AC/DC TCP: Virtual Congestion Control Enforcement for Datacenter Networks

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ABSTRACT

Multi-tenant datacenters are successful because tenants can seamlessly port their applications and services to the cloud. Virtual Machine (VM) technology plays an integral role in this success by enabling a diverse set of software to be run on a unified underlying framework. This flexibility, however, comes at the cost of dealing with out-dated, inefficient, or misconfigured TCP stacks implemented in the VMs. This paper investigates if administrators can take control of a VM's TCP congestion control algorithm *without* making changes to the VM or network hardware. We propose AC⚡DC TCP, a scheme that exerts fine-grained control over arbitrary tenant TCP stacks by enforcing per-flow congestion control in the virtual switch (vSwitch). Our scheme is light-weight, flexible, scalable and can police non-conforming flows. In our evaluation the computational overhead of AC⚡DC TCP is less than one percentage point and we show implementing an administrator-defined congestion control algorithm in the vSwitch (i.e., DCTCP) closely tracks its native performance, regardless of the VM's TCP stack.

CCS Concepts

•Networks → Transport protocols;

Keywords

Datacenter Networks; Congestion Control; Virtualization;

1. INTRODUCTION

Multi-tenant datacenters are a crucial component of today's computing ecosystem. Large providers, such as Amazon, Microsoft, IBM, Google and Rackspace, support a diverse set of customers, applications and systems through their public cloud offerings. These offerings are successful in part because they provide efficient performance to a wide-class of applications running on a diverse set of platforms. Virtual Machines (VMs) play a key role in supporting this diversity by allowing customers to run applications in a wide variety of operating systems and configurations.

And while the flexibility of VMs allows customers to easily move a vast array of applications into the cloud, that same flexibility inhibits the amount of control a cloud provider yields over VM behavior. For example, a cloud provider may be able to provide virtual networks or enforce rate limiting on a tenant VM, but it cannot control the VM's TCP/IP stack. As the TCP/IP stack considerably impacts overall network performance, it is unfortunate that cloud providers cannot exert a fine-grained level of control over one of the most important components in the networking stack.

Without control over the VM TCP/IP stack, datacenter networks remain at the mercy of inefficient, out-dated or misconfigured TCP/IP stacks. TCP behavior, specifically congestion control, has been widely studied and many issues have come to light when it is not optimized. For example, network congestion caused by non-optimzed stacks can lead to loss, increased latency and reduced throughput.

Thankfully, recent advances optimizing TCP stacks for datacenters have shown high throughput and low latency can be achieved through novel TCP congestion control algorithms. Works such as DCTCP [3] and TIMELY [43] provide high bandwidth and low latency by ensuring network queues in switches do not fill up. And while these stacks are deployed in many of today's private datacenters [36, 59], ensuring a vast majority of VMs within a public datacenter will update their TCP stacks to a new technology is a daunting, if not impossible, task.

In this paper, we explore how operators can regain authority over TCP congestion control, regardless of the TCP stack running in a VM. Our aim is to allow a cloud provider to utilize advanced TCP stacks, such as DCTCP, without having control over the VM or requiring changes in network hardware. We propose implementing congestion control in the virtual switch (vSwitch) running on each server. Implementing congestion control within a vSwitch has several advan-

SIGCOMM '16, August 22 - 26, 2016, Florianopolis , Brazil

DOI: http://dx.doi.org/10.1145/2934872.2934903

tages. First, vSwitches naturally fit into datacenter network virtualization architectures and are widely deployed [52]. Second, vSwitches can easily monitor and modify traffic passing through them. Today vSwitch technology is mature and robust, allowing for a fast, scalable, and highly-available framework for regaining control over the network.

Implementing congestion control within the vSwitch has numerous challenges, however. First, in order to ensure adoption rates are high, the approach must work without making changes to VMs. Hypervisor-based approaches typically rely on rate limiters to limit VM traffic. Rate limiters implemented in commodity hardware do not scale in the number of flows and software implementations incur high CPU overhead [54]. Therefore, limiting a VM's TCP flows in a fine-grained, dynamic nature at scale (10,000's of flows per server [46]) with limited computational overhead remains challenging. Finally, VM TCP stacks may differ in the features they support (e.g., ECN) or the congestion control algorithm they implement, so a vSwitch congestion control implementation should work under a variety of conditions.

This paper presents Administrator Control over Datacenter TCP (AC⚡DC TCP, or simply AC⚡DC), a new technology that implements TCP congestion control within a vSwitch to help ensure VM TCP performance cannot impact the network in an adverse way. At a high-level, the vSwitch monitors all packets for a flow, modifies packets to support features not implemented in the VM's TCP stack (e.g., ECN) and reconstructs important TCP parameters for congestion control. AC⚡DC runs the congestion control logic specified by an administrator and then enforces an intended congestion window by modifying the receive window (RWND) on incoming ACKs. A policing mechanism ensures stacks cannot benefit from ignoring RWND.

