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C-Share: Optical Circuits Sharing for Software-Defined Data-Centers

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Abstract

Integrating optical circuit switches in data-centers is an on-going research challenge. In recent years, state-of-the-art solutions introduce hybrid packet/circuit architectures for different optical circuit switch technologies, control techniques, and traffic rerouting methods. These solutions are based on separated packet and circuit planes which do not have the ability to utilize an optical circuit with flows that do not arrive from or delivered to switches directly connected to the circuit's end-points. Moreover, current SDN-based elephant flow rerouting methods require a forwarding rule for each flow, which raise scalability issues. In this paper, we present *C-Share* – a practical, scalable SDN-based circuit sharing solution for data center networks. *C-Share* inherently enable elephant flows to share optical circuits by exploiting a flat upper tier network topology. *C-Share* is based on a scalable and decoupled SDN-based elephant flow rerouting method comprised of elephant flow detection, tagging and identification, which is utilized by using a prevalent network sampling method (e.g., sFlow). *C-Share* requires only a single OpenFlow rule for each optical circuit, and therefore significantly reduces the required OpenFlow rule entry footprint and setup rule rate. It also mitigates the OpenFlow outbound latency for subsequent elephant flows. We implement a proof-of-concept system for *C-Share* based on Mininet, and test the scalability of *C-Share* by using an event driven simulation. Our results show a consistent increase in the mice/elephant flow separation in the network which, in turn, improves both network throughput and flow completion time.

1. INTRODUCTION

In recent years, optical circuit switching has emerged as a promising solution for scaling data center networks. Current optical-circuit-switch/electrical-packet-switch (referred to as OCS/EPS) solutions, e.g. [1, 17, 27, 35], are based on separated OCS and EPS planes, employing the OCS for high-bandwidth, slowly varying, and long-lived flows (*elephant flows*), and the EPS for fast varying and short-lived flows (*mice flows*). Accordingly, each solution presents a method for detecting and rerouting elephant flows.

In the following we explain the lack of mice/elephant flow separation and scalability issues in current solutions. First, OCS can create low-latency high-bandwidth circuits[1] using a relatively slow reconfigurable cross-board. OCS reconfiguration penalty, which is the time to establish a circuit, is tens of μs for 2D MEMS wavelength selective switches, e.g., [27, 30], and tens of ms for 3D MEMS optical circuit switches, e.g., [1, 4, 11, 17, 35]. Despite this penalty, previous solutions utilize a given optical circuit by transmitting only elephant flows that arrive from and delivered to switches directly connected to the optical circuit's end-points – referred to as a *private* circuit. Therefore, other elephant flows that are not assigned to an optical circuit are transmitted through the EPS plane. These elephant flows are usually high persistent TCP flows, which tend to fill the network buffers end-to-end. In turn, both elephant and mice flows that share these buffers are introduced with a non-trivial queuing delay. Therefore, delay sensitive mice flows and especially *coflows*[2] [12, 13, 31, 37] , are adversely affected.

Second, state-of-the-art-solutions, e.g. [1, 17], introduce a coupled architecture in which both the detection and rerouting of elephant flows are employed over the switches directly connected to the OCS plane. In particular, for OpenFlow (OF) based solutions [1], such coupling dictates the installation of an OpenFlow rule for each detected elephant flow in order to reroute it to the OCS plane – referred to as *per-flow setup*. This approach results in a significant OpenFlow entry footprint [14]. Furthermore, the OF rule setup rate is usually limited to tens of rules per second [21], and the OF rule installation requires *outbound latency* to take effect in the data-plane.

In this paper, we present a different approach for integrating OCS in DCN. *C-Share* inherently enables sharing of optical circuits, leading to better mice/elephant flow separation, by introducing a *scalable* OpenFlow-based solution.

In recent years, data-centers have been evolving towards a flatter aggregation/core hierarchy with more densely interconnected switches, also known as spine-leaf topologies. Such topologies can deploy and adjust capacity more easily, with better manageability, and offer more deterministic network performance, particularly in latency [32]. *C-Share* takes this trend one step further, and presents flat topology

[1] In this paper we use *circuit* and *optical circuit* interchangeably.
[2] Collection of flows with a shared completion time that depends on completion time of the last-flow.

