A Switch-Based Approach to Throughput Collapse and Starvation in Data Centers

Alexander Shpiner and Isaac Keslassy
Department of Electrical Engineering
Technion - Israel Institute of Technology
Haifa, 32000, Israel
{shalex@tx, isaac@ee}.technion.ac.il

***Abstract*—Data center switches need to satisfy stringent low-delay and high-capacity requirements. To do so, they rely on small switch buffers. However, in case of congestion, data center switches can incur throughput collapse for short TCP flows as well as temporary starvation for long TCP flows.**

In this paper, we introduce a lightweight hash-based algorithm called HCF (Hashed Credits Fair) to solve these problems at the switch level while being transparent to the end users. We show that it can be readily implemented in data center switches with $O(1)$ complexity and negligible overhead. We illustrate using simulations how HCF mitigates the throughput collapse of short flows. We also show how HCF reduces unfairness and starvation for long-lived TCP flows as well as for short TCP flows, yet maximizes the utilization on the congested link. Last, even though HCF can store packets of a same flow in different queues, we also prove that it prevents packet reordering.

I. Introduction

A. Motivation

The recent emergence of the *data center switch market* has required switch vendors to answer new stringent requirements and rethink their switch architectures. This is because switch vendors of both Ethernet switches and Internet routers want to enter the data center switch market as well, ideally by using variants of their next-generation switch architecture. However, while Ethernet switches typically require extremely low delay with reasonable capacity, and Internet backbone routers require extremely high capacity with reasonable delay, data center switches require *both* extremely low delay and extremely high capacity. As a result, the data center switch stringent requirements on delay and capacity are now becoming generalized requirements on most high-end next-generation switch designs as well.

Data center switch vendors need to address two crucial problems that result from the low-delay requirements. First, they need to address the *TCP incast problem, i.e., the throughput collapse of short flows* [1]–[5]. The throughput of TCP-based applications drastically reduces when multiple senders communicate with a single receiver in high-capacity low-delay networks. Fast and highly bursty data transmissions overfill the switch buffers, causing intense packet loss that leads to TCP timeouts. These timeouts last hundreds of milliseconds on a network whose round-trip-time (RTT) is hundreds of microseconds, i.e. three orders of magnitude lower. Protocols that have some form of synchronization requirement, such as filesystem reads and writes or highly parallel data-intensive queries found in large memory-cached clusters, keep waiting for timed-out connections to finish before issuing new requests. These timeouts and the resulting delay can reduce application throughput by up to 90% [2], [5].

The second crucial problem is the *starvation of long TCP flows*. As we will further show in this paper, during congestion, long TCP flows can be temporarily starved during *tens of seconds*, even though the total switch throughput stays high. These high delays are unacceptable for latency-sensitive data center applications. For instance, an algorithmic trading application needs a guarantee that its information will most probably not be delayed beyond a millisecond, or even a few microseconds. Small delays also play a crucial factor in switch benchmarks. For instance, a recent benchmark study favored two switches over a third because they essentially achieved lower delays for large Ethernet frames, reaching 750 ns vs. 3.4 μs [6].

The *throughput collapse of short flows* and the *starvation of long flows* actually have shared reasons, stemming from the high-capacity and low-delay requirements of data center switches. The high-capacity requirement, needed to deal with a large number of flows, would require significant buffer sizes to prevent a high loss rate for the TCP flows, as in Internet high-speed links [7]–[10]. However, the low-delay requirement imposes the use of small switch buffer sizes, and as a result typically incurs a large loss rate and many timeouts for TCP flows in case of congestion. These timeouts cause *unfairness* among flows, which experience a high delay variability.

This paper is about reducing the short-flow throughput collapse and long-flow starvation by reducing the delay unfairness among flows. To do so, we want to use a *lightweight switch-based mechanism* that does not significantly impact the switch architecture or require any meaningful additional buffering. In contrast to previous papers on TCP incast [1]–[5], we assume that it is forbidden to change the TCP protocol implementations both at the sources and destinations. Thus, the switch-based mechanism should be transparent to the end hosts.

B. Contributions

In this paper, we introduce a simple switch-based algorithm to reduce the TCP unfairness in data centers. To our knowl-

edge, this paper is unique in that it is the first to point out the fundamental starvation properties of long TCP flows in data center networks, even when there is no throughput collapse. It is also the first to suggest a specific switch-based mechanism to address this starvation.

We propose to use the HCF (Hashed Credits Fair) algorithm, a novel lightweight algorithm for data center switches that is transparent to TCP-based applications. HCF relies on hashing to aggregate flows into bins, and therefore needs to maintain only a limited number of bins credits using a few bits of information. In addition, HCF regularly updates the hashing functions to prevent persistent hash collisions between the same flows. Last, HCF combines the credit hashing mechanism with a queueing mechanism that provides a higher priority to flow aggregates that have not been recently served.

Although HCF allows packets of a same flow to join different queues, we demonstrate that HCF prevents reordering by using a special updating mechanism. We also prove that HCF has an $O(1)$ time complexity, and that it requires significantly less resources than competing fairness algorithms. In addition, we explain why HCF does not require any change at the end stations, and in particular does not require any change to the standard TCP protocol.

