

BurstBalancer: Do Less, Better Balance for Large-scale Data Center Traffic

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Abstract—Layer-3 load balancing is a key topic in the networking field. It is well acknowledged that flowlet is the most promising solution because of its good trade-off between load balance and packet reordering. However, we find its one significant limitation: it makes the forwarding paths of flows unpredictable. To address this limitation, this paper presents BurstBalancer, a simple yet efficient load balancing system with a sketch, named BalanceSketch. Our design philosophy is *doing less changes* to keep the forwarding path of most flows fixed, which guides the design of BalanceSketch and our balance operations. We have fully implemented BurstBalancer in a small-scale testbed built with Tofino switches, and conducted both large-scale event-level (NS-2) and ESL (electronic system level) simulations. Our results show that BurstBalancer achieves 5%~35% smaller FCT than LetFlow in symmetric topology and up to 30× smaller FCT in asymmetric topology, while 58× fewer flows suffer from path changing. All related codes are open-sourced at GitHub.

Index Terms—Data Center Networks, L3 Load Balancing, Sketch, Flowlet

1 INTRODUCTION

1.1 Background and Motivation

As enterprises continue to shift services like big-data analytics, web services, and cloud storage into cloud environments, the number of data centers has grown exponentially [2]–[7]. Typical data center networks (DCNs) feature symmetric topologies such as Fat-Tree [8] and VL2 [9], which offer multiple equivalent paths between any pair of servers. How to evenly allocate the traffic to these candidate paths is well known as the layer-3 (L3) load balance. L3 load balance has been acknowledged as one key topic in the networking field for many years [10]–[13].

Existing L3 load balancing schemes can be broadly classified into three categories. First, packet-level load balancing schemes [14]–[19] select a path for each packet to achieve optimal traffic split. However, these schemes are susceptible to packet reordering issues when there is a significant discrepancy in the delay of candidate paths. Second, flow-level load balancing schemes [20]–[26] assign a fixed path to all packets within a flow. These schemes avoid packet reordering, but cannot well balance the traffic due to the skewed distribution of flow sizes and hash collisions among large flows [27]. Third, flowlet-level load balancing schemes [2], [28]–[33] attempt a compromise between minimizing packet reordering and evenly balancing traffic. In these schemes, the packets of a flow are divided into many groups, with the time interval between two consecutive groups being

larger than a predefined threshold δ . Each group of packets is called a flowlet [28]. Flowlet-level schemes select a path for each flowlet, so as to achieve a good trade-off between packet reordering and load balance [3], [33]–[35]. However, these schemes cannot precisely detect flowlets using small memory, and make a lot of unnecessary manipulation: 1) The forwarding paths of the flows in these schemes are unfixed and unpredictable, which hampers network measurement and management. 2) Due to the limited memory on hardware and the large number of concurrent flows, they cannot precisely identify all flowlets. 3) They unnecessarily divide small flows into flowlets and distribute them across multiple paths, which contributes little to load balance and rather increases the risk of packet reordering.

While existing load balancing schemes have made excellent contributions, they overlook the *flow-regulation* of the network. “Flow-Regulation” refers to that given any flow, its forwarding path can be easily calculated, and does not change with time. In many existing schemes, the forwarding paths of flows are unfixed and unpredictable. Intuitively, if most members of a group follow a simple rule, then the management of this group would be simple. For many network operations, such as network diagnosis [36]–[39], congestion control [40]–[43], network measurement and management [44]–[51], it is often assumed or expected that the forwarding paths of most flows can be obtained easily. For example, the well known 007 system [37] is designed for a network where all flows use ECMP. It needs the forwarding paths of flows to locate the congested link. If the forwarding path of flow changes rapidly and randomly, 007 cannot pinpoint the congested link timely and accurately, resulting in unreliable diagnostic results. For another example, the pioneering work using INT for congestion control, HPCC [42], uses the link load information to adjust the sending rate of flows. If the forwarding paths of flows are fixed, HPCC works excellently; but otherwise, the link load information cannot match the culprit flow, so the advantages of HPCC

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cannot be guaranteed. Hence, our goal is to develop a solution that not only effectively balances traffic, but also ensures adherence to the flow regulation principle as much as possible. The *ideal solution should manipulate as few packets/flows as possible*, so as to make network measurement and management easier.

1.2 Our Proposed Solution

Towards the above goal, we propose BurstBalancer, an efficient load balancing system, with the aim of manipulating only a small number of flowlets that are critical to load balance, namely FlowBursts. In BurstBalancer, most flows follow ECMP [20] and we can easily get their forwarding paths. BurstBalancer devises a sketch, namely BalanceSketch, and deploys it on each switch to detect and make forwarding decisions for FlowBursts. BurstBalancer only needs small on-chip memory to keep critical flowlets (FlowBursts), achieving high memory efficiency and perfectly embracing the skewed flow distribution [52], [53]. Further, BurstBalancer only manipulates the critical flowlets which are very limited in number, minimizing packet reordering and keeping the paths of most flows fixed. In addition, BurstBalancer is easy to implement without any changes to end-hosts or protocol stacks, and can be incrementally deployed in existing networks.

The design philosophy of our BurstBalancer is *doing less manipulations while better balancing the traffic*, which is guided by the well-known Occam’s Razor principle: entities should not be added beyond necessity. The philosophy of *doing less* includes two dimensions based on our two key observations. The first dimension of doing less is based on *Observation I*: only a minority of flowlets are fast and large enough to cause load imbalance, and we call these critical flowlets *FlowBursts*¹. Therefore, we *manipulate only critical flowlets (FlowBursts)*. For example, in the IMC data center trace [54] used in our experiments, there are about 27,000 concurrent flowlets, of which only 1.1% are *FlowBurst*. Therefore, if we identify, maintain, and manipulate only FlowBursts, it is possible to save on-chip memory up to 100 times while achieving similar load balance performance as those schemes identifying all flowlets. In this way, we classify all flowlets into two categories: FlowBursts and unnecessary flowlets², and we only manipulate FlowBursts. Identifying unnecessary flowlets causes a huge memory overhead³, and manipulating them only exacerbates network chaos and the risk of packet reordering.

The second dimension of doing less is based on *Observation II*: It is expensive and unnecessary to accurately detect and manipulate all FlowBursts. Hence, we choose to *manipulate most rather than all FlowBursts* for the following reasons. 1) Identifying all FlowBursts is expensive for hardware resources. 2) By manipulating most FlowBursts while leaving other FlowBursts to follow ECMP, we can still attain effective load balancing. 3) Detecting all FlowBursts needs

1. A formal definition of FlowBurst is provided in § 2.1.

2. Unnecessary flowlets are defined as: 1) flowlets formed by small flows; 2) flowlets formed by low-density flows (e.g., some persistent flows that last for long time but send packets at a very slow speed).

3. In our experiments, LetFlow [2], a load balancing scheme identifying and manipulating all flowlets, consumes about $10 \times$ more on-chip memory to achieve a similar load balancing performance to our BurstBalancer (see Figure 15).

complicated design of data structure. A strawman solution to identify FlowBursts is to first identify flowlets using existing methods and then check whether the identified flowlet is a FlowBurst. However, this solution is memory inefficient because it records the information of all flowlets, most of which are unnecessary to manipulate. We propose a simple data structure, namely BalanceSketch, to track the most relevant, rather than all FlowBursts (See details in $\times 3$) and evict unnecessary flowlets. To the best of our knowledge, we are the first work that applies sketches to the field of L3 load balancing.

We extensively evaluate BurstBalancer on a small-scale testbed and two large-scale simulation platforms. Our testbed consists of 4 Tofino switches [55] and 8 end-hosts in a leaf-spine topology. For simulations, we use both an event-level simulator (NS-2 [56]) and an ESL (electronic system level) simulator (HDCN, which is developed and used by Huawei for years). Our results show that compared to LetFlow [2], BurstBalancer better balances the traffic using smaller memory, while manipulates 58 times fewer flows at the same time. In symmetric topologies, BurstBalancer achieves 5%–35% smaller FCT (flow completion time) than state-of-the-art LetFlow [2] and DRILL [14]. In asymmetric topologies, BurstBalancer achieves up to 30% smaller FCT than LetFlow and up to 6.4% smaller FCT than WCMP [21]. We also conduct CPU experiments, and results show that BurstBalancer achieves > 90% recall rate in finding FlowBursts with small memory. In addition, we mathematically derive the ability of BalanceSketch to identify FlowBursts (see $\times 3.7$). All related codes are open-sourced [57].

2 BACKGROUND AND RELATED WORK

In this section, we begin with the problem statement of FlowBurst in $\times 2.1$. Then we discuss the related work of load balance solutions for data center networks in $\times 2.2$. The main symbols used in this paper are shown in Table 1.

TABLE 1: Symbols frequently used in this paper.

Notation	Meaning
	Flowlet threshold that spaces two adjacent flowlets or FlowBursts
\mathcal{V}	Lower bound of the speed of FlowBurst
\mathcal{F}	Voting threshold used by our BalanceSketch to identify flowlets with high speed and large size
	Flow timeout threshold used for identifying whether a flow ends
l	Number of buckets in BalanceSketch
$\mathcal{B}[i]$	The i^{th} bucket of BalanceSketch
$h(\cdot)$	Hash function mapping a flow into a bucket
d	Number of cells in each bucket in the multi-cell version of BalanceSketch

2.1 Problem Statement

Network Stream: A network stream is an unbounded timing evolving sequence of items $S = \bar{r}p_1, p_2, \dots, g$, where each item $p_i = (f_i, t_i)$ indicates a packet of flow f_i arriving at time t_i .

Flow: A flow consists of packets $\bar{r}p_1^g, \dots, p_n^g$ sharing the same flow ID f_i , which can be any combination of 5-tuple: source IP address, source port, destination IP address, destination port, protocol type.

