Software Defined Green Data Center Network with Exclusive Routing

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***Abstract*—The explosive expansion of data center sizes aggravates the power consumption and carbon footprint, which has restricted the sustainable growth of cloud services and seriously troubled data center operators. In recent years, plenty of advanced data center network architectures have been proposed. They usually employ richly-connected topologies and multi-path routing to provide high network capacity. Unfortunately, they also undergo inefficient network energy usage during the traffic valley time. To address the problem, many energy-aware flow scheduling algorithms are proposed recently, primarily considering how to aggregate traffic by flexibly choosing the routing paths, with flows fairly sharing the link bandwidths.**

In this paper, we leverage software defined network (SDN) technique and explore a new solution to energy-aware flow scheduling, i.e., scheduling flows in the time dimension and using exclusive routing (EXR) for each flow, i.e., a flow always exclusively utilizes the links of its routing path. The key insight is that exclusive occupation of link resources usually results in higher link utilization in high-radix data center networks, since each flow does not need to compete for the link bandwidths with others. When scheduling the flows, EXR leaves flexibility to operators to define the priorities of flows, e.g., based on flow size, flow deadline, etc. Extensive simulations and testbed experiments both show that EXR can effectively save network energy compared with the regular fair-sharing routing (FSR), and significantly reduce the average flow completion time if assigning higher scheduling priorities to smaller flows.

I. Introduction

The explosive expansion of data center sizes aggravates the power consumption and carbon footprint. The statistics show that 1.5% of the global electricity usage came from data centers in 2011 [1], [2]. The ever increasing energy consumption of data centers has restricted the sustainable growth of cloud services and raised economic and environmental concerns. Recently people pay attention to the contribution of networking part to the energy consumed by the whole data center. In typical data centers, the network accounts for 10-20% of the overall power consumption [3], while the proportion can be up to 50% if the mature server-side power management techniques are employed [4].

In order to achieve higher network capacity, plenty of "richly-connected" data center network architectures have been proposed to replace the traditional tree architecture, such as Fat-Tree [5], BCube [6], FiConn [7], uFix [8], etc. These architectures employ abundant switches and links to enjoy full bisection bandwidth at traffic peak time. Although these architectures significantly enhance the network performance, there are two *side effects* on the data center energy consumption. First, they increase the energy consumption proportion of the networking part due to the usage of much more switches. Second, they cause inefficient network energy consumption at traffic valley time, because of the low utilization of switches. The fundamental reason for network energy waste is that the energy consumption of today's switches is not proportional to the traffic loads [9], which leads to the fact that idle or under-utilized switches still consume considerable energy.

In order to save the network energy in "richly-connected" data centers, many energy-aware flow scheduling approaches are proposed [10], [11]. The general idea is to aggregate network flows into a subset of switches/links and use as few switches/links as possible to carry the flows. In this way, the active switches can carry more traffic and the idle switches can be put into sleep mode for energy saving. This kind of traffic aggregation naturally results in multiple flows sharing the same switches/links. Based on the TCP congestion control algorithm, the flows get their throughputs by fairly sharing the bandwidths of bottleneck links. We call this kind of energy-aware flow scheduling approach *fair-sharing routing*, or FSR for short.

In this work, we find that FSR in high-radix data center networks usually results in low utilization of some non-bottleneck switches/links, wasting the energy consumption on them. We thus design a more energy-efficient flow scheduling approach called *exclusive routing* (EXR for short), leveraging the emerging software defined network (SDN) technique. Instead of letting flows compete and fairly share the link bandwidths, EXR schedules flows in the time dimension and lets each flow always exclusively utilize the links of its routing path when transmitting data.

At any time, EXR always tries to spread flows to different paths, but it needs to guarantee that every link is occupied by at most one flow at the time, and there are no bottleneck active links in the network. If some flows have to inevitably share links in their routing paths, they are scheduled to transmit one after another without time overlap. EXR leaves flexibility to operators to assign flows with different scheduling priorities, and the priority can depend on flow size, flow deadline, etc. For example, if operators want to reduce the expected flow completion time, they can assign higher priorities to smaller-sized flows; while if the application has deadline requirements, flows with shorter deadlines should be assigned with higher priorities, so as to maximize the number of flows that can be completed before their deadlines.

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EXR scheduling intelligence is put into the SDN controller and virtual switches inside the physical servers, and it requires no update of virtual machines or SDN switches. The design of EXR enjoys additional merits besides improving the energy efficiency of the network. First, it is unnecessary to synchronize the time among servers. The SDN controller globally manages the flows' states and explicitly notifies the virtual switches to permit or suspend a flow. Hence, servers do not need to set timers to trigger flow transmission or worry about the time synchronization among each other. Second, there is no need of bandwidth allocation for specific flows. Since each active flow exclusively occupies all the links in its routing path, EXR does not require rate limiter at the sender or bandwidth reservation at switches for a flow.

We conduct extensive simulations to evaluate EXR in typical data center network topologies, including Fat-Tree and BCube. The results demonstrate that compared with FSR, EXR can effectively save network energy and reduce the average flow completion time if assigning smaller flows with higher scheduling priorities. Besides, we prototype EXR in an SDN environment, and the experiment on a small Fat-Tree testbed shows that EXR makes almost full utilization of the active links, which significantly outperforms FSR and helps reduce the network energy consumption.

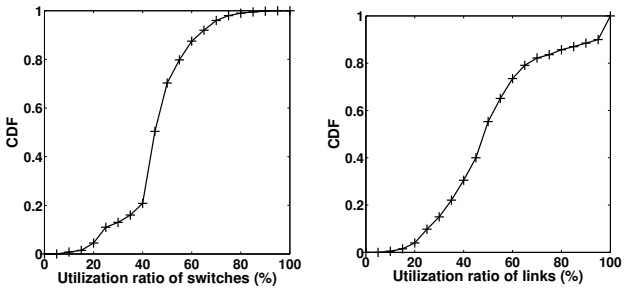
II. Background and Motivation

A. Energy Consumption Model of Data Center Networks

The power consumption of an active switch is composed of two parts, the *fixed* part and the *dynamic* part. The fixed part includes chassis, fans, switching fabric, etc., which always consumes constant power when the switch is on. The dynamic part includes ports. A port can be put into sleep mode with almost zero power consumption, but consumes nearly full power in the active state. We take two examples, namely, Cisco Catalyst 6500 switch and Cisco Nexus 2224TP switch, to show the power consumptions of the two parts. The former switch contains 2 linecards and 48 Gigabit ports in each linecard. The power of the fixed part is 472W while that of each port is 3W [12]. Hence, the dynamic part occupies 38% of the switch's power. The latter switch contains 1 linecard and 24 Gigabit ports. Its fixed part consumes 48W while each port consumes 2W [13], which indicates that the dynamic part occupies 50% of the switch's power.

