FB: A Flexible Buffer Management Scheme
for Data Center Switches

Maria Apostolaki
ETH Zurich

Manya Ghobadi
MIT

Vamsi Addanki
ETH Zurich

Laurent Vanbever
ETH Zurich

ABSTRACT
Today, network devices share buffer across priority queues to avoid drops during transient congestion. While cost-effective most of the time, this sharing can cause undesired interference among seemingly independent traffic. As a result, low-priority traffic can cause increased packet loss to high-priority traffic. Similarly, long flows can prevent the buffer from absorbing incoming bursts even if they do not share the same queue. The cause of this perhaps unintuitive outcome is that today’s buffer sharing techniques are unable to guarantee isolation across (priority) queues without statically allocating buffer space. To address this issue, we designed FB, a novel buffer sharing scheme that offers strict isolation guarantees to high-priority traffic without sacrificing link utilizations. Thus, FB outperforms conventional buffer sharing algorithms in absorbing bursts while achieving on-par throughput. We show that FB is practical and runs at line-rate on existing hardware (Barefoot Tofino). Significantly, FB’s operations can be approximated in non-programmable devices.

1 INTRODUCTION
To reduce cost and maximize utilization, network devices often rely on a shared buffer chip whose allocation across queues is dynamically adjusted by a buffer management algorithm [2, 19, 29]. The most commonly-used buffer management algorithm today is Dynamic Thresholds (DT) [3, 18, 19, 25, 34]. DT dynamically allocates buffer per queue proportionally to the still-unoccupied buffer space. As a result, the more the queues are using the buffer, the less buffer each of them is allowed to occupy.

Despite its wide deployment, DT does not meet the requirements of today’s multi-tenant data-center environments for three key reasons. First, DT cannot reliably absorb bursts, which are of paramount importance for application performance [17, 36]. Second, DT is unable to offer any isolation guarantee, meaning that the performance of traffic (even of high priority) is dependent on the instantaneous load on each device it traverses. Finally, DT is unable to react to abrupt changes in the traffic demand, as it keeps the buffer highly utilized (to improve throughput), even if this brings little benefit. Worse yet, as we shall show, more sophisticated approaches e.g., Cisco IB [1] inherit DT’s limitations. To compensate for these limitations, data-center operators often statically allocate part of the buffer space to queues, effectively wasting precious buffer space that could be put to better use (e.g., to absorb bursts).

While Congestion Control (CC) algorithms and scheduling techniques can alleviate the shortcomings of DT, they are unable to address them fully. Indeed, CC could decrease the buffer utilization, indirectly leaving more space for bursts, while scheduling could allow preferential treatment of certain priority queues across those sharing a single port. Yet, each of these techniques senses and controls distinct network variables. First, CC can only sense per-flow performance (e.g., loss or delay) but is oblivious to the state of the shared buffer (buffer pressure [7]) and the relative priority across competing flows. Worse yet, CC controls the rate of a given flow but cannot affect the rate at which other flows are sending. Thus, CC cannot resolve buffer conflicts across flows sharing the same device. Second, scheduling can only sense the per-queue occupancy and control the transmission (dequeue) of packets via a particular port after and only if they have been enqueued. As a result, scheduling cannot resolve buffer conflicts across queues not sharing the same port.

To address DT’s shortcomings without statically allocating buffer, we design FB. FB is a novel buffer management algorithm that manages the buffer as a multi-dimensional entity. Unlike DT, FB allocates buffer by sensing not only the absolute buffer occupancy but also its content and temporal characteristics. In particular, FB (i) guards the distribution of traffic across multiple dimensions (e.g., per priority), preventing sets of queues from monopolizing the buffer; and (ii) favors queues that free-up their used buffer faster, making the buffer available to more traffic. As a result, FB can keep the buffer usage under control and offer provable performance guarantees without resorting to static allocations.

Despite its benefits, FB is deployable today. We implemented FB on a programmable device (Barefoot Tofino Wedge 100BF-32X [5]). We also describe how to approximate FB’s behavior by periodically reconfiguring DT with reduced-yet-significant benefits.

We show that FB outperforms alternative buffer management techniques even when they are combined with DCTCP. Indeed, FB (with TCP) improves burst absorption (measured as Query Completion Time) compared to Dynamic Thresholds with DCTCP by 10% (53%) when the network utilization
is 40% (90%). Moreover, FB reduces the Flow Completion Time (FCT) 99-th percentile of DT with DCTCP by 38% even when the network utilization is 20%. Importantly, FB achieves on-par throughput compared to other techniques. While FB’s benefits increase with contention of the buffer, it never deteriorates performance, even at low utilization or in the absence of high-priority or bursty traffic.

Our main contributions include:

- The first analysis of DT (the most widely-used buffer management algorithm today) in a multi-queue setting. Our analysis reveals DT’s inefficiencies both experimentally (§6) and analytically (§2).
- A novel approach for buffer management that can provide performance guarantees without statically allocating buffer (§4).
- A novel hardware design and implementation of FB on a Barefoot Tofino switch [5] that demonstrates its practicality in today’s hardware (§5.1), together with an approximation of its behavior that extends its deployability to more-commonly-used devices (§5.2).
- A comprehensive evaluation demonstrating that FB outperforms state-of-the-art buffer management algorithms even when combined with DCTCP (§6).

2 BACKGROUND & MOTIVATION

In this section, we first describe our model, namely the network device architecture we consider (§2.1). Next, we explain how Dynamic Thresholds (DT), the most commonly-used buffer management algorithm, works (§2.2). Finally, we reveal DT’s core inefficiencies (§2.3).

2.1 Switch Model

Fig. 1 shows a simplified output-queued shared-memory packet switch.\(^1\) The switch implements a fixed or programmable logic which maps each packet to a particular queue of a port. The switch stores incoming packets in its buffer for future transmission. The switch cannot store all incoming packets, as the space in the buffer is limited. A mechanism in the switch, namely the Traffic Manager (TM)\(^2\) determines whether to store or to drop incoming packets. To that end, the TM compares the queue’s length with a threshold that it calculates according to a buffer management algorithm, e.g., DT.

We assume that the operator groups traffic into classes. Each class exclusively uses a single queue at each port to achieve cross-class delay isolation [4]. For instance, in Fig. 1, Storage, VoIP and MapReduce belong to distinct traffic classes.

We also assume that each traffic class is of high or low priority. Distinguishing classes to high and low priority facilitates prioritizing of certain classes over others in times of high load. This prioritization concerns the use of the shared buffer and does not affects scheduling. The operator can configure multiple low-priority classes and multiple high-priority classes. In a cloud environment, traffic that is subject to Service Level Agreements (SLAs) would be high-priority. In Fig. 1 the MapReduce class is of high priority, while all other classes are of low priority.

2.2 DT’s workings

We now describe Dynamic Thresholds (DT), the most common buffer management algorithm in today’s devices [3, 9, 25, 31, 34]. DT [18] dynamically adapts the instantaneous maximum length of each queue, namely its threshold \(T^i_c(t)\) according to the remaining buffer and a configurable parameter \(\alpha\), as we see in Eq.(1). DT’s per-queue threshold is: (i) directly proportional to the remaining buffer \((B - Q(t))\) i.e., the less unoccupied buffer there is, the less a queue can grow; and (ii) directly proportional to a parameter \(\alpha\) often configured per class\(^3\): the higher the \(\alpha\), the more the queue can grow.

\[
T^i_c(t) = \alpha^i_c \cdot (B - Q(t)) \tag{1}
\]

\(T^i_c(t)\): Queue threshold of class \(c\) in port \(i\)
\(\alpha^i_c\): \(\alpha\) parameter of class \(c\) in port \(i\)
\(B\) : Total buffer space \(^4\)
\(Q(t)\) : Total buffer occupancy at time \(t\)

The \(\alpha\) parameter of a queue impacts its maximum length and its relative length with respect to the other queues. Thus, an operator is likely to set higher \(\alpha\) values for high-priority traffic classes compared to low-priority ones\(^5\). Despite its importance, there is no systematic way to configure \(\alpha\), meaning different vendors and operators reportedly use different

\(^1\)We describe the mapping of our model to RMT architecture in §5.
\(^2\)TM’s architecture is the same for both fixed-function and reconfigurable switches [41], including Barefoot’s Tofino and Broadcom’s Trident series.
\(^3\)While \(\alpha\) can be configured per queue, it is often configured per class.
\(^4\)For simplicity, we assume a single buffer-chip per device.
\(^5\)We use ‘priorities’ to categorize traffic classes; it is not related to scheduling.
Figure 2: At $t_0$ an incoming burst (Q2) rapidly changes the buffer occupancy. In the transient state ($t_0 - t_2$), the threshold of Q1 is lower than its length. Thus all its incoming packets are dropped to free buffer for Q2. Still, Q2 experiences drops before reaching its steady-state allocation ($t_1 - t_2$).

$\alpha$ values. For instance, Yahoo uses $\alpha = 8$ [25] while Cisco $\alpha = 14$ [3] and Arista $\alpha = 1$.

The buffer alternates between steady and transient state:

**Steady-state** is the state during which all queues sharing the buffer are shorter or equal to the threshold that DT calculates.

**Transient-state** is the state during which at least one queue in the buffer is longer than its threshold.

**DT in action.** To understand how the buffer alternates between steady and transient state, we walk through an example scenario. Consider a switch with a 60-packet buffer shared across multiple queues mapped to two distinct traffic classes; one of high and one of low priority. Fig. 2 illustrates the evolution of the length of two queues and their thresholds over time, illustrated in solid and dotted lines respectively. One queue, say Q1 belongs to the low-priority class and is colored in yellow. The other queue, say Q2 belongs to the high-priority class, is colored in red. The operator has configured $\alpha = 1$ for the class of Q1 and $\alpha = 2$ for the class of Q2.