Flowlet: Given a predefined flowlet threshold δ , a flowlet refers to a group of continuous packets $\bar{r}p_1^g, \dots, p_m^g$ of a

given owlet f_i , such that $80 < j < m$, $t_{j+1} > t_j$. This owlet is active if $j t_{now} - t_m < \tau$, where t_{now} is the current time, and is outdated otherwise. Intuitively, the packets of a owlet are divided into many groups/owlets, where the interval between adjacent owlets is large enough (τ). FlowBurst: For a owlet f_i , p_m^0 ; p_m^0 g, we define its size as m , and define its speed as $\frac{m}{T}$, where $T = t_m - t_1$. This owlet is a FlowBurst if $\frac{m}{T} > V$ and $m > k$, where k is the size of the k^{th} largest owlet among all active owlets whose speed are larger than V . Intuitively, FlowBursts refer to a particular kind of owlets that are fast and large enough to cause a load imbalance. For all active owlets whose speed exceed a predefined threshold V , we define the owlets of the largest k sizes as the FlowBursts.

2.2 Related Work

Existing load balancing solutions for data centers can be classified into three categories: packet-level schemes, ow-level schemes, and owlet-level schemes. For other hybrid schemes, kindly refer to references [33], [58]–[60].

1) Packet-level schemes [14]–[19] choose a desirable path for each packet. They achieve ideal splitting ratio at the cost of packet reordering. DRILL [14] makes per-packet decisions at each switch based on local-queue occupancies and randomized algorithms. NDP [15] presents a multipath-aware transport-layer protocol that manipulates each packet, and introduces a handshake mechanism to alleviate reordering. MP-RDMA [16] proposes a per-packet multi-path protocol for RDMA network, where the packets are distributed in a congestion-aware manner. Other packet-level schemes include Fastpass [19], DeTail [18], and DRB [17].

2) Flow-level schemes [20]–[26], [61] assign a path to each ow. They avoid packet reordering but cannot well balance the traffic because of collisions between large ows. The well-known ECMP [20] uses ow-level hashing to select a path for each ow. ECMP achieves excellent performance when there are only small ows but no large ows [25], [26]. WCMP [21] assigns each path a weighted cost, and distributes the traffic based on the cost. MPTCP [61] splits each TCP ow into several sub ows, and assigns each sub ow to a non-congested path. AuTO [23] forwards small ows using ECMP, and dynamically changes path, priority, and sending speed for large ows. Other ow-level schemes include FlowBender [22], SOFIA [24], VMS [62], Hedera [25], Mahout [26], MicroTE [63].

3) Flowlet-level schemes [2], [28]–[33], [64] make a trade-off between packet-level schemes and ow-level schemes in consideration of minimizing reordering and maximizing performance at the same time. Flowlets widely exist in data centers where most applications send traffic in on-off patterns [3], [65]. CONGA [31] designs a distributed algorithm to obtain global congestion information in leaf-spine topologies, and assigns each owlet to the least congested path at leaf switches. LetFlow [2] randomly picks paths for owlets, and lets their elasticity naturally balance the traffic on different paths. The excellent work Contra [66] builds a system for performance-aware routing based on owlet switching, which can operate seamlessly over any network topology and routing policies. Other owlet-level schemes include DASH [64], FLARE [28], HULA [67], and more [29], [30], [32]. A owlet scheme needs to strike a balance between

load balance and packet reordering. A owlet switching scheme has no danger of packet reordering only when the timeout threshold τ is larger than the maximum latency of the set of parallel paths. In order to avoid packet reordering, the timeout threshold must be set to a large value. However, large timeout threshold will degrade the system to a ow-level scheme. Therefore, the timeout threshold should be carefully chosen to achieve good performance.

Existing owlet-level schemes use a owlet table to detect owlets. Each table entry consists of a next_hop and a timestamp. In CONGA [31] and LetFlow [2], the timestamp is replaced with two bits, and they use a separate process to periodically clean the entries. This table must be very large to keep the collision rate small. Such a huge table incurs heavy memory burden when deployed on hardware platforms where on-chip memory is precious. By contrast, sketch is a compact data structure that uses small memory to perform various measurement tasks [43], [68], [69]. Typical sketches include CM [70], CU [71], Count [72], and more [73]–[75]. We can use sketches to detect and schedule owlets in real time, which is still an open area.

3 THE BALANCE SKETCH ALGORITHM

In this section, we first present a strawman solution to detect FlowBursts in x 3.1, and introduce the rationale of BalanceSketch in x 3.2. We show the data structure and workflow of BalanceSketch in x 3.3 and x 3.4. We demonstrate how BalanceSketch handles different traffic patterns in x 3.5. We propose some optimizations of BalanceSketch in x 3.6. We mathematically analyze the ability of BalanceSketch to identify FlowBursts in x 3.7. Finally, we present how to extend BalanceSketch to network measurement in x 3.8.

Fig. 1: A strawman solution to detect FlowBursts ($\tau = 5\text{ms}$, $t_{now} = 150\text{ms}$, $V = 1.5\text{Kpps}$).

3.1 A Strawman Solution

One strawman solution to find FlowBursts is to first identify all owlets using existing methods, and then check whether each identified owlet is a FlowBurst. 1) In the first step, same as existing solutions [28]–[30], we use a timestamp array to find owlets. For each incoming packet of owlet f_i at time t_{now} , we first compute a hash function $h_1(f_i)$ to map the packet to one timestamp. If the gap between t_{now} and timestamp is larger than the predefined owlet threshold τ , we consider the packet as the start of a owlet. Otherwise, we consider the packet as part of an existing owlet. At the end of this step, we update the mapped timestamp to t_{now} . As shown in Figure 1, the interval between the current time and the last arrival time of f_2 exceeds τ , so we report the packet of f_2 as the start of a owlet. 2) In the second step, we use a hash table with many buckets to detect FlowBursts, i.e., the owlets with high

speed. Each bucket maintains a flow ID and the recent speed of the flow. For a flowlet of flow f_i detected in step one, we map f_i into one bucket in the hash table. If another flowlet is already in this bucket and its speed is slow ($< V$), we replace it with f_i . Specifically, each bucket in the second step consists of a Flow_ID field, a Start_time field recording the start time of the flowlet, and a Counter field recording the flowlet size. Given an incoming packet of f_i at t_{now} , we first compute hash function $h_2(f_i)$ to map the packet into one bucket. Then, we check whether f_i is recorded in this bucket. If so, we increment the Counter by one. Otherwise, if the packet is the start of a flowlet (detected in the first step), we check whether its speed Counter / ($t_{now} - \text{Start_time}$) is below the speed threshold V : If so, we replace the old flowlet with f_i ; we set Flow_ID to f_i , set Start_time to current time t_{now} , and set Counter to one. As shown in Figure 1, for the detected flowlet of f_2 , its mapped bucket is taken by f_3 and the speed of f_3 is slow ($< V$), so we replace f_3 with f_2 . This solution is simple and easy to deploy. However, it is memory inefficient because it records the information of all flowlets, including the exact flow IDs and their recent speed, whereas most flowlets are unnecessary flowlets. The ideal goal is keeping only FlowBursts while evicting all unnecessary flowlets.

3.2 Rationale of BalanceSketch

The design of BalanceSketch embraces two dimensions of doing less: 1) Different from the aforementioned strawman solution, we manage to maintain only FlowBursts and evict unnecessary flowlets. 2) We identify most rather than all FlowBursts, in exchange for the simplicity of our data structure and its operations. Beyond the principle of doing less, we have another design tactic: follower approximation. Ideally, upon the arrival of the first packet of a FlowBurst, we should immediately recognize and manipulate it. However, it is almost impracticable to identify a flowlet as a FlowBurst at its onset, but it is not hard to assert a FlowBurst when it ends. Instead of manipulating a FlowBurst, we make a follower approximation by manipulating the BurstFollower: the flowlet that immediately succeeds a FlowBurst. The rationale is that BurstFollower is very likely to be a potential FlowBurst, incurring a risk of load imbalance. Interestingly, we find this approximation achieves similar performance to the ideal solution. Consider a typical traffic pattern: FlowBurst, FlowBurst, . . . Ideally, we manipulate each FlowBurst at it commences; Approximately, we manipulate each BurstFollowers, which essentially includes all FlowBursts except for the first one. These two methods yield the same load balance performance. More interesting patterns are elaborated upon in x 3.5. To the best of our knowledge, we are the first work that uses sketches instead of flow/flowlet table to perform L3 load balancing.

3.3 Data Structure

As shown in Figure 2, the data structure of BalanceSketch is an array of I buckets. Let $B[i]$ be the i^{th} bucket. Each packet of flow f_i is mapped into one bucket $B[h(f_i)]$ through a hash function $h(\cdot)$. Each bucket consists of four fields: 1) A flow_ID field $B[i]:ID$ records the ID of the flow mapped into this bucket, and we call the flow in the bucket as the residing flow. 2) A vote field $B[i]:vote$ used

Algorithm 1: Work ow of BalanceSketch

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Input: A packet with timestamp  $t_i$  of flow  $f_i$ 
Output: The next port to send this packet
// Insert the packet into BalanceSketch
if  $B[h(f_i)]$  is empty or  $t_i - B[h(f_i)]:time > \tau$  then
   $B[h(f_i)] = h(f_i, 1; t_i; \text{Null } i$ ;
else if  $B[h(f_i)]:ID = f_i$  then
  if  $B[h(f_i)]:vote > F$  and  $t_i - B[h(f_i)]:time > \tau$  then
     $B[h(f_i)]:nexthop =$  the randomly picked next hop;
   $B[h(f_i)]:vote += 1$ ;
   $B[h(f_i)]:time = t_i$ ;
else if  $B[h(f_i)]:ID \neq f_i$  then
  if  $B[h(f_i)]:vote > 0$  then
     $B[h(f_i)]:vote = 1$ ;
  if  $B[h(f_i)]:vote = 0$  and  $B[h(f_i)]:nexthop = \text{Null}$  then
     $B[h(f_i)] = h(f_i, 1; t_i; \text{Null } i$ ;
// Select the next hop to forward the packet
if  $B[h(f_i)]:ID = f_i$  and  $B[h(f_i)]:nexthop \neq \text{Null}$  then
  return  $B[h(f_i)]:nexthop$ ;
else
  return ECMP_next_port( $f_i$ );

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to identify FlowBursts. 3) A timestamp field $B[i]:time$ records the arrival time of the last packet of the residing flow. 4) An next_hop field $B[i]:nexthop$ records the next hop. For the flow residing in $B[i]$, if $B[i]:nexthop$ is not Null, we forward the flow through this next hop. Otherwise, we forward it using ECMP [20]: forwarding it through the next hop hashed by its 5-tuple. For the flows not residing in BalanceSketch, we also forward them using ECMP. All fields in the data structure are initialized to 0 or Null.

