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RWADMM: Routing and Wavelength Assignment for Distribution-based Multiple Multicasts in ONoC

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***Abstract*—Multicast communication widely exists in cache coherence protocols for Chip Multiprocessors (CMPs) in various parallel applications. The system performance can be significantly deteriorated if no effective routing method is supported for multicast. Optical Network-on-Chip (ONoC) has become the mainstream for CMPs design because of its unique merits of high bandwidth density and low energy consumption. Although existing multicast routing and wavelength assignment methods have improved system performance, such as reducing packets delay and wavelengths, they only consider one multicast request in their design. In this paper, we target on dealing with multiple multicasts problem regarding to fully utilizing the network resources. We propose a Routing and Wavelength Assignment method for Distribution-based Multiple Multicasts, RWADMM, in which routing and wavelength assignment are determined by the distribution of the nodes involved in the multicasts. We first derive 4 Routing Theorems for particular scenarios according to the distribution of source and destination nodes, which need only a minimum of one wavelength. Then, a Group-partitioning routing algorithm for general cases is proposed by decoupling all multicast nodes into several small groups and each group can be routed by one of the 4 Routing Theorems. As a result, the number of wavelengths is equal to the number of groups. Simulation results show that our proposed scheme outperforms other routing methods in terms of the number of wavelengths used, especially being effective in the case of large number of multicast requests.**

***Index Terms*—Optical Network-on-Chip, Multiple multicasts, Distribution-based, Routing and Wavelength Assignment**

I. Introduction

In the past decade, one important developing trend in programmable chips is the many-core Chip Multi-Processors (CMPs), in which many cores are integrated on a single chip to improve performance, e.g.72-core Tilera TILE-Gx, 192-core CSX700, 256-core Kalray MPPA and 4096-core IBM TrueNorth [1][2][3]. As CMPs play a critical role in system performance and energy efficiency, the design of efficient and scalable on-chip communication system is becoming more and more important. As a result, Network-on-Chip (NoC) has been proposed as a promising solution to handle the interconnect parallelization provided by multicore systems. As thousands of cores will fit on one chip [4], the inherent problems of NoC, such as signal reflection, crosstalk and electromagnetic interference, will deteriorate the performance of Chip Multiprocessors.

In order to overcome drawbacks of NoC, Optical Network-on-Chip (ONoC) [5][6], a chip-scale inter-core optical network has been proposed. By inserting silicon nanophotonics into on-chip interconnection networks, ONoC can utilize the unique merits of optical communication (e.g. high bandwidth density, immunity to electro-magnetic effects) to improve network performance. Compared with the electrical interconnect network, ONoC has many advantages: ***i***) High bandwidth by using WDM (Wavelength-Division-Multiplexing) which enables multiple optical signals with different carrier wavelengths to transmit along a single waveguide [7][8]; ***ii***) Low energy consumption by using end-to-end bufferless communication; ***iii***) CMOS compatibility to increase readability because silicon photonics offer compatibility with standard CMOS fabrication process. Although ONoC boosts low-power and high-throughput communication, it still has some design challenges that limit the performance of ONoC, such as limited chip area, limited number of wavelengths (e.g., Preston, et al. showed that a maximum wavelength limitation of 62 when assuming 10 Gbps data rate [9]), reliability constraint, etc. In order to design a high-performance and scalable ONoC, these challenges need to be addressed.

Multicast communication, where packets from one source node need to be delivered simultaneously to multiple destinations, widely exists in a number of applications of CMPs, such as replication [11], clock synchronization [12] and multi-reading programs in distributed shared memories. Previous analyses[13][14] have shown that multicast traffic contributes to a large percentage of the total traffic in various cache coherence, token coherence and directory-based protocols. Fig.1 shows the percentage of multicast packets for a set of PARSEC benchmark applications in a 64-core system [15], which were running with the Token Coherence and HyperTransport respectively. We can see that the multicast traffic takes a large percentage in each application. In Token Coherence, it accounts for nearly 50% of the total traffic. Without hardware support, a multicast message can be replicated to multiple copies and sent to all destinations separately (termed as unicast-based multicast) [16]. This method will result in performance inefficiency, such as congestion and packets delay. In addition, redundant packets will be transmitted on the network and consume more power which is a significant consideration for CMPs design. Therefore, efficient multicast support has a large impact on the performance of chip multicast systems. In ONoC, the routing algorithm as a multicast support plays a critical role because it determines the directions of the transmitted packets. More importantly, the selection of routing schemes will have significant impacts on