Before time $t_0$, the only non-empty queue in the buffer is the low-priority yellow class: Q1. During this time, the buffer is in steady state, meaning all queues’ length is lower or equal to DT’s thresholds. Indeed, Q1’s length is 30 packets, the remaining buffer space is equal to 30 packets; thus from Eq. (1) Q1’s threshold is $1 \times 30 = 30$.

At time $t_0$, a burst of packets belonging to the high-priority red class arrives at the switch. The burst causes Q2’s length to increase in the time frame ($t_0 - t_2$) (solid red line).

At time $t_1$, Q2’s length increase is inhibited: Q2 continues to grow but at a lower rate as its length starts being controlled by Q2’s threshold (red dashed line), which DT calculates. Q2’s threshold decreases due to Q2’s growth in the buffer, which reduces the overall remaining buffer. Thus, during the time frame ($t_1 - t_2$), some of the packets mapped to Q2 are dropped. In the time frame ($t_0 - t_1$), the reduction of the remaining buffer also causes Q1’s threshold to decrease. Notably, Q1’s threshold decreases at a rate higher than its length does. In the time frame ($t_0 - t_2$), the buffer is in transient state, as Q1’s length is higher than its threshold.

At $t_2$, the buffer reaches steady state again. This time, the remaining buffer is 15 packets, Q1 occupies 15 packets, resulting from Q1’s threshold $T_{q1} = 1 \times 15$ packets, while Q2 occupies 30, as $T_{q2} = 2 \times 15$.

**To sum up,** the high-priority burst was dropped before the buffer had reached steady state. Importantly, these drops could have been avoided if (i) there was more available buffer when the burst arrived (steady-state allocation); or (ii) the buffer could have been emptied faster to make room for the burst (transient-state allocation).

**2.3 DT’s inefficiencies**

Having explained the importance of steady and transient-state allocation in the buffer management’s behavior, we now explain why DT is fundamentally unable to control any of the two. In particular, we show analytically and using intuitive examples that DT blindly maximizes the buffer utilization at the expense of predictable allocations. As a result, DT cannot offer any minimum buffer guarantee nor any burst-tolerance guarantee. The former is only affected by DT’s steady-state allocation, while the latter by both steady- and transient-state allocation, as we explained in §2.2.

Figure 3: High-priority traffic can use only a fraction of the buffer because DT allocates unrestrictedly more buffer to low-priority queues as their number increases (x-axis).

**DT offers no minimum buffer guarantee.** DT enforces the precedence of a queue or class over the others via a static parameter ($\alpha$). Yet, $\alpha$ offers no guarantee as the actual per-queue threshold depends on the overall remaining buffer (Eq. (1)), which can reach arbitrarily and uncontrollably low values, even in the steady state.\(^6\)

\(^6\)An operator can statically allocate space for each queue; in this case, though, the buffer space will be wasted unless used by the corresponding queue.
To better understand this limitation, consider the switch shown in Fig. 4a with a 60-packet buffer shared across four non-empty queues. Each queue is mapped to a distinct port. The queue of port 1 belongs to a high-priority class and is colored in red; The three other queues mapped to port 2 – 4 belong to a low-priority class and are colored in yellow.

The operator intended to preferentially treat the high-priority class. Thus, she configures $\alpha = 2$ for the high-priority and $\alpha = 1$ for low-priority. Indeed, this configuration allows the red queue to occupy a large portion of the buffer (up to 40 packets) and 2x more buffer than any yellow queue.

In the practice though, the red queue’s threshold is unpredictable and can get very low. Indeed, in the illustrated instance (Fig. 4a), the red queue’s threshold (and length) is 20 packets as the remaining is 10 and $\alpha = 2$. The three other queues collectively occupy 30 packets, namely more than the high-priority red queue.

In fact, the buffer available to a high-priority queue can even approach zero. As an illustration, Fig. 3 shows the buffer that a high-priority queue occupies compared to the aggregate buffer the low-priority queues occupy as a function of the number of low-priority congested queues\(^7\). This insight is experimentally supported by [43], in which authors observed the behavior of programmable switches of different vendors. While the operator could potentially configure $\alpha$ values to achieve a desirable buffer distribution given the number of congested queues in all ports, the latter cannot be accurately predicted.

To sum up, when DT is used, the buffer occupancy and thus the remaining buffer depends on the number of congested queues, and that, independently of the priority or class they belong to. Indeed, as we observe in Eq. 2, the buffer occupancy $Q(t)$ increases with the number of congested queues $N$ in the numerator i.e., $\sum N \alpha_c$.

\[ Q(t) = \frac{B \cdot \sum N \alpha_c}{1 + \sum N \alpha_c} \quad (2) \]

\(Q(t)\): Buffer occupied
\(N\): set of queues (i.e., congested

**DT offers no burst-tolerance guarantees.** In addition to the unpredictability of its steady-state allocation, DT’s transient-state allocation is uncontrollable. This is particularly problematic when it comes to burst absorption. The main reason for this limitation is that DT perceives buffer space as a scalar quantity ignoring its expected occupancy over time.

To better understand this limitation we use an intuitive example shown in Fig. 4b and Fig. 4c. The two figures illustrate the same 60-packet buffer before and after the arrival of a burst.

In Fig. 4b, the buffer is shared across five non-empty queues of low-priority classes (all in yellow colors). Notably, all queues are mapped to a single port (port 2). DT allows each queue to occupy 10 packets, as they are configured with $\alpha = 1$ and the remaining buffer space in the steady-state is 10.

In Fig. 4c, a high-priority 5:1 incast occurs at port 1, meaning 5 incoming ports simultaneously send to port 1. Due to DT’s prior allocations, though, the buffer cannot keep up with the incoming traffic. Concretely, the buffer has not enough unoccupied space, nor can it be emptied fast enough to make room for the burst. As a result, the high-priority burst (caused by the incast) starts to experience drops while it only occupies 8 packets in the buffer, that is 9 packets less than the steady-state allocation of the corresponding queue, which would be ~ 17 packets. In other words, the high-priority traffic class is experiencing drops in the transient state, which could have been avoided if the buffer could reach steady state faster. The reason of this slowdown is that the 5 low-priority queues share the dequeue rate of a single port. Notably, DT has no way to distinguish between 5 queues coexisting in a single port and 5 queues, each attached to a separate port.

---

7 As a reminder we use high-priority as a term to define the importance of a traffic class and is not related to scheduling.
To sum up, DT has unpredictable transient state. In effect, the time frame during which a queue experiences drops before it allocates its fair share of the buffer (steady-state allocation) can be arbitrary long. Thus, DT cannot guarantee the absorption of a burst.

3 OVERVIEW

As we showed in §2.3, DT fails to offer predictable buffer allocations and thus any performance guarantee. In this section, we describe FB: a novel buffer management scheme which - unlike DT- manages to control both steady- and transient-state allocation. We explain how FB addresses DT’s limitations by running it on the same example scenarios we used in §2.3.

FB dynamically bounds the buffer allocation in steady-state. FB prevents traffic of any priority from monopolizing the buffer by dynamically bounding buffer usage per priority. In effect, FB guarantees a minimum allocation to both priorities. FB is not equivalent to statically allocating space to a single queue (complete partitioning) or to a group of queues (application pools) as it does not statically reserve buffer.

To illustrate the difference between the steady-state allocations of FB and DT we use Fig. 5a, which shows FB’s allocation under the same scenario we used for DT in Fig. 4a. Unlike DT, which decreases the buffer space occupied by high-priority traffic proportionately to the number of low-priority queues, FB bounds low-priority (yellow) queues to 15 packets on aggregate, equally shared across the three queues. As a result, the high-priority (red) queue can use 30 packets of buffer. In §4, we show that FB makes the buffer that high-priority occupies independent of the number of non-empty low-priority queues. Note that no allocation is static: if the high-priority queue does not use/need its maximum buffer occupancy, the yellow low-priority will get more buffer.

FB makes bursts first-class citizens in the buffer by minimizing transient-state drops. FB is able to offer burst-tolerance guarantees by allocating buffer such that there is always a combination of (i) enough unoccupied buffer space; and (ii) adequately high aggregate dequeue rate (i.e., the buffer can be emptied fast enough) to accommodate a given burst. Indeed, both these factors are critical for a burst to be absorbed. On the one hand, an incoming burst can be absorbed independently of the free buffer space at its arrival, iff the aggregate dequeue rate of the allocated buffer space is at least as high as the enqueue rate \(^8\). On the other hand, an incoming burst can also be absorbed independently of the aggregated dequeue rate of the buffer at its arrival, iff the unoccupied buffer is sufficient to directly accommodate it. FB achieves a balance between the two extremes as we explain in §4, which allows it to achieve high throughput while proving burst-tolerance guarantees.

To illustrate the difference in FB’s allocation to that of DT we use Fig. 5b and Fig. 5c which show FB’s allocation before and after the arrival of a burst. We again consider the same example as in Fig. 4b and Fig. 4c for DT.

In Fig. 5b, FB detects that the aggregate dequeue rate is inevitably low (queues share a single port) and limits each low-priority queue to 6 packets, effectively leaving an incoming burst enough free buffer to be stored. As a result, when the 5:1 high-priority burst arrives (Fig. 5c), the buffer can reach steady state fast enough to avoid transient drops.

4 DESIGN

Having explained FB’s high-level properties (§3), we now describe FB in detail. We elaborate on FB’s threshold calculation (§4.1), before we explain its consequences in FB’s performance and guarantees (§4.2). Finally, we explain how FB’s design applies to a single-queue-per-port scenario.