Fig. 2: Examples of BalanceSketch ($\tau_{now} = 200\text{ms}$, $\tau = 30\text{ms}$, $\tau_{evict} = 5\text{ms}$, $F = 30$).

3.4 Work ow

The pseudo-code of the work ow is shown in Algorithm 1. For an incoming packet p_c of flow f_i at time t_{now} , BalanceSketch takes two phases to process it: insertion and forwarding. In the insertion phase, BalanceSketch inserts f_i into one bucket. In the forwarding phase, BalanceSketch selects appropriate next hop to forward this packet. The insertion work ow of BalanceSketch processes each packet in one pass, and is of $O(1)$ time complexity. We have fully implemented the insertion work ow in the pipeline of programmable switch (with Tofino ASICs) using P4 [76] language, which has 1.2GHz clock frequency (see x 4.2).

Insertion: First, we compute the hash function $h(f_i)$ to map f_i into the bucket $B[h(f_i)]$, and try to insert it. There are three cases as follows.

Case 1: If $B[h(f_i)]$ is empty or $t_{now} > B[h(f_i)]:time$, where t_{now} is the predefined ow timeout threshold to identify whether a ow ends, we just insert ow f_i into $B[h(f_i)]$. Specially, we set $B[h(f_i)]$ to $\{f_i; 1; t_{now}; Null\}$, where "Null" means forwarding ow f_i through ECMP. In this case, $t_{now} > B[h(f_i)]:time$ means the resided ow ends.

Case 2: If $B[h(f_i)]$ is not empty and f_i is the residing ow, we check whether this packet is the start of a FlowBurst. Specially, we check whether $t_{now} > B[h(f_i)]:time$ and $B[h(f_i)]:vote > F$ are both true, where F is the owlet threshold and F is a predefined voting threshold for identifying FlowBursts. If so, it means that the previous owlet of f_i is a FlowBurst and just ends, and a new owlet just starts. The new owlet is potentially a FlowBurst, and thus we manipulate it by randomly picking a next hop and update $B[h(f_i)]:nexthop$. Finally, we increment $B[h(f_i)]:vote$ by one and update $B[h(f_i)]:time$ to the current time t_{now} . Note that randomly picking a next hop is one design choice, and we can also choose the least loaded next hop or use the "power of two choices" techniques [77]. We will discuss different manipulating choices in Figure 17.

Case 3: If $B[h(f_i)]$ is not empty and f_i^0 is the residing ow where $f_i^0 \neq f_i$, we decrement $B[h(f_i)]:vote$ by one if $B[h(f_i)]:vote > 0$. Afterwards, if $B[h(f_i)]:vote = 0$ and $B[h(f_i)]:nexthop = Null$, we replace f_i^0 with f_i by setting $B[h(f_i)]$ to $\{f_i; 1; t_{now}; Null\}$. Note that if $B[h(f_i)]:vote = 0$ but $B[h(f_i)]:nexthop \neq Null$, we do not immediately evict f_i^0 , and will evict it only when it is outdated (the ow timeout threshold t_{out}) in Case 1. In this way, the FlowBursts in BalanceSketch will not be frequently replaced, and thus the number of manipulated ow decreases. This is consistent with our design philosophy of doing less.

Forwarding: After inserting f_i into BalanceSketch, we select the next hop to forward the incoming packet p_c . If f_i is the residing ow and $B[h(f_i)]:nexthop \neq Null$, which means that f_i is experiencing a FlowBurst, we forward p_c through $B[h(f_i)]:nexthop$. Otherwise, we forward p_c using ECMP.

Discussion: BalanceSketch makes two approximations: 1) BalanceSketch uses the "vote" field to approximately identify FlowBursts. Recall that in x 2.1, we formally define FlowBurst using speed and size. Although we can use more fields to exactly represent the speed, size, and hash collisions, we find that using just the "vote" field can already achieve high accuracy. Therefore, to save memory, BalanceSketch only use one "vote" field to approximately reflect the speed and size of owlets. 2) BalanceSketch uses the follower approximation strategy to make load balance decisions for FlowBurst followers. BalanceSketch considers subsequent owlets after crossing the "F" threshold as FlowBursts and manipulates them. We make this approximation because we cannot immediately predict a owlet as FlowBurst when it just starts. Experimental results show that under these approximations, BalanceSketch still has high accuracy (x 5.1).

Example settings (Figure 2): We use three examples to illustrate the work of BalanceSketch, where the three packets of ow f_1 , f_2 , f_3 arrive simultaneously at time $t = 200ms$, the ow timeout threshold t_{out} is 30ms, the owlet threshold F is 5ms, and the voting frequency threshold Δ is 30.

Example 1 (upper of Figure 2): When a packet of f_1 arrives, it is mapped into bucket $B[h(f_1)]$. As $t = 200ms > B[h(f_1)]:time$, we replace the residing ow with f_1 . As $B[h(f_1)]:nexthop = Null$, we forward the packet using ECMP.

Example 2 (center of Figure 2): When a packet of f_2 arrives, it is mapped into bucket $B[h(f_2)]$. Since bucket $B[h(f_2)]$ is not empty and f_2 is the residing ow, we check whether this packet is the start of a FlowBurst. Since $t = 200ms > B[h(f_2)]:time$ and $B[h(f_2)]:vote > F$ are both true, we think a previous FlowBurst of f_2 just ends, and the new owlet has high probability to be a FlowBurst. Thus, we manipulate the new owlet by changing $B[h(f_2)]:nexthop$ to a randomly picked next hop. We increment $B[h(f_2)]:vote$ by one and update $B[h(f_2)]:time$ to t_{now} . Finally, since f_2 is the residing ow and $B[h(f_2)]:nexthop \neq Null$, we forward the packet through $B[h(f_2)]:nexthop$.

Example 3 (lower of Figure 2): When a packet of f_3 arrives, it is mapped into bucket $B[h(f_3)]$. Since bucket $B[h(f_3)]$ is not empty and f_3 is not the residing ow, we decrement $B[h(f_3)]:vote$ by one. Afterwards, since $B[h(f_3)]:vote = 0$ and $B[h(f_3)]:nexthop = Null$, we replace the residing ow f_6 with f_3 . Since $B[h(f_3)]:nexthop = Null$, we forward the packet using ECMP.

Fig. 3: Examples of typical traf c patterns.

3.5 Handling Different Traf c Patterns

We examine four typical traf c patterns to demonstrate how BalanceSketch manages them, showcasing that our FlowBurst follower approximation technique attains comparable load balancing performance to the optimal solution of manipulating each FlowBurst at start. In our examples, all FlowBursts/ owlets belong to the same ow. Suppose the default next hop is 0, and the backup next hop is 1. We assume the traf c of each ow consists of high-density FlowBursts and low-density owlets. An ideal load balance solution should distribute these high-density FlowBursts among all equivalent links as uniformly as possible. Manipulating other owlets benefits little for load balance as low-density owlets contribute little to link congestion.

Pattern 1 (upper-left of Figure 3): This pattern consists of continuous owlets mixed by a FlowBurst. BalanceSketch manipulates the BurstFollower (the owlet bounded by black-box in the figure), achieving the same load balance performance as the ideal solution. In this case, manipulating other owlets benefits little for load balance. BalanceSketch does not manipulate them and manages to achieve least change of the next hop. Since there is no frequent manipulation, BalanceSketch minimizes packet reordering. This idea is consistent with our design philosophy of doing less.

Pattern 2 (lower-left of Figure 3): This pattern consists of FlowBurst1, owlet1, FlowBurst2, owlet2, BalanceSketch changes the next hop for each owlet, and the following FlowBurst is forwarded through the same next hop of the previous owlet. It achieves similar performance as the ideal solution that manipulates each FlowBurst.

Pattern 3 (upper-right of Figure 3): This pattern consists of FlowBurst1, owlet1, owlet2, FlowBurst2, owlet3, owlet4, . BalanceSketch manipulates each BurstFollower (e.g, owlet1), and forwards following owlet2 and FlowBurst2 through the same next hop. The next hops of BalanceSketch are $h; 1; 1; 1; 0; 0; i$, while that of the ideal solution are $h; 1; 1; 1; 0; 0; i$. Both BalanceSketch and the ideal solution select one next hop for every two owlets and one FlowBursts, and thus they have similar performance. Pattern 4 (lower-right of Figure 3): This pattern consists of FlowBurst1, FlowBurst2, owlet1, FlowBurst3, FlowBurst4, owlet2, . BalanceSketch manipulates each latter FlowBurst and each owlet, and its next hops are $h; 1; 1; 1; 0; 0; i$. It achieves similar performance as the ideal solution with the next hops of $h; 1; 0; 1; 1; 0; i$.

3.6 BalanceSketch Optimizations

Flow Fingerprint: We use fingerprints (hash values) to replace ow IDs (usually 104 bits) in BalanceSketch, to improve its memory efficiency. In this way, the memory overhead of BalanceSketch is independent to the size of ow ID. Due to hash collisions, some ows could share the same fingerprint, making BalanceSketch regards multiple ows as one ow. Given a ow, the probability that it suffers from fingerprint collisions is $\Pr[\text{collision}] = 1 - (1 - 2^{-n})^M$, where n is the fingerprint size (in bit), M is the number of distinct ows in the network stream, and L is the number of buckets in BalanceSketch. This probability is low, and thus has little impact on performance. For example, when using 16-bit fingerprints and $L = 50,000$ buckets, for $M = 1,000,000$ concurrent ows in the network, the probability of fingerprint collision is just 3.05×10^{-4} , which is negligible. Experiments show that the accuracy of BalanceSketch does not decrease when using 16-bit fingerprints.

