RAP-NoC: Reliability Assessment of Photonic Network-on-Chips, A simulator

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ABSTRACT

Nowadays, optical network-on-chip is accepted as a promising alternative solution for traditional electrical interconnects due to lower transmission delay and power consumption as well as considerable high data bandwidth. However, silicon photonics struggles with some particular challenges that threaten the reliability of the data transmission process. The most important challenges can be considered as temperature fluctuation, process variation, aging, crosstalk noise, and insertion loss. Although several attempts have been made to investigate the effect of these issues on the reliability of optical network-on-chip, none of them modeled the reliability of photonic network-on-chip in a system-level approach based on basic element failure rate. In this paper, an analytical model-based simulator, called Reliability Assessment of Photonic Network-on-Chips (RAP-NoC), is proposed to evaluate the reliability of different 2D optical network-on-chip architectures and data traffic. The experimental results show that, in general, Mesh topology is more reliable than Torus considering the same size. Increasing the reliability of Microring Resonator (MR) has a more significant impact on the reliability of an optical router rather than a network.

CCS CONCEPTS

• **Hardware** → **Hardware reliability**; • **Networks** → **Network components**.

KEYWORDS

Photonic network-on-chip, Microring resonator, RBD, Reliability

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1 INTRODUCTION

Network-on-Chips (NoCs) have become a scalable solution for connecting cores and other on-chip modules [13] in the Many-Core Systems-on-Chip era. The increase of processing power due to the progressive parallelism of computation and the limited power budget of multi-core chips have confronted on-chip communications with new challenges. These challenges force designers to adopt novel communication approaches in traditional electrical interconnects [3] or advanced communication technologies such as silicon photonics [16, 23] or on-chip wireless data transmission [4]. In this context, adopting low-power, low latency, and high bandwidth on-chip interconnect is a prerequisite for enhancing computational efficiency through parallel computing associated with multi-core platforms. Thanks to silicon photonics (SiP) technology, Photonic Network-on-Chip (PNoC) is a proper approach for realizing high bandwidth, low latency, and significantly low power on-chip communications. A PNoC comprises several main components including laser source, waveguides, MRs, modulators, and photodetectors [6].

Due to technology scaling and consequently increasing the level of integration, chips have become much smaller and more complex throughout the years. By increasing the complexity and decreasing the size of the chips, susceptibility to

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process variation and thermal variation is increased, which makes chips more fault-prone. Thus, in multi- and many-core chips, especially those exploiting PNoC the failure rate is considerable. This is due to using various optical components with high complexity and transistor density. Optical components are relatively immune to transient faults resulted from radiation [15], but their sensitivity to thermal, process variation, and aging can cause unreliable operations in the optical domain [22]. In this domain, active components, as well as the ones undergoing thermal variation, suffer more from aging [14]. Other issues that threaten PNoC reliability are insertion loss and crosstalk, which arise from intrinsic characteristics of photonic components [7]. These issues are caused by the unwanted coupling of the optical signals, which degrades the power of the optical signals, and consequently Signal-to-Noise Ratio (SNR) [1]. Therefore, faults can occur in every component like photodetectors, MRs, waveguides, routers, etc. However, the failure rate in the active components such as MRs, is higher than in passive ones such as waveguides [21].

Given the above, while the SiP approach provides promising prospects for chip designers to improve throughput, power consumption, and latency, it is still essential to overcome the reliability challenges. Major issues that threaten the reliability of PNoC technology are integration challenges (e.g., process and thermal variations) and functional challenges (e.g., insertion loss and crosstalk). Existing studies on PNoC reliability and performance assessment have attempted to quantify the reliability based on SNR, Bit-Error Rate (BER), and latency parameters by overcoming the aforementioned reliability challenges [2]. The common models used to evaluate the reliability are divided into two classes: combinational models and stochastic models. In combinational models like Reliability Block Diagram (RBD) which is our adopted model in this work, it is assumed that the failures of system components are independent of each other. In contrast, in stochastic models like the Markov chain, dependencies between system component failures are taken into account [17].

