

Original Research Article

Architecting Network Structure for Data Center: a Scalable Hierarchical Approach

ABSTRACT

This paper presents a server centric approach for architecting data center network(DCN) by using a hierarchical model. Considering that the network infrastructure must be scalable to a large number of servers and allow for incremental expansion, sparse hierachical graph(SHG) is recursively defined based on complete hierachical graph(CHG). Focusing on efficient routing in the case of intermediate node failures, we design a fault-tolerant routing algorithm that comes from both SHG's rich physical connectivity and parallel paths. The simulation experiments indicate that SHG provides low aggregate bottleneck throughput(ABT) and low mean-latency(ML). The results imply that SHG structure is more feasible, and possess the good regularity and expandability that help reduce the cost of further expansions.

Keywords: data center network; topology; routing; parallel paths

1. INTRODUCTION

As web search, e-commerce, data storage, video online, high-performance computing, data analysis and other information services develop toward socialization, dynamization and centralization, applications, computing and storage resources on Internet are migrating to the data center. DCN is a core component of the data center, it is responsible for the interconnection of tens or hundreds of thousands of servers, and provides efficient network communication and data transmission capabilities for the upper computing services. That DCN faces to the challenge of the application environmental change makes it different from the traditional interconnection networks, such as ethernet, grid and high performance distributed computing system, in the fields of design requirement, construction of topology, application environment and evaluation standard. The new application service models represented by cloud computing put forward new requirements for DCN performances in scalability, and fault tolerance.

From the point of view of DCN application environments and its own technological evolutions, we must deal with some new research problems and needs that are identified throughout DCN.

(1) DCN topology. Through network cable, and according to certain rules of interconnection, servers and switches are connected to form a specific topology, DCN is a fundamental problem of data center. Today, the total amount of data processing and storage of data center have been increasing at a rapid rate. The data storage volume for now is already PB-level, and the number of node servers reach hundreds of thousands or even millions. With the rapid growth and large-scale deployment, DCN's structure has become increasingly complex and DCN's size is expanding. For existing DCN expansion, maintenance, reconstruction and cost, these are a great challenge. Therefore, we need a new kind of DCN

topology which has the following characteristics, such as low cost, easy build and expansion, and simple maintenance and wiring.

(2) Fault tolerant routing. The node servers of DCN is not only used to process and store data, but also to participate in forwarding and routing. In order to reduce the construction cost, DCN generally adopts the low price commercial servers. This makes in node failure normalization. When a failed node is used as an intermediate node, routing can not be forwarded. Therefore, DCN need a fault tolerant routing mechanism, so as to efficiently complete routing in the case of intermediate node failures.

In response to these new demands, the paper researches on DCN topology, fault-tolerant routing, and intends to solve the underlying technical problems and actual application deployment challenges caused by the rapid development of new applications.

The rest of the paper is organized as follows. In Section 2, we review some related works. Our main methods including SHG networks structure, and routing algorithm in SHG are presented in Section 3 and Section 4, respectively. The performance evaluations are given in Section 5. Finally, the paper is concluded in Section 6.

2. RELATED WORK

In order to solve this problem and put our work in perspective, we give a brief overview of related works. A major approach is switch centric, which organizes switches into structures other than tree and puts the interconnection intelligence on switches. Al-Fares M et al. (2008) leverage largely commodity Ethernet switches to support the full aggregate bandwidth of clusters consisting of tens of thousands of elements. Based on the fat-tree, they present techniques to perform scalable routing while remaining compatible with Ethernet, IP, and TCP[1]. Mysore R N et al. (2009) observe that in DCN, the baseline multi-rooted topology is known and relatively fixed, and leverage this observation in the design of PortLand, a set of Ethernet-compatible routing, forwarding protocols specially tailored for data center deployments[2]. Heller B et al. (2010) examine the trade-offs between energy efficiency, performance and robustness, and present ElasticTree, a network-wide power manager, which dynamically adjusts the set of active network elements (links and switch) to satisfy changing data center traffic loads[3]. VL2 (Greenberg A et al., 2011) uses flat addressing, valiant load balancing, and end system-based address resolution, to support huge data centers with uniform high capacity between servers, performance isolation between services, and Ethernet layer-2 semantics[4]. Helios (Farrington N et al., 2011) is a hybrid electrical/optical switch architecture that can deliver significant reductions in the number of switching elements, cabling, cost, and power consumption relative to recently proposed data center network architectures[5]. Wang G et al. (2011) propose a hybrid packet and circuit switched DCN architecture, namely c-Through, which augments the traditional hierarchy of packet switches with a high speed, low complexity, rack-to-rack optical circuit-switched network to supply high bandwidth to applications[6]. OSA (Chen K et al., 2014) is an optical switching architecture for DCN. Leveraging runtime reconfigurable optical devices, OSA dynamically changes its topology and link capacities, thereby achieving unprecedented flexibility to adapt to dynamic traffic patterns[7]. The above Helios, c-Through and OSA belong to hybrid optical-electric switching scheme. Flyway (Chen K et al., 2014) and WDCN (Vardhan H et al., 2014) are presented that the data center environment is well suited to a deployment of 60 GHz links contrary to concerns about interference and link reliability, and explore its use to relieve hotspots in oversubscribed DCN[8,9].

