing
VLSI	Very Large-Scale Integration
VR	Virtual Reality
2D	Two Dimensional
3D	Three Dimensional

LIST OF SYMBOLS

λ	Wavelength
H	Height
H_{max}	Maximum Number of Hop Count
L	Circumference
m	Mode
n_{eff}	Refractive Index
ng	Group Refractive Index
nm	Nano-Meter
N_L	Number of Waveguide
$\dot{N_{OR}}$	Number of MRR Used in a Horizontal Direction
$\ddot{N_{OR}}.$	Number of MRR Used in a Vertical Direction
p	Reliability of Each MRR
R_{O-NoC}	Systems Reliability
R	Radius
R_L	Reliability of the Waveguide
$\dot{R_{OR}}$	Reliability of the Horizontal MRR
$\ddot{R_{OR}}$	Reliability of the Vertical MRR
t	Time
W	Width
x	X-Axis
X	Destination X-Axis
y	Y-Axis
Y	Destination Y-Axis
π	Pie
∂_m	Failure Probability

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CHAPTER 1

INTRODUCTION

1.1 Introduction

From last few decades, researchers have diverted their focus from the solutions based on single powerful microprocessors, towards parallel systems made of an increasing amount of PE cores integrated on a single chip. As we are scaling down in the deep microns from micro-meter to nano-metre [1, 2]. The speed of processing elements is increasing and the speed of communicational media between them is decreasing. With the reduction in fabrication scale, the productivity gap between the computation elements and the communication element is increasing. In order to separate the gap between communication and computation, network-on-chip (NoC) is the architecture that provides flexibility and quality of service (QoS).

System on chip (SoCs) was introduced in the early 1990s, the solution for providing high communication power or the communicational structure has been generally distinguished by traditional methods like buses, point-to-point links, and dedicated wires [2,3]. Figure 1.1, represents some examples of traditional communication structures used to provide proper communicational power. In these traditional structures, the number of processing elements (PE) like RAM, ROM, GPU, CPU, and input/output are connected to perform proper communication between them. While performing communication at a particular time some of the PE uses the provided channel while others go into the wait condition, this wait provides a bottleneck for overall computation power.

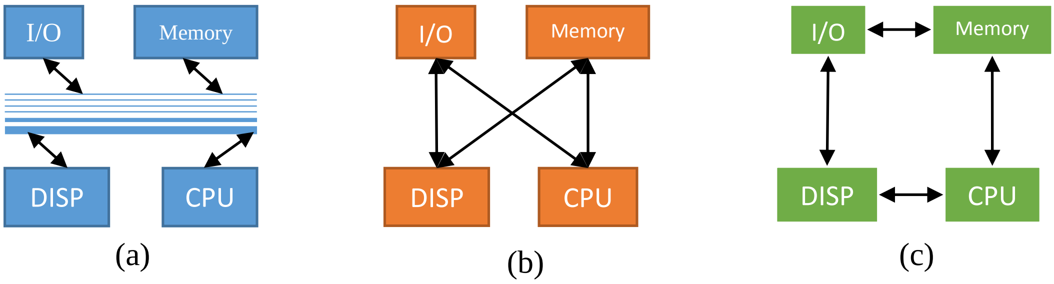


Figure 1.1: Examples of traditional communication channels, (a) Bus Interconnects, (b) Point-to-point Interconnects and (c) Dedicated wires interconnects

In this context, on-chip communication structures play a critical role in overall performance. This infrastructure provides the required provision to distribute the desired computation between different PEs. A proper communication channel that provides high communication power directly impacts the overall system's power consumption and performance. NoCs are one of the brilliant paradigms for maintaining as well as organizing the communication in SoCs due to their modular and scalable nature. Although, these NoCs are still restrained by several challenges like latency, power consummation, noise, and bandwidth [3].

1.2 Network on Chip

Network-on-chip is a concept of moving from computational-centric design to the communicational-centric design and implementing scalable communication structure. The combination of both off-chip networks and VLSI design gave rise to the formation of NoCs. These NoCs are seen to be a promising unifying concept rather than a specific new solution. This network plays an important role in providing proper communication among PEs. Figure 1.2, represents the basic idea of NoC, these are basically consist of four major parts known as the core, network adaptor, routing node, and link [2]. These components work together to provide efficient communication among PEs to achieve high performance.

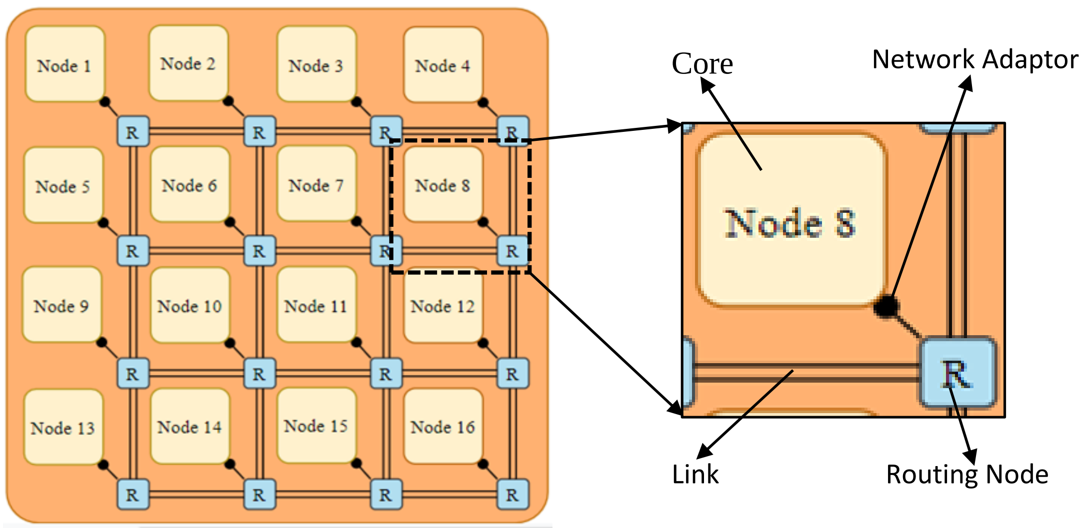


Figure 1.2: Topical illustration of 4x4 NoC structure.

- The core consists of the processing elements and memory unit that are used to perform specific computations in NoCs. It is considered one of the main components of NoC.
- Network Adaptors are used to implement an interface by which cores (node, PEs) are attached to the NoC. Its main function is to separate computation from communication.
- Routing nodes were used to provide a specific data route between PE nodes according to the chosen protocol. They work on specific protocols and routing strategies.

- Link acts as a communication channel between nodes, which provides bandwidth power to NoC. These links may consist of one or more channels.

Figure 1.2 only shows the basic composition of NoCs, while the diversity of NoCs is dependent upon the type of composition and clustering used. There are particularly three types of NoCs, (i) homogenous NoCs: in this configuration same type of cores and routers are used, (ii) heterogeneous NoCs: in this configuration different cores are used and (iii) application-specific NoCs: in this configuration different cores as well as network is customized to perform specifically according to the application.

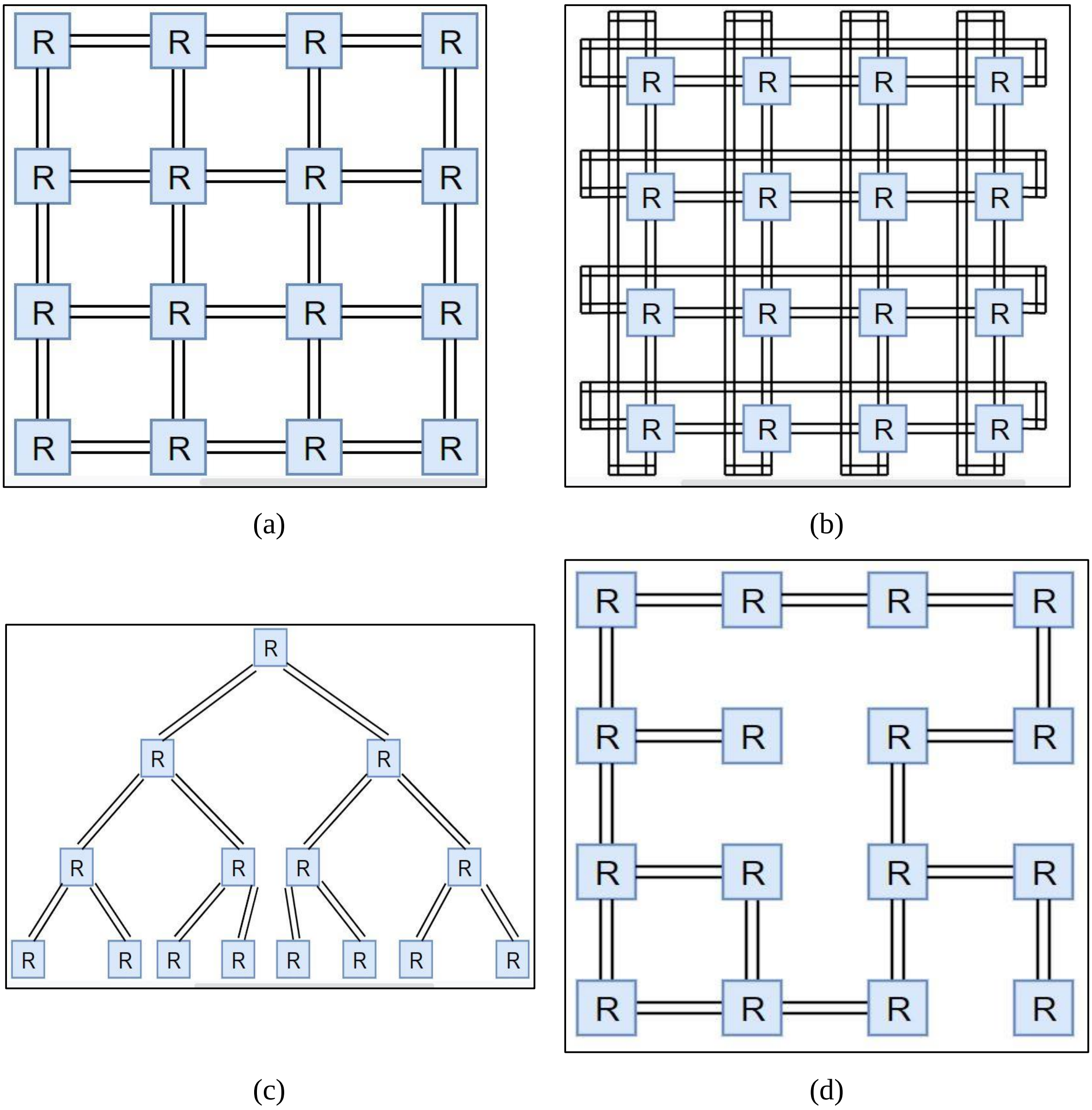


Figure 1.3: Different types of topological designs (a) 2D mesh, (b) 4x4 tours, (c) binary tree and (d) Irregular connectivity.

Figure 1.3, represents some topological designs used in NoCs. This topology concerns the connectivity as well as the layout of the PE nodes and links on the chip. These links between the PE nodes provide desired communication power which helps to support high computation. Some of the properties of NoCs are reliability of system, predictable electrical nature, easy to scale regular geometry, guarantees flexible QoS, higher bandwidth, reusable components, and physical nature.

1.3 Types of On-Chip Interconnect

Links between PE cores plays an important role in enhancing overall performance. There are mainly four types of on-chip interconnects, wired NoCs, wireless NoCs, Optical NoCs, and Hybrid NoCs. Figure 1.4 shows the graphical representation of on-chip interconnects and shows how the combination of two or more interconnects provides hybrid interconnects.

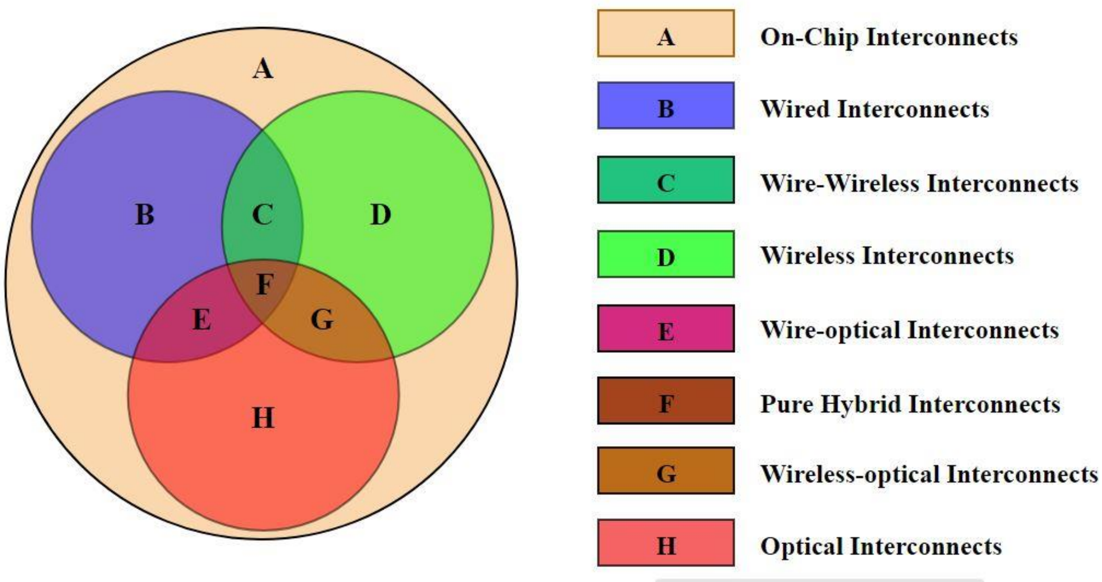


Figure 1.4 : Types of On-Chip Interconnect

1.3.1 Wired Network on chip

The instable market requires a new solution regarding old interconnects. To fulfill these requirements, early NoC uses wires as interconnect between nodes. Instead of using traditional connections use of copper and gold wires was introduced due to their friendly nature [3, 4]. These wired networks help each PE node to provide a proper communication channel, as compared to the traditional link they are more capable of providing efficient communication power.

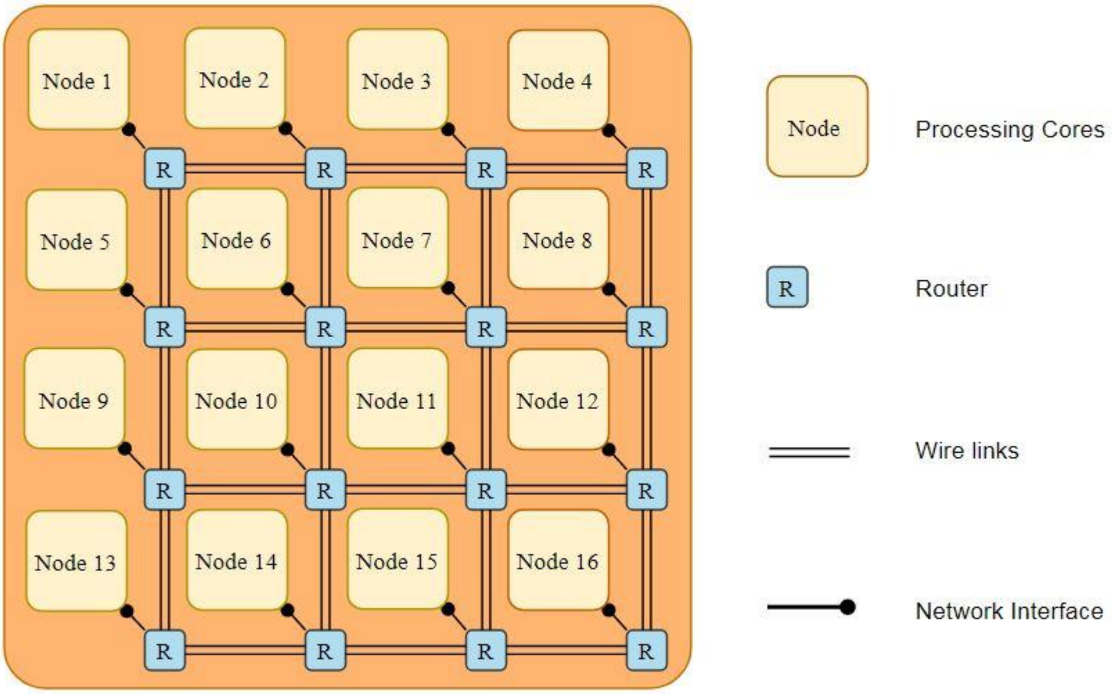


Figure 1.5: Illustration of 4×4 2D wired NoC

As per Figure 1.5, a basic idea of wired NoC is presented in which wire interconnects are used to provide proper communication among nodes. In this, we have demonstrated 4×4 2D mesh architecture which contains the total of 16 PE nodes. This figure only demonstrates the topological aspect, while in the case of performing communication this figure may employ circuit switching, packet switching, or entirely different logic. The promising factors of using wired NoCs over traditional methods is that they provide scalability to the architecture, eliminate traditional interconnect, provide energy-efficient communication, eliminate design complexity, and derives high overall throughput [5].

There were many routing techniques introduced to perform proper communication in NoCs. These routing algorithms were divided into two parts oblivious routing technique and adaptive routing technique [6, 7]. The oblivious routing follows predefined steps to reach its destination. In this routing algorithm, the packet will be transmitted to a defined path regardless of the result. Another routing technique rather than oblivious routing is known as adaptive routing [7, 8, 9, 10], this technique is useful to avoid deadlock and livelock conditions. This technique defines its own path at run time and reach its destination by choosing the best path. Some examples of common routing techniques used in NoCs are XY, XYX, direction first, and odd-even routing.

1.3.2 Wireless Network on Chip

In the early days wired NoCs are capable of providing efficient results by supporting proper communication required with respect to the computation power. Due to the increase in demand for computation power, some limitations have emerged in wired-NoCs like less bandwidth to support high computation, high overall latency, multiple hop count, and use of excess power. Out of all these limitations hop counts become the bottleneck for enhancing efficiency and energy consumption [11, 12].

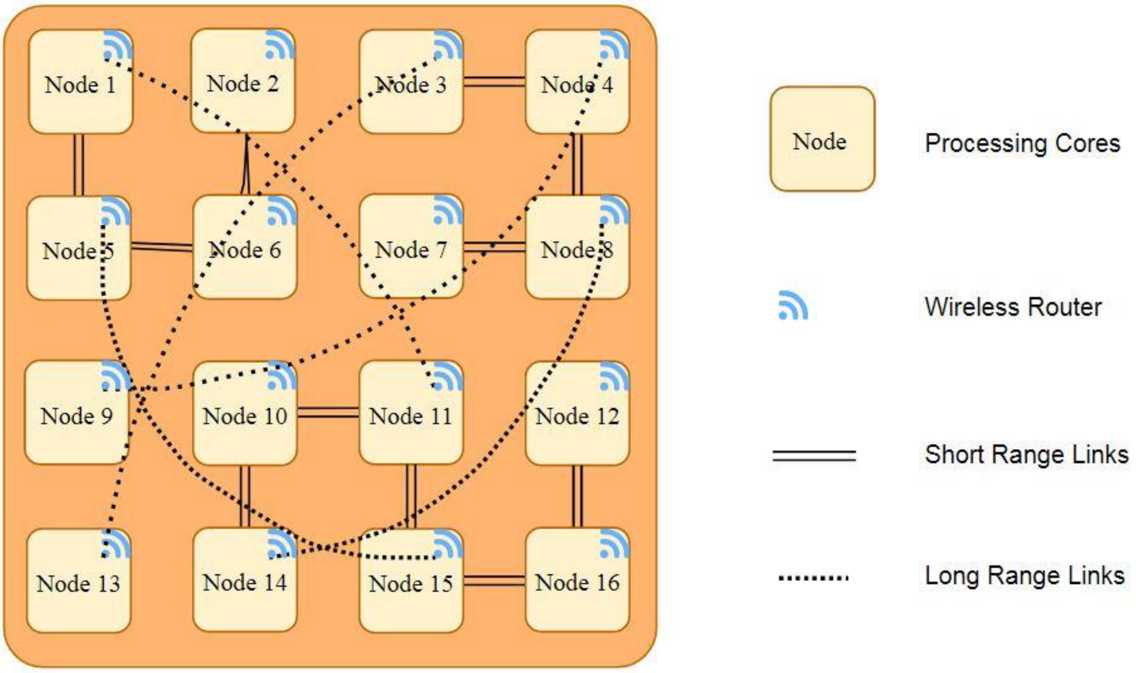


Figure 1.6: Illustration of 4x4 2D Wireless NoC

These new emerging limitations motivate researchers to use other interconnect instead of wires in NoCs. The use of new interconnects instead of wire gave rise to the new architecture known as wireless NoC, in wireless NoCs wires are replaced by radio frequency (RF) signals or Wi-Fi signals[13,14,15,16]. Figure 1.6, shows a common diagram of wireless NoCs which uses wireless routers to provide proper communication among PE nodes. The topology used in Wireless NoC is mostly mesh-based, as they are more efficient in terms of energy consumption, area utilization, and overall performance.

The most promising results provided by wireless NoCs are high communication power as compared to wired interconnect, reduce heating problems, less energy consumption, and less hop count while performing communication. Hop count is considered as one of the promising results of NoC as it directly affects overall latency as well as QoS [17, 18]. Minimum hop count in Wireless NoC was achieved up to one, thus wireless NoC is the best alternative to enhance communication power as compared to wired NoCs.

1.3.3 Optical Network on Chip

As per the continuous growth of processing cores in high computation systems and as per Moore's law, other interconnects (wire, wireless, and hybrid) are becoming a bottleneck for overall systems performance [19]. As new advancements are continuously done over computation elements while on the same hand communication channels are lacking behind. After all, efficient and powerful communication infrastructures are the backbone of high computational systems [20]. The interconnects like wire and wireless have many limitations like low bandwidth, less communicational latency, low QoS, and high power usage as compared to optical interconnects. Thus, the previous interconnect methods were not that much efficient in terms of providing high communication especially in the case of real-time application [21].

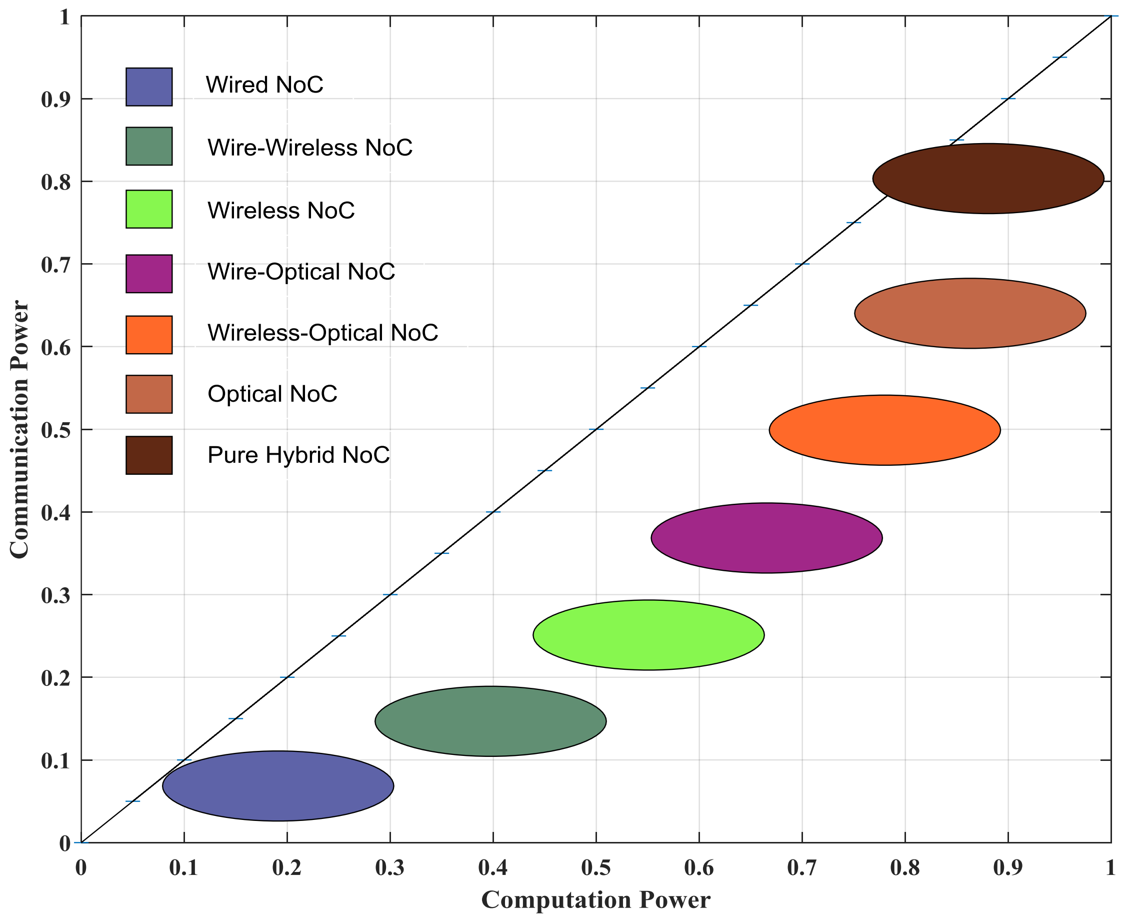


Figure 1.7: Communication power vs. computation power

The concept of using optical interconnects to perform communication was introduced in late 1980s, but the use of optics on such a small scale has recently came into existence. These optical interconnects consist of carrier waveguide to provide proper connection among PE nodes instead of wire and wireless interconnects. There are many researchers who compared the optical interconnects with other interconnects [21, 22, 23, 24, 25, 26]. In those works, the authors studied the power consumption, bandwidth and also provided benefits of using on-chip optical interconnects over traditional interconnects. In terms of power consumption, the traditional systems consuming more as compared to optical interconnects. While in the case of bandwidths optical interconnects work in Tbps, whereas traditional interconnects works in Gbps which is one of the promising factors for using optical interconnects. As per Figure 1.7, optical interconnects show the capability to achieve proper communication power to support high computation power and provide better overall performance.

As per its promising nature towards NoC, many researchers are still working to produce efficient optical on-chip architectures. There are many drawbacks that degrade optical NoC's performance like noise, complex waveguide configuration, and less reliable nature. Although, many researchers are working on new hybrid techniques for NoCs that includes making dedicated optical interconnects, wire-optical NoCs and wireless-optical NoCs to achieve better results and enhance NoC's overall performance [25, 27, 28].

1.3.4 Hybrid Network on Chip

Hybrid NoCs are constructed by combining one or more interconnects on a single chip. There are many hybrid interconnects like wire-wireless, wires-optical, wireless optical, and wire-wireless-optical on a single chip [19, 21, 24, 25, 26]. These NoCs provide high performance by using PE node links as per data rate requirements. But on the other hand implementation of hybrid interconnects on a single chip as well as routing algorithms to perform proper communication is very complex in nature.

1.4 Motivation

Communication barriers are still one of the emerging issues for supporting high computational requirements. This problem is addressed by many researchers through theoretical as well as practical point of view. It can be described as the communication power of traditional interconnects (wired and wireless) that are not capable of providing the balance between computation power and communication power. Many solutions are proposed to support high computation power and to counter this problem [1, 3, 10, 12, 13, 17]. Some solution regarding this problem includes wired NoCs, wireless NoCs, optical NoCs, and hybrid NoCs. Out of all these solutions, optical NoCs show promising results and have proven their significance by providing high communication power to support high computation. Some of the promising results shown by researchers are high bandwidth, less overall communication latency, provides an energy-efficient system, and improves overall performance [20, 22, 23, 24, 25]. It is also observed that these optical NoCs are highly efficient in terms of real-time application-specific computation (VR and AR) as they require high computation as well as communication at the same time. Some of the major promising factors of using optical interconnects are:

- Provides a high communicational bandwidth.
- Allows less power consumption while communicating.
- Provides latency in pico-seconds and femto-seconds in small-scale systems.
- Used in optical-based cloud serves.
- Design application-based systems with high computation.
- Provides a hybrid switch technique for fast decision-making.
- Provide virtual channels in wire and wireless-NoC.

Apart from all the promising factor, there are many research gaps that are encounter from several research papers.

- Different Topological Optical-NoC architecture.
- Lack of efficient waveguide deployment.
- Proper Routing techniques.
- Using path reservation criteria.
- Fault Occurrence in Optical-NoC.

1.5 Objective

Motivated by the above discussion, it is clear that there is a large room for the development of optical NoCs architecture. Furthermore, the optical NoC architecture has major challenges regarding topological design, waveguide allocation criteria, routing technique, and efficient routing algorithm for flawless communication. The aim of this work is to provide proper waveguide deployment among PE nodes as well as routing algorithms to perform proper communication. The objectives of this work are based on motivation featured as:

- To develop a new architecture to overcome topology techniques in Optical-NoC architecture.
- Design new routing algorithm which works on the proposed architecture.
- To develop a fault-tolerant system that provides high reliability in Optical-NoC.

1.6 Thesis Organization

The thesis is structured as follows:

Chapter 1: Introduction

This chapter gives a brief representation of the introduction about NoC and interconnects used in NoCs, motivation behind our work, and objectives of the research.

Chapter 2: Related Literature

This chapter gives a review and essential background about an Optical-NoCs architectures design schemes and communication algorithms. The literature survey is categorized into optical-NoC architectures, routing algorithm for communication, and fault-tolerant methods for optical-NoC.

Chapter 3: Modern Architecture For Optical Networks On Chip

This chapter discusses the first objective, which involves the design of new architecture for optical interconnects in NoC. Additionally, it explores waveguide design as well as micro-ring resonator (MRR) design. These MRRs are proposed to efficiently perform communication among different PE nodes.

This chapter is drawn from the following publication:

- Kapil Sharma, Vivek Kumar Sehgal. "Modern architecture for photonic networks-on-chip." The Journal of Supercomputing (2020): 9901-9921. DOI: 10.1007/s11227-020-03220-2.

Chapter 4: Sustainable Communication For Optical Networks-On-Chip

This chapter is based on the second objective, which includes the design of a new routing algorithm. The proposed routing algorithm works on different optical-NoC architectures, configured from several brick like structure. Proposed algorithm derives optimal path and provides proper communication among PE nodes.

This chapter is drawn from the following publication:

- Kapil Sharma, Vivek Kumar Sehgal, "Energy-efficient and sustainable communication in optical networks on chip", Sustainable Computing: Informatics and Systems, Volume 28, 2020, 100426, ISSN 2210-5379
  DOI: 10.1016/j.suscom.2020.100426
- Kapil Sharma, and Vivek Kumar Sehgal, "Optical-NoC: Future of New Computational Systems," 2020 IEEE 17th India Council International Conference (INDICON), 2020, pp. 1-6.
  DOI: 10.1109/INDICON49873.2020.9342176

Chapter 5: Dealing With Fault Occurrence in Optical Networks-On-Chip

In this chapter, we have proposed a methodology that makes our optical-NoC fault-tolerant in nature, because of their delicate nature. These optical components have a higher probability of getting faulty, thus it affects overall architecture's reliability.

This chapter is drawn from the following publication:

- Kapil Sharma, and Vivek Kumar Sehgal, "Improved and Efficient Optical-NoC Architecture," 2021 6th International Conference for Convergence in Technology (I2CT), 2021, pp. 1-5.
  DOI: 10.1109/I2CT51068.2021.9417946.

- Kapil Sharma, and Vivek Kumar Sehgal, "Dealing with Fault Occurrence in Optical Networks-on-Chip", IEEE Transactions on Computers. (communicated)

Chapter 6: Simulation Methodology

This chapter gives an insight about the software and hardware tools used to validate the proposed new techniques in Optical NoC.

Chapter 7: Results and Discussion

This chapter includes overall simulation results which are obtained to validate our proposed new techniques. It also helps to overcome the research gaps in the field of Optical NoC.

Chapter 8: Conclusion and Future Scope

This chapter concludes and summaries the work of the thesis and the future direction of our work in the field of Optical-NoC.

CHAPTER 2
RELATED LITERATURE

2.1 Introduction

Interconnects are one of the major components of NoC. These interconnects help to join each PE node efficiently to provide proper communication power among them. The communication power achieved through these interconnects, helps to maintain the computation power. Although, communication power is the backboned of every high end computation system, higher the communication power higher will be its over computation power. These are mainly three types of interconnects used in NoCs wired-interconnects, wireless interconnects and optical-interconnects. In wired interconnects wires like gold and copper wires were used to connect PE nodes [1, 2, 3]. In wireless interconnects wires were eliminated and replaced by wireless signals like RF signal and Wi-Fi signal [14, 16, 17, 18], because wires provides less communication power as compared to wireless. The previous interconnects shows many limitation in terms of overall communication power. Thus optical interconnects are introduced to replace wire and wireless link with carrier waveguides [22, 23, 25]. In this Nano-optical fibres or waveguides are used to provide connection between PE nodes.

2.2 Review of Optical Interconnect

The related literature survey is mainly focused on optical interconnects. This section is divided into three sub-parts which includes architecture design of Optical-NoC, algorithm used in Optical-NoC and fault-tolerant methods used in Optical-NoC. Architecture design in Optical-NoC includes configuration of optical interconnects i.e waveguide among PE nodes. While routing algorithms in Optical-NoC were used to perform proper communication among PE nodes. Fault tolerant methods are defined as the measures used in Optical-NoC to deal with faulty situation and provide proper communication among PE nodes.

We have summarise some of the important papers which includes architecture design, routing algorithm and fault tolerant methods used in Optical-NoC. Subsection 2.2.1 includes related review on architecture design, subsection 2.2.2 includes important papers regarding algorithm used to perform communication among PE nodes and in last subsection 2.2.3 includes fault tolerant methods used in Optical-NoC.

2.2.1 Optical-NoC Architecture Design.

This section explores various Optical-NoC architectures which are used to provide proper waveguide deployment among nodes, concluded in Table 2.1. These waveguides are used to provide high communication speed among PE nodes by replacing both wire and wireless interconnect. There are different architectures proposed to achieve optimal deployment of waveguides because network complexity and power usage are directly dependent upon the waveguide deployment in Optical-NoC.

Calo et al. [29], proposed a hybrid Optical-NoC architecture which includes both optical and wireless interconnect to proposer proper communication in NoC. The proposed work is used to perform wireless communication at an optical frequency to provide better communication at higher bandwidth. The simulation result shows complex switching matrices for the large network as well as the reduction in loss and crosstalk issue for long communication. Furthermore proposed work shows an increase in overall complexity by combining wireless and optical interconnect together in NoC.

Beux et al. [30], proposed a new optical retexture to overcome the issue regarding optical communication. The proposed work represents contention-free architecture known as optical ring network on chip (ORNoC). This architecture uses circular ring waveguides to provide a connection between nodes. The proposed architecture is capable of joining 1296 nodes with only 102 waveguides and each waveguide uses 64 wavelengths. The simulation result shows better communication among nodes with better wavelength placement.