Field Combination: Once a FlowBurst is detected, we change the next_hop field to manipulate it. After that, even if the vote field is decremented to zero, we do not evict this ow in consideration of manipulating less ows (Case 3 in x 3.4). In other words, once next_hop is set to a non-Null value, we do not need vote field any more. Thus, we can combine vote and next_hop into one field vote_hop .

Fig. 4: Compact timestamp ($k = 4$).

Compact Timestamp: We propose to compress the full timestamp into s -bit cell, and use the cell to compactly record the approximate time. Below we take 3-bit cell as an example. As shown in Figure 4, noticing that 3-bit cell can represent eight states, we cyclically divide the timeline into eight kinds of time slices ($0 \sim 7$), and the length of each time slice is $\frac{1}{8}$. We record these time slices ($0 \sim 7$) rather than the full timestamps in BalanceSketch. If two adjacent packets of a ow are spaced by at least one time slice, we think the second packet is the start of a owlet. Suppose $k = 4$, then if the last arrival time of a ow f_i and the current time

are spaced by at least k time slices, we think f_i ends. Figure 4 shows four consecutive packets mapped into the same bucket. The two packets of f_1 are spaced by one time slice, so we report the second packet as the start of a owlet. Suppose $k = 4$, then since the last packet of f_1 and the first packet of f_2 are spaced by four time slices, when the first packet of f_2 arrives, we think f_1 ends and evict it.

The compact timestamp technique gains memory efficiency at the cost of perceiving time in a fuzzy way. When the interval between two adjacent packets is among $2 \sim k$, BalanceSketch might not be able to correctly report the second packet as the start of a owlet, depending on the relative offset of the timeline. Specifically, only when the interval span three time slices can BalanceSketch report the owlet correctly. This issue is illustrated in the last two packets in Figure 4. Although the interval between the two packets of f_2 exceeds k , BalanceSketch cannot correctly divide them into two owlets because the interval span just two time slices. Actually, more precision can be attained by using more bits per timestamp or using multiple timestamps with different timeline offsets, but we find that one 8-bit timestamp suffice for good performance in our experiments (see x 5.1.1).

Analysis: We derive the error of our Compact Timestamp technique. For an arbitrary ow f , we assume all of its owlets arrives according to a Poisson process of intensity λ . Let flowlet i be the i th owlet of f , and let x_i be the time interval between the arrival time of flowlet $i-1$ and flowlet i . In our derivation, we ignore the timespan of owlet because it does not affect the final conclusion. Thus, we have x_i follows an exponential distribution $\text{Exp}(\lambda)$. For flowlet i , BalanceSketch cannot correctly report it if the interval between flowlet $i-1$ and flowlet i span only two time slices, i.e., x_i only spans two slices. For a certain x_i , the probability that it spans two slices is $\frac{2-x_i}{2}$. Let A_i be the event that BalanceSketch fails to detect flowlet i . We have $\Pr[A_i] = \int_0^2 e^{-\lambda x_i} \frac{2-x_i}{2} dx_i = \frac{1}{\lambda} (1 - e^{-2\lambda})$. Let $\tau = \frac{1}{\lambda}$ be the average interval between adjacent owlets, which are usually of RTT scale [2]. In practice, we set τ to be of sub-RTT scale, meaning that $\tau > \frac{1}{8}$, i.e., $\lambda < 8$. Thus, we have $\Pr[A_i] < \frac{1}{8}$. As stated above, we can also use multiple timestamps with different timeline offsets to further reduce the error rate. Actually, using y timestamps can reduce the error by y times. When $\tau = 0.1$ and $y = 3$, we have $\Pr[A_i] = 1.2 \times 10^{-4}$, which is negligible.

Multi-cell BalanceSketch: To further improve the accuracy, we propose the multi-cell version of BalanceSketch by extending each bucket of BalanceSketch into an array of d (e.g, 4) cells. Each cell consists of four fields: flow_ID, timestamp, vote, and next_hop. For each incoming packet of ow f_i at t_{now} , it is mapped into bucket $B[h(f_i)]$. We first check whether f_i is recorded in a cell in $B[h(f_i)]$. If so, we increment vote and update timestamp. Otherwise, we second check whether there is an empty or outdated cell in $B[h(f_i)]$. If so, we insert f_i into this cell. Otherwise, we third find the cell with the minimum vote, and decrement its vote by one. If vote is decremented to zero and next_hop is Null, we replace the residing ow in this cell with f_i . Finally, if f_i is recorded in a cell in $B[h(f_i)]$ and its next_hop is not Null, we forward the packet through next_hop. Otherwise, we forward the packet using ECMP.

The insertion work ow of multi-cell BalanceSketch can be accelerated by SIMD instructions [78] on CPU platforms. Experimental results show that using 8-cell buckets can improve the accuracy of BalanceSketch by up to 20%.

Automating Parameter Con guration: As described in x 2.1 and x 3.4, we use a speed threshold V to de ne FlowBurst, and use a voting threshold F in BalanceSketch to identify FlowBursts. However, we should need different thresholds in different environments. Intuitively, under low network load, there are less risk of load imbalance, and thus we should manipulate less traf c to avoid making the network more chaotic. In such case, we should use large V and F to reduce the number of FlowBursts. Whereas under high network load, we should manipulate more traf c to better balance the load, and thus we need smaller V and F to increase the number of FlowBursts. On the other hand, these thresholds should not be too small to overwhelm the sketch with excessive FlowBursts. Based on these ideas, we devise a method to automatically setting V and F according to current network load (or remaining bandwidth) as follows:

$V = V_0 \exp \frac{4}{\max(0.6; 1 - \rho)}$, and $F = V \frac{4}{\rho}$, where V_0 is the maximum bandwidth and ρ is the current network load. We conduct experiments to evaluate the performance of our automatic parameter con guration method, where we evaluate the ratio of the theoretically/experimentally manipulated ows/packets under different network load. As show in Figure 5, under low network load, we manipulate a small fraction of traf c. As network load increases, we gradually manipulate more ows/packets to better balance the load. When network load exceeds ($\rho = 40\%$ in our experiments), as network load increases, we no longer manipulate more traf c, so as to avoid overwhelming BalanceSketch with too many FlowBursts. In practice, ρ can be dynamically set according to the scale/skewness of traf c, and the size of BalanceSketch.

(a) Manipulated ows. (b) Manipulated packets.

Fig. 5: Ratio of manipulated ows/packets under automatic parameter con guration.

3.7 Mathematical Analysis

We mathematically analyze the ability of BalanceSketch to identify FlowBursts, and validate our theoretical results with experiments. To simplify the derivation, we rst make the following assumptions for the traf c model.

Assumption 3.1. Given a bucket in BalanceSketch, we assume that all active owlets mapped into this bucket have the same speed, i.e., the interval between any two consecutive packets of any owlet is constant. Therefore, we can divide the timeline into

4. These formulas might not be optimal. We can further consider the size of BalanceSketch and devise smarter formulas. But the results show that these formulas can already well achieve our design goal.

consecutive time slots of equal length. Each ow has at most one packet in each time slot. A owlet is a group of continuous packets that arrive in several consecutive time slots.

Assumption 3.2. Given a bucket in BalanceSketch, we assume that the ows mapped into this bucket are: 1) A large ow whose owlet size is always n_1 (in packets), and the interval between its any two consecutive owlets is always s_2 (in time slots). Note that we de ne the interval between two owlets as the time gap between their rst packets. 2) Many small ows. We divide the small ows into owlets, and assume that these owlets obey the $M=M=1$ queuing theory model: the interval between any two consecutive owlets obeys the exponential distribution with parameter λ_1 , and the size of each owlet obeys the exponential distribution with parameter λ_2 .

We give the well-known conclusion of $M=M=1$ model in queuing theory through the following lemma.

Lemma 3.1. In each time slot, the number of packets of small ows satisfies Poisson distribution with parameter $\lambda = \frac{\lambda_2}{\lambda_1}$. Let Y_i be the number of packets of small ows arriving in the time slot, then $\Pr[Y_i = k] = e^{-\lambda} \frac{\lambda^k}{k!}$.

To simplify the derivation, we assume Y_i is independent and identically distributed for different i , and that the packet belonging to the large ow f is always the last to arrive in each time slot.

Assumption 3.3. Given a bucket in BalanceSketch, let X_i be the value of its vote held after the i th time slot ($X_0 = 0$). For the large ow f , we assume that it starts at the first time slot. For the other small ows, to simplify the derivation, we assume that the number of packets of small ows in each time slot is independent and identically distributed, and according to Lemma 3.1, all obey Poisson distribution with parameter λ . We also assume that the packet belonging to the large ow f is always the last to arrive in each time slot, therefore the flow_ID is always f during the first n_1 time slots according to our algorithm.

We can derive the following conclusions about the Markov process of random variable X_i (Lemma 3.2), and the ability of BalanceSketch to detect FlowBurst (Theorem 1).