Since the energy consumption of a switch is not proportional to the traffic load [9] and the dynamic part contributes considerable power to the whole switch, a feasible approach to saving the energy of data center network is to let the idle switches/ports enter sleep mode. It is also recommended by IEEE 802.3az standard [14]. We can then use Eq.(1) to calculate the total amount of network energy used for transmitting a group of traffic flows in a data center. $\mathcal{I}$ and $\mathcal{J}(i)$ denote the set of switches and the set of ports in switch i, respectively. P_i denotes the fixed power consumption in switch i, t_i denotes the active working duration of switch i, $Q_{i,j}$ denotes the power of port j in switch i, and $t'_{i,j}$ denotes the active working duration of port j in switch i.

$$E = \sum_{i \in \mathcal{I}} (P_i * t_i + \sum_{j \in \mathcal{J}(i)} Q_{i,j} * t'_{i,j}) \quad (1)$$



(a) Switch utilization (b) Link utilization

Fig. 1. Cumulative distribution formulation (CDF) of active switch and link utilizations in a Fat-Tree network using FSR.

Since most data center networks employ a homogeneous set of switches to interconnect servers, we assume all the switches have equal fixed power P and all the ports have equal power Q. We further suppose the bandwidth capacity of each port is C. Then we can calculate the total network energy consumption as Eq.(2), where m_i and $m'_{i,j}$ denote the aggregate traffic amount traversing switch i and its port j respectively, while U_i and $U'_{i,j}$ represent the average utilization ratio of switch i and its port j in the transmission duration, respectively.

$$E = P * \sum_{i \in \mathcal{I}} \frac{m_i}{U_i * C * |\mathcal{J}(i)|} + Q * \sum_{i \in \mathcal{I}} \sum_{j \in \mathcal{J}(i)} \frac{m'_{i,j}}{C * U'_{i,j}} \quad (2)$$

From Eq.(2) we draw inspiration that energy consumption of a data center network can be effectively reduced by increasing the utilization ratios of active switches and ports/links, while putting idle switches/ports into sleep mode. Therefore, an energy-efficient flow scheduling approach should improve the utilization of active switches/links as high as possible.

B. Switch/Link Utilization of Data Center Network

As aforementioned, existing works use FSR to schedule data center flows in an energy-efficient way. In order to motivate the necessity of introducing exclusive routing to improve the switch/link utilization, we make a measurement study on the utilization ratio of switches/links under FSR by simulation. We conduct the simulation in a Fat-Tree topology containing 24 pods (3456 servers), and use ECMP [15] to choose the routing paths for network flows given the multiple equal-cost paths between servers. We randomly choose half servers and generate all-to-all traffic flows among them.

Fig. 1(a) and 1(b) show the cumulative distribution of the utilization of active switches and active links, respectively. It demonstrates that the switches/links with zero utilization are less than 5%. On the other side, most switches and links are active but have a low utilization. For switches, about 80% of them have a utilization ratio below 55%, and about 20% of them have a utilization ratio of less than 40%. For links, the utilization of 80% of links is no more than 65%, and about 24% of links have less than 40% utilization. Only less than 1% of switches and less than 10% of links have a utilization higher than 90%. The low utilizations of active switches/links come from inevitable bandwidth competition among flows. These

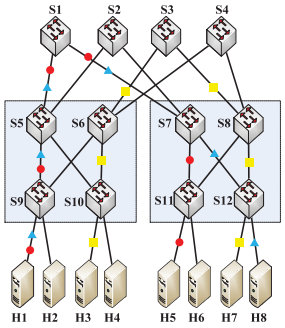
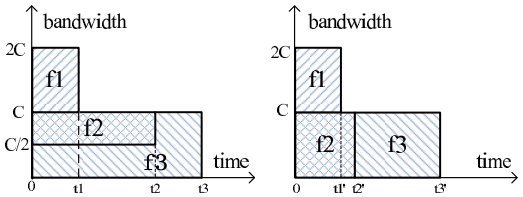


Fig. 2. Route selection of the three flows in a partial 4-ary Fat-Tree network.



(a) Fair sharing routing (c) Exclusive routing

Fig. 3. Scheduling sequence of the three flows. $t1 = \frac{m_1}{C}$, $t2 = \frac{2m_2}{C}$, $t3 = \frac{m_2+m_3}{C}$, $t1' = \frac{m_1}{C}$, $t2' = \frac{m_2}{C}$, $t3' = \frac{m_2+m_3}{C}$.

flows fairly share the bandwidth of bottleneck links by TCP congestion control, and only fully utilize the bandwidth of the bottleneck links. Meanwhile, a great number of non-bottleneck links are under-utilized, which leaves room for more energy-efficient flow scheduling approaches.

III. EXR Design

In this section, we present the design of EXR.

A. Working Example

In order to let readers get a clear idea of how EXR works and illustrate the benefit of EXR over FSR, we first give a working example as follows. As shown in Fig. 2, there is a partial 4-ary Fat-Tree network which contains 12 switches marked with "S" and 8 servers marked with "H". We assume every switch has equal power consumption P, every port has equal power consumption Q, and every link has equal bandwidth capacity of C. Three flows need to be transmitted in the network, namely, flow 1 "H3→H7", flow 2 "H1→H5", and flow 3 "H1→H8". The sizes of the three flows are $m1$, $m2$ and $m3$ respectively (without loss of generality, we assume $m1 \leq m2 \leq m3$). In the network, between any two inter-pod servers there are four available paths, traversing $S1$, $S2$, $S3$ and $S4$ respectively. We assume the three flows arrive at time t=0 simultaneously. When scheduling the flows, flow 1 chooses the path across switch $S3$ (marked with yellow squares), while flow 2 selects the path across switch $S1$ (marked with red circles). The two flows can be transmitted immediately at $t = 0$ since they do not have overlapping links with each other. At what follows we discuss two scheduling solutions for flow 3.