Chittamuru et al. [31], proposed a solution regarding the SNR issue in Optical-NoC architecture. In Optical-NoC optical loss and crosstalk is one of the major issues which reduces overall QoS. The proposed work uses a novel encoding technique to improve the effect of crosstalk noise in the micro ring resonator. Simulation results show improvement in a worst-case scenario by using high radix and low diameter crossbar Optical-NoC.

Abellan et al. [32], compare the performance of three different architecture which include electronic interconnects, electrical/photonic links, and pure optical links. All architecture is considered under private cache and shared cache to investigate large bandwidth impact. Simulation results show improvement in all-over communication among nodes and also support high bandwidth. Furthermore proposed architecture and results show a capability to support kilo-core systems.

Kao et al. [33], proposed to combine waveguide network with high radix NoC topology to enhance the performance. Proposed work provides buffer less Optical-NoC architecture known as BLOCON with a scheduling algorithm to maintain proper communication among nodes. The proposed algorithm also helps to provide contention-aware routing to deal with deadlock situations. Simulation results show improvement in delay, power consumption under synthetic traffic patterns.

Abellan et al. [34], proposed a solution regarding unsigned signal filtering due to thermal sensitivity. To avoid this error proposed work uses micro-heaters for thermal tuning and trimming less overall power usage. This work uses adaptive frequency tuning (AFT) and frequency aligns workload allocation policy that helps to maintain proper temperature control over the micro ring resonator. The simulation result shows less tuning power usage, increases overall performance and is capable of working under high load.

Li et al. [35], proposed to construct energy-efficient Optical-NoC architecture. The proposed work provides three major contributions, first, a novel architecture uses the nanophotonic network to convert full architecture into subnets for better efficiency, second provides the proper and pure optical connection between PE nodes and last, the distributive arbitration schemes as well as channel sharing in the same waveguide for proper communication among PE nodes. Simulation results are performed under a synthetic traffic pattern that shows fewer latencies and higher throughput.

Zhou et al. [36], proposed work for a better and efficient optical switch that helps to provide proper packet exchange between PE nodes and network. The proposed work provides a five-port silicon switch by substituting a 2x2 optical switch using waveguide crossing for 2D mesh architecture. Simulation results show less power usage, a decrease in insertion loss, and provides high data transmission rate. Furthermore proposed work shows proper packet exchange between nodes and increase overall transmission power in Optical-NoC.

Jia et al. [37], proposed work also demonstrates the new optical switch to provide proper packet exchange while communication among nodes. This work demonstrates a four-port optical switch for fat-tree architecture, these optical switches elements are tuned by the plasma dispersion effect. The simulation result shows less SNR ratio under wavelength range between 1525 to 1565 nm, providing high data rate by using WDM technique. Furthermore proposed work shows less power consumption while performing communication.

Gambini et al. [38], proposed a new approach for the construction of Optical-NoC. In Optical-NoC waveguide deployment is one of the key factors for increasing overall data rate. The proposed work uses multi-microring architecture to provide a proper connection between the waveguide and PE node. Simulation results show a high data rate between nodes and provide less cross-talk. This crosstalk is one of the issues which degrade overall performance and QoS in Optical-NoC communication.

Bahirat et al. [39], Proposed to use both electrical connections and optical connections between nodes. The proposed work uses a hybrid photonic ring mesh known as METEOR utilizing both circular ring waveguide couples with electric links. Simulation result provides a reduction in power consumption, improved throughput, and less latency compared to traditional 2D mesh architecture. Furthermore increased throughput is achieved using hybrid connection with less area overhead as well as maintaining throughout.

Karanth et al. [40], proposed to use two interconnect on a single chip to enhance the overall communication power. The proposed work uses wireless links as well as optical links to perform communication among nodes known as Optical-wireless networks on chip (OWN) and runtime reconfigurable wireless channel (R-OWN). In this work photonic channel uses time-division multiplexing (TDM) while wireless uses frequency division multiplexing (FDM) to perform shared communication. Simulation results show an increase in throughput as well as latency with less area overhead.

Peter et al. [41], proposed to use waveguide connection between PE nodes. The proposed work provides a tuneable micro ring (MRs) resonator which helps these PE nodes to connect through the waveguide. This active MR provides transient phases between off-resonance and on-resonance for proper optical filtering of a specific wavelength. The simulation result shows a high data transfer rate with less error rate. Furthermore proposed MR uses very little time of 500ps to tune into specific resonance.

Pan et al. [42], proposed a hybrid firefly network architecture with cluster technique. The proposed architecture uses firefly clusters nodes which are connected using electrical signaling and conventional signal to provide inter-cluster communication. The simulation result shows improvement in performance, proper traffic pattern, less energy usage. Furthermore proposed solution provides better traffic management all over the network and improves the efficiency as compared to CMESH and OPBAR.

Shacham et al. [43], propose to construct hybrid architecture which used both electrical as well as optical links. The proposed work uses electrical links to provide communication between short nodes and optical links to provide communication between long links. This works also shows a routing algorithm to provide a proper path setup rate with path reservation criteria. Simulation results show better communication with better path setup/tear down procedure, less power usage, and less overall latency while performing communication.

Killge et al. [44], proposed a solution regarding through silicon via (TSV) for vertical communication on 3D chips. The proposed work uses an optical waveguide as TSV with less internal roughness to perform communication between 3D tiles. The simulation result shows a high data rate between tiles as compared between waveguide TSV and non-waveguide TSVs. Furthermore, the communication power provided by the proposed TSV between tiles shows less overall optical loss and provides a promising solution for TSVs.

Venkataraman et al. [45], proposed to construct an architecture without using buffer technology. The proposed work uses buffer-less architecture as well as uses ant lion optimization (ALO) routing topology to perform proper communication. The proposed work's power dissipation is evaluated with conventional topologies such as octagon, cliché, and spin. Results show better communication performance with fault tolerance ability, perform at a higher overall operational frequency, and provide good throughput under fault rate.

Pintus et al. [46], proposed to compare the effects of different architecture. This work is used to compare two different architectures based on ring topology and bus topology. First, they represent the theoretical analysis to compare the performance using the scattering matrix method. Simulation results show better communication under both topologies with legible or limited crosstalk. Furthermore proposed ring-based architecture outperforms bus-based architecture and shows the less filtering effect as compared to bus architecture.

Fusella et al. [47], propose to construct hybrid NoC combining both electrical as well as optical interconnects. The proposed work uses a hybrid electronic/photonic hybrid topology known as H2ONoC to eliminate insertion loss as well as crosstalk noise. Architectures are examined over synthetic benchmarks and real-world applications as well as compared with hybrid mesh and torus-based NoC. Simulation results show less overall energy consumption, less insertion loss, and acceptable SNR when the size of architecture increases.

Wang et al. [48], proposed an architecture known as ring-based packet-switched NoC (RONoC). This architecture uses few optical divides and employs only a single-waveguide which uses space division multiplexing to make architecture more and more scalable. The simulation result shows novel wavelength assignment as well provides guarantees deadlock freedom and low complexity at the same time. Evaluation is carried out on 64 node architecture with other packet-switched Optical-NoC, which shows overall low energy consumption.

Table 2.1:

Demonstrates the different approaches used for Optical-NoC architectures

Referenced Articles	**Methodology**	**Topology Adoption**	**Positive Aspect**	**Shortcoming**
Calo *et al.* [29]	Proposed Integrated Vivaldi antennas to perform communication among ndoes.	Hybrid NoC	Enhance communication power, Low over all energy consumption.	Combining two interconnects provides throughput at cost of design complexity.
Beux *et al.* [30]	Proposed optical ring network among nodes.	Ring mesh	Provides high communication power, Proper path setup while communication.	Different architecture uses different routing algorithm.
Chittamuru *et al.* [31]	Novel encoding mechanisms to	2D Mesh	Reduction in crosstalk as	It showed that MR provides

	improve worst-case SNR by reducing crosstalk noise		well increases reliability	high throughput as well as noise
Abellan *et al.* [32]	Electric with photonic multi crossbar are proposed to overcome design issues in NoC.	2D Mesh	Give better performance in term of bandwidth, Less power usage	Electric provides less overall throughput as compared to optical links.
Kao *et al.* [33]	Propped a buffer less deign in Photonic NoC architecture	2D Mesh	Improves over all communication delay, Reduction in overall power consumption.	Optical interconnects are used to replace long interconnects.
Abellan *et al.* [34]	Proposed an adaptive tuning for photonic devices (MRs)	2D Mesh	Reduction in thermal tuning power, Increases overall performance	Using thermal tuning for MRs increases throughput but also increases energy consumption.
Le *et al.* [35]	Proposed an Nano photonic architecture, with subnet network partitions	2D Mesh	Low latency, Increased throughput	Using particular wavelengths increases chances of contention.

Zhou *et al.* [36]	Proposed rearrange able-non blocking five port silicon optical switch	2D Mesh	Provides proper path diversity, Less overall latency	Enhances throughput in cost of design complexity
Jia *et al.* [37]	Proposed a four port optical switch for fat-tree Optical-NoC.	Fat tree	Increases overall bandwidth between channels, Reduced power consumption.	Crosstalk are one of the main issue in Optical-NoC.
Gambini *et al.* [38]	Multi mirroring NoC are proposed for datacom applications.	2D mesh	Provides acceptable bandwidth with less overall crosstalk	MR provides better throughput in cost of faulty nature.
Bahirat *et al.* [39]	Several ring based waveguides were used to connect PE nodes	Ring-Mesh	power consumption, Low latency Throughput	Sharp turning points in waveguide provides high optical loss.
Karanth *et al*. [40]	New architecture was proposed using MR to connect PE nodes.	Hybrid Optical-NoC	Increase in through put, Latency	MRs Other than opto-MR uses external energy

Peter *et al*. [41]	Use of tunable resonator work better optical filtering.	2D Mesh	500ps to tune MR Less power usage	and increase overall energy
Pan *et al*. [42]	Proposed new architecture uses Nano-photic connection between PE nodes	2D Mesh	Provides high performance with minimum energy consumption	Increases deign complexity as well as routing complexity by managing both electric paths as well as optical paths.
Sachman *et al*. [43]	Proposed an architecture which works on both electric and optical signals.	2D Mesh	Provides better communication by using optical in long distance and electrical signal in short distance	
Killge *et al*. [44]	Providing TSV using waveguide	3D Chip	Data rate of 18 Gbit/s	Using waveguide as a TSV increases computation power in cost of deign complexity.
Venkataraman *et al*. [45]	Uses buffer less architecture to make efficient use of area and power.	2D Mesh	Reduce energy consumption as well increase operational frequency	Increases congestion situation in case of high traffic load.

Pintus *et al.* [46]	Comparison between bus and ring architecture.	2D Mesh	In bus the filtering effects are limited as compared to micro-ring.	MR have high probability of gaiting faulty as compared to bus.
Fusella *et al.* [47]	Proposed a hybrid electronic/photonic Optical-NoC.	Hybrid Optical-NoC	Provides highly energy efficient under synthetic traffic patterns	Increases over all design complexity by combining two or more interconnects.
Wang *et al.* [48]	Proposed number of circular waveguide to provide connection between PE nodes.	Multi waveguide architecture.	Provides high scalability. Low energy consumption.	Unique architecture requires specific algorithm to maintain its communication.

2.2.2 Optical-NoC Routing Algorithm.

This section represents various work done regarding routing algorithms used to perform proper communication in Optical-NoC architectures, concluded in Table 2.2. Different routing algorithms are proposed due to different Optical-NoC architecture and these architectures don't support common routing algorithms. Thus to perform better communication and to utilize the full potential of proposed NoC's architecture-specific algorithm are designed.

Guo et al. [49], proposed a new routing algorithm in 2D mesh architecture which includes IP core mapping. The proposed work is used to perform a full IP mapping algorithm known as CGSA (Cataclysm Genetic-based Simulated Annealing) which uses cataclysm strategies in order to speed up the searching process. This work provides a better path setup rate and reduces idle node usage. Simulation results show an increase in reliability of architecture as well as increases all over performance. Furthermore, optimal mapping of IP core increases information gain of each PE node.

Choi et al. [50], proposed to use a machine learning technique for performing communication in heterogeneous NoC architecture. Proposed work includes hybrid NoC architecture which uses resource-intensive backpropagation techniques to improve the network latency while performing communication. Simulation results show 25% saving in energy usage and 1.9-time decrease in all over network latency. Furthermore, works show all over inverse in performance but also show an increase in computation by using machine leering techniques in NoC.

Abadal et al. [51], proposed a communication methodology to enhance the overall throughput in NoC. The proposed work uses full channel capacity by using both network planes in hybrid NoC. Using both networks provides multiples available links to perform communication as well as adjusts high traffic load all over the network. Simulation results show an increase in overall communication performance and also provide energy efficiency. Furthermore, using multiple interconnects increases algorithm complexity as well computation complexity all over the network.

Liu et al. [52], proposed to use wavelength reuse methodology to perform communication among nodes. The proposed work uses limited wavelength in architecture and uses those wavelengths to perform communication among PE nodes. This work also uses limited hardware requirements to perform overall communication in Optical-NoC architecture. Simulation results show a reduction in delay by 46% and an increase in overall throughput. This work also showed that increase use of wavelength directly increases overall energy usage and increases algorithm complexity.

Wang et al. [53], proposed architecture as well as routing algorithm to provide deadlock-free routing. The proposed work uses ring topology for providing packet switching among nodes with wavelength assignment methods to eliminate the deadlock situation. Simulation results show better performance as compared to other packer switching techniques as well as reduced number of hop count. This work also provides less overall latency and low energy consumption while performing communication under different traffic patterns.

Imre et al. [54], proposed to use a dual-mode approach to perform communication among 2D mesh optical architecture. The proposed work uses two routing algorithms that were selected exclusively depending upon the data exchange requirement. This work also shows contention-free and deadlock-free dense data exchange rates between PE nodes. Simulation results show better communication performance and archive better data flow among nodes.

Wang et al. [55], proposed two adaptive routing algorithms to perform proper communication among nodes and help to achieve better reliability. This work provides two different routing algorithms known as lifetime-aware routing algorithms and multiple objective routing algorithms. This algorithm provides a lifetime budget with each router to indicate the maximum allowed workload. This work shows a better path setup rate and provides a lifetime reliable nature. Both of the algorithms are tested under synthetic traffic patterns and real benchmarks. Simulation results show better performance as compared to XY routing, odd/even, and north first routing.

Lee et al. [56], proposed a methodology to reduce several loss in Optical-NoC. The proposed work uses three different routing algorithms to reduce insertion loss which degrades energy efficiency as well as signal reliability. Insertion loss deterministic is used to minimize the loss while another two adaptive routing algorithms are used to deal with loss path as loss constrains routing respectively. Simulation results show a reduction in latency, increased throughput, and better energy efficiency. Furthermore, work shows to adopt appropriate optimized techniques for better design goals.

Falahati et al. [57], proposed a reconfigurable routing architecture to provide better optical communication among nodes. The proposed work uses dynamic reconfiguration architecture which helps to provide good routing paths between nodes. The specific set of wavelengths are utilized to provide packets between nodes which is the key idea for configuring dynamic paths. The simulation result shows better performance in terms of less power usage, energy consumption is reduced by 54%, and provides deadlock-free routing among nodes.

Desai et al. [58], proposed to use a machine learning technique to provide routing among nodes. Proposed work suggested eliminating the shortest path every time to eliminate congestion problems. Thus paths are selected based on demand, priority, and traffic present on the network. Selecting an appropriate path according to the traffic removes congestion problems and provides deadlock-free routing. Simulation is done over periodic and non-periodic traffic patterns. Results show better delivery time and reduce all over power consumption.

Khoroush et al. [59], proposed a mapping algorithm to illustrate the impact of hop count, congestion, and path selection in NoC. The proposed work suggested four mapping algorithms, namely hop count, congestion, no-turn, and turn to reduce insertion loss and energy consumption. Simulation results show a comparison between each other on the basis of insertion loss which better results in both the worst case as well in the best case. Furthermore, works show improvement in insertion loss and energy dissipation compared with random mapping algorithms.

Li et al. [60], proposed a routing algorithm based on routing criteria to perform better in the case of thermal heating and help to minimize the conflicts. The proposed work shows two algorithms known as mixed-integral linear programming (MILP) and contention aware routing (CAR) to perform better communication in Optical-NoC. The proposed approach achieves excellent performance by reducing design complexity. Simulation results show good results in the case of communication between nodes as well as reducing energy consumption by 4.18%.

Ye et al. [61], proposed a thermal aware adaptive routing mechanism to provide proper communication. The proposed work uses a thermal-sensitive optical power loss model which is used to move traffic towards available links. This traffic movement reduces overall thermal balance and provides high thermal reliability. The experiment is done over different 8x8 mesh architectures to study thermal-aware routing algorithm efficiency. Simulation results show better temperature management in Optical-NoC and eliminate traffic from hot spot areas.

Path reservation criteria play an important role in exploring the full potential of Optical-NoC. Regarding path set in Optical-NoC Fussella et al. [62], proposed to use flooding technique to find all available paths in Optical-NoC. This work shows the importance of path setup in optical transmission as they provide high throughput. By using the flooding technique all available links are used to provide contention-free routing as well as reduced idle link usage. Simulation results show a better path setup rate as compared to the traditional path setup mechanism as well increases both energy efficiency and performance.

Wang et al. [63], proposed a thermal aware routing to resolve thermal issues in Optical-NoC. The proposed work uses thermal aware routing based on ant colony optimization to optimize the routing decisions. This work achieves uses approximate ACO-based routing to eliminate table overhead. Simulation results present better solutions regarding optical power usage and temperature variations. Furthermore work also explores the scalability of proposed ACO-based routing in large Optical-NoC architectures.

Yao et al. [64], proposed a methodology to provide better and traffic efficient routing among PE nodes. The proposed work provides several techniques to tackle routing problems like loss-aware adaptive routing (LAA), priority-based round-robin virtual queen section, Q-learning-based technique, and local transfer link technique. Simulation results are done over 356 nodes are architecture which provides better performance in terms of improved network throughput, end-to-end delay, and low optical loss while performing communication.

Guo et al. [65], provide an interesting solution towards network failure due to faulty ORs. Regarding this problem prosed work provides a new OR structure to reduce insertion loss as well as an adaptive routing algorithm (FTRA-BL). The proposed algorithm selects waveguides in disabled ORs and uses them as a backup path between source and destination. These backup links provide the best guarantees macroscopic restore path. Simulation results show improvement in overall transmission latency and well reliability of the Optical-NoC.

Lee et al. [66], proposed a solution regarding hybrid Optical-NoC architecture. The proposed work provides a new shortest path routing algorithm to perform better communication among nodes. This algorithm combines both rollback scheme and rapid flow control method to promote a fast path setup rate. This path setup rate increases the overall parallel data transfer rate between nodes. Simulation results show a reduction in latency, improvement in throughput, and energy-efficient communication in hybrid Optical-NoC. Furthermore proposed methodology performs better under an increase in network size in terms of resource utilization.

Asadi et al. [67], proposed a new routing algorithm that helps to reduce optical loss while providing better communication under different traffic patterns. This work uses a non-blocking five port router and 2D mesh architecture to test the proposed routing algorithm. The proposed routing algorithm chooses different nodes that select the optimal path with less optical loss to perform communication. Simulation results use three scenarios (best case, worst case, and average case) to evaluate the routing algorithm, which shows improvement in optical loss and better performance as compared to XY routing.

Mayer et al. [68], propped a routing algorithm that helps to increase the QoS in optical communications. The proposed work provides a traffic-aware routing algorithm that helps to provide fewer congestion problem as well as helps to distribute proper traffic in a network. The proposed routing algorithm also helps to avoid faulty links in the network and reduces miss-delivery in Optical-NoC. The simulation result shows all overbalance in network traffic, reduction in blocked path issue, and increase overall communication performance.

Table 2.2:

Demonstrates different routing techniques used in Optical-NoC

Referenced Articles	**Methodology**	**Topology Adoption**	**Positive Aspect**	**Shortcoming**
Guo *et al.* [49]	Proposed a novel IP-core mapping in order to speed up the searching process.	3D Mesh	higher reliability, Increases over all performance.	Mapping schemes enhances performance and increases information table.
Choi *et al.* [50]	Proposed to use back propagation algorithm to enhance communication among GPU and CPU	2D Mesh	Energy efficient communication among priority nodes.	Provides efficiency but increases overall computation

Abadal *et al.* [51]	Proposed to use dual channel communication among PE nodes.	2D mesh	Improves execution time speedups and energy efficient communication	Increases algorithm complexity.
Liu *et al.* [52]	Proposed to reuse the limited number of available wavelengths different routers.	2D Mesh	Enhance the data rate and reduce end to end delay	Increase in wavelength directly effects increase in power consumption.
Wang *et al.* [53]	Proposed to use wavelength assignment method and deterministic routing algorithm	2D Mesh	Reduce deadlock situation, Low energy consumption	Shows that electric switching in Optical-NoC increase chances of congestion.
Imre *et al.* [54]	Proposed to use dual-mode routing approach based on conventional per-message-based routing or a collective routing technique.	2D Mesh	Deadlock-free and contention-free dens data flow between nodes.	Providing several paths at each step increase computation among nodes.
Wang *et al.* [55]	Proposed to use two adaptive routing algorithm (lifetime aware routing and	2D Mesh	Improves better compared to both XY routing	Provides high throughput but increase overall

	multi-objective routing)		and odd/even routing.	computation complexity.
Lee *et al.* [56]	Proposed three types of routing (insertion loss-minimized deterministic routing; minimized loss path-prioritized adaptive routing; and insertion loss-constrained adaptive routing)	2D Mesh	Provides high throughput as well less energy consumption.	Increase in use of wavelengths increase overall power usage.
Falahati *et al.* [57]	Proposed to use mapping specific set of wavelengths and utilizes its dedicated routing.	2D mesh	Provides high through, Reduce energy consumption.	Optical NoC are more complex to design.
Desai *et al.* [58]	Proposed an optimized reinforcement-based routing algorithm based on predictive mechanism	2D Mesh	Provides shortest path between source and destination.	Shows path setup provides throughput in term of high computation.
Khoroush *et al.* [59]	Different routing algorithm were proposed study the impact of hop count and energy dissipation.	2D Mesh	Mapping is improved, Reduce energy dissipation.	Increase in hop count directly effects QoS and other performance parameters.

Li et al. [60]	Proposed routing algorithm to eliminate communication conflict between two nodes.	2D Mesh	Increase in overall performance Reduction in energy usage by 4.18%.	Proposed algorithm act as adaptive routing which increases overall performance in cost of complexity.
Ye et al. [61]	Thermal aware adaptive routing mechanism.	8x8 2D Mesh	Achieves better network optimization in hotspot areas.	
Fusella *et al.* [62]	Flooding technique is used to find free optical links in Optical-NoC	2D Mesh	Find all available optical links in architecture, Provides less energy consumption.	Path reservation criteria is beneficial but also provides limitation to the Optical-NoC.
Wang *et al.* [63]	ALO routing is compared over odd even and west first routing.	8x8 2D Mesh	Effective routing optimisation scheme	Common routing techniques are less efficient in case of adaptive routing.
Yao *et al.* [64]	Loss aware and priority based adaptive routing.	2DMesh and Fat Tree	Network throughput is increased and overall delay is decreased.	Adaptive routing increases time complexity.

Guo *et al.* [65]	Propose a new OR structure and adaptive routing algorithm	3D Torous	Increase system reliability as compared to previous technique of abandoning faulty ORs.	Using faulty MR increases chances of miss delivery in Optical-NoC.
Lee *et al*. [66]	Proposed a rollback scheme and a rapid flow control method to promote the fast routing path setup.	Hybrid Optical-NoC	Better network utilization, Efficiency in term of Latency	Roll back provides extra computation as well as complexity.
Asadi *et al.* [67]	Proposed routing algorithm to choose most efficient routing path.	2D Mesh	Performs better as compared to XY routing.	Providing alternate path requires high computation again and again.
Meyer *et al.* [68]	Distribute traffic throughout NoC to maximize the traffic flow which increases overall throughput	3D Mesh	Proper balancing of load in NoC Eliminate Path blocking issue	Using flow control limits overall throughput by blocking full flow of packets in NoC.

2.2.3 Optical-NoC Fault Tolerant Methods

This subsection represents the various work done in the direction of fault-tolerant NoCs, concluded in Table 2.3. There are many methods observed to deal with the faulty situation in NoCs and provide communication among nodes. The most common approach to tackle faulty situation are re-routing, as they require less system updating, adds less complexity towards NoC's design, and achieve high reliability[69]. They act as a backup routing algorithm to deal with the faulty situation and provide the optimal solution.

Pai et al. [70], proposed a graph topological approach that uses the feed-forward network. This approach is beneficial to identify the columns with non-interacting nodes, nullify them and adjust them simultaneously to perform communication between nodes. Father, simulation result shows enhancement in the fault-tolerant nature of NoC as well as a reduction in computation complexity required to identify the faulty nodes. In this approach, they use tuneable MRs to use N number of wavelength which uses more energy as compared to simple opto-MRs. Thus opto MRs are more preferable to construct energy-efficient NoC.

An interesting solution is presented to eliminate crosstalk and noise issues in Optical-NoC. Chittamuru et al. [71] presented an approach to increase the wavelength spacing while performing communication among nodes. In DWDM use of small spacing between different wavelengths increase the chances of crosstalk and noise between nodes. The simulation was conducted on both firefly and corona architecture which shows less crosstalk and noise while performing optical communication between nodes. This work also showed that optical signal is capable of providing high communication power but also suffers from noise issues which may act as a bottleneck for overall communication.

Bakhtiar et al. [72], proposed a solution regarding thermal aware fault occurrence in NoC. In Optical-NoC thermal heating is one of the major issues, thus the proposed work uses redundant MRs which work according to the different thermal conditions. In different thermal condition, MRs provides proper communication and eliminate the probability of miss delivery. Future, the simulation result shows low overall latency up to 16% and also provided energy-efficient routing under different thermal conditions. The approach helps to provide a solution in high thermal conditions and showed that MRs are highly capable of getting faulty under overheating/ thermal conditions in Optical-NoC.

Zhang et al. [73], proposed a fault-tolerant routing algorithm that helps to achieve proper communication between nodes under faulty conditions. The proposed algorithm is use to discover the potential live lock condition due to particular faulty links. These live lock reduce the overall throughput and degrades overall performance. Simulation results show avoidance from live lock as well as from deadlock situations. Furthermore enhances the fault-tolerant nature of NoC and provides less complex methods to deal with single link fault.

Xiang et al. [74], proposed a unified test technique to deal with the faulty situation in Optical-NoC. This approach uses a particular delivery test by sending a packet over the network through a separate none faulty network. Simulation results show a better path setup rate through available links and avoid packet corruption. The proposed approach enhances the fault-tolerant nature and provides a better solution to deal with the faulty situation. This work also shows that re-routing works better than other techniques used to deal with the faulty situation.

3D NoC is more capable of getting faulty as compared to 2D NoCs, as in 3D if any layer gets faulty then other layers may face packet loss issues. Li et al. [75], proposed a solution regarding the faulty situation in 3D NoC by providing 3D floor mapping technique. This technique is known as a known-good-dies (KGD) test which is used to ensure every die nature in NoC. This approach provides better results as compared to a previously known method as well provides a better fault-tolerant nature in 3D NoCs. Furthermore, the proposed approach shows that higher results can be achieved in the cost of degraded performance and increased power consumption.

Ahmed et al. [76], proposed to use conventional hybrid Optical-NoC to provide proper connection among nodes. This work also proposed a contention-aware routing algorithm that helps to provide proper communication in case of excess packet delivery. This contention situation degrades overall performance and provides less throughput. Simulation results show proper control signaling between PE nodes, show a reduction in overall latency, and provide a reduction in energy consummation. Furthermore, this work shows the positive aspects as well as shortcomings of the path setup process used in Optical-NoC.

In 3D Optical-NoC a single layer fault may cause the message to be miss deliver and provide overall less performance. Schley et al. [77], proposed an interesting solution reading multiple-layer NoC architecture. This work is used to perform cross-layer information flow of each node which helps to identify the faulty link. Simulation is performed to check the impact of fault links on the QoS and performance of NoC. Results show an increase in overall performance as well acceptable QoS while communicating among nodes. Furthermore proposed work shows an increase in computation while performing faulty link diagnosis over multiple layers which includes different links.

Li et al [78], proposed a fault-tolerant routing algorithm to counter the faulty links in NoC and provide better communication under faulty situations. This work uses congestion-aware adaptive routing to predict the next optimal path with minimal hardware overhead. Simulation results are compared with traditional XY routing and Dy XY routing, which shows better results. Furthermore, this work shows that adaptive routing is better in the faulty situation but increases overall computation cost in NoC.

Fadhel et al. [79], proposed to use extra components in Optical-NoC to enhance the reliability as well fault-tolerant nature. The proposed work uses an extra ring waveguide between nodes to provide a backup path in case of a faulty situation. While the use of a fault-tolerant routing algorithm helps to maintain proper communication among nodes. Simulation shows a better result as compared to traditional fault-tolerant methods as well increased reliability of the system and fault-tolerant nature. This work also shows that using extra components in Optical-NoC increases reliability over the cost of design complexity.

Optical-NoC has a less reliable nature due to the delicate components of optical interconnects. Guo et al. [80], proposed a fault-tolerant routing algorithm that helps to reuse faulty MRs and provide a backup path between source and destination. This work also calculates the reliability of architecture theoretically and shows the probability of becoming another MRs invalid due to some faulty MRs. Simulation results show better performance in the faulty situation and showed good results as compared to traditional fault-tolerant methods. Furthermore, this work showed that using faulty MRs again and again increases the chance of packet loss in Optical-NoC.

Virtual channels have many positive aspects by providing throughput between high-priority nodes. Xiang et al. [81], proposed to use express virtual channel (EVC) between nodes. These EVCs are used to transmit multiple data between high-priority nodes. Simulation results show better performance as compared to XY, DyXY, and DyAD approaches. Also provides high reliability and fault-tolerant nature due to dedicated connection between nodes. This work also showed that the use of virtual channels provides high throughput in cost of design complexity and energy usage.

Rad et al. [82], proposed to use adaptive routing to deal with the faulty situation in NoC. This work represents the solution for permanent faults occurrence. Adaptive routing helps to find the next optimal path between source and destination while neglecting faulty links at the same time. The simulation result shows better results under permanent fault that occurs due to inactive MRs and links between nodes. Furthermore, the use of adaptive routing increases all over computation complexity as compared to simple routing used to deal with the faulty situation.

Zhu et al. [83], proposed a routing algorithm to deal with faulty occurrences in NoC. The proposed work uses a congestion-aware prediction technique to eliminate traffic load. Proposed routing is compared with traditional techniques like XY and odd/even routing. Simulation results provide a better path setup rate between nodes and enhance overall performance. This work also gives a better solution with path reservation criteria which increases overall throughput between particular nodes and increases idle node usage.

Virtual channels are very beneficial for achieving high communication power between priority nodes. Panem et al. [84], proposed to use virtual channels to support fault-tolerant nature in a mesh topology. This work uses a virtual channel to eliminate extra links and the probability of getting faulty at the same time. Simulation results show an increase in reliability as well as the throughput of the architecture. On the other hand design complexity increases of architecture by using extra virtual channels.

Abdollahi et al. [85], proposed to use extra backup paths between source and destination. This work is used to place extra MRs on architecture or add duplicate MRs which perform the same work in case of fault occurrence. Simulation results are compared with simple routers which provide better results and enhance the fault-tolerant power of Optical-NoC. Another interesting solution was presented of using adaptive path configuration by Meyer et al. [86]. The proposed work uses to configure different paths if a minimal path fails to transmit packets between nodes. This work also uses a duplicate router for configuration a new path setup. Furthermore, simulation results show fault-tolerant nature under faulty MR situations and are able to provide the number of minimal paths between source and destination. Both work also shows an increase in design complexity by adding extra elements (that is MRs in this work) to deal with the faulty situation.

Karimi et al. [87], proposed or use a specific waveguide in Optical-NoC architecture prevent fault occurrence. This work is used to move traffic from hot regions or traffic from congestion links to eliminate deadlock or livelock situations. The proposed solution also helps to avoid thermal fault occurrence in Optical-NoC. The simulation result shows an increase in thermal reliability as well as the fault-tolerant nature of the architecture. Furthermore, the use of extra waveguides to enhance the reliability may increase all over design complexity of the architecture.

Thermal reasons are one of the main reasons to create the fault in Optical-NoC due to the delicate nature of the MRs. Li et al. [88], provide thermal awareness as well as contention-aware routing to deal with the faulty situation. In thermal aware routing, high traffic is moved from busy links to the normal links to eliminate heating problems due to high communication. In contention-aware routing, available links are used more to provide a path between source and destination. Simulation results show thigh thermal aware reliability as well as helps to use proper traffic flow all over the network.

Seyednezhad et al. [89], proposed to use multiple paths between source and destination. This work shows that multiple path setup methods are more beneficial as compared to single-path setup. This method helps in a case of miss-delivery in which packets are rerouted again between nodes by another available path. Simulation results show high QoS as well as decreased delivery error while performing communication between nodes. The proposed work shows an increase in computation power to find multiple paths at each node while performing communication.

Table 2.3:

Demonstrates different fault tolerant approaches used in Optical-NoC

Referenced Articles	**Methodology**	**Topology Adoption**	**Positive Aspect**	**Shortcoming**
Pai *et al.* [70]	Proposed a graph-topological approach to nullify the power in nodes via	2D Mesh	Enhance fault tolerant nature of NoC,	Tunable MRs uses more energy usage

	optoelectronic feedback.		Reduce computation complexity	as compared to opto-MRs
Chittamuru *et al.* [71]	Proposed to increase the wavelength spacing to eliminate crosstalk.	2D Mesh	Improves SNR ratio, Reduction in crosstalk.	Optical interconnect shows more loss as compared to any interconnects.
Bakhtiar *et al.* [72]	Propped to use redundant MRs to reduce the thermal variations-based errors	2D Mesh	Latency overhead by 16%, Energy efficient.	MRs are more capable of getting faulty in thermal conditions.
Zhang *et al.* [73]	Proposed a fault tolerant routing algorithm for the discovery of a potential live lock problems.	2D Mesh	Provide deadlock and live lock freedom. Tolerance to a single-link-fault.	Single link fault may provide full system failure.
Xiang *et al.* [74]	Proposed a unified test technique by delivering test packets on the network.	2D Mesh	Avoids packet corruption. Enhances fault tolerant nature	Adding extra elements in Optical-NoC may increase overall complexity.