Later, through simulations, we show the short-flow throughput collapse in the TCP incast problem. We also point out the long-flow starvation problem. We show how HCF can help solve these problems by providing an increased fairness among flows.

The rest of the work is organized as follows. We first survey the related work in Section II. Then we present our proposed algorithm in Section III. Next, we show alternative implementation parameters in Section IV. Last, we present simulation results in Section V, before concluding.

II. Related Work

To solve the TCP incast problem, former papers typically suggest changing the TCP protocol in data centers, e.g., by reducing the value of the minimal retransmission time-out (RTO) from 200 ms to 1 ms or less [1], [2], [5]. Additional suggested changes affect the application itself, such as increasing the request sizes, limiting the number of servers, throttling data transfers and using global scheduling [3]. However, all these solutions require changing the protocols at the end users, and therefore cannot be implemented at the switch level in a transparent way.

Another possible solution is to increase the switch buffer size by making it proportional to the number of flows, since packet loss and timeouts tend to decrease with the buffer size [7]–[10]. However, this would incur high delays that are unacceptable in data center switches. In addition, it would typically require off-chip memory, and therefore a major hardware change with significant issues of power consumption, chip in/out pin SERDES implementation, buffer area, and memory cost. A related solution is to only increase the buffer size for TCP ACKs (acknowledgments). However, while the needed additional memory size would be lower, this solution would still violate the stringent low-delay data center requirements.

There are many fairness algorithms in the literature to provide increased fairness among flows, such as WFQ (Weighted Fair Queueing) [11] or DRR (Deficit Round Robin) [12]. But these fairness algorithms need per-flow queues, and therefore significantly increase the switch implementation complexity given thousands of possible flows. Fairness algorithms like SFQ (Stochastic Fair Queueing) [13] solve this by using hashing to reduce the number of needed queues. However, while they fit Internet requirements, these algorithms do not work well with the shallow buffers in data centers. In order to provide fairness, they statically divide these small buffers among the many flow aggregates. Thus, they can barely keep some buffering for each flow aggregate, incurring large loss rates to bursts even without any congestion. Likewise, active queue management algorithms based on the queue sizes like RED (Random Early Detection) [14] do not work well with small buffers of a few packets, which do not provide enough information.

Explicit congestion notification (ECN) [15] allows end-to-end notification of network congestion without dropping packets. Constantly setting the ECN congestion indication at the switch level could force flows to restrict the congestion window size to 1. However, such a solution would force endpoints to use ECN. It would also need a guarantee that ACK packets use the same path as data packets and go through the same switch.

Last, each switch could implement a full TCP proxy and manage a list of high-priority flows [16]. However, such a solution obviously requires again a prohibitive complexity and a full change of the switch hardware.

III. Hashed Credits Fair (HCF) Algorithm

In this section we introduce the Hashed Credits Fair (HCF) algorithm. The algorithm is implemented in the intermediate switches, and its objective is to provide increased fairness among flows using a lightweight implementation.

A. HCF Overview

The HCF algorithm sorts arriving packets into two queues: the High-Priority (HP) and the Low-Priority (LP) queues. The HP queue receives packets of flows which *have recently been under-served,*, while the LP queue receives the other packets. The HP queue is always served first.

HCF needs to know which flows have recently been under-served, while avoiding memory-expensive per-flow crediting mechanisms. To do so, flows are hashed into bins, and credits are attributed per bin. Through the number of bins, the HCF algorithm trades off memory size and fairness. Moreover, the hash function is often updated to avoid persistent hash collisions between the same flows.

B. HCF Algorithm

Figure 1 illustrates the switch architecture for the HCF algorithm. For simplicity, we assume that all packets have the

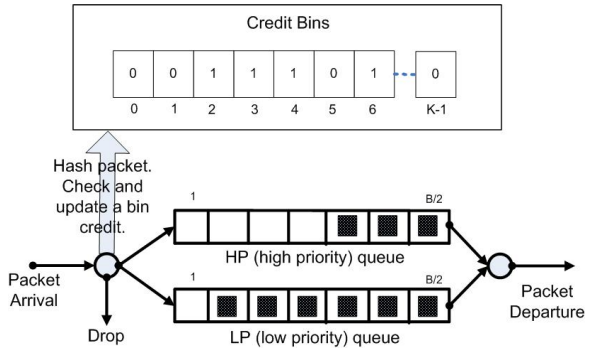


Fig. 1. Architecture of the HCF algorithm.

same length.The architecture relies on a buffer of size B and on K credit counters.

The buffer is divided into the HP and LP queues. For instance, assuming that the total buffer size is B, the sizes of the HP and LP queues can be $B/2$ each. Other buffer divisions are possible, as discussed in Section IV, together with additional implementation alternatives.

Time is divided into *priority periods*. The period length is dynamic and determined by the HP queue size: whenever the HP queue becomes empty, the priority period ends. Then, the next priority period lasts until at least one HP packet has been serviced and the HP queue is empty again.

The objective of the priority periods is to keep changing the hashing function. Each priority period uses a unique hashing function, possibly chosen among a predetermined set of functions. The inputs of the hashing function are the source/destination IP addresses and ports, and its output is the index of the hashed bin among the K possible indices.