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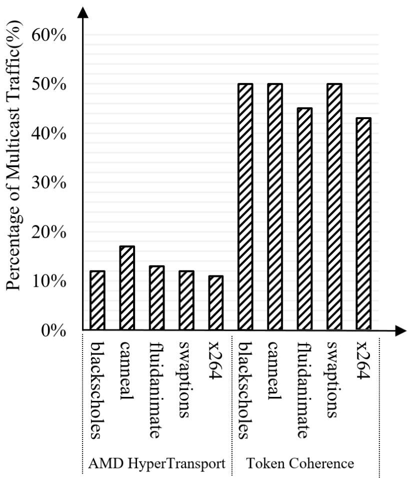


Fig. 1. Multicast ratios for a set of standard PARSEC benchmark applications for Token Coherence and HyperTransport in a 64-core system[15]

performance, power consumption and transmission latency of the on-chip system. Currently, multicast routing methods can be classified into two categories: tree-based [17][18] and path-based method [19][20] (see detailed explanation in Section II). Although these methods have improved network performance in different aspects, they only consider one multicast request (one source node and multiple destination nodes that originate from this source).

In this paper, we investigate the routing and wavelength assignment solutions to accommodate multiple multicast requests, and design an efficient algorithm to achieve the minimum number of wavelengths.To the best of our knowledge, there has been no effective routing and wavelength assignment method focusing on multiple multicast requests. The main contributions can be summarized as follows: (1) We give the definition of the Routing and Wavelength Assignment problem for Multiple Multicast requests in ONoC. (2) We design a routing and wavelength assignment algorithm for special multicast cases and derive 4 Routing Theorems and each theorem only uses one wavelength. (3) We design a group-partitioning routing algorithm for general cases in which the distribution of nodes is random.

The rest of the paper is organized as follows. Section II introduces related work and motivation. Section III presents the problem definition. Section IV gives the routing design algorithm for particular scenarios and general cases in detail. Section V evaluates performance through simulations. Finally conclusions are given in Section VI.

II. Related work and motivation

As multicast traffic extensively exists in various parallel applications, there have been several methods to improve the performance of multicast communication in ONoC. Path-based and tree-based methods are two major approaches used in ONoC. Although these multicast routing algorithms have been proposed for ONoC, most of them consider only one multicast request.

In tree-based methods [17][18], a packet is transmitted from the root (the source node) to individual leaves (all destinations) along the spanning tree. In this method, the packet will be replicated at intermediate nodes, resulting in the blockage of messages. In [21], authors have proposed a hardware support approach named VCTM (Virtual Circuit Tree Multicasting), which uses a virtual circuit table to construct the multicast tree incrementally by sending a unicast packet to the next closest multicast destination. This method can achieve low latency for packets. But in several cases, it is not power efficient due to maintaining a table at every switch to store a virtual tree. Another tree-based multicast routing schemes are called Optimize Tree (OPT) and Left-xy-Right-Optimized Tree (LXYROPT), which were designed based on VCTM [22]. OPT tries to optimize the multicast tree by using less links. It uses the west-first turn model, which could avoid deadlock. LXYROPT partitions destinations into two subsets. For the first subset that contains destinations left to the source node, XY routing method is used to construct the multicast tree. For the destinations on the right of the source node, west-first turn model is used. These two algorithms both try to minimize the number of links in the multicast tree to achieve low multicast latency and power consumption. Switch Tree-Based Algorithm (STBA) [23] is a newly proposed multicast routing method which supports multicast tree construction on reconfigurable mesh NoC. It uses switches in a reconfigurable network to construct a minimal spanning tree using the Kruskal minimal spanning tree algorithm and west-first routing algorithm.

In path-based routing methods, one message is sent along a fixed Hamiltonian path. Packets do not replicate at the intermediate node along the path, which will decrease message contentions. However, all packets will visit every switch, which will suffer from long latency. In order to overcome this shortcoming, a destinations-partitioning method has been derived. The popular partitioning methods are Dual-Path (DP), Multi-Path (MP) and Column-Path (CP) [24][25]. DP partitioning is a base method that destinations are divided into two parts. One part contains destinations that have higher labels than the source node, while the other has remaining destinations. A packet will be sent along ascending or descending order respectively according to the label of every destination. MP partitioning algorithm has been proposed by dividing destinations into 4 parts based on DP method. In Column-Path (CP) partitioning method, destinations are divided into more number of subsets depending on the number of vertical columns. In this method, each packet will be transmitted in a shorter path compared with DP and MP approaches, so it can achieve a high level of parallelism and reduce the network latency. However, this scheme does not guarantee balanced partitions and more packets will be delivered to the network. DP, MP, CP partitioning methods are supported by a deterministic routing in which the routing path is predetermined, so they lack flexibility and will increase network latency under heavy traffic loads. Therefore, many adaptive algorithms have been proposed. Compared with the deterministic algorithm, the adaptive routing method does not give a fixed path in advance to transmit packets. The packet may adjust the path according to the network state. In [26][27], adaptive routing algorithms called HAMUM and HOE were proposed respectively, which can achieve the high degree of adaptiveness by prohibiting the minimum turns using odd-even algorithm.