Li *et al.* [75]	Proposed a 3D floor planning process to support fault tolerance in NoC.	3D NoC	Increase performance as compared to previous methods and increases fault tolerant nature	Increase in the cost of performance penalty and elevated power level
Ahmed *et al.* [76]	Proposed to use contention-free routing for photonic NoC.	2D Mesh	Provides control signalling between nodes. Reduce latency, Energy consumption.	Path setup provides both negative as well as positive aspect.
Schley *et al.* [77]	Proposed to use cross-layer information flow between layers to identity faulty links.	3D Mesh	Increases overall performance, Improves quality	Increases computation as compared to single layer diagnostic scheme.
Li *et al.* [78]	Presented a fault-tolerant and congestion-aware adaptive routing algorithm.	2D mesh	Performs better than XY and DY XY routing.	Increases performance I cost of computation.
Fadhel *et al.* [79]	Proposed to use extra ring waveguide which provides backup paths.	2D Mesh	Increases reliability of ORs as well as	Increases reliability in cost of design complexity.

			fault tolerant nature.	
Guo *et al.* [80]	Reliability of architecture, Fault tolerant routing algorithm	3D Optical-NoC	Provides better results as compared to traditional fault tolerant method.	Using faulty MR again and again increases chance of packet loss.
Xiang *et al.* [81]	Use of Express virtual channel (EVC) are used to transmit multiple packet.	8x8 2D mesh	Proposed EVC approach provides better results as compared to XY, DyXY and DyAD.	Virtual channel provides high throughput in cost of complexity and energy usage.
Rad *et al.* [82]	Proposed adaptive fault tolerant routing algorithm	3D Mesh	Increases performance in case of permanent faults.	increase in computational complexity
Zhu *et al.* [83]	Routing algorithm is proposed based on congestion prediction technique.	2D Mesh	Perform better as compared to XY and Odd/Even routing Provides better path setup rate.	Provides better solution in term of path reservation criteria.
Panem *et al.* [84]	Using virtual channel over mesh topology to support fault	3D Mesh	Increase in reliability and throughput.	Increases over all design complexity

	tolerant nature of Optical-NoC			
Abdollahi *et al.* [85]	Propose to add extra backup path and MR duplication to enhance the reliability of architecture	2D Mesh	Proposed routers performs well as compared to simple routers. Backup MRs enhances the fault tolerant power	Adding extra elements to the architecture increases overall design complexity.
Meyer *et al.* [86]	Adaptive path-configuration and routing algorithm is proposed to deal with faulty situation	3D Mesh	Provides high fault tolerant power in case of faulty MRs Configuration of duplicate MR to provide extra path to destination	
Karimi *et al.* [87]	Using a specific waveguide connection to move traffic from hot region.	2D Mesh	Provides thermal resilience and increase throughput by providing alternate path.	Waveguide deployment are complex in nature.

Li *et al.* [88]	Provides thermal aware and contention aware routing between nodes	2D Mesh	Provide high thermal reliability in Optical-NoC	Only works in case of thermal fault occurrence.
Seyednezhad *et al.* [89]	Provides multiple paths between source and destination	2D Mesh	Provides high quality of service. More than one path is beneficial for making proper decision.	Requires high computation to find multiple paths.

2.3 Shortcomings of the current techniques

These are some of the major shortcomings that we have observed from the literature survey. Although Optical-NoC is capable of providing high communication power but the following shortcomings limit and degrades its overall performance.

- **Different Topological Optical-NoC architecture.**

To overcome the need for high communication power many researchers proposed different Optical-NoC architectures. These Optical-NoC architectures are capable of achieving efficient optical communication among PE nodes. These architectures use different topologies to provide connections among PE nodes and achieve high communication power. On contrary, there are a few limitations while modifying the size of the architecture like 4x4, 6x6--NxN.

- **Lack of efficient waveguide deployment.**

As compared to traditional NoC architecture, Optical NoC requires optical waveguides to provide connection among PE nodes. These waveguides are capable of providing high communication power but these are delicate and require proper deployment among PE nodes.

These deployments may affect architecture's design complexity, fault rate, and algorithm's complexity.

- **Proper Routing techniques.**

These Optical-NoC architectures help to achieve good optical transmission power among PE nodes. Routing techniques help to maintain proper and efficient communication, but in Optical-NoC different architectures require different routing algorithms. Due to new architectures, some common routing algorithms like XY routing, XYX routing, directional first routing, and Odd/Even routing fails to work efficiently. These algorithms may encounter a deadlock situation and fail to achieve the shortest path between source and destination.

- **Using path reservation criteria.**

Another limitation that we have encountered in routing techniques is path reservation criteria. In path reservation two PE nodes achieve high communication power by reserving the required path for a particular time. This technique provides high communication among specific PE nodes, but there are some limitations like path blocking issues, deadlock situations, idle node usage, and resource starvation. These limitations eventually provide a bottleneck for the overall optical communication power in Optical-NoC.

- **Fault Occurrence in Optical-NoC.**

In Optical-NoC optical components are very delicate, a slight external or internal factor may trigger it into a faulty situation. The internal factors are overheating, micro-waves, and sound waves while pressure, bending, and external temperature are comes under external factors. These faulty situations affect communication which results in miss delivery of packets, decrease in performance, or results in overall system failure

.

CHAPTER 3

MODERN ARCHITECTURE FOR OPTICAL NETWORKS ON CHIP

3.1 Introduction

Recently, a large number of optical-NoC architectures have been developed to achieve an efficient and optimum waveguide network between PE nodes. These architectures are capable of achieving higher bandwidth to support high computation power. As per the literature review, different architectures are observed which provide different waveguide deployments for handling a large number of PE nodes [39, 40, 42, 43, 53, 67]. While doing a literature survey there are some drawbacks that we have observed in optical-NoC architectures. It has been noticed that different waveguide deployments or different topologies are constructed in the optical-NoC. Additionally, these different architectures require different routing techniques to perform proper communication. Furthermore, in case we want to change the size of the architecture, the whole waveguide deployment is to be modified. Thus, the proposed work represents 2×2 optical-NoC architecture to address the respective challenges. This architecture uses a circular waveguide and MRR to provide a proper connection among PE nodes. The proposed architecture was developed to act as a brick-like structure. This small brick architecture may help to construct other big optical-NoC architectures.

3.2 Optical-NoC Communication System

This section includes a brief idea about optical communication systems, before entering into the optical-NoC architecture's design. Every communicational system has its own components that work to provide proper communication among sender and reviver. In optical-NoC, an optical signal is used to perform communication among PE nodes. These optical-NoC communication systems consist of several optical components which help to achieve a proper transmission. These optical components are used to convert an electrical signal into an optical signal and then help to transmit the optical signal from the source to the destination. The optical-NoC communication system is divided into three major parts generation, routing, and reception [90]. Figure 3.1, shows a pictorial representation of the optical-NoC communication system.

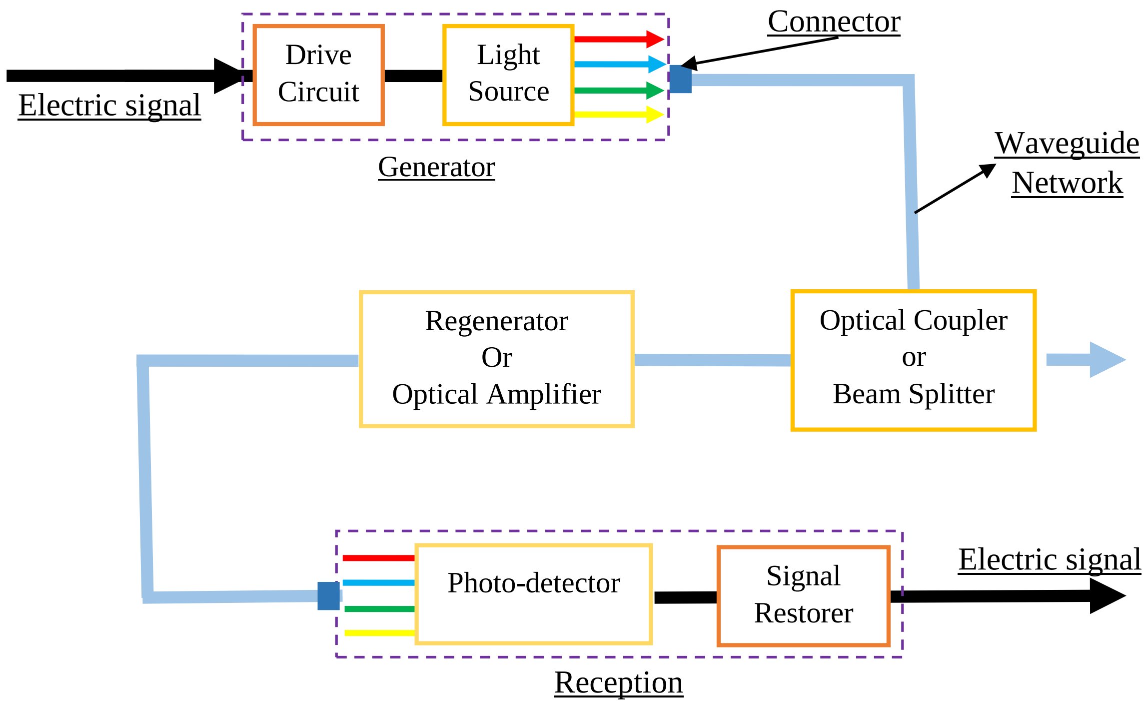


Figure 3.1: Optical-NoC Communication System

Generator is considered the first component used while performing optical transmission between nodes. This section includes the conversion of an electric signal into an optical signal. This process includes mainly four parts, first includes encoding of the received electric signal in which error detection/correction involves to improve QoS. Secondly, it includes the control over the data rate and packet latency rate through a transfer of electric data into the serialization section. Then at the third stage, it includes a drive circuit which is used to provide an electrical interface between electrical and optical sources. Lastly, it includes a modulator that helps to modulate generated optical signals into the waveguide.

Routing is considered one of the main components of any communication system. Routing helps generated signals to travel between source and destination in a specific manner or we can say efficiently. Proper routing technique in any system adds many positive features like QoS, scalability, reduction in complexity, better communication, low error rate, and less miss rate. In the case of optical communication, we use waveguides or nano-optical fibers as interconnect between the PE nodes. These channels are capable of providing specific wavelengths as well as multi wavelengths at a particular time.

Reception is considered as the last part of optical communication, this includes the collection of optical data from the major waveguide. This part also performs some major functions on the optical signal to convert back into the electric signal. This section includes four sub-parts, firstly, it includes a detector that helps to detect an optical signal and convert that optical signal into an electric signal. Secondly, it passes through an amplifier which provides enough electrical power to perform an operation. Thirdly, it includes converting a high clock signal into low clock signals through a deserializer. Lastly, the decoder helps to convert the signal into its original form for further processing.

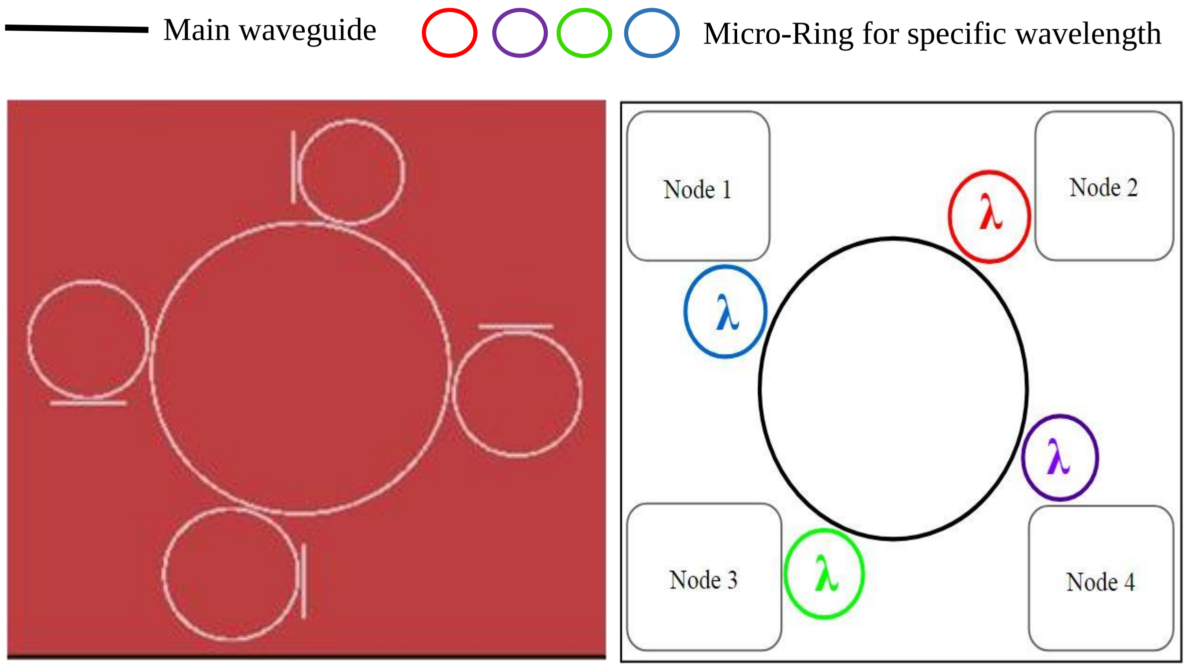
3.3 Proposed Optical-NoC Architecture

This section discusses the new proposed optical-NoC architecture which helps to eliminate some of the drawbacks that were observed. Out of all those drawbacks, we have observed that different waveguide deployments are proposed to perform connections between PE nodes. Additionally, these architectures fail to increase the size of the Optical-NoC with the same waveguide deployment [39, 40, 42]. Thus, new 2×2 optical-NoC architecture was proposed that acts as a brick-like structure.

To construct optical architecture, different research papers and survey papers are studied [90, 91, 92]. These papers help to observe how different optical components are used to construct efficient optical-NoC. In this architecture, waveguides are used as an interconnect medium between nodes. These waveguides consist of specific materials with special properties like total internal reflection, less crosstalk, and less SNR ratio. These waveguides are used to guide optical signals between nodes or we can say to manipulate optical signals between source and destination. In the proposed architecture we have also proposed MRR which helps to connect PE nodes with these waveguides.

These MRR were used to extract particular optical signals from the waveguide into the PE node. In some architectures, direct connections are also provided between nodes without the use of MRR. Those architectures provide less optical loss while performing communication but results in complex optical-NoC design. Thus, the proposed architecture aims to construct efficient optical-NoC waveguide deployment among PE nodes, which helps to achieve a less complex architecture design. Further subsections explain briefly how waveguides are fabricated between nodes, which type of material is used to construct optical-NoC architecture. This material is used to construct waveguide, substrate, and MRR which are used to filter optical signals from the main waveguide.

3.3.1Architecture Overview



(a) (b)

Figure 3.2: (a) Simulated proposed 2×2 optical-NoC architecture, (b) Graphical representation of 2×2 optical-NoC architecture.

This section illustrates an overview of our proposed architecture. Firstly, Figure 3.2 (a), represents simulated proposed 2×2 2D optical-NoC architecture. In this architecture, we have used a circular waveguide to connect four PE nodes. These PE nodes are then connected through MRR which are used to extract optical signals from the main waveguide. Our proposed architecture uses SiO_2 as a waveguide material while substrate as a Si (briefly mentioned in subsection 3.3.2). These MRRs work on the property of optical components known as the coupling effect.

Figure 3.2 (b), represents a pictorial representation of 2×2 2D optical-NoC architecture. This figure represents four MRRs to connect the PE node to the major waveguide. Each MRR is used to extract optical signal from waveguide to PE node. These MRR can extract specific wavelengths thus represented in different colors (briefly mentioned in subsection 3.3.4). Proposed 2×2 optical-NoC architecture each PE node has its own MRR to extract optical signal from the waveguide.

3.3.2 Material Initialization

Optical interconnects are considered as one of the main components for providing optical signals between PE nodes. These interconnects consist of nano-fibers and waveguides, which consist of specific materials to maintain the maximum QoS and minimum loss during communication. According to the literature survey, there are many materials that are used to construct efficient waveguides like TiO_2, Al_2O_3, SiN, and SiO_2 [90]. Out of all these materials, we select SiO_2 for the construction of the waveguide and Si for the construction of the substrate. Figure 3.3, represents the side view of architecture.

There are many promising factors that support considering SiO_2 as our main waveguide material [93].

- It's a cheap and affordable cost for making proper waveguide material.
- Provides high QoS by providing less overall light intensity loss.
- It provides a high durability threshold i.e. high mechanical strength against pulling as well as bending.
- The chemical stability of SiO_2 is more as compared to other materials
- This material is not hygroscopic i.e. good for electric components.
- This material provides high optical transparency, mostly in the zone around 1.5μm wavelength.

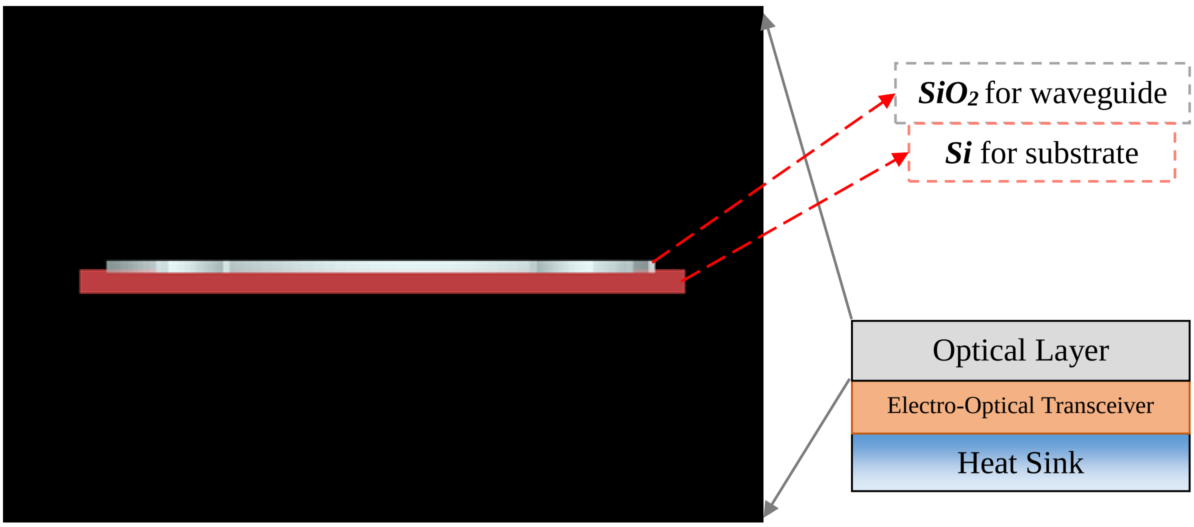


Figure 3.3: Side view of the architecture consists of SiO_2 waveguide and Si as a substrate.

3.3.3 Proposed Waveguide

This section discussed the waveguide fabrication in our proposed architecture. Waveguide is used to provide proper optical interconnect between PE nodes. These PE nodes are connected with major waveguides through MRR discussed briefly in the next section. We have used a circular waveguide in this architecture to reduce loss while optical transmission. In figure 3.4, we fabricated our proposed waveguide of cross-section denoted by "$H \times W$" of $500nm \times 220nm$ respectively. Mostly, the width of the waveguide is under $600nm$ to achieve acceptable mode operations. The radius of our circular waveguide or main waveguide was denoted by "R" of 20,000 *nm*. Figure 3.4 shows the proposed waveguide deployment between nodes as well as MRR placement to connect PE nodes with the main waveguide.

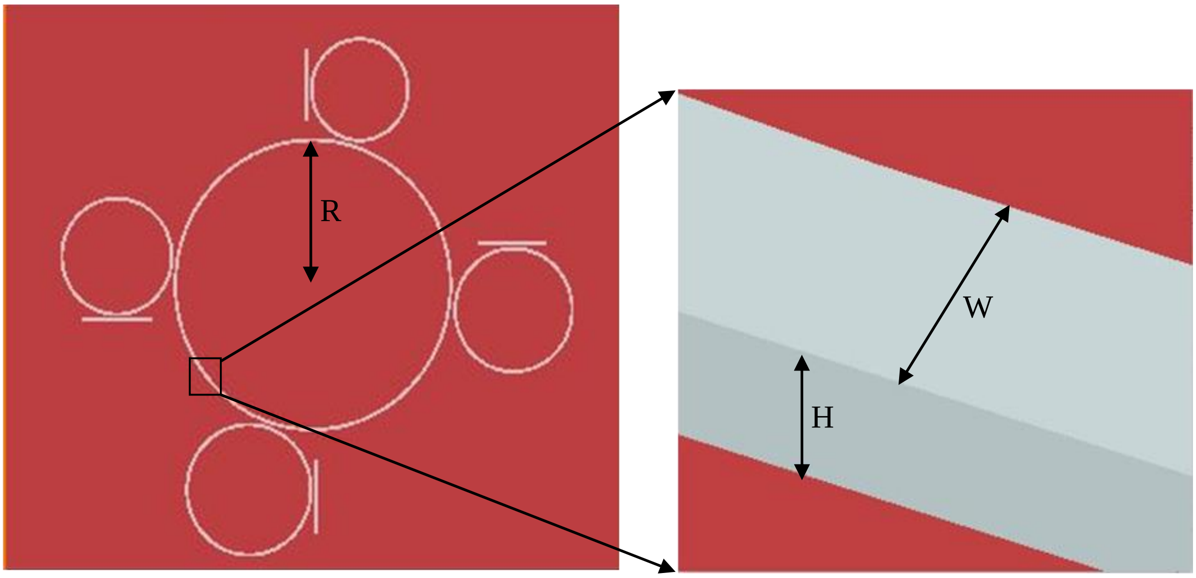


Figure 3.4: SiO_2 waveguide network between PE node 1, PE node 2, PE node 3 and PE node 4 over *Si* Substrate.

There are mainly four types of waveguides used while performing communication among PE nodes in optical-NoC [90, 91]. Each has its own properties and helps to provide flawless communication without creating any deadlock situation between sender and receiver. These waveguides are known as a single writer and multiple reader (SRMR), single writer and single reader (SWSR), multiple writer and single reader (MWSR), and multiple writer and multiple reader (MWMR). In SWMR, one sender is placed to transmit optical signals and many receivers are placed to filter optical signals from the major waveguide. In SWSR, only one sender and one receiver are used to communicate between PE nodes. In MWSR, multiple writers are placed to transmit optical signals, and a particular receiver is used to accept that signal from the waveguide. In MWMR, multiple writers are used to transmit optical signals and multiple readers are used to filter optical signals from the waveguide. Out of all these optical waveguides, we have used a SWMR waveguide to construct the proposed architecture. Figure 3.5 shows a pictorial representation of the SWMR waveguide in which one transmitter is used to transmit different optical signals into the waveguide while several receivers are used to filter optical signals at a receiver end.

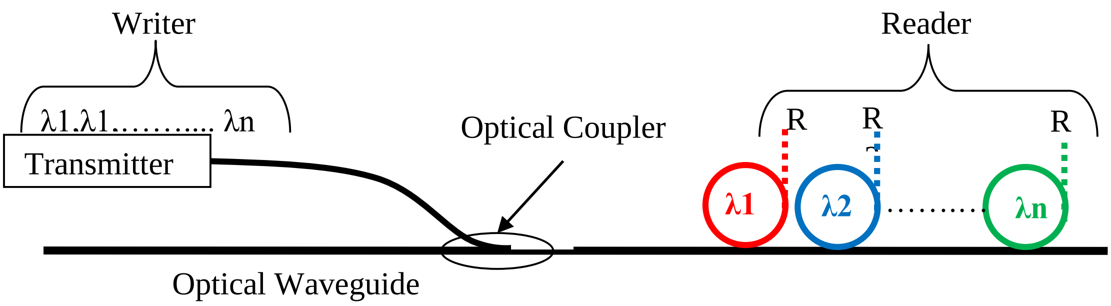


Figure 3.5: SWMR waveguide representation among sender and receiver

3.3.4 Proposed Micro-Ring Resonator

This section discusses the proposed MRR used for the configuration of the proposed 2×2 optical-NoC architecture. Originally MRR based PE nodes are constructed to achieve specific optical signals from the main waveguide. These resonators work on the property of optics known as the coupling effect, which helps to extract optical signals from the main waveguide to the respective PE nodes. In our proposed architecture, we have used four MRRs for each PE node (Node 1, Node 2, Node 3, and Node 4) respectively as per Figure 3.2 (b). There are many techniques used to construct MRRs, some of the well-known techniques are thermo-optic MRR, electro-optical MRR, acousto-optic MRR, magneto-optic MRR, and opto-optic MRR [90].

All these MRRs helps to extract optical signal from the waveguide, but differ on the basic construction and different operating procedures. In thermo-optic MRRs, it uses heat energy to extract optical signals from the waveguide. In electro-optic MRR, PN junctions are used around the MRR to extract specific optical signals from the waveguide. In acousto-optic MRR, it uses stress signals to manipulate optical signals from the waveguide. In magneto-optic MRR, it uses magnetic fields to filter optical signals from the waveguide. In opto-optical MRR, it doesn’t require any external energy to perform optical filtering from the waveguide. This MRR was constructed in such a way that helps to extract a particular optical signal.

Out of all these MRRs, we have chosen opto-optic MRR for the construction of the proposed 2×2 optical-NoC. These opto-optic MRR doesn't require any external energy to perform optical filtering as compared to other MRRs. Furthermore, these opto-optic MRR are less complex to construct which helps to reduce architecture's design complexity. These two promising factors help to choose opto-optic MRR with respect to the other MRRs. In the proposed architecture as per Figure 3.2 (b), each PE node has its own specific MRR. These MRRs are of different colors which represent their unique properties. These MRRs are constructed in specific dimensions as per equation 3.1, which helps in filtering specific optical signals from the waveguide without affecting other optical signals. Table 3.1 shows the configuration of MRR's, which contains specific radius as well as wavelength (λ) which are filtered from these MRR.

Table 3.1:

MRRs configuration used in the proposed architecture.

Nodes	**Radius (nm)**	**Wavelength (**λ)
MRR 1	8,000	1400
MRR 2	7,000	1300
MRR 3	9,000	1600
MRR 4	8,500	1530

These radii of MRRs are between 7000*nm* to 9000*nm* while the gap between MRR and waveguide lies between 100*nm* to 300*nm*. These MRRs work on a specific wavelength (λ), refractive index (n_{eff}), comparable mode (m), and radius (R). From equation 3.1, we can derive resonating wavelength (λ) for a unique radius (R) for each MRR. These respective refractive index are achieved from an online database [94] for SiO_2 material.

$$m\lambda = 2\pi n_{eff} * \mathrm{R} \tag{3.1}$$

These MRRs are considered as one of the major components which help to provide proper optical commutation among PE nodes. There is some figure of merits that are used to evaluate MRRs performance which includes FSR value (Free Spectral Range), FWHM value (Full-Width Half-Maximum), finesse value, and Q-factor (Quality factor). Equations 3.1 to 3.4 are used to evaluate each MRRs figure of merits [95]. The first one is FSR value, which determines the distance between resonant peaks, the FSR value can be calculated by equation (3.2). In this equation wavelength is represented by (λ), group refractive index is denoted by (*ng*) taken from database [94], and lastly circumference of MRR is represented by *L=2πr*.

$$FSR = \frac{\lambda^2}{n_g * L} \tag{3.2}$$

The second figure of merit for MRR is known FWHM value, which determines the width of the resonant peak filtered from the main waveguide. The third figure of merit is known as finesse value, it is the ratio derived from FSR value and FWHM value. Equation 3.3 helps to achieve both FWHM value and finesse value of each MRR. In this equation, *t* denotes the coupling time and π is constant.

$$F = \frac{\text{FSR}}{\text{FWHD}} = \pi * \frac{\text{t}}{1-\text{t}^2} \tag{3.3}$$

Last and the most important figure of merit is known as Q-factor. The Q-factor of each MRR determines the sharpness in the resonator or the sharpness of the proposed MRR. Q-factor directly dependent upon the finesse i.e higher the finesse value higher the Q-factor. Equation 3.4 helps to calculate Q-factor of each MRR.

$$Q = \pi * \frac{n_{eff} * \text{L}}{\lambda} * \frac{\text{t}}{1 - \text{t}^2}$$

$$Q = \frac{n_{eff} * \text{L}}{\lambda} * F \tag{3.4}$$

From all equations 3.1 to 3.4, calculated respective values are represented in Table 3.2. Each MRR used in Node 1, Node 2, Node 3, and Node 4 have its own FSR value, FWHM value, Finesse value, and Q-factor. The average Q-factor of our proposed architecture is achieved up to 2,238.45 while using an optical signal wavelength between 1300nm to 1600nm.

Table 3.2:

Regarding MRR's configuration specifications.

Node	**Radius (nm)**	**λ (nm)**	n_{eff}	**Mode (m)**	**FSR (nm)**	**FWHM (nm)**	**Finesse value**	**Q-factor**
MRR 1	8000	1400	1.5297	55	25.20	0.62	40.72	2,235.29
MRR 2	7000	1300	1.5310	52	24.83	0.70	35.35	1,830.12
MRR 3	9000	1600	1.5270	54	29.23	0.59	48.80	2,632.33
MRR 4	8500	1530	1.5280	53	28.31	0.66	42.32	2,256.08

As per Figure 3.2 (b), a pictorial representation of 2×2 optical-NoC architecture is presented. In which proper waveguide deployment is used between PE nodes while MRRs are used to connect each PE node to the waveguide. These MRRs are constructed in a specific manner to filter optical signals of desired wavelength (λ).

3.4 Summary

This chapter describes the workflow of the proposed methodology that helps to overcome the different topological designs and lack of efficient waveguide deployment in Optical NoC. Firstly, the proposed 2x2 optical NoC architecture act as a brick-like structure to configure other big NoC architecture. Thus, while modifying the size of the architecture overall reconstruction is not required. Secondly, while configuring other architectures proposed brick-like structure helps to provide optimal waveguide deployment among PE nodes.

CHAPTER 4

SUSTAINABLE COMMUNICATION FOR OPTICAL NETWORKS-ON-CHIP

4.1 Introduction

Optical-NoC is considered as the perfect alternative to support high computation power by providing proper communication channels. As per the previous chapter, optical-NoC architectures with waveguide deployment among PE nodes helps to achieve proper optical transmission between them. This architecture requires routing algorithms to maintain proper and efficient optical transmission between nodes. There are many routing protocols proposed by researchers to perform optical routing in NoCs [49, 54, 55, 58, 59, 60]. These routing protocols help to maintain and implement flawless optical communication in NoCs. This chapter deals with routing protocols used in the proposed optical-NoC architecture constructed through several brick-like structures. The proposed architecture and routing protocols help to achieve the shortest path between source and destination without causing any deadlock situation. While doing the literature survey there are some research gaps that we have encountered that affect the overall performance of optical-NoCs. The main focus of this chapter is to provide proper optical communication among PE nodes as well as to overcome some research gaps.

4.2 Routing Algorithms used in Optical-NoCs

There are many routing algorithms proposed by researchers to support proper communication in Optical-NoCs. These routing algorithms help to attain maximum power of the optical channels by providing proper resource management and less deadlock occurrence, which limits the overall performance of NoCs. There are some research gaps that we have encountered in optical-NoC routing techniques, which affect the overall communicational performance. This section elaborates the different routing techniques that are used in NoCs as well as some research gaps that we have noticed in the optical-NoC routing technique.

Some of the common routing algorithms that are used in NoCs are XY routing, XYX routing, direction first routing, and odd-even routing [67, 96, 97]. These routing algorithms are used to perform proper communication among PE nodes with less computation complexity. In XY routing, packets are first traveled in X-axis direction and then in Y-axis direction until it reaches their destination. In XYX routing packets are free to move in X-axis and Y-axis depending upon the destination. Both routing algorithms are known as turn model routing in which packets are moved either in a clockwise direction or in an anticlockwise direction to reach their destination. These algorithms are very beneficial to avoid deadlock situations and very reliable in terms of 2D mesh architectures. Furthermore, XY routing prohibits at least four turns to escape deadlock situations as compared to other routing models.

In direction first, packets are move mostly in any direction like north first and west first. The packet will choose the next appropriate step on the basis of the destination. While these routing algorithms are more complex as compared to XY routing. This directional first routing achieves the shortest path between source and destination with fewer deadlock situations. While odd-even routing is considered as one of the most popular routing techniques which achieve adaptive routing. Odd-even routing is known as a partial adaptive routing technique without any virtual channel usage. These algorithms are consist of some set of rules which help to decide its next appropriate steps like east turn cannot be taken in an even column, north turn cannot be taken in an odd column.

It is observed that different optical-NoC architecture does not work on these common routing algorithms. Different optical-NoC architecture has different waveguide deployment, thus different routing algorithms are used to perform communication among PE nodes. Different authors proposed different routing algorithms, which are the combination of common routing techniques to perform communication in their proposed optical-NoC architectures. Other problems statement that we have observed in these routing algorithms are known as path reservation criteria.

Many researchers have proposed a solution to provide deadlock-free routing in optical-NoC architecture. Most of the researchers follow a particular step while performing communication between nodes known as path reservation criteria [39, 43]. As per Figure 4.1, a qualitative time diagram is mentioned which shows how optical transmission between nodes is done. This diagram shows three major steps known as path-setup process, message transmission, and path-teardown process. In the path-setup process, a particular packet is used to reserve a path between source and destination before performing actual optical transmission. In some work, this path reservation packet is transmitted through an electric signal while in others a specific optical path is used. In message transmission optical signal is transmitted between nodes once the path is successfully reserved between the nodes. In last path-teardown process is used, this process works when the optical transmission is successfully completed. This packet is used between source and sender to free the reserved path and make the path available for other PE nodes.

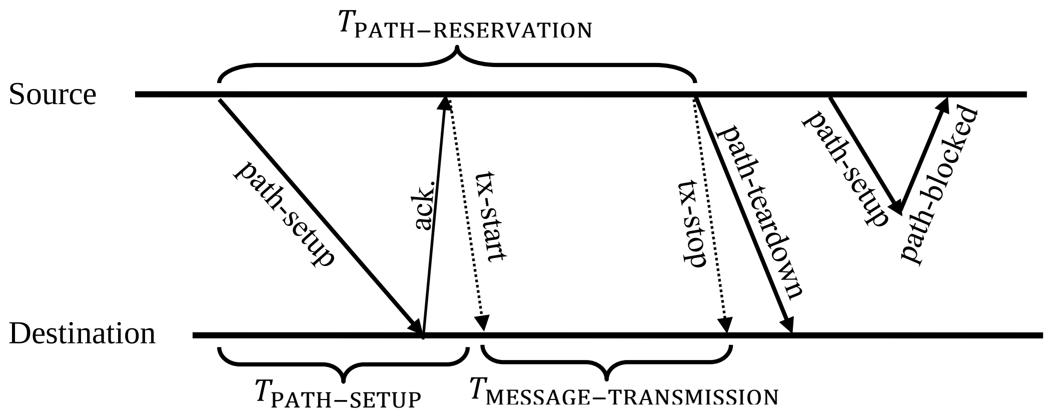


Figure 4.1: Qualitative time diagram between source and destination.

