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Fine-grained Energy-efficient Data Center Traffic Scheduling Mechanism Based on Hierarchical Control

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Abstract. *With the continuous expansion of the data center, its energy consumption is also increasing. Aiming at the problem that the high redundancy of modern data center network causes low energy-consumption utilization, this paper proposes an energy-saving traffic scheduling algorithm (IMV-MLF) based on improved multi-layer-virtual-topology combined with maximum link-utilization path priority, which realizes more fine-grained control of each layer of virtual topology in data center network. Firstly, the relevant shaping linear programming mathematical model is established according to the optimization goal of energy conservation, which can minimize the energy consumption of the whole network as far as possible under the premise of meeting all network-flow requirements; Then, according to the optimization goal, the existing SDN based energy saving multi-layer-virtual-topology (EMV-SDN) method is improved. Whether the network devices in other layers are enabled is determined by the overall traffic level rather than the traffic level of a single link. On the basis of the opened level, the newly arrived network flows are preferentially allocated to the path with the highest link utilization, and overload link set is introduced, we can effectively use the available link routes with sufficient residual bandwidth to reduce congestion when the topology changes by marking the links whose link utilization reaches the critical value, and further count and close the links and switches which no network flows pass through. The experimental results show that the performance of IMV-MLF algorithm is better than multi-layer virtual topology energy saving (EMV-SDN) algorithm and the equivalent multipath (ECMP) algorithm in saving network energy. This result is helpful to provide another new idea for energy conservation of data center.*

Keywords: SDN (software defined network); energy saving; data center network; multi-layer virtual topology; link utilization

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1. Introduction.

In recent years, thanks to the rapid upgrading of computer networks and communication technologies, the Internet industry has ushered in a vigorous development. Clients have more demands and restrictions on network flows. In order to effectively cope with the increasing demand for large-scale network flows, the scale of the data center network, as an important part of the information world, has also experienced explosive growth. However, the problem of high energy consumption not only poses a huge challenge to energy, but also in turn restricts its own operation, maintenance and development [1]. At the same time, it is accompanied by huge heat production and heat dissipation consumption of electric energy, and it further increases the energy consumption of the data center. In the past five years, the energy consumption of China's data centers has maintained a growth rate of 15%, and the power consumption in 2020 has exceeded 2% × 1011 kW·h, accounting for 2.7% of the total power consumption of the country [2]. In the future, with the expansion of network demand and scale, this proportion will further increase. Therefore, the research on energy conservation of data center network has become a hot topic at present.

The traditional data center network is mostly a traditional three-layers tree-type network structure [3], which is restricted by the root node. Its poor scalability, complex management and high maintenance costs make it difficult to adapt to the needs of new business development [4]. And because of the coupling characteristics of the control part and the forwarding part, the traditional data center switch can not be managed uniformly, nor can it obtain the information of the entire topology and the overall real-time traffic, so it can hardly achieve energy saving traffic scheduling from a global perspective .In view of the limitations of the traditional data center network in terms of technology and structure, the Software Defined Network (SDN) technology proposed by Professor Mckeown of Stanford University in the United States and the Fat-Tree network topology proposed by a team from the Department of Computer and Engineering in California in the United States came into being [5]. The former decoupled the switch forwarding plane from the control plane [6], The control part of each switch is concentrated in the software programmed controller, so that the controller can uniformly schedule and manage the traffic from the global perspective; As a "rich-connection" network structure, the latter has the characteristics of simple structure and high redundancy [7]. It can provide multiple available paths for communication between servers, and also effectively solve the problem of link congestion. Therefore, the Fat-Tree network structure based on SDN is widely used by modern data center networks.

At present, the Equal Cost Multi-Path (ECMP) routing algorithm [8] is used in many data center networks to schedule network flows. Based on the high redundancy of the network structure of modern data centers [9], there are multiple available equivalent paths for data flows with the same origin and purpose. The ECMP routing algorithm evenly distributes network flows to multiple alternative equivalent paths through hash functions, thus balancing the load of network, effectively avoiding one or more links from being occupied too much to affect the network quality of service. Although many experts and scholars have proposed new schemes for data center network structure optimization and flow load balancing, these schemes do not focus on energy conservation. Because of its highly redundant design concept, the Fat-Tree data center network has many other equivalent links and devices in addition to the basic links that ensure each server node can reach [10]. Obviously, it will waste energy if all devices work under low traffic load, so there is still a lot of room for improvement in energy conservation [11].

Aiming at the common energy consumption problem of the SDN based Fat Tree network architecture in modern data center networks, this paper proposes This paper proposes an energy saving traffic scheduling algorithm based on improved multi-layer virtual topology and maximum link utilization path first (IMV-MLF). The rest of this paper is arranged as follows: Firstly, introduce the work related to energy saving flow scheduling in the modern data network center, and then establish the corresponding mathematical model with the minimum energy consumption as the optimization objective function. Secondly, describe the energy saving flow scheduling mechanism IMV-MLF, which is based on the improved multi-layer virtual topology combined with the maximum link utilization priority method, for solving the mathematical model. Finally, the performance of this method is verified by the comparative analysis of simulation experiments, and the above work is summarized.

2. Related Work.

The existence of SDN technology enables the controller to conduct traffic scheduling and network equipment management from a global perspective, thereby achieving energy saving for the entire data center network. Some scholars have studied and proposed related energy saving methods.

Kurroliya et al. [12] put forward the method of grey wolf perceived energy saving, which is different from the traditional edge weight optimization algorithm. It takes network energy saving and load balancing as the goal, randomly assigns weights to links, treats the combination of link weights as chromosomes, and constantly updates the combination of link weights through genetic algorithm and grey wolf strategy in iteration to find the optimal path solution for flow requests. This method makes a balance between energy saving and load balancing, but obviously there is still much room for improvement in energy saving performance.