Another relevant method is server centric, which puts the interconnection intelligence on servers and uses switches only as cross bars. Guo D et al. (2011) present HCN, the structure for data centers owning the advantages of expansibility and equal degree. HCN

93 offers high degree of regularity, scalability and symmetry which very well conform to the
 94 modular design and implementation of data centers[10]. MDCube (Wu H et al., 2009) is a
 95 high performance interconnection structure to scale its containers to mega-data centers, and
 96 uses the high-speed up-link interfaces of the commodity switches in the containers to build
 97 the inter-container structure, reducing the cabling complexity[11]. To alleviate the growing
 98 concern of energy waste in networked devices, Huang L et al. (2011) present PCube, a
 99 server-centric data center structure that conserves energy by varying bandwidth availability
 100 based on traffic demand[12]. Kliazovich D et al. (2013) underlines the role of communication
 101 fabric in data center energy consumption and presents a methodology, termed DENS, that
 102 combines energy-efficient scheduling with network awareness[13]. Leveraging the
 103 introduction of all-optical switching technologies inside the data center, LIGHTNESS (Perelló
 104 J et al., 2013) aims at realizing a flexible and scalable DCN solution featuring ultra-high data
 105 throughput and low-latency server-to-server communication[14]. Ghosh A et al. (2013)
 106 investigate two semi-centralized designs that lie at practical points along the spectrum
 107 between fully-distributed and fully-centralized solutions, and achieve scalability by
 108 distributing computation across multiple tiers of an optimization machinery[15]. By exploring
 109 smart grid technologies that can be applied to a telecommunication network to achieve
 110 energy-efficient data center networking, Koutitas G et al. (2014) establish an active role in
 111 the energy market by adjusting power consumption in real time[16]. Singla A et al. (2014)
 112 present the first non-trivial upperbound on network throughput under uniform traffic patterns
 113 for any topology with identical switches. and show that random graphs achieve throughput
 114 surprisingly close to this bound[17].

115
 116 There are three challenges for DCN. First, the network infrastructure must be scalable to a
 117 large number of servers and allow for incremental expansion. Second, DCN must be fault
 118 tolerant against various types of server failures, link outages, or server-rack failures. Third,
 119 DCN must be able to provide high network capacity to better support bandwidth-hungry
 120 services. Existing switch centric structures cannot support one-to-x traffic well and need
 121 upgrading switches. Existing server centric structures either cannot provide high network
 122 capacity or use a large number of server ports and wires.

123
 124 Inspired by our previous work[18], this paper proposes a scalable hierarchical approach for
 125 architecting network structure for data center, and addresses two issues:
 126 (1) The establishment of SHG that allow for DCN incremental expansion.
 127 (2) The design and implementation of routing algorithm in SHG that include shortest path
 128 routing and fault-tolerant routing.

129
 130 Compared with other works on DCN, the major contributions of this paper are summarized
 131 as follows.

- 132 (1) Switch centric approaches need upgrading switches to support for DCN incremental
- 133 expansion. Because SHG belongs to server centric approaches, the deployment of new
- 134 SHG topology is more feasible, and SHG topology can be used to improve the end-to-end
- 135 throughput.
- 136 (2) Server centric approaches usually use more than two ports per server to scale to a large
- 137 server population. Because SHG is sparse graph with the server degree 2, SHG possess the
- 138 good regularity and expandability that help reduce the cost of further expansions.

139 140 **3. THE SHG NETWORKS STRUCTURE**

141 142 **3.1 Basic concept and definitions**

143
 144 SHG is an approach for modeling and implementing the DCN. The concepts associated with
 145 SHG are defined as follows.