This path reservation criteria is beneficial for providing better performance in terms of high bandwidth by transmitting the large data packet. But on the other hand, these criteria add some issues in optical-NoC transmission. Firstly, if anyone wants to set up a path and a path is already reserved in that case, communication is not achieved. In this case, particular PE nodes are sent into the waiting stage, which increases idle node usage. These criteria are used in many recent research works like [39, 40, 43, 96]. As per Shacham *et al*. [43], "*Once the path is acquired, the transmission latency of the optical data is very short and depends only on the group velocity of light in a silicon waveguide*", which sums up a huge overall optical transmission latency.

Moreover, the path setup technique contributes to a resource starvation problem, also holds all other nodes while providing flawless transmission only between a particular sender and destination. As per optical communication, in the proposed optical-NoC architecture results of transmission latency between nodes are very low as compared to the path reservation process. Thus, path-reservation criteria are not efficient as well as not preferable to perform communication in the proposed optical-NoC architecture. In our proposed algorithm, we have adopted another technique rather than path reservation criteria to perform optical communication among nodes and remove some issues like resource starvation, idle nodes usage, and a deadlock situation.

4.3 Proposed Routing Algorithm

This section elaborates on the proposed routing algorithm which is used to perform optical communication in the proposed architecture. Proposed optical-NoC architectures are constructed by combining several brick-like structures. This proposed algorithm is independent of the size of the architecture and helps to perform communication in any optical-NoC architectures (4×4, 6×6, 8×8, --- N×N). The proposed routing algorithm uses a token-based protocol instead of path reservation criteria. The token-based protocol is used to provide starvation-free mutual exclusive on shared resources (waveguide). The token protocol is used to provide a specific time interval for each PE node to transmit an optical signal without causing any deadlock situation.

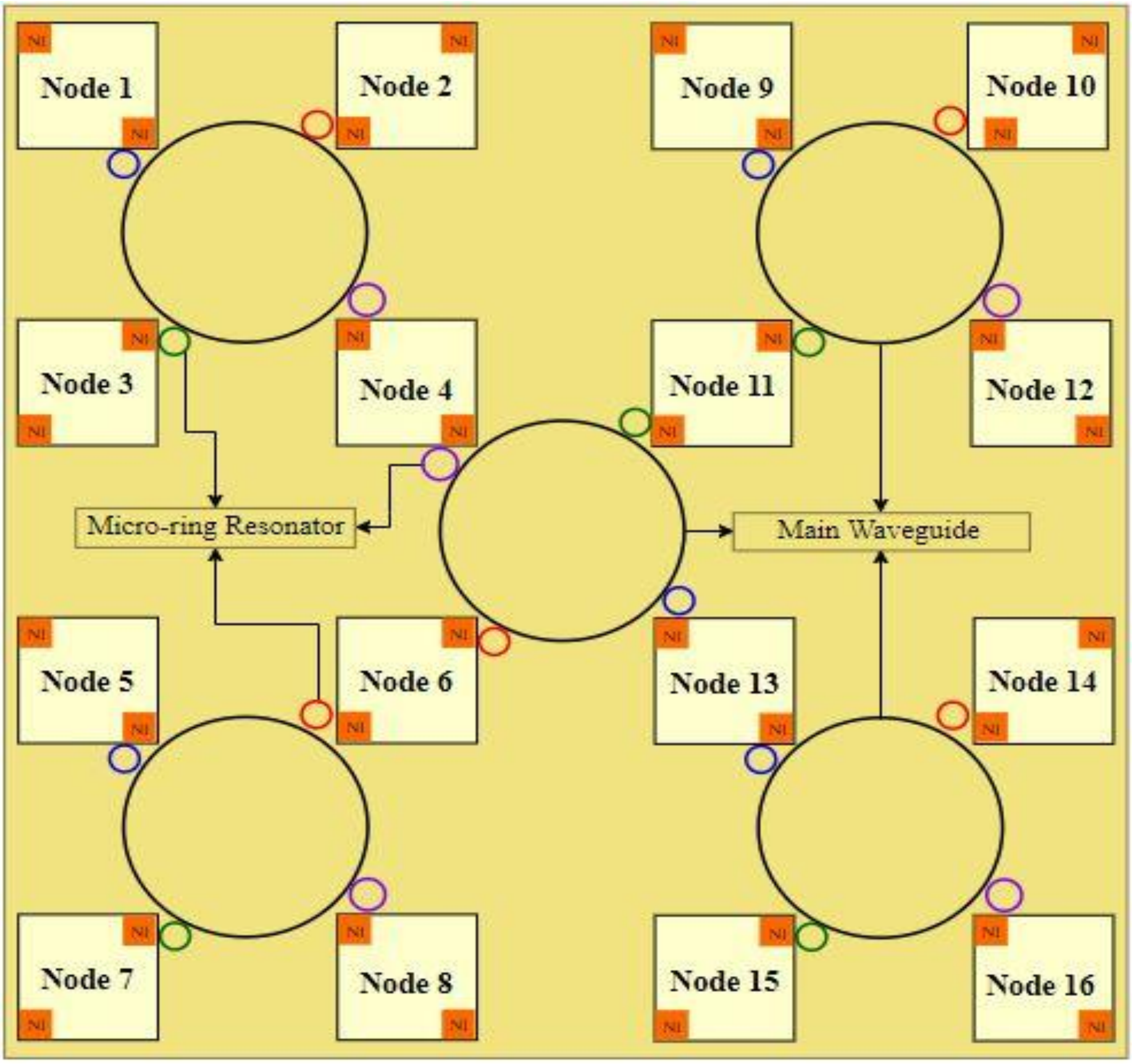


Figure 4.2: Representation of 4×4-mesh architecture.

The proposed routing algorithm is inspired by both XY routing as well as odd-even routing. This algorithm helps to achieve the shortest path between source and destination or achieves minimal routing. As per Figure 4.2, this section uses 4×4 optical-NoC architecture (using five bricks of 2×2 optical-NoC architecture) to demonstrate the algorithm's working and different processes. These processes include PE nodes position, selection process, and searching process which helps to achieve the shortest path between source and destination.

4.3.1 PE Node Position

This section illustrates the first process used in the proposed algorithm. This process includes the initialization of each PE node with its specific node information. As per Figure 4.3, each PE node has its information in terms of X-axis, Y-axis, PE node number, and Weight. X-axis and Y-axis represent the coordinates of each PE node. PE node number represents the unique number as per architecture's configuration. In last weight is calculated by adding its X-axis and Y-axis as per equation 4.1.

$$Weight = (x + y) \tag{4.1}$$

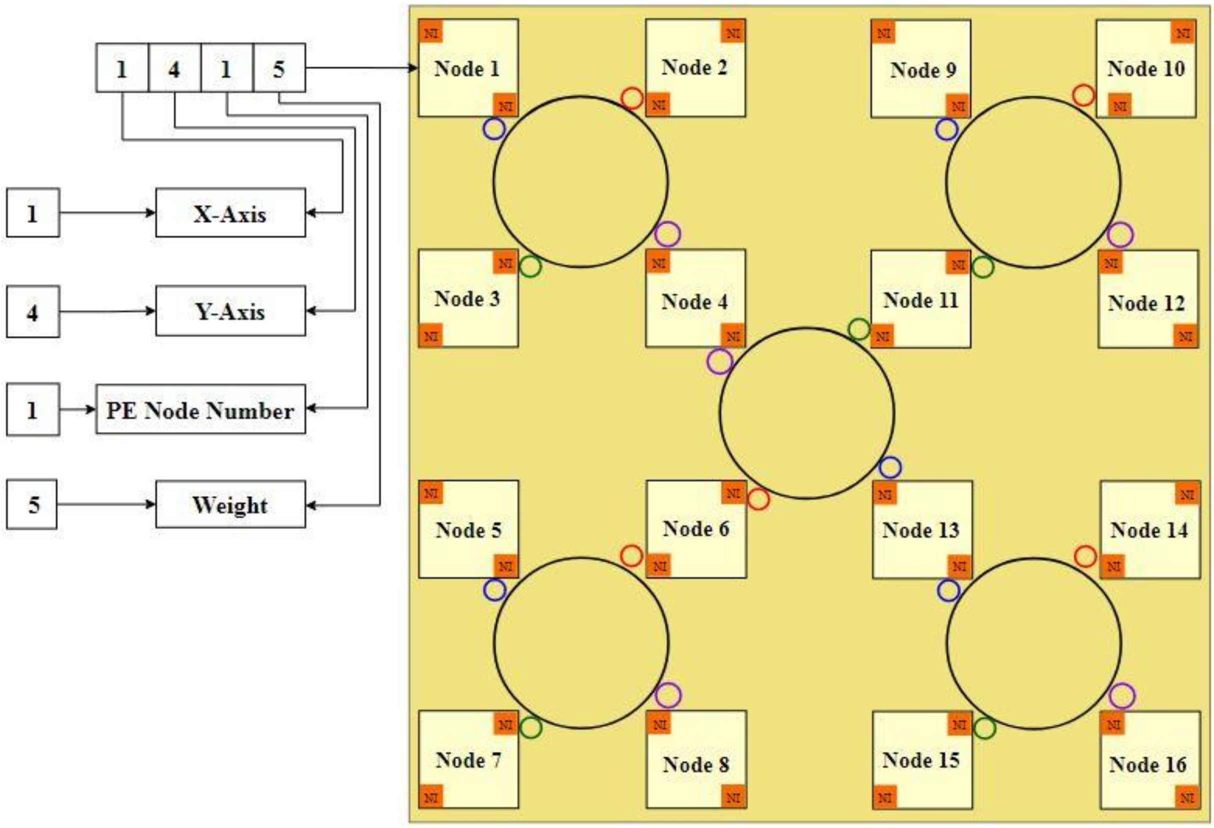


Figure 4.3: 4x4 Optical-NoC architecture.

This calculated weight helps to determine each PE node in terms of odd and even position. This process helps to work the next process by differentiating between nodes according to their respective weights.

4.3.2 Selection Process

This section includes the selection process, in which particular PE nodes are selected before performing optical transmission. The proposed architecture consists of several brick-like structures as per Figure 4.4 two different scenarios are presented which show the selection process according to their respective PE node position. These selection processes are performed by equations 4.2 and 4.3 for odd position and even position respectively.

$$ODD_{position}\, node = (x-1\,, y), (x\,, y+1), (x-1\,, y+1), (x\,, y-1), (x+1\,, y), (x+1\,, y-1) \tag{4.2}$$

$$EVEN_{position}\, node = (x+1\,, y), (x\,, y+1), (x+1\,, y+1), (x\,, y-1), (x-1, y), (x-1\,, y-1) \tag{4.3}$$

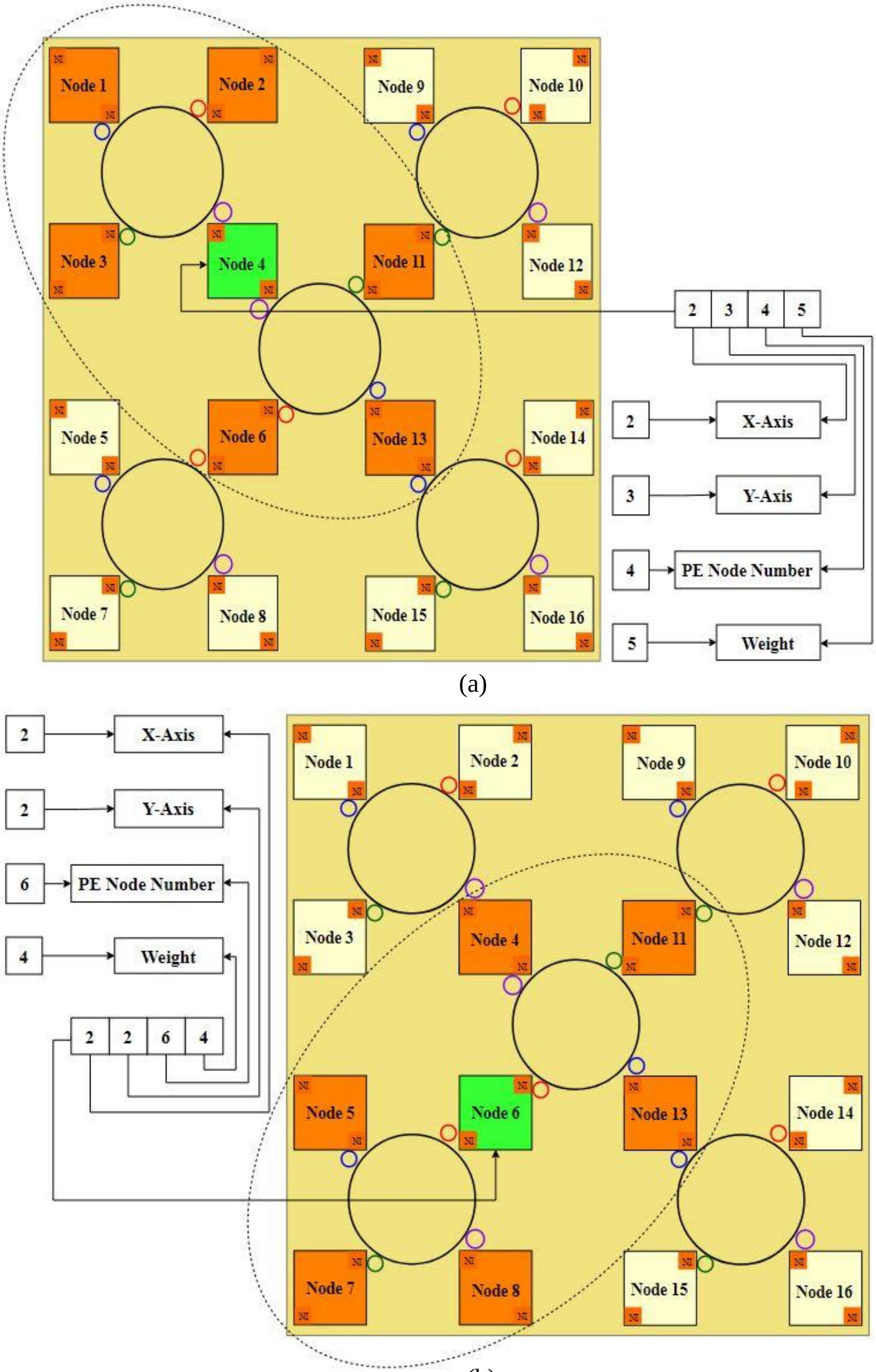
This equation uses coordinates of the particulate PE node and then performs a selection process to select appropriate PE nodes. Figure 4.4 (a), shows the odd position's PE node selection process and Figure 4.4 (b), shows the selection process for even weight PE nodes. These selected PE nodes are used by the next process to select suitable PE nodes for performing optical communication.

4.3.3 Searching Process

This section elaborates on the searching technique used to find the nearest PE node towards the destination node. In this, we are using the Euclidian distance formula to measure the distance between selected PE nodes coordinates and then selecting appropriate PE nodes to transmit optical data. This formula of Euclidian distance is represented in equation 4.4.

$$\text{Euclidian distance} = \sqrt{(X-x_i)^2 + (Y-y_i)^2} \tag{4.4}$$

As per equation 4.4, (X, Y) represents the coordinates of the destination PE node, while (x_i, y_i) represents the coordinates of PE nodes. These PE nodes are selected according to their respective position, as per the previous process known as the selection process. While calculating each distance between selected PE nodes and destination nodes, the PE node containing minimum distance is selected to perform optical signal is transmitted.



(b)

Figure 4.4: One scenario of the selection process. (a) The selection process in ODD PE node, (b) Selection process in EVEN PE node.

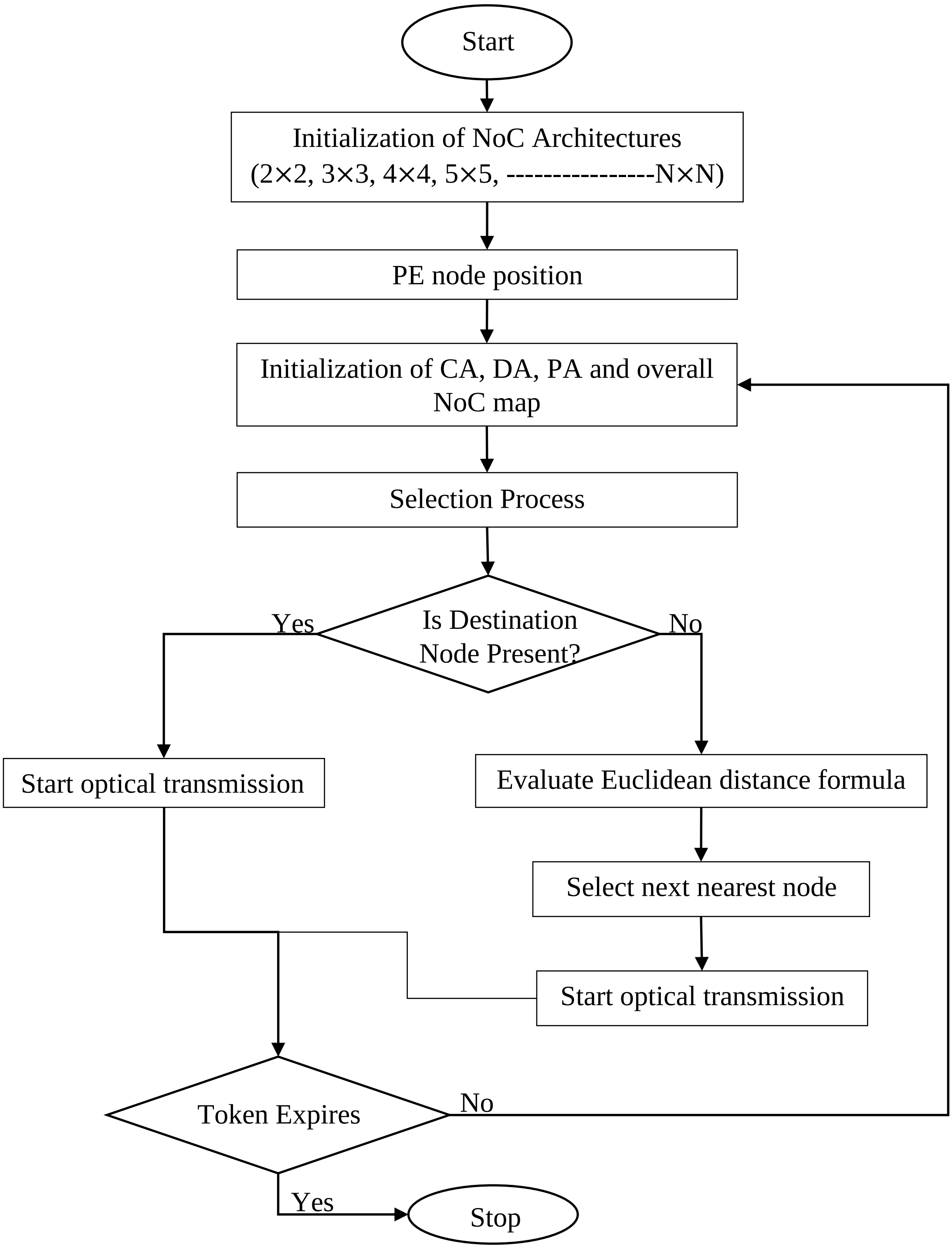


Figure 4.5: Flow chart of proposed routing algorithm

Figure 4.5 presents the flow chart of the proposed routing algorithm, these all processes are used to achieve the shortest distance between source and destination. The proposed algorithm contains all these steps to perform flawless work. The steps of the proposed routing algorithm are summarised in algorithm 4.1.

Algorithm 4.1: Pseudo code of proposed routing algorithm

Input: Token achieved, **C**urrent node axis (CA); Possible axis(PA); 4x4 node axis information (map); Destining axis(DA)

Output: Co-ordinates of nearest node(NR);

1: Initialize the coordinates of each node as per initialization process which includes providing respective coordinates to each PE node.

2: Assign weights to each PE node.

3: Initialize Current node axis (CA), Possible axis (PA), overall PE node map and Destination axis (DA) according to packet.

4: Perform selection process as per equation 4.2 and 4.3 to evaluate (PA).
PA = **SelectionProcess** (CA)

5: Check for DA in PA
if (any PA == DA)
Start transmission
else
Move to **searching process**

6: Perform **Euclidian Distance** on PA with respect to DA
Update CA = minimum distance (between PA and DA)
Start transmission to CA
Move to step 3 until token expires.

4.4 Routing Mechanism

This section illustrates the working of the proposed routing algorithm, which helps to perform optical signal transmission between PE nodes. Figure 4.6, represents how the token-based protocol is used to provide proper sharing of resources between them. This shows particular scenarios in which the PE node is denoted by "S" when the token is achieved while other PE nodes are denoted by "R".

The proposed routing algorithm works on big optical-NoC architecture and helps to find the shortest path between source and destination. The working of the routing algorithm can be easily understood by taking an example. Let suppose in this, we consider PE node 7 as a sender while PE node 12 as a destination as per figure 4.2, in which 4×4 optical-NoC is constructed by five 2×2 bricks.

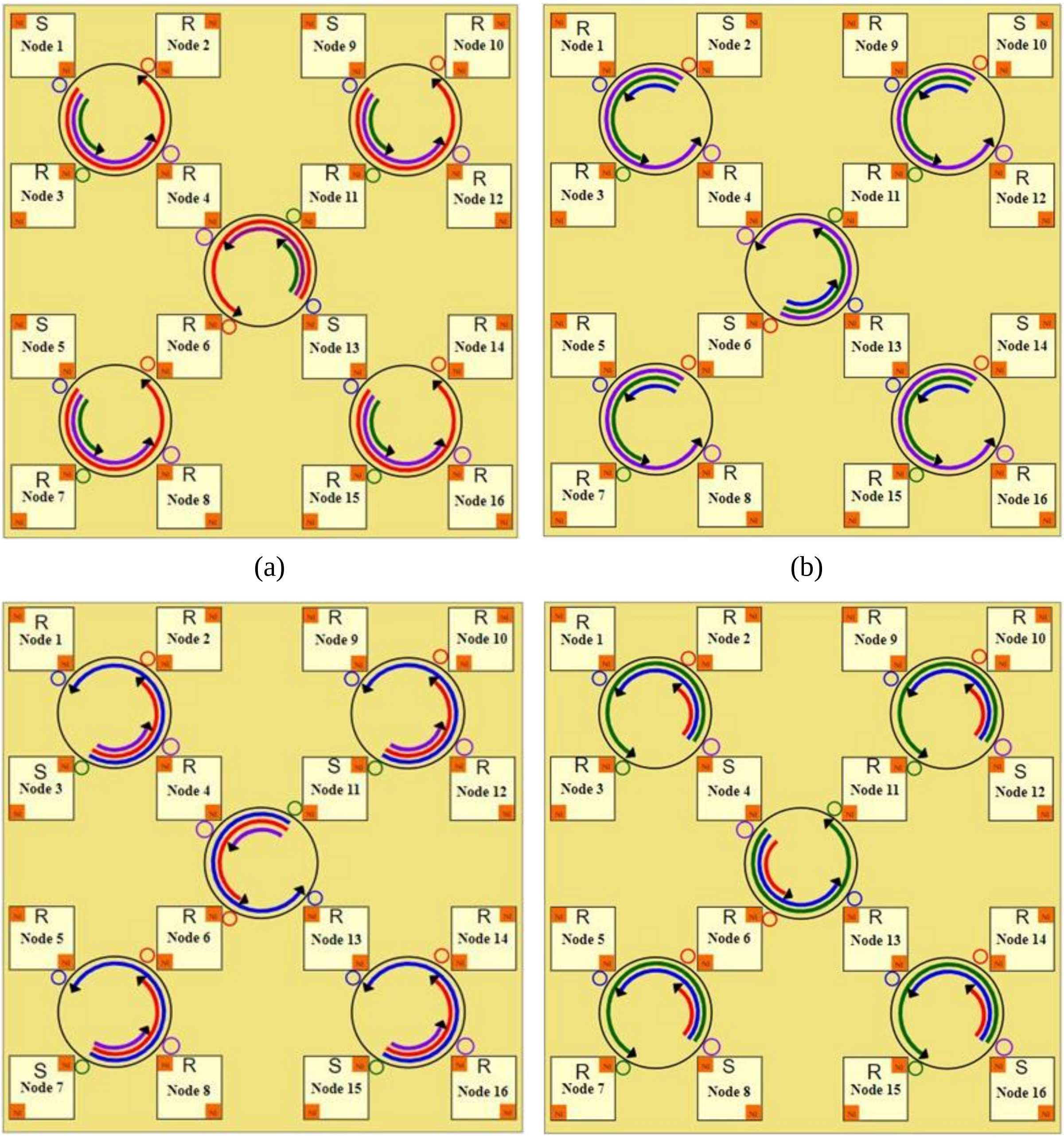


Figure 4.6: (a) Token achieved by PE node (1, 9, 5, 13), (b) Token achieved by PE node (2, 10, 6, 14), (c) Token achieved by PE node (3, 11, 7, 15) (d) Token achieved by PE node (4, 8, 12, 16)

In this Figure 4.7, each PE node has its info like PE node 7 have (1, 1, 7, and 2): which represents its coordinates (1, 1) it node number (7), and the weight assigned to it as (2). After going through the selection process it selects three PE nodes (PE node 5, PE node 6, and PE node 8). After that using searching process (calculating Euclidian distance) between each selected PE node and destination PE node. The nearest PE node is selected (PE node 6) and then an optical signal is transmitted to PE node 6. Now PE node 6, having coordinates (2, 2, 6, and 4) follows the same steps to transmit signal towards the destination node. In the selection process, it selects six PE nodes (PE node 4, PE node 5, PE node 7, PE node 8, PE node 11, and PE node 13). After performing the searching process nearest PE node is selected (PE node 11) out of all selected PE nodes, to transmit optical signal towards it. Again PE node 11 will perform a selection process to select appropriate PE nodes (PE node 4, PE node 6, PE node 13, PE node 9, PE node 10, and PE node 12). Before going to the searching process, it checks for the destination PE node in selected PE nodes, if the destination PE node is present then it eliminates the searching process. Thus in the last, PE node 11 selects destination PE node 12 to transmit optical data. The overall routing algorithm used (PE node 7 → PE node 6 → PE node 11 →PE node 12) to transmit optical data efficiently as well as in the shortest way possible as shown in Figure 4.7.

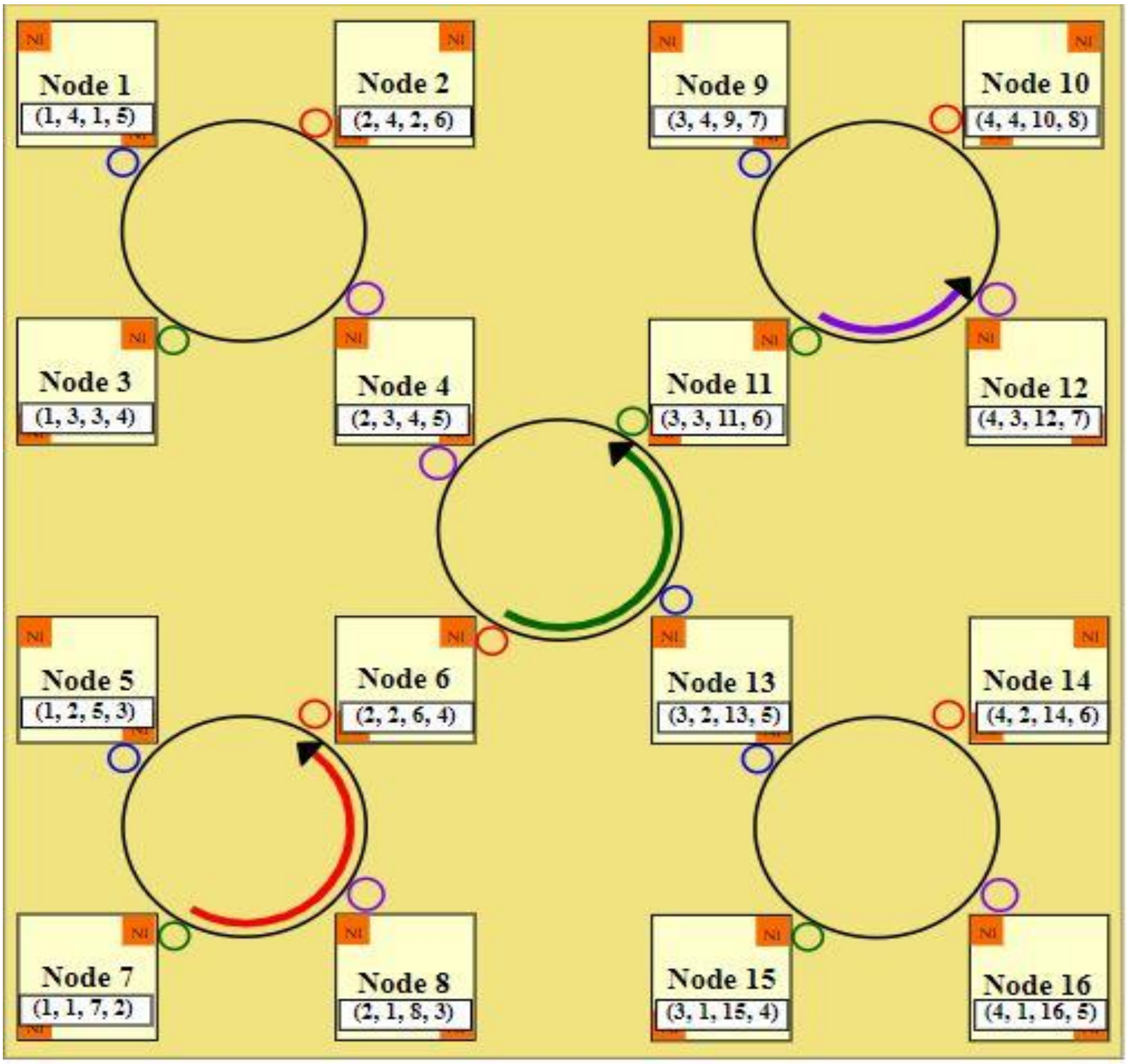


Figure 4.7: Routing mechanism for 16 nodes Optical-NoC (Between PE node 7 and PE node 12).

4.5 Summary

This chapter presents the proposed routing algorithm that helps to overcome the shortcomings like proper routing techniques and path reservation criteria. This algorithm helps to maintain proper optical communication and achieves the shortest path between source and destination. Additionally, this algorithm uses an alternate method instead of path reservation criteria and removes issues like path blocking, idle node usage, and deadlock situations.

CHAPTER 5

DEALING WITH FAULT OCCURRENCE IN OPTICAL NETWORKS-ON-CHIP

5.1 Introduction

Optical interconnects or we may say optical components used in optical-NoC are very delicate in nature. As we are advancing into the deep microns from micrometer to the nanometer technology, these components are more vulnerable to defects during fabrication and during the systems lifetime [72, 78, 97]. These optical-NoCs are considered as important or valuable parts for the future of complex many-core and multicore chips. Thus, fault-tolerant techniques are essential to improve the overall performance of the complex optical-NoC. This chapter explores the different cases which lead to faulty situations in optical-NoC architectures. These works discuss the proposed architecture's reliability analysis and the proposed fault-tolerant routing algorithm. The proposed fault-tolerant routing algorithm helps to keep the negative effects of the faulty situation on the optical-NoC's performance as low as possible [82, 83, 87]. Targeting random faults, the proposed algorithm achieves fault tolerance by using a fast and simple mechanism which includes, optical-NoC monitoring and alternate path adaption. The proposed work is tested under different faulty situations from 0% fault rate to 20% fault rate. The experimental results show the fault-tolerant nature as well as the effectiveness of the proposed algorithm.

5.2 Fault Occurrence in Optical Networks-on-chip

This section elaborates on the fault occurrence in optical-NoC, due to their delicate nature. Some of the vulnerable components in optical-NoC are waveguides and MRRs, which helps to provide proper optical communication between PE nodes. There are many internal and external factors that cause a faulty situation in optical-NoC, which results in overall low performance [71, 72, 74, 77]. Some internal factors include microwaves, sound waves, and overheating while external factor includes pressure, bending, and external temperature. These factors affect optical-NoC components, which results in the miss delivery of data packet and cause faulty path setup rate while performing optical communication. The key component of the proposed architecture is MRRs, which are very sensitive to temperature fluctuation or manufacturing error. A single MRRs failure can cause the message to be miss-delivered and lost, which results

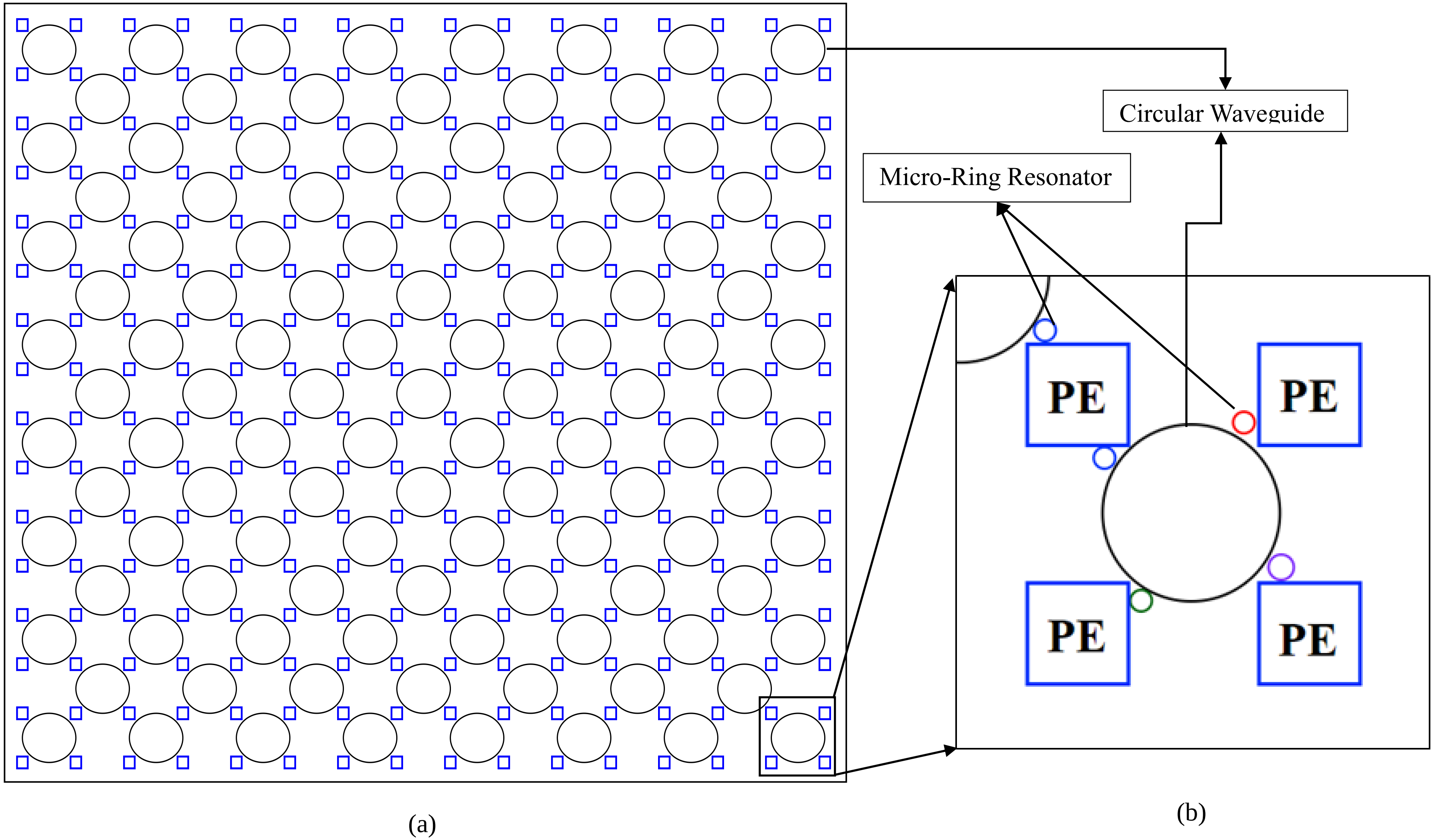


Figure 5.1: Presented optical-NoC architecture, (a) Represents 16×16 Optical-NoC architecture consisting of 113 bricks, (b) one brick of 2x2 optical-NoC architecture

in complete failure of the system. The proposed algorithm helps to deal with the faulty situation and provides an alternate path to ensure packet transmission. We have considered 16×16 Optical-NoC architecture, as they are more vulnerable to getting faulty and causing an overall system failure.