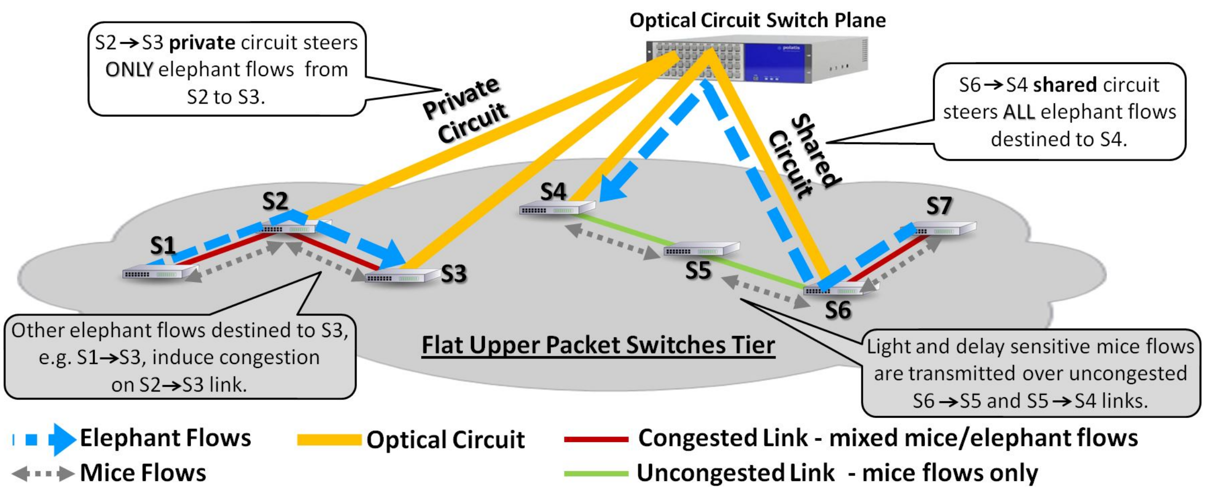


Figure 1: The *C-Share* topology concept. *Private* optical circuit results in inefficient mice/elephant flow separation over $S2 \rightarrow S3$ link. On the other hand, a *shared* optical circuit reduces the load over $S6 \rightarrow S5$ and $S5 \rightarrow S4$ links by better mice/elephant flow separation.

for the upper data-center packet tier by exploiting high-radix packet switches, as depicted in Figure 1. The OCS is used to transmit elephant flows by creating network path shortcuts over the flat topology of the upper tier, hence dynamically allocating bandwidth between the packet switches. The flat upper tier topology used by *C-Share* inherently enables sharing of optical circuits by elephant flows which do not arrive from or delivered to switches directly connected to the circuit's end-points.

Figure 1 presents an example of *private optical circuit* between $S2$ and $S3$, which transmits only elephant flows that arrive from $S2$ and delivered to $S3$, through the optical circuit. Therefore, elephant flows from $S1$ to $S3$ are transmitted through the $S2 \rightarrow S3$ packet link by $S2$. In turn, these elephant flows share the network buffers with mice flows between $S2$ and $S3$, which increases the end-to-end latency of both elephant and mice flows. On the other hand, the *shared optical circuit* between $S6$ and $S4$ transmits any elephant flow that is delivered to $S4$ regardless its origin switch (by a corresponding $S6$ switch configuration). Therefore, elephant flows from $S7$ to $S4$ are transmitted through the *shared* circuit by $S6$. Hence, a better mice/elephant flow separation is obtained in the network, significantly reducing the load over the packet links between $S4$, $S5$, and $S6$, and resulting in better network performance for all flows.

C-Share introduces SDN-based scalable elephant flow rerouting method supporting optical circuit *sharing*. *C-Share* exploits the servers to detect and tag elephant flows by setting the DSCP IP field, which is usually used for packet classification. Then, the DCN orchestrator identifies the elephant flows by sampling the upper tier packet switches. Therefore, in order to redirect *all* elephant flows to a given optical circuit by a packet switch, a single OF rule is required that matches the elephant flow DSCP tag and its destination. Hence, the OF rule footprint and OF flow setup rate are significantly reduced; and the outbound latency is mitigated for subsequent elephant flows after the circuit has been established.

The contributions of this work include:
1) New topology concept for EPS/OCS DCN that further separates mice and elephant flows, thus improves network performance.
2) Scalable SDN-based architecture that reduces the OF rule footprint and setup rate. It also mitigates the outbound latency problem of OF switches.

2. C-Share TOPOLOGY

In this section, we present the concept of *C-Share* topology without delving into design and options of the upper packet tier topology.

Current DCN switches offer up to 128 ports of 25*Gbps* [2]. In the near future, switches with 256 ports of 25*Gbps* are expected and apparently will be followed by switches with 256 ports of 50*Gbps*. As the port density increases, data-center networks become flatter with flat upper tier topology, such that the packet switches are intra-connected, thus omitting the need for an additional network layer above it. There are several well-known topologies, such as, multi dimensional torus or mesh, Flattened Butterfly [23], Dragonfly [24], and HyperX [6] that can be used to that end. In *C-Share* topology (Figure 1), the OCS plane is connected to all of the packet switches at the upper tier, and employs network path shortcuts and dynamic bandwidth allocation among them. We introduce two types of optical circuits that can be used in *C-Share* topology.

Private Circuit is utilized only by elephant flows that arrive from and delivered to switches directly connected to the optical circuit's endpoints, e.g. [1, 17].

Shared Circuit is inherently supported by *C-Share* topology, and can be utilized also by elephant flows that are transmitted through switches connected to the circuit's endpoints, but arrive from or delivered to other switches.