Our scheme provides the following benefits. First, AC⚡DC allows administrators to enforce a uniform, network-wide congestion control algorithm without changing VMs. When using congestion control algorithms tuned for datacenters, this allows for high throughput and low latency. Second, our system mitigates the impact of varying TCP stacks running on the same fabric. This improves fairness and additionally solves the ECN co-existence problem identified in production networks [36, 72]. Third, our scheme is easy to implement, computationally lightweight, scalable, and modular so that it is highly complimentary to performance isolation schemes also designed for virtualized datacenter environments. The contributions of this paper are as follows:

1. The design of a vSwitch-based congestion control mechanism that regains control over the VM's TCP/IP stack without requiring any changes to the VM or network hardware.

2. A prototype implementation to show our scheme is effective, scalable, simple to implement, and has less than one percentage point computational overhead in our tests.

3. A set of results showing DCTCP configured as the host TCP stack provides nearly identical performance to when the host TCP stack varies but DCTCP's congestion control is implemented in the vSwitch. We demonstrate how AC⚡DC can improve throughput, fairness and latency on a shared datacenter fabric.

The outline of this paper is as follows. Background and motivation are discussed in §2. AC⚡DC's design is outlined in §3 and implementation in §4. Results are presented in §5. Related work is surveyed in §6 before concluding.

2. BACKGROUND AND MOTIVATION

This section first gives a brief background of congestion control in the datacenter. Then the motivation for moving congestion control into the vSwitch is presented. Finally, AC⚡DC is contrasted from a class of related bandwidth allocation schemes.

2.1 Datacenter Transport

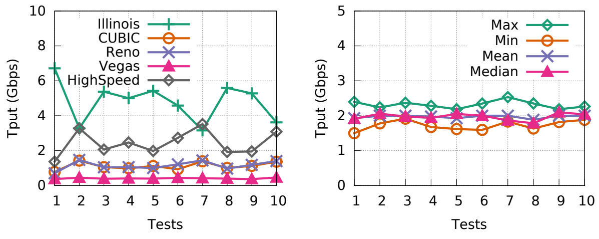
Today's datacenters host applications such as search, advertising, analytics and retail that require high bandwidth and low latency. Network congestion, caused by imperfect load balancing [1], network upgrades or failures, can adversely impact these services. Unfortunately, congestion is not rare in datacenters. For example, recently Google reported congestion-based drops were observed when network utilization approached 25% [59]. Other studies have shown high variance and substantial increase in the 99.9th percentile latency for round-trip times in today's datacenters [45, 69]. Large tail latencies impact customer experience, result in revenue loss [3, 17], and degrade application performance [26, 33]. Therefore, significant motivation exists to reduce congestion in datacenter fabrics.

TCP's congestion control algorithm is known to significantly impact network performance. As a result, datacenter TCP performance has been widely studied and many new protocols have been proposed [3, 35, 43, 62, 71]. Specifically, DCTCP [3] adjusts a TCP sender's rate based on the fraction of packets experiencing congestion. In DCTCP, the switches are configured to mark packets with an ECN bit when their queue lengths exceed a threshold. By proportionally adjusting the rate of the sender based on the fraction of ECN bits received, DCTCP can keep queue lengths low, maintain high throughput, and increase fairness and stability over traditional schemes [3, 36]. For these reasons, we implement DCTCP as the vSwitch congestion control algorithm in AC⚡DC.

2.2 Benefits of AC⚡DC

Allowing administrators to enforce an optimized congestion control without changing the VM is the first major benefit of our scheme. This is an important criteria in untrusted public cloud environments or simply in cases where servers cannot be updated due to a dependence on a specific OS or library. [36]

The next benefit is AC⚡DC allows for *uniform* congestion control to be implemented throughout the datacenter. Unfairness arises when stacks are handled differently in the fabric or when conservative and aggressive stacks coexist.



(a) 5 different CCs. (b) All CUBIC.

Figure 1: Different congestion controls lead to unfairness.

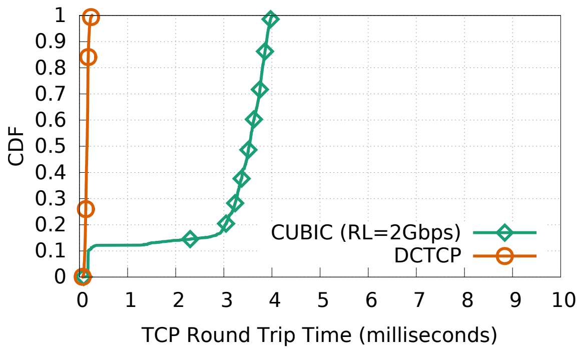


Figure 2: CDF of RTTs showing CUBIC fills buffers.