The algorithm takes the following steps as packets arrive to the queue.

Initialization — At the start of each priority period,

1) Reset the number of credits $c(k)$ of each bin k, with $0 \leq k \leq K-1$, to $c(k) = c_0$ credits.
2) Pick a new hashing function f.

Packet arrival — At the arrival of each packet p,

1) Apply the hashing function f on the packet's IP header and obtain the corresponding bin $k = f(p)$ of the packet.
2) Check the number of credits in bin k and the queue sizes. If the bin has credits and the HP queue is not full, packet p joins the HP queue. Otherwise, if the LP queue is not full, p joins the LP queue. If both queues are full, p is simply dropped.
3) If p joins the HP queue, decrement the number of credits in its bin: $c(k) \leftarrow c(k) - 1$. (With variable-size packets, credits can be based on the packet length instead. For simplicity, we restrict explanations to fixed-size packets.)
4) If p joins the LP queue, set the number of credits in its bin: $c(k) \leftarrow 0$. [1] (This ensures packet order preservation within a flow.)

[1]This condition was not included in the conference version. We would like to thank Ahmad Omary for this helpful remark.

Algorithm 1 Hashed Credits Fair (HCF)

```
init(){
 ∀k : c(k) ← c_0;
 *f() ← createHashFunction(time);
}

arrive(p){
 k ← f(p.srcIP, p.destIP, p.srcPort, p.destPort);
if c(k) > 0 and HP.full = false then
   HP.enqueue(p);
   c(k) ← c(k) − 1;
else if LP.full = false then
   LP.enqueue(p);
   c(k) ← 0;
else
   drop(p);
end if
}

transmit(){
if HP.empty = false then
   HP.dequeue();
   if HP.empty = true then
      init();
   end if
else
   LP.dequeue();
end if
}
```

Packet departure — When the output line can service the queues,

1) Give priority to the HP queue: if it is not empty, read the head-of-line packet in the HP queue. Else, read from the LP queue.
2) If the HP queue was serviced, check its number of packets. If the HP queue becomes empty, the priority period ends. Re-enter the initialization step.

Algorithm 1 describes the detailed pseudo-code for the HCF algorithm. It shows that the HCF algorithm holds in a few lines of code, and relies on three functions that respectively implement the initialization of the priority period, the packet arrivals, and the packet departures.

As shown in the simulation results of Section V, a high packet arrival rate typically causes the LP queue to rarely get empty, thus practically ensuring a near-100% utilization of the bottleneck link. In addition, the credit mechanism significantly reduces the unfairness among flows and the flow starvation.

C. HCF Complexity

The objective of the HCF algorithm is to be very lightweight and easily implementable, so as to fit data center switches without additional hardware requirements.

The above pseudo-code shows that both the packet arrival and the packet departure functions have an $O(1)$ time complexity. Their main functions are queueuing/dequeueing packets, and checking/updating bin credits. Therefore, assuming that the initialization of the credit bins in the registers to fixed predetermined values is $O(1)$, the HCF algorithm runs in an $O(1)$ time complexity.

In addition, the required memory space overhead for the management of the algorithm is the memory of the bin array that holds the amount of credits. Since the maximum credit of each bin is c_0 and there are K bins, the memory needed is $K \cdot \lceil \log(c_0+1) \rceil$. For instance, it could easily be implemented in hardware using $K = 32$ counters of 8 bits each, thus only holding 32 bytes. In addition, we need to manage two queues instead of one, and potentially store the timestamp of the priority period, thus adding a negligible overhead. Therefore, the total overhead of the HCF is essentially negligible in front of the memory size needed for the queue (e.g., 32 bytes are negligible in front of an Ethernet packet of 1500 bytes).

In addition, note that the priority period of HCF adjusts dynamically to the traffic through the size of the HP queue. It does not need to be predetermined.

D. Packet Reordering

The HCF algorithm presented so far *does not prevent packet reordering* during the priority-period change. For instance, consider two packets p_1 and p_2 from the same flow successively arriving to the switch. It might be that the flow does not have credits left, and therefore p_1 is stored in the LP queue. Then, the HP queue might get empty, thus generating a new priority period with bin credits re-initialized to c_0. When p_2 arrives, it might therefore use a credit and be stored in the HP queue, which has higher priority. Thus, p_2 would depart earlier than p_1, and the packets would be reordered.

A simple solution to this packet reordering problem is to *swap* the HP and LP queues at each new priority period, while the credits are initialized, by redefining the LP queue as the HP queue, and vice versa. The following theorem demonstrates that this solution ensures that non-dropped packets are not reordered.

Theorem 1: HCF with queue swapping prevents reordering among packets of a same flow that leave the switch.

Proof: First, packets that leave the switch have not been dropped, and therefore we can restrict the proof to packets currently in the queues HP and LP.

Consider the set $\mathcal{S}_F$ of all packets in the queues from a given flow F, and define the following total order relation $\leq$ on any two packets $\{x, y\} \in {\mathcal{S}_F}^2$: $x \leq y$ iff (x and y are in the same queue and x is ahead of y) OR (x is in HP and y is in LP). Then the relation clearly satisfies anti-symmetry, transitivity and totality over $\mathcal{S}_F$.