For *private* circuit configuration, elephant flows which are not assigned to an optical circuit are transmitted through the

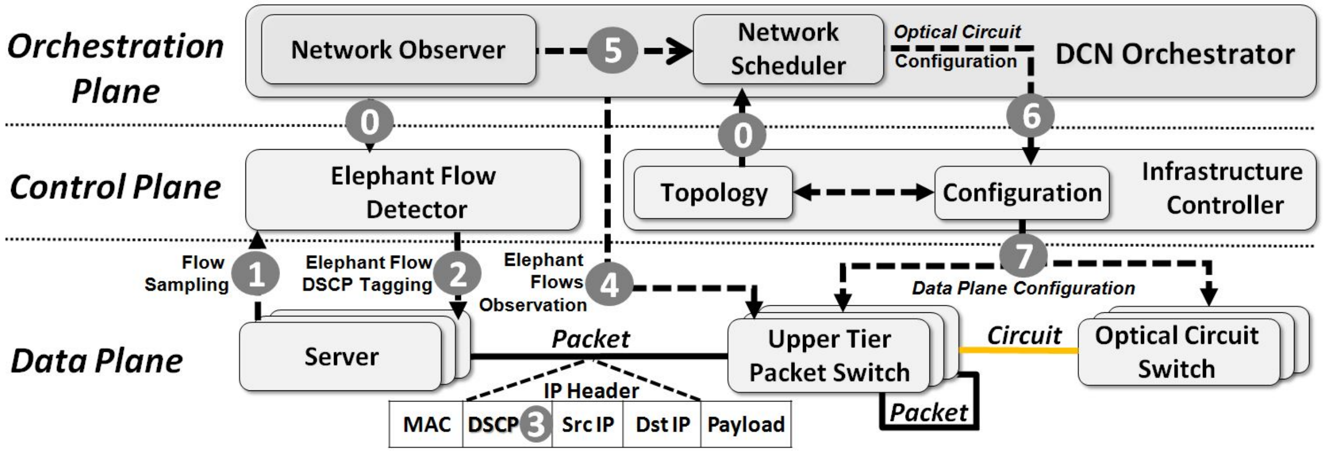


Figure 2: *C-Share* architecture block diagram and workflow.

packet switches, thus might overload them. This, in turn significantly degrades the mice flows performance [10]. However, as opposed to previous solutions, *C-Share* topology dictates that some of these elephant flows are transmitted through switches which are already connected to an optical circuit. Therefore, by using *shared* optical circuits, better mice/elephant flow separation is obtained, which results in lower congestion over the upper packet tier links, leading to better network performance.

3. C-Share ARCHITECTURE

Figure 2 depicts block diagram of *C-Share* architecture, which decouples the elephant flow detection and rerouting phases to elephant flow detection and tagging, observation, and rerouting phases. First, the egress network traffic of each server is sampled and tracked by the *Elephant Flow Detector* (step 1 in Figure 2). Each flow that exceeds a given threshold for the transferred bytes and/or the flow duration (according to the criteria initialization in step 0) is detected as elephant flow, similar to [7, 14, 15]. Then, each detected elephant flow is tagged by setting a predefined value to the IP DSCP field[3], notated by DSCP_e (steps 2 and 3, over the *Server*[4] and the *Packet Network*, respectively). The *Upper Tier Packet Switches* (which are directly connected to the OCS plane) are monitored by the *Network Observer* plane to observe *only* the tagged elephant flows and track their bandwidth and duration[5] (step 4). Studies on live DCN traffic [22] show that elephant flows account for less than 10% of all flows. Therefore, tagging the elephant flows in advance by the servers and only tracking them over the packet switches significantly reduces the number of tracked flows by the *Network Observer*, which reduces CPU, memory and network usage. On the contrary, detecting the elephant flows over the packet switches require significantly more network and compute resources since *all* flows should be monitored.

The *Network Scheduler* decides which circuits to establish according to the current flow demand in the network (step 5), and informs the *Infrastructure Controller* (step 6). In turn, the *Infrastructure Controller* configures the data-plane accordingly (step 7). Then, each pair of packet switches connected to a circuit's endpoints are installed with an OF rule to reroute matched elephant flows through this circuit. The OF rule matches the DSCP_e value in the IP header and the destination subnet connected to the switch at the other end-point of the circuit. *Private circuit* is configured by matching only flows ingress from ports connected to the lower tier. *Shared circuit* is configured by matching also ports connected to packet switches at the upper packet tier (section 3.1).

C-Share architecture requires only a single flow rule in order to transmit all of the elephant flows through a given optical circuit, either *shared* or *private*. Furthermore, subsequent elephant flows, which are generated and tagged after the corresponding optical circuit has been established, are also matched by the flow rule over the packet switches to be redirected through the optical circuit. Hence, the outbound latency is mitigated, and the required OF rule footprint and OF rule setup rate are reduced (section 3.2).

3.1 Private / Shared Circuit Configuration

Private and *shared* optical circuits are differed by setting which of the switch's input ports are matched by the rerouting rule of elephant flows through the optical circuit. Therefore, different metadata values are assigned to packets from input ports connected to the lower and the upper packet tiers. Then, by mask matching on the metadata value of an ingress packet, one can configure the switch either to use the optical circuit as *private* by serving only packets from the lower tier, or *shared* by serving packets also from the upper tier.

[3] A 6-bit field in the IP header for packet classification purposes that can be used to tag different flows types. For instance, *C-Share* can be extended to tag elephant flows according to different levels of bandwidth/duration thresholds, or according to different QoS.

[4] In bare-metal based DCNs, one can tag the elephant flows by any packet modification method (e.g., by `iptables` for Linux). Alternately, in overlay virtualized DCNs, one can use the overlay controller to configure the hypervisor to tag DSCP fields in the IP header encapsulation.

[5] The bandwidth and duration of the tagged elephant flows can also be obtained from the *Elephant Flow Detector*.