Wei et al. [13] proposed a routing algorithm based on polynomial logic regression model, which uses the polynomial logic model to calculate the transmission probability on each transmission path based on the energy consumption cost for the network flow, set the priority for the flow according to its size, and select the appropriate path for the flow according to the priority order. This method performs well in saving energy and shortening the streaming time, but the performance in terms of network throughput remains to be considered.

Li et al. [14] proposed the exclusive routing scheme, aiming to achieve energy conservation by reducing the average completion time of stream transmission to reduce the working time of the switch. The scheme assigns priority to the flow according to the size of the network flow. The size of the flow is inversely proportional to the priority, while the high priority flow will occupy all the resources of the transmission path in a preemptive manner for transmission. The results show that the scheme can effectively improve the link utilization while achieving energy conservation.

Liu et al. [15] proposed a flow aggregation model based on flow correlation. Its core idea is to transfer network flows to devices with high traffic for routing in consideration of the cost of convection migration and energy consumption, so as to close devices without traffic flow to achieve energy conservation. This model aims at the problem that the network link has the maximum capacity. Because there are two different characteristics between network flows, in which the positively correlated network flows may overlap with each other and exceed the constraint of the maximum capacity of the link. Therefore, the model specifically sets the relevant threshold to integrate the network flows whose correlation coefficient is within the constraint range to release more idle devices and sleep them. The performance of this method in terms of energy saving is in line with expectations, but it will add a small amount of time cost.

Zhang [16] proposed an energy saving algorithm based on algebraic connectivity. This algorithm calculates the algebraic connectivity of the graph theory model corresponding to the network topology, and assigns each link with the corresponding link criticality according to the obtained algebraic connectivity. The lower the criticality value, the easier it is for the link to be shut down or hibernated. Then, it is arranged in ascending order according to the criticality of each link, and sleep operations are performed in a queue manner, At the same time, it checks whether the graph algebraic connectivity after link removal is lower than the preset threshold to ensure the minimum connectivity of the network. This method has better application because of its low computational complexity and no need to obtain real-time traffic data. However, the correlation between algebraic connectivity and network connectivity needs further research.

Zhang and Han [17] put forward the scheme of independent path set management, which divides the original topology into several parallel minimum independent path sets that have no high-level relationship with each other by addressing the device. There is no overlapping link between each path set and it can meet the minimum connectivity requirements. This scheme can ensure the quality of network service, but its performance in long-term traffic prediction needs to be improved. Li et al. [18] proposed an energy saving traffic scheduling algorithm based on multi-layer virtual topology, which divides the original physical topology into multi-level virtual topology, determines the switch status of each layer of virtual topology according to the traffic situation, and reduces the number of working switches as much as possible by controlling the whole layer of virtual topology to achieve energy conservation. This method is superior to traditional ECMP and Dijkstra algorithms in reducing energy consumption. However, the determination of whether to enable the topology of other layers is easily affected by the accidental factors of individual links, which may be too sensitive to the traffic changes of a single link and lack stability. In addition, there is still room for refinement in the management granularity of the hierarchical control method, which has the potential to achieve better energy-saving effects.

Therefore, this paper proposes an energy saving traffic scheduling mechanism based on improved multi-layer virtual topology method and maximum link utilization path first algorithm (IMV-MLF) . This mechanism improves the original multi-layer virtual topology method. The average link utilization of the network as a whole replaces the maximum link utilization of a single link with the set threshold as the judgment basis for the status of other layers of virtual topology. The level of the opened topology is determined by the overall traffic level in the network, It can avoid the network jitter caused by the frequent changes of the working state of the whole layer equipment caused by the accidental factors of a single link, and improve the stability of the network. After determining the specific level of the virtual topology, the controller collects the current link information to get a collection of all available paths. Taking the link utilization value as the weight value, the average weight value of each available path is calculated and sorted. The path with the largest weight value is selected as the forwarding path of the new flows, and then the flow table is issued to the switch to route the network flows, Then, the switches and links that no traffic passes through are further closed, so as to achieve more fine-grained control of the overall network and further improve energy efficiency.

3. **Mathematical model of energy-saving flow scheduling problem.** Aiming at the problem of energy saving traffic scheduling in data center network, this paper establishes a corresponding mathematical model. This model takes the pursuit of minimum energy consumption as the objective function. On the premise that all data flows meet all constraints, the whole network can process as many network flows as possible with as few switches and links as possible to improve energy efficiency. The introduction of symbols and variables and the specific description of the model are as follows:

In this paper, graph $G(N, L)$ is used to represent the original physical topology of the data center network, where N is the collection of switch nodes, and L represents the collection of all network links. At the same time, symbol F is introduced to represent the collection of all network flows that need to be scheduled. For $n \in N$, $l \in L$ and $f \in F$, they respectively correspond to a single element in each set, that is, a single switch, a single link and a single network data flow, and c_l represents the maximum network bandwidth (capacity) that a single link can withstand. For any network flow f, the source switch node, the destination switch node and the required bandwidth of the network flow are represented respectively as n_f^s, n_f^d and b_f.

In order to describe the constraints in the mathematical model more accurately, the paper introduces five binary variables with values of 0 or 1 such as $\lambda_n, \lambda_l, \lambda_f^l, \lambda_f^s$ and λ_f^d . Among them, λ_n and λ_l indicates whether switch node n and link l are in the enabled state respectively. If they are enabled, set the value to 1. Otherwise, set the value to 0. λ_f^l indicates whether the stream f flows through the link l. λ_f^s and λ_f^d respectively describe whether the network flow f is sent from the source switch s to the destination switch d. In addition, the symbols S and D are used to indicate source switches and destination switches of the network flow matrix F respectively. $Ln+$ and $Ln-$ indicates the set of inbound and outbound links connected to node n.