Lemma 3.2. The random variable X_i , i.e., the value of the vote held satisfies the following Markov process when $\rho < n_1$,

$$X_i = \max(X_{i-1} + 1 - Y_i; 0): \quad (1)$$

Further, we can obtain that $0 \leq X_i \leq n_1$, and for $\forall i \geq 2$,

$$\Pr[X_i = k] = \sum_{j=0}^{X_{i-1} - k} \Pr[X_{i-1} = k + j + 1] e^{-\lambda} \frac{\lambda^j}{j!} + \sum_{k=2}^{n_1} P_{i-1, k} \Pr[X_{i-1} = k] \quad (2)$$

Theorem 1. Given the owlet threshold $\rho < n_2$, and the voting threshold $F < n_1$, where s is the length of the time slot, if the probability P_f that the largest ow f is successfully reported as FlowBurst after the $(n_1 + n_2)$ th time slot satisfies

$$P_f > \Pr[X_{n_1} > F + \sum_{i=1}^{X^2} Y_{n_1+i} > 1] \frac{n_1 + n_2}{n_1 F} \quad (3)$$

Proof. Based on Lemma 3.2, we have $X_i > 1 + X_{i-1} - Y_i$, therefore X_{n_1} satisfies

$$X_{n_1} = X_0 + \sum_{i=1}^{n_1} (X_i - X_{i-1}) > n_1 - \sum_{i=1}^{n_1} Y_i$$

Then according to the Markov inequality, we have

$$\begin{aligned} P_f &> \Pr \left[X_{n_1} - \sum_{i=1}^{n_1} Y_i > F \right] \\ &> \Pr \left[n_1 - \sum_{i=1}^{n_1} Y_i > F \right] = 1 - \Pr \left[\sum_{i=1}^{n_1} Y_i > n_1 - F \right] \\ &> 1 - \frac{E \left[\sum_{i=1}^{n_1} Y_i \right]}{n_1 - F} = 1 - \frac{n_1 + n_2}{n_1 - F} \end{aligned}$$

(a) P_f v.s. voting threshold F . (b) P_f v.s. n_1 and n_2 .

Fig. 6: Numerical verification of probability P_f with default setting of $n_1 = 70; n_2 = 30; \rho = 0.5; F = 10$.

Experimental analysis (Figure 6): We conduct experiments to validate our mathematical analyses. Although we cannot directly obtain the analytical solution of P_f from Lemma 3.2, we can give the numerical solution of P_f under a specific setting by numerical simulation. By setting $n_1 = 70; n_2 = 30; \rho = 0.5; F = 10$ as default, we show how P_f changes with F in Figure 6(a), and how P_f changes with n_1 and n_2 in Figure 6(b). The numerical results show that when the flow f is large (i.e., n_1 is large), the number of concurrent small flows is small (i.e., n_2 is small), and the voting threshold is small (i.e., F is small), the largest flow will be correctly reported as FlowBurst with a high probability.

3.8 Extension to Network Measurement

Besides L3 load balancing, our FlowBursts and BalanceSketch can do more to improve the network. In this subsection, we show how to utilize FlowBursts to perform robust per-flow per-hop measurement. We focus on four important tasks: tracing forwarding path, finding the flows consuming huge bandwidth (heavy hitters), finding the flows experiencing packet drops, and finding the flows experiencing increased queuing delays. The information of these abnormal flows can guide the network operator to quickly locate culprit devices and further debug the network.

In BurstBalancer, we deploy one BalanceSketch on each switch. We configure all BalanceSketches to report the detected FlowBursts along with their attributes (including the timespan, packet count, etc) to control planes. A central analyzer periodically collects the information of FlowBursts from all switches, and further analyze these information to identify abnormal flows. In practice, the clocks of different network devices are hard to be perfectly synchronized [79], [80], which brings errors to existing measurement systems [48], [81], [82]. Fortunately, we find that by performing

network measurement with FlowBursts, BurstBalancer is robust to imperfect clock synchronization. Below we describe how to configure BurstBalancer to perform the four tasks. Tracing forwarding path: We add two fields to each bucket of BalanceSketch (or each cell in multi-cell BalanceSketch. We will no longer emphasize this point.), which record the start/end Sequence Number of the FlowBurst. We configure each switch to report the Sequence Number range, and the next-hop for each detected FlowBurst. For any FlowBurst, the central analyzer can use its Sequence Number range and per-switch next-hop to track its forwarding path, so as to find the culprit devices where network anomalies happen. Finding per-hop heavy hitters: We add a packet count field to each bucket, and let each switch report the packet count for each FlowBurst. For each active flow f , the analyzer acquires its per-hop size by summing up the packet counts of all FlowBursts in f . In this way, the analyzer can find those flows that are consuming a large amount of bandwidth on each switch, so as to decide whether to impose some restrictions on them (e.g, reducing their priorities). Locating packet drops: We add three fields to each bucket: a packet count field, two fields recording the start/end Sequence Number of the FlowBurst. We configure each switch to report the packet count, the Sequence Number range, and the next-hop for each FlowBurst. As stated above, the central analyzer uses the Sequence Number range and per-switch next-hop to track each FlowBurst along its forwarding path. For each FlowBurst, the analyzer can locate those culprit switches where its packet count decreases, so as to further troubleshoot the network.

Locating increased queuing delays: We add four fields to each bucket: two timestamp fields recording the start/end time of the FlowBurst, and two fields recording the Sequence Number range of the FlowBurst. We configure each switch to report the timespan, the Sequence Number range, and the next-hop for each FlowBurst. The central analyzer uses Sequence Number range and next-hop to trace each FlowBurst, and finds those culprit switches where the FlowBurst timespan suddenly increases.

Discussion: As a network measurement system, BurstBalancer has three advantages. 1) Fine-grained: BurstBalancer can acquire per-flow per-hop information, and thus can perform network-wide measurement tasks; 2) Lightweight: Unlike many systems that collect packet-level information for all flows [43], [81], [83], BurstBalancer only records a small fraction of critical flows, and these flows are important to network performance. Thus, BurstBalancer significantly reduces the memory and bandwidth overhead; 3) Robust: BurstBalancer uses FlowBurst to perform network measurement, which is robust to imperfect clock synchronization. In conclusion, besides L3 load balancing, another promising direction is to use FlowBursts to perform accurate and lightweight network measurement.

4 THE BURSTBALANCER SYSTEM

4.1 Overview of BurstBalancer

BurstBalancer deploys BalanceSketch on switches to detect and make forwarding decisions for each FlowBurst. As

5. We define a flow as an active flow if the time interval between the arrival time of its last packet t_{last} and the current time t_{now} is smaller than the flow timeout threshold τ , namely $|t_{now} - t_{last}| < \tau$.

shown in Figure 7, we deploy one BalanceSketch on each edge switch and let it process all packets arriving from the line side. Given an incoming packet, we first insert its flow ID into one bucket in our BalanceSketch. We check whether the packet is the start of a FlowBurst. If so, we change the next hop of this flow by randomly picking a next hop. Afterwards, we forward the packet through the recorded next_hop if its flow ID is recorded, otherwise, we forward it using ECMP. In this way, BurstBalancer divides large and dense flows into FlowBursts, and distributes them to different paths. And for small flows and low-density flows, BurstBalancer just neglects them and forwards them using ECMP. BurstBalancer achieves good load balancing performance while manipulates less flows at the same time.

Fig. 7: BurstBalancer overview.

4.2 Testbed Implementation

We fully implement BurstBalancer on a testbed with 4 Edgecore Wedge 100BF-32X switches (with Tiano ASIC) [55] and 16 end-hosts in a Leaf-Spine topology. On each switch, we develop BalanceSketch using P4 language [76].

4.2.1 Challenges on Programmable Switches

To process packets at line rate, Tiano switch requires the algorithms running on it to comply with many constraints. Although BalanceSketch is easy to implement on software platforms (e.g. middleboxes, etc), when deploying it on hardware, we face the following key challenges.

Resource limitation: We implement BalanceSketch in registers and use the Logical Units in each stage to lookup and update the elements of registers in real time. Recall that each bucket of BalanceSketch consists of four fields (flow_ID, timestamp, vote, and next_hop). However, each Stateful ALU can only access one pair of 32-bit elements in each register. Thus, we must divide one bucket into multiple parts and store them in different registers.

Pipeline limitation (I): Tiano switches process packets in a pipelined manner, where each register can only be read or modified once in one pipeline stage. Therefore, each incoming packet can only access each register exactly once, which brings difficulty in clearing the outdated buckets. Due to the first challenge, we have to store the flow_ID and timestamp of a bucket in two different registers. For each incoming packet, we first check the flow_ID register and then update the timestamp register if ID matches. However, when ID mismatches and the timestamp is outdated (smaller than t_{now}), BalanceSketch needs to clear the bucket by setting flow_ID to Null (Case 1 in x 3.4). This backward operation is impossible on Tiano

architectures. In our implementation, we consider to use the mirror and recirculate mechanism: once a bucket is identified as outdated, we create a mirror packet and re-send it to the ingress port. We use this mirror packet to clear the flow_ID register. Here, the mirror and recirculate mechanism would not cause performance issue. First, only a few packets (< 0.5%) need this mechanism. Second, this mechanism is only used to clear the outdated bucket, which would not affect the scheduling and forwarding of packets.

Pipeline limitation (II): In the software version of BalanceSketch, if flow_ID mismatches and vote is decremented to zero, we check whether next_hop is Null, and evict the residing flow f_{old} if so (Case 3 in x 3.4). This check operation ensures that the FlowBursts in BalanceSketch are not frequently replaced, and also prevents f_{old} from packet reordering incurred by immediately evicting. However, as explained above, this backward operation cannot be implemented in pipeline. Therefore, in our implementation, when vote is decremented to zero, we must decide whether to evict the residing flow before checking next_hop. To address this issue, we consider dividing BalanceSketch into two parts: a selector and a scheduler. The selector detects FlowBursts and informs the scheduler to schedule them. And the scheduler maintains the next hop information for all scheduled flows. Once a flow is selected to schedule and enters the scheduler, it will be kept until ends. In this way, we approximately implement the software operation of BalanceSketch in a pipelined manner.

Hardware constraints: In x 3.6, we propose a field combination technique to combine vote and next_hop fields into one vote_hop field. However, if we combine these two fields in our hardware implementation, there will be three fields that have pairwise dependencies on each other: flow_ID, timestamp, and vote_hop. For example, for each incoming packet, we first check flow_ID field, and then update timestamp and vote_hop field. After checking timestamp and vote_hop, we decide whether to evict the residing flow by changing flow_ID field. Unfortunately, P4 [76] only supports simultaneously accessing at most two variables. Thus, we need a kind of redundant design to resolve the mutual dependencies of the three fields, which is done by creating a duplicate for each field in our implementation.