146
 147 Definition 1 regular identifier(RI). Let $\chi = \{\sigma_i | 1 \leq i \leq n\}$ be an alphabet, a non-empty finite set. A
 148 regular identifier over χ is a finite sequence of elements from χ , and satisfies one of two
 149 ways.
 150 (1) σ_{-1} is a regular identifier.
 151 (2) $\sigma_{i_1} \sigma_{i_2} \dots \sigma_{i_p}$ is a regular identifier, for any $\{\sigma_{i_1}, \sigma_{i_2}, \dots, \sigma_{i_p}\} \subseteq \chi - \{\sigma_{-1}\}$, where $p(p \geq 1)$ is
 152 integer number, and $i_1 < i_2 < \dots < i_p$.
 153
 154 Some notations concerning the RI are as follows. First, $RI(p) = \sigma_1 \sigma_2 \dots \sigma_p$, $RI(<p) = \sigma_1 \sigma_2 \dots \sigma_{p-1}$,
 155 $RI(>p) = \sigma_{p+1} \sigma_{p+2} \dots \sigma_n$, where $p(p \geq 1)$ is an integer number, Similarly, $RI(<i, \geq j) = \sigma_{i-1} \sigma_{i-2} \dots \sigma_i$.
 156 Second, let $\chi^* = \chi^0 \cup \chi^1 \cup \dots$, where $\chi^0 = \{\sigma_{-1}\}$, $\chi^1 = \chi - \{\sigma_{-1}\}$, $\chi^i = \{RI(i) | i > 1\}$. Third, given an
 157 arbitrary RI, its alphabet is denoted by $\chi(RI)$. Its length is the number of elements in RI, and
 158 is denoted $|RI|$. Finally, given two arbitrary RI_1 and RI_2 , they are called the adjacent RIs iff
 159 $|RI_1| - |RI_2| = 1$, or $|RI_1| - |RI_2| = -1$.
 160
 161 Definition 2 multiplication & subtraction. Given two arbitrary RIs RI_1 and RI_2 . Multiplication is
 162 signified by the circle sign($\circ$), $RI_1 \circ RI_2 = \sigma_{i_1} \sigma_{i_2} \dots \sigma_{i_p}$, where $\{\sigma_{i_1}, \sigma_{i_2}, \dots, \sigma_{i_p}\} = \chi\{RI_1\} \cup \chi\{RI_2\}$,
 163 and $\sigma_{i_1} \sigma_{i_2} \dots \sigma_{i_p}$ is a RI. Subtraction is signified by the minus sign($-$). $RI_1 - RI_2$ represents the
 164 operation of removing all characters which are not in $\chi - \chi(RI_2)$.
 165
 166 Definition 3 CHG. A CHG over χ , denoted by $CH_{|\chi|}(V, E)$ (also called $CH_{|\chi|}$ for short), is an
 167 undirected graph with $V = \chi^*$, and then $(RI_1, RI_2) \in E$ if and only if RI_1 and RI_2 are adjacent.
 168
 169 Definition 4 SHG. A SHG over χ , denoted by $SH_{(M, |\chi|)}(V, E)$, also called $SH(M, |\chi|)$ for short,
 170 comprises $M \in (2^{|\chi|-1}, 2^{|\chi|})$ nodes, is recursively defined as follow: $SH(M, |\chi|) = CH_{(|\chi|-1)} + SH(M - 2^{|\chi|-1}, k)$,
 171 where $CH_{(|\chi|-1)}$ is a SHG over $\chi - \{\sigma_n\}$, $k = \lfloor \log_2(M - 2^{|\chi|-1}) \rfloor$. Let RI_1, RI_2 denote
 172 respectively the nodes in $CH_{(|\chi|-1)}$ and $SH(M - 2^{|\chi|-1}, k)$, there is a link between the two nodes if
 173 and only if RI_1 and RI_2 are adjacent.
 174
 175 The following observation is drawn from the definition 4. All CHGs in a SHG are ordered
 176 according to the ascending order of their subscripts, then they constitute a hierarchical
 177 structure.
 178
 179 Definition 5 vector. Given an arbitrary $SH(M, |\chi|)$, it can be denoted by a n-bit vector
 180 $V(SH(M, |\chi|)) = (1, b_{n-2}, \dots, b_1, b_0)$, where b_i is a binary number, where $b_i = 1$ iff $Ch_i(0 \leq i \leq n-2)$ is in
 181 $SH(M, |\chi|)$, otherwise $b_i = 0$.
 182
 183 Definition 6 subspace(SS). Let $SS(Ch_i) = RI'(>i) \circ \{RI(<i)\}$, where $RI'(>i)$ is a RI, and denotes
 184 the multiplication for all elements whose subscript is $j(b_j = 1 \wedge j > i)$. $SS(Ch_i)$ is called subspace
 185 about Ch_i .
 186
 187 Some notations concerning the RI' are as follows. $RI'(\leq i, > j)$ is a RI, and denotes the
 188 multiplication for all elements which subscript is $q(b_q = 1 \wedge q > j \wedge q \leq i)$. $SS(Ch_i)$ is called
 189 subspace about Ch_i . Similarly, $RI'(< i, > j)$ can be defined.
 190
 191 In SHG, the link between the node RIs A and B is labeled as $\lambda(A, B)$. $\lambda(A, B)$ is the i -th link if
 192 and only if A and B are the i -th adjacent RIs. The i -th link is denoted as λ_i .
 193

3.2 SHG construction

We use servers equipped with two network ports and switches to construct SHG architecture. In SHG, all switches are used as nodes, all servers are considered as links. A server is connected to two switches via communication links, which are assumed to be bidirectional. In addition, a link in SHG can express only a communication link, namely, not including a server.

