Design and Performance Evaluation of Hexagonal Topology Networks with Novel Routing Algorithms

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***Abstract*—The heuristic shortest path routing algorithms and performance evaluation are proposed to find the most suitable optical path between the two nodes of the optical switch in hexagonal topology network. The advantages of hexagonal optical switching network are easy to expand and have flexible fault tolerant. If we want to expand hexagonal topology network, we can increase the number of levels. A 7-level hexagonal topology network with 294 nodes has been designed and its routing algorithm has also been designed. Finally, we evaluated the performance of 4-level hexagonal topology network with different algorithms such as SPRA-AI (Shortest Path Routing Algorithm with Artificial Intelligence using decision tree), SPRA-SPT (Shortest Path Routing Algorithm with Spanning Tree), and SPRA-PDP (Shortest Path Routing Algorithm with Pure Distance Prediction). The simulated traffic mode is also captured from the actual core network to obtain the authenticity of the simulation results.**

Keywords—Shortest Path Routing Method; Hexagonal Optical Switching Network

I. INTRODUCTION

Today, high-capacity high-speed optical switches have become an important part of the success of future ultra-broadband services, such as 5G valuable services. Various optical switching technologies are also proposed [1-10], including OCS (Optical Circuit Switching), Optical Flow/Frame Switching (OFS) without buffer module plus intelligent scheduling, Optical Burst Switching (OBS) with advanced scheduling and advanced Optical Packet Switching (OPS) with optical buffers plus FPGA-based label switching.

In this paper, we propose a resilient fault-tolerant high-speed switching network using a hexagonal optical switch [11], which is used in a high-speed switching network of an Internet data center, and uses a hexagonal 8×8 OFS as a switching core element in a two-dimensional space network. On this topology, the hexagonal cell deployment and extension are very easy for implementing. This design makes the overall network flexible and fault-tolerant. Using 8×8 OFSs, it can be quickly deployed and expanded into a large scale data center. The all-optical high-speed switch network achieves the goals and advantages of flexible fault tolerance, high frequency bandwidth, power saving, full photochemical, and one-time investment in equipment. In the future, this topology network can be applied to an all-optical high-speed switching network in a data center to perform fast switching services. The heuristic shortest path routing algorithms are proposed to find the most suitable optical path between the two nodes of the optical switch in hexagonal topology network; the optical path transmission route is quickly searched and obtained. Furthermore, we will compare and analyze the results of performance evaluation of three routing algorithms. To improve performance, we also use the best algorithm under multiple links to simulate the hexagonal topology network.

A brief description of the other sections follows. In Section 2, we describe the operation of a hexagonal topology network. In Section 3, we will discuss decision tree-based routing algorithms using artificial intelligence techniques. We will introduce the performance simulation of the 4-Level hexagonal topology network with three routing algorithms in Section 4. Some conclusions will be drawn in Section 5.

II. HEXAGONAL TOPOLOGY NETWORK ARCHITECTURE AND OPERATION PRINCIPLE

Figure 1 shows a 1-level simple ring hexagonal topology network with 6 nodes. The advantage is simple and easy to implement for 1-ring hexagonal topology network, but the throughput is low. If we need to improve performance, we can use multiple links or wavelengths between the two nodes, but multiple links require a larger OFS.

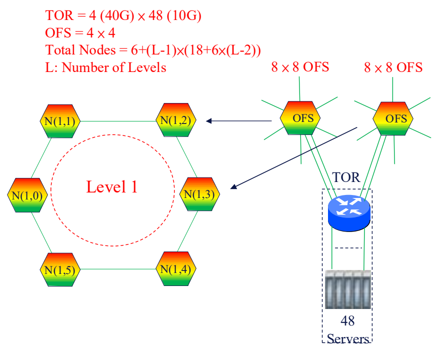

Fig. 1 1-level simple ring hexagonal topology network with 6 nodes.

If we want to expand our network, we can increase the number of levels. Fig. 2 shows a 7-level hexagonal topology network with 294 nodes, where increasing a hexagonal topology network will increase 2 nodes, but some of the hexagonal topology networks (shown in red) in Fig. 2 will increase 3 nodes. Of course, when we only add the first hexagonal topology network only at any level other than level 1, we can get 4 nodes. For example, six hexagonal topological networks (indicated in red) will increase 3 nodes, while other hexagonal topological networks (indicated in yellow) will increase only 2 nodes. Other conditions are also shown in Fig. 2. For the fault tolerance function, two ToRs are connected with two nodes through two links, and two WAN switches are also connected to the other two links, as shown in Fig. 2. How many ToR and WAN switches are needed based on the data center traffic distribution.