4.1 FB’s workings

FB limits the buffer space each queue can use depending on both queue-level and buffer-level information. Particularly, as shown in Eq. 3, FB’s per-queue threshold equals the product of: (i) an \(\alpha\) value assigned to the class that the queue belongs to: \(\alpha_c\); (ii) the inverse number of congested (non-empty) queues of the priority (low or high) that the class belongs to: \(\frac{1}{N_{p}(t)}\); (iii) the per-port-normalized dequeue rate of this queue: \(\gamma_p^c(t)\); and (iv) the remaining buffer space: \(B - Q(t)\).

\(^8\)We are, of course, referring to a burst with size smaller than the total buffer.
\[ T_c^i(t) = \alpha_c \cdot \frac{1}{N_p(t)} \cdot \gamma_c^i(t) \cdot (B - B_{oc}(t)) \] (3)\\

\( N_p(t) \): Number of congested queues of priority \( p \) at time \( t \)

\( B - B_{oc}(t) \): remaining buffer

\( \gamma_c^i(t) \): per-port-normalized dequeue rate of \( q_c^i \)

**FB on a single queue per port.** Eq.3 can be naturally adapted to work in a deployment where only a single queue is available per port. Particularly, \( \gamma_c^i \) will always be 1 and \( N_p(t) \) will correspond to all congested queues in the buffer. Thus, the threshold of a packet of class \( c \) destined to port \( i \) will depend on the \( \alpha_c \), the total number of congested queues and the remaining buffer space. In essence, FB applies different thresholds for packets that are mapped to the same queue.

FB’s threshold calculation differs from that of DT (Eq. 1) by two factors: (i) \( N_p \); and (ii) \( \gamma_c^i \). We explain how each of those differentiates FB’s buffer allocation below.

\( N_p(t) \) **bounds steady-state allocation.** FB divides per-queue thresholds with \( N_p \): the number of congested (non-empty) queues of the priority that the class belongs to, as seen in Eq.3. The consequence of this factor to FB’s allocation is twofold: (i) it bounds per-class and per-priority occupancy; and (ii) it allows weighted fairness across classes of the same priority.

First, dividing by \( N_p(t) \) prevents any single class, and any single priority from monopolizing the buffer. As more queues of the same class (or priority) use the buffer, the threshold of each of them decreases, effectively setting an upper bound to the per-class occupancy to \( \frac{\alpha_c}{1+\alpha_p} \) of the total buffer and one to the per-priority occupancy to \( \frac{\alpha_p}{1+\alpha_p} \) of the total buffer, where \( \alpha_p \) is the highest alpha of the priority. As a result, the overall buffer occupancy \( (B_{oc}(t)) \) is also upper-bounded, as shown in Eq.4 where \( \alpha_L \) and \( \alpha_H \) are the maximum alpha values of the classes of high and low priorities, respectively. Observe that the maximum aggregate buffer allocation of FB is independent of the number of congested queues. Consequently, the minimum buffer available for a high-priority class is also independent of the number of queues or low-priority classes in the buffer and vice versa.

Other than bounding allocation, dividing by \( N_p(t) \) offers weighted fairness across classes of the same priority. Namely, the buffer occupied by a priority is split into classes proportionately to their \( \alpha \) values. As a result, if the operator wishes to favor a traffic class among those that belong to low priority, she can do so by assigning higher \( \alpha \) to this class.

\[ B_{oc}(t) \leq \frac{B \cdot (\alpha_L + \alpha_H)}{1 + (\alpha_L + \alpha_H)} \] (4)

\( \gamma_c^i(t) \) **reduces transient state’s duration.** FB allocates buffer to each queue proportionately to its dequeuing rate \( (\gamma) \). The \( \gamma \) factor, combined with the upper bounds, minimizes the duration of the transient state. Indeed, given some amount of buffer per priority, FB splits it into queues proportionately to their service rate, effectively minimizing the time it takes for the buffer to be emptied. In effect, FB reduces the time needed to transition from one steady-state allocation to another.

### 4.2 FB benefits

Having explained FB’s properties, we discuss how those affect FB in performance metrics.

**FB improves throughput and reduces queuing delays.** While FB bounds the amount of buffer used, it maximizes its effectiveness to achieve higher aggregated throughput. Previous research has shown that TCP throughput benefits from buffer size proportionate to the capacity of the bottleneck link [20, 23, 30]. Reflecting this observation to the buffer management scheme FB multiplies the thresholds with the queues’ dequeue rate, effectively benefiting throughput and reducing buffer pressure while being agnostic to the scheduling algorithm used. Indeed, FB allocates on average less buffer than DT. Comparing Eq.3 with Eq.1 we observe that the added factors decrease the allocated buffer. As a result, FB keeps queuing delays lower than DT and the buffer ready to absorb bursts, while not sacrificing throughput.

**FB guarantees the absorption of a given burst.** A burst is characterized by its incoming rate \( r \) (normalized) and duration \( t \) [18]. Whether a burst will be absorbed depends on: (i) its incoming rate \( r \); (ii) the state of the buffer at its arrival (steady state); and (iii) the buffer’s ability to dequeue fast (transient state). We can configure FB to provide two types of guarantees.

First, FB can guarantee that a burst of a given incoming rate \( r \) will be absorbed without any transient losses. Concretely, the incoming traffic will provably occupy the fair steady-state buffer space that corresponds to its queue before experiencing any drops. Indeed, Eq. 5 shows the maximum \( \alpha \) with which the low-priority classes would need to be configured to allow a burst with an incoming rate of \( r \) to pass.

\[ \alpha_L \leq \frac{1}{r - 2} \] (5)

Second, owing to its strategic steady-state and transient-state allocation, FB can guarantee that a burst of a given incoming rate \( r \) and duration \( t \) will be fully absorbed\(^9\). Concretely, FB guarantees that such a burst will provably experience no drops if \( \alpha_T \) and \( \alpha_L \); i.e., the maximum \( \alpha \) values of high and low priorities respectively are set according to Eq. 7

\(^9\)Of course we refer to bursts that are smaller than the buffer.
and 6. Observe that neither is dependent on the number of queues occupying the buffer or their class/priority.

\[
\alpha_L \leq \frac{B}{(r-2) \cdot t} - 1 \quad (6)
\]

\[
\alpha_H > \frac{1}{(r-1) \cdot t} \cdot \frac{r-2}{r-1} \quad (7)
\]

**Sketch of proof.** While we moved the full proof to Appendix A.5, we include the key intuition below. The proof is centered around the time at which a hypothetical burst \((r, t)\) will begin to experience drops, say \(t_1\). \(t_1\) plays such a critical role in burst absorption as it must be greater than the duration \(t\) of a burst for the latter to be absorbed. We first express \(t_1\) as a function of \(\alpha_L\), \(\alpha_H\) and the arrival rate \(r\) and derive an upper bound on \(\alpha_L\). Indeed, the use of \(N_p\) and \(\gamma_L\) in FB’s allocation eliminates the dependency on the state of the buffer. As a result, we are able to obtain guarantees.

Observe that traditional buffer management schemes can only provide such guarantees by statically reserving buffer space for a given burst. Even DT, which is assumed to be more dynamic, would have to limit all other priorities extremely, effectively assuming the worst-case scenario all the time to provide burst-tolerance guarantees.

5 HARDWARE DESIGN

Having explained the benefits of FB, in this section, we demonstrate its deployability. To this end, we first explain how we implemented FB on a protocol-independent switch (PISA) (§ 5.1). Next, we describe how we can approximate FB’s behavior on any device supporting DT, by dynamically adapting the \(\alpha\) (§ 5.2).

5.1 FB on PISA

Naturally, one would implement FB on the Traffic Manager (TM), which is responsible for managing the buffer. Yet, this is not possible as the TM is not programmable [41]. Thus, we implemented FB exclusively on the ingress and egress pipelines, which creates three challenges:

**C1** Deciding whether a packet should be buffered requires comparing the corresponding queue length with a threshold. Yet, queue lengths are only available in the egress pipeline; thus, after a packet has been buffered [41].

**C2** Calculating FB’s thresholds requires aggregated metrics over multiple queue lengths, e.g., remaining buffer. Yet, accessing multiple values of a single memory block is not possible in PISA switches [13, 16].

**C3** Calculating FB’s thresholds requires floating-point operations, which is not supported by PISA.

Next, we describe FB’s high-level design and a packet’s journey before we describe how it addresses each of the aforementioned challenges.

**FB’s high-level design** We built FB upon five main components: four register arrays and two Match & Action (M&A) table as shown in Fig. 6. We use the register arrays to keep the required state for deciding whether a packet should be buffered or dropped. This decision needs to be taken in the ingress pipeline, i.e., before the TM accesses the packets. The aforementioned state includes the instantaneous remaining buffer \((\text{Remaining})\), the number of congested queues per port and priority \((N_{\text{Port}}, N_{\text{Priority}})\) as well as the queues’ length \((\text{Qlength})\). We use a M&A table \((\text{Routing})\) to map a packet based on its destination and priority tag to a port and queue for transmission as well as to multiple FB-specific fields. Finally, we use another M&A table \((\text{Shift})\) to approximate the required floating-point operations.

**Packet’s journey** Upon arrival \(\text{1}\), a packet’s destination and priority tag are matched against the Routing table to multiple action parameters: an \(\alpha\) value and three indexes. These indexes are used to read the relevant information about the state of the buffer (e.g., corresponding queue length from the Qlength array or the number of congested queues of a specific priority from the N_Priority, etc.) \(\text{2}\). This information is used to find the required number of shifts \(\text{3}\) to apply to the remaining to calculate the threshold of the corresponding queue \(\text{4}\). If the threshold is higher than the corresponding queue’s length \(\text{5}\), the packet is enqueued \(\text{6}\). While being at the queue, the packet writes the queue length of its queue to the Qlength array in the egress \(\text{7}\).