As far as we know, these methods mainly focus on one multicast request. When there are multiple multicast requests in ONoC simultaneously, these methods are very likely to cause high contentions on both routing and wavelength resources. Fig.2 gives a motivation example by showing a multicast traffic with two multicast requests in a 4×4 ONoC. We use the multicast routing methods which were designed for single multicast request to this example. Fig.2(a) shows the unicast-based routing scheme, where source nodes 10 and 7 generate 4 copies of packets respectively and transmit each copy to the destination with 3 wavelengths. Fig.2(b) presents the tree-based routing scheme. Packets will be sent along two spanning trees from the sources to the destinations using 2 wavelengths. Fig.2(c) demonstrates the path-based routing scheme which uses 2 wavelengths. These existing routing methods only consider single multicast request, which do not consider the optimization of the multiple multicasts problem in terms of utilization of network resources (wavelengths, energy consumption, and etc.). It may be feasible if the network resources are sufficient with a small number of multicast requests. When the network resources become insufficient and the number of multicast requests increase, these unoptimized methods are not efficient enough with the possibility of using more wavelengths and consuming more energy. To deal with this problem, it is necessary to consider the combination of the group of multiple multicast requests as a whole and design a routing algorithm from the global perspective. At present, this problem has not been well studied. So, the main objective of this paper is to design an efficient routing and wavelength assignment algorithm to accommodate multiple multicast requests using minimum wavelengths. Fig.2(d) shows that using our proposed routing algorithm, only one wavelength is needed.

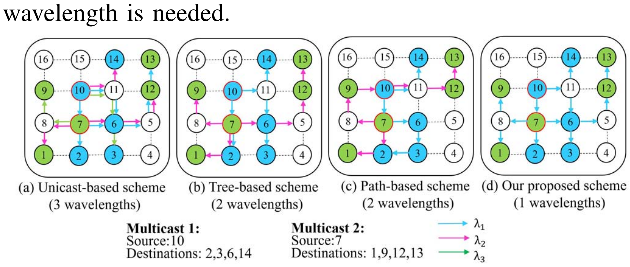


Fig. 2. Examples of multiple multicast routing schemes on a 4×4 ONoC

III. Problem Description for Multiple Multicasts in ONoC

A. Preliminaries

We first introduce some general concepts and terms used in this paper. A path in ONoC is a set of links which is established by transmitting a packet from a source node to a destination node. Multicast communication involves the transmission of packets from one source node to multiple destination nodes, so a multicast path contains paths established between one source node and multiple destination nodes of a multicst request. When there are more than one multicast requests on chip simultaneously, it is called Multiple Multicasts. If any paths which belong to two multicast requests share one or more links, they conflict with each other and two wavelengths are needed. For the topology, we use mesh in this paper, which is most commonly used topology for ONoC [28]. Each node in $n \times n$ mesh-based ONoC is indexed by the coordinate location (x_i, y_j) $(0 \leq i \leq n-1,\ 0 \leq j \leq n-1)$.

The interconnection of an ONoC can be represented by an undirected graph G=(V, E), where V is the set of nodes and the total number of nodes is N $(\left|V\right| = N)$. E is the set of edges and the total number of edges is L $(\left|E\right| = L)$. We denote the set of multicast requests as P=$\{p_1, p_2, \ldots, p_M\}$, where M is the total number of multicast requests and p_t is the t^{th} multicast request. p_t can be represented by p_t=$(s_t, \mathbf{D}_t)$ $(1 \leq t \leq M)$, where s_t is the source and $\mathbf{D}_t$ is the destination set of p_t.

B. Problem Definition

As far as we know, the routing and wavelength assignment problem for multiple multicasts in ONoC (RWA-MM-ONoC) has not been formally defined in previous research. We define this problem as follows:

Definition (RWA-MM-ONoC): Given an Optical Network-on-Chip and a set of multicast requests, RWA-MM-ONoC problem is to find routes and assign proper wavelength(s) for each multicast request, so that the total number of wavelengths is minimized.

RWA-MM-ONoC can be decoupled into two subproblems, **a)** Routing problem for Multiple Multicasts (R-MM-ONoC) and **b)** Wavelength Assignment problem for Multiple Multicasts (WA-MM-ONoC). R-MM-ONoC and WA-MM-ONoC have a close relationship and they interact with each other. If the traffic pattern in ONoC is known in advance, a routing scheme is first decided followed by wavelength assignment. This scheme is called static RWA, in which the routing scheme will not be changed during the wavelength assignment. On the other hand, the routing scheme can adjust flexibly according to the state of wavelengths assignment, which is called adaptive RWA. Adaptive routing could not guarantee the order of packets and may increase both design complexity and communication latency, so our work in this paper is a static RWA scheme. We first identify special scenarios for RWA-MM-ONoC with corresponding routing theorems which only need one wavelength to realize a set of multicast requests. Then, we extend these special scenarios to solve the general cases of RWA-MM-ONoC by partitioning one multicast request into multiple multicast sub-requests.