Assume that two packets p_1 and p_2 of the same flow arrive in that order but leave the queues reordered: we want to show that this is impossible.

Let's first show that $p_1 \leq p_2$. Clearly, if they were reordered in the switch, at some point, both p_1 and p_2 were in the switch queues. There are three possible cases. First, if both p_1 and p_2 are in the same queue, since the HP and LP queues are FIFO, then necessarily p_1 is ahead of p_2 and $p_1 \leq p_2$. Otherwise, if p_1 is in HP and p_2 is in LP, $p_1 \leq p_2$ as well by definition. In the last case, if p_1 is in LP, it means that the flow does not have credits left. If p_2 arrives in the same priority period, it will hash into the same bin with no credits left, and therefore cannot be stored in HP. Else, if it arrives after the priority period of p_1, then p_1 is now in HP by swapping, and as shown above necessarily $p_1 \leq p_2$ again. Therefore, in all cases, $p_1 \leq p_2$.

Let's now show that whenever $p_1 \leq p_2$, p_1 necessarily leaves before p_2. First, whenever first defined in some priority period, the relation $p_1 \leq p_2$ is kept during the entire priority period (as long as no packet has departed): if p_1 is ahead of p_2 in the same queue, it stays ahead, and likewise, if p_1 is in HP and p_2 is in LP, they stay in their respective queues. In addition, by definition, p_2 cannot leave before p_1 during this priority period: either p_1 is ahead of p_2 in the same FIFO queue, or p_1 is in HP and p_2 is in LP, which cannot be serviced before HP gets emptied. Therefore, to be reordered, neither p_1 not p_2 can leave during the first priority period in which the relation $p_1 \leq p_2$ is defined.

Last, after the priority period ends, by definition, the HP queue is empty. Therefore both p_1 and p_2 were necessarily in the LP queue, and p_1 was necessarily ahead of p_2. Since the LP queue (which becomes the HP queue) is FIFO, p_2 cannot leave before p_1, hence there cannot be reordering. ■

IV. Implementation Alternatives

There are several possible implementation alternatives for the HCF algorithm, involving a broad span of tradeoffs between cost and performance. While we detail below several of these alternatives that often introduce additional parameters, we have attempted to reduce the number of parameters needed in the main HCF variant described above, since we only need to define the number of bins K (in addition to the queue size B, which is needed even in droptail). The objective of reducing the number of parameters is to enable both an easier implementation and a range-free scalability of the algorithm.

A. Bloom Counter

Instead of using a single hash function, it is possible to combine several hash functions by using a *Bloom counter*, where the counter is successively decremented from c_0 to 0 [17], [18].

For instance, a possible implementation using Bloom counters with conservative updates would work as follows. Each arriving packet is mapped to several bins. If at least one bin has a remaining credit, the packet is stored in HP, and all of its corresponding positive hashed credits are decremented. Else it is stored in LP. Therefore, the credits represent the complementary of the Bloom counter values within c_0 credits.

In particular, when $c_0 = 1$, this implementation reduces to a simple *Bloom filter* (more precisely, it shows the complementary of the Bloom filter bit values). Therefore, it is a generalization of the HCF algorithm for any number of

hash functions, and reduces to HCF when using a single hash function.

The goal of the Bloom filter is to represent *set membership* while minimizing the false positive error. In our case, it represents whether a flow belongs to the set of flows that have already used a credit, while minimizing the probability that a flow is wrongly tagged as having already used a credit. The ideal number of hash functions κ in such a Bloom filter is provided by

$$\kappa \approx \frac{K}{N} \cdot \log 2,$$

where K is the number of bins and N the number of flows to represent [17], [18]. Since we want a small number of bins, we often use $K \ll N$, and therefore there is no point in using more than one hash function. Simulations with $K = 20$ bins and $N \approx 400$ flows confirmed that Bloom filters with $\kappa \geq 2$ hash functions did not improve the performance of HCF.

B. Number of Bins

The number of hashed bins K has a significant influence on the performance of the system. On the one hand, an HCF switch with a single bin is similar to a FIFO-based switch. On the other hand, a large number of bins minimizes hash collisions, and therefore maximizing the fairness among flows. However, a large number of bins also consumes slightly more system resources, and in particular takes more memory and increases the implementation complexity. The simulation results in Section V-C provide a performance comparison using different numbers of bins. It appears that $K = 20$ bins are often enough both for fairness and starvation.

C. Priority Period

In the presented algorithm we use a dynamic priority period, i.e. the period length dynamically changes depending on the queue occupancy. To simplify the implementation, a *fixed* period length can be used, so that the credits are initialized and a new hash function is determined at predetermined periodic times. However, while a fixed priority period might be simpler to implement and avoid initializing credits too often, it requires tuning the period parameter. In addition, simulations in Section V-C show that a fixed priority period has a negative impact on the system performance.

D. Hash Function

A hash function is used to map packets to their corresponding bins. There are many possible alternative hash functions that can be used [13]. Since the input size and the output ranges for the hash function are fixed, the hash function can be easily implemented. In addition, in order to implement a different hash function for each priority period, it is possible to use an XOR of the packet header with the local time-stamp of the priority period start. The algorithm is fully distributed, and therefore there are no synchronization issues between different ports.