**Queue lengths available to the ingress pipeline** The length of any given queue is only available as a metadata field to packets that have been enqueued, thus while they traverse the egress pipeline. Yet, FB requires visibility of queue lengths in the ingress. To address this, we transfer queue lengths from the egress to the ingress in two steps. First, we create a register array, which resides in the egress pipeline and stores the length of every queue in the device. Each index in the array corresponds to a queue, namely a pair of port and traffic class. Each packet traversing the egress pipeline triggers an
update the value corresponding to the length of the queue it belongs to. Second, we maintain a copy of this register array in the ingress to make it available to FB’s logic. To keep the copy up-to-date, we asynchronously generate specially crafted packets, namely SYNC packets. These packets read the queue lengths from the egress register, re-enter in the ingress pipeline via recirculation, and copy the read values to the ingress register array, as shown in Fig. 6. Due to the PISA constraints, which prevent accessing multiple values of a register array in a single pipeline pass, copying all values in one pipeline pass is not possible. Instead, each SYNC packet recirculates as many times as queues there are in a device. While SYNC packets need to be sent frequently to allow real-time visibility over the queue lengths, the overhead is minimal as the traffic generator of the device itself can create them, and they use a special pipe that is reserved for recirculation[41].

Calculating aggregated metrics Other than the length of the queue of interest, calculating FB’s thresholds requires visibility over: (i) its normalized dequeue rate; (ii) the number of congested queues of the same priority; and (iii) the remaining buffer space, as seen in Eq. 3. These metrics need to be dynamically calculated based on all queues’ instantaneous lengths. Doing so is challenging for three reasons. First, the dynamic calculation requires accessing multiple values in the same array e.g., the number of active queues per port. Second, it requires accessing selective indexes of the array, namely those corresponding to the subset of queues of interest e.g., number of controlled queues per priority. Third, the result of this calculation needs to be available in the ingress pipeline. We addressed these challenges again using SYNC packets, which read a subset of the indexes of the egress register array, recirculate and write the aggregated results in the ingress register arrays. In particular, we use three types of such packets. First, SYNC packets copy queue lengths from the egress to ingress (as described above) and update the Remaining register array as they anyway traverse all indexes. Second, SYNC packets count the congested queues per port, which is equivalent to the normalized dequeue rate per queue given the scheduling algorithm. Each SYNC packet updates a single port’s count with the number of queues above a threshold. Finally, SYNC packets count the congested queues per priority. All SYNC packets contain in their custom header the indexes from which they start and finish reading from Qlengths, the index at which they write and their pivot (indexes they skip).

Approximating floating-point operation Even after having all required information available, FB needs to multiply the remaining buffer with other factors (i.e., the reverse of the number of congested queues \( \frac{1}{M(i)} \)), the reverse of the number of active queues per port \( \frac{1}{N(p)} \) and the \( \alpha \) to calculate the thresholds. Yet, PISA does not allow floating-point operations. To address this issue, we shift the remaining space value so many times as the logarithm of two of the product of all the factors mentioned above. The calculation of the number of required shifts is not done in the data-plane. Instead, we pre-calculate it for all possible values and store all the results using match-action rules matching on three values \( \alpha, N_p, \) and \( N_c \). Observe that all three values are discrete and bounded, so the number of required rules is manageable. As an intuition, \( n \) is in the range of \( 2 – 8 \); there are only a couple of possible \( \alpha \) (8 for Tofino), and a few decades congested queues at most.

5.2 FB on top of DT (FBA)

We can approximate FB’s behavior (FBA) by periodically reconfiguring \( \alpha \) per queue according to the buffer occupancy. Recall from Eq. 3 that FB’s formula deviates from DT’s \( \alpha \), say \( \alpha_{dt} \), such that \( \alpha_{dt} = \alpha_c \cdot \frac{1}{N(p)} \cdot \gamma(i)(t) \). Both the number of congested queues \( N_p \) and the normalized dequeue rate \( \gamma \) change over time; thus, we need to monitor both variables to calculate \( \alpha \). Fortunately, chip manufacturers (e.g., Broadcom) expose the queue lengths and the remaining buffer (at least as watermarks). Thus, we can build FBA by using a software controller that (i) periodically pulls the queue lengths and the remaining buffers; (ii) calculates the number of congested queues; and (iii) infers the per-queue dequeue rate considering the scheduling algorithm per port and the number of active queues. The periodicity of the \( \alpha \) updates depends on the capabilities of the device in terms of monitoring queues and updating \( \alpha \). In §6, we consider the update period of \( 1 \)s which already brings considerable benefits. Intuitively, as we increase the frequency of the updates, FBA will approach the performance of FB.

Despite its benefits, FBA cannot approximate FB if only a single queue is available per port. As FBA relies on DT it cannot use different thresholds for packets of the same queue. In this case, FBA will have the same performance as DT. Still, provided that traffic is stable, FB’s insights can be used to configure static \( \alpha \).

6 EVALUATION

We evaluate FB aiming at answering four main questions:

**Q1** How does FB compare against other buffer schemes?

**Q2** Is FB useful if DCTCP is already deployed?

**Q3** Does FB deteriorate performance under low load?

**Q4** Is FB useful if traffic is not already marked/classified?

We demonstrate that: (Q1) FB outperforms all buffer management algorithms in terms of burst tolerance while achieving on-par throughput; (Q2) FB even with TCP improves burst absorption compared to DT with DCTCP by 53% under high load and by 10% under low load; (Q3) FB does not deteriorate throughput even in the absence of bursts or under low load as it does not statically allocate buffer; and (Q4) FB brings even more benefits when the traffic classification is done directly on the device. We first give a summary of our
Figure 7: Summary of results comparing average Query Completion Time (QCT), throughput (THP), and buffer usage (BUF) across various buffer management schemes (rows) for high and low load (left, right tables) considering multi- and single-queue deployment scenarios (top, bottom tables). Greener cells illustrate better performance. FB (top 2 rows in each table) achieves the best burst absorption measured as QCT without sacrificing throughput. FB’s approximation (FBA) (bottom 2 rows in the top tables) improves burst absorption but decreases throughput.

6.1 Key Findings

Fig. 7 summarizes our key findings in four tables. Rows correspond to a combination of a buffer management algorithm with a TCP version. Columns present average metrics for Query Completion Time (QCT), throughput (THP), and buffer utilization (BUF). Greener cells illustrate better performance. FB (top 2 rows in each table) achieves the best burst absorption measured as QCT without sacrificing throughput. FB’s approximation (FBA) (bottom 2 rows in the top tables) improves burst absorption but decreases throughput.

We do not evaluate FAB and IB in the multi-queue scenario as they are not compatible with marked traffic, i.e., they classify packets on their own.
Figure 8: Multi-queue scenario: FB outperforms in QCT while achieving on-par throughput compared to all other schemes even when they are paired with DCTCP. FB’s 99-th percentile (99p) buffer occupancy increases mostly to accommodate bursts.

6.2 Methodology

Having briefly discussed our key insights, we elaborate on the topology, traffic mix, priority assignment and deployment scenarios we used.

**Topology.** We evaluate FB’s performance in a Leaf Spine topology [6] of two leaves and two spines with four links connecting each pair of leaf and spine. We use ECMP to load-balance traffic across uplinks. We set the buffer size to 1MB and the bandwidth per port to 1Gbps. Each leaf is connected to 40 servers (oversubscription of 5). We set $\text{RTT} = 200\mu s$. The results we describe are not sensitive to concurrent increases of bandwidth and buffer size. Naturally, the buffer management is less important, if the buffer size increases with static aggregate bandwidth.

**Traffic mix.** We generate two types of traffic: (i) web search (realistic workload based on traffic measurements in deployed datacenters); and (ii) query traffic (models the user queries of a web application backend). We selected these two traffic types as examples of non-bursty and bursty traffic, respectively. Our results hold for similar distributions that require both burst absorption and high throughput.

For the former type, we use the flow size distribution from [7] and tune the mean of Poisson inter-arrivals such that a 20–90% load is achieved.

For the latter type, we assume that a query arrives at each server according to a Poisson process with mean 1 query/second following [6]. We vary the size of the query from 0 to 90% of the buffer size. Burst of zero size corresponds to the case when no high-priority traffic arrives. Each query consists of a server attached to a leaf requesting a Query-Size file from all the servers connected to the other leaf. Each request is then responded by 40 servers, each transmitting $\frac{1}{40}$ of the file. Each pair of servers has a persistent TCP connection as in [6]. A query is completed when the requester receives the Query-Size file.

**Deployment Scenarios.** We consider two deployment scenarios: multi-queue and single-queue, which differ on the number of priority queues and the marking scheme.

In the multi-queue scenario, we assume five queues per port and Round-Robin scheduling. Incoming packets are mapped to a queue according to the tag they carry. The query traffic is marked with a high-priority tag and the web-search traffic with 4 equally-low-priority tags. Tags are added by the
servers uniformly at random. In effect, packets belonging to a burst carry a high-priority tag and are mapped to a separated priority queue in the multi-queue deployment scenario. In this scenario, we compare FB and its approximation with two other buffer management schemes: (i) Complete Sharing (CS), which allows queues to grow arbitrarily large in the shared buffer until it is full; and (ii) Dynamic Thresholds (DT), which we extensively describe in §2.2. Unlike in the single-queue scenario, for this scenario we do not evaluate other buffer management algorithms i.e., the Cisco Intelligent Buffer (IB) [1] and FAB [9] as they use a classifier that overwrites the pre-marked traffic.