IV. Multiple Multicasts Routing Design for Mesh-based ONoC

Unlike the single multicast request, RWA-MM-ONoC attempts to deal with routing and wavelength assignment problem for a set of multicast requests. If there is only one multicast request in the network, the main focus is on satisfying the request itself. But for multiple multicast requests in ONoC, the objective should not only try to deal with an individual request but also consider the whole set of multicast requests as a combined problem. In this section, we first propose a routing algorithm which can identify request patterns for mesh-based ONoC and then extend this routing algorithm to general cases.

A. Basic Routing Schemes

XY, YX, XYX and YXY routing schemes are four basic routing schemes that are used in our proposed routing algorithm. We give the detailed explanation about these four routing schemes as follows:

XY routing: In this scheme, a packet which is sent from a source node goes along the x-axis first and turns to the y-axis until the packet reaches the destination node. For example, (x_s,y_s) and (x_d, y_d) are coordinates of the source and destination node. At first, a packet from the source (x_s,y_s) starts to go along the x-axis. When the packet arrives the intermediate node (x_i,y_s) which has the same x-axis coordinate with the destination node (x_i=x_d), the packet turns around and goes along the y-axis until it reaches the destination node (Fig.3(a)).

YX routing: In this scheme, a packet which is sent from a source node goes along the y-axis first and turns to the x-axis until the packet reaches the destination node (Fig.3(b)).

XYX routing: In this scheme, a packet which is originated from a source node goes along the x-axis first. When this packet reaches a column in which all links are available, it turns to the y-axis and goes along the y-axis until it gets to the intermediate node which has the same y-axis coordinate with the destination node. At last, the packet arrives the destination node along the x-axis again. Paths in this scheme are along x-axis, y-axis, x-axis sequentially, so we call this scheme XYX routing scheme (Fig.3(c)). XY routing scheme is the special case of XYX routing scheme with the last hop to the x-axis is zero.

YXY routing: In this scheme, the paths are along y-axis, x-axis, y-axis sequentially, so we call this method YXY routing scheme (Fig.3(d)). YX routing scheme is the special case of YXY routing scheme with the last hop to the y-axis is zero.

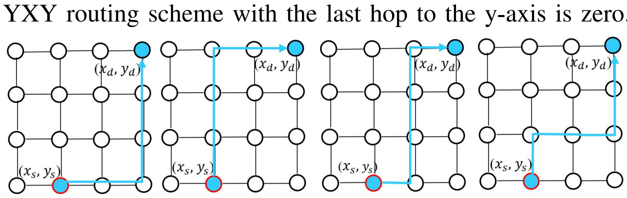


Fig. 3. 4 basic routing schemes in a 4×4 ONoC

B. Multiple Multicasts Distribution

A routing scheme is related to the distribution of source and destination nodes on the mesh network. The distributions of nodes on a mesh network can be grouped based on the following four criteria: same row, same column, different rows, different columns. Same row means all nodes have same y-axis coordinates and same column means all nodes have same x-axis coordinates. Different rows means all nodes have different y-axis coordinates, while different columns means all nodes have different x-axis coordinates. For multiple multicast requests, there are two kinds of nodes: source nodes and destination nodes. Each of them has these 4 types of distributions. If we combine distributions of source and destination nodes respectively, there are 4×4=16 particular distributions for multiple multicast requests in ONoC. Several of the 16 particular distributions have same features and they can merge with each other. Hence, we reduce the 16 distributions to 4 distributions. We call these 4 particular distributions 4 scenarios. Table I shows the four scenarios and we present the routing algorithm for each scenario in Section IV-C.

C. Theorem of routing scheme for particular scenarios

According to the distribution of source and destination nodes of multiple multicast requests, we propose a routing algorithm which selects a proper routing scheme from the basic routing schemes for each scenario using only one wavelength. Since the proposed routing algorithm highly depends on the locations of source and destination nodes, we call it Distribution-based Routing Algorithm. By analyzing the 4 scenarios, we find that only 2 basic routing schemes are needed: YXY and XYX routing. We derive the following routing theorems for these scenarios.

Theorem 1: For a set of multicast requests, if the source and destinations of any multicast request in the set do not share any columns with any other multicast requests of the set, YXY routing can be used to establish multicast paths for the set of multicast requests using only one wavelength.

Proof: Since any multicast request in the set does not share any columns with any other multicast requests, each column belongs to only one multicast request and the links of the column can be used by the multicast request exclusively. It can be also deduced that there are at most n multicast requests in the set. Since there are at most n multicast requests, we can assign one row to each request so that each multicast request has a dedicated row.