In PNoC, among the various optical components, MRs play a key role in the functionality of the network. Indeed, optical switches are constructed from MRs. These components act as modulators and demodulators at the source and destination, respectively so that they provide optical routing functionality. Many issues such as process and temperature variations, jeopardize the reliability of MRs. Many works have been done to cope with these issues to improve the reliability of these components and consequently PNoC [19, 20, 28]. However, to the best of our knowledge, the impact of failure rate of MRs on the system-level reliability of optical switches and, ultimately, the whole PNoC has not been investigated so far. The main contributions of the paper are summarized as follows:

- System-level modeling of the reliability of PNoC based-on the traffic pattern and the reliability of basic elements.
- Proposing an analytical simulator called Reliability Assessment of Photonic Network-on-Chips (RAP-NoC)

The rest of the paper is organized as follows: The related work is discussed in Section 2. In Section 3, the background and motivation of this paper are introduced as the most important preliminaries and models which are applied in our work. The main idea of the RAP-NoCs is discussed in Section 4 followed by the experimental results and analyses in Section 5. Finally, Section 6 concludes the paper.

2 RELATED WORK

In recent years, there are several research works in the literature which have focused on reliability challenges on silicon photonics and optical network-on-chips. Some of these investigations discuss various physical phenomena threaten the reliability of silicon photonics devices such as variation, process variation, crosstalk noise and insertion loss. On the other hand, there are another approach which try to alleviate these problems through device-level, circuit-level and system-level techniques.

In one side, discovering the effect of thermal variation, process variation, crosstalk noise, and insertion loss on the reliability parameter of PNoC have been performed in several papers. [8] proposed a novel high reliable optical switching element with lower crosstalk noise and insertion loss. Thakkar et. al [24] proposed a novel method through generation of four-amplitude-level optical signals in Dense Wavelength Division Multiplexing (DWDM) which increases the aggregated bandwidth without imposing extra wavelengths or photonic hardware and reducing BER.

On the other hand, many researchers have focused on different methods to improve reliability ranging from device to system-level techniques. Zheng et al. [19] properly modeled the performance and reliability of PNoC which originate from sensitivity to variations (i.e., thermal and process variations). They also proposed run-time techniques to compensate these effects. Mohamed et al. [22] suggested a reliability-aware design flow with various techniques (from device to system-level) to address the variation-induced reliability challenges. Chittamuru et al. [25] proposed a novel reliability-aware run-time framework called LIBRA which consists of a device-level reactive MR assignment method along with a system-level proactive task migration to avoid thermal threshold violations. Ye et al. [28] proposed a thermally resilient PNoC architecture, called Aurora, which provided a reliable and low BER on-chip data transmission in the presence of significant temperature variations. Xu et al. [26] proposed a series of techniques to prevent bandwidth loss besides maintaining PNoC reliability by solving wavelength drifting problem on MR due to process variation. Some papers such as [12, 18] focused on the reliable routing algorithms in the presence of thermal susceptibility or fault situations. Bakhtiar et al. [5] presented a reliable communication platform for PNoC through hardware and information redundancies.

Although several techniques have been proposed for reliable optical on-chip data transmission, there is not yet a system-level approach to evaluate the reliability of the whole system. In this paper, after discussing the reliability model, the proposed RAP-NoC simulator is introduced for 2D network architectures. Furthermore, there are several research attempts which have investigated the design challenges of 3D integration of optical on-chip networks [11, 27]. In our future work, the reliability of such 3D network architectures also will be discussed and added to RAP-NoC.

3 BACKGROUND AND MOTIVATION

Optical communication consists of three functional stages: generation, routing, and reception. At the source of communication, the generation stage converts digital data from the electrical domain into the optical through the creation of an optical waveform. The routing stage carries out all the actions that are required for the effective transferring of optical signals from source to destination node. Eventually, at the reception stage, the optical signal is reverted into the electrical domain. The reception process is the inversion of the actions that occurred at the generation stage. At the generation and reception stages, most of the actions are done in the electrical domain, while the routing process occurred in the optical domain. In this paper, our focus is on the reliability of the optical domain, i.e., the routing stage. To this end, we introduce our reliability model that is adopted for modeling the reliability of an optical router as a fundamental element of the routing stage and consequently PNoC. Also, for clarifying the functionality of an optical router, the internal structure of this optical element is detailed.

3.1 Reliability Assessment Model

One of the most common dependability models that provides an abstract representation of the system is Reliability Block Diagram (RBD). In this analytical model, the reliability assessment is done based on the probability theories. In RBD model, system components represented as blocks are connected in series and parallel forms. In this way, the operational dependencies between system components can easily be realized. The serial connection represents that the correct operation of all serial components is required to the proper operation of the system. In a parallel connection, the correct operation of only one component is sufficient for the proper operation of the system. In this way, by combining the serial and parallel models, the reliability of a whole complex system can be modeled [17].