In the single-queue deployment scenario, we assume a single queue per port. Traffic is not marked with priority tags by end hosts, but a flow classifier is available to all buffer management algorithms. The availability of the classifier allows us to compare more buffer management schemes. Thus, other than FB, DT and CS we also compare against the Cisco Intelligent Buffer (IB) [1] and FAB [9] which require a classifier and cannot use the pre-marked traffic. In particular, the Cisco Intelligent Buffer (IB) [1] combines DT, a fair dropping mechanism, and a priority queue, while FAB is a newer scheme which prioritizes short flows [9].

**Configuration.** We configure FB with $\alpha_L = 0.5$ and $\alpha_H = 20$ for short and long flows, respectively in the single-queue scenario; and for low-priority and high-priority traffic, respectively in multi-queue scenario.\(^\text{11}\) We configure DT with $\alpha = 0.5$ in the single-queue scenario;\(^\text{12}\) and with $\alpha_L = 0.5$ and $\alpha_H = 20$ for low-priority and high-priority traffic, respectively in the multi-queue scenario. We configure IB with $\alpha = 0.5$. IB uses headroom for short flows. IB also uses a separated priority queue for short flows in the single-queue scenario. Finally, IB uses Approximate Fair Dropping (thus cannot use DCTCP). When DCTCP is used, all queues are RED [22] with min and max thresholds set to 20 ($K = 20$) following the recommendations in [7]. When TCP is used, all queues are DropTail, except for IB. TCP minRTO is set to 100ms.

We use the ns-3 Simulator, version 3.31.\(^\text{13}\) We perform 10 experiments and report average values.

### 6.3 Results

**FB burst absorption capabilities are independent of the background load.** Fig. 8a illustrates the average QCT as a function of the low-priority load, while the burst size is fixed to 75% of the buffer. While QCT increases as the load increases for most of the buffer management algorithms, QCT for FB is consistently low. FB guarantees high burst absorption even under high load by bounding the buffer usage of low-priority traffic. DCTCP demonstrates similar behavior. Particularly, when paired with DCTCP both CS and DT have better burst absorption capabilities (lower QCT). Still, FB demonstrates lower QCT starting from 40% load compared to all alternatives, even when paired with TCP.

**FB uses more buffer as the burst size increases.** Fig. 8d illustrates average QCT as a function of burst size, while the load is fixed to 90%. The benefits of FB in terms of burst absorption increase as the burst size increases but it starts being superior even when the burst size is 10% of the buffer. The key reason for this behavior is that FB increases its buffer usage only in case of a burst of high-priority traffic. Indeed,\(^\text{13}\) We implement the evaluated buffer-management algorithms in ns-3 will be made available online.

\(^{\text{11}}\) We derive the parameters for FB based on our analysis in Appendix A.5 optimized for burst sizes ≤ 75% of the buffer size.

\(^{\text{12}}\) Setting $\alpha = 20$ would approximate absence of buffer management.

\(^{\text{13}}\) Our implementation of the evaluated buffer-management algorithms in ns-3 will be made available online.
as we observe in Fig. 8f, FB’s 99p (99-th percentile) buffer occupancy increases as the burst size increases.

**FB achieves on-par throughput under any background load and buffer size.** Fig. 8b illustrates the achieved throughput as a function of load on the device, while Fig. 8e as function of burst size. Naturally, the throughput increases with the load for all algorithms as well as for FB. Observe that when CS is paired with TCP (not DCTCP) the throughput decreases, because the buffer allocation of CS is first-come-first-served, thus highly sensitive to bursts and flows’ relative order. Importantly, the approximation of FB (FBA) demonstrates slightly lower throughput when paired with TCP. This is due to the short duration of burst combined with the infrequent change of $\alpha$, that causes FBA to reduce the buffer given to low-priority for longer than necessary to absorb the burst.

**In the single-queue scenario FB has higher benefits.** Fig. 9a, 9b illustrate average QCT and 99p FCT as a function of background load, respectively. FB improves average QCT by 83% and 99p FCT by 38% compared to DT with DCTCP when background load is only 20%. All algorithms (other than CS paired with TCP) achieve on-par throughput as we observe in Fig. 9c. When paired with DCTCP, FAB and CS also improve DT’s performance in terms of QCT and FCT. Still FB decreases QCT by 12% and FCT by 24% under 60% even when FAB uses DCTCP and FB uses TCP. Of course, FB’s performance further improves with DCTCP.

**FB blindly adheres to the marking, thus erroneous marking might lead to undesirable performance.** As an intuition, short flows of low-priority traffic might experience high tail FCT if they compete with long flows of the same class. Thus, if the operator wants to avoid it, she should mark all short flows as high priority. If the operator does not wish to mark packets then she can leave this operation to an classifier residing in the network device as in the single-queue scenario. Similarly, if the operator configures UDP traffic as high-priority then that might significantly affect the performance of other high priority-traffic.

### 7 CASE STUDY

We implement our hardware design (§5) on a Barefoot Tofino Wedge 100BF-32X to verify that it works on real hardware and can improve performance. Our program includes 850 LoC in P4 and uses 6 stages in the ingress and 3 stages in the egress pipeline.

Our testbed (Fig. 10a) includes one Tofino switch and two servers (S1 and S2). S1 connects to the Tofino via port $p_1$, while S2 via ports $p_2$ and $p_3$. Each port is mapped to 8 queues with aggregate bandwidth 80Kbps per port. Among the 8 queues, 1 is used for high-priority TCP traffic and 7 for low-priority UDP traffic. We configure $\alpha = 0.8$ for high-priority traffic and $\alpha = 0.6$ for low.$^{14}$ All queues share the same buffer pool limited to 9000 cells. We did not use all the buffer space provided in a Tofino due to the low-traffic rate. We generate UDP flows from S1 to S2 on port $p_2$. We also generate 100 TCP flows 8KB in size from S2 $p_3$ to S1. We run the experiment once with DT and once with FB. Fig. 10b presents the CDF of FCT results. FB limits the buffer used by low-priority UDP flows, allowing short flows of high-priority to achieve good performance. As a result, FB achieves at least 50ms smaller FCTs.

### 8 RELATED WORK

FB is related but complementary to algorithms operating at the port level (e.g., queue management, scheduling) and host level (e.g., TCP). First, active Queue Management and scheduling algorithms can facilitate preferential treatment of some flows over others, but only if they are mapped to the same output port. Indeed, AQM pro-actively controls individual queues e.g., RED [22], Codel [27], PIE [35], limits the per-flow buffer or bandwidth [12, 21, 26, 33] on per-port level. Second, scheduling techniques e.g., pFabric [8] and PIAS [11] allow certain flows to be dequeued faster than others of the same port. Third, congestion control mechanisms, such as [7, 14, 15, 32, 39, 45, 46] reduce the unwanted buffer usage, but cannot detect or react to high overall buffer occupancy, neither can they change the allocated buffer at the device level.

Regarding buffer algorithms more recent works such as EDT [40], FAB [9] and Cisco IB [1] empirically recognize bursts and prioritize them. While intuitive, such algorithms cannot consistently (under various loads) absorb bursts as we show in §6 and cannot be trivially mapped to multi-queue scenarios. On the contrary, FB offers provable guarantees under various scenarios. Other buffer management algorithms such as [24, 28, 37, 38] are not applicable to Call Admission Control (CAC), while pushout-based ones such as [44], [42] are considered impractical [10].

$^{14}$The selection of $\alpha$ is affected by design choices specific to Tofino and beyond our control. Still, higher $\alpha$ would make DT’s performance worse.
9 CONCLUSION
In this paper, we demonstrate the inefficiencies of today’s most common buffer management algorithm, Dynamic Thresholds, both experimentally and analytically. We present FB, a novel algorithm that offers provable burst-tolerance guarantees, without sacrificing throughput or statically allocating buffer. We show that FB outperforms all other buffer management techniques even when they are combined with DCTCP. Finally, we show that FB’s design is practical by implementing it on a Barefoot Tofino.