Fig. 8: BalanceSketch on programmable switch.

4.2.2 Workload

As shown in Figure 8, the workload of BalanceSketch has two parts: a selector and a scheduler. The selector detects

FlowBursts and selects the flows to be scheduled. The scheduler keeps the next hop information of the scheduled flows. Both the two parts are implemented in ingress pipeline. Selector: Each bucket in selector consists of three fields: flow_ID, vote, and timestamp. The selector uses two registers, where flow_IDs and votes are implemented in one register, and timestamps in another. For each incoming packet of f_i , we first check and update the hashed flow_ID and vote in the first register, i.e. increment vote if ID matches and decrement it otherwise. If vote is decremented to zero, we replace flow_ID with f_i . Then we access the hashed timestamp in the second register: 1) We check whether the bucket is outdated, i.e., check whether the time gap exceeds Δ . If so, we create a mirror packet and use it to clear the bucket. 2) We check whether the packet is the start of a FlowBurst, i.e., check whether ID matches, vote exceeds F , and time gap exceeds Δ . If so, we inform the scheduler to manipulate this flow by setting a temporary variable sch_flag . 3) We finally update the timestamp to the current time t_{now} if ID matches.

Scheduler: Each bucket in scheduler consists of three fields: flow_ID, timestamp, and next_hop. The scheduler also uses two registers, where flow_ID and timestamp are implemented in one register, and next_hop in another. For each incoming packet of f_i , if it is the start of a FlowBurst, i.e., sch_flag is set, we try to update the scheduler: we check the hashed flow_ID and timestamp. If ID matches or the timestamp is outdated (smaller than t_{now}), we update flow_ID to f_i , timestamp to t_{now} , and next_hop to a randomly chosen next hop. Finally, if the flow_ID is f_i , we forward the packet through next_hop. Otherwise, we forward the packet using ECMP.

4.2.3 Hardware Resources Utilization

We show the utilization of different types of hardware resources in Table 2. We can see that the average resources usage is less than 10% across all resources, except for Stateful ALUs, which is used for accessing registers and performing transactional read-test-write operations on BalanceSketch. We implement BalanceSketch in 9 stages on To no switch: 4 stages for the selector and 2 stages for the scheduler. In addition, we use 3 stages to implement the basic functions of the switch, such as route matching and packet forwarding.

4.3 Discussion

BurstBalancer differentiates itself by manipulating only a small fraction of flows. This aspect enables it to seamlessly integrate with numerous network measurement and management systems, including but not limited to 007 [37] and HPC [42]. To illustrate, let's consider the 007 system, which assumes all flows follow ECMP. After detecting TCP retransmission on end-hosts, 007 triggers a path discovery mechanism to acquire the routing links of the victim flow. Subsequently, it employs a voting scheme based on the paths of flows that had retransmissions, and the top-voted links are reported in each measurement epoch. In LetFlow, all flows have unxed forwarding path, which changes rapidly and randomly, making the path tracing scheme impossible to implement. By contrast, in BurstBalancer, most flows follow ECMP and thus have xed forwarding paths. In BurstBalancer, if a TCP retransmission is detected

for a ECMP flow, 007 can still trace its forwarding path and update the votes for each link along the path. The voting outcomes can then accurately reflect the real-time congestion level of each link. Thus, BurstBalancer maintains its compatibility with systems like 007.

TABLE 2: H/W resources used by BalanceSketch.

Resource	Usage	Percentage
Hash Bits	390	7.81%
SRAM	92	9.59%
Map RAM	26	4.51%
TCAM	0	0%
Stateful ALU	13	27.08%
VLIW instr	16	4.17%
Match Xbar	109	7.10%

5 EXPERIMENTAL RESULTS

We extensively evaluate BurstBalancer (BB) with CPU experiments (x 5.1), large-scale simulations (x 5.2), and testbed experiments (x 5.3). Our experiments aim to answer the following questions.

Can BalanceSketch accurately detect FlowBursts? We implement BalanceSketch using C++ and evaluate its accuracy. The results show that BalanceSketch achieves > 90% Recall Rate in finding FlowBursts. (x 5.1.1)

Can BurstBalancer manipulate less flows to balance the traffic? We evaluate the load balance performance of BurstBalancer on a single switch, comparing that compared to LetFlow [2], BurstBalancer manipulates 58 times less flows while better balances the traffic. (x 5.1.2)

In symmetric topologies, can BurstBalancer better balance the traffic? We extensively evaluate BurstBalancer using simulations. As a whole, BurstBalancer achieves 5%–35% better FCT than state-of-the-art LetFlow [2] and DRILL [14] in symmetric topologies. (x 5.2)

In asymmetric topologies, can BurstBalancer better balance the traffic? We evaluate BurstBalancer on a small-scale testbed with asymmetry. The results show that BurstBalancer achieves up to 30% better FCT than LetFlow and up to 6.4% better FCT than WCMP [21]. (x 5.3)

Can BurstBalancer be well deployed into commercial switches? We evaluate BurstBalancer on an electronic system level (ESL) simulation platform. The cycle-level results show that BalanceSketch can be well deployed into commercial chips and BurstBalancer achieves good load balancing performance in RDMA networks. (x 5.2.2)

Metrics: We use flow completion time (FCT) as the primary metric. We also consider the statistics of the queue lengths across ports and the packet reordering ratio. We use the Recall Rate (RR) and Average Relative Error (ARE) to evaluate the accuracy of BalanceSketch, which are defined as follows.

1) Recall Rate (RR): Ratio of the number of correctly reported instances to the number of ground-truth instances.

2) Average Relative Error (ARE): $\frac{1}{|\mathcal{F}|} \sum_{f_i \in \mathcal{F}} \frac{|n_i - \hat{n}_i|}{n_i}$, where n_i is the real size/timespan of FlowBurst f_i , \hat{n}_i is its estimated size/timespan, and \mathcal{F} is the set of all FlowBursts.

Workloads: We use three realistic workloads and one synthetic workload: 1) Web search workload [84] from a production cluster running web search services, where the average flow size is 2.5×10^6 bytes; 2) RPC workload [85] that contains many small flows, where the average flow size is 2×10^2 bytes; 3) Enterprise workload that is derived

(a) Web search. (b) RPC. (c) Enterprise. (d) Synthetic.

Fig. 9: Traffic distributions. The Bytes (Pkts) CDF shows the distribution of traffic bytes (packets) across flow sizes.

(a) BalanceSketch. (b) Multi-cell BSketch. (c) BalanceSketch. (d) Multi-cell BSketch. (e) Speed of BalanceSketch.

Fig. 10: Performance of BalanceSketch (BSketch) and optimized BalanceSketch.

from our Huawei data center running Hadoop applications, where the average flow size is $5.7 \cdot 10^4$ bytes. 4) Synthetic workload that is of heavy-tailed distribution, where the average flow size is 30 packets. The traffic distribution is shown in Figure 9. All the four workloads are heavy-tailed: a small fraction of large flows contribute to most traffic.

Parameter selection: We set the parameters of BurstBalancer intuitively: 1) We set the flowlet timeout threshold to a sub-RTT timescale. As suggested in LetFlow [2], α controls the trade-off between load balance and packet reordering. Larger α goes with fewer reordering packets and greater risk of load imbalance. A sub-RTT timescale α can well divide TCP bursts into flowlets and achieve good performance. 2) We set the flow timeout threshold to a RTT timescale. BalanceSketch uses β to identify whether a residing flow ends, so we set β to 3-5 times of RTT. 3) We set the voting threshold F to a small value, because we find that the BalanceSketch using small F can accurately detect FlowBursts.

5.1 CPU Experiments

5.1.1 Performance of BalanceSketch.

We evaluate the performance of BalanceSketch under small memory usage. As we are the first to propose the concept of FlowBurst, and considering that there are no existing works that can be directly used to find FlowBursts, we implement the strawman solution described in x 3.1 as the baseline approach. We implement basic BalanceSketch, and the optimized BalanceSketch using 16-bit flow ID fingerprints and 8-bit compact timestamps.

Dataset: We use the IMC packet traces [54] collected in a data center network, which contains about 19.9M packets belonging to 7.6M different flows. We set the flowlet threshold $\alpha = 50$ μ s, set V to the 70th percentile of the speed of all active flowlets, and set k to the size of the 200th largest flowlets with $v > V$ speed. In other words, we define the top-200 largest flowlets with $v > V$ speed as FlowBursts.

Accuracy of basic BalanceSketch (Figure 10(a)): We find that the RR of BalanceSketch greatly outperforms the strawman solution, and the RR of the optimized BalanceSketch is higher than basic BalanceSketch. Compared to the strawman solution, RR of BalanceSketch is about 20% higher on average. The optimized BalanceSketch improves RR by about 10% - 33% compared to the basic version.

Accuracy of multi-cell BalanceSketch (Figure 10(b)): We find that for multi-cell BalanceSketch, larger d goes with higher RR. Compared to the basic BalanceSketch, the multi-cell BalanceSketch with $d = 8$ improves RR by about 20% on average. The results show that when using 50KB of memory, the multi-cell BalanceSketch with $d = 8$ achieves RR of 90%.

Accuracy of FlowBurst size estimation (Figure 10(c)-10(d)): We find that the ARE of BalanceSketch is one order of magnitude lower than the strawman solution, and the ARE of the optimized BalanceSketch is lower than basic BalanceSketch. When using 40KB of memory, ARE of the strawman solution, the basic BalanceSketch, and the optimized BalanceSketch are 1.51, 0.20, and 0.13, respectively. We also find that for multi-cell BalanceSketch, larger d goes with lower ARE. Compared to the basic BalanceSketch, the multi-cell BalanceSketch with $d = 8$ improves ARE by 1-2 orders of magnitudes on average. When using 50KB of memory, the multi-cell BalanceSketch with $d = 8$ achieves ARE of $7.6 \cdot 10^{-4}$.