5.2.1 Optical NoC Architecture

This section includes the construction of 16×16 Optical-NoC architecture, which is used to perform experimental analysis. The proposed architecture consists of organizing several bricks as mentioned in chapter 3. Figure 5.1 (a), represents 16×16 Optical-NoC architecture which is capable of containing 256 PE nodes on a single chip. Figure 5.1 (b), represents one brick 2×2 Optical-NoC architecture, we have used 113 bricks and a total of 452 MRR to construct 16×16 Optical-NoC architecture. These MRRs are used to connect each PE node to the circular waveguide which helps to extract an optical signal of a specific wavelength as mentioned in chapter 3.

5.2.2 Architecture's Reliability Analysis

The proposed architecture is represented in Figure 5.1, architecture is fully working under non-faulty conditions. Architecture's reliability is calculated theoretically to gather information regarding NoC's working under faulty conditions. To evaluate reliability, we have considered NoC architecture under worst-case scenarios.

$$R_{O-NoC} = \prod_{i=1}^{N_L} R_L(i) \times \prod_{j=1}^{\dot{N_{OR}}} \dot{R_{OR}}(j) \times \prod_{k=1}^{\ddot{N_{OR}}} \ddot{R_{OR}}(k) \tag{5.1}$$

Equation 5.1 is used to calculate systems reliability [80], denoted by R_{O-NoC}, where N_L represents the number of waveguides used to connect PE nodes. These PE node uses MRR to perform operations using optical signals. In this equation, we have presented the number of horizontal MRR with $\dot{N_{OR}}$ while the number of MRR used in a vertical direction is denoted by $\ddot{N_{OR}}$. The reliability of the waveguide is resented by $R_L(i)$, where the reliability of MRR used in horizontal and vertical MRR are presented by $\dot{R_{OR}}(j)$ and $\ddot{R_{OR}}(k)$ respectively. In our purposed architecture we assume the working of the waveguide in normal conditions thus.

$$R_L = 1 \tag{5.2}$$

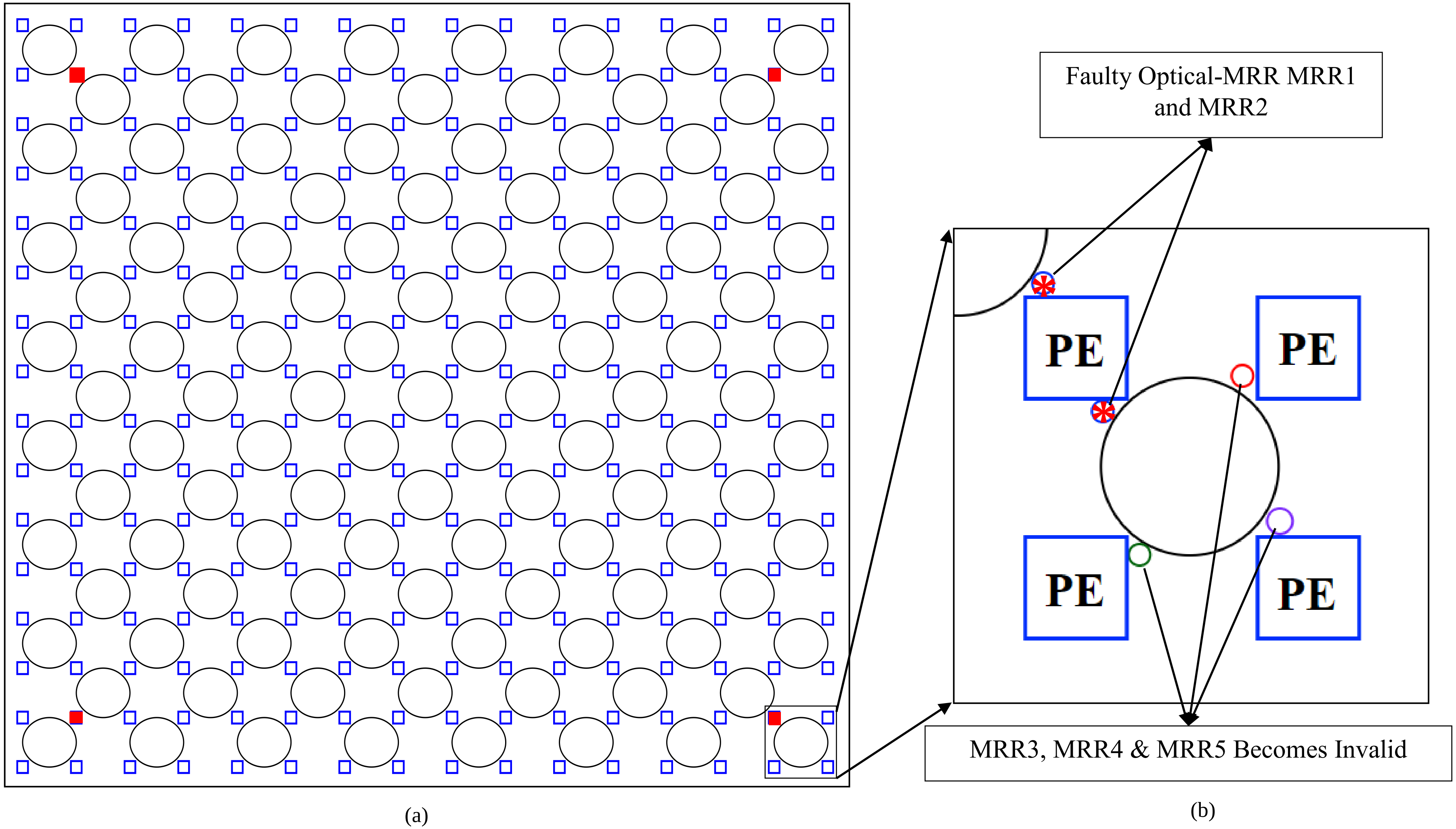


Figure 5.2: (a) Represents worst-case scenarios in 16x16 optical NoC. Figure 5.2 (b) Representing one worst-case in16x16 2D faulty optical- NoC architecture

As per optics, opto-optic MRR is considered as most delicate part of optical NoC. Opto-optic MRRs are fabricated to construct more energy-efficient NoC. In opto-optic MRR external energy is not required to perform a function, thus any internal or external energy may provide fault to the MRR. The reliability of both horizontal and vertical MRRs is calculated by equation 5.3 [80].

$$\dot{R_{OR}}(j) or \ddot{R_{OR}}(k) = 1 - \sum_{m=0}^{n} \partial_m \binom{n}{m} (1-p)^m (p)^{n-m} \tag{5.3}$$

As per equation 5.3, p is considered as the reliability of each MRR used in the construction of PIC architecture. In this, each fault that occurred in MRR is independent of the other. Where the total number of valid PE nodes is denoted by *n* and invalid nodes are represented by *m*. The failure probability of MRR presented in architecture is represented by $\partial_m (0 < \partial_m < 1)$. In this, we have considered worst-case scenarios which result in major system failure.

As per Figure 5.2 (a), optical NoC architecture is represented which shows red-colored PE nodes. These PE nodes are considered faulty nodes or we can say invalid nodes. The total number of PE nodes is 256, in which 452 MRR are used, where n represents 452 and m denotes nodes that become invalid MRR. In such case, if m=0 represents no invalid node, results in full NoC working or may say proper working. While if one MRR doesn't work (m=1) i.e. one invalid MRR is present in that case our architecture works properly. Then we can say in both m=0 and m=1, the probability of getting any fault is zero $\partial_0 = 0$ and $\partial_1 = 0$.

But as per Figure 5.2 (b), if both MRR of those red-colored PE nodes are present that another MRR becomes invalid. As per Figure 5.2 (b), MRR 1 and MRR 2 become invalid at the same time thus resulting in generating three invalid MRR (MRR3, MRR4, and MRR5). As per equation representation.

$$\partial_2 = 3/\binom{452}{2} \tag{5.4}$$

$$\partial_2 \binom{452}{2} = 3 \tag{5.5}$$

By calculating ∂_0 , ∂_1 and ∂_2 from equation (5.5) evaluating $\dot{R_{OR}}$ as follows:

$$\dot{R_{OR}} = 1 - \sum_{m=0}^{452} \partial_m \binom{452}{m} (1-p)^m (p)^{452-m} \tag{5.6}$$

$$\geq 1 - 3(1-p)^2 (p)^{450} - \sum_{m=3}^{452} \binom{452}{m} (1-p)^m (p)^{452-m} \tag{5.7}$$

As per optical MRR in our proposed architecture we haven’t used any vertical connections, thus reliability of vertical opto MRR are considered as per equation 5.8.

$$\ddot{R_{OR}} = 1 \quad (5.8)$$

$$R_{O-NoC} = 1 \times [\dot{R_{OR}}]^{mn} \times 1 \quad (5.9)$$

$$R_{O-NoC} \geq [1 - 3(1-p)^2(p)^{450} - \sum_{m=3}^{452} \binom{452}{m} (1-p)^m (p)^{452-m}]^{mn} \quad (5.10)$$

All over structure's reliability is calculated by equations 5.1, 5.7 and 5.8 represented by equation 5.10.

5.3 Fault Tolerance in Optical Networks-on-Chip

Fault tolerance provides the capacity to the architecture for tackling a faulty situation and provides a runtime solution for maintaining proper communication among PE nodes. There are several fault-tolerant methods to eliminate the faulty situation in Optical-NoC. These methods can be categorized into two parts detection type and recovery type [86]. In this work, we have adopted recovery-type methods which help to maintain workflow under a faulty situation. Under the recovery method, there are mainly four types which include modular redundancy, thermal tuning, noise, and re-routing. In modular redundancy, use of WDM which provides multiple wavelengths between PE nodes to counter the faulty situation. In thermal tuning, critical components like MRR and waveguides are preserved from overheating. To reduce overheating, traffic management is used to move high traffic from overused MRR, by switching MRR off for some time and by using extra components to reduce overall systems temperature. In noise, the use of specifically designed optical switches is used to reduce the SNR ratio and also help to decrease the faulty situation. In re-routing, specific algorithms or also known as adaptive routing are designed to counter the faulty situation in Optical-NoC.

From the above-mentioned techniques, we adopted re-routing to deal with the faulty situation. One of the main reasons for choosing re-routing is to generate optimal and less complex solutions regarding the faulty situation. In other techniques, extra components are used to deal with a faulty situation which increases design complexity in Optical-NoC, while in re-routing backup routing algorithm is used which acts under faulty situations. These routing algorithms help to generate the next optimal path and eliminate faulty nodes between source and destination. The proposed routing algorithm is known as the faulty tolerant routing algorithm discussed in the next subsection.

5.3.1 Proposed Fault-Tolerant Routing Algorithm

This section explains the proposed algorithm known as the fault-tolerant routing algorithm. Proposed work helps to deal with the faulty situation and act as a backup routing algorithm. This algorithm works if, the simple routing algorithm proposed in the previous chapter fails to achieve a destination under a faulty situation. This algorithm act as a re-routing by neglecting faulty nodes and achieves a destination with other optimal paths. The previous routing algorithm helps to generate the shortest path between sender and destination as shown in Figure 5.3, when faulty nodes are not present. Under the faulty condition, the simple routing fails to achieve the destination or create a dead-end. Thus, the proposed fault-tolerant routing algorithm adds some additional operations in the simple routing algorithm proposed in the previous chapter. Some of the major processes used in fault-tolerant routing algorithms are PE nodes position, Selection process, elimination technique, and searching process. These additional operations provide runtime checking of the faulty nodes which helps to decide the next appropriate step while on the other side it also provides adaptive nature to the proposed fault-tolerant routing algorithm.

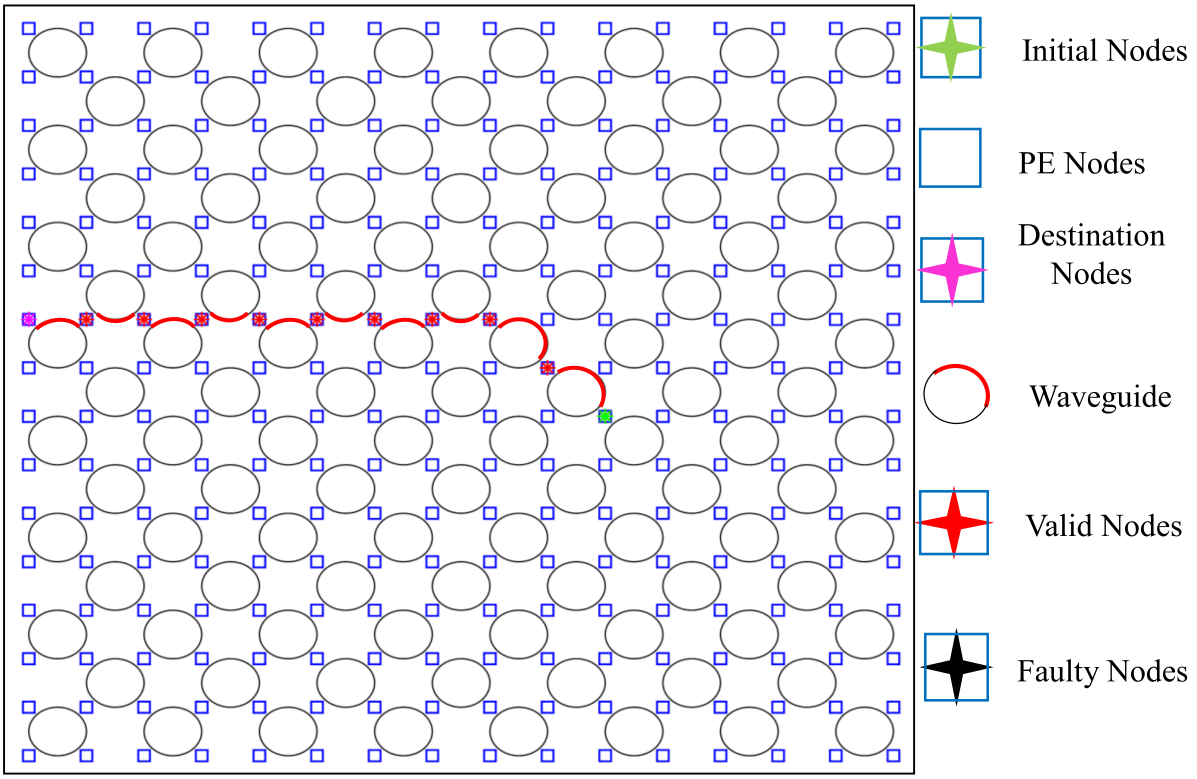


Figure 5.3: Represents communication in 16x16 2D Optical-NoC (no faulty node available)

5.3.1.1 PE Node Position

This section includes the first process used in the proposed fault-tolerant routing algorithm. This process helps to provide each PE node with its information. This information includes X-axis, Y-axis, PE node number, and Weight. The X-axis and Y-axis represent the coordinates of each PE node. PE node number represents the unique number as per Optical-NoC's configuration. In last as per equation 5.11, weight is calculated by addicting the X-axis and Y-axis. This calculated weight helps to determine each PE node's position in terms of odd and even position.

$$Weight = (x + y) \tag{5.11}$$

5.3.1.2 Selection Process

This section includes the selection process, which helps to select specific PE nodes before performing optical transmission. This process uses calculated weight to perform its operation, as per equations 5.12 and 5.13. PE node with odd weight uses equation 5.12 while PE node with even weight uses equation 5.13 to select appropriate PE nodes before optical transmission. In these equations x, y represents the coordinate of PE node performing selection process.

$$ODD_{position}\, node = (x-1\,,y),(x\,,y+1),(x-1\,,y+1),(x\,,y-1),(x+1\,,y),(x+1\,,y-1) \tag{5.12}$$

$$EVEN_{position}\, node = (x+1\,,y),(x\,,y+1),(x+1\,,y+1),(x\,,y-1),(x-1,y),(x-1\,,y-1) \tag{5.13}$$

5.3.1.3 Elimination Technique

This section includes the elimination techniques, which are added newly to update the previous simple routing algorithm to a fault-tolerant routing algorithm. This section includes major steps like maintaining a knowledge base, checking selected PE nodes from the selection process, and last includes eliminating faulty nodes at the same time known as elimination. These major steps help faulty tolerant routing algorithms to deal with the faulty situation and make communication possible.

Knowledgebase: This part includes maintaining a log file that includes all PE node's information (whether it's working or not working). This log file is used to check each PE node status from time to time and update if necessary.

Checking: This part includes comparing PE nodes selected at a time of the selection process with the log file. This step helps to identify the faulty PE nodes before transmitting an optical signal, which results in energy wastage as well as failed transmission. This section also helps to update the log file if any failure is encountered while transmission. This step also makes a list of those PE nodes which are faulty and helps to execute the next step.

Elimination: This section includes eliminating faulty nodes before performing optical transmission. This step eliminates the selected PE nodes from the selection process and then updates new selected PE nodes. This information is also updated in the knowledge base. These newly selected PE nodes (excludes all faulty PE nodes) are used by the next step.

These processes are added to transform a simple routing algorithm into a fault-tolerant routing algorithm. This process also helps to make our fault-tolerant routing algorithm adaptive.

5.3.1.4 Searching Process

This section includes a searching technique that requires the Euclidian Distance formula as per equation 5.14 to evaluate the next nearest PE node towards the destination PE node. This section uses the coordinates that were picked by the selection process as well as the elimination technique to determine the shortest path between two PE nodes.

$$\text{Euclidian distance} = \sqrt{(X - x_i)^2 + (Y - y_i)^2} \tag{5.14}$$

As per equation 5.14, (X, Y) represents the coordinates of the destination PE node, while (xi, yi) represents the coordinates of PE nodes selected by our previous steps.

These all processes are used to determine the shortest path between source and destination despite fault occurrence. This algorithm also provides alternate paths between source and destination and overcomes the faulty situation at runtime. Figure 5.4 represent the flow chart of the proposed fault-tolerant routing algorithm while steps followed by the proposed algorithm are summarised in algorithm 5.1

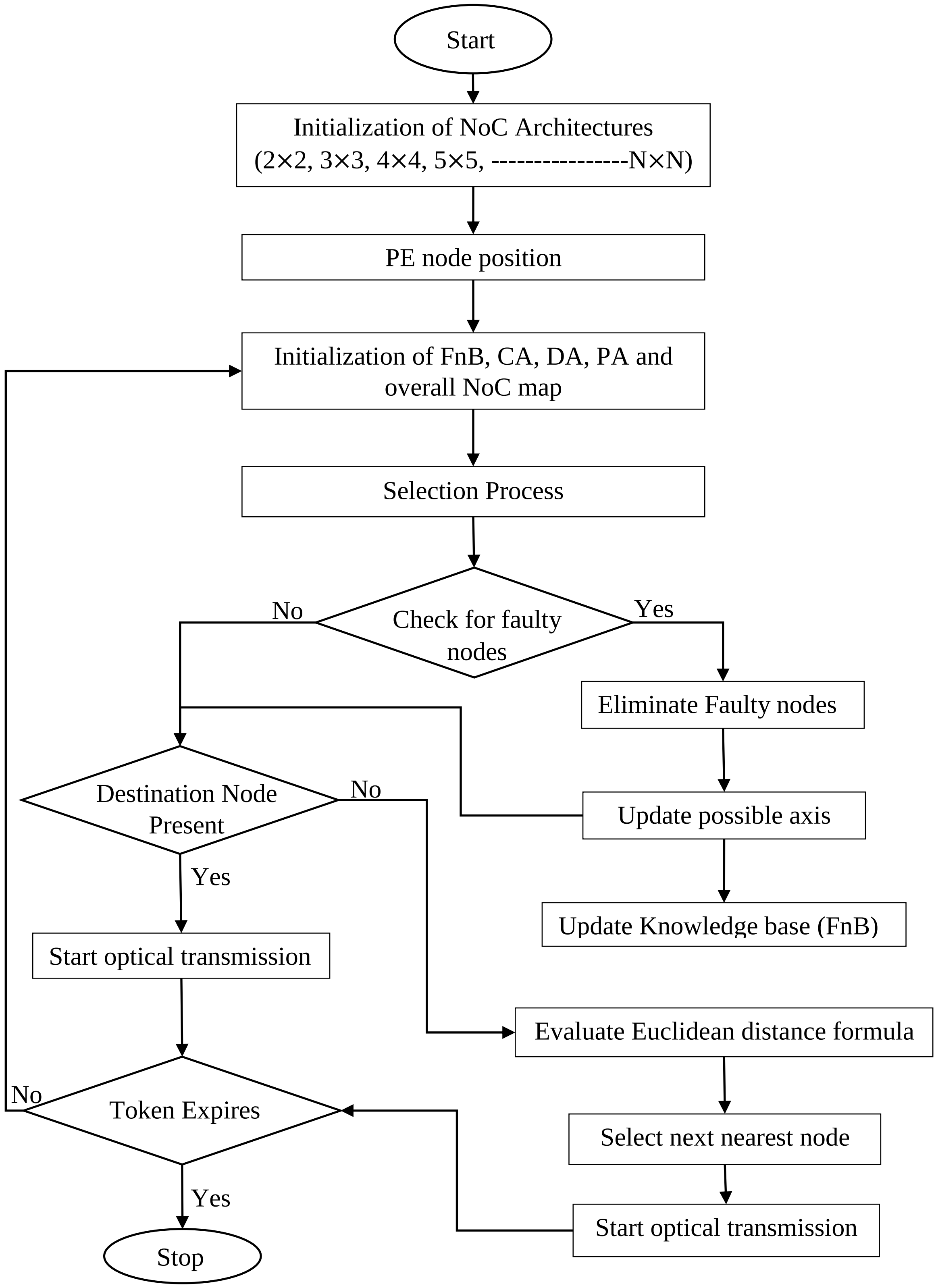


Figure 5.4: Flow chart of Fault-Tolerant routing algorithm

Algorithm 5.1: Pseudo code for fault tolerant routing algorithm

Input: Token achieved; Faulty node base (FnB); current node axis (CA); Possible axis(PA); 16x16 node axis information (map); Destining axis(DA)

Output: Coordinates of nearest node(NR);

```
1: Initialize the coordinates of each node which includes providing respective
   coordinates to each PE node.
2: Assign weights to each PE node.
3: Initialize Faulty node base (FnB), Current node axis (CA), Possible axis (PA),
   overall PE node map and Destination axis (DA).
4: Perform selection process evaluate (PA).
   PA = SelectionProcess (CA)
5: Check for PE nodes in faulty nodes as per FnB
   If (any PA == FnB)
   Eliminate (that PA)
   Update (PA)
   Update (FnB)
6: Check for DA in PA
   if ( any PA == DA)
   Start transmission
   else
   Move to searching process
7: Perform Euclidian Distance for each PA with respect to DA
   Update NR = minimum distance (between PA and DA)
   Start transmission to NR
   Move to step 3 until token expires.
```

5.3.2 Routing Mechanism

This section represents the routing mechanism of the proposed fault-tolerant algorithm to provide proper communication between source and destination. In this, we have considered the same destination and sender as shown in Figure 5.3. In this, we have considered two scenarios to represent the working of the fault-tolerant routing algorithm. In these scenarios, one PE node is faulty as shown in Figure 5.5 (a) and Figure 5.5 (b). In such a faulty situation proposed fault-tolerant routing algorithm provides the next alternate path to reach the destination. The

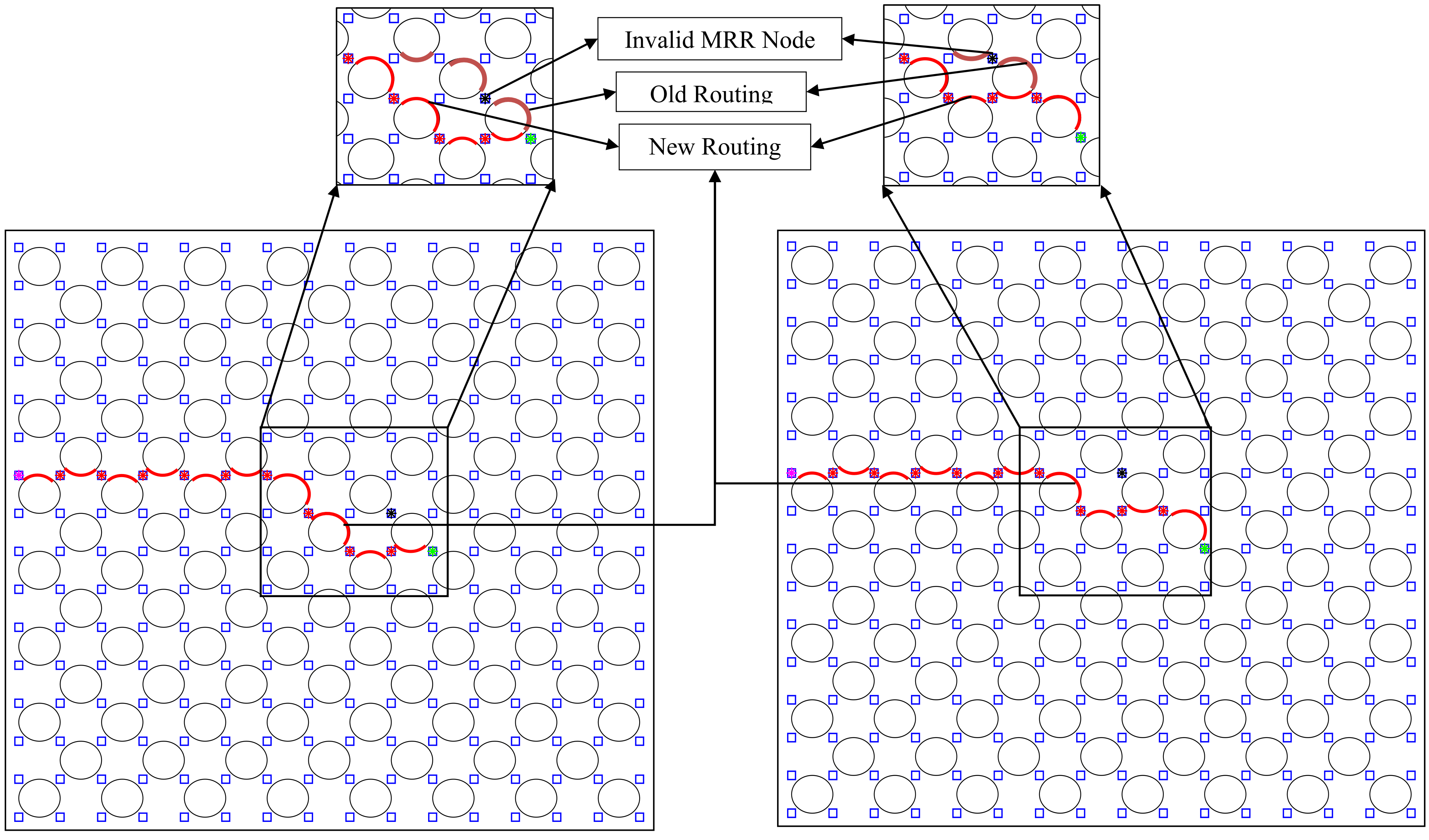


Figure 5.5: (a) and (b) representing communication when one node is faulty in 2D 16x16 Optical-NoC

proposed algorithm helps to eliminate the old routing path used by simple routing as shown in Figure 5.3 and adopt new routing at the same time. This elimination of old routing helps to remove miss-delivery as well as provides solutions regarding the faulty situation.

5.4 Summary

This chapter helps to overcome the major research gap known as fault occurrence in Optical NoC. The proposed routing algorithm is known as the fault-tolerant routing algorithm act as a backup routing algorithm that works when the normal routing algorithm fails to achieve the destination. This algorithm helps to determine the next optimal path between PE nodes under faulty situations and helps to maintain communication among PE nodes.

CHAPTER 6
SIMULATION METHODOLOGY

6.1 Introduction

This chapter discusses the simulation methodology which are used to evaluate our proposed new techniques. This includes simulation software used to construct and configure our proposed architecture and two routing algorithms respectively. To achieve desired results the proposed techniques are used to run on a machine configured with CPU Ryzen 3 3300x @4.2 GHz, GPU NVidia 1660 super 6 GB, RAM 16GB, and Windows 10 64 bit operating system. Subsection 6.2 discusses about the new architecture Optical NoC design. After that subsection 6.3 discusses the simulation methodology for the proposed new routing algorithm and at the end, the simulation methodology for the proposed new fault-tolerant routing algorithm are discussed in subsection 6.3

6.2 Simulation Methodology for Modern Architecture for Optical NoC

This section illustrates our simulation framework used to simulate our proposed 2×2 optical-NoC architecture. This architecture is constructed by using Lumerical FDTD 2018a, which includes the construction of the proposed waveguide as well as proposed MRRs presented in section 3.3. The proposed 2×2 optical-NoC architecture is observed by passing optical signals of different wavelengths between MRRs as mentioned in Table 3.2 (of chapter 3rd). This simulation includes four MRRs and one SWMR waveguide as shown in Figure 3.2 (a) (of chapter 3rd).

To support our proposed MRR design we have used to compare the figure of merits like FSR value, FWHM value, finesse value and Q-factor with respect to Karanth et al. [40] work. The author used the same technique of using MRR to connect PE nodes with waveguides and uses the same material for the construction of MRRs. Although the 2D design is different we have compared our proposed MRRs with Karanth et al. proposed MRRs. Additional results that are used to evaluate the performance of the proposed architecture which includes optical signal filtered at each MRRs and optical signal latency.

6.3 Simulation Methodology for Sustainable Communication for Optical NoC

This section elaborates the simulation methodology used to evaluate our proposed routing algorithm's working in big optical-NoC architecture. We have considered many optical-NoC architecture configurations to evaluate our proposed algorithm like 8×8, 10×10, 12×12-----16×16 2D optical-NoC. Simulation is done over Lumerical FDTD 2018a and MATLAB 2019a to build a configuration and run routing algorithm respectively. We have used two synthetic traffic patterns that include random uniform traffic and hotspot traffic to evaluate our routing algorithm. This simulation includes the configuration of a minimum of 64 nodes architecture to a maximum of 256 nodes architecture. Table 6.1, represents the simulation parameters used while performing an evaluation [21, 39, 91]. Where DDE is considered as data-dependent energy and SE stands for static energy. In this simulation, each PE node transmits optical data when a token is achieved.

Table 6.1

Simulation Parameters used in Optical-NoC

Parameters	Delay	DDE	SE
E/O backend	9.5ps	20fJ/bit	5fJ/bit
Modulator	3.1ps		
O/E backend	4.0ps	20fJ/bit	5fJ/bit
Detector	0.2ps		
Waveguide	<1ps	-	-
Traffic pattern	Random Uniform and Hotspot Traffic		
Token time	5ns		
Packet size	1024		

6.4 Simulation Methodology for Dealing with Fault Occurrence in Optical NoC

This section elaborates the simulation methodology that helps to support our proposed algorithm to tackle the faulty situation in Optical-NoC. We have used Lumerical FDTD and MTALB 2019a to simulate our proposed architecture and fault-tolerant routing algorithm. The proposed routing algorithm helps to act as a re-routing or backup routing algorithm to tackle a major problem statement known as fault occurrence in Optical-NoC. To test our proposed architecture, different faulty situations are considered which are discussed in the next subsection. Table 6.2 contains the simulation parameters used in the simulation of the proposed fault-tolerant routing algorithm. We have evaluated different parameters which support our proposed algorithm to deal with the faulty situation in Optical-NoC. These parameters include availability ratio, algorithm running time, average hop count, successful delivery ratio, and energy consumption.