REFERENCES
[1] [n. d.]. Cisco Nexus 9000 Series Switches. https://www.cisco.com/c/en/us/products/collateral/switches/nexus-9000-series-switches/white-paper-c11-738488.html. ([n. d.]).
[2] [n. d.]. Input and output queueing. https://cs.nyu.edu/anirudh/lectures/lec12.pdf. ([n. d.]).
[3] [n. d.]. Nexus 9000 Architecture. ([n. d.]). https://www.cisc Colive.com/c/dam/tr/cisc live APC/docs/2018/pdf/BRK DCT-3640.pdf.
[4] [n. d.]. Traffic Class and Traffic-Class Groups Overview. https://www.juniper.net/documentation/en_US/junos/e15.1/topics/concept/qos-traffic-classes-traffic-class-groups.html. ([n. d.]).
[5] 2020. Barefoot Tofino. (2020). https://barefootnetworks.com/products/brief-tofino/.
[6] Mohammad Alizadeh and Tom Edsall. 2013. On the data path performance of leaf-spine datacenter fabrics. In 2013 IEEE 21st annual symposium on high-performance interconnects. IEEE. 71–74.
[7] Mohammad Alizadeh, Albert Greenberg, David A Maltz, Jitendra Padhye, Parveen Patel, Balaji Prabhakar, Sudipta Sengupta, and Murari Sritharan. 2011. Data center tcp (dctcp). ACM SIGCOMM computer communication review 41, 4 (2011), 63–74.
[8] Mohammad Alizadeh, Shuang Yang, Milad Shirif, Sachin Katti, Nick McKeown, Balaji Prabhakar, and Scott Shenker. 2013. fabric: Minimal near-optimal datacenter transport. In ACM SIGCOMM Computer Communication Review, Vol. 43. ACM. 435–446.
[9] Maria Apostolaki, Laurent Vanbever, and Manya Gobadi. 2019. FAB: Toward Flow-aware Buffer Sharing on Programmable Switches. In ACM Workshop on Buffer Sizing.
[10] M. Arpaci and J. A. Copeland. 2000. Buffer management for shared-memory ATM switches. IEEE Communications Surveys Tutorials 3, 1 (First 2000), 2–10. https://doi.org/10.1109/COMST.2000.5340716
[11] Wei Bai, Li Chen, Kai Chen, Dongsu Han, Chen Tian, and Weicheng Sun. 2014. PIAS: Practical information-agnostic flow scheduling for data center networks. In Proceedings of the 13th ACM Workshop on Hot Topics in Networks. ACM. 25.
[12] Andreas V Bechtolsheim and David R Cheriton. 2003. Per-flow dynamic buffer management. (Feb. 4 2003). US Patent 6,515,963.
[13] Ran Ben-Basat, Xiaojie Chen, Gil Einziger, and Ori Rottenstreich. 2018. Efficient measurement on programmable switches using probabilistic recirculation. In 2018 IEEE 26th International Conference on Network Protocols (ICNP). IEEE. 313–323.
[14] Lawrence S Brakmo, Sean W O’Malley, and Larry L Peterson. 1994. TCP Vegas: New techniques for congestion detection and avoidance. In Proceedings of the conference on Communications architectures, protocols and applications. 24–35.
[15] Neal Cardwell, Yuchung Cheng, Soheil Jeganeh, and Van Jacobson. 2017. BBR congestion control. Working Draft. IETF Secretariat, Internet-Draft draft-cardwell-icrg-bbr-congestion-control-00 (2017).
[16] Xiaojie Chen, Shir Landau Feibish, Yaron Koral, Jennifer Rexford, and Ori Rottenstreich. 2018. Catching the microburst culprits with snappy. In Proceedings of the Afternoon Workshop on Self-Driving Networks. 22–28.
[17] Yanpei Chen, Ran Griffith, Junda Liu, Randy H Katz, and Anthony D Joseph. 2009. Understanding TCP incast throughput collapse in data-center networks. In Proceedings of the 1st ACM workshop on Research on enterprise networking. ACM. 73–82.
[18] Abhijit K Choudhury and Ellen L Hahne. 1998. Dynamic queue length thresholds for shared-memory packet switches. IEEE/ACM Transactions On Networking 6, 2 (1998), 130–140.
[19] Sujal Das and Rochan Sankar. 2012. Broadcom smart-buffer technology in data center switches for cost-effective performance scaling of cloud applications. Broadcom White Paper (2012).
A ANALYSIS

A.1 Assumptions
The analysis is based on a fluid model where packet (bits) arrivals and departures are assumed to be fluid and deterministic. A switch with arbitrary number of ports with arbitrary number of queues per port is considered. In particular, each port has only one queue per class as defined in §2).

\( B \) : Total shared buffer space of switch.

\( Q(t) \) : Instantaneous occupied buffer space at time \( t \)

\( \alpha_c \) : A parameter for buffer-management algorithm, for each class.

A.2 FB
FB works based on two-levels of hierarchy i.e class and priority. The general notion of class remains same i.e., each class is associated with a separate queue at each port. In addition, FB requires the classes to be mapped to priorities. A Low priority is a set of classes which share the buffer fairly proportionate to their alpha values. A High Priority is simply a set consisting of one class.

FB buffer-management algorithm requires an \( \alpha_c \) parameter per class. The buffer-allocation is based on threshold calculations per queue. In particular, the threshold of a queue at port \( i \), of class \( c \) and belonging to a priority \( p \) is calculated by FB algorithm as,

\[
T_{ci}(t) = \alpha_c \cdot \beta_p(t) \cdot \gamma_i(t) \cdot (B - Q(t))
\]

where, \( \beta_p(c)(t) \) is the inverse of the total number of congested queues of priority \( p \) (to which the class \( c \) belongs to) at time \( t \) i.e., \( \frac{1}{\sum_{c \in P} \beta_p(c)(t)} \) and \( \gamma_i(t) \) is the normalized dequeue rate (or normalized service rate) of the queue at time \( t \).

Observe that, \( \beta_p(c)(t) \) remains same for all the priorities belonging to a group and can be expressed as \( \beta_P(t) \) where \( P \) denotes the priority \( p \).

Here after for simplicity \( \omega_{ci}(t) \) is defined as,

\[
\omega_{ci}(t) = \alpha_c \cdot \beta_P(t) \cdot \gamma_i(t)
\]

Key properties of Omega:

\[
\sum_i \sum_{c \in P} \omega_{ci}(t) = \beta_P(t) \cdot \sum_i \sum_{c \in P} \alpha_c \gamma_i(t)
\]

If, all the queues of all classes of priority \( P \) share same alpha parameters (say \( \alpha_P \)) and have same normalized dequeue rate at time \( t \) (say \( \gamma_P \)), then Eq. 10 reduces to,

\[
\sum_i \sum_{c \in P} \omega_{ci}(t) = \alpha_P \cdot \gamma_P
\]

Further, if \( \gamma_P = 1 \),

\[
\sum_i \sum_{c \in P} \omega_{ci}(t) = \alpha_P
\]

In general there exists a limit given by,

\[
\sum_i \sum_{c \in P} \omega_{ci}(t) \leq \max_{c \in P}(\alpha_c) = \alpha_{max}
\]

We will see later, how these properties enable FB to achieve certain isolation and burst-tolerance guarantees.

A.3 Steady-State Analysis
In this subsection, it is assumed that load-conditions remain stable and a steady-state of buffer is achieved. Following this assumption, all the equations in this subsection are expressed without the time variable. Under this state, the queue lengths remain stable at less than or equal to the corresponding threshold. For simplicity, it is assumed that all the queues-lengths are at their respective thresholds. Then the total buffer occupancy can be expressed as,
\[ Q = \sum_i \sum_c Q^i_c \]

From the assumption that the queue-lengths are equal to their thresholds, using Eq. 8 and Eq. 9,

\[ Q = \sum_i \sum_c \omega^i_c \cdot (B - Q) \]

Solving for \( Q(t) \) gives,

\[ Q = \frac{B \sum_i \sum_c \omega^i_c}{1 + \sum_i \sum_c \omega^i_c} \]  \hspace{1cm} (12)

where \( \omega^i_c \) is given by Eq. 9.

Using Eq. 12, the remaining buffer space \( B - Q(t) \) can be expressed as,

\[ \text{Remaining} = \frac{B}{1 + \sum_i \sum_c \omega^i_c} \]  \hspace{1cm} (13)

Under steady-state, from Eq. 13 and Eq. 8, the threshold of a queue at port \( i \) and of class \( c \) is given by,

\[ T^i_c = \frac{B \cdot \omega^i_c}{1 + \sum_i \sum_c \omega^i_c} \]  \hspace{1cm} (14)

**Key properties of Remaining Buffer space:**

Using the notion of groups, Eq. 13, can be expanded as,

\[ \text{Remaining} = \frac{B}{1 + \sum_p \sum_i \sum_{c \in p} \omega^i_c} \]

Using the maximum limit of \( \omega \) property from Eq. 11,

\[ \text{Remaining} \geq \frac{B}{1 + a_p \alpha_{max}} \]  \hspace{1cm} (15)

This key property shows how the remaining buffer space and buffer-occupancy are bounded. For example, lets consider, there exists two classes \( c_0 \) and \( c_1 \) with alpha parameters \( a_0 \) and \( a_1 \), each of which belongs to a separate priority. The remaining buffer space, irrespective of the number of queues and their dequeue rates, Eq. 15 can be expressed as,

\[ \text{Remaining} \geq \frac{B}{1 + a_0 + a_1} \]

**A.4 Transient-State Analysis**

Given a steady-state of buffer assuming that all the queue lengths are controlled by a threshold, when traffic to empty queues appear, load conditions change. The new queues increase in length creating changes in the remaining buffer. As a result, the thresholds and queue lengths undergo a transient state. Due to the appearance of new queues, \( \omega^i_c \) of some of the existing queues get affected due to the changes in \( \beta_{c(p)} \) (number of queues belonging to a class \( c \) of priority \( p \)) and \( \gamma^i_c \) (normalized dequeue rate).

Let \( G_e \) denote the set of queues whose \( \omega^i_c \) gets affected and \( G_{ne} \) denote the set of queues whose \( \omega^i_c \) does not get affected. Note that the \( \omega^i_c \) values of \( G_e \) only reduce. (It is not possible that \( \omega^i_c \) increases due the appearance of a new queue). For simplicity lets denote the queue at port \( i \) and of class \( c \) with ordered pairs as \((i, c)\). The set of ordered pairs of existing queues is denoted as \( S_{old} \). The ordered pairs of new queues that trigger transient state are denoted as \( S_{new} \). Observe that \( S_{old} = C_{ne} \cup C_e \).

The arrival rate of traffic at each new queue is denoted by \( r_i \) and the arrival process is fluid and deterministic. At \( t = 0 \),

\[ T^i_c(0) = \frac{\omega^i_c \cdot B}{1 + \sum_{(i, c) \in S_{old}} \omega^i_c} \]  \hspace{1cm} (16)
At $t = 0^+$, $\omega^i_c$ of $G_e$ change and remain same for the entire duration of transient state. At the same time, the $\omega^i_c$ of $G_{ne}$ remain unchanged. Hence such changes are assumed to happen and the time variable is dropped for $\omega^i_c$ in the equations.