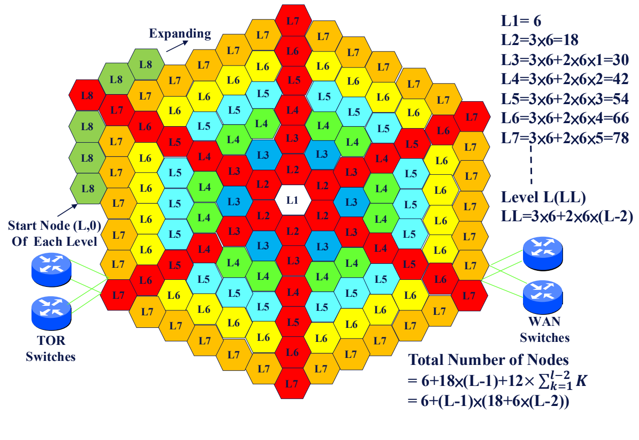

Fig. 2 7-level hexagonal topology network with 294 nodes.

In Fig. 2, Level 8 has been expanded to 14 nodes, which are nested like bees according to the requirements of the expanded network. Therefore, if we assume that the number of levels is L, then we can obtain [11]

Total number of nodes

$$= 6+(L\text{-}1)\times(18+6\times(L\text{-}2)) = 6L^2 \quad (1).$$

If L=7, we can get 294 nodes to implement a very large switching network. If we use a ToR to connect to a node, and a ToR connects to 48 servers, the total number of servers will reach 14,112.

Of course, some links to certain nodes at each level will be connected to the WAN to communicate between different data centers. How many links and nodes are required at a level depends on different traffic and applications. All nodes are defined as Node (i, j), where i is the number of levels and j is the number of nodes in Level i. The start node number of each level is from 2 quadrant of the x-axis. Therefore, we can get

Node (i, j), i=1 to L and j=0 to $3\times6+2\times6\times(i\text{-}2)\text{-}1=6(2i\text{-}1)\text{-}1$ (2).

For example, the three shortest paths are shown in Fig. 3. Path 1 (green) is routed from the source Node (3, 5) to the destination Node (5, 4) through 15 links, and Path 2 (blue) is from the source Node (4, 2) reaching the destination Node (3, 14) through 11 links. Although Path 1 and Path 2 use the same link (shown in red), they use different directions so there is no contention. However, path 3 (black) is routed from the source Node (5, 47) to the destination Node (5, 32) through 13 links, and contention between Path 1 and Path 3 occurs using the same link and direction. It is also shown single direction in red. How to resolve disputes is a big issue. If the incoming data packet or flow of the source Node (3, 5) in Path 1 arrives first, Path 1 is established first according to the FIFO algorithm. After releasing Path 1, Path 3 can be established, and then send its packet or flows of source Node (5, 47) to the destination Node (5, 32).

The results of the rerouting are shown in Fig. 3 (black dotted line), where Path 1 and Path 3 both use the link (green) because they use different directions, so there is no contention. Rerouting increases only two links without waiting for Path 1 to complete. The two rerouting methods are described in detail below.

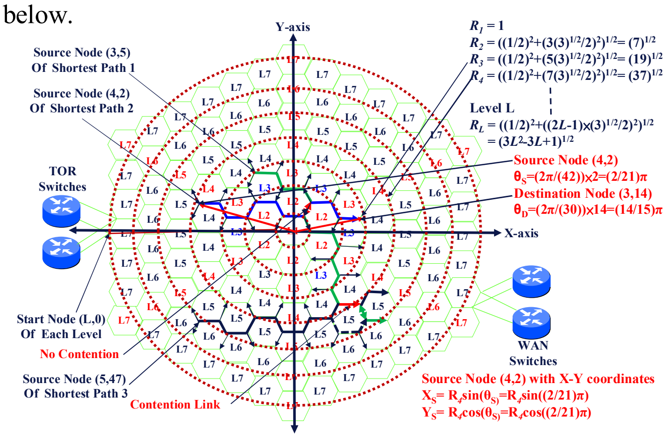

Fig. 3 The routing structure of shortest paths with X-Y coordinates.

III. SHORTEST PATH ROUTING ALGORITHMS

An L-level hexagonal network routing algorithm using artificial intelligence technology (decision tree) is designed, which includes the shortest path routing algorithm, where the path is defined as Path (S_L, S_N ,D_L ,D_N), where S_L and S_N represent the source level and node, D_L and D_N represent the destination level and node, respectively. The link is also defined as Link (S_L, S_N, D_L, D_N), but paths can contain many links, and a link has only one link.

Fig. 3 also shows the shortest path routing structure with X-Y coordinates, where each node has a coordinate value. In the following, we will calculate the coordinate value of each node. It is assumed that the link distance between adjacent nodes is equal to one unit, which can be 1m, 10m, or 100m, and so on.