The following example illustrates how a SHG is constructed. Firstly, we construct CH_4 , CH_3 and CH_1 , which are the building block to construct larger SHGs. Secondly, $SH(26,5)$ is constructed from CH_4 , CH_3 and CH_1 . In $SH(26,5)$, each $CH_i (i=1,3,4)$ is connected to all the other $CH_j (j=1,3,4, \text{ and } i < j)$ with one link. CH_i connects the other two CH_j as follows. Assign each server a 2-tuple (RI_i, RI_j) , where RI_i and RI_j are adjacent nodes. Then two switches with IDs RI_i and RI_j are connected with the server. For simplicity, if $|RI_i| > |RI_j|$, the server also can be labeled as RI_i , else labeled as RI_j . The linking result for $SH(26,5)$ is shown in Fig.1. The solid-line connects two nodes which belong to the same CH , while the dotted-line connects the two nodes which belong to the two different CH s. For an arbitrary switch node, its name is a RI . As can be seen from the figure, CH_1 , CH_3 and CH_4 constitute a hierarchical structure.

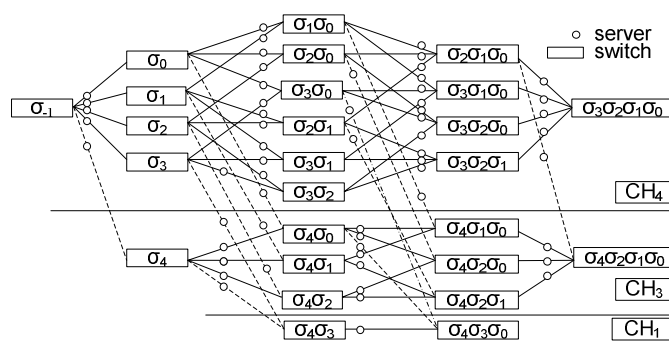


Fig.1. SH(26,5) network

4. ROUTING ALGORITHM IN SHG

4.1 Shortest path routing

In SHG, routing between any two servers is equivalent to routing between the corresponding switches. For simplicity, we only involve the switches. Switch is called as node in the following routing algorithms and paragraphs. SHG uses a simple and efficient single-path routing algorithm for unicast by exploiting the hierarchical structure of SHG.

Give node RI s A and B in $SH(M, |X|)$, let $Tag(A, B) = (A - B) \circ (B - A)$, and the shortest distance between them denoted as $\Delta(A, B) = |A - B| + |B - A|$. The shortest path routing algorithm, called SPRouting, is shown in Fig. 2. Consider the source node identifier A and the destination node identifier B . When computing the path from A to B in a SHG, we first call the function search to calculate σ_i whose subscript is the minimum value in all subscripts of the tag(A, B)'s characters, and return the first link that interconnects A and $\sigma_i \circ A$. Then, through an iterative process, we can calculate the sub-path from $\sigma_i \circ A$ to B . The final path of SPRouting is the combination of link $(A, \sigma_i \circ A)$ and the sub-path $(\sigma_i \circ A, B)$.

```

Input: packet  $\mu$ , source node A, and target node B
Output: the server node B outputs the packet  $\mu$ 
1. If  $\text{tag}(A, B) = \emptyset$ 
2. {Send  $\mu$  to the local node;}
3. Else
    {Let  $i$  be the minimum value in all subscripts of the
     tag(A, B)'s characters, and  $\lambda_i$  exists.
4.    $i = \text{Search}(A, B)$ ;
5.   Send  $\mu$  to the next node over link  $\lambda_i$ ;
6.    $\text{tag}(A, B) = \text{tag}(A, B) - \sigma_i$ ; //delete  $\sigma_i$  in tag
    }

```

Fig.2. SPRouting algorithm

A message carries with it a tag and is sent through λ_i link only if the subscript i is the minimum value in all subscripts of the tag and the λ_i link exists. The algorithm checks the tag rightwards, starting from the current minimum subscript. The following take again the Fig.1 as examples, in order to illustrate SPRouting algorithm. In order to facilitate our discussion, as shown in table 1, we classify the positions of the source and the destination nodes into the following classes.

- (1) A and B nodes belong to the same CH.
- (2) A and B nodes don't belong to the same CH, and all λ_i exist.
- (3) A and B nodes don't belong to the same CH, and there is one link λ_i at least that doesn't exist.