Figure 3 demonstrates Open vSwitch [29] configuration for *private* and *shared* circuits. At initialization, metadata values of 0b01 and 0b11 are assigned to packets arriving from the upper and lower tier, respectively. For a *private* circuit, a *single* OF rule is set to match packets with metadata values of 0b1* by using 0b10 mask. Therefore, only packets from *all* input ports connected to the lower tier are matched and transmitted though the circuit. Similarity, for a *shared* circuit, packets with metadata of 0b*1 are matched by using 0b01 mask. Hence, packets arriving from *all* input ports connected to both upper and lower tiers are matched and transmitted through the circuit. As described above, the OF rule is also set to capture the DSCP$_e$ value (*nw_tos*), and the lower tier subnet destination (*nw_dst*) of the switch connected to the other end of the optical circuit.

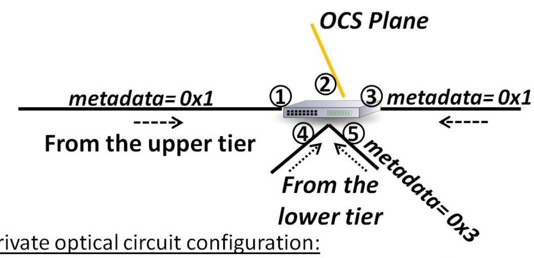
3.2 Scalable Elephant Flow Rerouting

By leveraging the DSCP tagging of the elephant flows and the packet metadata assignment according to their corresponding input ports, *C-Share* results in a single OF rule for each switch that is connected to an optical circuit's endpoint. Therefore, *C-Share* significantly reduces the OF footprint, as compared to previous works which requires an OF rule for each rerouted flow – *per-flow setup*, e.g. [1, 7, 14].

Assuming that there are on average 1k simultaneous elephant flows [7, 9, 22] between two packet switches at the upper tier, means that existing approaches require 1k OF rules for each of the packet switches, which might consume most of current OF switches flow table size. For instance, HP ProCurve 5400zl switches support up to 1.7K OpenFlow entries [14]; HP ProCurve J9451A supports 1.5k OF entries [21]; HP ProCurve 5406zl, Pica8 P-3290, and Dell PowerConnect 8132F support up to 1.5k, 2k and 750 rules, respectively [25]. Hence, the currently used *per-flow setup* approach results in average flow table consumption of 50%-67% for elephant flows rerouting. Since *C-Share* requires only single OF rule for each circuit, it result in a significantly smaller OF footprint, as we demonstrate in our evaluation (section 4). Furthermore, OF switches have limited OF rule setup rate. For instance, [21] indicates that flow rule setup rate of OF switches is limited to approximately 40 flow/sec. Clearly, *C-Share* significantly reduces the required OF setup rate; hence, proposes feasible solution for current OF switches.

Once an optical circuit is configured, subsequent ingress elephant flows arriving to the packet switches are matched by the OF rule and ,in turn, transmitted through the optical circuit. Consequently, *C-Share* mitigates the OF outbound latency[6] for such subsequent flows. The OF outbound latency has been measured by previous works; [20] reports that the outbound latency can be as high as 30ms. [33] measures the outbound latency of two switches by using OFLOPS. They report ranges of 50-1000ms and 8-2000ms depending on the number of inserted flow entries. [25] measures outbound latency of up to 400ms. The outbound latency is at the same order of the 3D MEMS OCS reconfiguration penalty or even higher. However, the OCS reconfiguration penalty affects the network only once for each optical circuit configuration. Whereas, the outbound latency penalty has a larger network degradation potential. Therefore, by avoiding this additional latency for each subsequent elephant flow served by an optical circuit, *C-Share* results in better network performance.

[6] The latency of the switch to install/modify/delete OpenFlow rules provided by the SDN controller.



Private optical circuit configuration:
*table=1,ip,**metadata=0x3/0x2**,nw_tos=252,nw_dst=10.0.0.0/24, actions=output:2*

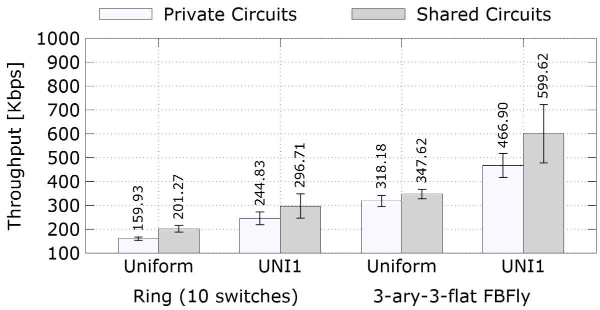
Shared optical circuit configuration:
*table=1,ip,**metadata=0x3/0x1**,nw_tos=252,nw_dst=10.0.0.0/24, actions=output:2*

Figure 3: Open vSwitch example – Private/Shared circuits configuration. A *single* OF rule matches packets arriving from *all* input ports of the switch connected to either lower or upper tier, by using a predefined assignment of packet metadata.