FSR: Flow 3 chooses the path across switch $S1$ (marked with blue triangles in Fig. 2, and it sends data at time $t = 0$, concurrently with flow 1 and 2.

EXR: Flow 3 chooses the same path as FSR, but it begins transmitting data only after flow 2 finishes at time $t = \frac{m_2}{C}$, since its path has overlapping links with flow 2.

TABLE I. FLOW COMPLETION TIME AND NETWORK ENERGY CONSUMPTION IN THE TWO SCHEDULING SOLUTIONS.

	FSR	EXR
Flow 1's completion time	$\frac{m_1}{C}$	$\frac{m_1}{C}$
Flow 2's completion time	$\frac{2m_2}{C}$	$\frac{m_2}{C}$
Flow 3's completion time	$\frac{m_2+m_3}{C}$	$\frac{m_2+m_3}{C}$
Overall network energy	$\frac{P}{C} * (5m_1 + 7m_2 + 5m_3) + \frac{Q}{C} * (10m_1 + 16m_2 + 10m_3)$	$\frac{P}{C} * (5m_1 + 5m_2 + 5m_3) + \frac{Q}{C} * (10m_1 + 10m_2 + 10m_3)$

We show the data transmission processes of the two solutions in Fig. 3, and show the flow completion time and network energy consumption in Table.I. When calculating the network energy, we only consider the active working duration of the involved switches, without taking the power state transition time into account. In FSR, flow 1 sends at rate C as it exclusively occupies the routing path. From t=0 to $t = \frac{2m_2}{C}$, flow 2 and 3 have overlapping links with each other, and hence the transmission rate for each is $\frac{C}{2}$. When flow 2 finishes, the remaining size of flow 3 $(m_3 - m_2)$ can be sent at rate C. By calculating the number of active switches and ports used in each time period, FSR takes a total network power of $\frac{P}{C} * (5m_1 + 7m_2 + 5m_3) + \frac{Q}{C} * (10m_1 + 16m_2 + 10m_3)$ to finish transmitting the three flows.

If we use EXR, flow 3 is not sent before flow 2 finishes. It enables all the three flows to exclusively occupy the full bandwidth C of all links in their routing paths during transmission. Since the bandwidth capacity of the corresponding links can be fully utilized, the overall network energy decreases to $\frac{P}{C} * (5m_1 + 5m_2 + 5m_3) + \frac{Q}{C} * (10m_1 + 10m_2 + 10m_3)$. We can easily figure out that EXR can indeed save network energy compared with FSR. In practical data center network with more switches/links and more flows, the room for energy saving will be much larger.

B. Design Overview

Fig. 4 shows the architecture overview of EXR. EXR works based on SDN. The EXR scheduling intelligence only requires modifying the SDN controller and the virtual switches within servers. The sender/receivers (virtual machines) of the flows and the physical switches in the network are both transparent to EXR. All the flows in the network are classified into two categories, active flows and suspended flow. The virtual switches at the senders permit active flows (at most one active flow from a sender at any time) but block suspended flows.

The EXR scheduling algorithm is triggered when a new flow arrives at the virtual switch or an active flow finishes transmission. In both cases, the virtual switch reports to the SDN controller, and the controller runs the scheduling algorithms presented in Section III-C to update the sets of active flows and suspended flows. There are three cases for the computation results. First, if a new flow becomes active, the controller immediately installs the forwarding entries in the switches and notifies the virtual switch at the sender to permit the flow. Second, if a suspended flow becomes active, the controller just notifies the virtual switch to permit the flow. Third, if an active flow becomes suspended, the controller notifies the virtual switch to block the flow. In whatever case, it is the controller that manages the global flow states. The

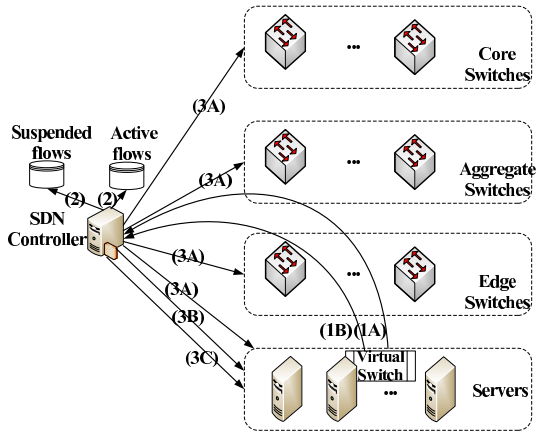


Fig. 4. EXR design overview. (1A) The virtual switch receives a new flow and directs it to SDN controller. (1B) An active flow finishes and the virtual switch reports to SDN controller. (2) SDN controller runs EXR scheduling algorithm, and updates active flows and suspended flows. (3A) If a new flow becomes active, SDN controller installs forwarding entries in switches and notifies the virtual switch to permit the flow. (3B) If a suspended flow becomes active, SDN controller notifies the virtual switch to permit the flow. (3C) If a new flow or active flow becomes suspended, SDN controller notifies the virtual switch to block the flow.

servers do not need to maintain timers to launch specific flows, so it is unnecessary of time synchronization among servers for correct flow scheduling.

When the SDN controller schedules flows by EXR, every active flow exclusively occupies links in its routing path. As a result, there is no need of bandwidth reservation or rate limit for specific flows. If there is no flow in a link, the two ports at the ends of the link are put into sleep mode. When all the ports in a switch are asleep, the switch can be put into sleep. Network energy saving comes from high utilization of switches/links. Note that in the current design, we simply assume all the flows are network-limited, i.e., the applications can generate traffic as fast as possible to saturate the bandwidth capacity of links. It is not difficult to generalize EXR to support application-limited flows, by putting more flows in a link if the available bandwidth allows. But in order to present our idea in a clean way, throughout this paper we focus on network-limited flows.