This model takes improving energy efficiency (energy conservation) as the core. For the arriving flow matrix F in the network topology graph $G(N, L)$ of the certain structure, while ensuring the network service quality, the energy conservation effect is measured by the energy consumption cost of the network equipment in the working state. The energy consumption of the network equipment is mainly the sum of the energy consumption $COST_n$ of the working switches and the energy consumption $COST_l$ of the working links. Therefore, the optimization objective function and constraint conditions of the model can be expressed in the following Equations (1) to (9):

$$\min \sum_{n\in N, l\in L} (COST_n * \lambda_n + COST_l * \lambda_l) \tag{1}$$

$$\sum_{f\in F} c_f \bullet \lambda_f^l \le c_l; l \in L \tag{2}$$

$$\sum_{s\in S} c_f \bullet \lambda_f^s = \sum_{d\in D} c_f \bullet \lambda_f^d; f \in F \tag{3}$$

$$\sum_{l\in L_{n^+}} c_f \bullet \lambda_f^l - \sum_{l\in L_{n^-}} c_f \bullet \lambda_f^l = -c_f; n = n_f^s, f \in F \tag{4}$$

$$\sum_{l\in L_{n^+}} c_f \bullet \lambda_f^l - \sum_{l\in L_{n^-}} c_f \bullet \lambda_f^l = 0; n = N - \{n_f^s, n_f^d\}, f \in F \tag{5}$$

$$\sum_{l\in L_{n^+}} c_f \bullet \lambda_f^l - \sum_{l\in L_{n^-}} c_f \bullet \lambda_f^l = c_f; n = n_f^d, f \in F \tag{6}$$

$$\lambda_n = \max \lambda_l; n \in N, l \in L_{n^+} \bigcup L_{n^-} \tag{7}$$

$$\lambda_l \le \lambda_n; n \in N, l \in L_{n^+} \bigcup L_{n^-} \tag{8}$$

$$\lambda_n, \lambda_l, \lambda_f^l, \lambda_f^s, \lambda_f^d \in \{0,1\}; n \in N, l \in L, f \in F \tag{9}$$

Equation (1) is the objective function of the model, which represents the minimum energy consumption of network devices (switches and links) when scheduling network flows under the constraints. Equation (2) indicates that the sum of the bandwidth of all network flows simultaneously routed in any link should not exceed the maximum bandwidth of the link. Equation (3) is a flow conservation constraint, that is, the size of all data flows originating from the source switch node and the size of all data flows received at the destination switch should be consistent. Equation (4) Equation (6) are the flow constraints of each type of switch node on the path of network flow *f*, that is, the source node can only send the network flow, the intermediate node can receive the flow and the forwarded flow offset each other, and the destination node can only receive the network flow. Equation (7) and Equation (8) are the shutdown/hibernation conditions of network equipment, where Equation (7) is the shutdown condition of switch node. When any link connected to it is in working state, the switch cannot be shut down, otherwise, it can be shut down; Equation (8) is the link energy saving condition, and its principle is similar to Equation (7). Equation (9) declares the value range of the five introduced binary variables.

The above problem is a NP-hard energy-saving optimization problem with multiple constraints [19]. Traditional flow scheduling algorithms often only aim at minimizing the average/maximum link utilization, without considering energy conservation, and it can not achieve an effective balance between network performance and energy efficiency. The proposed EMV-SDN method is based on the idea of whole layer's control to achieve energy conservation. Although it has a good performance in improving energy efficiency, it can obviously be further refined to specific equipment individuals in the layer in terms of control granularity to further save energy. Therefore, on the basis of EMV-SDN, this paper improves this method, so that it can be opened to the corresponding topology level according to the overall traffic level, and further close the non-traffic devices at the current level by using the flow merging strategy.

4. Energy saving traffic scheduling algorithm IMV-MLF.

4.1. **Algorithm description.** The IMV-MLF energy-saving traffic scheduling mechanism proposed in this paper is an improvement based on the existing EMV-SDN method. This method uses the original minimum spanning tree method to build the virtual topology of each layer. In order to avoid network jitter caused by frequent changes in the topology opening level affected by a single link, the maximum link utilization is replaced by the average link utilization that can better reflect the overall level of traffic in the topology as the judgment basis for changing the virtual topology level. At the same time, the method of giving priority to the one with the highest link utilization is combined, It realizes the combination of whole layer control and inner layer control to pursue higher energy efficiency. In addition, on the logic level, the original settings of network device pre-startup are removed, the time threshold T and link utilization threshold U are adjusted, and overload link sets and other logic are added to avoid link overload and affect network quality of service. The algorithm is shown in Figure 1 and is described as follows:

(1)According to the minimum spanning tree algorithm, the entire physical topology is generated into a multi-layer virtual topology with corresponding layers according to the number n of core-layer switches.

(2) Open the first layer of virtual topology.

(3) Input the network flow matrix and the flow monitoring software sflow-rt summarizes and analyzes the sampling data of the sflow agents configured on each switch to obtain the current link conditions and the overall flow level.

(4) Calculate the average link utilization u of all current working links. If $u \geq threshold U_1$ and duration $t \geq threshold T$, a higher layer of virtual topology will be enabled; Otherwise, the current topology level will remain unchanged.

(5) At the enabled virtual topology level, calculate all available paths.

(6) According to the source node and destination node of the flow, select the appropriate path from the set of available paths, and take the link utilization of the link as the weight value to select the optimal path as the routing path.

(7) According to the calculated optimal path, the controller sends the flow table to the corresponding switches for routing.

(8) Count the switches and links that are enabled at the current level but no traffic flows through, and perform the shutdown/hibernation operation.

