Machine learning-based dynamic reconfiguration algorithm for reconfigurable NoCs

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\textbf{Abstract:} Hybrid optical-electro Network-on-Chip (HOE\textsubscript{NoC}) is a disruptive technology that can provide high bandwidth and low latency for global communication. However, optical links suffers with a problem of large static power consumption in network. For different applications, traffic distribution in space and time may differ largely. Therefore, it is necessary to dynamically provide optical link bandwidth to network for higher power efficiency under all traffic distribution. In this paper, we propose a machine learning-based dynamic reconfiguration algorithm for reconfigurable NoCs (RH\textsubscript{OE}\textsubscript{NoC}) to reduce the static power. With machine learning prediction technique, we reconfigure the optical nodes dynamically to adapt different traffic demands while maintaining higher performance. Experimental results shown that as compared to electronic network latency has been reduced by 51\%, while throughput has been improved by 14\% for 64 node network architecture and energy consumption has been reduced by 26\%. We have also compared RH\textsubscript{OE}\textsubscript{NoC} with HOE\textsubscript{NoC} without reconfiguration, results show that static energy consumption has been reduced by about 28\%.

\textbf{Keywords:} reconfiguration, machine learning, RH\textsubscript{OE}\textsubscript{NoC}

\textbf{Classification:} Integrated circuits

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1 Introduction

Hybrid electro-optical NoC (HNoC) has recently been proposed to solve the problem of large scale interconnection. Which fully exploits the higher bandwidth and lower delay features of optical links and preserve higher flexibility alongwith low cost of electrical links [1, 2]. Ye et al. [3] has proposed a torus-based hierarchical optical-electronic NoC architecture THOE. Vantrease et al. [4] proposed a cluster-based optoelectronic hybrid topology.

Although HNoC has significant advantages in terms of delay and bandwidth, there are several challenges [5, 6], especially in terms of power consumption. Different from ENoCs which consume large dynamic power, static power consumption induced by external laser and microring resonators (MRRs) tuning dominate the power budget of ONoCs. In order to reduce static power, RW Morris et al. [7] proposed an energy-efficient and reconfigurable NoC. To maximize performance, they also proposed an efficient reconfiguration algorithm that dynamically reallocates channel bandwidth by adapting to traffic fluctuations. Li Zhou et al. [8] proposed PROBE: Prediction-based Optical Bandwidth Scaling for Energy-efficient NoCs to reduce the static power consumption.

Our previous work has proposed method to solve static power consumption. Yan et al. [9] has proposed a novel non-cluster based hybrid electro-optical network architecture, in which Mesh topology of electronic NoC is used alongwith an auxiliary optical NoC is built for the global communication speed up. However, it has not yet solved the issue of large static power consumption when the network load is low. In optical networks, the laser is still turned on even under low network
traffic that consumes unnecessary static power. Due to different applications, the global communication and local communication requirements have different spatio-temporal distribution characteristics, network traffic is often unbalanced. It is necessary to dynamically reconfigure the optical nodes so that the network can provide sufficient bandwidth under higher load, while consuming reasonable power under low load.

This paper first introduces a reconfigurable based hybrid electro-optical network architecture (RHOE.NoC), which is an improvement to our previous work. In addition to that, we propose a machine learning-based dynamic reconfiguration algorithm to keep the static power low. Through the statistical analysis of the load of the network in the previous period, the traffic at the next moment is predicted and some optical nodes are dynamically shut down or opened according to the predicted value to meet performance requirements, thereby realizing dynamic reconfiguration and reducing static power consumption.

2 Architecture of RHOE_NoC

We initially discuss the design of RHOE.NoC architecture, due to different applications, communication load of each optical and electrical interconnection node have large differences, that leads to low utilization of the optical network and cause more static power consumption. Therefore, in the case of different communication loads, it is necessary to dynamically reconfigure the optical nodes to reduce the power consumption of the network. Our proposed RHOE.NoC topology design follows the following principle:

(1) After an optical node is shut down due to a reconfiguration process, its adjacent resource nodes can find alternative optical nodes for global communication and must not increase the overhead significantly, incurred due to optical interconnect global communications.

(2) The reconfiguration operation of a single optical node should not affect the network connectivity between other optical nodes.