3.2 Optical Router Structure

Optical routers are the fundamental components in realizing PNoC technology. Inside an optical router, there is a switching fabric through which packets are switched from an input port to an output port. The switching fabric is composed of MRs and waveguides such that a combination of them makes two switching elements: crossing and parallel elements. The configuration of a switching fabric is done through a control unit that uses electrical signals to setup optical paths. MR has on- and off-state resonance wavelength that can be controlled by voltage through a control unit. Figure 1 shows the optical signal transmission through the crossing and parallel switching elements (an optical add/drop filter) in both on and off states [10]. In the case of powered-off, the resonance wavelength of the MR is λ_{off} (i.e., off-state), and while powered-on, the resonance wavelength change to λ_{on} (i.e., on-state). In this way, if the optical signals use the single wavelength, i.e., λ_{on}, by controlling the switching fabric through powering on/off MRs the switching elements can be configured in such a way that packets are switched to the drop/through port.

In an optical router, optical waveguides are passive components while MRs are active components. It was demonstrated that in PNoC architecture, the failure rate in active components is higher than in passive ones [14, 21]. Therefore, the reliability of MRs plays a big role in the reliability of an optical router and consequently the reliability of PNoCs. As mentioned before, the reliability of MRs suffers from multiple reliability issues such as process variation, temperature variation, and aging. On the other hand, MRs failure can expose the single-point of failure. The MR failure may lead to optical router malfunction, which could cause packet loss and consequently system failure [21].

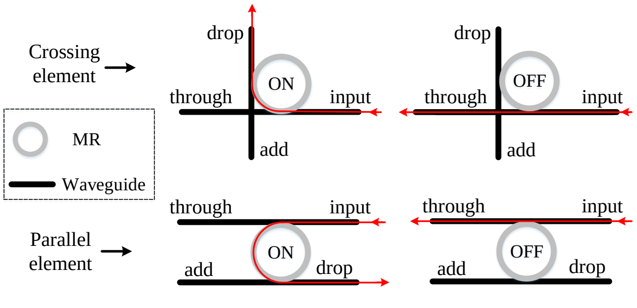
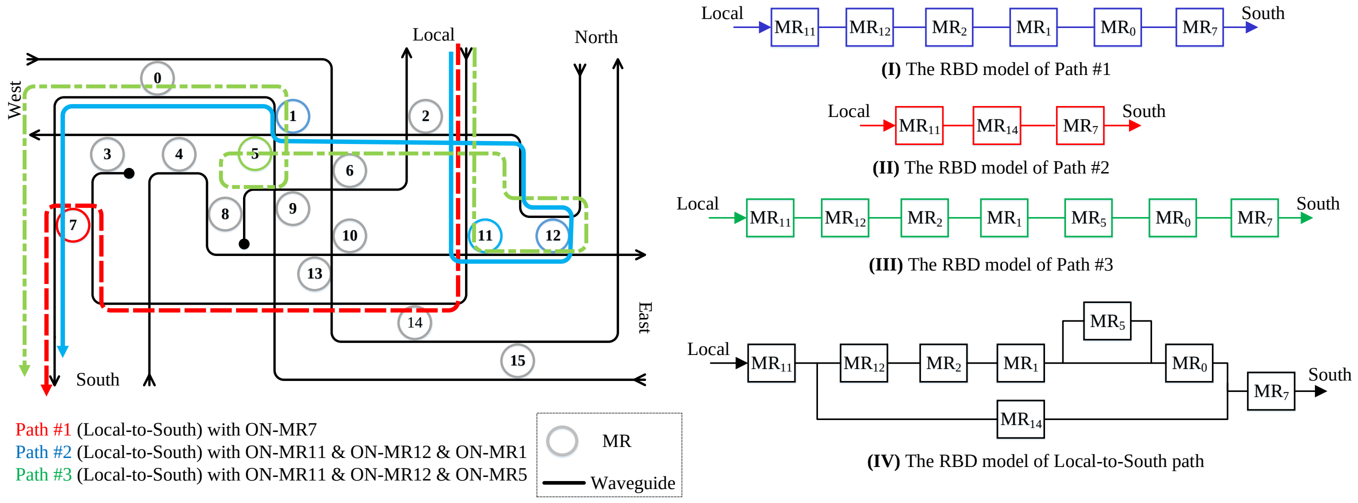


Figure 1: Basic optical switching elements



(a) Optical router and multi-path within the router

(b) RBD models of Local-to-South path

Figure 2: A typical optical router with three different paths from Local-to-South port and its RBD model