(9) If the average link utilization $u \leq threshold U_2$ and the duration time $t \geq threshold T$, the current highest level virtual topology is closed, otherwise, go to step (6).

(10) Judge whether the currently opened virtual topology level is 1 and there is no network flow requiring scheduling and routing. If yes, the algorithm ends and waits for the new network flow matrix input; Otherwise, perform step (6).

4.2. **Construction method of multi-layer virtual topology.** Based on the feature that the data center network mostly adopts the Fat-Tree topology structure, in order to realize the whole layer control, the whole physical topology can be divided into several virtual layers at the logical level from the perspective of the core layer switches. Now, take the Fat Tree topology with k=4 as an example to elaborate the method of multi-layer virtual topology. The specific steps are as follows:

(1)Obtain key information such as original topology switch nodes and links through the controller.

(2) According to the number of core layer switches ($n = 4$), the Kruskal algorithm is used to generate n minimum spanning trees ($MST_1, MST_2, \ldots, MST_n$).

(3) Use MST_1 as the first layer virtual topology.

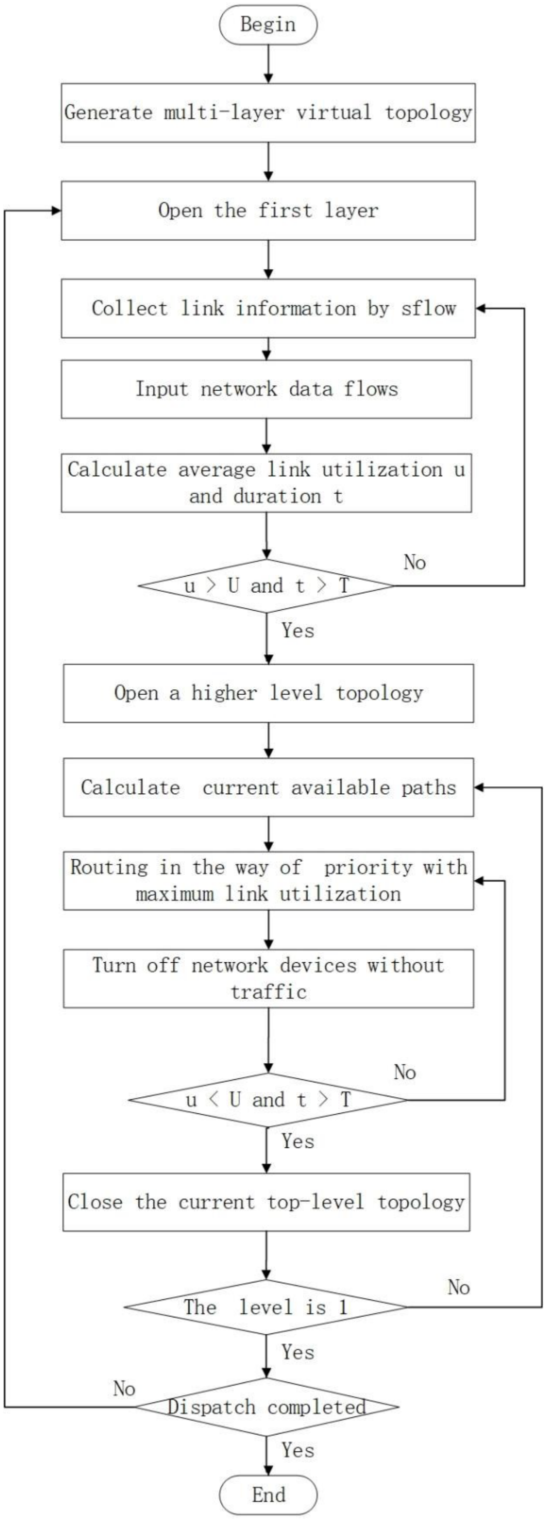

Figure 1. IMV-MLF Algorithm Flow Chart

(4) Traverse MST_2 to see if there are elements that are duplicate with MST_1. If there are, use MST_2 after deleting duplicate elements as the second layer virtual topology; Otherwise, directly use MST_2 as the second layer virtual topology.

(5) For $MST_i (i = 3, 4)$, traverse all $MST_m (m < i)$ to see if there are elements that are the same as MST_i. If there are, use MST_i after deleting duplicate elements as the layer i virtual topology; Otherwise, MST_i is directly used as the layer i virtual topology.

(6) If $i < n$, return to step (5); If $i \geq n$, it ends.

Each layer of virtual topology with relatively independent logical layers constructed by the above method is the certain set of elements that are determined and have no intersection. The original physical topology can also be regarded as the superposition of all virtual topologies. The number and energy consumption of switch nodes and links in the virtual topology of each layer constructed by this method are shown in Table 1.

Table 1. Energy consumption of each layer of virtual topology.

Virtual level	Switch number	Link number	Energy consumption/W	Proportion
1	13	12	1818.76	0.6215
2	1	4	184.36	0.063
3	5	12	738.76	0.252
4	1	4	184.36	0.063

4.3. **Fine-grained control method in the inner layer.** After the original EMV-SDN method determines the level of virtual topology, it adopts the greedy algorithm routing strategy with the goal of minimizing the maximum link utilization in the layer. This strategy pursues the minimum number of hops and selects the path with the minimum link utilization from the shortest path set to achieve load balancing. However, its disadvantage is that the topology status can only be controlled through the whole layer, which leads to a single and fixed topology change mode and a lack of greater space for energy saving. Therefore, in this paper, we choose the method of giving priority to the one with higher link utilization to achieve intra layer fine-grained control to further save energy. The specific steps are as follows:

Step 1: Get the available path set

For active topologies with levels turned on, topology information is collected by the controller. In order to reduce the time complexity, the logic of overloaded link sets is introduced. The links whose link load exceeds the set threshold are included in the overloaded link set. All link elements in the set are not considered when calculating the available paths, and the path set containing all available paths in the current topology is counted.