Studies have shown ECN-capable and ECN-incapable flows do not exist gracefully on the same fabric because packets belonging to ECN-incapable flows encounter severe packet drops when their packets exceed queue thresholds [36, 72]. Additionally, stacks with different congestion control algorithms may not share the same fabric fairly. For example, Figure 1 shows the performance of five different TCP flows on the topology in Figure 7a. Each flow selects a congestion control algorithm available in Linux: CUBIC [29], Illinois [41], HighSpeed [21], New Reno [22] and Vegas [13]. Figure 1a shows aggressive stacks such as Illinois and HighSpeed achieve higher bandwidth and thus fairness is worse than all flows using the same stack (Figure 1b).

Another benefit of AC⚡DC is it allows for different congestion control algorithms to be assigned on a per-flow basis. A vSwitch-based approach can assign WAN flows to a congestion control algorithm that optimizes WAN performance [20, 63] and datacenter flows to one that optimizes datacenter performance, even if these flows originate from the same VM (e.g., a webserver). Additionally, as shown in §3.4, a flexible congestion control algorithm can provide relative bandwidth allocations to flows. This is useful when tenants or administrators want to prioritize flows assigned to the same quality-of-service class. In short, adjusting congestion control algorithms on a per-flow basis allows for enhanced flexibility and performance.

Finally, congestion control is not difficult to port. While the entire TCP stack may seem complicated and prone to high overhead, the congestion control aspect of TCP is relatively light-weight and simple to implement. Indeed, studies show most TCP overhead comes from buffer management [42], and in our evaluation the computational overhead of AC⚡DC is less than one percentage point. Porting is also made easy because congestion control implementations in Linux are modular: DCTCP's congestion control resides in `tcp_dctcp.c` and is only about 350 lines of code. Given the simplicity of congestion control, it is not hard to move its functionality to another layer.

2.3 Tenant-Level Bandwidth Allocation

While AC⚡DC enforces congestion control, transport layer schemes do not provide fair bandwidth allocation among tenants because a tenant with more concurrent flows can obtain a higher share of bandwidth. In order to provide performance isolation in the network, datacenter operators can implement a variety of bandwidth allocation schemes by either guaranteeing or proportionally allocating bandwidth for tenants [10, 28, 33, 34, 38, 53, 56, 58, 73]. Some of these schemes share high-level architectural similarities to AC⚡DC. For example, EyeQ [34] handles bandwidth allocation at the edge with a work-conserving distributed bandwidth arbitration scheme. It enforces rate limits at senders based on feedback generated by receivers. Similarly, Seawall [58] provides proportional bandwidth allocation to a VM or application by forcing all traffic through a congestion-controlled tunnel configured through weights and endpoint feedback.

The fundamental difference between these schemes and our approach is the design goals determine the granularity on which they operate. Performance isolation schemes generally focus on *bandwidth allocation on a VM-level* and are not sufficient to relieve the network of congestion because they do not operate on flow-level granularity. For example, the single switch abstraction in EyeQ [34] and Gatekeeper [56] explicitly assumes a congestion-free fabric for optimal bandwidth allocation between pairs of VMs. This abstraction doesn't hold in multi-pathed topologies when failure, traffic patterns or ECMP hash collisions [1] cause congestion in the core. Communication between a pair of VMs may consist of multiple flows, each of which may traverse a distinct path. Therefore, enforcing rate limits on a VM-to-VM level is too coarse-grained to determine how specific flows should adapt in order to mitigate the impact of congestion on their paths. Furthermore, a scheme like Seawall [58] cannot be easily applied to flow-level granularity because its rate limiters are unlikely to scale in the number of flows at high networking speeds [54] and its allocation scheme does not run at fine-grained round-trip timescales required for effective congestion control. Additionally, Seawall violates our design principle by requiring VM modifications to implement congestion-controlled tunnels.