For any multicast request of the set, we can use the YXY routing via its dedicated row to find its multicast path that is non-overlapping with other multicast requests. The multicast path can be found as follows. First, from the column of the source, move in the Y-axis to find the dedicated row, then move in the X-axis of the dedicated row, find the column of each destination of the multicast request, and finally move in the Y-axis to reach the destination. Since the columns and the rows belong to the multicast request exclusively, the resulting multicast path will not overlap with the paths of any other multicast requests in the set.

Therefore, only one wavelength is needed for routing a set of multicast requests that satisfy the condition of this theorem. ■

Theorem 2: For a set of multicast requests, if any source does not share any rows with any other sources in the set and the destinations of any multicast request in the set do not share any columns with the destinations of any other multicast requests in the set, XYX routing can be used to establish multicast paths for the set of multicast requests using only one wavelength.

Proof: Since any source in the set do not share any rows with any other sources, each row belongs to only one multicast request and the links of the rows can be used by the multicast request exclusively.

Since the destinations of any multicast request in the set does not share any columns with the destinations of any other multicast requests, each column belongs to only one multicast request and the links of the column can be used by the multicast request exclusively.

For any multicast request of the set, we can use the XYX routing via its dedicated row to find its multicast path that is non-overlapping with other multicast requests. The multicast path can be found as follows. First, from the row of the source, move in the X-axis to find the column of each destination of the multicast request, and then move in the Y-axis to reach the destination. Since the columns and the rows belong to the multicast request exclusively, the resulting multicast path will not overlap with the paths of any other multicast requests in the set.

Therefore, only one wavelength is needed for routing a set of multicast requests that satisfy the condition of this theorem. ■

Theorem 3: For a set of multicast requests, if any source does not share any columns with any other sources in the set and the destinations of any multicast request in the set do not share any rows with the destinations of any other multicast requests in the set, YXY routing can be used to establish multicast paths for the set of multicast requests using only one wavelength.

The proof is straightforward. We can regard this distribution as the rotation for 90 degree of the network that satisfies the Theorem 2. Therefore, we can use YXY routing method for this scenario and only one wavelength is needed.

Theorem 4: For a set of multicast requests, if the source and destinations of any multicast request in the set do not share any rows with any other multicast requests of the set, XYX routing can be used to establish multicast paths for the set of multicast requests using only one wavelength.

We can also regard this distribution as the rotation of the distribution in the Theorem 1, XYX routing can be used for this scenario.

TABLE I
4 PARTICULAR SCENARIOS ACCORDING TO THE DIFFERENT DISTRIBUTION OF SOURCES/DESTINATIONS AND CORRESPONDING ROUTING THEOREMS

Destinations \ Sources	Different columns	Different rows
Different columns	Scenario 1	Scenario 2
Different rows	Scenario 3	Scenario 4

▦ YXY routing ▦ XYX routing

Table I shows the 4 particular scenarios and the Routing Theorems. For each scenario, only one wavelength is needed using the corresponding routing theorem. These 4 Routing Theorems provide us a principle to choose a routing method for the particular distribution of source and destination nodes. If the traffic pattern is given and belongs to one of the 4 particular scenarios (as shown in Table I), we can use the corresponding routing theorem to transmit packets by only one wavelength.

D. Group-partitioning Routing Algorithm for General Cases

The Distribution-based routing algorithm is useful for the particular scenarios because it is easy to implement and only needs one wavelength for each scenario. However, a general routing algorithm is still needed to process multiple multicast requests. In reality, the distribution of multicast nodes is random and it will be hard to classify all multicast nodes to one particular scenario. So, we can extend the distribution-based routing algorithm to solve general cases of RWA-MM-ONoC by partitioning one multicast request into multiple multicast sub-requests. If a multicast request is divided into multiple sub-requests, the source may send packets to the destinations using different wavelengths for the different sub-requests. Although it may increase power consumption, the decrease of wavelengths will offset the loss. Besides, there is no obvious influence on average packet delay in ONoC. Hence, this method is feasible.

The multiple multicast routing problem for general cases is equivalent to dividing all nodes of the multicast requests into minimum number of groups, each of which satisfies one of the four Routing Theorems. We propose a heuristic routing algorithm called Group-partitioning Routing Algorithm below for the multiple multicast routing problem.

The Group-partitioning Routing algorithm works as follows.

Step 1 Sort the multiple multicast requests in ascending order according to their number of nodes.

Step 2 Assign to the multicast requests unique priorities from high to low according to the above sorted order. The nodes in a multicast request inherit the priority of the multicast request.

Step 3 From the mesh network where the multicast requests reside, remove the nodes with the highest priority in each row (or column if the orientation of partitioning is column-based according to the rules below) and put them as one group.