V. Simulation Results

We run simulations of a congested link using an NS2 simulator [19]. We assume a simple dumbbell topology with N flows going through the congested link. We further assume that the congested link corresponds to an output of an output-queued switch.

We successively simulate the effects of HCF on *short-flow throughput collapse* and on *long-flow starvation*. We then analyze the impact of changing the HCF parameters, and finally check mixes of short and long flows.

We attempt to provide some intuition for all these simulations. Yet, note that the reasons behind data center fairness problems such as the TCP incast are often hard to model because of the complex interactions involved [1], [2], [5].

A. Short-Flow Throughput Collapse

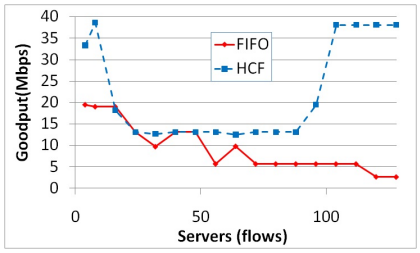
1) Typical Data Center: We first run simulations of the TCP incast problem with short-flow throughput collapse using the parameters of the data center incast scenario from [2]. We use 1 Gbps links, a 32 MB switch buffer, a 0.1 ms round-trip transmission time and data blocks of 1 MB. Therefore, each flow sends $1/N$ MB of data, where N is the varying number of flows. We simulate TCP-Reno flows with packets of size 1KB. The HCF switch hashes flows into 16 bins with 1 credit per bin, and uses a dynamic priority period. The buffer is divided equally between the HP and the LP queues with 16 packets per queue. The *block goodput* of the short TCP flows is *defined* as the size of the transmitted data (block size) divided by the longest finish time (latency) of the flow, as in [1]–[5]. We measure *block goodput* as a function of the number of flows (servers).

Figure 2(a) compares FIFO and HCF. HCF outperforms FIFO over most flow numbers, which are roughly divided into three regions:

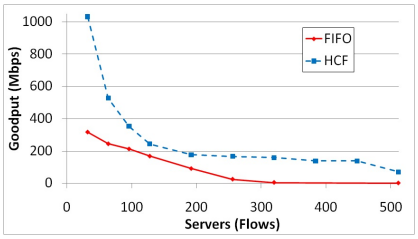
- *Goodput collapse* — below 25 servers (flows), the size of each flow is long enough, so the influence of HCF on fairness is noticeable.
- *Goodput preservation* — between 25-100 servers, the flow lengths are too small to notice the influence of HCF on fairness.
- *Goodput recovery* — above 100 servers, the large number of flows causes increased congestion in both FIFO and HCF, but the HCF credit mechanism balances the packet drops across the flows, thus balancing the timeouts as well.

Therefore, HCF works better in two cases: with few flows per block, and with increased congestion.

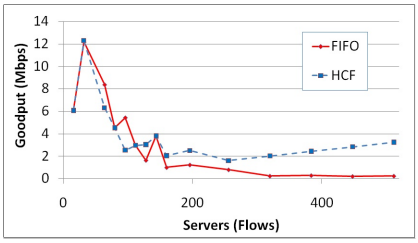
2) Next-generation Data Center: Next, we analyze next-generation data centers with parameters from [2], where the round-trip times are decreased from 100 μs to 20 μs, the transmission link capacity is increased from 1 Gbps to 10 Gbps, and the block size is increased from 1 MB to 80 MB. Figure 2(b) shows the comparison of FIFO and HCF. As in the previous case, HCF outperforms FIFO over the whole range.



(a) Comparison of goodput at a Typical Data Center using FIFO and HCF switches with fixed block size flows.

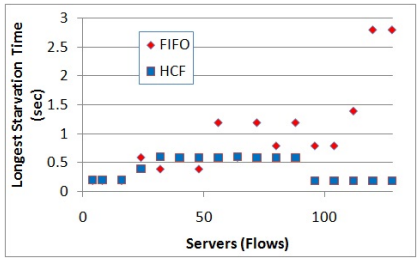


(b) Comparison of goodput at a Next-Generation Data Center using FIFO and HCF switches with fixed block size flows.

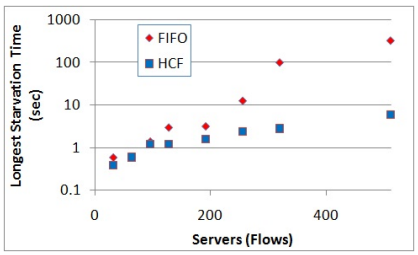


(c) Comparison of goodput at a Typical Data Center using FIFO and HCF switches with fixed flow size.

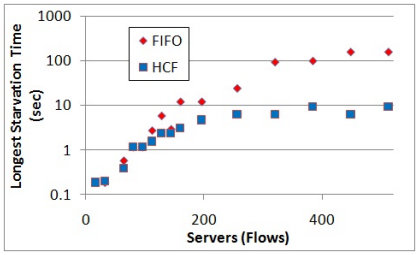
Fig. 2. Comparison of goodput using FIFO and HCF switches under TCP incast scenario.



(a) Comparison of Maximal Starvation Time at a Typical Data Center at FIFO and HCF switches with fixed block size flows.