Speed of BalanceSketch (Figure 10(e)): We find that on CPU platform, our BalanceSketch achieves > 60 Million operations per seconds processing speed, which is faster than most sketch algorithms [74]. In our hardware implementation ($\times 5.3$), we deploy BalanceSketch into the pipeline of the switch ASICs, whose speed is only affected by the clock frequency. For example, the Tofino switches used in our testbed have 1.2GHz clock frequency.

Analysis: We find that BalanceSketch greatly outperforms the strawman solution. The results are consistent with our analysis in x 3.1. The main reason is that the strawman solution records information of all flowlets, most of which are unnecessary flowlets, incurring enormous redundancy. In contrast, BalanceSketch only keeps FlowBursts and discards unnecessary flowlets, gaining high memory efficiency. We also find that optimized/multi-cell BalanceSketch is more efficient. The results show that 16-bit flow fingerprint and 8-bit compact timestamp are sufficient for good performance. In summary, BalanceSketch well achieves our design goal of accurately identifying FlowBursts using small memory.

5.1.2 Load Balance Performance on a Single Switch

We evaluate the load balance performance of BurstBalancer on single switch and compare it against ECMP [20] and LetFlow [2]. We use C++ to simulate the load

(a) # pkts at all ports. (b) Manipulated ows. (c) Reordering pkts. (d) Load distribution.

Fig. 11: Performance of BalanceSketch on single switch.

(a) Heavy hitter detection. (b) Heavy hitter detection. (c) Ratio of recorded ows. (d) Ratio of recorded pkts. (e) Packet drops detection.

Fig. 12: Performance on nding high-bandwidth-consuming ows (a-d) and detecting packet drops (e).

balancing module of a 128-port switch, on which we deploy the Flowlet Tables (LetFlow) and the BalanceSketchs with different sizes (2K/4K # entries/buckets). In our setting, there are two switches connected by 128 links. We generate the traf c according to the synthetic workload (Figure 9(d)) at switch 1. We measure the traf c distribution across the 128 links, and count the reordering packets at switch 2.

Load distribution across all ports (Figure 11(a)): We nd that compared to LetFlow, BurstBalancer better balances the traf c using smaller memory. The results show that the standard deviation of BurstBalancer using 2K buckets is smaller than LetFlow using 4K entries. This is because due to the limited memory and the large number of concurrent ows, LetFlow inevitably regards multiple ows as one, leading the number of detected owlets decreases a lot. In other words, the large volume of concurrent ows makes LetFlow harder to divide ows into owlets, resulting in unbalanced load.

Ratio of manipulated ows (Figure 11(b)): We nd that compared to LetFlow, BurstBalancer manipulates fewer ows while better balance the load. The results show that the manipulated ows of BurstBalancer is 1.0 % ~ 1.65%, while that of LetFlow is > 95%. Note the the load balance performance of BurstBalancer_2K is better than LetFlow_4K.

Ratio of reordering packets (Figure 11(c)): We nd that compared to LetFlow using 4K entries, BurstBalancer using 2K buckets has less reordering packets while achieves better load balance performance. We simulated a scenario where two switches S_1 and S_2 are connected by 128 links. We generate traf c at S_1 , and measure the packet reordering rate at S_2 by counting the mismatches between actual and expected sequence number.

Load distribution for high-density traf c (Figure 11(d)): To better demonstrate the advantages of our BurstBalancer over LetFlow, we accelerate the synthetic workload by 5 times to create a high-density traf c model. We repeat the experiments using LetFlow_4K and BurstBalancer_2K. The results show that the performance of LetFlow and ECMP is almost the same, because the high-density traf c makes it dif cult for LetFlow to detect owlets, and thus LetFlow degenerates into ECMP. BurstBalancer can still well balance the traf c since it only manipulates critical owlets and ignores abundant unnecessary owlets.

5.1.3 Performance on Network Measurement

We evaluate the performance of BurstBalancer on performing the measurement tasks in x 5.1.2. We conduct experiments using CAIDA [86] dataset. For the experiments of locating packet drops and in ated queuing delay, we randomly choose packets and let the switch proactively drops these packets or increases their queuing delays.

Accuracy on nding per-hop heavy hitters (Figure 12(a)-12(d)): We nd that BalanceSketch can accurately nding heavy hitters with small memory usage. As shown in Figure 12(a), when using 50KB memory, BalanceSketch achieves > 95% Recall Rate in nding top-200 heavy hitters, which is significantly higher than that of the strawman solution. Figure 12(b) shows the performance of multi-cell BalanceSketch. We can see that larger d goes with higher accuracy for heavy hitter detection. We x the memory usage to 300KB, and illustrate the ratio of ows/packets recorded in BalanceSketch (i.e., the packets/ ows that are manipulated by BurstBalancer) in Figure 12(c)-12(d). We can see that BalanceSketch only records a small fraction of ows (< 20%), and these ows contribute to a large amount of traf c (> 80%), meaning that BalanceSketch can effectively nding those high-bandwidth-consuming ows.

(a) In ated delay detection. (b) FlowBurst timespan est.

Fig. 13: Performance on detecting in ated delays. Accuracy on detecting packet drops (Figure 12(e)): We nd that BurstBalancer achieves up to 97% Recall Rate in detecting packet drops. We can see that larger packet drop rate goes with higher accuracy, and even under $\rho = 0.5\%$ packet drop rate, BurstBalancer can still achieve up to 73% Recall Rate to detect packet drops.

Accuracy on detecting in ated queuing delays (Figure 13): We nd that BurstBalancer achieves up to 94% Recall Rate in detecting in ated queuing delays. From Figure 13(a), we can see that as the in ated delay rate decreases, the accuracy of BurstBalancer only slightly decreases. Under $\rho = 0.5\%$ delay rate, BurstBalancer can still achieve up to 90% Recall

Rate to detect in-ordered delays. We also evaluate the accuracy of BurstBalancer on estimating the timespans of FlowBursts in Figure 13(b). We can see that BalanceSketch achieves up to 10^{-3} ARE, and the basic BalanceSketch can still achieve nearly 10^{-2} ARE, which is very accurate.

5.2 Simulations

5.2.1 Event-level Simulations (NS-2).

We evaluate BurstBalancer using an event-level network simulator, Network Simulator 2 (NS-2) [56], in large-scale symmetric topologies, where we compare BurstBalancer against ECMP [20], DRILL [14], and LetFlow [2] under different network loads. We also evaluate the performance of BurstBalancer and LetFlow using tables of different sizes, validating the memory efficiency of BurstBalancer.

Topology and traffic: We conduct experiments in a two-tier Leaf-Spine topology with 8 spine and 8 leaf switches. Each leaf switch is connected to 16 servers. All links run at 10Gbps. Here, we have a convergence rate of 2 at the leaf level, which is common in modern data centers [2], [3]. We configure 90% of the bandwidth to deliver the web search workload (Figure 9(a)), and the rest to deliver the RPC workload (Figure 9(b)) as background traffic.

Setting: For BurstBalancer and LetFlow, we configure the BalanceSketch/Flowlet Table to have 250 buckets/entries by default. In practice, such a small table can fit into one single 1R1W on-chip memory bank, and consumes negligible die area. We set the flowlet threshold $\tau = 200$ s, set the flow timeout threshold $\tau_{out} = 50$ ms, and set $F = 0$.

FCT v.s. network load (Figure 14): We find that the overall average FCT of BurstBalancer is always lower than ECMP, DRILL, and LetFlow under different network loads as shown in Figure 14(a), as network loads vary, the overall average FCT of BurstBalancer changes from 13.6ms to 54.9ms, while that of ECMP, DRILL, and LetFlow changes from 14.7ms, 15.4ms, and 15.3ms to 58.6ms, 60.6ms, and 57.7ms, respectively. In summary, BurstBalancer achieves up to 25.2%, 20.1%, and 25.8% lower overall average FCT than ECMP, DRILL, and LetFlow, respectively. We further study the average FCT of small flows (< 100 KB), medium flows ($0.1 - 10$ MB), and large flows (> 10 MB) in Figure 14(b)-14(d). The results show that for small flows, DRILL has the lowest average FCT because it balances the traffic at the finest granularity. But for medium flows and large flows, the average FCT of DRILL is high because it suffers significant packet reordering. BurstBalancer always achieves the lowest average FCT for medium flows and large flows among all schemes.

FCT v.s. number of buckets/entries (Figure 15): We find that the overall average FCT of BalanceSketch always outperforms LetFlow under different table sizes. The experiments are conducted under 90% network loads. As shown in Figure 15(a), as the number of buckets varies, the overall average FCT of BurstBalancer changes from 44.2ms to 40.1ms, while that of LetFlow changes from 77.7ms to 42.2ms. The results show that the gap between BurstBalancer and LetFlow becomes larger as the number of buckets decreases. This is because LetFlow cannot accurately divide flows into flowlets under small memory usage. In summary, BurstBalancer achieves up to 43.1% lower average FCT than LetFlow. We further study the average FCT of flows of different sizes in Figure 15(b)-15(d), and the results are similar to Figure 15(a).

Analysis: BurstBalancer has lower FCT than LetFlow when using the flowlet tables of the same sizes. When the amount of storage is sufficient, BurstBalancer has similar performance as LetFlow. When the amount of storage is small, LetFlow has poor load balance performance but BurstBalancer can still well balance the traffic. This is because when the number of concurrent flows exceeds the size of the flowlet table, LetFlow inevitably regards multiple flows as one, making it difficult to detect flowlets. And thus, LetFlow cannot well balance the traffic when using small flowlet tables. By contrast, BurstBalancer only manipulates a small amount of critical flowlets, which is memory efficient.

5.2.2 ESL Simulations (HDCN)

We evaluate BurstBalancer on an electronic system level (ESL) network simulator named Hyper Data Center Network (HDCN), where we build a large-scale RDMA network to observe how well can BurstBalancer balance the load, and to what extent is the reordering ratio. We compare BurstBalancer against ECMP [20], per-packet random routing (Random), per-packet round-robin routing (Packet-Spray, PS), LetFlow [2], and DRILL [14].