Table 1. Discussion on SPRouting algorithm

Class	Tag	Discussion
Class 1: $A = \sigma_1 CH_4$, $B = \sigma_3 \sigma_2 \sigma_1 CH_4$	$\{\sigma_3, \sigma_2\}$	A message is sent to $\sigma_2 \sigma_1$ through λ_2 link on σ_1 .
Class 1	$\{\sigma_3\}$	A message is sent to $\sigma_3 \sigma_2 \sigma_1$ through λ_3 link on $\sigma_2 \sigma_1$
Class 2: $A = \sigma_3 \sigma_2 \sigma_1 CH_4$, $B = \sigma_4 \sigma_0 CH_3$	$\{\sigma_4, \sigma_3, \sigma_2, \sigma_1, \sigma_0\}$	A message is sent to $\sigma_3 \sigma_2 \sigma_1 \sigma_0$ through λ_2 link on $\sigma_3 \sigma_2 \sigma_1$
Class 2	$\{\sigma_4, \sigma_3, \sigma_2, \sigma_1\}$	A message is sent to $\sigma_3 \sigma_2 \sigma_0$ through λ_1 link on $\sigma_3 \sigma_2 \sigma_1 \sigma_0$.
Class 2	$\{\sigma_4, \sigma_3, \sigma_2\}$	A message is sent to $\sigma_3 \sigma_0$ through λ_2 link on $\sigma_3 \sigma_2 \sigma_0$.
Class 2	$\{\sigma_4, \sigma_3\}$	A message is sent to σ_0 through λ_3 link on $\sigma_3 \sigma_0$.
Class 2	$\{\sigma_4\}$	A message is sent to $\sigma_4 \sigma_0$ through λ_4 link on σ_0 .
Class 3: $A = \sigma_4 \sigma_3 \sigma_0 CH_1$, $B = \sigma_4 \sigma_2 \sigma_0 CH_3$	$\{\sigma_3, \sigma_2\}$	On the node $\sigma_4 \sigma_3 \sigma_0$, there are three edges $\lambda_0, \lambda_3, \lambda_4$, and no edge λ_2 . So, a message cannot be sent through λ_2 link, but only sent to $\sigma_4 \sigma_0$ through λ_3 link on $\sigma_4 \sigma_3 \sigma_0$.
Class 3	$\{\sigma_2\}$	A message is sent to $\sigma_4 \sigma_2 \sigma_0$ through λ_2 link on $\sigma_4 \sigma_0$.

In SPRouting algorithm, the number of iterations depends on the shortest distance between A and B. Time complexity of the algorithm is $O(|X|)$.

4.2 Parallel paths

Two or more parallel paths between a source server and a destination server exist if they are node-disjoint, i.e., the intermediate servers and switches on one path do not appear on the other. The following theorem shows how to generate parallel paths between two switches.

Theorem 1. Consider any two node RIs $A, B \in CH_i$, and $|Tag(A, B)| = h \leq i$. Between A and B, there are i parallel paths whose length are less than or equal to $h+2$.

Proof. Let CH_i be over χ_i where $|\chi_i| = i$. And $Tag(A, B) = \{\sigma_{k_1}, \sigma_{k_2}, \dots, \sigma_{k_h}\}$.

(1) Because CH_i is a CHG, all links $\lambda_m (0 \leq m \leq i)$ exist in CH_i . We use $(\sigma_{k_1}, \sigma_{k_2}, \dots, \sigma_{k_h})$ to indicate a path from A to B. After a message carries with it a tag and is sent through $\lambda_{k_j} (1 \leq j \leq h)$ link, σ_{k_j} is deleted from the tag. Then, either there exist the character σ_{k_j} in the address of both A and B, or not. This process can be expressed as a $\lambda_{k_j} (1 \leq j \leq h)$ shift on $(\sigma_{k_1}, \sigma_{k_2}, \dots, \sigma_{k_h})$. So, there are h parallel paths whose length is h, namely shortest paths: $\{\sigma_{k_1}, \sigma_{k_2}, \dots, \sigma_{k_h}\}^h$. Where $\{\sigma_{k_1}, \sigma_{k_2}, \dots, \sigma_{k_h}\}^h$ denoted as h shifts on $(\sigma_{k_1}, \sigma_{k_2}, \dots, \sigma_{k_h})$.

(2) Let $\chi_i - Tag(A, B) = \{\sigma_{n_1}, \sigma_{n_2}, \dots, \sigma_{n_p}\}$. Where $p+h=|\chi_i|$,

$\{\sigma_{k_1}, \sigma_{k_2}, \dots, \sigma_{k_h}\} \cap \{\sigma_{n_1}, \sigma_{n_2}, \dots, \sigma_{n_p}\} = \{\}$, and $\{\sigma_{k_1}, \sigma_{k_2}, \dots, \sigma_{k_h}\} \cup \{\sigma_{n_1}, \sigma_{n_2}, \dots, \sigma_{n_p}\} = \chi_i$.

To clarify, we use $(\sigma_{k_1} | \sigma_{n_j})(\sigma_{k_2}, \dots, \sigma_{k_h})(\sigma_{n_j} | \sigma_{k_1})$ to indicate $(\sigma_{n_j}, \sigma_{k_2}, \dots, \sigma_{k_h}, \sigma_{k_1})$, which is a path from A to B. On this path, firstly, a message is sent through λ_{n_j} link. And then, the message is sent to along $(\sigma_{k_2}, \dots, \sigma_{k_h})$. Finally, the message is sent to B through λ_{n_j} link. The length of this path is $h+2$. Similarly, from A to B, all the paths whose length equal to $h+2$ are described as follows.