C. Algorithms

Next we describe the EXR scheduling algorithms run at the SDN controller.

Alg. 1 shows the overall scheduling algorithm of EXR. F_{active} and $F_{suspend}$ denote the set of active flows and suspended flows, respectively. The scheduling is triggered when an active flow finishes transmission or a new flow arrives. The algorithm needs to decide both the routing path and the scheduling state (active or suspended) for each target flow. There are three cases. First, if a path without any other flows can be found for the target flow, the target flow becomes active. This path is called an *idle path* for the target flow. Second, there is no idle path for the target flow, but there exists a path in which all the existing flows in the path have lower priorities than the target flow. Then the target flow will become active,

Algorithm 1: EXR Scheduling

Input:
G: data center network topology;
F_{active}: set of active flows;
$F_{suspend}$: set of suspended flows.
Output:
$\{< e.state, e.path >, \forall e \in F_{suspend} \cup F_{active}\}$:
scheduling state and path of each flow.

```
1  if a flow f in F_active finishes then
2      F_active ← F_active − {f} ;
3      return ScheduleSuspend(G,F_active,F_suspend);
4  end
5  else if a new flow f arrives then
6      < t, p >← PathCalculation(G,F_active,f);
7      if (t =IDLEPATH ∥ t =PREEMPTPATH) then
8          f.state ← ACTIVE; f.path ← p;
9          F_active ← F_active + {f} ;
10         if (t =PREEMPTPATH) then
11             ScheduleSuspend(G, F_active, F_suspend);
12         end
13     end
14     if (t =NOPATH) then
15         f.state ← SUSPENDED; f.path ← p;
16         F_suspend ← F_suspend + {f} ;
17     end
18     return
       {< e.state,e.path >,∀e ∈ F_suspend ∪ F_active};
19 end
```

with existing flows in the path being preempted and suspended. This path is called a *preemptive path* for the target flow. Third, if there is neither idle path nor preemptive path for the target flow, the target flow will be suspended. In each case, if there are multiple eligible paths, the one that traverses the minimum number of idle switches will be preferentially chosen. The purpose is to increase the utilization ratio of active switches.

When a flow f in F_{active} finishes, it is removed from F_{active} and invokes the sub-algorithm ScheduleSuspend(.) to check in turn whether the suspended flows in $F_{suspend}$ can become active (Lines 1-4). When a new flow f arrives at the network, we use the sub-algorithm PathCalculation(.) to calculate the routing path and path type for the flow f (Line 6). If the flow has an idle path or a preemptive path, it is added into F_{active} (Lines 7-9) and scheduled immediately with the calculated routing path. Otherwise, flow f is suspended (Lines 14-17). Note that if calculating a preemptive path for flow f, all the other flows in the suspended set require rescheduling (Lines 10-12) for two reasons. First, the preempted flows may have higher priorities than some active flows. Second, the preempted flows may leave available paths for some other suspended flows.

The sub-algorithms PathCalculation(.) and ScheduleSuspend(.) are described in Alg. 2 and Alg. 3, respectively. Alg. 2 is responsible for calculating the routing path and path type for a target flow f. We first calculate multiple available routing paths for flow f out of the network topology G (Line 1), which is easy to get in regular "richly-connected" data center network. For example, in a Fat-Tree network containing k pods, there are $(k/2)^2$ available paths between two servers

Algorithm 2: PathCalculation(G,F_{active},f)

Input:
G: data center network topology;
F_{active}: set of active flows;
f: the target flow.
Output:
$\{< t, p >\}$: the type and ID of the path for flow f

1 $A \leftarrow$ GetAvailablePathSet(G,f);
2 $B \leftarrow$ SelectIdlePath(A,F_{active});
3 **if** *($B \neq \phi$)* **then**
4 $b \leftarrow$ SelectMxPath(B);
5 **return** <*IDLEPATH*,b >;
6 **else**
7 $c \leftarrow$ SelectPreemptPath(f,A,F_{active});
8 **if** *($c \neq$ NULL)* **then**
9 $D \leftarrow$ PreemptedFlowSet(G,F_{active},f,c);
10 **for** *each flow* $d \in D$ **do**
11 $d.state \leftarrow$ SUSPENDED; $d.path \leftarrow$ -1;
12 $F_{active} \leftarrow F_{active} - \{d\}$;
13 $F_{suspend} \leftarrow F_{suspend} + \{d\}$;
14 **end**
15 **return** <*PREEMPTPATH*,c >;
16 **else**
17 **return** <*NOPATH*,*-1*>;
18 **end**
19 **end**

Algorithm 3: ScheduleSuspend(G, F_{active}, $F_{suspend}$)

Input:
G: data center network topology;
F_{active}: set of active flows;
$F_{suspend}$: set of suspended flows.
Output:
$\{< e.state, e.path >, \forall e \in F_{suspend} \cup F_{active}\}$: scheduling state and path of each flow in $F_{suspend}$ and F_{active}

1 $x \leftarrow 1$;
2 **while** $x = 1$ **do**
3 $x \leftarrow 0$;
4 Sort $F_{suspend}$ by flow priority in a descending order;
5 $F'_{suspend} \leftarrow F_{suspend}$;
6 **for** *each flow* $e \in F'_{suspend}$ **do**
7 $< t, p >\leftarrow$ **PathCalculation**(G,F_{active},e);
8 **if** *(t =IDLEPATH $\parallel$ t =PREEMPTPATH)* **then**
9 $e.state \leftarrow$ ACTIVE; $e.path \leftarrow p$;
10 $F_{suspend} \leftarrow F_{suspend} - \{e\}$;
11 $F_{active} \leftarrow F_{active} + \{e\}$;
12 **if** *(t =PREEMPTPATH)* **then**
13 $x \leftarrow 1$;
14 break;
15 **end**
16 **end**
17 **end**
18 **end**
19 **return** $\{< e.state, e.path >, \forall e \in F_{suspend} \cup F_{active}\}$;

in different pods. In a level-k BCube network, each pair of servers has $k + 1$ disjoint paths. Then we use the function SelectIdlePath(.) to choose an idle path for flow f from the multiple candidates (Line 2). If there is no such path, we use the function SelectPreemptPath(.) to calculate a preemptive path for flow f (Line 7). For the flows that share links with flow f and have lower priorities than flow f (Line 9), they are preempted and put to the suspended set (Lines 10-15). The details of calculating the preemptive path is shown in Alg. 4, where the function FlowSetCrossPath(p,F_{active}) is used to compute the set of active flows whose routing paths share links of path p. The function SelectMxPath(.) is to choose the path that traverses the minimum number of idle switches from multiple candidates.