(3) Minimize the impact of reconfiguration process on communication of resource nodes to avoid sharing of topological reconfiguration information in a wide range and reduce reconfiguration overhead.

2.1 Minimum number and optimal layout

To satisfy the design principle (1), it can be achieved by increasing the redundancy of the optical nodes. For instance, any resource node at least $r_{\text{min}}$ (Minimum optical node number) optical nodes can be found within $h_{\text{max}}$ (Manhattan Distance). Since the layout and numbers of optical nodes have a great influence on the communication performance of the topology, we use the Integer Linear Programming (ILP) method to solve the minimum number of optical nodes and the optimal layout under constraint conditions [10]. The optimized layout should satisfy the following conditions:

(1) Within a specified number of hops, any resource node can find at least 2 optical nodes.

(2) To ensure performance, number of optical nodes should be as small as possible.
(3) After the number of optical nodes is determined, number of optical nodes that each resource node accesses within a specified hop count is as many as possible.

CPLEX, ILP software solver, is utilized to find the minimized number and optimal layout of optical nodes. We set $h_{\text{max}} = 2$ and $r_{\text{min}} = 2$, optimization results show that for $8 \times 8$ mesh network, there are at least 14 optical nodes. The optimal layout of the optical nodes in $8 \times 8$ mesh network is shown in Fig. 1(a). For reconfiguration, every common node without an optical node can find at least two optical nodes within two hops, to avoid increasing overhead of global communication due to closure of optical node. For example, when the optical node 11 is closed because of the reconfiguration operation, the resource node 19 can still find the optical node 17 and 28 for global communication within 2 hops.

![Fig. 1. (a) placement of optical nodes (b) Reservation-assisted SWMR (R-SWMR)](image)

### 2.2 Nanophotonic crossbar implementation for reconfiguration

According to the design principle (2) and (3), a Reservation-assisted Single Write Multiple Read (R-SWMR) crossbar is an appropriate choice. R-SWMR is shown in Fig. 1(b), all detectors are disabled by default. When the optical node needs to send a data packet, first, the transmitter broadcasts a reservation signal including the destination node and the packet length information to all the detectors on the waveguide and then only the destination optical node will allow corresponding detector to receive data for respective data channel.

Based on the SWMR optical cross-switch, all optical nodes are one-hop communication. Therefore, when a single optical node is closed by reconfiguration, it will not affect the communication of other optical nodes. When the transmitter is reconfigured, it only needs to share the reconfiguration information among resource nodes in its communication domain. According to whether the optical nodes are in their communication domain are closed, each resource node dynamically decides which communication nodes in the communication domain to carry out global communication. When the detector is reconfigured, it is only necessary to share the reconfiguration information among the resource nodes in its communication domain. After the nodes receive the topology reconfiguration information, the request is initiated to the nearest optical node through the domain and the global communication for the target node will be received and forwarded through the adjacent optical node. Both transmitter and detector reconfiguration can avoid topological information sharing in the whole network.
2.3 RHOE_NoC architecture

RHOE_NoC can now be designed using the building blocks presented till now, its 3D architecture is shown in Fig. 2. RHOE_NoC consists of an electrical layer and an optical layer. Each layer is connected through a 3D technology via TSVs. The electrical layer uses a 2D Mesh to provide electrical connections for any two adjacent nodes. The optical layer which mainly consists of optical nodes and waveguides, the optical nodes are connected by R-SWMR buses, so all optical nodes are one hop communication and it will not affect the communication of other optical nodes if the node is closed by reconfiguration.