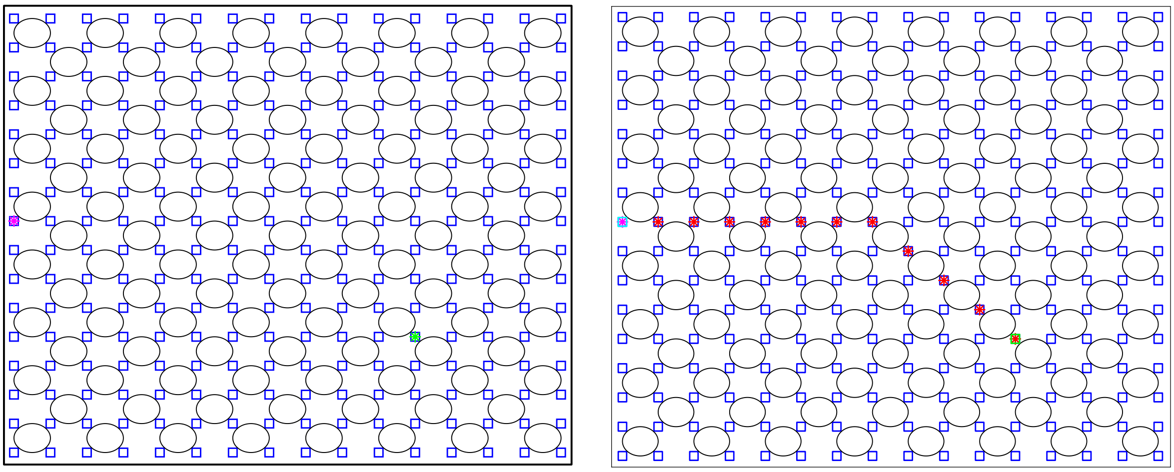
Table 6.2:

Optical-NoC parameters used while simulation

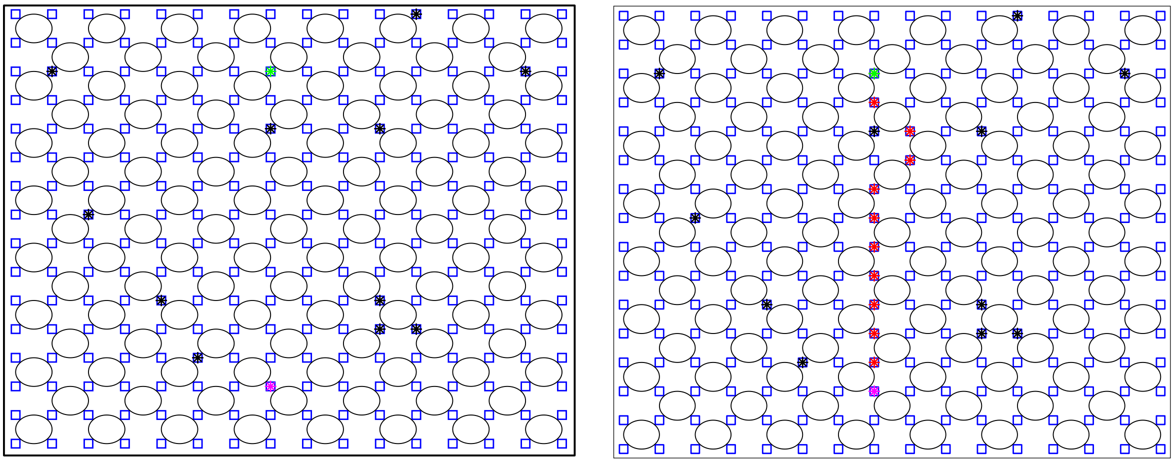
Network Configuration Parameters	
Topology Type	2D optical-NoC
Optical-NoC Size	16x16
Packet size	1024 bit
Synthetic Traffic	Random Uniform, Hotspot, Transpose, Bit-compliment
Fault Rate	0%, 5%, 10%, 15%, 20%
Energy Consumption in Optical Elements [21, 39, 91]	
E/O backend Modulator	20fJ/bit (DDE),5fJ/bit (SE)
O/E backend Detector	20fJ/bit (DDE),5fJ/bit (SE)
Waveguide	-

6.4.1 Experimental Setup

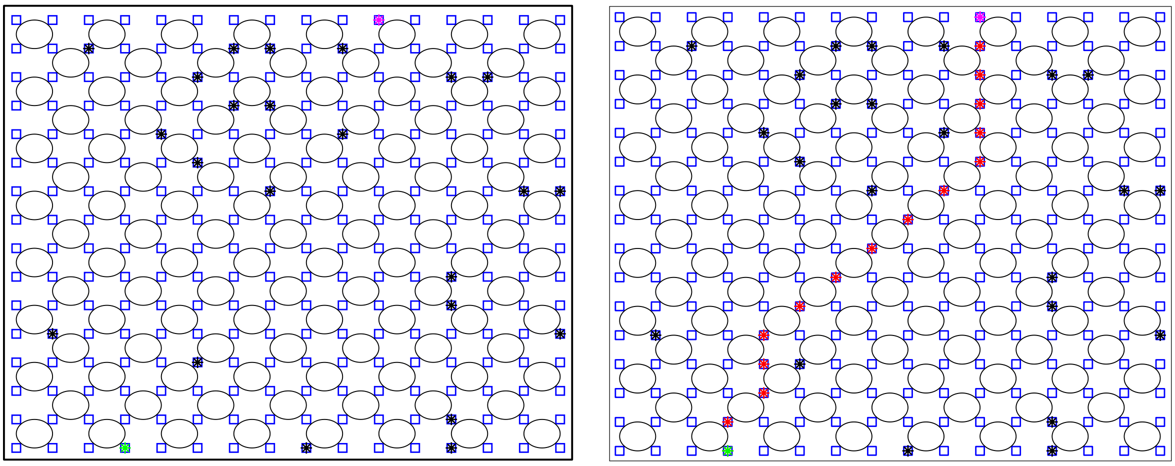
This section explains our experimental setup which helps to show the power of the proposed routing algorithm in faulty conditions. In this setup, we have considered several synthetic traffic patterns and various faulty situations. Under synthetic traffic patterns, we have considered uniform random traffic, hotspot traffic, bit-complement traffic, and transpose traffic. We have also considered faulty situations of 0% to 20% faulty rate. Under these faulty conditions proposed fault-tolerant routing provides the best optimal path between source and destination.



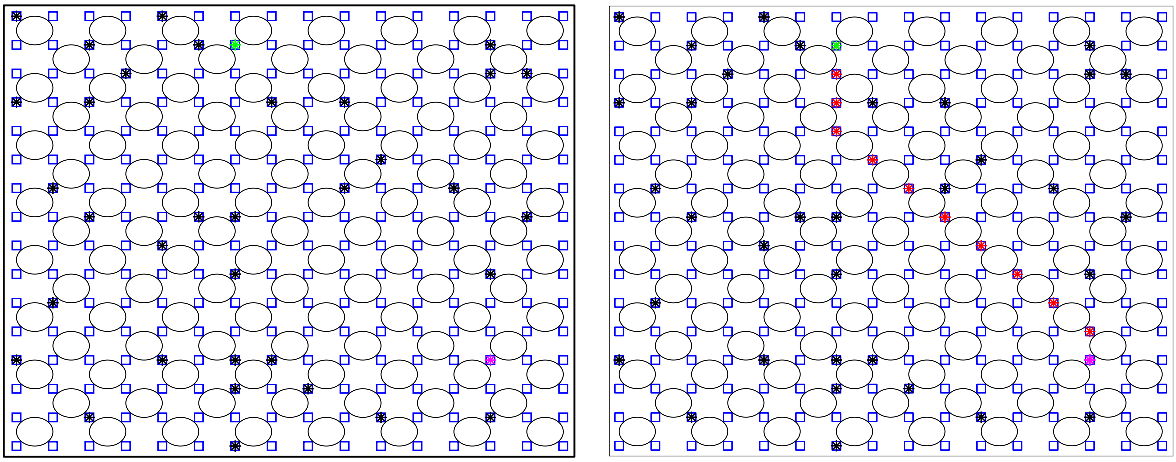
(a): Routing done under 0% fault rate (i.e no faulty PE nodes are present)



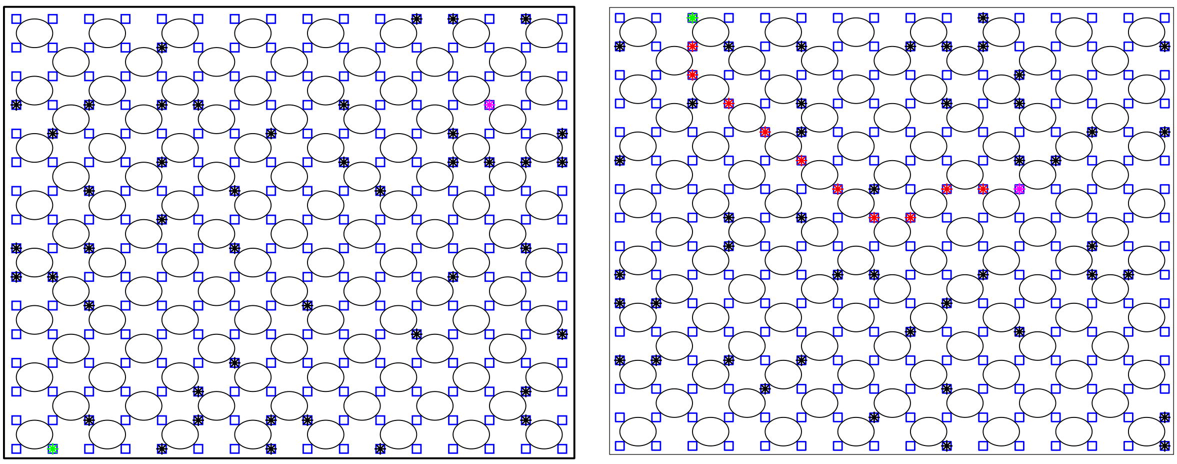
(b): Routing done under 5% fault rate (i.e 11 faulty PE nodes are present)



(c): Routing done under 10% fault rate (i.e 22 faulty PE nodes are present)



(d): Routing done under 15% fault rate (i.e 34 faulty PE nodes are present)



(e): Routing done under 20% fault rate (i.e 45 faulty PE nodes are present)

Figure 6.1: Represents plotting of faulty nodes and routing in Optical-NoC under different faulty conditions using fault-tolerant routing algorithm.

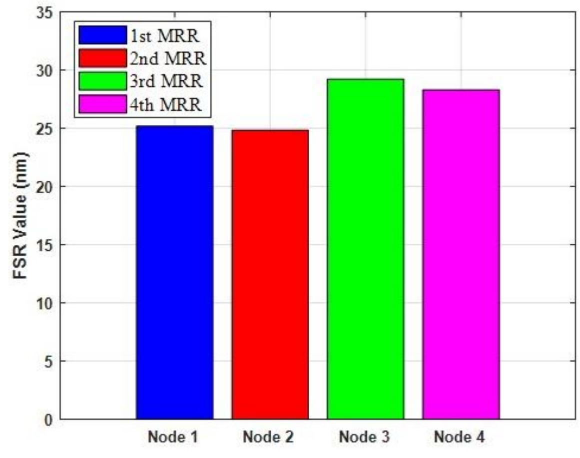
Figure 6.1, represents the communication done under faulty situations. Where Figure 6.1 (a) represents the communication under 0% faulty rate in which simple routing is done. In Figure 6.1 (b) in the case of a 5% faulty rate, there are approx. 11 faulty PE nodes are present. In this, we have used a fault-tolerant routing algorithm to perform communication. There are nearly about 22 faulty PE nodes present at a 10% faulty rate as per Figure 6.1 (c), in which the fault-tolerant routing algorithm performs proper communication. In the case of 15%, there are about 34 faulty PE nodes are present and 45 faulty PE nodes are present at a 20% faulty rate. In both cases, fault-tolerant routing algorithms perform perfect communication among nodes as shown in Figure 6.1 (d) and Figure 6.1 (e) respectively.

CHAPTER 7
RESULTS AND DISCUSSION

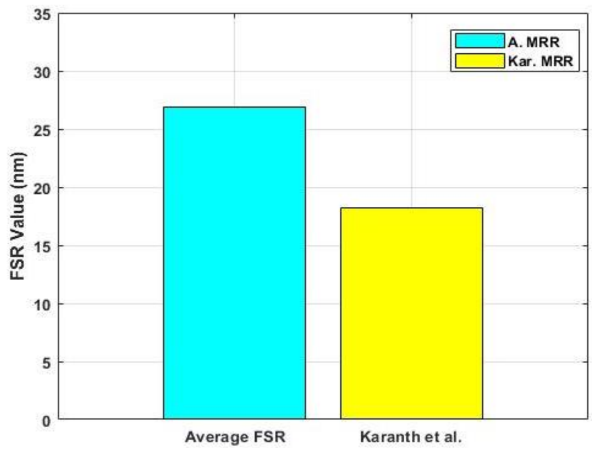
7.1 Results and Discussion for Modern Architecture for Optical NoC

This section discusses the proposed architecture's results which include FSR value, FWHM value, Finesse value, Q factor, Latency analysis, and optical signal analysis. This result supports our proposed 2×2 2D optical-NoC architecture, which was used as a brick-like structure to configure other new big architectures without changing overall waveguide deployment.

- **FSR value** is considered as one of the important figure of merit for evaluating the proposed MRRs. This value represents the spacing between the received resonant peaks filtered through MRRs. It often some time limits the optical frequency ranges in which it may be used. However, for achieving a good Finesse value, a higher FSR value is preferable which leads to achieving better resonator bandwidth. As per Figure 7.1 (a), the FSR value of each MRR is presented while Figure 7.1 (b) represents the comparison between our evaluated FSR values with respect to the Karanth et al. work which represents better results up to 28.89*nm*.



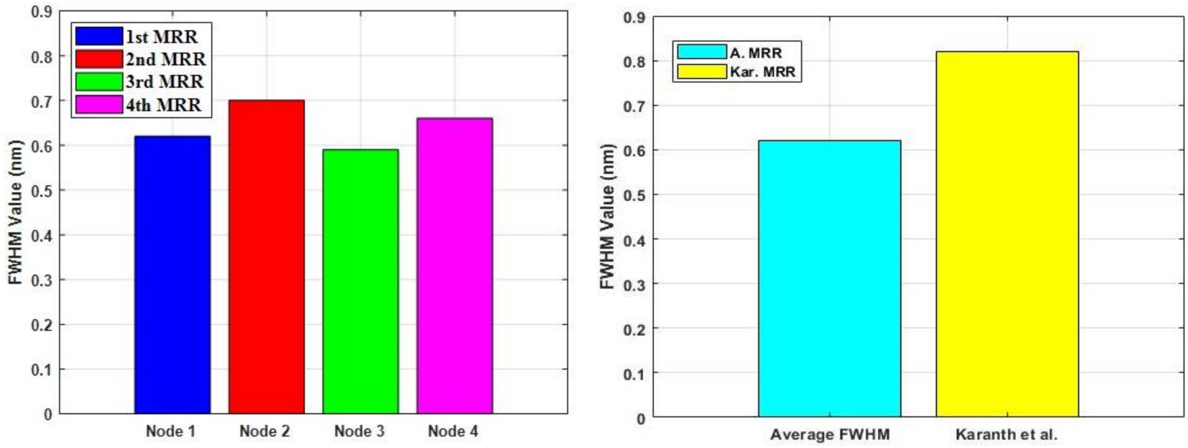
(a)



(b)

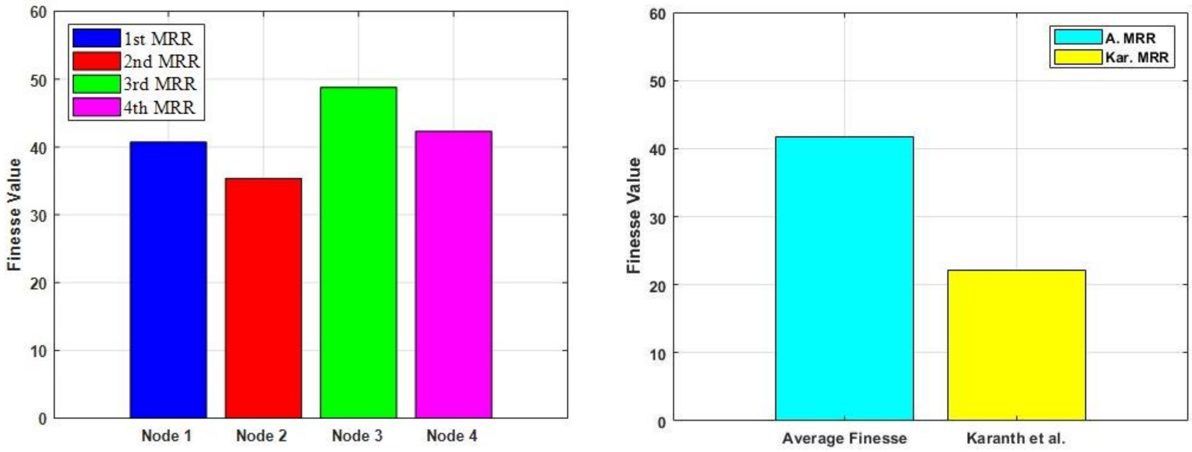
Figure 7.1: MRRs achieved FSR value. (a) FSR value of four MRR used in the proposed architecture. (b) Comparison between achieved avg. FSR value of four MRRs compared to Karanth et al.

- **FWHM value** is used to describe the transmission characteristics of a particular MRR. The FWHM value represents the width of the wavelengths that were filtered from the waveguide. Figure 7.2 (a) represents the FWHM value of the proposed four MRR, while Figure 7.2 (b) represents the comparison of achieved FWHM value with respect to the Karanth et al. proposed MRR.



(a) (b)

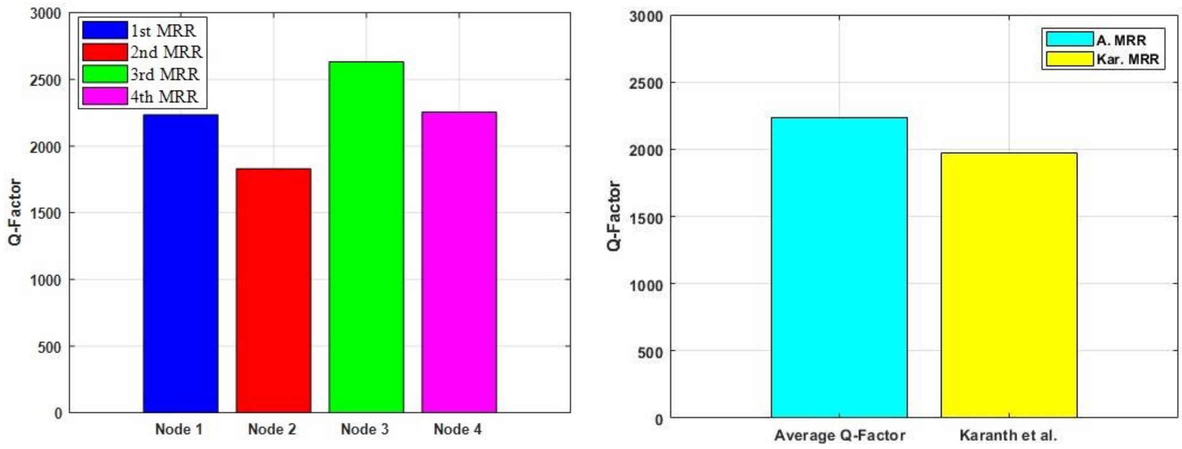
Figure 7.2: MRRs achieved FWHM value. (a) FWHM value of four MRR used in the proposed architecture. (b) Comparison between achieved avg. FWHM value of four MRRs compared to Karanth et al.



(a) (b)

Figure 7.3: MRRs achieved finesse value. (a) Finesse value of four MRRs used in the proposed architecture. (b) Comparison between achieved avg. finesse value of four MRRs compared to Karanth et al.

- **Finesse value** is defined as the ratio of FSR value and FWHM value. It is decided by the losses acquired by MRR and independent of the proposed resonator's length. Thus higher the finesse value achieved higher its Q-factor as well as less probability of getting losses while performing optical communication. As per Figure 7.3 (a), the proposed MRR's finesse value is presented while Figure 7.3 (b), shows a comparison of the proposed finesse value with Karanth et al. finesse value. Our proposed architecture obtained finesse value is up to 41.79, which is much better as compared to Karanth et al. work.

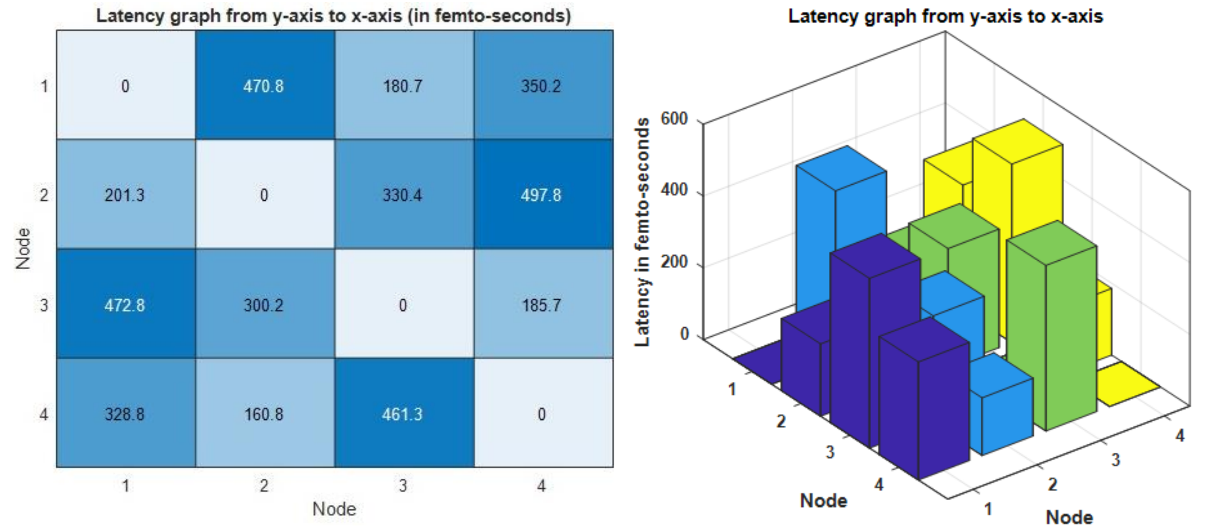


(a) (b)

Figure 7.4: MRRs achieved Q-factor. (a) Q-factor of four MRRs used in the proposed architecture. (b) Comparison between achieved avg. Q-factor of four MRRs compared to Karanth et al.

- **Q-factor** is considered as one of the main figure of merit which is used to evaluate any resonators. The higher the Q-factor, the higher be the essence of the signal filtered from the respective waveguide. This property shows a better and good quality of optical signal filtering at the specific node from the respective waveguide. As per Figure 7.4 (a), the Q-factor of each MRR is presented while in Figure 7.4 (b), a comparison of our achieved Q-factor with Karanth et al. work. Q-factor also represents the amount of signal quality received at the receiver. The achieved Q-factor of our proposed MRR is about 2238.4 while using optical wavelength between 1300*nm* to 1600*nm*.
- **Latency analysis** represents the time required to communicate between nodes. We have simulated the proposed architecture in Lumerical FDTD 2018a, to transmit optical signals from one node to another. Although optics is one of the fastest ways of communication but in material (used for waveguide) optical signal reduces its speed. Latency in optical-NoC architecture is very low as well as it consumes less power for generating an optical signal. Communication latency is one of the promising factor for the construction of optical architectures. Figure 7.5 (a), represents the optical signal latency between nodes in femtoseconds. In this figure, x-axis represents the receiver while the y-axis represented the sender node. While as per Figure 7.5 (b), 3D representation of optical signal latency is presented

where receiver and sender are represented by x-axis and y-axis respectively and time is represented by z-axis.



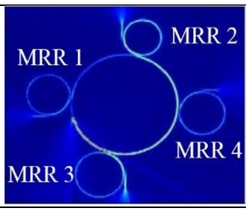
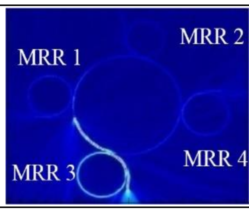
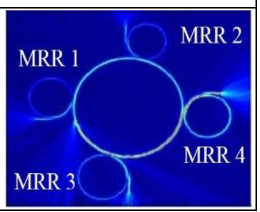
(a) (b)

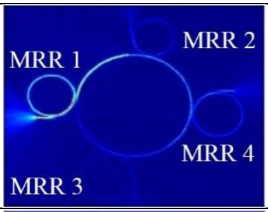
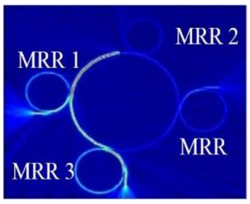
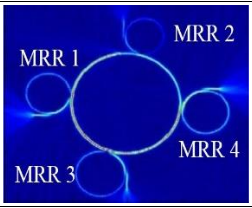
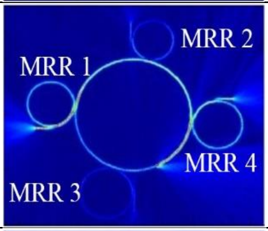
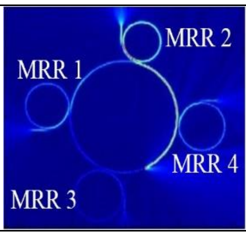
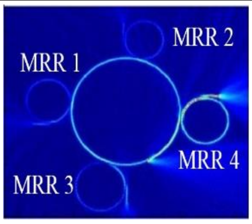
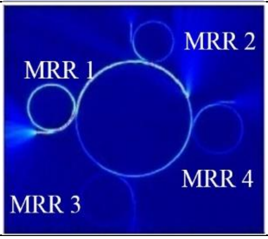
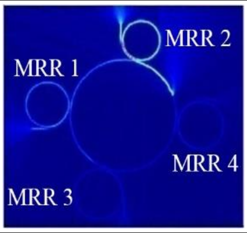
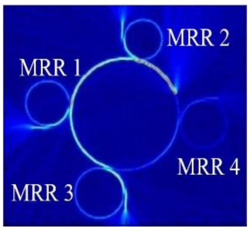
Figure 7.5: Latency analysis between different PE nodes. (a) The latency between PE nodes in 2D graph representation, (b) Latency between PE nodes in 3D graph representation.

- **The optical signal analysis** represented the simulation of the proposed architecture in FDTD simulator. In this, we represent the visual representation of our MRR working in 2×2 optical-NoC. As per Table 7.1, each MRR's work is presented and how optical signal is filtered or neglected with respect to different wavelengths. These MRRs works as per their configuration such as their radius and gap between respective waveguide. These wavelengths are deployed from PE nodes to other MRRs. Thus overall 2×2 2D optical-NoC works perfectly as shown in Table 7.1, which helps to extract the particular optical signal of the desired wavelength.

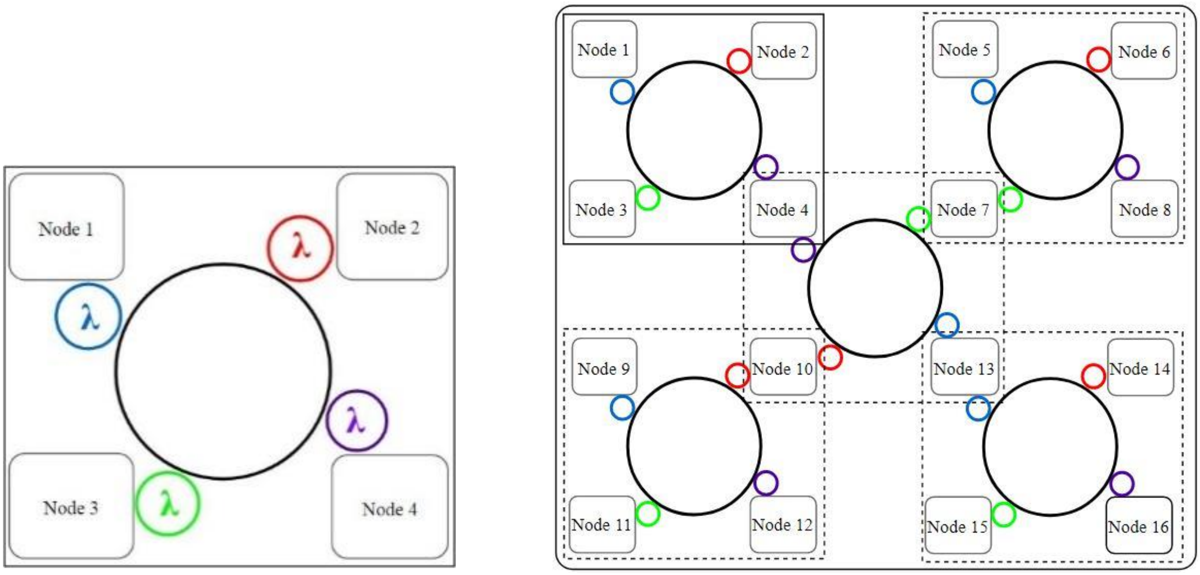
Table 7.1:

Optical signal analysis between MRR.

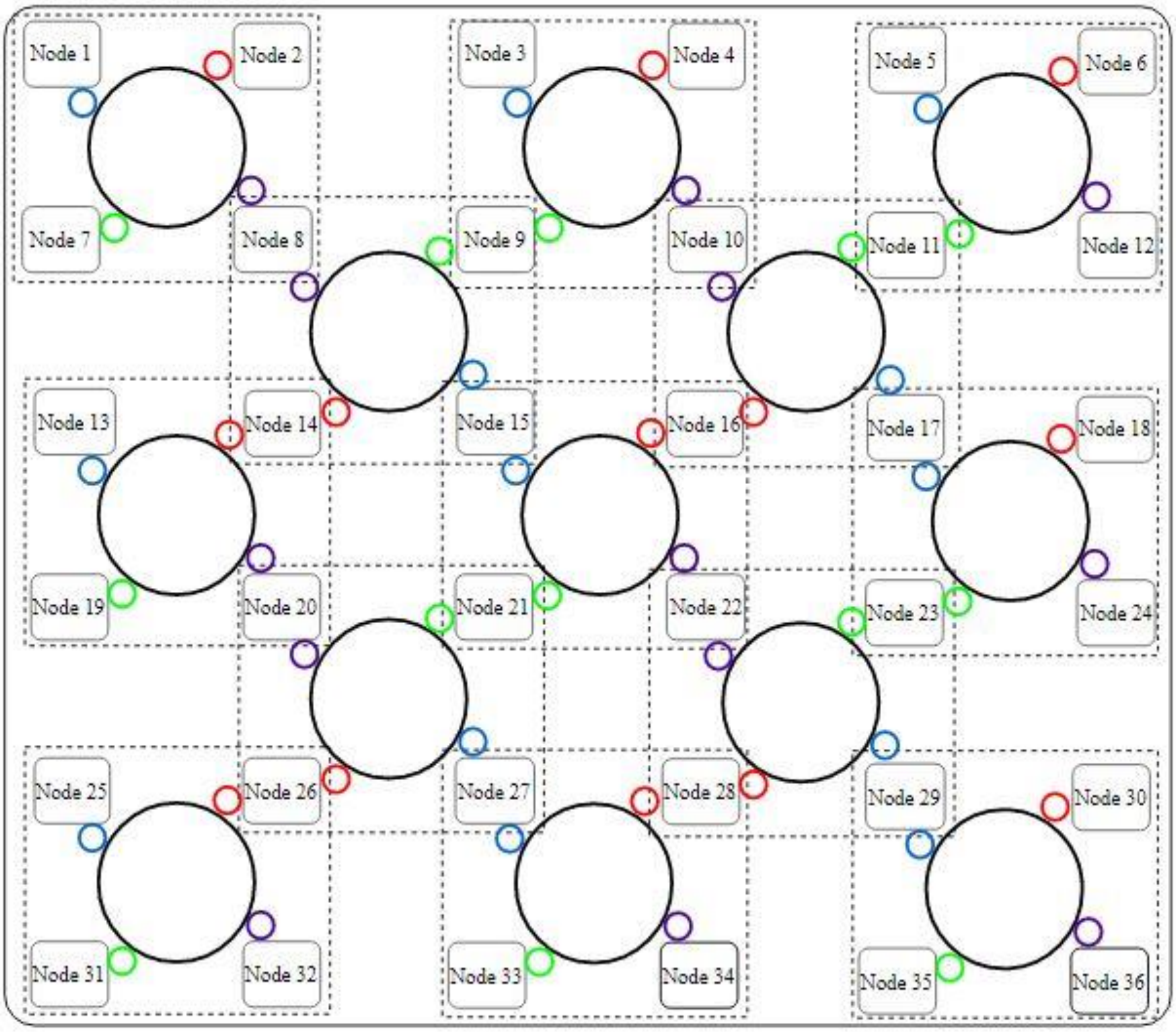
To / From	MRR 1	MRR 2	MRR 3	MRR 4
MRR 1	NULL			

MRR 2		NULL		
MRR 3			NULL	
MRR 4				NULL

- **Brick-like structure**, the constructed 2×2 optical-NoC is proposed to overcome a major drawback observed in optical-NoC architectures. In those architectures, waveguide deployment plays a major role in providing proper communication among PE nodes. These waveguide deployments between nodes are very complex in nature as compared to the wired and wireless links. While on the other hand in case to increase the size of the optical-NoC architecture, most of the architectures have to modify overall waveguide deployment among nodes.



(a) (b)



(c)

Figure 7.6: Optical-NoC architectures (a) 4×4 optical-NoC using 5 2×2 brick, (b) 2×2 optical-NoC architecture as a brick, (c) 6×6 optical-NoC using 13 2×2 brick

As per Figure 7.6 (a), the proposed 2×2 optical-NoC architecture act as a brick-like structure to configure other big architectures. Figure 7.6 (b), shows 4×4 optical-NoC architecture in which five bricks are used i.e. five 2×2 optical-NoC architectures are used. Figure 7.6 (c), shows the configuration of 6×6 optical-NoC architecture in which 13 bricks are used. Thus our proposed architecture helps to construct other optical-NoC architecture without modifying overall waveguide placement among PE nodes. Furthermore, the proposed 2×2 architecture helps to construct different big architecture like 4×4, 6×6, 8×8, 10×10, 12×12, -----N×N with the same bricks and less complex design nature.

7.1.1 Summary

This section addresses our first objective, which deals with the construction of new 2×2 optical-NoC architecture. This architecture is constructed to provide a proper waveguide deployment among PE nodes. The PE nodes are connected to waveguide through MRR, which are designed to filter specific optical signals of defined wavelength from the main waveguide. Proposed MRR shows better results as per specific figure of merits. While other performance parameters show better results that support our optical-NoC architecture, one of the promising results that we have achieved is communicational latency. As per the communication, latency is one of the promising factors in any NoC architecture. The communicational latency of the proposed architecture is measured between 200 to 400 femtoseconds. Furthermore, this architecture is proposed to use as a brick-like structure, which helps to construct other new optical-NoC architectures like 4×4, 6×6, 8×8, ----- N×N.

7.2 Results and Discussion for Sustainable Communication for Optical NoC

This section elaborates the result parameters that we have taken to evaluate our proposed algorithm. These parameters include a new qualitative diagram, deadlock prevention, average hop count, link utilization, algorithm running time, and energy communication while communicating among PE nodes. All these evaluations include random uniform traffic and hotspot traffic patterns in different NoC configurations.

- **The qualitative diagram** provides detailed information about optical transmission in NoC. In this, each process is mentioned from starting an optical transmission to stopping an ongoing optical transmission. Each step carries its work to perform optical transmission successfully as per Figure 4.1 as mentioned in chapter 4. The path reservation criteria have many flaws like providing resource starvation, idle node usage, and path blocking issues.

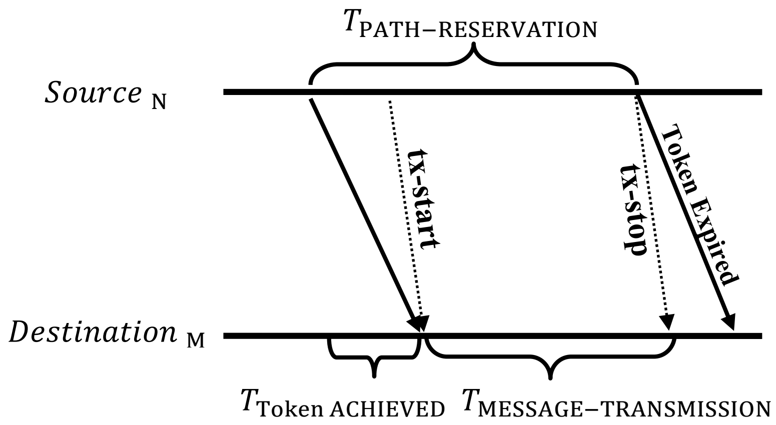


Figure 7.7: New qualitative time diagram between source and destination.