$(\sigma_{k_1} | \sigma_{n_j})(\sigma_{k_2}, \sigma_{k_3}, \dots, \sigma_{k_h})(\sigma_{n_j} | \sigma_{k_1}), \sigma_{n_j} \in \{\sigma_{n_1}, \sigma_{n_2}, \dots, \sigma_{n_p}\}$

$(\sigma_{k_q} | \sigma_{n_j})(\sigma_{k_1}, \dots, \sigma_{k_{q-1}}, \sigma_{k_{q+1}}, \dots, \sigma_{k_h})(\sigma_{n_j} | \sigma_{k_q}), \sigma_{n_j} \in \{\sigma_{n_1}, \sigma_{n_2}, \dots, \sigma_{n_p}\}$

$(\sigma_{k_h} | \sigma_{n_j})(\sigma_{k_2}, \dots, \sigma_{k_{h-1}})(\sigma_{n_j} | \sigma_{k_h}), \sigma_{n_j} \in \{\sigma_{n_1}, \sigma_{n_2}, \dots, \sigma_{n_p}\}$

So, there are i-h paths whose length equal to $h+2$.

According to the above (1) and (2), we can come to the conclusion.

Definition 7 pivot set & pivot. Give $CH_i, CH_j (j < i)$. The pivot set between CH_i and CH_j is defined as follows: $P_{i,j} = \{A | A \in SS(CH_i) \text{ and } \exists B \in CH_j, A \text{ is adjacent to } B\}$. $\forall x \in P_{i,j}$ is called the pivot.

Theorem 2. Give $CH_i, CH_j (j < i)$. There are only 2^j links λ_i between the pivots in $P_{i,j}$ and the nodes in CH_j .

Proof. (1) Prove the existence.

$SS(CH_i) = RI'(>i) \circ \{RI(<i)\} = RI'(>i) \circ \{RI(<i, \geq j)\} \circ \{RI(<j)\}$ (1)

$SS(CH_j) = RI'(>j) \circ \{RI(<j)\} = RI'(>j) \circ RI'(\leq i, >j) \circ \{RI(<j)\} = RI'(>j) \circ \sigma_i \circ RI'(<i, >j) \circ \{RI(<j)\}$ (2)

Let $\{RI(<i, \geq j)\}$ in Eq.1 be $M'(<i, >j)$ in Eq.2. Then, there are 2^j links λ_i .

(2) Prove the uniqueness by reductio.

Assume that A and B are adjacent. Then there exists $\lambda_q (q \neq i)$ which is a link between node $A \in SS(CH_i)$ and node $B \in SS(CH_j)$.

For A, B, then $A-B = \sigma_q$ (3)

299 For any node $C \in SS(Ch_i)$, and $D \in SS(Ch_j)$,
 300 then $\exists \sigma_i \chi(SS(Ch_i)) \wedge \sigma_i \in \chi(SS(Ch_j))$, and $\sigma_i \in \chi(C \rightarrow D)$. (4)

301 According to Eq.3 and Eq.4, There are at least two different characters between A and B,
 302 such as σ_q and σ_i . So, A and B can't be adjacent.
 303

304 4.3 Fault-tolerant routing

305
 306 Link failure between a source and a target server is defined as follows: the source and the
 307 destination servers are valid, but the source server is unable to communicate with the target
 308 server. The basic idea of fault-tolerant routing is to find an alternative link for the failure link,
 309 and complete the routing process between the source and target servers. We take source
 310 routing approach to achieve fault-tolerance routing. The source server establishes a set of
 311 parallel paths to the destination server, and probes packet path on the set. When a path
 312 corresponding to packets fails, the source server selects an alternative available path from
 313 the detected paths, and continues packet transfer process to realize fault-tolerant routing.
 314 The fault-tolerant routing algorithm, called FTRouting, is shown in Fig.3.
 315

```

Input: source node A, target node B, and  $V(SH(M, |X|))$ 
Output: A path between A and B
1. Path= $\emptyset$ ; CHS= $\emptyset$ ;
2. If i=j
    { //According to theorem 1, SearchPath generates a path which
    ensures reliable transmission
3.   Path=SearchPath(A, B);
4.   Return
   }
5. Else
    { //Calculate the sum of the elements in V
6.   q=Add( $V(SH(M, |X|))$ );
7.   For r=0 To q Do
8.     For p=1 to  $C_q^r$  Do
        { //Choose CH from IH to form a set which had not been
        selected and the number of elements is p.
9.       CHS=Select(q, IH);
        //Given CHS =  $\{CH_{I_1}, CH_{I_2}, \dots, CH_{I_p}\}, I_1 < I_2 < \dots < I_p$ 
10.      If  $x_{I_1} \in P_{I_1, I_2}$  and ... and  $x_{I_p} \in P_{I_{p-1}, I_p}$  and
          Path( $x_{I_1}, \dots, x_{I_p}$ ) is valid
11.      {Path=Path+Path( $x_{I_1}, \dots, x_{I_p}$ );
12.      Path=Path+SearchPath(A,  $x_{I_1}$ )+SearchPath( $x_{I_p}$ , B);
13.      Return;
        }
14.      Else exit;
        }
    }
    }
    
```

316
 317
 318 **Fig.3. FTRouting algorithm**
 319

320 Consider $SH(M, |X|)(V, E)$. When computing the path from A to B in a SHG through FTRouting
 321 algorithm, we determine whether A and B belong to the same CGH. If so, we calculate a
 322 path between A and B according to the theorem 1. If not, we first calculate the number of
 323 CHs in the SHG, and assign to q. Then follow the steps below to search a path.