![3D RHOE_NoC Architecture](image)

Fig. 2. 3D RHOE_NoC Architecture

3 Machine learning-based dynamic reconfiguration algorithm

3.1 Traffic statistics and prediction

The dynamic reconfiguration algorithm of optical node performs a reconfiguration operation according to the load state of the optical interconnect node. Based on existing research, the network load can be determined by link utilization $L^i_u$ and average buffer utilization $B^i_u$, defined by equations (1) and (2), respectively. In fact, the data traffic sent and received by optical nodes is not necessarily symmetrical, so the transmitter and receiver of the optical node will be managed separately.

\[
L^i_u = \frac{\sum_{n=1}^{W} E^i_i(n)}{W} \tag{1}
\]

\[
B^i_u = \frac{\sum_{n=1}^{W} B^i_{occupy}(n)/B_{size}}{W} \tag{2}
\]

Where $W$ is the reconfiguration window, $E^i_i(n)$ counts the link communication events for node $i$, $E^i_i(n)$ is 1 if flit traverses the link in cycle $t$, or is 0 if no flit is transmitted on the link for a given cycle. $B^i_{occupy}(n)$ is the number of buffer occupied at each time $t$, and $B_{size}$ is the total number of buffers for the given link.

When network traffic fluctuates dynamically due to short-term bursts, the buffer may fill up immediately. This can adversely affect the dynamic reconfiguration algorithm, resulting in fluctuations in bandwidth allocation. In order to prevent the fluctuation of time and space traffic from affecting performance, we use the network traffic data collected at the current time to take a machine learning algorithm to predict the network’s buffer $B_{ip}$ at the next moment. In order to achieve such prediction, we adopt $L^i_u$ and $B^i_u$ to track the network traffic load and take
measurements every cycle by using hardware counters. Each hardware counter is associated with an optical transmitter and receiver and to monitor the traffic utilization and provide the link and buffer information to a local reconfiguration controller (RC) which is located at each node. The corresponding relationship between buffer occupancy and time can be established as a linear regression model, the formula is as follows:

\[ Y = \beta_1 + \beta_2 X + e \]  

(3)

Where X is the explanatory variable (predictor), \( \beta_1 \) is the intercept of Y, \( \beta_2 \) is the slope, e is the random error, and Y is the response variable (predicted variable).

For the one-dimensional linear regression model, as shown in the Fig. 3, assume that n groups of observations \((X_1, Y_1), (X_2, Y_2), \ldots, (X_n, Y_n)\) are obtained from the population. For these n points in the plane, an infinite number of curves can be used for fitting. In order to make the sample regression function fit the set of values as well as possible, the observation value \( e_i \) of each group should be as small as possible to minimize the total fitting error (the total residual error). In this paper, the Ordinary Least Square method is used to determine the best-fit curve.

In order to make the prediction more accurate, we combine \( B_{iq} \) with statistical data. The transformation formula is as follows:

\[ B_{iu}^{'} = \frac{\sum_{n=1}^{W} B_{occupy}^i(n)/B_{size} + B_{iq}/B_{size}}{2} \]  

(4)

3.2 Algorithm implementation

Based on the statistical prediction of network link utilization and average buffer utilization, we propose a dynamic reconfiguration logic algorithm. After each W, each counter will gather its link statistics and send it to its RC for analysis. Next, each RC\(i\) will evaluate the traffic load conditions for each optical node depending on the \(L_{iu}^{'}\) and \(B_{iu}^{'}\) and will classify it into three different grades: Under-Utilized, Normal-Utilized and Over-Utilized. If optical node \(i\) is Under-Utilized, RC\(j\) will send request information to other RCs in the communication domain to obtain the availability of the optical nodes, and closes \(i\) if any optical node is available. On the other hand, if \(i\) is Over-Utilized, and there is optical node has been closed before in its communication domain, open it. If \(i\) is Normal-Utilized, keep it without reconfiguration. Table I shows the reconfiguration algorithm. We set \(L_u(low) = 0.1, L_u(congest) = 0.5\) and \(B_u(congest) = 0.5\).
4 Experiments and evaluation

We implemented three networks in cycle-accurate NoC simulator JADE [11], including mesh based electronic network (E.Mesh), our proposed without reconfiguration (NRHOE.NoC) and with reconfiguration (RHOE.NoC). Average latency, throughput and power efficiency of each network have been evaluated and compared according to following simulation parameter listed in Table II. Considering the spatio-temporal variability of different applications, we improve the random traffic pattern and dynamically adjust the packet injection rate at intervals. For example, increasing the injection rate at low injection rate, decreasing the injection rate when it is high, and realizing the dynamic change of network load.