When an active flow finishes transmission or is suspended due to preemption, the sub-algorithm ScheduleSuspend(.) will be invoked. It is used to check whether the existing suspended flows can be reactivated. In Alg. 3, we first sort the suspended flows in a descending order by their priorities, and then calculate their routing paths and path types (Line 4). If a flow has an idle path or a preemptive path, it becomes active and is scheduled immediately (Lines 8-11). Note that during the process some other active flows may be preempted and become suspended (Line 12-14), which will update the set of suspended flows (refer to Lines 10-14 in Alg.2). When the set of suspended flows changes, we need to immediately reschedule the flows in $F_{suspend}$ (Lines 12-15), for the same reason as that in Alg. 1. The process ends when no more flows are added into the set of suspended flows (Line 2-3).

IV. Simulation

In this section, we evaluate EXR by simulations in typical data center topologies. We will show that compared with FSR, EXR has obvious advantages in saving network energy and reducing the average flow completion time if assigning higher scheduling priorities to smaller flows.

A. Simulation Setup

Network Topology: We use three representative data center topologies, i.e., Fat-Tree, Blocking Fat-Tree and BCube. The capacity of each link is 1Gbps. The oversubscription ratio of the original Fat-Tree network is 1:1, since it provides rearrangeble non-blocking communication service to end servers. As for the blocking Fat-Tree network, we vary its oversubscription ratio by cutting the number of core switches. In a blocking Fat-Tree with k:1 oversubscription ratio, the number of core switches is $1/k$ of that in the original Fat-Tree. Fig. 5 shows an example of a blocking Fat-Tree topology with a 2:1 oversubscription ratio. In all the Fat-Tree and blocking Fat-Tree topologies, we use switches with 24 ports, hence the total number of servers is 3456. For BCube network, we use level-3 BCube with 8-port switches, in which the total number of servers is 4096.

Traffic Flows: Based on the real traces from production data centers, we assume the flow size follows an exponential distribution with the expected size of 64MB, which is the typical size in distributed file system in data centers [16]. The source and destination servers of each flow are randomly cho-

Algorithm 4: SelectPreemptPath(f,A,F_{active})

Input:
f: target flow;
A: set of available paths for f;
F_{active}: set of active flows.
Output:
t: the preemptive path for f.

```
t ← NULL;
T ← φ;
for each path p ∈ A do
    F' ← FlowSetCrossPath(p,F_active) ;
    i ← 0 ;
    for each flow f' ∈ F' do
        if (Priority(f) ≤ Priority(f')) then
            i ← 1 ;
            break;
        end
    end
    if (i=0) then
        T ← T + {p}
    end
    t ← SelectMxPath(T);
end
return t;
```

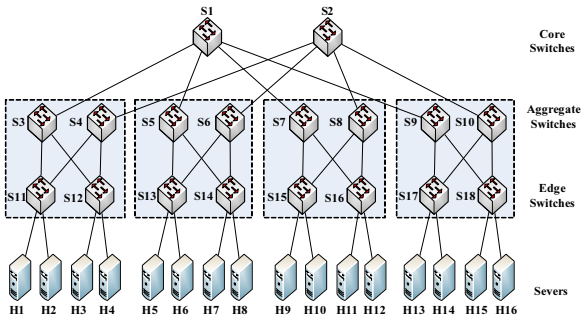


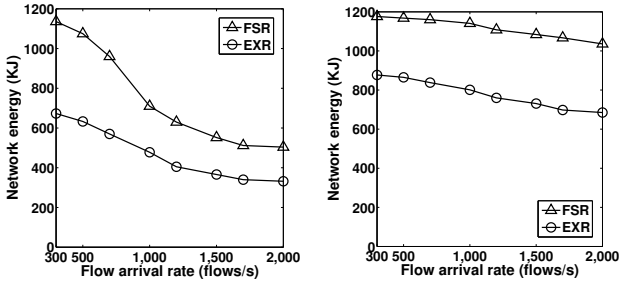
Fig. 5. A blocking Fat-Tree with oversubscription ratio of 2:1.

sen. The arrival rate of the flows follows Poisson distribution. We simulate a total number of 10,000 flows.

Power Parameters: We take the power parameters of a Cisco Nexus 2224TP switch in the simulation. The fixed part consumes 48W while each port consumes 2W [13]. The transition time between active state and sleeping state of switches/ports will account for the total network energy, and we study the impact in Section IV-D. The network energy is calculated using Eq.(1) in Section II.A.

Bandwidth Sharing in FSR: In FSR, each flow is scheduled to run immediately after arrival, and the flows use TCP congestion control algorithm to share the link bandwidths in a max-min fairness manner. ECMP routing is used to choose the next hop given multiple equal options.

Flow Priorities in EXR: We take flow size as the parameter to assign the priorities. A smaller flow always has higher priority than a larger one.



(a) Fat-Tree (b) BCube

Fig. 6. Network energy against flow arriving rate in Fat-Tree and BCube networks.