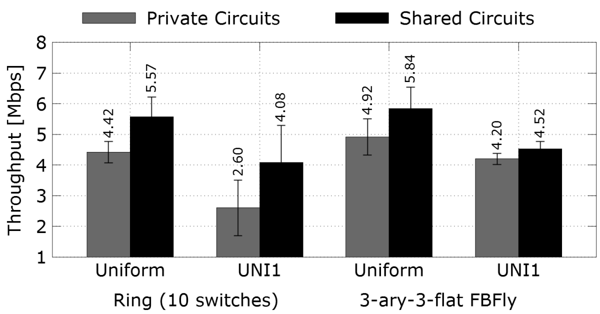
4. EVALUATION

Topologies: we evaluate *C-Share* for two flat upper tier topologies: Ring and Flatted Butterfly [23]. Ring topology offers a simple wire connectivity, and is used by industrial DCNs. Facebook [16] presents a DCN architecture which uses Ring topology to connect the cluster and aggregation switches; and Google [34] uses Ring topology to connect cluster routers. Flattened butterfly (FBFly) takes advantage of high-radix switches to create a scalable, yet low-diameter network. Google [5] show that FBFly is a power efficient topology for high-performance datacenter networks. For both topologies, the bandwidth of the packet and circuit links are set for 1/10 ratio, as used by [27]. We use two DCN traces to simulate aggregated traffic to the upper packet tier, with skewed and uniform traffic patterns.

Traces from the University of Wisconsin (*UNI1*) are presented in [9], which contain recorded traffic among approximately 2900 servers for a one hour duration. Analysis of this trace by [28] shows mostly *sparse and skewed traffic*. We analyze *UNI1* pcap traces and extract the TCP sessions properties, and their start time. Then, in order to simulate DCNs with different number of hosts, we consolidate the hosts by subnets, and merge the traffic for each subnet to represent a node in our modified trace. The subnet sizes are chosen accordingly to meet the required number of hosts. In addition, we reduce the time intervals between the sessions to obtain moderate network load.



(a) Average Mice Throughput



(b) Average Elephant Throughput

Figure 4: Average throughput as reported by `iperf3` for Mininet environment under *moderate* network load.

Synthetic Data Center Trace (*Uniform*) is created based on traffic characteristics from [7, 8, 22, 27], such that elephant flows are 10% of the number of flows and accommodate 90% of the demand. We generate traffic with random distribution of sessions between mice flow traffic (2KB to 32KB) and elephant flows (up to 100MB) [8, 19], with *uniform traffic* distribution [7].

4.1 Emulation

We develop an emulated environment of *C-Share* by using Mininet [26] version 2.2.1 running over an IBM x3550 M4 server with 196GB of RAM, 24 Xeon-E5-2630@2.3GHz CPUs (with six cores each), and Ubuntu 14.04 with Linux 3.19 kernel. We use sFlow [36] to sample the egress flows of the hosts by the *Elephant Flow Detector*, and to sample the Open vSwitches by the *Network Observer*. The OCS is emulated by a constrained Open vSwitch to employ optical circuits, such that only one input port can be configured to transmit to any given output port. Each OCS reconfiguration is emulated by first removing the colliding optical circuits, and configuring the new requested optical circuits after a 20*ms* delay to emulate 3D MEMS OCS typical reconfiguration penalty, e.g. [4]. We evaluate an upper tier Ring with 10 packet switches and 3-ary-3-flat FBFly (9 packet switches) with packet and circuit links of 10*Mbps* and 100*Mbps*, respectively. The network traffic is generated by `iperf3` [3] according to *UNI1* and uniform traces configured for moderated network load without hitting the CPU-bound of the server that running Mininet.

Trace|Method \ Topology|Circuit		Ring (10 Switches) Private	Ring (10 Switches) Shared	3-ary-3-flat FBFly Private	3-ary-3-flat FBFly Shared
UNI1	*Per-flow setup*	445	449	398	384
	C-Share	26	31	20	17
Uniform	*Per-flow setup*	563	588	486	435
	C-Share	45	52	37	31

Table 1: OF rule footprint for elephant flow rerouting during one minute of trace, under *moderate* network load. *C-Share* significantly reduces the OF footprint.

Figure 4 presents a comparison of the average throughput as reported by `iperf3` between mice and elephant flows, for both network traces over the Ring and FBFly topologies. In general, *shared* circuits improve the throughput of both elephant and mice flows as compared to *private* circuits. In particular, we observe that: (1) Skewed traffic (*UNI1* trace) introduces patterns which can be exploited by *shared* circuits, such as many elephant flows from different sources to the same destination. Therefore, *shared* circuits further improve the network performance of skewed traffic, for instance by 29% for mice flows over FBFly, and 57% for elephant flows over Ring; whereas, uniform traffic is improved by 9% and 26%, respectively. (2) The connectivity of Ring topology is limited, which results in degraded performance as compared to FBFly. Therefore, the connectivity and network throughput of Ring topology can be further improved by the *shared* circuits. In particular, the *shared* circuits improve the network throughput of Ring topology by 21%-57%, as compared to FBFly which is improved by 8%-28%. In addition, Table 1 presents the OF rule footprint of *UNI1* and *uniform* traces, under moderate network load.

4.2 Simulation

We use an event driven simulation to evaluate the completion time of mice coflows and elephant flows, and measure the corresponding OF rule footprint for rerouting elephant flows by the packet switches through *private* or *shared* circuits. We use the synthetic *uniform* traces to demonstrate the scalability of *C-Share* under *intensive* network load. Specifically, we generate network traffic comprised of mice coflows and elephant flows. The mice coflows are 90% of the number of flows, and accommodate 10% of the total demand. We simulate Ring and Flattened Butterfly upper packet tier topologies, with varied number of packet switches. Each packet switch serves 40 hosts. The packet and circuit links are set to 10*Gbps* and 100*Gbps*, respectively.