| Table I. | Reconfiguration algorithm |
|---|---|
| Step 1: | Wait for Reconfiguration window, W |
| Step 2: | For all optical nodes i, each hardware counter calculate $L_u^i$ and $B_u^i$ in the current W and sends data to RC$_i$ |
| Step 3: | Each RC$_i$ performs load determination and reconfiguration decisions on the transmit and receive links respectively:  
  - Under-Utilized: Need to turn off the corresponding transmitter or receiver  
  - Normal-Utilized: Without reconfiguration  
  - Over-Utilized: Need to open adjacent optical nodes that were closed |
| Step 4: | If i is Under-Utilized or Over-Utilized, send request information to other RCs in the communication domain |
| Step 5: | Check whether there are available or closed optical nodes |
| Step 6: | If i is Under-Utilized and there is availability optical node, close i. If i is Over-Utilized and there is closed optical node, open it |
| Step 7: | The reconfigured optical node sends topology reconfiguration information to all nodes in its communication domain. After receiving the message, each node initiates a join request to its nearest optical node communication domain |
| Step 8: | Reconfiguration completed, goto Step 1 |

| Table II. | Simulation parameter |
|---|---|
| Topology Size | 64 nodes |
| Buffer Depth | 16 flits |
| Flit Width | 128 bit |
| Packet Size | 4 flits |
| ONI Buffer | 32 flits |
| Clock Frequency | 2.5 GHz |
| Optical Baud Rate | 10 Gbps |
| Traffic Pattern | Improved uniform random |
| Simulation Time | 5000 cycles |

- **Latency**

Latency comparison result under 64 nodes topology size is shown in Fig. 4(a). It is observed that, as compared to E.Mesh network, latency of the RHOE.NoC has been greatly reduced, at most 51% reduction has been observed. NRHOE.NoC has
better performance than RHOE,NoC, at most 54% reduction has been observed. That is reconfiguration increased a part of delay.

- **Throughput**

Throughput comparison result under 64 nodes topology size is shown in Fig. 4(b). E.Mesh get saturated at the packet injection point of 0.35. Both NRHOE,NoC and RHOE,NoC have extend the point to 0.4. Further the saturation throughput has been improved by 14%, compared to E.Mesh under the same topology size.

- **Power Efficiency**

The power consumption of the laser source is determined by the insertion loss of the optical transmission path, the main parameters we used are listed in Table III. Based on insertion loss, the power consumption of the laser source is calculated from Design Space Exploration of Network Tool (DSENT) [12]. Power efficiency comparison result under 64 nodes topology size is shown in Fig. 4(c). Compared to the E.Mesh, the proposed RHOE.NoC has reduced the energy consumption by about 26% when the network load gets saturated, and much better than NRHOE,NoC, especially when the network load is light, at most 28% reduction has been observed. Due to optical links incur large static power consumption, NRHOE,NoC shows low power efficiency, even worse than E.Mesh, when the injection rate is under 0.35.

Although RNHOE,NoC shows minimal latency and higher throughput as compared to E.Mesh, power efficiency of RNHOE,NoC is extremely worse than RHOE,NoC. It is shown that optical network can produce huge static power consumption, even for low channel utilization. Since, RHOE,NoC can reduce

**Table III.** Power parameter

| Component          | Value  |
|--------------------|--------|
| Laser Efficiency   | 0.25 dB|
| Couple             | 1 dB   |
| Through Loss       | 0.01 dB|
| Drop Loss          | 1 dB   |
| Waveguide Bending  | 0.005 dB|
| Waveguide Loss     | 0.1 dB/mm|
| Waveguide Crossing | 0.05 dB|
| Optical Receiver   | 1 dB   |

**Fig. 4.** Comparison of latency, throughput and power efficiency
the static power by dynamically reconfiguring the optical routers, it has the best power efficiency performance.

5 Conclusion

In this paper, we present a machine learning-based dynamic reconfiguration algorithm for reconfigurable NoCs, which reduces the static power consumption of optical network through dynamic reconfiguration based on past network traffic and machine learning. Experimental comparisons show that, compared with E_Mesh and NRHOE_NoC, our proposed architecture with reconfiguration not only reduces power consumption, but also improves latency and throughput performance. Therefore, it effectively solves the problem of huge static power consumption in hybrid Optical-Electronic NoCs.

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