B. Impact of Flow Arriving Rate

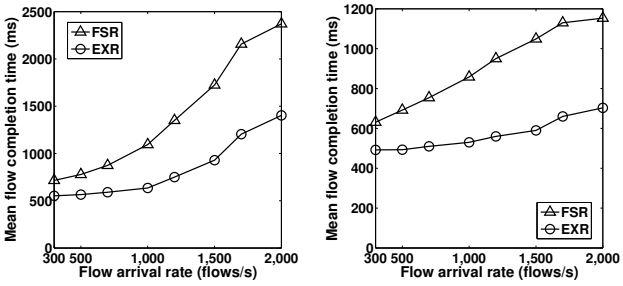
We first study the impact of flow arriving rate in the Poisson arrival. Fig. 6(a) and 6(b) show the network energy used to transmit all the flows against the flow arriving rate in the Fat-Tree and BCube networks, respectively. In Fig. 6(a), we find that the Fat-Tree network energy decreases in both EXR and FSR as the flow arriving rate increases. It is because higher flow arriving rate provides more opportunities for concurrent flows to share the switches, and thus increases the switch utilization ratio and leads to more efficient network energy usage. EXR saves considerable network energy compared with FSR. For example, when the flow arriving rate is 500/second, EXR consumes 40% less network energy than FSR.

Similar results are shown in Fig. 6(b). When the flow arriving rate varies from 300/second to 2000/second, the BCube network energy decreases by more than 20%. The curve of the BCube network is smoother than that of the Fat-Tree network, because the switches in BCube network have much less ports than those in Fat-Tree network, hence the impact of switch multiplexing is lower than in Fat-Tree. In BCube, EXR also consumes much less power than FSR. When the flow arriving rate is 2000/second, EXR saves about 36% network energy compared with FSR.

Fig. 7(a) and 7(b) show the average flow completion time against the flow arriving rate in Fat-Tree and BCube networks, respectively. We find that the average flow completion time ascends with the increase of flow arriving rates. It follows the intuition because when the flow arriving rate is higher, flows are more likely to compete the link bandwidths with each other and as a result they will be transmitted by slower speeds. Compared with FSR, EXR effectively reduces the average flow completion time, in particular at high flow arriving rates. For example, when the flow arriving rate is 2000/second, the average flow completion time in EXR is about 60% of that in FSR, in both Fat-Tree and BCube networks.

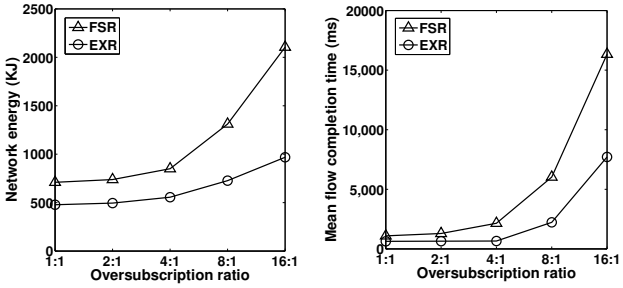
C. Impact of Network Oversubscription Ratio

The non-blocking Fat-Tree topology enjoys high bisection bandwidth and 1:1 oversubscription ratio. However, most of the current data centers still employ blocking multi-rooted tree topologies [17]. Therefore, next we study the energy conservation and flow completion time of EXR in blocking Fat-Tree with different oversubscription ratios. We proportionally eliminate the core switches from the non-blocking Fat-Tree to build the blocking Fat-Tree, and show the simulation results



(a) Fat-Tree (b) BCube

Fig. 7. Average flow completion time against flow arriving rate in Fat-Tree and BCube networks.



(a) Network energy (b) Average flow completion time

Fig. 8. Network energy and average flow completion time in a blocking Fat-Tree against oversubscription ratio.

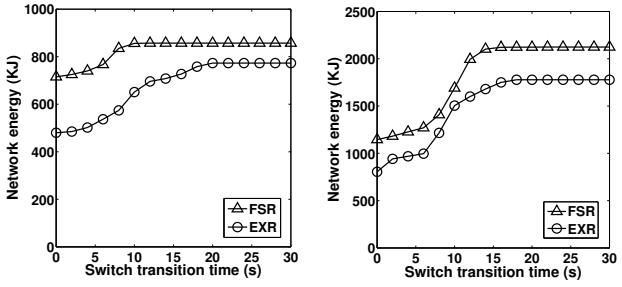
with oversubscription ratios of 1:1, 2:1, 4:1, 8:1 and 16:1, respectively. In this group of simulations, we set the average flow arriving rate as 1000/second.

Fig. 8(a) demonstrates that EXR effectively reduces the network energy consumption in blocking Fat-Tree topologies, and the benefit is more obvious with higher oversubscription ratio. The network energy in either EXR or FSR rises with the increase of the oversubscription ratio. It is because when the network is highly blocked, the traffic loads in active switches are quite unbalanced and many active switches are under-utilized. EXR performs even better than FSR in higher-oversubscribed network, because the active links in EXR are always fully utilized. When the oversubscription ratio is 16:1, EXR can save more than 50% of the overall network energy compared with FSR.

Fig. 8(b) shows the average completion time of the flows, which increases as the oversubscription ratio gets higher. Higher oversubscription indicates more competition among flows. When the oversubscription ratio increases to 16:1, the average flow completion time in FSR is almost twice than that in EXR.

D. Impact of Power State Transition Time

In the simulations above, we do not take the power state transition time of switches and ports into account, and ideally assume that they can go to sleep soon upon idleness. However, in practice the transition time between active mode and sleep mode cannot be simply ignored. It usually takes tens of microseconds to complete a sleep/wake transition for an Ethernet port and several seconds for a data center switch [14], [18], [19].



(a) Fat-Tree (b) BCube

Fig. 9. Network energy against the power state transition time of switches in Fat-Tree and BCube networks.

Next we study the impact of the power state transition time in EXR. We set the average flow arriving rate as 1000/second, and assume that switches and ports can go to sleep only if their sleeping durations are longer than the transition time required.