(b) Comparison of Maximal Starvation Time at a Next-Generation Data Center at FIFO and HCF switches with fixed block size flows.



(c) Comparison of Maximal Starvation Time at a Typical Data Center at FIFO and HCF switches with fixed flow size.

Fig. 3. Comparison of Maximal Starvation Time using FIFO and HCF switches under the TCP incast scenario.

3) Fixed-sized Flows: Next, we keep the length of each flow constant to 10 KB (i.e. each flow sends the same amount of data regardless to N). We simulate a data center with typical parameters of a 1 GB link capacity and a 100 μs round-trip time. We compare the performance of a FIFO switch with an HCF switch, which hashes flows into 128 bins.

Figure 2(c) compares FIFO and HCF. We see that HCF outperforms FIFO only for a large number of flows. For a small number of flows, there is not enough congestion, so the advantages of HCF are limited; and at the same time, the HCF buffer space is not fully utilized, because HCF drops more packets then FIFO (to save space for HP packets).

4) Starvation Time: We define starvation time as the time between two packet arrivals (at the destination). The maximal starvation time is affected by the retransmission exponential back-off value, which grows with the number of consecutive RTO events.

Figures 3(a), 3(b) and 3(c) show the maximal observed starvation time at the FIFO-queue based switch and the HCF-queue based switch as a function of the number of servers. In most cases, the maximal starvation time in the HCF-queue based switch is smaller, which provides some basis for the better goodput.

B. Long-Flow Starvation

1) Settings and Metrics: In the long-lived flow simulations, we run $N = 400$ long TCP New Reno flows [20] with $RTT = 100\mu$s. We also run UDP packets with average arrival rate of 5% of the switch output link capacity. The capacity C of the switch congested output link is 100 Mbps, with other links running at a much higher capacity so as to have the switch output link form a single bottleneck in the network. The total buffer size B in the switch output is 20 packets, with a uniform packet size L of 1500 bytes. Therefore, in the HCF switch, the buffer is divided equally between the HP and LP queues with 10 packets per queue. The HCF algorithm relies on a dynamic priority period, the flows are hashed in the simulation using a real hash function into $K = 20$ bins, and each bin receives an initial credit of $c_0 = 1$ credit unit. Each simulation is run for 3 minutes, and simulation results are measured during a final *measuring time* of $T = 10$ seconds.

In the simulations we measure two performance indicators that can reflect on the extreme unfairness among flows in the data center network: the *unfairness* and the *starvation percentage*.

In an ideally-fair system, all flows would be able to send the same amount of traffic during the measured time of $T = 10$ seconds. This intuitively suggests to define the unfairness based on the deviations between the number of packets sent by each flow and the average across all flows. Therefore, we define the *unfairness* as the variance of the cumulative number of packets sent by each flow during some time T.

A significant unfairness often causes long periods of temporary starvation for flows. We want to characterize such temporary starvation, and will simply define *starvation percentage* as the percentage of all flows that have not sent any packet during the measuring time T.

In addition, we also consider the *throughput* and *utilization*

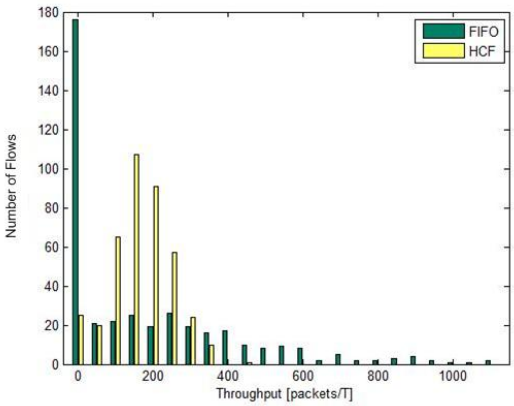


Fig. 4. Distribution of per-flow throughput using FIFO and HCF switches.

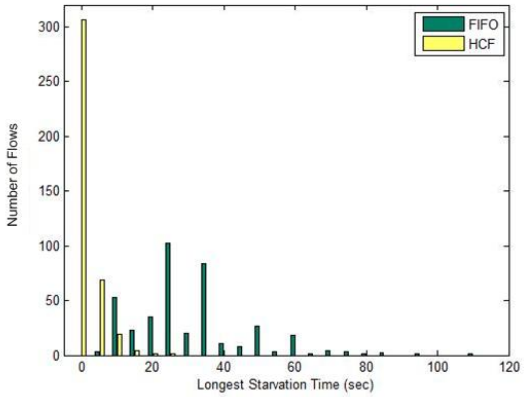


Fig. 5. Distribution of the longest flow starvation times using FIFO and HCF switches.

of the bottleneck link. The bottleneck link *throughput* is defined as the rate of all packets transmitted through the bottleneck link during time T, and the bottleneck link *utilization* is defined as the ratio of its throughput by the bottleneck link capacity. The goal is to keep the bottleneck link utilization close to 100%, thus maximizing the throughput. In simulations, we found that both for HCF and FIFO, the bottleneck link utilization was extremely close to 100%. Therefore, there was no point plotting it.