Platform and implementation: HDCN is an electronic system level (ESL) simulation platform used by Huawei for years. Developed based on SystemC kernel, HDCN offers cycle-level simulation capability, which cannot be achieved by event-level simulators [56], [87], [88]. HDCN integrates general switch models and general NIC models, and allows users to customize network configurations. It also offers multiple congestion control algorithms (DCQC-N/ECN/PFC). In addition, HDCN utilizes MPI to support distributed/multi-threaded parallel acceleration, achieving simulation speeds significantly higher than current open-sourced simulators like NS2 [56], NS3 [87] and NSPY [88]. Currently, HDCN is extensively used within Huawei for the research and development of novel network-wide algorithms and chip architectures [89]. We implement BalanceSketch by extending a generalized chip model with small modifications of its pipeline processing logic. We set the number of buckets of BalanceSketch to 50 - 200, which can fit into a single 1R1W on-chip memory bank. Thanks to the chip-level visibility of HDCN to any network device, we can directly observe the queue lengths across all fabric ports in our experiments, and use their average or standard deviation to reflect the load balancing performance.

Topology, traffic, and setting: We conduct experiments in a VL2 topology with 4 core, 8 aggregation, and 8 edge switches in 4 pods. The bandwidth of all fabric links are 100Gbps. Each edge switch is connected to 16 servers through 50Gbps links. Each server runs Remote Direct Memory Access (RDMA) [90] transport logic in network interface card (NIC). To better observe the distribution of traffic on multi-paths, we disable the go-back-N mechanism of RDMA. We use the enterprise workload (Figure 9(c)) and configure each client in a pod to send ON-OFF traffic to servers in the other pod, so that all traffic traverses the fabric. The ratio of the ON/OFF duration is 1 : 5. The experiments are conducted under 75% network loads. We set τ to about 1:5 RTT, set $\tau_{out} = 10$ s, and set $F = 15$.

(a) All ows. (b) Small ows (< 0.1MB). (c) Medium ows. (d) Large ows (> 10MB).

Fig. 14: NS-2 simulation results: FCT statistics under different network loads.

(a) All ows. (b) Small ows (< 0.1MB). (c) Medium ows. (d) Large ows (> 10MB).

Fig. 15: NS-2 simulation results: FCT statistics of LetFlow and BurstBalancer using tables of different sizes.

(a) Average queue length. (b) SD of queue length. (c) Ratio of reordering pkts.

Fig. 16: HDCN simulation results: queue length statistics and ratio of reordering packets.

Statistics of the queue lengths (Figure 16(a)-16(b)): We find that BurstBalancer better balances the traffic than ECMP and LetFlow, and achieves similar load balance performance as DRILL and per-packet random routing. As shown in Figure 16(a), the average queue lengths of BurstBalancer are smaller than ECMP and LetFlow, and similar to DRILL and per-packet random routing. Per-packet round-robin has the smallest average queue length. Figure 16(b) shows the standard deviation of the average queue length across all fabric ports. The results are similar to that of the average queue lengths. Ratio of reordering packets (Figure 16(c)): We find that BurstBalancer achieves the lowest packet reordering ratio among candidate schemes (except ECMP). We can see that packet-level schemes (DRILL, per-packet random, and per-packet round-robin) have the highest reordering rate. LetFlow has higher reordering rate than BurstBalancer due to the large difference in path latency caused by unbalanced load. Note that the results in our experiments are worse than that in real scenes because of the high-density workload.

Analysis: Through the cycle-level results in our ESL simulations, we can see that BurstBalancer well balances the traffic with small reordering ratio in RDMA networks. Our ESL experiment also validates that BurstBalancer can be well deployed into commercial chips. The results have been acknowledged by the committee of Huawei, and we have deployed BurstBalancer into our commercial chips as a load balancing function.

5.3 Testbed Experiments

As described in x 4.2, we build a small-scale testbed in an asymmetric topology, on which we compare BurstBalancer against WCMP [21], and LetFlow [2].

Topology and traffic: As shown in Figure 19, we use a two-tier Leaf-Spine topology consisting of 2 spine switches and 2 leaf switches, each of which is connected to 8 servers. All links run at 40Gbps. We fail one of the two links between a leaf and a spine to create asymmetry. We use a client-server program to generate dynamic traffic [91], where the client application generates requests through persistent TCP connections based on a Poisson process, and the server application responds with the requested data. On each leaf, we configure 6 servers to generate requests to 6 servers under another leaf according to the web search workload (Figure 9(a)). We configure the other 2 servers to generate single-packet requests to 2 servers under another leaf. The single-packet requests are used as background traffic to improve the number of concurrent ows. We configure the bandwidth usage of the single-packet traffic as 5Gbps.

Fig. 19: Testbed topology.

(a) Average queue length. (b) Ratio of reordering pkts.

Fig. 17: Performance under different manipulating choices.

Performance under different manipulating choices (Figure 17): We find that in symmetric topologies, for BurstBalancer, randomly picking a port for each FlowBurst and picking the least loaded port have similar performance. This is because BurstBalancer balances the traffic so well that there is little room for improvement. For LetFlow, the difference between the two manipulating choices is pronounced.

Setting: For BurstBalancer and LetFlow, we configure BalanceSketch/Flowlet Table to have 128 or 256 buckets/en-

(a) All ows. (b) Small ows (< 0.1MB). (c) Medium ows. (d) Large ows (> 10MB).

Fig. 18: Testbed results: FCT statistics under different network loads in asymmetric topology.

tries. For WCMP, we configure the weighted cost only according to the localized link status of the switch. We set the owlet threshold = 500 s, set the ow timeout threshold = 50ms, and set the voting threshold $F = 0$.

FCT v.s. network load (Figure 18): We find that in asymmetric typologies, the overall average FCT of BurstBalancer is always better than WCMP and LetFlow under different network loads. As shown in Figure 18(a), as network loads vary, the overall average FCT of WCMP changes from 1.62ms to 64.4ms. The overall average FCT of BurstBalancer using BalanceSketch of 128 buckets and 256 buckets change from 1.68ms and 1.65ms to 13.8ms and 10.2ms, respectively. And the overall average FCT of LetFlow using Flowlet Table of 128 entries and 256 entries change from 1.64ms and 1.61ms to 232ms and 32.8ms, respectively. Due to asymmetry, the average FCT has a sudden increase between 50%–60% network loads. As a whole, the average FCT of BurstBalancer is significantly lower than WCMP and LetFlow, and the BurstBalancer using 128 buckets and 256 buckets have similar performance. LetFlow has higher FCT than BurstBalancer because when using Flowlet Table of 128/256 entries. Note that when using 128 table entries, the average FCT of LetFlow is significantly higher than the others. This is because such small memory makes it difficult for LetFlow to detect owlets, and thus the next_hop s in the Flowlet Table almost remains unchanged. In LetFlow, each ow is forwarded through the next_hop recorded in one of the 128 entries. Since the distribution of the 128 next_hop s is uneven, the load balance performance is bad. We further study the average FCT of ows of different sizes in Figure 18(b)-18(d). The results are similar to that in Figure 18(a).

As shown in Figure 20(b), for BurstBalancer, the traffic distribution ratio is 1:1.03:1.45:1.47. As explained in LetFlow [2], owlet switching schemes have the implicit feedback mechanism: once a ow is routed through a congested link, this ow is more likely to experience a owlet timeout, and thus it is more likely to be rerouted through other links. The results show that BurstBalancer also keeps this implicit feedback mechanism, and achieves the traffic distribution closer to the optimal ratio.

5.4 Discussion

In our experiments, we juxtaposed the load balance performance of BurstBalancer with LetFlow under the same owlet table sizes. With sufficient memory allocated for the owlet table, the load balance performance of BurstBalancer and LetFlow appear to be similar. However, it is worth noticing that BurstBalancer only manipulates a small fraction of ows (< 2%), whereas LetFlow manipulates almost all ows (> 98%) (Figure 11(b)). The forwarding paths of most ows in BurstBalancer are fixed and predictable. As a result, BurstBalancer experiences less packet reordering, thereby simplifying network measurement and management. On the other hand, under conditions of limited available memory for the owlet table, BurstBalancer outperforms LetFlow in load balance performance. Considering the current trend of switch bandwidth growing much faster than the on-chip SRAM, we project that BurstBalancer's efficient memory usage will become increasingly valuable for future networks.

6 CONCLUSION

This paper presents BurstBalancer, an efficient load balancing system for data center networks. The design philosophy of BurstBalancer is to only manipulate a small amount of critical owlets, which are formally defined as FlowBursts. BurstBalancer proposes a compact sketch algorithm, namely BalanceSketch, to accurately identify and manipulate most FlowBursts under small memory usage. Experiments on a testbed and simulations show that BurstBalancer outperforms state-of-the-art LetFlow in both symmetric and asymmetric topologies, while manipulates less ows at the same time. Our ESL platform (HDCN) has verified the effectiveness and efficiency of BurstBalancer on commercial chips. The results have been acknowledged by the committee of Huawei, and we have deployed BurstBalancer into our commercial chips as a load balancing function.

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(a) # pkts (ECMP). (b) # pkts (BurstBalancer).

Fig. 20: Testbed results: Number of forwarded pkts.

Forwarding statistics of the four ports in a leaf switch (Figure 20): We find that in asymmetric topologies, BurstBalancer achieves the traffic distribution closer to the optimal ratio. We measure the number of forwarded packets of the four fabric ports in a leaf switch (shown in Figure 19) under 90% network loads. In this asymmetric topology, the optimal traffic distribution ratio among Port#1–Port#4 is 1:1:2:2. As shown in Figure 20(a), for ECMP, the traffic distribution ratio is 1:0.96:1.12:1.14. This ratio is not 1:1:1:1 thanks to the implicit feedback mechanism of persistent connections: the probability of reusing congested connections is small.

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