Fig. 9(a) and 9(b) show the network energy with EXR and FSR against different power state transition times of switches in Fat-Tree and BCube, respectively. We fix the transition time of each port as 10 milliseconds. The results in the two figures demonstrate that EXR enjoys much less network energy than FSR, under whatever power state transition times of switches. For example, when the switch's power transition time is 2 seconds, EXR saves more than 30% and more than 20% network energy compared with FSR, in Fat-Tree and the BCube networks respectively. The network energy also increases when the power transition time is longer, because higher transition time will prevent switches with short idle durations from sleeping. Besides, we observe that when the switch's power transition time is longer than a threshold, the network energy consumed becomes constant. It is because in these cases no switches can go to sleep during the flow transmission process, while the energy saving of EXR comes from that the flows can finish transmission earlier than FSR.

V. Implementation and Experiments

We implement both EXR and FSR by modifying SDN/OpenFlow protocol. For both the scheduling approaches, when a new flow is generated by a virtual machine and arrives at the first-hop switch (virtual switch in the hypervisor), it is directed to the controller. For FSR, the controller directly configures the forwarding entries in the switches along the flow's routing path and replies to the virtual switch to permit the flow. For EXR, the controller should calculate the routing path and scheduling state for the new flow. If the flow is in active state, the controller also immediately configures the forwarding tables in corresponding switches and notifies the virtual switch to permit the flow; otherwise, the controller notifies the virtual switch to block the flow. In EXR, the virtual switch also monitors the completion of flow transmission and reports to the controller, which will also trigger the EXR flow scheduling. Given any change of the flows' states, the controller directly tells the virtual switch to permit a flow or block a flow.

We conduct experiments in a partial Fat-Tree test bed, which contains two pods and 8 servers. The topology is the

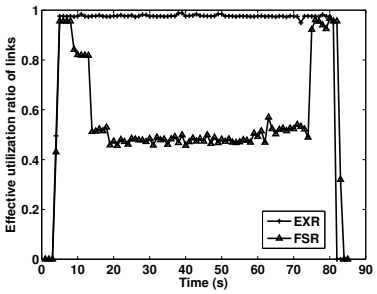


Fig. 10. Effective utilization ratio of links in a Fat-Tree testbed.

same with Fig. 2. All the servers are Desktops with 2.80GHz Intel Duo E7400 processors and 2GB of RAM, and the network cards in the servers are Intel 82574L Gigabit Ethernet cards. H3C S5500-24P-SI series switches are employed to connect the servers in the testbed. We use iperf [20] to generate 16 flows, with average size of 500MB and arrival interval of 1 second. The source and destination servers of the flows are chosen randomly. We run EXR and FSR respectively in the controller to schedule these flows, and show the experiment results in Fig. 10.

We measure the metric of effective link utilization, which indicates the average utilization ratio of all the active links. As aforementioned, a higher effective utilization ratio of links indicates more efficient energy usage of switches/ports. In Fig. 10, we find that the effective link utilization ratio under EXR almost reaches 100% at most time. It is because when using the EXR scheme, there is no competition of link bandwidth among flows. Hence, every flow can fully utilize the link bandwidth of its routing path. In contrast, when using FSR, the average effective link utilization ratio only hovers at around 50% at most time, due to flow competition in bottleneck links and under-utilization in other links.

The experiment results demonstrate that EXR can make flows sufficiently utilize the bandwidths of active links, which helps improve the energy efficiency of data center networks and save the overall network energy given the same traffic load.

VI. Related Works

A. Greening Networks

1) Device-level Techniques: The device-level energy conservation schemes aim to improve the energy efficiency of individual network devices with advanced hardware techniques. Nedevschi et al. [19] claimed that the energy consumption of network devices could be effectively improved by applying the sleep-on-idle and the rate-adaptation technique. Gupta et al. [21] studied the time to put idle and under-utilized Ethernet interfaces to the low-power mode, based on the number of arriving packets in a given time period, and analyzed the tradeoff between energy conservation and packet loss and delay. Similarly, Gunaratne et al. [22] designed the policies of link rate adaption by monitoring the link utilization and the queue length of output buffers to effectively save the Ethernet link energy. The authors in [12] designed shadow ports to buffer ingress packets, and used the schemes of time window prediction and power save mode to reduce the energy consumption of switch ports.

2) Network-wide Techniques: The network-wide energy conservation schemes study how to reduce the gross network energy consumption from the perspectives of topology design and routing. Chabarek et al. [23] formulated the problem of minimizing network energy consumption as a multiple commodity network flow problem, and investigated the energy-efficient network and protocol designs with mixed-integer program techniques. Vasic et al. [24] proposed a two-step flow scheduling scheme to balance the optimal energy conservation and the computational complexity. In the scheme, a group of energy-critical paths were pre-computed and a scalable traffic engineering mechanism was then used to schedule network flows in an online manner. Abts et al. [4] proposed an energy-efficient flattened butterfly topology and reconfigured the transfer rates of links periodically to make data center networks more energy proportional. Heller et al. [10] designed a network energy optimizer, namely, ElasticTree, which studied how to choose a subset of links to transmit traffic flows under the restrictions of network performance and reliability. Furthermore, Shang et al. [11] designed a throughput-guaranteed power-aware routing algorithm, which used a pruning-based method to iteratively eliminate switches from the original topology while meeting the network throughput requirement.

B. Flow Scheduling in Data Center Networks

Many flow scheduling schemes have been proposed in data center networks to achieve different optimization objectives, such as maximizing network utilization, minimizing flow completion time and meeting the deadline constraints of network flows.

Al-Fares et al. [25] proposed a dynamic flow scheduling scheme, i.e., Hedera, for multi-rooted hierarchical tree topologies used in data center networks. It can efficiently utilize link resources without significant compromise on the control and computation overheads. The experiment results demonstrated that Hedera achieves higher bisection bandwidth than ECMP routing. Wilson et al. [26] presented a deadline-aware control protocol, named D^3, which controlled the transmission rate of network flows according to their deadline requirements. D^3 can effectively improve the latency of mice flows and burst tolerance, and increase the transmission capacity of data center networks. Hong et al. [27] proposed a preemptive distributed quick flow scheduling protocol, i.e., PDQ, which aimed to minimize the average completion time of network flows as well as to meet their deadlines. The evaluation results showed that PDQ outperformed TCP and D^3 [26] in terms of the average flow completion time and the number of flows meeting deadlines. Zats et al. [28] proposed DeTail, which designed a cross-layer network stack aiming to improve the tail of completion time for delay-sensitive flows.