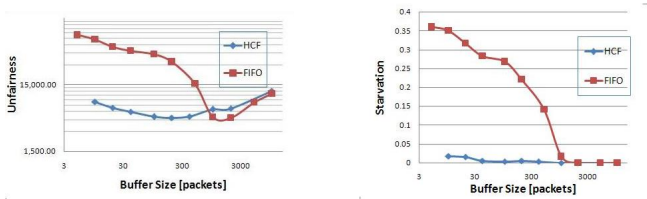
2) Throughput Distribution: Figure 4 plots the distribution of the *per-flow throughput*. For the FIFO-based switch, we can see that most of the flows have a low throughput during time T, while several flows have a high throughput. Therefore, the distribution is extremely unfair, because a few flows send significantly more packets than the others.

On the other hand, the distribution of the HCF algorithm is more concentrated around its mean, thus displaying a *lower unfairness*. This lower unfairness is reflected by the lower distribution variance: while the FIFO switch has a computed variance of $5.55 \cdot 10^4$, the HCF switch has a lower variance of $6.74 \cdot 10^3$.

Likewise, we can also see that fewer flows are significantly impacted by sending nearly no packets (25 flows for HCF are in the first histogram bin vs. 175 flows for FIFO), thus reflecting as well on the *lower starvation*. More precisely, 32% of flows in FIFO are fully starved during this period of 10 seconds, while only 1.5% of HCF are fully starved.

Figure 5 illustrates the impact of HCF on starvation time. For each TCP flow, we measure the longest starvation time, i.e. the longest inter-ACK time, over a 3-minute simulation. We then plot the distribution of this longest starvation time.

Given a simple *FIFO*-based switch with droptail queueing and output-queued switching, the plot shows that several flows have a starvation time that exceeds a minute, and that the starvation time of most flows exceeds 20 seconds. On the other hand, when using *HCF* in the switch, it can be seen that most starvation times are under 20 seconds, thus potentially having a significant impact on application performance (even though the performance might of course still not be acceptable for the applications that are most latency-sensitive).



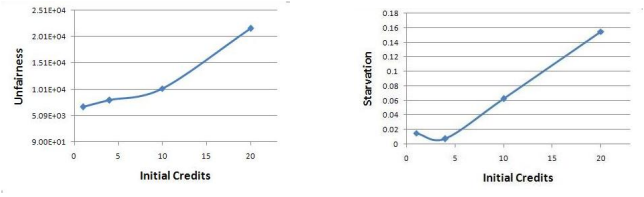
(a) Unfairness. (b) Starvation Percentage.

Fig. 6. Influence of the buffer size. Comparison between an HCF switch and a FIFO-based switch.

3) Buffer Size: Figure 6 shows the influence of the buffer size on the unfairness and starvation. It is obtained by changing the buffer size B in the baseline defined above.

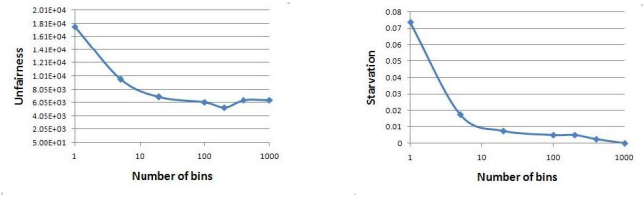
We can see that for low buffer sizes, the unfairness and starvation with HCF are significantly lower than with FIFO. This is the case we are most interested in, since data center buffers are often shallow and only consist of a few packets. This simulation illustrates how buffers with a few packets are enough with HCF to provide low starvation, while FIFO needs buffers of some 1000 packets. In fact, this can impact the switch architecture: given a packet size of 1500B, this scaled-down example with 400 flows would need at least 1.5MB of buffering per output. Therefore, a real-life switch with some 40000 flows might require some 100 times more buffering, thus not being able to store all packets in the internal memory, and requiring some external memory with significant hardware changes.

In addition, for higher buffer sizes, the unfairness and starvation are about similar. In particular, the unfairness is a bit lower with FIFO and starts increasing with large buffer sizes. A possible explanation is that large buffer sizes favor larger window sizes, and therefore a larger traffic burstiness, thus increasing the variance of the per-flow instantaneous throughput.



(a) Unfairness. (b) Starvation Percentage.

Fig. 7. Influence of the initial number of credits per bin.



(a) Unfairness. (b) Starvation Percentage.

Fig. 8. Influence of the number of bins.

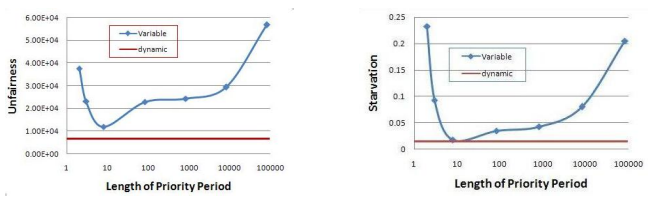
C. Analysis of HCF switch parameters

We now want to analyze how the parameters of the HCF algorithm impact its performance. These parameters were detailed in Section IV. We use a *baseline* for the set of simulation settings, and for each simulation vary a single parameter in this baseline. The *baseline* settings follow those defined in Section V-B.