Step 4 For any destination in the group, if its source is not included in the group, remove it from the group and put it back to the mesh network. A group is formed. For any source included in the group, if it still has some destinations left in the network, keep it in the mesh network as well.

Step 5 Repeat steps 3 & 4 until all nodes are removed from the mesh network.

According to the Routing Theorems, every group formed as above only needs one wavelength. Hence, the number of wavelengths used by the multiple multicast requests equals to the number of groups created by the Group-partitioning Routing algorithm.

In the Group-partitioning Routing algorithm, the orientation of partitioning in step 3 has two options: column-based and row-based. The column-based partitioning removes nodes column by column while the row-based partitioning removes nodes row by row.

Suppose $N_{i,row}$ is the number of multicast requests whose nodes are in the i^{th} row. Let $N_{max,row}$ be the largest number among $N_{i,row}$, where i=1,...n. Likewise, suppose $N_{i,column}$ is the number of multicast requests whose nodes are in the i^{th} column. Let $N_{max,column}$ be the largest number among $N_{i,column}$, where i=1,...n.

The orientation of partitioning is decided as follows:
(i) If $N_{max,row} > N_{max,column}$, use column-based partitioning;
(ii) If $N_{max,row} < N_{max,column}$, use row-based partitioning;
(iii) If $N_{max,row} = N_{max,column}$, use either column-based partitioning or row-based partitioning.

In step 3 of Group-partitioning routing algorithm, we can remove at least $N_{max,row}$ (or $N_{max,column}$) nodes using column-based partitioning (or row-based partitioning). When $N_{max,row} > N_{max,column}$, using column-based partitioning can remove more nodes than row-based partitioning. Likewise, when $N_{max,row} < N_{max,column}$, using row-based partitioning can remove more nodes than column-based partitioning. Since the objective of the Group-Partitioning Routing algorithm is to obtain minimum number of groups, selecting the proper orientation of partitioning can make the first derived group to contain as many nodes as possible. For (iii), using column-based or row-based partitioning has no difference so either way is fine but we use the row-based partitioning in our implementation.

An example is given to explain this partitioning method. We suppose there are M multicast requests and all nodes of the multicast requests are in a row ($N_{max,row} = M$, $N_{max,column} = 1$). Using column-based partitioning, we can remove one node in each column and all nodes can be removed from the mesh network once. Therefore, we can put all nodes in one group and only one wavelength is needed. If we use row-based partitioning, we can only remove the nodes of a multicast request every time and all nodes of the multicast requests will be divided into M groups. So, selecting column-based partitioning can achieve less number of groups than row-based partitioning for this situation ($N_{max,row} > N_{max,column}$).

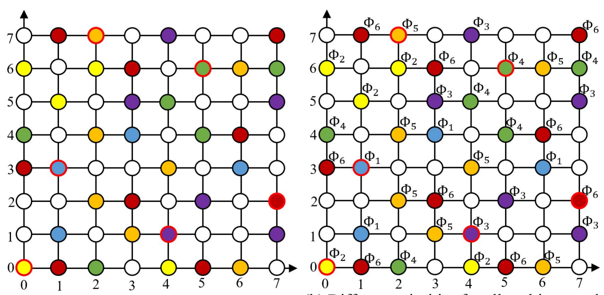
The pseudocode for Group-partitioning Routing Algorithm is given in Algorithm 1.

Example: An example of the routing algorithm for general cases in 8×8 ONoC are shown in Fig.4 and Fig.5. There are 6 multicast requests in the network (Fig.4(a)). According to the Group-partitioning Routing algorithm, the detailed routing process is as follows: In the first step, we sort all multicast requests in ascending order according to their number of nodes: $|\mathbf{D}_4| < |\mathbf{D}_1| < |\mathbf{D}_2| \leq |\mathbf{D}_5| < |\mathbf{D}_6| < |\mathbf{D}_3|$; At the second step, we assign unique priorities to the multicast requests in descending order. The nodes in a multicast request have the same priority. There are 6 priorities in this example: $\Phi_1 > \Phi_2 > \Phi_3 > \Phi_4 > \Phi_5 > \Phi_6$. The priority assignment is: Φ_1 to p_4, Φ_2 to p_1, Φ_3 to p_2, Φ_4 to p_5, Φ_5 to p_6, Φ_6 to p_3 (as shown in Fig.4(b)). Then, we remove multicast nodes to form the first group. Here, $N_{max,row} = N_{max,column}$ ($N_{max,row}$=4,