VII. Conclusion

In this paper, we explored a new flow scheduling method to save the energy consumed by data center networks, called EXR. The essence of EXR is to schedule traffic flows in the time dimension and let each flow exclusively occupy the link bandwidths on its routing paths. The advantage of EXR in saving more network energy comes from that it removes bottleneck active links in data center networks and improves

the utilization ratio of active switches/links. Besides saving network energy, EXR can also help reduce the expected flow completion time if assigning higher scheduling priorities to smaller flows, requires neither time synchronization among servers nor bandwidth reservation for flows, etc. Simulation and experiment results show that compared with FSR, EXR can effectively save network energy and shorten the average flow completion time.

REFERENCES

[1] J. Koomey, "Growth in data center electricity use 2005 to 2010," in *Analytics Press*, 2011.

[2] P. X. Gao, A. R. Curtis, B. Wong, and S. Keshav, "It's not easy being green," *SIGCOMM Comput. Commun. Rev.*, 2012.

[3] A. Greenberg, J. Hamilton, D. A. Maltz, and P. Patel, "The cost of a cloud: research problems in data center networks," *SIGCOMM Comput. Commun. Rev.*, January 2009.

[4] D. Abts, M. R. Marty, P. M. Wells, P. Klausler, and H. Liu, "Energy proportional datacenter networks," in *Proceedings of ISCA*, 2010.

[5] M. Al-Fares, A. Loukissas, and A. Vahdat, "A scalable, commodity data center network architecture," in *Proceedings of ACM SIGCOMM*, 2008.

[6] C. Guo, G. Lu, D. Li, H. Wu, X. Zhang, Y. Shi, C. Tian, Y. Zhang, and S. Lu, "BCube: a high performance, server-centric network architecture for modular data centers," in *Proceedings of the ACM SIGCOMM*, 2009.

[7] D. Li, C. Guo, H. Wu, K. Tan, Y. Zhang, and S. Lu, "FiConn: Using Backup Port for Server Interconnection in Data Centers," in *Proceedings of the IEEE INFOCOM*, 2009.

[8] D. Li, M. Xu, H. Zhao, and X. Fu, "Building Mega Data Center from Heterogeneous Containers," in *Proceedings of the IEEE ICNP*, 2011.

[9] P. Mahadevan, P. Sharma, S. Banerjee, and P. Ranganathan, "A Power Benchmarking Framework for Network Devices," in *Proceedings of IFIP NETWORKING*, 2009.

[10] B. Heller, S. Seetharaman, P. Mahadevan, Y. Yiakoumis, P. Sharma, S. Banerjee, and N. McKeown, "ElasticTree: Saving Energy in Data Center Networks," in *Proceedings of NSDI*, Apr 2010.

[11] Y. Shang, D. Li, and M. Xu, "Energy-aware routing in data center network," in *Proceedings of the ACM SIGCOMM workshop on Green networking*, 2010.

[12] G. Ananthanarayanan and R. H. Katz, "Greening the switch," in *HotPower*, 2008.

[13] "Cisco Nexus 2200 series data sheet," http://www.cisco.com/en/US/prod/collateral/switches/ps9441/ps10110/data_sheet_c78-507093.html.

[14] "IEEE P802.3az Energy Efficient Ethernet Task Force," www.ieee802.org/3/az/index.html.

[15] C. Hopps, "Analysis of an equal-cost multi-path algorithm," RFC 2992, IETF, 2000.

[16] S. Ghemawat, H. Gobioff, and S. Leung, "The Google file system," in *SOSP*, 2003, pp. 29–43.

[17] "Cisco Data Center Infrastructure 2.5 Design Guide," http://www.cisco.com/application/pdf/en/us/guest/netsol/ns107/c649/ccmigration_09186a008073377d.pdf.

[18] "IEEE 802.3az Energy Efficient Ethernet: Build Greener Networks," www.cisco.com/en/US/prod/collateral/switches/ps5718/ps4324/white_paper_c11-676336.pdf.

[19] S. Nedevschi, L. Popa, G. Iannaccone, S. Ratnasamy, and D. Wetherall, "Reducing Network Energy Consumption via Sleeping and Rate-Adaptation," in *Proceedings of NSDI*, 2008.

[20] "Iperf," http://iperf.sourceforge.net/.

[21] M. Gupta and S. Singh, "Using Low-Power Modes for Energy Conservation in Ethernet LANs," in *Proceedings of the IEEE INFOCOM*, 2007.

[22] C. Gunaratne, K. Christensen, B. Nordman, and S. Suen, "Reducing the Energy Consumption of Ethernet with Adaptive Link Rate (ALR)," *IEEE Transactions on Computers*, 2008.

[23] J. Chabarek, J. Sommers, P. Barford, C. Estan, D. Tsiang, and S. Wright, "Power Awareness in Network Design and Routing," in *Proceedings of the IEEE INFOCOM*, 2008.

[24] N. Vasić, P. Bhurat, D. Novaković, M. Canini, S. Shekhar, and D. Kostić, "Identifying and using energy-critical paths," in *Proceedings of the ACM CoNEXT*, 2011.

[25] M. Al-Fares, S. Radhakrishnan, B. Raghavan, N. Huang, and A. Vahdat, "Hedera: dynamic flow scheduling for data center networks," in *Proceedings of the NSDI*, 2010.

[26] C. Wilson, H. Ballani, T. Karagiannis, and A. Rowtron, "Better never than late: meeting deadlines in datacenter networks," in *Proceedings of the ACM SIGCOMM*, 2011.

[27] C.-Y. Hong, M. Caesar, and P. B. Godfrey, "Finishing flows quickly with preemptive scheduling," in *Proceedings of the ACM SIGCOMM*, 2012.

[28] D. Zats, T. Das, P. Mohan, D. Borthakur, and R. Katz, "Detail: reducing the flow completion time tail in datacenter networks," in *Proceedings of the ACM SIGCOMM*, 2012.