To counter this problem statement known as path reservation criteria, the proposed new architecture and routing protocol works on a new qualitative diagram shown in Figure 7.7. This approach is different from an old qualitative diagram in many ways, first, it removes path reservation criteria, supports several sources and destination nodes at a particular time, and also removes path blocking issues. Overall our proposed new qualitative diagram shows better performance while performing optical communication.

- **Dealing with the Deadlock** situation is one of the promising solutions of many systems. Deadlock situation occurs for any reason and causes huge loss for overall NoCs performance. For avoiding deadlock, many researchers have proposed dedicated algorithms, these algorithm uses extra computation time as well as a resource to eliminate deadlock situations. The most common techniques used by researchers are the use of virtual channels, a direct connection between high-priority PE nodes, and traffic load management.

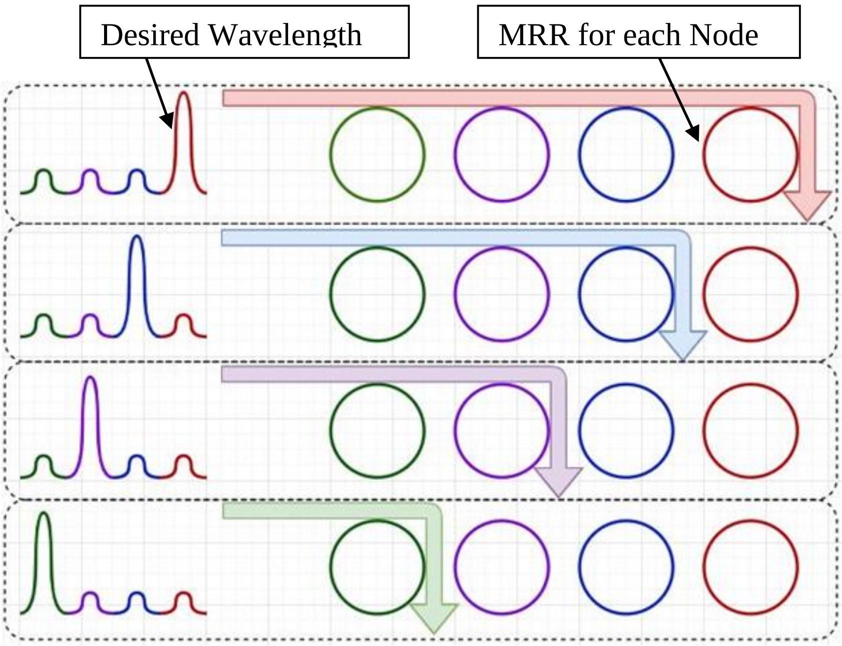


Figure 7.8: Working of each node with help of MRR for elimination deadlock situation.

To avoid a deadlock situation, we have used two major steps first one token time management, and second is the use of independent wavelengths while performing optical transmission. Using the token base protocol provides starvation-free resource management and also helps to eliminate path-blocking issues. On the other hand, the use of independent wavelength helps to communicate between nodes without interfering with other's optical signals as shown in Figure 7.8. These two steps help to achieve deadlock avoidance and proper communication among PE nodes.

- **Hop Count** is considered one of the promising results of NoCs. Hop count is considered as the total sub-destination covered by the packet before reaching its original destination. The number of sub destinations provides a huge impact on overall QoS while performing optical communication. In this, we have compared our proposed 4x4 Optical-NoC architecture with 4x4 wired-NoC and 4×4 wireless-NoC. We have considered two cases to compare hop count. Best case scenario, in which communication is done between neighbouring nodes, while the worst-case scenario contains communication between the edges.

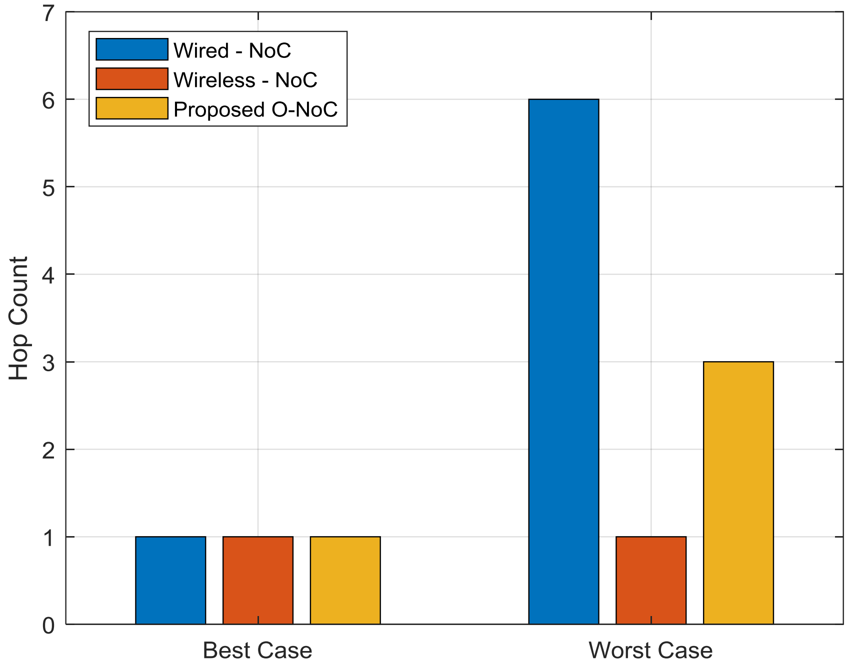


Figure 7.9: Comparisons of hop count in 4x4 mesh NoC architectures

The comparison of the hop count is presented in Figure 7.9, in the best-case scenario proposed Optical-NoC achieves the same results of one-hop count between neighbouring nodes. While in the worst-case scenario proposed Optical-NoC achieves higher results as compared to wireless-NoC and better results as compared to wired-NoC. Thus, the proposed Optical-NoC achieved the maximum of three hop counts in a worst-case scenario which may provide better QoS and help to reduce overall optical transmission latency.

- **Link Utilization** is also known as the amount of data traversing between nodes. The higher the link utilization higher be the reliability of the network. It also affects all-over performance as it removes idle node usage. The proposed routing methodology achieves good results in the case of link utilization, we have compared the proposed routing algorithm with MILP and CAR algorithm [60]. In this, we used different configurations between 8×8, 10×10 to 16×16 Optical-NoC architecture. As per Figure 7.10, the proposed algorithm achieved the same results as compared to MILP, which shows 100% link utilization. As compared to the CAR algorithm, the proposed routing algorithm achieves better results while the CAR algorithm degrades link utilization as network size increases. The achieved results show full utilization of the network and better performance while communicating among nodes.

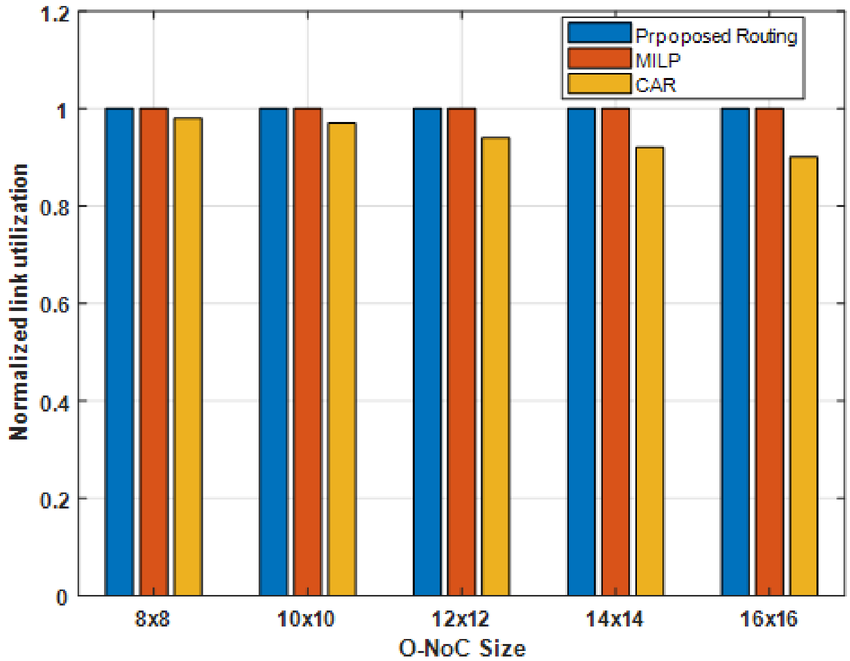


Figure 7.10: Comparisons of link utilization on different Optical-NoC sizes.

- **Algorithm Running Time,** this illustrate the required running time of the proposed new routing algorithm. The proposed routing algorithm was compared with MILP and CAR algorithms. As per Figure 7.11, the proposed routing algorithm provides good results (<1 second) as per MILP and shows the same results in the case of CAR. These algorithms are used to evaluate the same configuration of optical-NoC (8×8 to 16×16.)

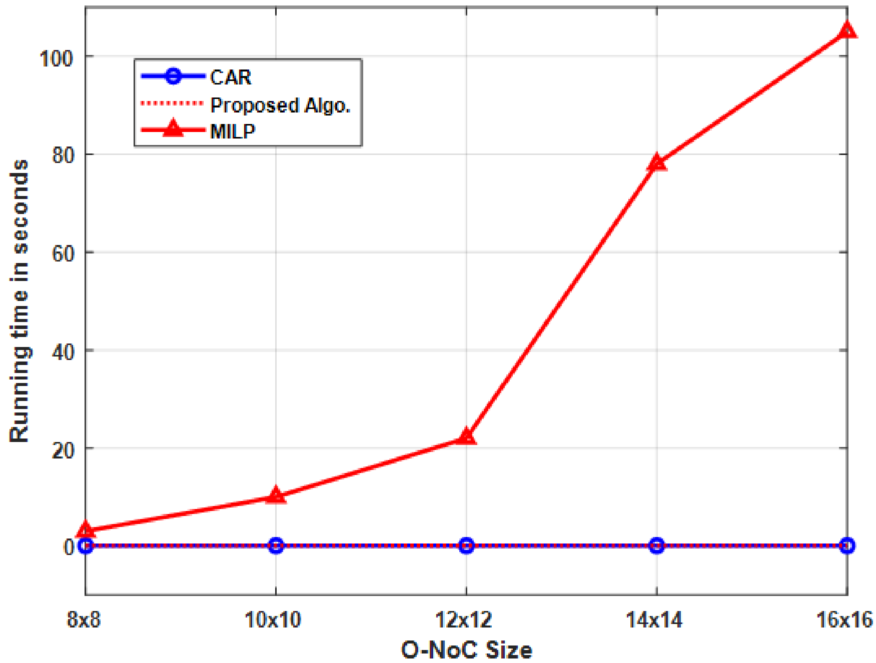


Figure 7.11: Comparisons of an algorithm running time.

- **Energy Consumption** is considered as one of the promising factors of every system. We have compared the energy consumption under synthetic traffic patterns and different Optical-NoC configurations. This synthetic traffic includes random uniform traffic and hotspot traffic.

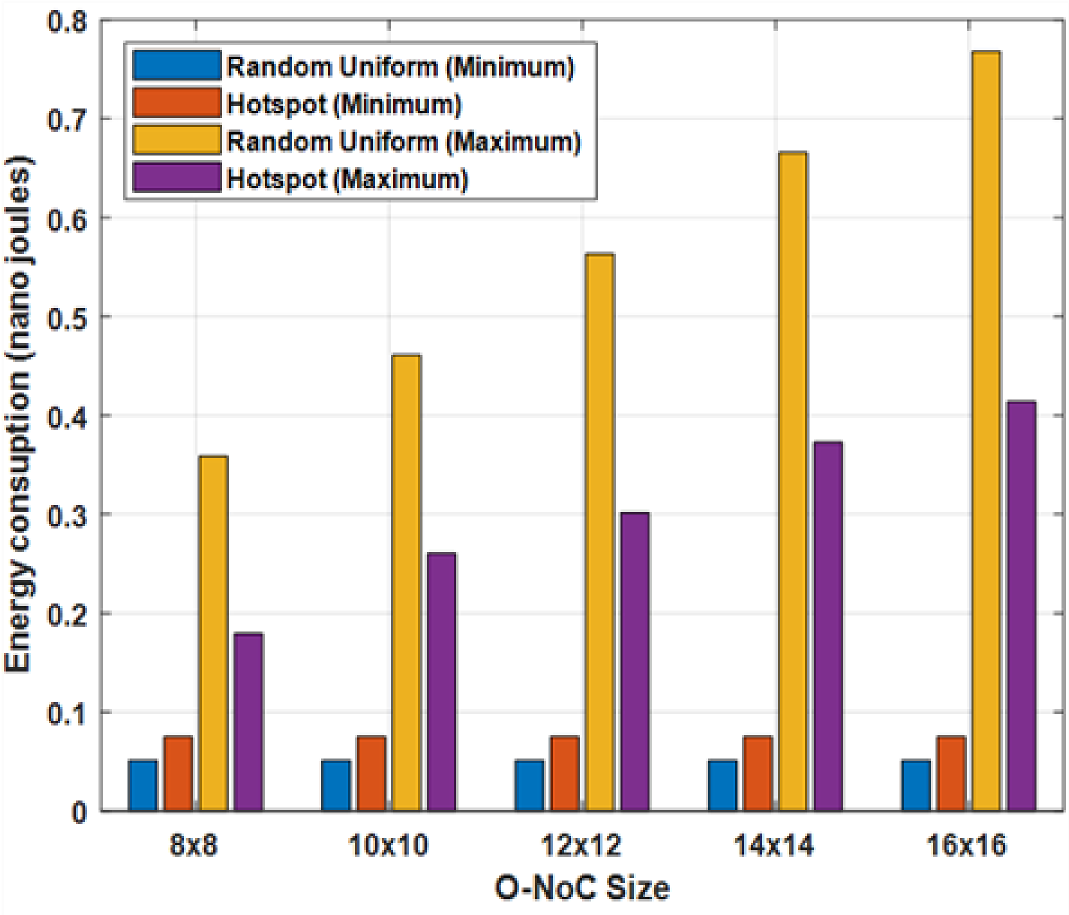


Figure 7.12: Energy consumption used to perform optical transmission on different Optical-NoC architecture under synthetic traffic patterns.

Figure 7.12, shows the energy usage while communicating data packets from one node to another node using an optical signal. Energy consumption directly depends upon the number of hops used to reach the destination. To evaluate these results we have used random uniform traffic in which sender and receiver are generated randomly all over the network. While in the case of hotspot traffic we consider the center as the main destination and senders are generated randomly. Simulation results show minimum energy usage of 0.06nJ/packet and maximum energy usage of 0.78nJ/packet while performing optical commutation between nodes.

7.2.1 Summary

Routing is one of the main processes that is used to transmit or forward the data packet in an appropriate path between source and destination. These appropriate paths increase the network performance in terms of efficient routing and maintaining optical QoS. The proposed routing algorithm provides a new qualitative diagram that removes the path reservation criteria. Using an alternate method instead of path reservation criteria helps to remove major issues in optical transmission like idle nodes usage, resource starvation issues as well as path blocking issues. This algorithm is independent of the network size and provides proper optical communication in different Optical-NoC architectures (8×8, 10×10, ---, 16×16). Simulation shows promising results in terms of hop count, link utilization, and deadlock avoidance. Furthermore, the proposed algorithm helps to achieve the shortest path between source and destination same as XY routing and odd-even routing.

7.3 Results and Discussion for Dealing with Fault Occurrence in Optical NoC

This section discussed the results that we have evaluated to support our proposed routing algorithm. Under different synthetic traffic patterns and the faulty rate, we have evaluated availability ratio, algorithm running time, successful delivery ratio, average hop count, and increase in energy consumption under faulty situations while finding an alternate optimal path between source and destination.

- **Network Availability** is considered as one of the main factors for evaluating fault tolerance in Optical-NoC architecture. This availability provides us the information regarding the network capability for performing communication in case of fault occurrence. In network availability we have to calculate Mean Time to Between Failure (**MTBF**) and Mean Time To Repair (**MTTR**), equation 7.1 helps to calculate the availability ratio [98].

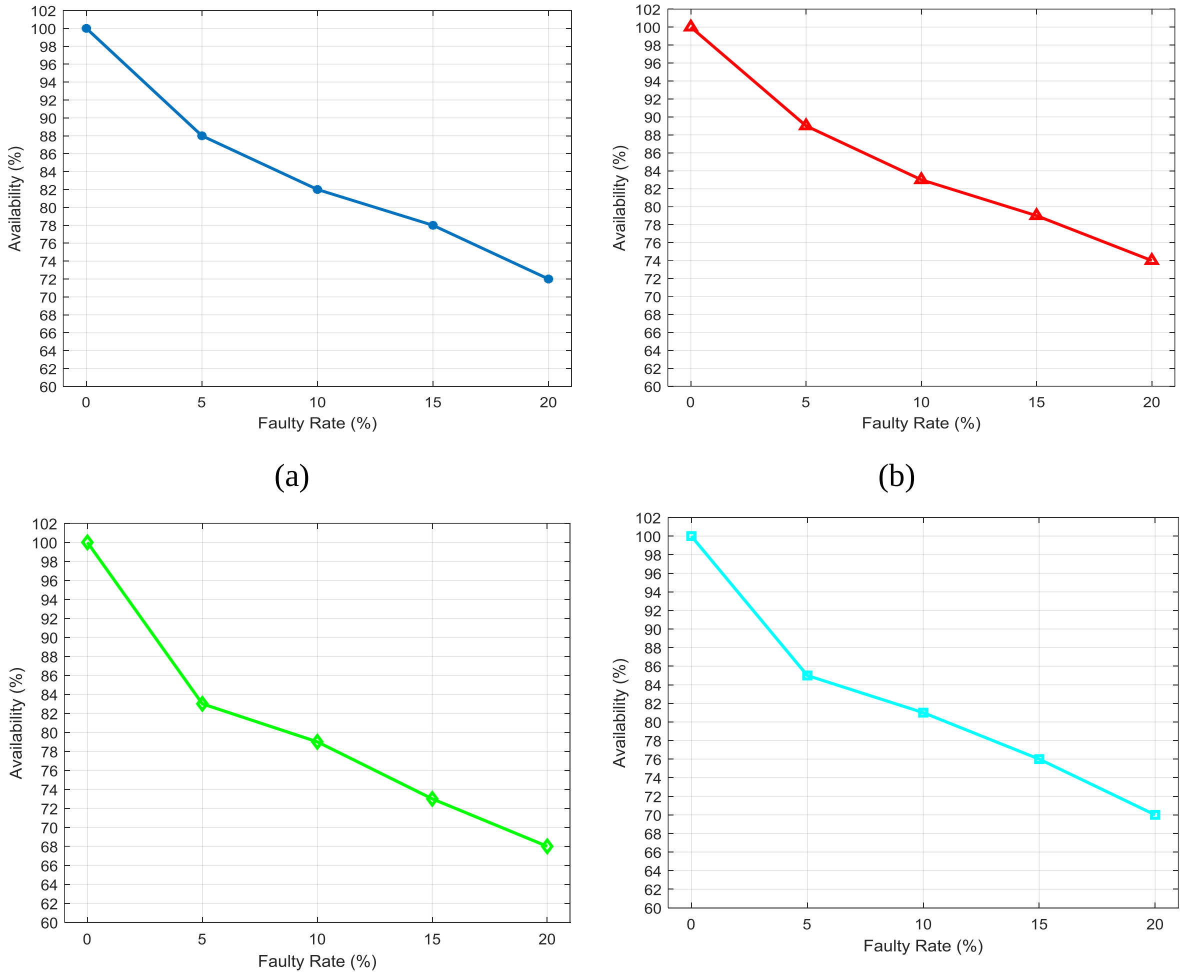
$$\text{Availability} = \frac{\text{MTBF}}{\text{MTTR+MTBF}} \times 100 \tag{7.1}$$

MTBF is considered as the number of failures encountered in a particular time period. In this, we have simulated our proposed architecture a number of times under a synthetic traffic pattern. This MTBF is calculated by equation 7.2, which includes total operating time over the number of failure encounters.

$$MTBF = \frac{Total\ Operating\ Time}{Number\ of\ Failuer\ Encouter} \tag{7.2}$$

MTTR represents the overall recovery power, i.e. it concludes the total time required to perform recovery in architecture over the total number of repairs done. As per equation 7.3, MTTR can be calculated represented below.

$$MTTR = \frac{Time\ Spent\ for\ Repair}{Number\ of\ Repair} \tag{7.3}$$



(a) (b)

(c) (d)

Figure 7.14: Availability ratio in 16x16 Optical-NoC (a) Random Uniform Traffic, (b) Hotspot, (c) Bit-complement, and (d) Transpose traffic under the different faulty percentage

Figure 7.14, represents the availability rate concluded by the above equation under different synthetic patterns. As per Figure 7.14 (a), random uniform traffic is considered in which under maximum faulty rates, 72% availability is achieved. In Figure 7.14 (b), the hotspot traffic pattern is considered under maximum fault rate, 74% of availability is achieved. In Figure 7.14

(c), bit-complement traffic under maximum fault rate achieves 68% availability. In last Figure 7.14 (d), transpose traffic is used which achieves 70% availability under maximum fault rate.

- **Algorithm Running Time** includes the overall running time of the fault-tolerant routing algorithm under faulty condition. This algorithm provides an alternate shortest path among nodes, eliminates faulty PE nodes at run time, and updates the knowledge base at the same time under different faulty conditions. As per Figure 7.15, the average algorithm running time is presented under different synthetic traffic patterns.

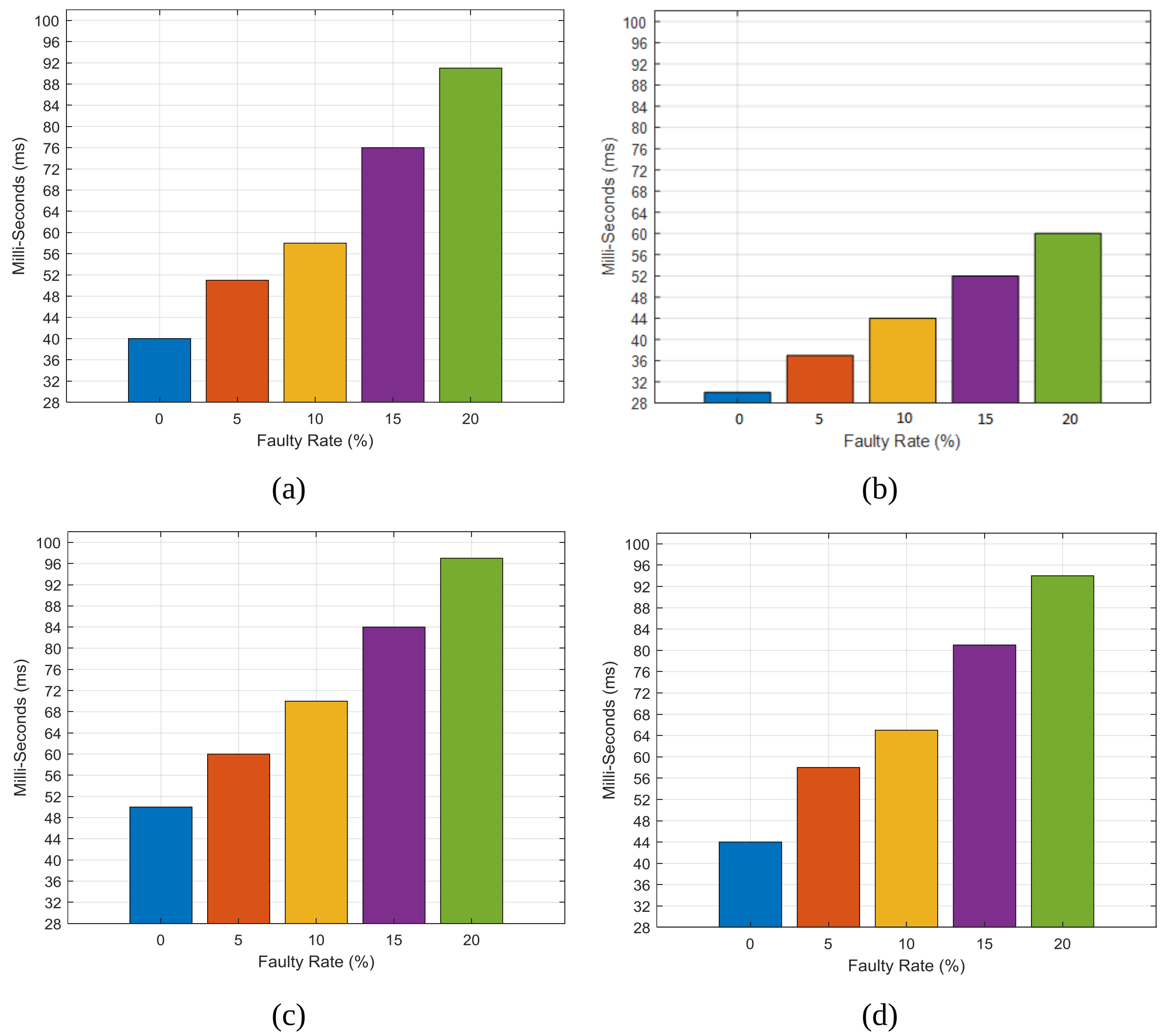
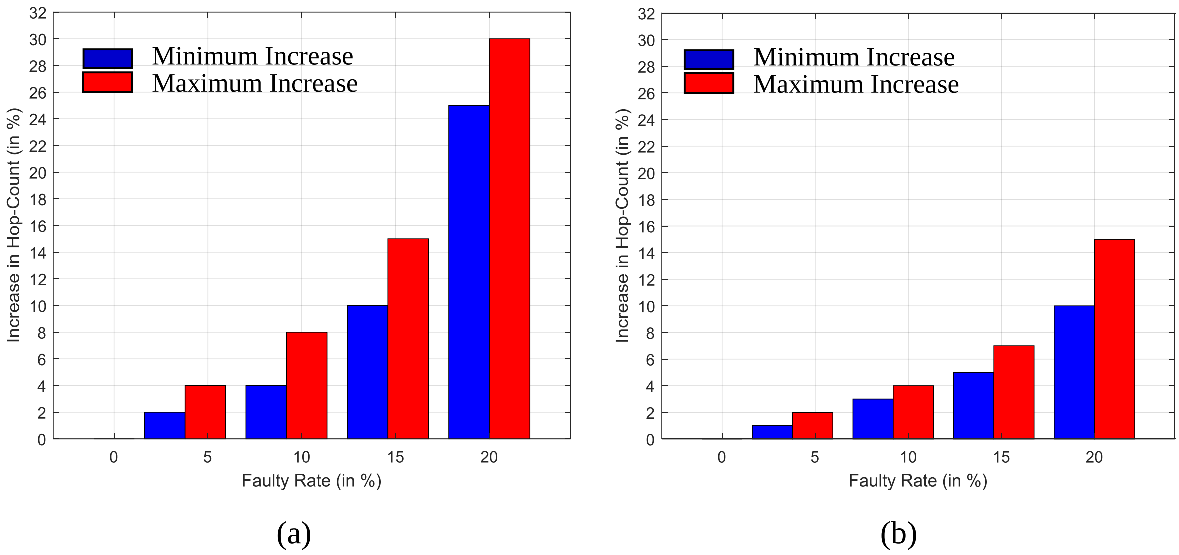


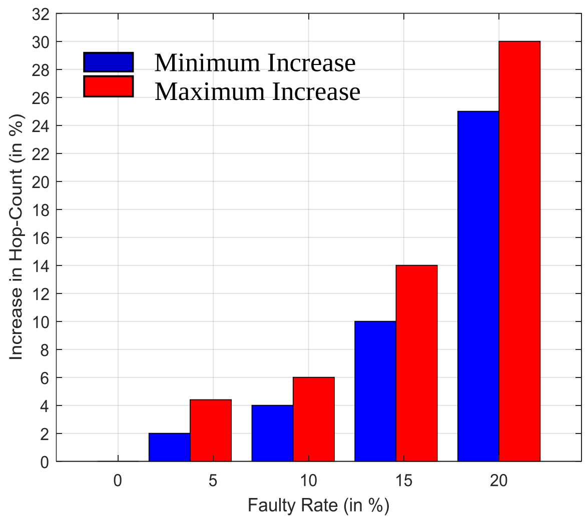
Figure 7.15: Running time of Fault tolerant-routing algorithm in 16x16 Optical-NoC. (a) Random Uniform Traffic, (b) Hotspot, (c) Bit-complement, and (d) Transpose traffic under different faulty percentages.

Figure 7.15, represents algorithm running time to achieve fault-tolerant nature in Optical-NoC. As per Figure 7.15 (a), random uniform traffic is considered in which under maximum faulty rates, 90ms is required to generate the next optimal solution. In Figure 7.15 (b), the hotspot traffic pattern is considered under maximum fault rate, 60ms is required to generate the next optimal solution. In Figure 7.15 (c), bit-complement traffic under maximum fault rate 98ms required to provide an alternate optimal path. In last Figure 7.15 (d), transpose traffic is used which requires 94ms to achieve the next optimal path.

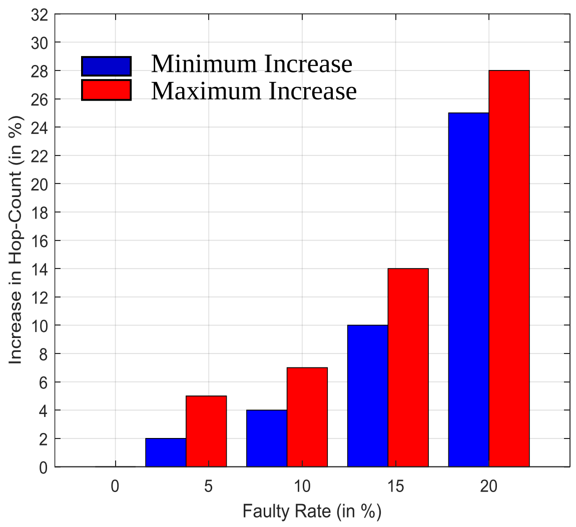
- **Average Hop Count** is considered as one of the important parameters of NoC. Hop count directly influences overall communication latency as well as QoS. Hop between the PE nodes means the number of intermediate devices a particular data packet passes before reaching its destination. These devices include a number of MRR, routers, and power amplifiers to boost a signal. In our proposed architecture number of hop count in 0% fault rate can be calculated by equation 7.4 as shown below where n represented the total number of PE nodes and H_{max} represents a maximum number of hop count.

$$H_{max} = \sqrt{n} - 1 \tag{7.4}$$





(c)



(d)

Figure 7.16: Average hop-count increase percentage in 16x16 optical-NoC. (a) Random Uniform Traffic, (b) Hotspot, (c) Bit-complement, and (d) Transpose traffic under the different faulty percentage

Figure 7.16, represents the average hop count required to deliver packets between source and destination. In random uniform traffic, the proposed routing algorithm achieves a maximum increase of up to 30% in the case of the 20% fault rate shown in Figure 7.16 (a). In the case of hot-spot traffic under maximum fault rate, a 15% increase is observed shown in Figure 7.16 (b). In the case of bit-compliment traffic, a 30% increase is observed in the case of maximum fault. In the last case of transpose traffic, a 28% increase is observed under the maximum fault rate.

- **Successful Delivery Ratio** is considered as the successful delivery of data packet or we may say a proper path between source and destination under faulty conditions. This also represents the working capability of Optical-NoC under faulty conditions. Figure 7.17 represents the successful delivery ratio under different synthetic traffic patterns.

As per Figure 7.17 (a), we have considered random uniform traffic in which we have achieved about 100% delivery in 0% fault rate and the delivery rate falls up to 90% in case of a maximum fault rate of 20%. As per Figure 7.17 (b), we have used hotspot traffic in which we received about 100% delivery ratio till 10% fault rate while maximum falls up to 95% in case of 20% fault rate. In the case of bit-compliment traffic, we have seen about 88% fall in delivery ratio under a maximum fault occurrence of 20%, as shown in Figure 7.17 (c). Lastly, we have used transpose traffic shown in Figure 7.17 (d), in which maximum fall is seen up to 87.8% under a maximum fault occurrence rate of 20%. In the proposed methodology, we have achieved about 88% of the lowest delivery ratio which shows acceptable results in case of a faulty situation.