Step 2: Calculate the average utilization of each path The weighted average value is calculated for all path elements in the available path set with the link utilization value as the weight value. For an available path Pi composed of links $l_1, l_2, \ldots, l_n$, and the current link utilization of each link is $U_1, U_2, \ldots, U_n$, then the weighted average value of the link utilization of the path is calculated as follows: $U_{P_i} = \frac{\sum_{i=1}^{n} l_n}{n}, (n \in N^+)$. At the same time, according to the calculated average link utilization U_{Pi}, the elements in the available path set are sorted from the largest to the smallest.

Step 3: Determine the route path

According to the source node and destination node of the newly arrived network flow, select all eligible path elements from the available path set, and select the path with the largest UPi value as the optimal path to route and forward the flow. If there are paths with the same maximum UPi value, the path with the least hops is preferred as the routing path to release the low load link as much as possible.

This method avoids the impact on the network service quality due to the excessive load of a single link. At the same time, the newly arrived flows are concentrated on the path with higher average load rather than the shortest path as far as possible, effectively leaving the network equipment with low link utilization empty to achieve further energy conservation.

5. **Analysis of experimental results.** In order to verify the energy saving effect of the proposed IMV-MLF algorithm, this paper compares ECMP and EMV-SDN energy saving algorithms as compared methods. In order to more objectively reflect the energy-saving effect of the algorithm, the energy consumption ratio and the maximum link utilization ratio are used as the evaluation indicators of the energy-saving effect of the algorithm and the formulafor calculating the proportion of energy consumption [18] is:

$$\text{Proportion of energy consumption} = \frac{COST_t}{COST_0}$$

In this formula, $COST_t$ is the total energy consumption of all network devices opened in the topology at time t after running the algorithm, and $COST_0$ is the total energy consumption of all network devices opened in the original physical topology [18]. It can be inferred that:

$$\text{Energy saving ratio} = 1 - \frac{COST_t}{COST_0}$$

Therefore, only when the proportion of energy consumption is lower, the proportion of energy saving will be higher, and the relationship between the two is linear and negative.

In terms of energy consumption ratio calculation, this paper divides the energy consumption of network topology into two parts [12], namely, the energy consumption of switches and links in core layer and edge layer. For the convenience of statistics and calculation, the energy consumption of the link is equal to the sum of the energy consumption of the two switch ports connected to the link. The specific reference energy consumption values of each part [19] are shown in Table 2:

Table 2. Energy consumption of network equipment/W

Arrangement	Switch	Link
Core layer	176	2.09
Marginal layer	135	1.80

5.1. Experimental environment.

5.1.1. *Network topology.*

The simulation network structure in this paper is mainly composed of three parts: control terminal, monitoring terminal and topology terminal. In the control terminal, the RYU controller based on python language is used; The monitoring terminal uses sflow-rt software to obtain real-time topology link information; The topology terminal refers to the modern data center network and generates a Fat-Tree topology with k = 4 through the mininet platform. The topology consists of 20 openflow switches, 32 links with bandwidth of 100Mb/s and 16 server hosts, and is connected to the control terminal and the monitoring terminal at the same time.

5.1.2. *Flow mode.*

The experimental network traffic is generated according to different modes by the extended iperf custom commands in the mininet platform. Due to the inhomogeneous distribution of traffic within the data center network, it has a large dynamic and difference. However, from the overall perspective, the size and time of its flow approximately follow the exponential distribution and Poisson distribution. In order to more realistically simulate the internal traffic of the actual data center network, this paper selects three typical traffic patterns [10]: Random, Stride, and Staggered. The specific description is as follows:

Random mode: Each host sends a random size data stream to other hosts with equal probability.

Stride mode: The server host with number i sends data streams to other hosts with number $(i+x)$ mod n, where n is the number of server hosts in the network and x is a user-defined parameter of this mode.

Staggered mode: Each host sends data streams to other hosts belonging to the same edge layer switch with probability P_1, sends data streams to other hosts in the pod partition with probability P_2, and sends data streams to other hosts in the pod with probability $1 - P_1 - P_2$, where P_1 and P_2 are parameters.

5.2. **Comparison of energy consumption proportion.** Based on the above three different traffic modes, this paper calls three energy-saving traffic scheduling algorithms, IMV-MLF, ECMP and EMV-SDN, to compare and verify the difference of energy consumption proportion of each method. In order to avoid the interference of unpredictable accidental factors, several experiments were carried out. Each experiment lasted for 10 minutes. The specific energy saving ratio values of each algorithm at different times were recorded. The experimental results were presented in the form of a line chart, as shown in the figure 2 - figure 4. Wherein, the abscissa represents the time of experiment, in minutes; The ordinate represents the proportion of energy consumption at that time. The experimental results of each algorithm are presented by polylines of different colors.

5.2.1. *Random mode.* The change of energy consumption proportion of the three algorithms in random mode is shown in Figure 2. It can be seen that in this traffic mode, the energy consumption proportion of IMV-MLF is reduced by 6.51%∼26.49% and 4.74% ∼18.64% compared with ECMP and EMV-SDN, and the average energy consumption proportion is reduced by 19.22% and 4.89% respectively.