From Eq. 8, the rate of change of thresholds and queue lengths can be expressed as follows,

$$\frac{dT_c^i(t)}{dt} = -\omega^i_c \cdot \sum_{\forall(i,c) \in S_{old} \cup S_{new}} \frac{dQ_c^i(t)}{dt} \tag{18}$$

$$\frac{dQ_c^i(t)}{dt} = \begin{cases} -\gamma^i_c, & \text{if } T_c^i(t) > T_e^i(t) \text{ and } (i,c) \in S_{old} \\ \max[-\gamma^i_c, \min\{\frac{dT_e^i(t)}{dt}, r - \gamma^i_c\}], & \text{if } T_c^i(t) = T_e^i(t) \text{ and } (i,c) \in S_{old} \\ r - \gamma^i_c, & \text{if } T_c^i(t) < T_e^i(t) \text{ and } (i,c) \in S_{new} \tag{19} \end{cases}$$

It can be proved by contradiction that $\frac{dT_c^i(t)}{dt} \leq 0 < r - \gamma^i_c$. Solving Eq. 18 and Eq. 19 for $t = 0^+$,

$$\left(\frac{dT_c^i(t)}{dt}\right)_{(t=0^+)} = -\omega^i_c \cdot \left( \sum_{\forall(i,c) \in G_e} \gamma^i_c \right) - \omega^i_c \cdot \sum_{\forall(i,c) \in G_{ne}} \left( \sum_{\forall(i,c) \in S_{old}} \frac{dT_e^i(t)}{dt} \right)_{(t=0^+)} \tag{20}$$

Recall that $S_{old} = G_e \cup G_{ne}$. All the queues belonging to $G_e$, will experience a change in their $\omega^i_c$ values at $t = 0^+$ resulting in their queue-lengths greater than threshold. As a result, the rate of change of their queue lengths is their corresponding dequeue rates. Eq. 20 can then be expanded as,

$$\left(\frac{dT_c^i(t)}{dt}\right)_{(t=0^+)} = -\omega^i_c \cdot \left( \sum_{\forall(i,c) \in G_e} \gamma^i_c \right) - \omega^i_c \cdot \sum_{\forall(i,c) \in G_{ne}} \left( \sum_{\forall(i,c) \in S_{old}} \frac{dT_e^i(t)}{dt} \right)_{(t=0^+)} -\omega^i_c \cdot \sum_{\forall(i,c) \in S_{new}} (r - \gamma^i_c) \tag{21}$$

From Eq. 21, arrival rate of traffic in new queues i.e $r$ can be expressed as,

$$r = \sum_{\forall(i,c) \in G_e} \gamma^i_c \left( \frac{dT_c^i(t)}{dt} \right)_{(t=0^+)} + \omega^i_c \cdot \sum_{\forall(i,c) \in G_{ne}} \left( \sum_{\forall(i,c) \in S_{old}} \frac{dT_e^i(t)}{dt} \right)_{(t=0^+)} \tag{22}$$

By applying summation across $\forall(i,c) \in G_e$ over Eq. 21 (will be seen later how this will be useful), $r$ can be expressed as,

$$r = \frac{\sum_{\forall(i,c) \in G_e} \gamma^i_c \left( \frac{dT_c^i(t)}{dt} \right)_{(t=0^+)} + \omega^i_c \cdot \sum_{\forall(i,c) \in G_{ne}} \left( \sum_{\forall(i,c) \in S_{old}} \frac{dT_e^i(t)}{dt} \right)_{(t=0^+)} \cdot \sum_{\forall(i,c) \in S_{new}} \omega^i_c}{\sum_{\forall(i,c) \in S_{new}} \omega^i_c} \tag{23}$$

Now it can be observed that the value of $r$ influences for all $\forall(i,c) \in G_e$, $\left(\frac{dT_c^i(t)}{dt}\right)_{(t=0^+)}$. In other words, the value of $r$ influences the total i.e $\sum_{\forall(i,c) \in G_e} \left(\frac{dT_c^i(t)}{dt}\right)_{(t=0^+)}$, which is the aggregate rate at which thresholds drop for the non affected set of queues i.e $G_{ne}$.
A.4.1 Case-1. In this case, the arrival rate \( r \) is such that, the queues belonging to \( G_{ne} \) are able to reduce in length exactly tracking the changes in their thresholds. As a result their queue-lengths remain equal to the threshold throughout the transient state i.e,

\[
\left. \left( \frac{dT_r^i(t)}{dt} \right) \right|_{t=0^+} \geq -\gamma_c^i
\]  

(24)

leading to,

\[
\sum_{\forall (i,c) \in G_{ne}} \left. \left( \frac{dT_r^i(t)}{dt} \right) \right|_{t=0^+} \geq \sum_{\forall (i,c) \in G_{ne}} -\gamma_c^i
\]  

(25)

Using Eq. 24 and Eq. 25 in Eq. 23, the condition on \( r \) can be expressed as,

\[
r \leq \frac{1}{\sum_{\forall (i,c) \in G_e} 1} \left( \sum_{\forall (i,c) \in G_e} \gamma_c^i \right) \cdot \left( \sum_{\forall (i,c) \in G_{ne}} \omega_c^i \right) : \left( \sum_{\forall (i,c) \in S_{new}} 1 \right)
\]  

(26)

Note that in Eq. 23, we deliberately apply summation over \( \forall (i,c) \in G_{ne} \) which can be a null set. If \( G_{ne} = \phi \), by applying summation over \( \forall (i,c) \in G_e \) in Eq. 21, \( r \) condition can be expressed as,

\[
r \leq \frac{1}{\sum_{\forall (i,c) \in G_e} 1} \left( \sum_{\forall (i,c) \in G_e} \gamma_c^i \right) \cdot \left( \sum_{\forall (i,c) \in G_{ne}} \omega_c^i \right) : \left( \sum_{\forall (i,c) \in S_{new}} 1 \right)
\]  

(27)

For generalization, observe the “\(*\)” over the summation terms in Eq. 26. Here after, the convention follows that, where ever “\(*\)” appears, it means that, the summation is deliberate and can be interchanged between \( \forall (i,c) \in G_{ne} \) and \( \forall (i,c) \in G_e \) if \( G_{ne} = \phi \). All the other summations have usual meaning.

Substituting Eq.24 and Eq.25 in Eq. 21 and using the result in Eq. 19 gives,

\[
\left. \left( \frac{dT_r^i(t)}{dt} \right) \right|_{t=0^+} = -\omega_c^i \left( \sum_{\forall (i,c) \in G_e} -\gamma_c^i + \sum_{\forall (i,c) \in S_{new}} (r - \gamma_c^i) \right)
\]  

\[
\left( \frac{dQ_r^i(t)}{dt} \right) \left|_{t=0^+} = \begin{cases} 
-\omega_c^i \left( \sum_{\forall (i,c) \in G_e} -\gamma_c^i + \sum_{\forall (i,c) \in S_{new}} (r - \gamma_c^i) \right) & \text{for } \forall (i,c) \in G_{ne} \\
-r \gamma_c^i & \text{for } \forall (i,c) \in G_e \\
r - \gamma_c^i & \text{for } \forall (i,c) \in S_{new} 
\end{cases}
\]

(28)

(29)

These differential equations will be valid as long as \( Q_r^i(t) = T_r^i(t) \) for \( \forall (i,c) \in G_{ne} \) &\& \( Q_r^i(t) \geq T_r^i(t) \) for \( \forall (i,c) \in G_e \) &\& \( Q_r^i(t) < T_r^i(t) \) for newly created queues i.e \( \forall (i,c) \in S_{new} \). Solving these equation, using the initial conditions, Eq. 16 and Eq. 17 leads to,
We can further simplify for a case where load variations occur for High Priority first touches the threshold. The transient state continues after \( t \) will experience zero drops i.e., no transient drops if its duration \( t \) when the threshold equals the queue length. It is considered that as we can observe from Eq. 30 and Eq. 31, the new queues will grow in length without dropping packets upto a time say \( t_c \). In order to offer guarantees, it is absolutely required that either \( \gamma \) is constant. As a result of this assumption, \( G_e = \emptyset \) and \( S_{old} = S_{new} \) and Eq. 32 reduces to,

\[
 t_{1c} = \frac{\alpha_H \cdot \frac{1}{N_{p(c)}} \cdot \gamma_c \cdot B \left((r - \gamma_c^i) \cdot (1 + \sum_{\forall(i,c) \in S_{old}} \omega_{i,c} + \sum_{\forall(i,c) \in S_{new}} \omega_{i,c})\right)}{\sum_{\forall(i,c) \in S_{new}} \left(1 + \sum_{\forall(i,c) \in S_{old}} \omega_{i,c} \right) \cdot \left(1 - \frac{1}{N_p(c)} \cdot \gamma_c \cdot B \right)}
\]

We can further simplify for a case where load variations occur for High Priority whose maximum \( \alpha \) value is \( \alpha_H \) and the existing Low Priority in the queues have a maximum \( \alpha \) value of \( \alpha_L \). We can then guarantee that for an arrival rate \( r \) that satisfies Case-1 will experience zero drops i.e., no transient drops if its duration \( t \) satisfies the following condition:

\[
 t_{1c} = \frac{\alpha_L \cdot \frac{1}{N_{p(c)}} \cdot \gamma_c \cdot B \left((r - \gamma_c^i) \cdot \left(1 + \sum_{\forall(i,c) \in S_{old}} \omega_{i,c} \right) \cdot \sum_{\forall(i,c) \in S_{new}} 1\right)}{\sum_{\forall(i,c) \in S_{new}} \omega_{i,c} \cdot \left(1 + \sum_{\forall(i,c) \in S_{old}} \omega_{i,c} \right) \cdot \sum_{\forall(i,c) \in S_{new}} 1} 
\]

Observe that Eq. 34 is independent of number of queues of Low Priority and hence it can be said that High Priority isolation can be guaranteed.