Algorithm 1: Group-partitioning Routing Algorithm

```
Input  : Multiple Multicast Set D
Output: Group
C ← ∅; F ← ∅; Group = 0; D′ = D;
Sort the multiple multicast requests in ascending order
  according to their number of nodes;
Assign to the multicast requests unique priorities from
  high to low according to the above sorted order;
do
    if N_max,row > N_max,column then
        Column_based_partitioning();
    end
    else if N_max,row < N_max,column then
        Row_based_partitioning();
    end
    else if N_max,row = N_max,column then
        Row_based_partitioning();
    end
    Check_destinations();
while C ≠ D;

Function Column_based_partitioning()
for each node in every column do
    if nodes has the highest priority then
        Put them to F;
        Check_sources();
        C ← C ∪ F;  F ← ∅; Group++; D′ = D − F;
    end
    return D′;
end

Function Row_based_partitioning()
for each node in every column do
    if nodes has the highest priority then
        Put them to F;
        Check_sources();
        C ← C ∪ F;  F ← ∅; Group++; D′ = D − F;
    end
    return D′;
end

Function Check_sources()
while the source of the picked destination is not in this
  group F do
    Remove the destinations from F and put it back to
      the mesh network;
    return F;
end

Function Check_destinations()
while the source in the group still has some destinations
  left in the network do
    Keep the source in the mesh network;
end
```

$N_{max,column}$=4), we use row-based partitioning to form the first group. In the row 0, there are 6 multicast nodes. (0,0) and (4,0) have the highest priority, so we remove them in row 0 and put them to the first group. Likewise, we remove (1,1), (5,2), (1,3), (6,3), (3,4), (1,5), (0,6), (2,6), (4,7) from row 1 to row 7 respectively. The source of nodes (5,2) and (4,7) is not in the group, so we remove them from the group and put them back to the mesh network.Then we get the first group (as shown in Fig.5 (a)) in which the distribution of nodes satisfy Routing Theorem 4, so we use XYX routing scheme for this group. For the sources in this group ((0,0), (1,3)), they do not have any destinations left in the mesh network, we do not need to keep the sources in the mesh network. There are still nodes on the mesh network, the partitioning continues. By repeating step3, we get the group 2, group 3 and group 4 (Fig.5(b),(c),(d)). Finally, we decouple all nodes of the multicast requests to 4 groups, each of which satisfies one of the 4 Routing Theorems and only needs one wavelength. Therefore, for this traffic pattern, 4 wavelengths are needed.



(a) Traffic pattern for multiple multicasts in 8×8 ONoC   (b) Different priorities for all multicast nodes

Multicast 1: Source: (0,0); Destinations: (4,0),(1,5),(0,6),(2,6)
Multicast 2: Source: (4,1); Destinations: (7,1),(5,2),(3,5),(7,5),(4,7)
Multicast 3: Source: (7,2); Destinations: (1,0),(5,0),(0,3),(3,2),(3,6),(6,4),(7,7)
Multicast 4: Source: (1,3); Destinations: (1,1),(6,3),(3,4)
Multicast 5: Source: (5,6); Destinations: (2,0),(0,4),(4,5),(5,4),(7,6)
Multicast 6: Source: (2,7); Destinations: (6,0),(3,1),(2,2),(4,3),(2,4),(6,6)
Priority: $\Phi_1>\Phi_2>\Phi_3>\Phi_4>\Phi_5>\Phi_6$

Fig. 4. Example of Multiple Multicasts routing algorithm for general cases in 8×8 ONoC

V. Performance

In this section, we evaluate RWADMM through extensive simulations using synthetic multicast traffic and compare it with other routing schemes (XY, YX routing). The number of wavelengths is the main factor in the power consumption, so only the number of required wavelengths is presented in the simulation results. In our simulation model, the network size is set to 8×8 in mesh topology. We randomly generate M multicast requests and select one node as the source and other nodes as destinations for each multicast request.

First, we investigate the average number of wavelengths for different number of multicast requests and ratio of multicast nodes (the proportion of multicast nodes to all nodes in the network) using RWADMM. When the number of multicast requests is given, we change the ratio of multicast nodes from 10% to 100%. We can see from Fig.6, when the ratio of multicast nodes is given, the average number of wavelengths is nearly the same for different number of multicasts. This is because our scheme divides every multicast request into multiple parts and combines different parts from different multicast requests to several groups. By doing so, the routing scheme can find other alternative paths to route packets via less congested links and alleviate the link sharing probability. We can reuse the same wavelength in link-disjoint paths; therefore it is feasible to decrease the number of wavelengths. In RWADMM, the number of wavelengths is related to the ratio of multicast nodes, which is consistent with our original objective: considering the combination of the group of multiple multicast requests as a whole and designing routing method from the global perspective.