1) Initial Number of Credits per Bin: Figure 7 shows the influence of the number of initial credits c_0 on the unfairness and starvation. It can be seen that a large number of initial credits decreases the performance of the system; an intuitive explanation is that an HCF switch with an infinite number of credits becomes a FIFO switch, and therefore loses the benefits of the credits. In addition, smaller credits enable smaller priority periods, and therefore a fast renewal of the hashing function, thus reducing the odds of persistent hash collisions between any two flows.

2) Number of Bins: Figure 8 shows the influence of the number of hash credit bins K on the unfairness and starvation. Of course, a smaller number of bins increases unfairness and starvation, and therefore decreases the performance of the system, because it increases hash collisions between flows. The plots show that a few dozen bins seem enough to provide a reasonable fairness and starvation. Given $c_0 = 1$, i.e. a single bit per bin, this means that only a few bytes stored in the register are needed for the HCF bins.

3) Priority Period Length: Figure 9 shows the influence of the priority period on the unfairness and starvation. The red solid line shows the value for the dynamic priority period. It is compared with different values of a fixed priority period. Simulations show that the dynamic priority period fares better than *any* of the fixed period values. Therefore, there is no need to fix the priority period value of HCF. It is an interesting result, in the sense that the system can learn to dynamically regulate itself better than any fixed regulation.



(a) Unfairness. (b) Starvation Percentage.

Fig. 9. Influence of the fixed priority period. The red solid line shows the performance with a dynamic priority period.

D. Short TCP Flows over Long Flows

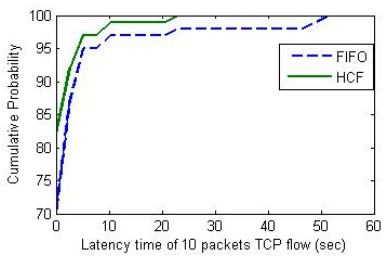
We have previously analyzed separately the performance of long-lived TCP flows and the short-lived TCP flows. We now want to analyze the performance of mixes of short and long flows, and in particular the influence of long flows on short flows. To do so, we change the simulation network to include only 100 long-lived TCP flows, and use a buffer size of $B = 10$ packets. We then add several short TCP flows, and check the total transfer latency time for each short TCP flow. We use three types of short flows: 10-, 30-, and 60-packet flows, and generate 100 flows of each type. The total simulation time is 5 minutes, and the start times of the short TCP flows are spread uniformly in the first half of the simulation time (i.e., the first 2.5 minutes).

Figure 10 compares the performance of the FIFO switch and the HCF switch under the same network parameters. It plots the CDF of the transfer latency when measured over the 100 flows of each type. For instance, a CDF value of 95% at a latency value of 25 seconds in the second plot indicates that 95% of the short flows of the second type (i.e., with 30 packets to send) finished transmission at most 25 seconds after they started.

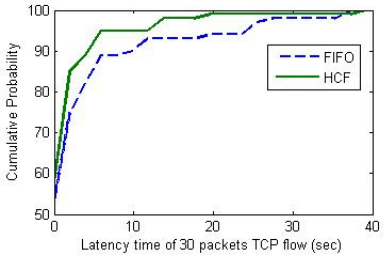
The plots show that HCF switches often provide a lower transfer latency than the FIFO switch. More significantly, they have lower odds of having long transfer latencies. This is especially meaningful for highly parallel applications, such as scientific computing and parallel database accesses, which start several flows in parallel and are dependent on the highest transfer latency among all of these.

VI. Conclusion

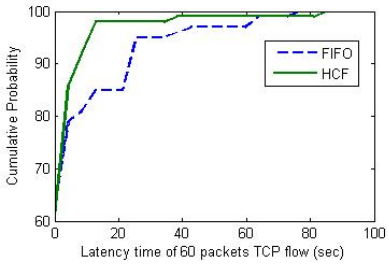
In this paper, we analyzed both the TCP-incast short-flow throughput-collapse problem, and the long-flow starvation problem. We presented the significant unfairness problem of TCP flows in data centers. To address it, we introduced HCF, a novel lightweight data center switch algorithm that is transparent to TCP-based applications. HCF combines a hashing-based credit allocation algorithm with a queueing mechanism that provides a higher priority to flows with credits. We further showed that HCF runs in an $O(1)$ time complexity, that it requires significantly less resources than competing fairness algorithms, that it does not incur reordering, and that it is transparent to the end-station users. Last, we illustrated



(a) CDF of Transfer Latency for TCP Flows of 10 packets.



(b) CDF of Transfer Latency for TCP Flows of 30 packets.



(c) CDF of Transfer Latency for TCP Flows of 60 packets.

Fig. 10. CDF of transfer latency for short TCP flows of different sizes.

through simulations that HCF can dramatically reduce unfairness and starvation for long TCP flows in data centers, as well as increase the goodput of short TCP flows that suffer from TCP incast problem.

It should be noted that while the HCF algorithm was especially studied in the framework of data centers, it can be readily adapted to provide fairness in other types of networks, since it uses a simple and compact structure that can be easily generalized.

ACKNOWLEDGEMENT

This work was partly supported by European Research Council Starting Grant n° 210389.

The authors would like to thank Gabi Bracha, Eyal Dagan, Ofer Iny and Eyal Soha from Broadcom (previously Dune Networks) for initially suggesting this problem and for providing helpful feedback.

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