3.3 Motivation

As mentioned in the previous subsection, MR's failure could threaten the reliability of an optical router and ultimately the reliability of PNoC. The overall impact of reliability challenges will result in a specific failure rate, called λ for MR. According to this failure rate, the reliability of MR can be modeled based-on the *exponential failure law* [9] as a function of time through Equation 1.

$$R_{MR}(t) = e^{-\lambda t} \tag{1}$$

Since the optical router consists of a number of MRs, the optical router's reliability will be affected by the MR's reliability model. So, we calculate the reliability of the PNoC in the presence of MR's failure. Moreover, we estimate the reliability of a PNoC by fault injection into different MRs in the router's structure. In this way, the effect of MR failure on the reliability of PNoC is assessed. Different scenarios can be evaluated by our novel proposed RAP-NoC simulator.

4 PROPOSED METHOD

In this paper, we aim to evaluate the reliability of PNoC and introduce our analytical simulator, called RAP-NoC, for the calculation of different scenarios. The user-friendly open-source simulator is developed using Python language. The most notable parts of the simulator are depicted in Figure3.

At the device level, we propose a model to estimate the reliability of MR. Then, we determine the reliability of paths within the optical router based on the reliability of MRs. At the third level, the reliability of an optical router is calculated base on the reliability of its longest path. At this level, the length of a path is defined as the number of MRs across the path. Finally, at the forth level, we estimate the PNoC's reliability based on the reliability of its optical routers. It should be noted that the reliability of the PNoC entirely depends on the application, which is mapped on the processing elements of the optical network-on-chip. Indeed, due to communications between the tasks of an application, various optical streams, and consequently specific paths with different hop counts, will be formed. In this way, the reliability of the longest path within the network determines the reliability of PNoC. According to the abovementioned, at each level, the obtained result from the previous level is used to assess the reliability.

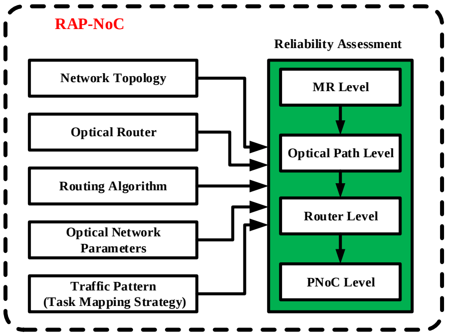


Figure 3: The overview of RAP-NoC simulator

As mentioned previously, MRs are essential components of optical routers and therefore of PNoCs. Given that, the reliability of MRs has a direct effect on the reliability of the PNoC. In an optical router, there is a set of MRs such that with the participation of each set, different paths are constructed within the router. As an example, in a PNoC with 2D mesh topology, each router has 6 ports, so there is at least $\binom{6}{2} = 15$ bidirectional paths. It is possible that there are more than one path from a specific port to another port in an optical router. As an example, within the depicted router in Figure 2a, there are three different paths from Local port to South port wherein each of them passes through a particular subset of MRs. In the following, we will study the reliability assessment of MR, a path, an optical router, and PNoC, separately.

4.1 MR Reliability

As discussed previously, there are various types of phenomena such as thermal and process variations, crosstalk noise and insertion loss parameters, and also aging which threaten the reliability of silicon photonic devices such as MR. Modeling with Markov chain as a stochastic process is one of the most popular solutions when we can estimate the failure rates and also recovery/repair rates of fault types [17]. In this paper, we calculate the failure rate of MR (i.e., λ_{MR}) using this approach.

4.2 Optical Path Reliability

As mentioned earlier, MR's reliability can be calculated based on its failure rate. Thus, given that each path in the optical router passes through a number of MRs, the reliability of all the paths within an optical router can be calculated using the RBD model. To clarify this, the RBD model of Local-to-South (LTS) path within the optical router of Figure 2a was shown in Figure 2b. In this figure, due to the existence of three different paths from Local to South port, we have shown the RBD model of Path #1, #2 and #3 in Figure 2b-I, Figure 2b-II, and Figure 2b-III, respectively. In this case, the reliability of three different paths can be calculated as follows;

$$\begin{aligned} R_{path\#1} = {} & R_{MR_{11}} \times R_{MR_{12}} \times R_{MR_2} \times R_{MR_1} \\ & \times R_{MR_8} \times R_{MR_7} \end{aligned} \tag{2}$$

$$R_{path\#2} = R_{MR_{11}} \times R_{MR_{14}} \times R_{MR_{13}} \times R_{MR_7} \tag{3}$$

$$\begin{aligned} R_{path\#3} = {} & R_{MR_{11}} \times R_{MR_{12}} \times R_{MR_2} \times R_{MR_1} \\ & \times R_{MR_5} \times R_{MR_0} \times R_{MR_7} \end{aligned} \tag{4}$$