Figure 5 presents the average completion run-time of mice coflows and elephant flows for *private* and *shared* circuit configurations over 60 trials. The *shared* circuits improve the average completion time by 20% for a Ring with 10 switches and up to 30% for a Ring with 16 switches. The Ring topology is unscalable in terms of connectivity. Therefore, the *shared* circuits can significantly increase the topology connectivity and mice/elephant flow separation, which results in increased improvement of the completion time as the Ring size increases. On the other hand, since FBFly is scalable, the improvement of the completion time by *shared* circuits

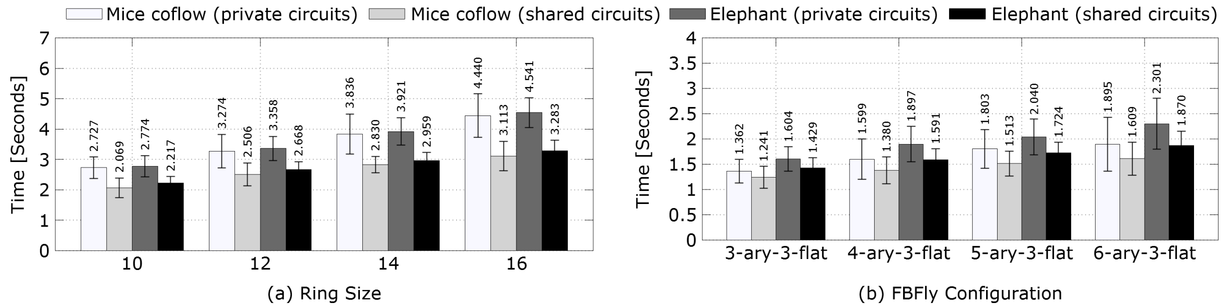


Figure 5: Average completion time of mice coflows and elephant flows under *intensive* network load, over two upper tier topologies: (a) Ring (10 to 16 packet switches) and (b) FBFly (9 to 36 packet switches).

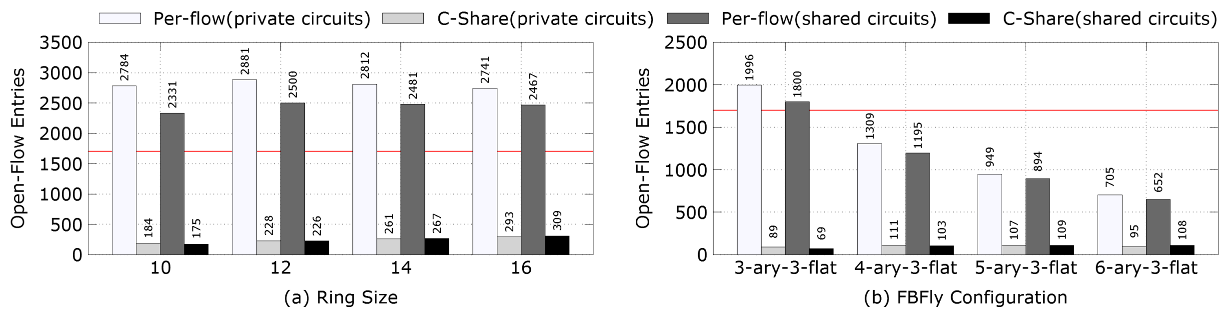


Figure 6: OpenFlow rule footprint per switch during one minute of network trace under *intensive* network load, over two upper tier topologies: (a) Ring (10 to 16 packet switches) and (b) FBFly (9 to 36 packet switches). The horizontal line indicates 1.7k OF rule entries. Any OF entries count above it might be an unfeasible scenario.

equals 15%-20% for all FBFly sizes; hence, the *shared* circuits results in relatively constant mice/elephant flow separation degree. The same applies for the OF rule footprint presented in Figure 6. The required OF rules of *per-flow setup* for Ring remains constant and higher than 1.7k (prevalent OF table size [14, 21, 25]). On the other hand, due to the scalability of FBFly, as the size of FBFly increases, less OF rules are required for rerouting the elephant flows through *private* or *shared* circuits. However, the OF footprint of *per-flow setup* is still high and is significantly reduced by *C-Share*.

5. RELATED WORK

EPS/OCS DCN solutions, e.g. [17, 27, 35], present different approaches for integrating OCS in DCN. The control planes presented in these works are based on non-SDN methods, thus limited as compared to SDN-based solutions. c-Through [35] uses predefined VLANs for static EPS/OCS planes, and tags elephant flows with the corresponding VLAN, without the ability to dynamically configure the network. Helios [17] implementation consists of Monaco packet switches and sets its forwarding table to reroute all flows that are delivered to a specific destination pod, without the ability to separate among mice and elephant flows to EPS and OCS planes, respectively. REACToR [27] presents state-of-the-art FPGA-based solution; however, do not propose an elephant tagging and rerouting technique. Furthermore, these works are based on separated EPS and OCS planes, which restrict the seperation of mice and elephant flows in the network. On the other hand, *C-Share* inherently supports such mice/elephant flow separation.