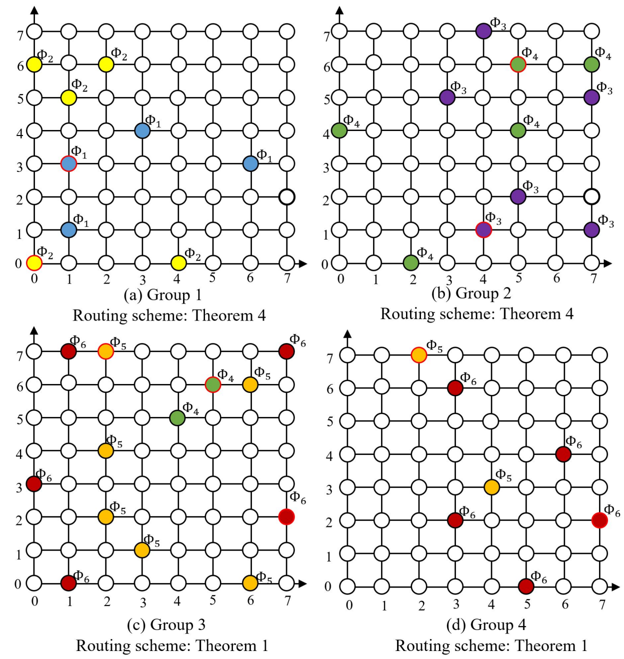


Fig. 5. Different groups derived by using Group-partitioning routing algorithm

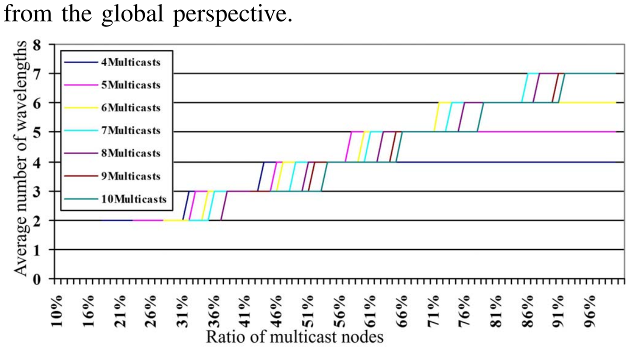


Fig. 6. Average number of wavelengths evaluation for different number of multicast requests under different ratio of multicast nodes

Then, we compare RWADMM with other routing schemes (XY, YX routing) under two different multicast nodes ratios: 30% and 80%. (1) Ratio of multicast nodes is 30%(Fig.7(a)). In this situation, there are at most 20 multicast nodes in a 8×8 ONoC (64 nodes). Considering a multicast request has at least 3 nodes (one source and two destinations), there will be at most 6 multicast requests. (2) Ratio of multicast nodes is 80%(Fig.7(b)). There are at most 52 multicast nodes in this situation and at most 17 multicast requests. We can see from Fig.7(a) and Fig.7(b), when the number of multcast requests is small, the effect of reducing number of wavelengths is not obvious. This is because there exists a saturation situation in which $N_{max,row} = N_{max,column} = M$. Once the distribution of multicast nodes satisfies this situation, the number of groups derived by the proposed routing algorithm is M and it will not increase with the increasing of number of multicast nodes. For the small number of multicast requests of different ratios of multicast nodes, the number of multicast nodes is far more than the number of multicast requests, the possibility of multicast nodes from different multicast requests exit in the same row or column is much higher. So, it is more easily to reach the saturation for less number of multicast requests. For the situation that the number of multicast requests is large, the effect of reducing number of wavelengths is much better. Therefore, Group-partitioning routing method is effective to the situation that the number of multciast requests is large.

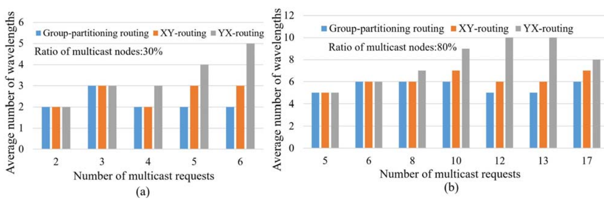


Fig. 7. Comparison with different routing schemes under two different ratio of multicast nodes

VI. Conclusion

In this paper, we studied the routing and wavelength assignment problem for multiple multicasts in ONoC. At first, we give the definition of routing and wavelength assignment problem for multiple multicasts in ONoC (RWA-MM-ONoC), which is the first time this problem is defined formally as far as we know. We investigate this problem by studying a distribution-based routing method for multiple multicast requests with nodes distributed in particular locations that only require one wavelength. Specifically, we derived 4 Routing Theorems for 4 particular scenarios according to the distribution of source and destination nodes. Based on the theorems, we can easily route the multicast requests with one wavelength as long as the distribution of the source nodes and destination nodes satisfies the conditions of one of the 4 theorems. We extended this routing method to solve the general cases of RWA-MM-ONoC by partitioning multiple multicast requests into groups with an algorithm called Group-Partitioning Routing Algorithm. Each group created by the algorithm only needs one wavelength. Therefore, with this algorithm, the number of wavelengths needed is equal to the number of groups created. The simulation results show that our proposed routing algorithm outperforms other routing methods in terms of the number of wavelengths and it is particularly effective for routing a large number of multicast requests.

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