If we want to find the shortest path between the source Node (S_L, S_N) and the destination Node (D_L, D_N), called the Path (S_L, S_N, D_L, D_N), we must first calculate the distance of the path. If the distance of the path is greater than one unit, it is necessary to find another link to route the data to the destination node. If R_L represents an L-level radius, and the link distance between adjacent nodes is equal to one unit, we can get

$$\boldsymbol{R_1=1} \quad (3)$$

$$\boldsymbol{R_2}=\sqrt{\left(\frac{1}{2}\right)^2+\left(3\frac{\sqrt{3}}{2}\right)^2}=\sqrt{7} \quad (4)$$

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$$R_L=\sqrt{\left(\frac{1}{2}\right)^2+\left((2L-1)\frac{\sqrt{3}}{2}\right)^2}$$

$$=\sqrt{3L^2-3L+1} \quad (5).$$

θ_S denotes angle of source Node (S_L, S_N), we can get

$$\theta_S=\frac{2\pi}{12L-6}\times N \quad (6).$$

(R_L, θ_S) polar coordinates are first converted to X-Y coordinates, we can get

$$X_S \text{ coordinate} = R_L \times \sin(\theta_S) \quad (7)$$

$$Y_S \text{ coordinate} = R_L \times \cos(\theta_S) \quad \text{b} \ (8).$$

Similarly, we can get X-Y coordinates of destination Node (D_L, D_N)

$$X_D \text{ coordinate} = R_L \times \sin(\theta_D) \quad \text{b} \ (9)$$

$$Y_D \text{ coordinate} = R_L \times \cos(\theta_D) \quad (10).$$

Calculating the X-Y coordinate distance between source node and destination node, we can get

$$D=\sqrt{(X_S-X_D)^2+(Y_S-Y_D)^2} \quad (11).$$

Table 1 The distance between two nodes

Node	(4,2)	(4,1)	(4,3)	(3,2)	(3,14)
R	6.082	6.082	6.082	4.358	4.35
θ	17.14	8.571	25.71	24	168
X	5.812	6.014	5.480	3.982	-4.26
Y	1.7929	0.9065	2.6392	1.7729	0.90
D	10.115	10.278	9.8969	8.2911	0

For example, the shortest paths are shown in Fig. 3, where Path 2 (blue) is routed from the source Node (4, 2) to the destination Node (3, 14) through 11 links. First, we can calculate the distance between the source Node (4, 2) and the destination Node (3, 14) according to the above equations. Table 1 shows the distance between two nodes. Obviously, the distance between the source Node (4, 2) and the destination Node (3, 14) is 10.115 units, which is more than one unit, so we must find another link to route the data to the destination Node (3, 14) . In Fig. 3, it is clear that each node has three adjacent nodes to be selected to route data to the destination node. In this example, the three neighbor nodes are Node (4, 1), Node (4, 3), and Node (3, 2). Therefore, we must calculate the distance between the three neighbor nodes and the destination Node (3, 14) according to the above equations. In Table 1, we can see that the distance between the Node (3, 2) and the destination Node (3, 14) is the shortest, so we can choose a link named Link (4, 2, 3, 2) to route the data to the destination Node (3, 14) (if this link is available). Otherwise, we will choose another link with a shorter distance to route the data to the destination Node (3, 14), such as Link (4, 2, 4, 3), and then Link (4, 2, 4, 7).

IV. Performance Evaluation

In this section, we introduce the performance simulation of a 4-level hexagonal topology network. The performance simulation routing algorithms include the shortest path routing algorithms with AI technologies (SPRA-AI, AI using traditional decision tree method), the shortest path simple routing algorithm with Pure Distance Prediction (SPRA-PDP, suppose each node has sufficient bandwidth of light path) and SPRA-SPT (with traditional SPanning Tree method). In addition, we will compare and analyze the performance evaluation results of these routing algorithms. In our simulation, based on the captured core network flow distribution, the total number of bytes in the transport stream of each switch in the hexagonal topology network is approximately 10^7. The number of switch for the first to fourth level of the hexagonal topology network are 6, 18, 30, and 42 respectively. Therefore, in our simulation, the total number of switches generating traffic is 96.

After generating traffic for each switch, that traffic is sent to the switch and switched to its randomly selected destination switch. If no physical optical path is available, this flow will be buffered in 100M bytes of conventional electrical memory. If the buffer memory is used up, the traffic is discarded, resulting in a loss of traffic.

According to our simulation results, Fig. 4 shows the throughput of three different routing algorithms, which are applied to a 4-level hexagonal topology network with 1 node link. For example, as shown in Fig. 4, the throughput is 0.16, 0.15 and 0.19 respectively when offered load is 0.6 for SPRA-AI, SPRA-SPT and SPRA-PDP routing algorithms with 1 node link.