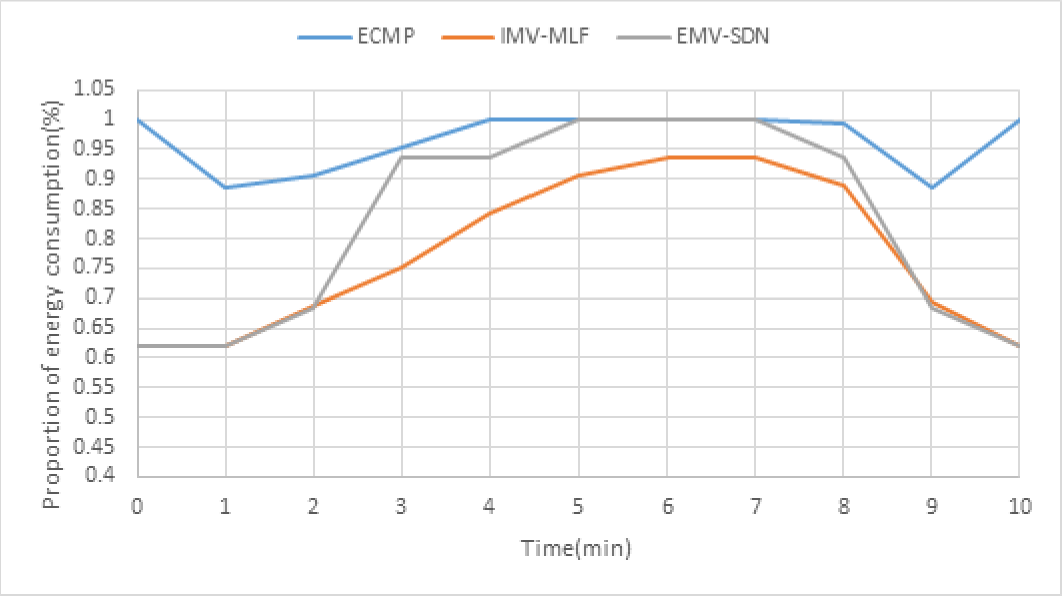

Figure 2. Proportion of energy consumption in Random mode.

5.2.2. *Stride mode.* The actual energy consumption ratio of each algorithm under the interval traffic mode with parameter x=4 is shown in the figure. It can be seen from Figure 3 that the energy consumption ratio of IMV-MLF is 9.47%∼20.57% and -4.75%∼19.08% lower than that of ECMP and EMV-SDN respectively, and the average energy consumption ratio is 17.57% and 6.97% lower respectively.

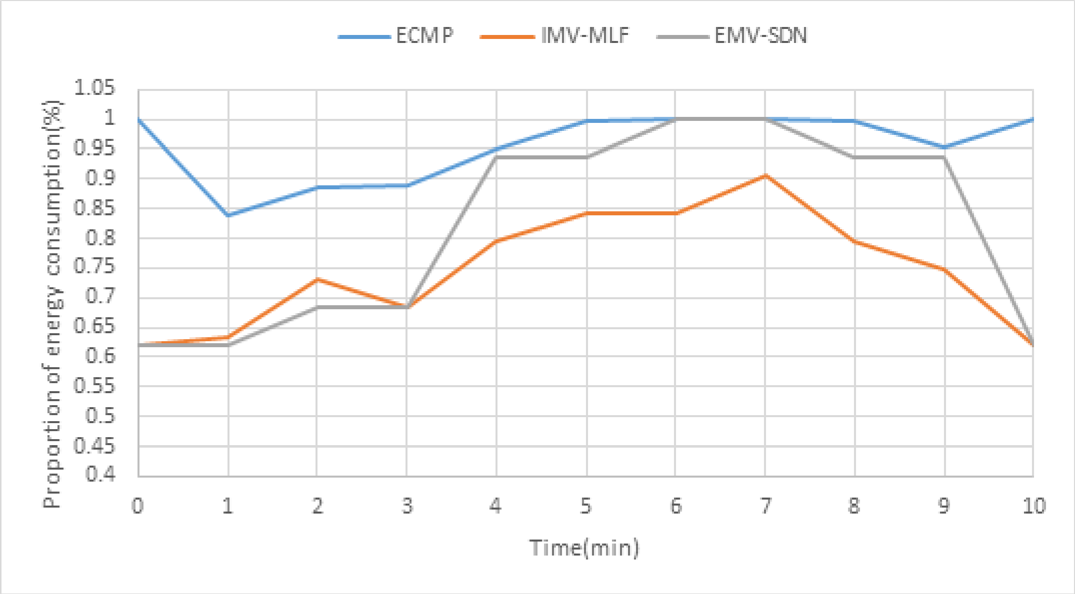

Figure 3. Proportion of energy consumption in Stride (4) mode

5.2.3. *Staggered mode.* Set the interleaving mode parameters P_1 and P_2 to 0 and 0.4 respectively, that is, each host in the topology will not send network flow to the host of the same edge layer switch, the probability of sending network flow to other hosts in the same pod partition is 0.4, and the probability of sending network flow to the host of other pod partitions is 0.6. It can be seen from Figure 4 that compared with ECMP and EMV-SDN, the energy consumption ratio of IMV-MLF decreases by 10.92%∼15.85% and -4.47%∼16.2% respectively, and the average energy consumption ratio decreases by 12.13% and 7.67% respectively. It can be seen from Figure 2 to Figure 4 that the energy consumption ratio of IMV-MLF algorithm is lower than that of EMV-SDN and ECMP algorithm under the three traffic modes. The reason is that the ECMP algorithm does not consider the change of topology, and only uses the hash function to simply select