ProjecToR [18] presents a free-space optics (FSO) solution for DCN, composed of *dedicated* and *opportunistic* optical links. *C-Share* can be employed over such solution, and offer optical circuit sharing over the *dedicated* optical links.

SDN-based works present elephant [14] and network-limited [7] flow scheduling for EPS-only DCNs. [1] presents SDN-based solution for OCS/EPS DCN. These works use a specific OF rule for each rerouted flow. Hence, they introduce the aforementioned OF scalability issues. Namely, table rule footprint, setup rate, and outbound latency. All are mitigated by *C-Share*.

6. CONCLUSIONS AND FUTURE WORK

In this paper we proposed *C-Share*, a new approach for integrating OCS in DCN. We demonstrated how *C-Share* inherently supports circuit sharing that further separates mice and elephant flows leading to increased performance. We presented a scalable SDN-based solution including elephant flow rerouting that requires only a single OF rule per circuit.

This work is a starting point on a way towards a full-fledged implementation of *C-Share*. We list two of *C-Share* advanced architectural aspects.

Advanced Circuit Sharing: We presented *shared* circuits only for *last hop routing*. Namely, the sharing is employed for elephant flows delivered to one of the circuit's endpoints. By advanced configuration, we can enable circuit sharing with elephant flows at any hop along their routes.

Upper Tier Topology: *C-Share* is evaluated for Ring and FBFly upper tiers. Other topologies might offer better mice/elephant flow separation by exploiting circuit sharing.

7. REFERENCES

[1] Calient. 3D mems optical circuit switching for software defined data centers and metro networks.

[2] High-Density 25/100 Gigabit Ethernet StrataXGS Tomahawk Ethernet Switch Series. `https://www.broadcom.com/products/ethernet-communication-and-switching/switching/bcm56960-series`.

[3] iPerf - The TCP, UDP and SCTP network bandwidth measurement tool. `https://iperf.fr/`.

[4] Polatis 6000n Protection Services Switch Data Sheet. `http://www.polatis.com/datasheets/products/Polatis_6000n_Protection_Services_Switch_Data_Sheet.pdf`.

[5] D. Abts, M. R. Marty, P. M. Wells, P. Klausler, and H. Liu. Energy proportional datacenter networks. In *ACM SIGARCH Computer Architecture News*, volume 38, pages 338–347. ACM, 2010.

[6] J. H. Ahn, N. Binkert, A. Davis, M. McLaren, and R. S. Schreiber. Hyperx: topology, routing, and packaging of efficient large-scale networks. In *Proceedings of the Conference on High Performance Computing Networking, Storage and Analysis*, page 41. ACM, 2009.

[7] M. Al-Fares, S. Radhakrishnan, B. Raghavan, N. Huang, and A. Vahdat. Hedera: Dynamic flow scheduling for data center networks. In *NSDI*, volume 10, pages 19–19, 2010.

[8] M. Alizadeh, A. Greenberg, D. A. Maltz, J. Padhye, P. Patel, B. Prabhakar, S. Sengupta, and M. Sridharan. Data Center TCP (DCTCP). In *ACM SIGCOMM computer communication review*, volume 40, pages 63–74. ACM, 2010.

[9] T. Benson, A. Akella, and D. A. Maltz. Network traffic characteristics of data centers in the wild. In *Proc. ACM SIGCOMM conference on Internet measurement*, 2010.

[10] J. Bowers, A. Raza, D. Tardent, and J. Miglani. Advantages and control of hybrid packet optical-circuit-switched data center networks. In *Photonics in Switching*, pages PM2C–4. Optical Society of America, 2014.

[11] K. Chen, A. Singla, A. Singh, K. Ramachandran, et al. OSA: An Optical Switching Architecture for Data Center Networks With Unprecedented Flexibility. *Networking, IEEE/ACM Transactions on*, 2014.

[12] M. Chowdhury and I. Stoica. Coflow: A networking abstraction for cluster applications. In *Proceedings of the 11th ACM Workshop on Hot Topics in Networks*, pages 31–36. ACM, 2012.

[13] M. Chowdhury, Y. Zhong, and I. Stoica. Efficient coflow scheduling with varys. In *ACM SIGCOMM Computer Communication Review*, volume 44, pages 443–454. ACM, 2014.

[14] A. R. Curtis, W. Kim, and P. Yalagandula. Mahout: Low-overhead datacenter traffic management using end-host-based elephant detection. In *INFOCOM, 2011 Proceedings IEEE*, pages 1629–1637. IEEE, 2011.

[15] A. R. Curtis, J. C. Mogul, J. Tourrilhes, P. Yalagandula, P. Sharma, and S. Banerjee. DevoFlow: scaling flow management for high-performance networks. In *ACM SIGCOMM Computer Communication Review*, volume 41, pages 254–265. ACM, 2011.

[16] N. Farrington and A. Andreyev. Facebook data center network architecture. In *IEEE Optical Interconnects Conf.* Citeseer, 2013.

[17] N. Farrington, G. Porter, S. Radhakrishnan, H. H. Bazzaz, V. Subramanya, Y. Fainman, G. Papen, and A. Vahdat. Helios: a hybrid electrical/optical switch architecture for modular data centers. *ACM SIGCOMM Computer Communication Review*, 41(4):339–350, 2011.