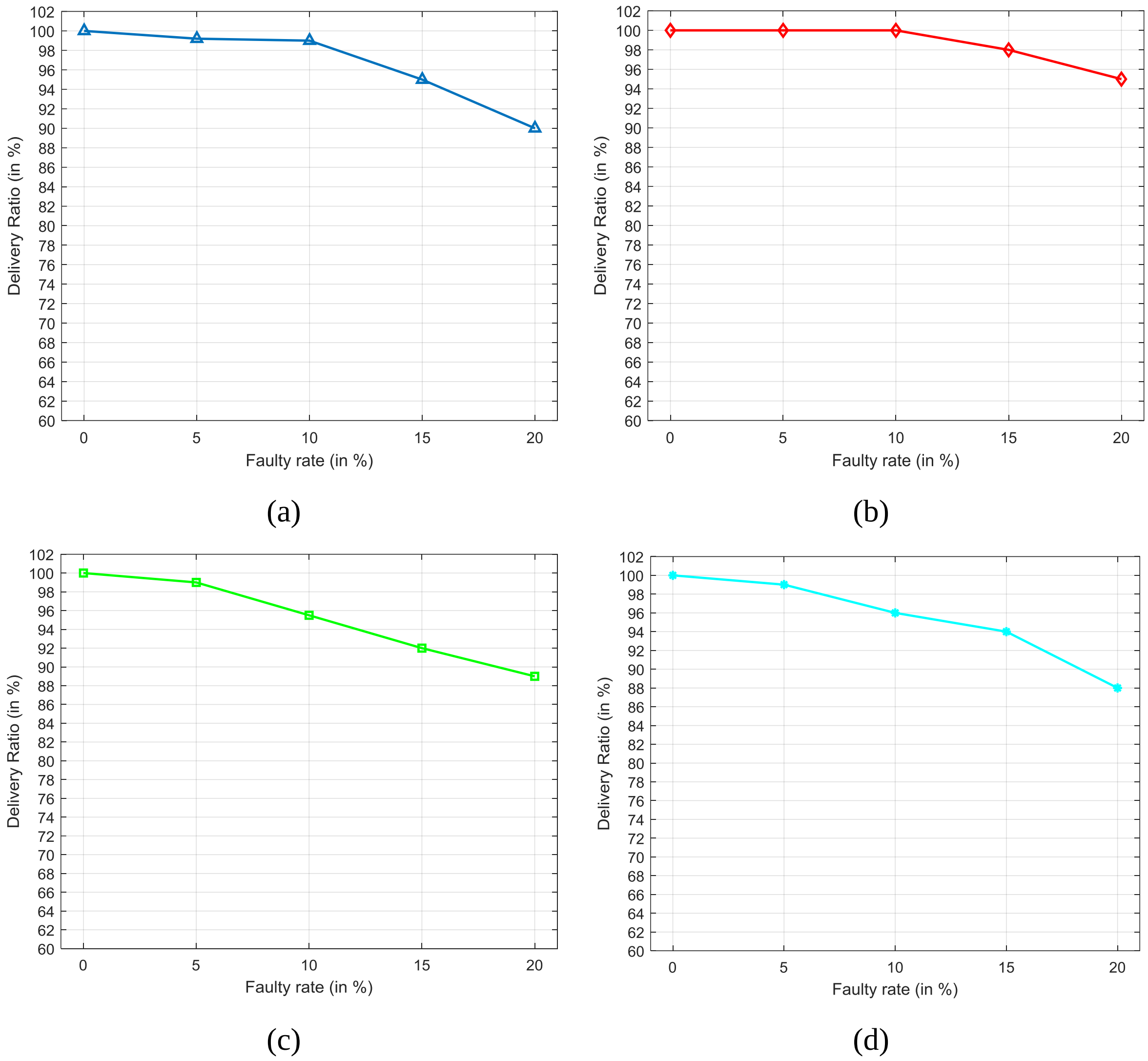
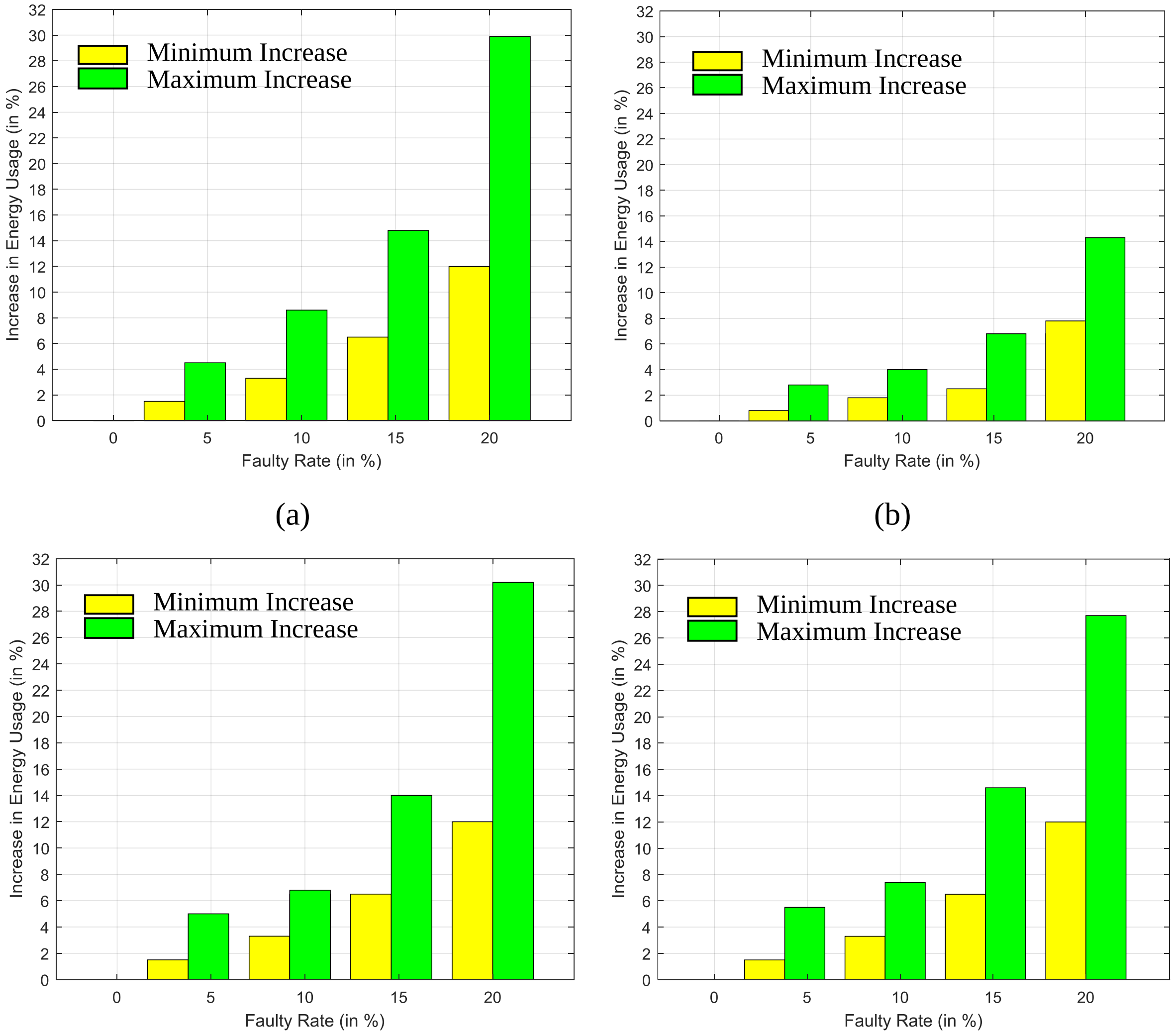


Figure 7.17: Successful Delivery ratio percentage in 16x16 optical-NoC (a) Random Uniform Traffic, (b) Hotspot, (c) Bit-complement, and (d) Transpose traffic under the different faulty percentage.

- **Average Energy Consumption,** energy consumption plays an important role in making the system energy efficient. These energy conservation properties help to achieve better throughput as well as increase overall performance. This simulation helps us to examine its overall increased energy consumption while determining a new path under faulty conditions.



(c) (d)

Figure 7.18: Energy Usage increase percentage in 16x16 optical-NoC (a) Random Uniform Traffic, (b) Hotspot, (c) Bit-complement, and (d) Transpose traffic under the different faulty percentage

As per Figure 7.18 (a), we have used a random uniform traffic pattern which helps to achieve a minimum of 12% increase in energy usage and a maximum of 30% increase under 20% fault rate. In Figure 7.18 (b), we have seen about a minimum of 7% minimum energy usage and a maximum of 15% increase in energy consumption under maximum fault rate. As per figure 7.18 (c), we have seen about an 11.5% minimum increase in energy consumption while 30% of maximum energy consumption is under the maximum fault rate. As per Figure 7.18 (d), we have used a transpose traffic pattern which shows 12% of the minimum increase in energy consumption and 27% maximum energy consumption under 20% fault rate. Although, the energy consumption in NoC to transmit data packets is directly dependent upon the number of hop count used. Thus, the maximum energy usage seen in the proposed architecture is up to 30% same as the hop count.

7.3.1 Summary

Fault occurrence is a natural phenomenon, while a large portion of research and development (R&D) costs are utilized to make a system more fault-tolerant. In this section, we have discussed the probability of getting a faulty situation in optical NoC and also proposed a fault-tolerant routing algorithm to deal with that situation. We have also calculated the system's reliability which tells us how reliable our proposed architecture is in case of fault occurrence. Additionally, we have evaluated our proposed fault-tolerant routing algorithm with several parameters which shows good results. These results support our proposed algorithm and show the fault tolerance power of our proposed architecture. These parameters include delivery ratio, energy consumption, hop count, algorithm running time, and availability rate. Out of all these parameter availability rate shows the main result which represents how much our architecture is ready to work under faulty conditions. Thus, we may say that our proposed algorithm makes optical-NoC more fault-tolerant and provides better results in case of fault occurrence.

CHAPTER 8

CONCLUSION AND FUTURE SCOPE

8.1 Conclusion

This work addresses the issues regarding optical-NoC architecture and routing algorithms, which are considered as the future of high computational systems. The purpose of this work is to develop an Optical-NoC architecture that helps to provide a proper communicational channel among PE nodes. The primary objective of this thesis was to develop a new Optical-NoC architecture to overcome some challenges. Overall work is divided into three objectives which include the proposed new Optical-NoC architecture and two routing algorithms that help to perform proper communication among PE nodes.

These works represent a new 2×2 Optical-NoC architecture, which helps to connect each PE node to the main waveguide. The proposed architecture is used as a brick-like structure to construct architectures. In this work, the opto-optic MRR was proposed to extract or provide proper optical filtering. This proposed MRR works on a specific wavelength according to their design specification, which helps to provide proper optical filtering. Furthermore, the simulation results show the proper working of the proposed architecture, optical signal filtering, and communication latency in femto-seconds between PE nodes. Proposed architecture helps to construct other big architecture like 4×4, 6×6-----N×N by configuring proposed brick-like structure.

In this thesis, a routing algorithm is proposed to perform efficient communication among PE nodes. The proposed algorithm helps to provide communication in big architecture composed of several 2×2 bricks. This work also helps to provide solutions regarding path reservation criteria, which results in overall performance degradation. The proposed algorithm is inspired by XY routing and odd-even routing which helps to determine the shortest path between PE nodes. Simulation results show promising results in terms of removing path reservation criteria, less hop count, proper link utilization, and dealing with deadlock situations. These results show proper working of the proposed algorithm which may help to provide optimal and efficient optical path for communication among the Optical-NoC’s architecture.

This work also proposed another routing algorithm known as fault-tolerant routing algorithm which helps to deal with faulty situations in Optical-NoC architecture. Fault occurrence is one of the major problem statements in Optical-NoC's architecture, due to its delicate nature. In case of fault occurrence simple routing fails to achieve destination, thus results in full system failure. To deal with faulty situations, the proposed fault-tolerant routing algorithm helps to achieve an alternate path set up between PE nodes. Furthermore, to evaluate our proposed algorithm's working, different faulty situations are created with a minimum of 0% fault rate to 20% maximum fault rate. The simulation results show proper working of the fault-tolerant algorithm under different faulty situations and provides better results in terms of availability, hop count, and delivery ratio. Thus, the proposed algorithm may help to construct fault-tolerant Optical-NoC architecture.

In this thesis, Optical-NoC's architecture and two routing algorithms are developed to provide high communication power. The performance of the proposed architecture and routing algorithm may help to overcome the gap between communication power and computation power. It is also noticed that adaptive routing algorithms are capable of providing high performance as well as helps to deal with faulty situations.

8.2 Future Scope

In the future, the use of real-time traffic patterns is used to determine the performance of the proposed architecture and two routing algorithms. Further, machine learning techniques will be used to design routing algorithms. These technique helps to generate the best optimal solution regarding deadlock situations, path setup rate, and faulty situations.

REFERENCES

[1] L. Benini and G. D. Micheli, "Networks on Chips: A New SoC Paradigm," Computer, pp. 70 - 78, 2002.

[2] T. Bjerregaard, S. Mahadevan. "A survey of research and practices of network-on-chip." ACM Computing Surveys (CSUR) 38, no. 1, pp. 1-es, 2006.

[3] A. Agarwal, C. Iskander, R. Shankar. "Survey of network on chip (noc) architectures & contributions." Journal of engineering, Computing and Architecture 3, no. 1, pp. 21-27, 2009.

[4] E. Bolotin, I. Cidon, R. Ginosar, A. Kolodny. "QNoC: QoS architecture and design process for network on chip." Journal of systems architecture 50, no. 2-3, pp. 105-128, 2004.

[5] M. S. Gaur, V. Laxmi, M. Zwolinski, M. Kumar, N. Gupta, "Network-on-chip: Current issues and challenges," 2015 19th International Symposium on VLSI Design and Test, pp. 1-3, 2015.

[6] V. Rantala, T. Lehtonen, J. Plosila, "Network on chip routing algorithms", Turku Centre Comput Science, 2006.

[7] M. Daneshtalab, M. Ebrahimi, T.C. Xu, P. Liljeberg, H. Tenhunen,"A generic adaptive path-based routing method for MPSoCs". J Syst Architect, 57(1), pp. 109–120, 2011.

[8] A. B. Gabis, M. Koudil. "NoC routing protocols–objective-based classification." Journal of Systems Architecture 66, pp. 14-32, 2016.

[9] A. Abbas, M. Ali, A. Fayyaz, A. Ghosh, A. Kalra, S. U. Khan, M. U. S. Khan, "A survey on energy-efficient methodologies and architectures of network-on-chip." Computers & Electrical Engineering 40, no. 8, pp. 333-347, 2014.

[10] M Ebrahimi, M. Daneshtalab, P. Liljeberg, J. Plosila, J. Flich, H. Tenhunen, "Path-based partitioning methods for 3D networks-on-chip with minimal adaptive routing", IEEE Trans Comput, 63(3), pp.718–733, 2012.

[11] K. Bhardwaj, K. Chakraborty, S. Roy, "Towards graceful aging degradation in NoCs through an adaptive routing algorithm", DAC Design Automation Conference, IEEE, pp. 382-391, 2012.

[12] A. Karkar, T. Mak, K.F. Tong, A. Yakovlev, "A survey of emerging interconnects for on-chip efficient multicast and broadcast in many-cores", IEEE Circuits Syst Mag 16(1), pp.58–72, 2016.

[13] A. Rezaei, M. Daneshtalab, D. Zhao, M. Modarressi M, “SAMi: self-aware migration approach for congestion reduction in NoC-based MCSoC”, IEEE International System-on-Chip Conference (SOCC), pp 145–150, 2016

[14] S. Abadal, A. Cabellos-Aparicio, E. Alarcon, J. Torrellas, “WiSync: an architecture for fast synchronization through on-chip wireless communication”, International Conference on Architectural Support for Programming Languages and Operating Systems (ASPLOS), pp 3–17, 2016.

[15] S. Deb, A. Ganguly, P. P. Pande, B. Belzer, D. Heo, “Wireless NoC as interconnection backbone for multicore chips: promises and challenges”, IEEE J EmergSel Top Circuits Syst 2(2), pp.228–239, 2012.

[16] A. Dehghani, K. Jamshidi, “A fault-tolerant hierarchical hybrid mesh-based wireless network-onchip architecture for multicore platforms”, J Supercomput 71(8), pp.3116–3148, 2015

[17] K. Duraisamy, Y. Xue, P. Bogdan, P. P. Pande, “Multicast-aware high-performance wireless networkon-chip architectures”, IEEE Trans Very Large Scale Integr VLSI Syst , 25(3), pp.1126–1139, 2017.

[18] F. Yazdanpanah, R. A. Mazayejani, M. Alaei, A. Rezaei, M. Daneshtalab. "An energy-efficient partition-based XYZ-planar routing algorithm for a wireless network-on-chip." The Journal of Supercomputing 75, no. 2, pp. 837-861, 2019.

[19] N. B. Renani, E. Yaghoubi. "A Review of Optical Routers in Photonic Networks-on-Chip: A Literature Survey." Journal of Advances in Computer Engineering and Technology 4, no. 3, 143-154, 2018.

[20] N. O. Malott, P. A. Wilsey. "Fast computation of persistent homology with data reduction and data partitioning." In 2019 IEEE International Conference on Big Data (Big Data), IEEE, pp. 880-889. 2019..

[21] S. Bahirat, S. Pasricha, “A particle swarm optimization approach forsynthesizing application-specific hybrid photonic networks-on-chip”, InThirteenth International Symposium on Quality Electronic Design (ISQED), IEEE, pp. 78–83, 2012.

[22] J. H. Collet, F. Caignet, F. Sellaye, and D. Litaize. "Performance constraints for onchip optical interconnects." IEEE Journal of Selected Topics in Quantum Electronics 9, no. 2 (2003): 425-432.

[23] G. Tosik, F. Gaffiot, Z. Lisik, I. O'Connor, F. Tissafi-Drissi. "Power dissipation in optical and metallic clock distribution networks in new VLSI technologies." Electronics Letters 40, no. 3, pp. 198-200, 2004.

[24] A. Pappu, A. Apsel, “Analysis of intrachip electrical and optical fanout”. Appl. Optics 44, 30, pp. 6361– 6372, 2005

[25] G. Chen, H. Chen, M. Haurylau, N. Nelson, D. Albonesi, M. Philippe, P. Fauchet, E. Friedman, G. Eby, “Predictions of cmos compatible on-chip optical interconnect”. In Proceedings of the International Workshop on System Level Interconnect Prediction (SLIP’05). ACM Press, New York, pp. 13–20, 2007.

[26] N. Kirman, M. Kirman, R. Dokania, J. Martnez, A. Apsel, M. Watkins, D. Albonesi, “Leveraging optical technology in future bus-based chip multiprocessors”, In Proceedings of the 39th Annual IEEE/ACM International Symposium on Microarchitecture (MICRO’06), 2006.

[27] D. Deb, J. Jose, S. Das, H. K. Kapoor. "Cost effective routing techniques in 2D mesh NoC using on-chip transmission lines." Journal of Parallel and Distributed Computing 123, 118-129, 2019

[28] J. Anantpur, R. Govindarajan. "PRO: Progress aware GPU warp scheduling algorithm." In 2015 IEEE International Parallel and Distributed Processing Symposium, IEEE, pp. 979-988, 2015.

[29] G. Calò, G. Bellanca, AE Kaplan, F. Fuschini, M. Barbiroli, M. Bozzetti, P. Bassi, V. Petruzzelli, “Integrated Vivaldi antennas, an enabling technology for optical wireless networks on chip”, Proceedingsof the 3rd International Workshop on Advanced Interconnect Solutions and Technologiesfor Emerging Computing Systems. ACM, pp. 1-4, 2018

[30] S. L. Beux, J. Trajkovic, I. O’Connor, G. Nicolescu, G. Bois, P. Paulin, “Optical ring network on- chip (ORNoC): architecture and design methodology”, Design, Automation & Test in Europe Conference & Exhibition DATE, pp 1–6, 2011

[31] S. V. R. Chittamuru, S. Pasricha. "Crosstalk mitigation for high-radix and low-diameter photonic NoC architectures”, IEEE Design & Test 32, no. 3, pp. 29-39, 2015.

[32] J. L. Abellán, C. Chen, A. Joshi. "Electro-photonic noc designs for kilocore systems." ACM Journal on Emerging Technologies in Computing Systems (JETC) 13, no. 2, pp. 1-25, 2016.

[33] Y. H. Kao, H. J. Chao. "Design of a bufferless photonic clos network-on-chip architecture." IEEE Transactions on computers 63, no. 3, pp. 764-776, 2012.

[34] J. L. Abellán., Ayse K. Coskun, Anjun Gu, Warren Jin, Ajay Joshi, Andrew B. Kahng, Jonathan Klamkin et al. "Adaptive tuning of photonic devices in a photonic NoC through dynamic workload allocation." IEEE Transactions on Computer-Aided Design of Integrated Circuits and Systems 36, no. 5 (2016): 801-814.

[35] C. Li, P. V. Gratz, S. Palermo. "Nano-photonic networks-on-chip for future chip multiprocessors." In More than Moore Technologies for Next Generation Computer Design. Springer, New York, NY, pp. 155-186, 2015.

[36] T. Zhou, H. Jia, J. Dai, S. Yang, L. Zhang, X. Fu, L. Yang, "Rearrangeable-nonblocking fiveport silicon optical switch for 2-D-meshnetwork on chip", IEEE Photon J 10(3) pp.1–8, 2018

[37] H. Jia, X. Yuhao, L. Zhang, J. Ding, X. Fu, L. Yang. "Four-port optical switch for fat-tree photonic network-on-chip." Journal of Lightwave Technology, 35, no. 15, pp. 3237-3241, 2017.

[38] F. Gambini, P. Pintus, S. Faralli, N. Andriolli, I. Cerutti. "Demonstration of a photonic integrated network-on-chip with multi microrings", In Optical Fiber Communication Conference, pp. W3D-6. Optical Society of America, 2015.

[39] S. Bahirat, S. Pasricha. "METEOR: Hybrid photonic ring-mesh network-on-chip for multicore architectures." ACM Transactions on Embedded Computing Systems (TECS) 13, no. 3s, pp. 1-33, 2014.

[40] A. Karanth, S. Kaya, A. Sikder, D. Carbaugh, S. Laha, D. DiTomaso, A. Louri, H. Xin, J. Wu. "Sustainability in network-on-chips by exploring heterogeneity in emerging technologies." IEEE Transactions on Sustainable Computing 4, no. 3, pp. 293-307, 2018.

[41] E. Peter, A. Thomas, A. Dhawan, S. R. Sarangi. "Active microring based tunable optical power splitters." Optics Communications 359, pp: 311-315, 2016.

[42] Y. Pan, P. Kumar, J. Kim, G. Memik, Y. Zhang, A. Choudhary, "Firefly: Illuminating future network-on-chip with nanophotonics". In ACM SIGARCH Computer Architecture News. ACM, 37, 3, pp. 429–440, 2009.

[43] A. Shacham, K. Bergman, L. P. Carloni. "Photonic networks-on-chip for future generations of chip multiprocessors." IEEE Transactions on Computers 57, no. 9, pp. 1246-1260, 2008.

[44] S. Killge, N. Neumann, D. Plettemeier, J. W. Bartha. "Optical through-silicon vias." In 3D Stacked Chips, Springer, Cham, pp. 221-234, 2016

[45] N.L. Venkataraman, R. Kumar, P. Mohamed Shakeel, "Ant lion optimized bufferless routing in the design of low power application specific network on chip", Circuits Syst. Signal Process. 39 (2), pp. 961–976, 2020.

[46] P. Pintus, F. Gambini, S. Faralli, F. D. Pasquale, I. Cerutti, N. Andriolli. "Ring versus bus: A theoretical and experimental comparison of photonic integrated NoC." Journal of Lightwave Technology 33, no. 23, pp. 4870-4877, 2015.

[47] E. Fusella, A. Cilardo. "H2ONoC: A hybrid optical–electronic NoC based on hybrid topology." IEEE Transactions on Very Large Scale Integration (VLSI) Systems 25, no. 1, pp. 330-343, 2016.

[48] X. Wang, H. Gu, Y. Yang, K. Wang, Q. Hao. "A highly scalable optical network-on-chip with small network diameter and deadlock freedom." IEEE Transactions on Very Large Scale Integration (VLSI) Systems, 24(12), pp.3424-3436, 2016.

[49] L. Guo, Y. Ge, W. Hou, P. Guo, Q. Cai, J. Wu, "A novel IPcore mapping algorithm in reliable 3D optical network-on-chips", Opt. Switch. Netw. 27, pp. 50–57, 2018.

[50] W. Choi, K. Duraisamy, R. G. Kim, J. R. Doppa, P. P. Pande, R. Marculescu, D. Marculescu, "Hybrid network-on-chip architectures for accelerating deep learning kernels on heterogeneous manycore platforms", In Proceedings of the International Conference on Compilers, Architectures and Synthesis for Embedded Systems, pp.1-10, 2016.

[51] S. Abadal, J. Torrellas, E. Alarc´on, A. Cabellos-Aparicio, "OrthoNoC: a broadcast-oriented dual-plane wireless network-on-chip architecture", IEEE Trans. Parallel Distrib. Syst. 29 (3), pp. 628–641, 2017.

[52] F. Liu, H. Zhang, Y. Chen, Z. Huang, H. Gu, "Wavelength-reused hierarchical optical network on chip architecture for manycore processors", IEEE Transactions on Sustainable Computing, 4(2), pp.231-244, 2017.

[53] X. Wang, H. Gu, Y. Yang, K. Wang, Q.Hao, " RPNoC: A ring-based packet-switched optical network-on-chip" IEEE Photonics Technology Letters, 27(4), pp.423-426, 2014.

[54] K. M İmre, "Dual-mode routing approach for photonic network on chip platforms." The Journal of Supercomputing 72, no. 3, pp. 904-925, 2016.

[55] L. Wang, X. Wang, T. Mak, "Adaptive routing algorithms for lifetime reliability optimization in network-on-chip", IEEE Transactions on Computers, 65(9), pp.2896-2902, 2015.

[56] J.H. Lee., M. S. Kim, T. H. Han, “Insertion loss-aware routing analysis and optimization for a fat-tree-based optical network-on-chip”, IEEE Transactions on Computer-Aided Design of Integrated Circuits and Systems, 37(3), pp.559-572, 2017.

[57] H. Falahati, S. Koohi, S. Hessabi. "Application-based dynamic reconfiguration in optical network-on-chip." Computers & Electrical Engineering 45, pp. 417-429, 2015.

[58] R. Desai, B. P. Patil. "Adaptive routing based on predictive reinforcement learning." International Journal of Computers and Applications 40, no. 2, pp. 73-81, 2018.

[59] S. Khoroush, M. Reshadi, A. Khademzadeh. "Application mapping in hybrid photonic networks-on-chip for reducing insertion loss." The Journal of Supercomputing 74, no. 9, pp. 4647-4671, 2018.

[60] M. Li, W. Liu, L. Yang, P. Chen, D. Liu, N. Guan. "Routing in optical network-on-chip: Minimizing contention with guaranteed thermal reliability." In Proceedings of the 24th Asia and South Pacific Design Automation conference, pp. 364-369, 2019.

[61] Y. Ye, W. Zhang, W. Liu. "Thermal-aware design and simulation approach for optical NoCs." IEEE Transactions on Computer-Aided Design of Integrated Circuits and Systems 39, no. 10, pp: 2384-2395, 2019.

[62] E. Fusella, J. Flich, A. Cilardo. "Path setup for hybrid NoC architectures exploiting flooding and standby." IEEE Transactions on parallel and distributed systems 28, no. 5, pp. 1403-1416, 2016.

[63] J. Wang, Y. Ye. "Ant Colony Optimization-Based Thermal-Aware Adaptive Routing Mechanism for Optical NoCs." IEEE Transactions on Computer-Aided Design of Integrated Circuits and Systems, 2020.

[64] R. Yao, Y. Ye. "Toward a High-Performance and Low-Loss Clos–Benes-Based Optical Network-on-Chip Architecture." IEEE Transactions on Computer-Aided Design of Integrated Circuits and Systems 39, no. 12, pp. 4695-4706, 2020.

[65] P. Guo, W. Hou, L. Guo. "Designs of low insertion loss optical router and reliable routing for 3D optical network-on-chip." Science China Information Sciences 59, no. 10, pp. 1-17, 2016.

[66] J. H. Lee, Y. S. Kim, C. L. Li, T. H. Han. "A shortest path adaptive routing technique for minimizing path collisions in hybrid optical network-on-chip." Journal of Systems Architecture 59, no. 10, pp: 1334-1347, 2013.

[67] B. Asadi, M. Reshadi, A. Khademzadeh. "A routing algorithm for reducing optical loss in photonic Networks-on-Chip." Photonic Network Communications 34, no. 1, pp. 52-62, 2017.

[68] M. C. Meyer, Y. Wang, T. Watanabe. "Fault-tolerant traffic-aware routing algorithm for 3-D photonic networks-on-chip." In 2019 IEEE 13th International Symposium on Embedded Multicore/Many-core Systems-on-Chip (MCSoC), IEEE, pp. 172-179, 2019.

[69] N. Sharma, P. R. Panda, F. Catthoor, M. Li, P. Agrawal. "Data Flow Transformation for Energy-Efficient Implementation of Givens Rotation--Based QRD." ACM Transactions on Embedded Computing Systems (TECS) 15, no. 1, pp. 1-23, 2016.

[70] S. Pai, I. A. D. Williamson, T. W. Hughes, M. Minkov, O. Solgaard, S. Fan, D. A. B. Miller. "Parallel fault-tolerant programming of an arbitrary feedforward photonic network." arXiv preprint arXiv: 1909.06179, 2019.

[71] S. V. R. Chittamuru, S. Pasricha, "Improving crosstalk resilience with wavelength spacing in photonic crossbar based network on chip architectures". In: 2015 IEEE 58th International Midwest Symposium on Circuits and Systems (MWSCAs). IEEE, pp 1 4. 2015b

[72] L. A. Bakhtiar, M. Hosseinzadeh, M. Reshadi. "Reliable communications in optical network on chip by use of fault tolerance approaches." Optik 137, pp. 186 194, 2017.

[73] Z. Zhang, W. Serwe, J. Wu, T. Yoneda, H. Zheng, C. Myers. "An improved fault-tolerant routing algorithm for a network-on-chip derived with formal analysis." Science of Computer Programming 118, pp. 24-39, 2018.

[74] D. Xiang, K. Chakrabarty, H. Fujiwara. "Fault-tolerant unicast-based multicast for reliable network-on-chip testing." ACM Transactions on Design Automation of Electronic Systems (TODAES) 23, no. 6, pp. 1-23, 2018.

[75] K. S. M. Li, S. J. Wang. "Design methodology of fault-tolerant custom 3D network-on-chip." ACM Transactions on Design Automation of Electronic Systems (TODAES) 22, no. 4, pp: 1-20, 2017.

[76] A. B. Ahmed, Y. Okuyama, A. B. Abdallah. "Contention-free routing for hybrid photonic mesh-based network-on-chip systems." In 2015 IEEE 9th International Symposium on Embedded Multicore/Many-core Systems-on-Chip, IEEE, pp. 235-242, 2015.

[77] G. Schley, A. Dalirsani, M. Eggenberger, N. Hatami, H. J. Wunderlich, M. Radetzki. "Multi-layer diagnosis for fault-tolerant networks-on-chip." IEEE Transactions on Computers 66, no. 5, pp. 848-861, 2016.

[78] M. Li, Q. Zeng, W. B. Jone. "DyXY: a proximity congestion-aware deadlock-free dynamic routing method for network on chip." In Proceedings of the 43rd annual Design Automation Conference, pp. 849-852. 2006.

[79] M. Fadhel, L. Huang, H. Gu. "RRW: A Reliable Ring Waveguide-Based Optical Router for Photonic Network-on-Chips." In International Symposium on Parallel Architectures, Algorithms and Programming, Springer, Singapore, pp. 429-438, 2020.

[80] P. Guo, W. Hou, L. Guo, W. Sun, C. Liu, H. Bao, L. H. K. Duong, and W. Liu. "Fault-tolerant routing mechanism in 3D optical network-on-chip based on node reuse." IEEE Transactions on Parallel and Distributed Systems 31, no. 3, pp. 547-564, 2019.

[81] D. Xiang, Q. Pan. "Low-power and high-performance adaptive routing in on-chip networks." CCF Transactions on High Performance Computing 1, no. 2, pp. 92-110, 2019.

[82] Z. M. Rad, E. Yaghoubi. "ADFT: an adaptive, distributed, fault-tolerant routing algorithm for 3D mesh-based networks-on-chip." International Journal of Internet Technology and Secured Transactions 10, no. 4, pp. 481-490, 2020.

[83] L. Zhu, H. Gu, Y. Yang, Y. Chen. "Making path selection faster: a routing algorithm for ONoC." Optics Express 29, no. 7, pp. 10221-10235. 2021.

[84] C. Panem, R. S. Gad, U. V. Rane, V. R. Gad. "Evaluation of 3D & 4D Two Layer Mesh NoC for Fault Tolerance over Combinations of Vertical Channel." In 2018 International Conference on Current Trends towards Converging Technologies (ICCTCT), IEEE, pp. 1-7, 2018.

[85] M. Abdollahi, S. Mohammadi. "Vulnerability assessment of fault-tolerant optical network-on-chips." Journal of Parallel and Distributed Computing 145, pp. 140-159, 2020.

[86] M. Meyer, Y. Okuyama, A. B. Abdallah. "Microring fault-resilient photonic network-on-chip for reliable high-performance many-core systems." The Journal of Supercomputing 73, no. 4, pp. 1567-1599, 2017.

[87] R. Karimi, S. Koohi, M. Tinati, S. Hessabi. "A thermally-resilient all-optical network-on-chip." Microelectronics Reliability 99, pp: 74-86, 2019.

[88] M. Li, W. Liu, L. HK Duong, P. Chen, L. Yang, C. Xiao. "Contention-Aware Routing for Thermal-Reliable Optical Networks-on-Chip." IEEE Transactions on Computer-Aided Design of Integrated Circuits and Systems 40, no. 2, pp. 260-273, 2020.

[89] R. Seyednezhad, N. Derakhshanfard, S. Rasouli Heikalabad. "Routing design in optical networks-on-chip based on gray code for optical loss reduction." Optik 228, pp. 166198, 2021

[90] K. Bergman, L. P. Carloni, A. Biberman, J. Chan, G. Hendry, “Photonic network-on-chip design” Springer New York, 2014

[91] S. Werner, J. Navaridas, M. Luján. "A Survey on Optical Network-on-Chip Architectures." ACM Computing Surveys (CSUR) 50, no. 6, pp. 89, 2017.

[92] B. Asadi, M. Reshadi. "Photonic network-on-chip: A survey." International Journal of Computer Science and Information Security 14, no. 11, pp. 786, 2016.

[93] Open Access (2018). https://www.rp-photonics.com/silica_fibers.html

[94] online data base (2018) : https://refractiveindex.info/?shelf=main&book=SiO2&page=Radhakrishnan-o

[95] D. G Radu. “Integrated ring resonators”, Springer-Verlag Berlin Heidelberg, 2007.

[96] K. Wang, S. Qi, Z. Chen, Y. Yang, H. Gu. "SMONoC: Optical network-on-chip using a statistical multiplexing strategy." Optical Switching and Networking 34, pp. 1-9, 2019.

[97] M. Palesi, M. Daneshtalab, “Routing algorithms in networks-on-chip”, New York: Springer, 2014.

[98] C. Grecu, L. Anghel, P. P. Pande, A. Ivanov, R. Saleh. "Essential fault-tolerance metrics for NoC infrastructures." In 13th IEEE International On-Line Testing Symposium (IOLTS 2007), pp. 37-42. IEEE, 2007.

PUBLICATIONS

Journal Publications:

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1. Kapil Sharma, Vivek Kumar Sehgal. "Modern architecture for photonic networks-on-chip." The Journal of Supercomputing (2020): 9901-9921. DOI: 10.1007/s11227-020-03220-2.

[**SCIE/SCOPUS INDEXED IF: 2.474]**

2. Kapil Sharma, Vivek Kumar Sehgal, “Energy-efficient and sustainable communication in optical networks on chip”, Sustainable Computing: Informatics and Systems, Volume 28, 2020, 100426, ISSN 2210-5379, DOI: 10.1016/j.suscom.2020.100426.

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1. Kapil Sharma, and Vivek Kumar Sehgal, “Dealing with Fault Occurrence in Optical Networks-on-Chip”, IEEE Transactions on Computers.

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Conferences Publications:

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1. Kapil Sharma, and Vivek Kumar Sehgal, "Optical-NoC: Future of New Computational Systems," 2020 IEEE 17th India Council International Conference (INDICON), 2020, pp. 1-6, DOI: 10.1109/INDICON49873.2020.9342176.

2. Kapil Sharma, and Vivek Kumar Sehgal, "Improved and Efficient Optical-NoC Architecture," 2021 6th International Conference for Convergence in Technology (I2CT), 2021, pp. 1-5, DOI: 10.1109/I2CT51068.2021.9417946.