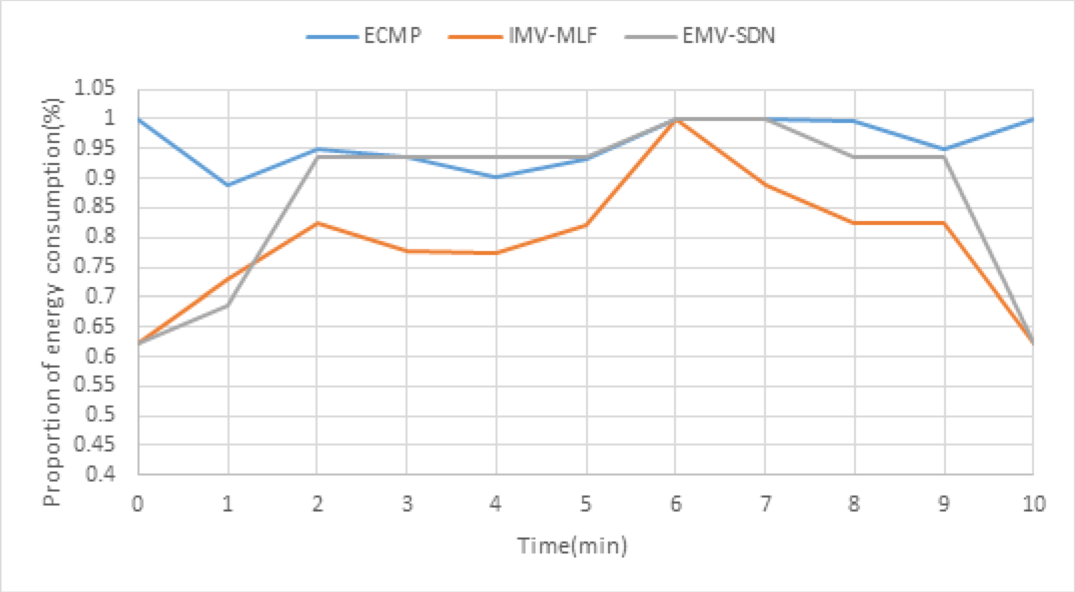

Figure 4. Proportion of energy consumption in Staggered (0, 0.4) mode

equivalent routing paths in the shortest path set. EMV-SDN algorithm can save energy by dynamically adjusting sub topology. The IMV-MLF algorithm is to find the path with the maximum link utilization for the flow in the layer on the basis of hierarchical control, and further release more network devices, so the energy saving effect is better than the other two algorithms.

5.3. **Comparison of maximum link utilization.** In order to reflect the energy saving effect of the algorithm more comprehensively, this paper introduces the maximum link utilization cumulative distribution function graph, and compares the maximum link utilization distribution of IMV-MLF, ECMP and EMV-SDN in random traffic mode. As shown in Figure 5, the horizontal axis represents the maximum link utilization, and the interval frequency is 0.1; The vertical axis represents the cumulative distribution function value, and the frequency is 0.1. The three curves in the figure show that the above three algorithms have been run independently for 20 times in Random mode, and each time lasts for 60 seconds. The data is summarized and the distribution of the maximum link utilization in each frequency interval is counted. It can be seen from the figure that the maximum link utilization of ECMP and EMV-SDN algorithms is concentrated in the range of 70%∼80% and 75%∼90% respectively, while the maximum link utilization of IMV-MLF algorithm is concentrated in 85%∼95%, which is 5%∼10% higher than that of ECMP and EMV-SDN on the whole. The change of maximum link utilization represents the concentration degree of network traffic routing path distribution. In general, when the overall traffic level is close, the higher the maximum link utilization, the more concentrated the traffic is on some links; On the contrary, it means that the traffic is relatively evenly distributed in the topology. Therefore, the maximum link utilization index can also be positively correlated with the energy saving effect of the algorithm to a certain extent.The distribution of the maximum link utilization reflects the balance of the network link traffic load. The higher the maximum link utilization value, the more concentrated the traffic is on some of the link resources as a whole. It also reflects that the traffic can be dormant in the idle state, indicating the high energy efficiency.

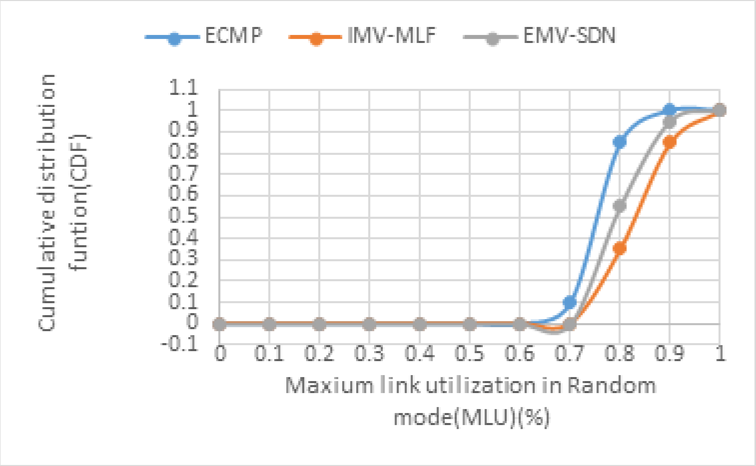

Figure 5. Cumulative Distribution Function of Maximum Link Utilization in Random Mode

5.4. **Comparison of average completion time.** The completion time of network flow mainly includes three parts: routing calculation of convection, flow table distribution and transmission. The comparison effect of the average flow completion time of IMV-MLF, EMV-SDN and ECMP algorithms is shown in Figure 6. The horizontal axis shows different flow patterns, and the vertical axis shows the average flow completion time. It can be seen from the figure that in Random mode, the average stream completion time of IMV-MLF is 1.41% higher than that of EMV-SDN and 18.84% lower than that of ECMP; In Stride (4) mode, IMV-MLF reduces 4.16% and 15.19% respectively compared with the other two methods; In Staggered (0,0.4) mode, it decreases by 6.71% and 19.93%. On the whole, the average stream completion time of IMV-MLF is similar to that of EMV-SDN, and both are significantly better than ECMP. Because IMV-MLF introduces an overloaded link set, the links whose current actual utilization exceeds the set threshold are included in the set, and the elements in the set are not considered in the subsequent path calculation for network flows, thus ensuring the flow transmission efficiency and effectively avoiding link congestion. EMV-SDN takes the maximum link utilization as the basis for changing the topology, and makes the network flow not too concentrated on a single path through equivalent multi-path routing in the layer, reducing the possibility of network congestion. However, ECMP only allocates an equivalent shortest path to the network flow through the hash function when calculating the path of the network flow, and does not take the link utilization as a consideration, so it may affect the quality of service of the network flow.