Based-on the RBD model shown in Figure 2b-IV, obtained by combining the RBD models of paths #1 to #3, Local-to-South path reliability can be calculated as follows:

$$\begin{aligned} R_{LTS} = {} & R_{MR_{11}} \times \big[1 - \big((1 - MR_{14}) \times (1 - MR_{12} \\ & \times MR_2 \times MR_1 \times MR_0)\big)\big] \times R_{MR_7} \end{aligned} \tag{5}$$

In this way, the reliability of all paths within an optical router can be calculated through the rules of RBD model (i.e., series, parallel, and complex paths) [9, 17].

4.3 Optical Router Reliability

Once we have the reliability of all paths within an optical router, the reliability of the router can be determined through the following definition:

Definition 1: The reliability of an optical router can be considered as the minimum reliability of its operational paths.

Operational paths within a router are those utilized under the adopted routing mechanism. As an example, under the XY routing mechanism, in a router, some turns like North-to-East, North-to-West, South-to-East, and South-to-West do not happen. Consequently, under the XY routing protocol, these paths do not affect the reliability of an on-chip router. According to the above definition, the reliability of an optical router with n different paths can be calculated as follows:

$$R_{Router} = min\{R_i w_i \mid i = 1, 2, ..., n\} \tag{6}$$

$$\begin{cases} w_i = 1 & \text{if path index } i \text{ is operatioal} \\ w_i = 0 & \text{otherwise} \end{cases}$$

where, R_i is the reliability of path i while n represents all different paths available from each port to another port in an optical router.

4.4 PNoC Reliability

The reliability of the whole PNoC is calculated in this step. Each optical network consists of several optical routers which are connected to each other through waveguides. The optical streams are transmitted from each source node to the destination node by traversing several of these optical routers. The reliability of a PNoC can be determined through the following definition:

Definition 2: The reliability of a PNoC can be considered as the minimum reliability of its different optical routers in the architecture through a specific task mapping and routing algorithm.

In each PNoC, there are several optical routers which transmit optical streams to run an application. Obviously, in this case, the reliability totally depends on the mapping strategies and also the efficiency of routing algorithms. According to these assumptions, the reliability of a PNoC can be calculated as follows:

$$R_{PNoC} = min\{R_j \mid j = 1, 2, ..., m\} \tag{7}$$

where R_j stands for the reliability of an optical router and m represents the number of optical routers in the structure of each PNoC.

4.5 Extension to 3D Network

The proposed approach can be adapted to 3D optical routers [11, 27]. In these networks, there are several vertical waveguides through silicon substrate for conducting the optical data stream through different 3D-stacked network layers. The failure rate of the vertical links can also be measured and the reliability of network will be calculated through our proposed method from MR level to PNoC level.

5 EXPERIMENTAL RESULTS

In this section, the experimental results are reported in two categories, i.e., router level and network level. For the router level analysis, six traditional optical routers (i.e., Crux, OXY, ODOR, Crossbar, Cygnus, and optical router) [10] are used as a benchmark for the reliability comparison. At the network level, although several synthetic traffic patterns are developed in the simulator, the uniform pattern is applied for the reported results. Also, Mesh and Torus topologies as traditional on-chip networks along with the XY routing algorithm with two different sizes of 4×4 and 8×8 are applied. In both levels, the reliability of MR is considered as the number of nines (i.e., from 0.9 to 0.999999999). In addition, two scenarios have been evaluated. In the first scenario, all MRs are considered fault-free elements in optical routers and also the whole PNoC. In the second scenario, one or several faults are injected randomly into the structure of routers or the network. In this scenario, ten different fault locations are randomly selected for each fault-injected simulation value, and the average result is reported. It should be considered that the reliability value of the faulty MR is considered pessimistically as 0 in our simulations.