[18] M. Ghobadi, R. Mahajan, A. Phanishayee, N. Devanur, J. Kulkarni, G. Ranade, P.-A. Blanche, H. Rastegarfar, M. Glick, and D. Kilper. Projector: Agile reconfigurable data center interconnect. In *Proceedings of the 2016 conference on ACM SIGCOMM 2016 Conference*, pages 216–229. ACM, 2016.

[19] A. Greenberg, J. R. Hamilton, N. Jain, S. Kandula, C. Kim, P. Lahiri, D. A. Maltz, P. Patel, and S. Sengupta. Vl2: a scalable and flexible data center network. In *ACM SIGCOMM computer communication review*, volume 39, pages 51–62. ACM, 2009.

[20] K. He, J. Khalid, S. Das, A. Gember-Jacobson, C. Prakash, A. Akella, L. E. Li, and M. Thottan. Latency in software defined networks: Measurements and mitigation techniques. In *Proceedings of the 2015 ACM SIGMETRICS International Conference on Measurement and Modeling of Computer Systems*, pages 435–436. ACM, 2015.

[21] D. Y. Huang, K. Yocum, and A. C. Snoeren. High-fidelity switch models for software-defined network emulation. In *Proceedings of the second ACM SIGCOMM workshop on Hot topics in software defined networking*, pages 43–48. ACM, 2013.

[22] S. Kandula, S. Sengupta, A. Greenberg, P. Patel, and R. Chaiken. The nature of data center traffic: measurements & analysis. In *Proceedings of the 9th ACM SIGCOMM conference on Internet measurement conference*, pages 202–208. ACM, 2009.

[23] J. Kim, W. J. Dally, and D. Abts. Flattened butterfly: a cost-efficient topology for high-radix networks. *ACM SIGARCH Computer Architecture News*, 35(2):126–137, 2007.

[24] J. Kim, W. J. Dally, S. Scott, and D. Abts. Technology-driven, highly-scalable dragonfly topology. In *ACM SIGARCH Computer Architecture News*, volume 36, pages 77–88. IEEE Computer Society, 2008.

[25] M. Kuźniar, P. Perešíni, and D. Kostić. What you need to know about SDN flow tables. In *Passive and Active Measurement*, pages 347–359. Springer, 2015.

[26] B. Lantz, B. Heller, and N. McKeown. A network in a laptop: rapid prototyping for software-defined networks. In *Proceedings of the 9th ACM SIGCOMM Workshop on Hot Topics in Networks*, page 19. ACM, 2010.

[27] H. Liu, F. Lu, A. Forencich, R. Kapoor, M. Tewari, G. M. Voelker, G. Papen, A. C. Snoeren, and G. Porter. Circuit switching under the radar with REACToR. In *11th USENIX Symposium on Networked Systems Design and Implementation (NSDI 14)*, pages 1–15, 2014.

[28] H. Liu, M. K. Mukerjee, C. Li, N. Feltman, G. Papen, S. Savage, S. Seshan, G. M. Voelker, D. G. Andersen, M. Kaminsky, et al. Scheduling techniques for hybrid circuit/packet networks. *CoNEXT*, 2015.

[29] B. Pfaff, J. Pettit, K. Amidon, M. Casado, T. Koponen, and S. Shenker. Extending networking into the virtualization layer. In *Hotnets*, 2009.

[30] G. Porter, R. Strong, N. Farrington, A. Forencich, et al. Integrating microsecond circuit switching into the data center. In *Proc. ACM SIGCOMM.*, 2013.

[31] Z. Qiu, C. Stein, and Y. Zhong. Minimizing the total weighted completion time of coflows in datacenter networks. In *Proceedings of the 27th ACM on Symposium on Parallelism in Algorithms and Architectures*, pages 294–303. ACM, 2015.

[32] E. Roberts and L. Paraschis. The role of optical interconnections in data-center architecture evolution. In *Optical Fiber Communication Conference*. Optical Society of America, 2013.

[33] C. Rotsos, N. Sarrar, S. Uhlig, R. Sherwood, and A. W. Moore. OFLOPS: An open framework for OpenFlow switch evaluation. In *Passive and Active Measurement*, pages 85–95. Springer, 2012.

[34] A. Singh, J. Ong, A. Agarwal, G. Anderson, A. Armistead, R. Bannon, S. Boving, G. Desai, B. Felderman, P. Germano, et al. Jupiter rising: A decade of clos topologies and centralized control in google's datacenter network. *ACM SIGCOMM Computer Communication Review*, 45(4):183–197, 2015.

[35] G. Wang, D. G. Andersen, M. Kaminsky, K. Papagiannaki, T. Ng, M. Kozuch, and M. Ryan. c-Through: Part-time optics in data centers. *ACM SIGCOMM Computer Communication Review*, 41(4):327–338, 2011.

[36] M. Wang, B. Li, and Z. Li. sFlow: towards resource-efficient and agile service federation in service overlay networks. In *Distributed Computing Systems, 2004. Proceedings. 24th International Conference on*, pages 628–635. IEEE, 2004.

[37] Y. Zhao, K. Chen, W. Bai, M. Yu, C. Tian, Y. Geng, Y. Zhang, D. Li, and S. Wang. Rapier: Integrating routing and scheduling for coflow-aware data center networks. In *Computer Communications (INFOCOM), 2015 IEEE Conference on*, pages 424–432. IEEE, 2015.