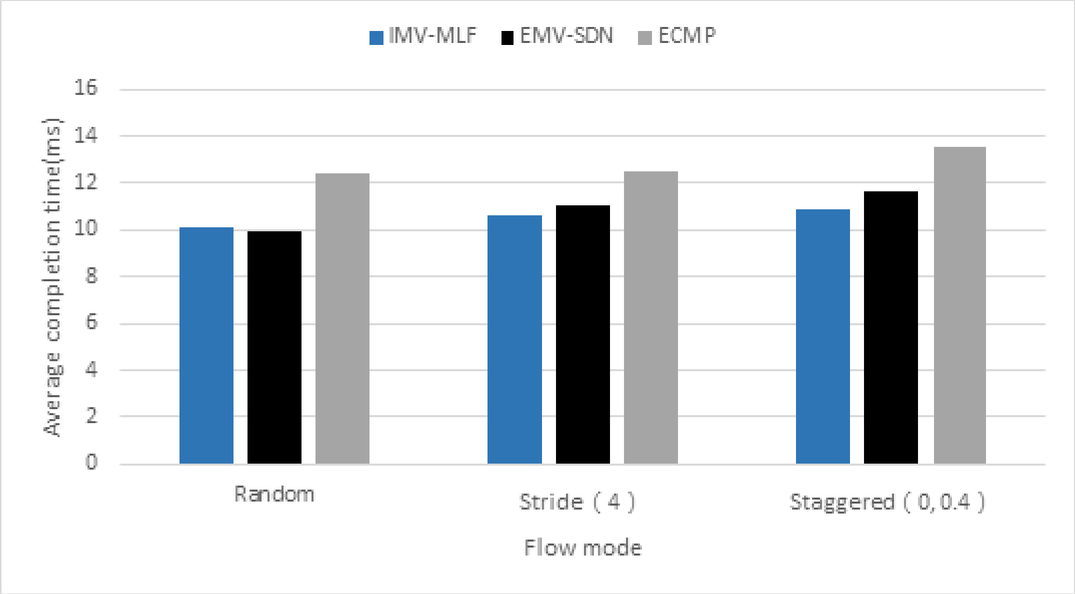

Figure 6. Comparison of Average Completion Time of Streams

In this paper, the energy saving effect of the algorithm is verified by combining the three indicators of energy consumption ratio, maximum link utilization and average flow completion time. From the above experimental results, it can be seen that when the overall traffic level is low at the initial stage, the energy saving effect of the IMV-MLF algorithm is similar to that of the EMV-SDN algorithm, and both are significantly better than the ECMP algorithm. With the increasing input traffic, the energy saving ratio of the IMV-MLF algorithm is obviously better than that of EMV-SDN and ECMP until it is close to the latter two algorithms. The reason is that EMV-SDN algorithm sleeps or turns on devices through the whole layer control, while IMV-MLF algorithm further realizes the fine-grained control of devices in each virtual layer on this basis. When the initial traffic is small, the traffic is distributed in a limited part of the path while ensuring the network quality of service, which can make the rest of the switches and links idle and sleep, and the EMV-MLF algorithm can further release and sleep more devices at the current level. However, when the traffic level gradually rises to a high level, in order to ensure the basic quality of service requirements of network flows(QoS), more network devices must be enabled to support the routing and forwarding of traffic. At this time, there are almost no idle sleepable devices. Therefore, the energy consumption ratio of the IMV-MLF algorithm at this stage has no significant advantage over the other two algorithms. But on the whole, the energy saving effect of IMV-MLF algorithm is better than that of ECMP and EMV-SDN.

6. **Conclusion.** This paper proposes a fine-grained energy-efficient traffic scheduling method based on hierarchical control. This method inherits the idea of hierarchical control of multi-layer virtual topology method. According to the structural characteristics of Fat-Tree topology itself, such as the connection relationship between the core layer switches and other layer switches, and the corresponding number of links, it carries out the topological division of the logical structure, and changes the strategy of intra-layer routing, Replacing the original intra-layer ECMP routing method with the maximum link utilization path priority method makes up for the shortcomings of the original method in terms of energy saving management granularity, and optimizes the control logic of hierarchical change, further improving the energy saving effect. By connecting the code to the corresponding module of Ryu controller and conducting experimental verification under the built simulation network environment, the results show that the energy saving algorithm proposed in this paper have higher energy efficiency than ECMP and EMV-SDN, and can effectively avoid network jitter and link congestion, and ensure the network service performance.

Aiming at the characteristics of high redundancy and high energy consumption of the modern data center network structure of Fat Tree based on SDN, firstly, the algorithm obtains topology information from LLDP message through Ryu controller analysis, divides multi-layer non intersection virtual topology with core layer switch as root node by minimum spanning tree method, determines the level of virtual topology according to the overall traffic level, and selects the path with the largest average weight as the optimal path of flow routing with link utilization as the weight, Sleep the connection and switch in idle waiting state at the same time to reduce energy consumption. The experimental results show that IMV-MLU algorithm is superior to EMV-SDN algorithm and ECMP algorithm in energy saving under three different mainstream traffic modes, and can effectively reduce the proportion of energy consumption. But at the same time, there are still problems to be improved. Because the algorithm takes energy conservation as the primary goal, although it can ensure the basic network quality of service, it does not give good consideration to network load balancing. Therefore, it is the focus of future work to effectively improve the load balancing while saving energy.

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