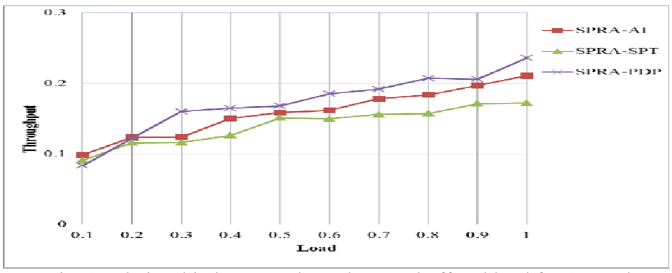

Fig. 4 Relationship between throughput and offered load for 4-Level hexagonal topology network with 1 node link.

As shown in Fig. 4, SPRA-PDP routing algorithm has the highest performance, SPRA-AI has the second highest performance, and SPRA-SPT has the lowest performance. This is due to the node link utilization of each routing algorithm. SPRA-PDP routing completely ignores the link status between switching nodes. It only selects the path by predicting the distance from the source to the destination through the network topology. Therefore, regardless of whether the link is available, SPRA-PDP will choose the theoretically shortest path. Therefore, the node link utilization of each path is the lowest, which may lead to higher performance. However, the SPRA-AI and SPRA-SPT routing algorithms consider the link status between switching nodes when choosing the shortest path. The SPRA-AI routing algorithm selects the shortest path by the link cost of the source node to the next hop affected by the traffic status, and the AI heuristic function predicts the distance of the next hop from the source node to the destination node. The shortest path of the SPRA-AI routing algorithm uses more links than the theoretically shortest path, so its performance is worse than SPRA-PDP. In addition, the SPRA-SPT routing algorithm calculates its shortest path by constructing a network topology in the form of a spanning tree, where the traffic between switching nodes will affect the link cost. As long as there is a path from the source node to the destination node, SPRA-SPT can find it, regardless of its high link utilization. Therefore, the shortest path of the SPRA-SPT routing algorithm uses more links than the SPRA-AI and SPRA-PDP algorithms, so its performance is worse than the SPRA-AI and SPRA-PDP algorithms.

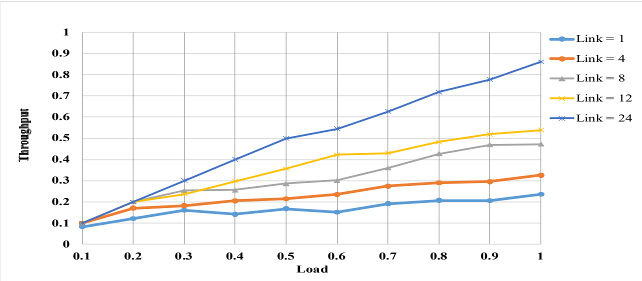

Fig. 5 Relationship between throughput and offered load for 4-Level hexagonal topology network with various node links.

Fig. 5 shows the relationship between throughput and offered load for a 4-Level hexagonal topology network with various node links. In our simulation, we use the SPRA-PDP routing algorithm to select the shortest path from the source node to the destination node. It can be seen that as node links increase, the throughput becomes greater. When node link achieves 24, the throughput is greater than 0.86 for offered load 1. That is, more than 86% of the generated traffic will successfully reach its destination through the 4-Level hexagonal topology network. And we noticed that for some specific number of node links, the throughput should increase as the load provided increases. This is the theoretical result of more traffic and greater throughput. In our simulation, the curve of the number of links at each node in Fig. 5 shows this progressively increasing trend.

However, as the number of links increases, not only does the cost increase, but also the complexity of the network. To reduce the complexity of the network, we can use multiple wavelengths for each link [12]. Currently, at least 80 wavelengths can be transmitted in a fiber optic link. Therefore, for 96 nodes, only a maximum of 48 paths need to be established, and a maximum of 48 wavelengths are required. A larger-scale hexagonal topology network can be built using 80-wavelength fiber links. However, using a wavelength fiber link requires a wavelength selective switch and a tunable wavelength converter. Although some elements must be added, the number of links between nodes is minimal, but the complexity of the network will be greatly reduced.

V. CONCLUSIONS

We have also introduced a hexagonal topology network with three novel shortest path routing algorithms. The advantages of the hexagonal optical switching network are that it is easy to expand and has flexible fault tolerance. If we want to expand a hexagonal topology network, we can increase the number of levels. A 7-level hexagonal topology network with 294 nodes has been designed and its shortest path routing algorithm is also designed. Performance simulations have also been performed.

We also discuss heuristic shortest path routing methods to find the most suitable optical path between two nodes of an optical switch in a hexagonal topology network. Among the performance evaluation results, the SPRA-PDP routing algorithm has the highest performance, the SPRA-AI has the second highest performance, and the SPRA-SPT has the lowest performance. This is due to the node link utilization of each routing algorithm.

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