324 (1) Choose CHs from SH, the number of elements in these CHs is p. these CHs are denoted
325 as $CHS = \{CH_{l_1}, CH_{l_2}, \dots, CH_{l_p}\}, l_1 < l_2 < \dots < l_p$.

326 (2) If there exist $x_{l_1} \in P_{l_1, l_2}, x_{l_p} \in P_{l_{p-1}, l_p}$, and a $Path(x_{l_1}, \dots, x_{l_p})$, then the calculated path is
327 as follows. $Path(A, x_{l_1}), Path(x_{l_1}, \dots, x_{l_p}), Path(x_{l_p}, B)$. Otherwise, return (1), and continue to
328 the next round of FTRouting.

329
330 In FTRouting algorithm, the number of iterations depends on the number of iterations
331 depends on the number of intermediate routing layers. Time complexity of the algorithm is
332 $O(|X|^2)$.

333

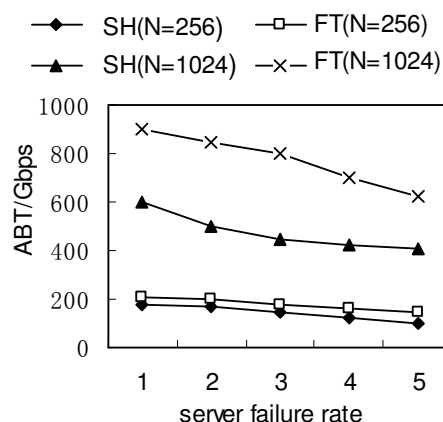
334 5. VALIDATION AND EVALUATION

335

336 The metric aggregate bottleneck throughput(ABT) is defined as the throughput of the
337 bottleneck flow times the total number of flows in the all-to-all traffic model. The metric mean
338 latency(ML) is defined as the number of cycles spent by a typical message from its source to
339 its destination in packet-switching, taking the queueing delay into consideration, and
340 throughput(TP) is the probability of a node receiving a message during a cycle, it indicates
341 accepted traffic, or equivalently, the load. ABT and ML are two aspects of DCN's
342 performance, they play important parts in the evaluation of system performance. In the
343 following experiments, we validate SHG by simulation, Java language is used to construct
344 SHG and Fat-Tree DCN simulation platforms.

345

346 (1) Experiment 1. We compare SHG with Fat-Tree. We assume that such network structures
347 interconnect the same number of servers with the same type of switches. and the network
348 traffic across all links is 1Gbps. By simulating the all-to-all traffic within the data center, we
349 test ABT trends under server failure rate. We kept the server scale fixed to 256 and 1024,
350 respectively. For SHG, Given SH(97,6), SH(384,9). Then 256 links and 1024 links are
351 randomly selected from SH(97,6) and SH(384,9), respectively. All the selected links are
352 used to place the servers. Fig.4 shows the results w.r.t. an increasing server failure rate. In
353 the legend, N and TF are denoted as the number of servers and Fat-Tree, respectively.



354

355

356

357

Fig.4. FTRouting algorithm

358 By Fig.4, it is clear that two kinds of structure show a relatively smooth downward trend with
359 the rise of the server failure rate. The declining trends in ABT of SHG structure become
360 more gradual, indicating that the impact of the expansion of SHG scale on performance is
361 small. In the same network scale, the ABT of SGH is lower than that of Fat-Tree. Moreover,

the larger the scale of DCN, the larger the ABT gap between SGH and Fat-Tree. This shows that the hierarchical structure of SGH makes the network traffic more evenly, thereby reducing the probability of occurrence of bottleneck flow.

(2) Experiment 2. Fig. 5 depicts ML vs. TP for three SHG of SH(536, 10)={CH₉, CH₄, CH₃}, SH(602, 10)={CH₉, CH₆, CH₄, CH₃, CH₁} and SH(794, 10)={CH₉, CH₈, CH₄, CH₃, CH₁}.

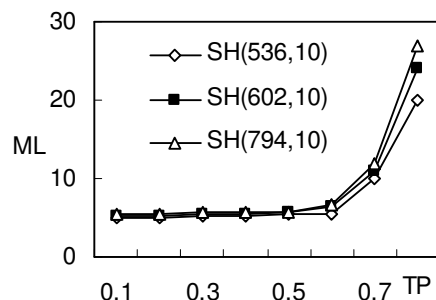


Fig.5. ML vs. TP for SH(536,10), SH(602,10), and SH(794,10)

For the three SHGs, ML grows slowly until T reaches 0.6, and starts to change quickly thereafter. The results imply that SHG can ensure good scalability.