5.1 Router Level

Figure 4 illustrates the effect of MR reliability on the reliability of six well-known optical routers and also the effect of faulty MRs. As it can be concluded from Figure 4a, ODOR and Crossbar has the best and the worst reliability values among all optical routers for different MR reliability values. Furthermore, the experimental results show that the MR reliability values of more than 0.9999 do not have a notable effect on the router reliability. Figure 4b depicts the effect of faulty MRs on the reliability of the Crux optical router with twelve MRs in its architecture [10]. Obviously, increasing the number of faulty MRs in the structure of an optical router has a considerable negative effect on the reliability parameter.

5.2 Network Level

Figure 5 show the MR reliability impact on the reliability parameter of an optical network. In this direction, Figure 5a shows that the Mesh topology offers better reliability than the Torus topology in the same network size. Moreover, the network reliability is decreased significantly by increasing the network size. Figure 5b proves that increasing the number of faulty MRs has not a notable impact on the optical network reliability due to existing various optical paths in each optical network. Just like the router level experimental results, in this level, the network reliability values have not changed significantly for MR reliability values bigger than 0.9999.

6 CONCLUSION

Although silicon photonics is a promising solution for the next generation of on-chip networks, there exists some critical concerns about its reliability. In this paper, a Python-based high-level and user-defined simulator is introduced for the reliability evaluation of optical networks-on-chip. At first, the basic idea of the paper which is the analytical modeling of the reliability parameter in different four levels of abstraction has been discussed. Then, the RAP-NoC simulator is introduced and several experimental results in the router level and also the network level are reported. In the future work, we intend to expand the simulator for different network topologies, optical router architectures, real-world benchmark applications and remove other limitations. We also extend the idea of the paper for reliability measurement of 3D-stacked optical on-chip networks.

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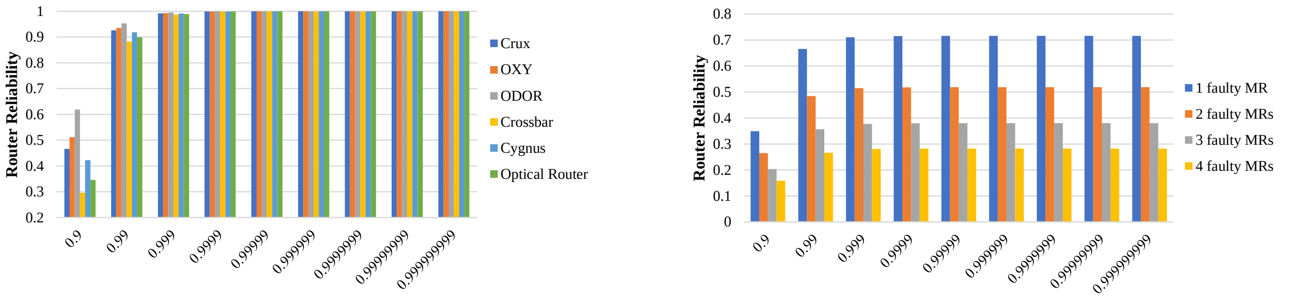
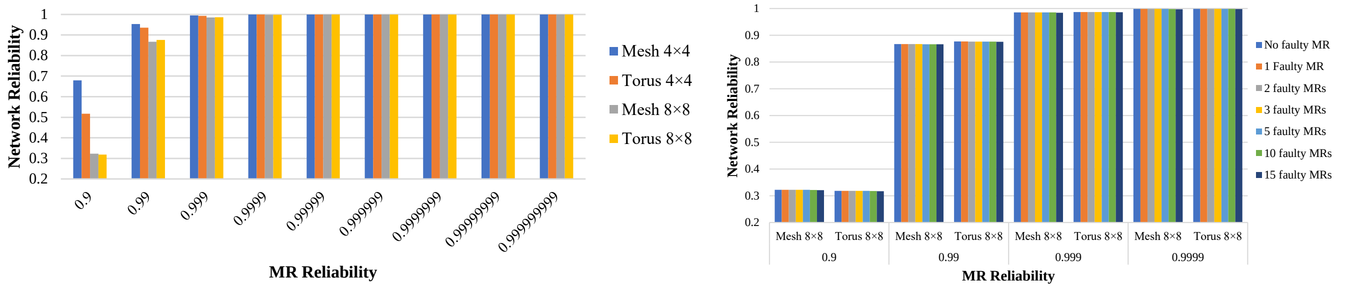


(a) Fault-free scenario **(b) Multiple-faults scenario**

Figure 4: The effect of MR reliability on the reliability of optical routers



(a) Fault-free scenario **(b) Multiple-faults scenario**

Figure 5: The effect of MR reliability on the reliability of optical networks

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