### A.4.2 Case-2

In this case, the arrival rate \( r \) is such that, the queues belonging to \( G_{ne} \) are unable to reduce in length in accordance with the changes in their thresholds. As a result their queue-lengths remain greater than the threshold throughout the transient state i.e,

\[
 \lim_{t \to 0^+} \frac{dT_i(t)}{dt} < -\gamma_c^i 
\]

leading to,

\[
 \sum_{\forall(i,c) \in G_{ne}} \frac{dT_i(t)}{dt} \left|_{t=0^+} \right. < \sum_{\forall(i,c) \in G_{ne}} \left. -\gamma_c^i \right| \sum_{\forall(i,c) \in G_{ne}} \left. \gamma_c^i \right| 
\]
Using Eq. 35 and Eq. 36 in Eq. 23, the condition on \( r \) can be expressed as,

\[
r > \frac{\sum_{\forall (i,c) \in S_{new}} \gamma^i_c}{1 + \sum_{\forall (i,c) \in G_e} \gamma^i_c} \cdot \left( \sum_{\forall (i,c) \in G_e} \omega^i_c \right) \cdot \left( 1 + \sum_{\forall (i,c) \in G_ne} \omega^i_c \right) - \frac{1 + \sum_{\forall (i,c) \in G_e} \omega^i_c}{1}
\]  

(37)

if \( G_{ne} = \phi \), then \( r \) the above condition is expressed as,

\[
r > \frac{\sum_{\forall (i,c) \in S_{new}} \gamma^i_c}{1 + \sum_{\forall (i,c) \in G_e} \gamma^i_c} \cdot \left( \sum_{\forall (i,c) \in G_e} \omega^i_c \right) \cdot \left( 1 + \sum_{\forall (i,c) \in G_ne} \omega^i_c \right) - \frac{1 + \sum_{\forall (i,c) \in G_e} \omega^i_c}{1}
\]  

(38)

Following similar procedure as in Case-1, the equations for Case-2 can be easily determined. Finally, the time \( t^i_L \) at which one of the queues that belong to \( S_{new} \) touches it’s threshold can be expressed as,

\[
t^i_L = \frac{\omega^i_c \cdot B}{(1 + \sum_{\forall (i,c) \in G_{old}} \omega^i_c) \cdot (r - y^i_c) + \omega^i_c \cdot \left( \sum_{\forall (i,c) \in G_{old}} y^i_c - \sum_{\forall (i,c) \in G_{new}} (r - y^i_c) \right)}
\]  

(39)

Further based on \( \omega \) properties and observing that \( \sum_{\forall (i,c) \in G_{old}} y^i_c = (-)\text{Number of congested ports of } S_{old} \) say \( \text{NUM} \).

\[
t^i_L = \frac{\alpha_L \cdot N^i_{p(c)} \cdot y^i_c \cdot B}{(1 + \alpha_L) \cdot (r - y^i_c) + \alpha_H \cdot \frac{1}{N^i_{p(c)}} \cdot y^i_c \cdot \left( \text{NUM} + \sum_{\forall (i,c) \in G_{new}} (r - y^i_c) \right)}
\]  

(40)

Notice that the presence of \( \text{NUM} \) in Eq. 40, is a dependency on the number of congested ports of \( \text{Low Priority} \). However, \( \text{NUM} \) only creates a positive effect on \( t^i_L \), i.e., greater the \( \text{NUM} \) greater is \( t^i_L \). On the other hand, Eq. 40 is independent of negative dependencies as was in the traditional algorithm DT.

A.5 How it all relates to Burst-Tolerance

First, if only arrival rate \( r \) is known and an operator wishes to guarantee zero transient losses, from Eq. 26, assuming that load variation occur on an empty port, \( \alpha_L \) is upper bounded by,

\[
\alpha_L \leq \frac{1}{r - (\text{NUM} + 1)}
\]  

(41)

where \( n \) is the number of congested ports. Observe that the worst case for FB is when only a single queue is congested at \( t = 0 \) when the burst arrives, \( \alpha_L \) can be easily determined by using good enough estimate on the number of congested ports \( \text{NUM} \). When the actual number of congested ports are \( < \text{NUM} \), FB cannot guarantee burst absorption. On the other hand, FB guarantees burst absorption for any number of congested ports \( > \text{NUM} \). In practice, this is a desirable property as one could use a conservatively low number for \( n \) to determine \( \alpha_L \) to guarantee burst absorption. If an operator still wants to achieve 100\% burst absorption, \( \text{NUM} = 1 \) must be used as follows,

\[
\alpha_L \leq \frac{1}{r - 2}
\]

Denote Burst-Tolerance for a queue of class \( p \) at port \( i \) as \( \text{Burst}_i^L \) can be defined as
\[ \text{Burst}_c = r \cdot t \text{t}_1 \]  

(42)

where \( r \) is the arrival rate of traffic.

Then, the maximum burst that can pass without experiencing drops is given by \( \text{Burst}_c \). Say an operator specifies \( \text{Burst}_c \) i.e \( r \) and \( t \text{t}_1 \) to be guaranteed to pass at all times. How can \( \alpha_c \) be optimized?

Given an arrival rate \( r \) and of duration \( t \) on a single queue, at a given state of buffer, we are interested in providing a guarantee such that the burst is successfully absorbed. Hence we consider worst case scenarios to derive bounds on \( \alpha_L \) and \( \alpha_H \), where \( \alpha_L \) is the maximum value for Low Priority and \( \alpha_H \) is the maximum for High Priority. Additionally for simplicity, it is assumed that a burst happens on an empty port leading to \( y_c = 1 \) and \( G_c = \phi \).

![Figure 11](image.png)

Figure 11: Comparison of the burst absorption capabilities of FB and DT showing how FB’s performance guarantees remain unaffected by the state of buffer. Parameters used are same as in (§6)

Considering a worst case arrival rate \( r \) that only satisfies Case-2, we are interested in the buffer required and made available by buffer management without drops i.e., \( (r-1) \cdot t \leq (r-1) \cdot \text{t}_1 \). Using Eq. 40 and letting \( NUM = 1 \) to consider worst case,

\[
(r-1) \cdot t \leq \frac{(r-1) \cdot \alpha_H \cdot B}{(1+\alpha_L) \cdot (-(r-1) + \alpha_H \cdot (-1 + (r-1)))}
\]

For an arbitrarily large value of \( \alpha_H \), there exists a limit such that,

\[
\alpha_L \leq \frac{B}{(r-2)} \cdot t - 1
\]

(43)

Similarly, using Eq. 40,
Further generalizing from the properties of Omega, for a burst that occurs on a queue at port $i$ and of class $c$, for Case-1 and Case-2, from Eq. 32 and Eq. 37, the conditions in terms of $\omega_c^i$ can be expressed as,

$$\alpha_L \begin{cases} \leq \left( \sum_{\forall (i,c) \in S_{new}} \frac{1}{Y_c^i} \right) \left( r - \left( \sum_{\forall (i,c) \in G_e \cup S_{new}} \frac{1}{Y_c^i} \right) \right) - 1! (G_{new}=\emptyset) \\ > \left( \sum_{\forall (i,c) \in S_{new}} \frac{1}{Y_c^i} \right) \left( r - \left( \sum_{\forall (i,c) \in G_e \cup S_{new}} \frac{1}{Y_c^i} \right) \right) - 1! (G_{new}=\emptyset) \end{cases}$$

Let $\alpha_H$ denote the alpha parameter for the new queues. For a burst with arrival rate $r$ upto time $t$ to pass, it is required that $t \leq t^i_1$. Then, whether $\alpha_L$ is determined based on the above guideline or chosen based on steady-state allocations, $\alpha_H$ can be expressed as,

$$\alpha_H \geq \frac{1}{Y_c^i \cdot \beta_{p(c)}} \cdot \frac{t \cdot (r - y_c^i) \cdot (1 + \alpha_L)}{B - t \cdot \left( \sum_{\forall (i,c) \in G_e} -y_c^i + \sum_{\forall (i,c) \in S_{new}} (r - y_c^i) \right)}$$

Note that, in Eq. 46, when the denominator is less than or equal to 0, $\alpha_H$ has no meaning, indicating an impossibility.

Finally, FB also scales to multiple priority levels. Our analysis considers a generalized model with arbitrary number of priorities. We observe that, FB’s allocation scheme regardless of number of queues of each priority using the buffer can always guarantee performance for the highest priority. For instance, let $\alpha_x = \alpha_1 + \alpha_2 + \alpha_3 + \ldots + \alpha_n$ where $\alpha_n$ is the maximum $\alpha$ of $n_{th}$ priority, then in order to guarantee a burst of incoming rate $r$ and duration $t$ to pass at all times, $\alpha_H$ (maximum $\alpha$ across the highest priority) can still be derived by simply replacing $\alpha_L$ with $\alpha_x$ in Eq. 44.

One could use the above analysis of transient state and generate analytical plots as shown in Fig. 11b, Fig. 11d (Showing FB), Fig. 11a, Fig. 11c (showing DT). The figures show, for a given $\alpha$ parameter setting, the variation of burst absorption (y axis) when the arrival rate changes. Further different lines correspond to different buffer states (with different number of pre occupied low priority queues). A buffer size ($B$) of 1MB, link capacity of 1Gbps, $\alpha_L = 0.5$ and $\alpha_H = 20$ are used in the equations. Notice that this setting is same as in (§6) enabling a comparison against analysis and simulation results.

We notice that, DT neither has an upper bound nor a lower bound. On the other hand, the strategic allocation of FB allows for a lower bound (corresponding to a buffer state with single queue) and as the arrival rate increases the performance of various buffer states tends towards the lower bound. As a result of such bound in burst absorption, an operator could easily guarantee the absorption of a burst (corresponding to the lower bound).