6. CONCLUSIONS

In this paper, we propose SHG, a scalable hierarchical approach, to provide the topology of architecting DCN. SHG is defined based on CHG. We design and implement the shortest path routing and the fault-tolerant routing algorithms in SHG, and derive conclusions from the simulation experiments. The results show that SHG can easily be constructed, while ensuring good scalability.

REFERENCES

- [1]Al-Fares M, Loukissas A, Vahdat A. A scalable, commodity data center network architecture. ACM SIGCOMM Computer Communication Review. 2008; 38(4): 63-74.
- [2]Mysore R N, Pamboris A, Farrington N, Huang N, Miri P, Radhakrishnan S, et al. PortLand: a scalable fault-tolerant layer 2 data center network fabric. SIGCOMM. 2009; 9: 39-50.
- [3]Heller B, Seetharaman S, Mahadevan P, Yiakoumis Y, Sharma P, Banerjee S, et al. ElasticTree: Saving Energy in Data Center Networks. NSDI. 2010; 10: 249-264.
- [4]Greenberg A, Hamilton J R, Jain N, Kandula S, Kim C, Lahiri P, et al. VL2: a scalable and flexible data center network. Communications of the ACM. 2011; 54(3): 95-104.
- [5]Farrington N, Porter G, Radhakrishnan S, Bazzaz H H, Subramanya V, Fainman Y, et al. Helios: a hybrid electrical/optical switch architecture for modular data centers. ACM SIGCOMM Computer Communication Review. 2011; 41(4): 339-350.
- [6]Wang G, Andersen D G, Kaminsky M, Papagiannaki K, Eugene Ng T S, Kozuch M, et al. c-Through: Part-time optics in data centers. ACM SIGCOMM Computer Communication Review. 2011; 41(4): 327-338.
- [7]Chen K, Singla A, Singh A, Ramachandran K, Xu L, Zhang Y, et al. OSA: an optical switching architecture for data center networks with unprecedented flexibility. IEEE/ACM Transactions on Networking (TON). 2014; 22(2): 498-511.

- 404 [8]Halperin D, Kandula S, Padhye J, Bahl P, Wetherall D. Augmenting data center networks
405 with multi-gigabit wireless links. *ACM SIGCOMM Computer Communication Review*,
406 ACM. 2011; 41(4): 38-49.
- 407 [9]Vardhan H, Ryu S R, Banerjee B, Prakash R. 60ghz wireless links in data center
408 networks. *Computer Networks*. 2014; 58: 192-205.
- 409 [10]Guo D, Chen T, Li D, Liu Y, Liu X, Chen G. BCN: Expansible network structures for data
410 centers using hierarchical compound graphs. *INFOCOM, 2011 Proceedings IEEE*. 2011;
411 61-65.
- 412 [11]Wu H, Lu G, Li D, Guo C, Zhang Y. MDCube: a high performance network structure for
413 modular data center interconnection. *Proceedings of the 5th international conference on*
414 *Emerging networking experiments and technologies*. ACM. 2009; 25-36.
- 415 [12]Huang L, Jia Q, Wang X, Yang S, Li B. Pcube: Improving power efficiency in data center
416 networks[C]//*Cloud Computing (CLOUD), 2011 IEEE International Conference*. 2011; 65-
417 72.
- 418 [13]Kliazovich D, Bouvry P, Khan S U. DENS: data center energy-efficient network-aware
419 scheduling. *Cluster computing*. 2013; 16(1): 65-75.
- 420 [14]Perelló J, Spadaro S, Ricciardi S, Careglio D, Peng S, Nejabati R, et al. All-optical
421 packet/circuit switching-based data center network for enhanced scalability, latency, and
422 throughput. *Network, IEEE*. 2013; 27(6): 14-22.
- 423 [15]Ghosh A, Ha S, Crabbe E, et al. Scalable multi-class traffic management in data center
424 backbone networks. *Selected Areas in Communications, IEEE*. 2013; 31(12): 2673-2684.
- 425 [16]Koutitas G, Tassiulas L. Smart grid technologies for future radio and data center
426 networks. *Communications Magazine, IEEE*. 2014; 52(4): 120-128.
- 427 [17]Singla A, Godfrey P B, Kolla A. High throughput data center topology design.
428 *Proceedings of the 11th USENIX conference on networked systems design and*
429 *implementation*. USENIX Association, Berkeley. 2014; 29-41.
- 430 [18]Dong B. Architecting Large Scale Wireless Sensor Networks Publish/Subscribe
431 Applications: A Graph-Oriented Approach. *Applied Mechanics and Materials*. 2013; 321:
432 2768-2771.
- 433