The above points are not intended to criticize any given work, but rather support the argument that it is important for a cloud provider to enforce *both* congestion control and bandwidth allocation. Congestion control can ensure low latency and high utilization, and bandwidth allocation can provide tenant-level fairness. Bandwidth allocation schemes alone are insufficient to mitigate congestion because certain TCP stacks aggressively fill switch buffers. Consider a simple example where five flows send simultaneously on the 10

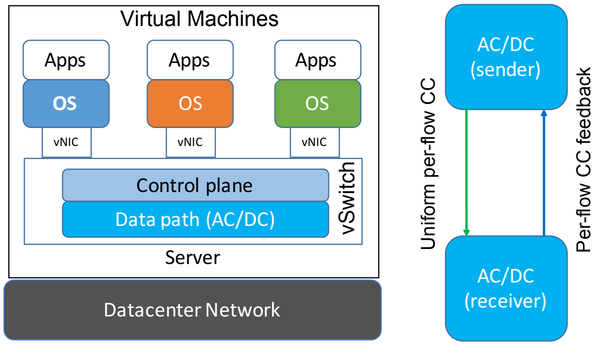


Figure 3: AC⚡DC high-level architecture.

Gbps topology in Figure 7a. Even when the bandwidth is allocated "perfectly" at 2 Gbps per flow, CUBIC saturates the output port's buffer and leads to inflated round-trip times (RTTs) for traffic sharing the same link. Figure 2 shows these RTTs for CUBIC and also DCTCP, which is able to keep queueing latencies, and thus RTTs, low even though no rate limiting was applied. Therefore, it is important for cloud providers to exercise a desired congestion control.

In summary, our vision regards enforcing tenant congestion control and bandwidth allocation as *complimentary* and we claim an administrator should be able to combine any congestion control (e.g., DCTCP) with any bandwidth allocation scheme (e.g., EyeQ). Flow-level congestion control and tenant performance isolation need not be solved by the same scheme, so AC⚡DC's design goal is to be modular in nature so it can co-exist with any bandwidth allocation scheme and its associated rate limiter (and also in the absence of both).

3. DESIGN

This section provides an overview of AC⚡DC's design. First, we show how basic congestion control state can be inferred in the vSwitch. Then we study how to implement DCTCP. Finally, we discuss how to enforce congestion control in the vSwitch and provide a brief overview of how per-flow differentiation can be implemented.

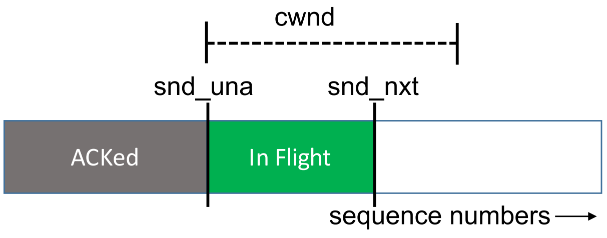


Figure 4: Variables for TCP sequence number space.

3.1 Obtaining Congestion Control State

Figure 3 shows the high-level structure of AC⚡DC. Since it is implemented in the datapath of the vSwitch, all traffic can be monitored. The sender and receiver modules work together to implement per-flow congestion control (CC).

We first demonstrate how congestion control state can be inferred. Figure 4 provides a visual of the TCP sequence number space. The snd_una variable is the first byte that has been sent, but not yet ACKed. The snd_nxt variable is the next byte to be sent. Bytes between snd_una and snd_nxt are in flight. The largest number of packets that can be sent and unacknowledged is bounded by CWND. snd_una is simple to update: each ACK contains an acknowledgement number (ack_seq), and snd_una is updated when ack_seq > snd_una. When packets traverse the vSwitch from the VM, snd_nxt is updated if the sequence number is larger than the current snd_nxt value. Detecting loss is also relatively simple. If ack_seq ≤ snd_una, then a local dupack counter is updated. Timeouts can be inferred when snd_una < snd_nxt and an inactivity timer fires. The initial CWND is set to a default value of 10 [14]. With this state, the vSwitch can determine appropriate CWND values for canonical TCP congestion control schemes. We omit additional details in the interest of space.

3.2 Implementing DCTCP

This section discusses how to obtain DCTCP state and perform its congestion control.

ECN marking DCTCP requires flows to be ECN-capable, but the VM's TCP stack may not support ECN. Thus, all egress packets are marked to be ECN-capable on the sender module. When the VM's TCP stack does not support ECN, all ECN-related bits on ingress packets are stripped at the sender and receiver modules in order to preserve the original TCP settings. When the VM's TCP stack does support ECN, the AC⚡DC modules strip the congestion encountered bits in order to prevent the VM's TCP stack from decreasing rates too aggressively (recall DCTCP adjusts CWND proportional to the fraction of congested packets, while traditional schemes conservatively reduce CWND by half). A reserved bit in the header is used to determine if the VM's TCP stack originally supported ECN.

Obtaining ECN feedback In DCTCP, the fraction of packets experiencing congestion needs to be reported to the sender. Since the VM's TCP stack may not support ECN, the AC⚡DC receiver module monitors the total and ECN-marked bytes received for a flow. Receivers piggy-back the reported totals on ACKs by adding an additional 8 bytes as a TCP Option. This is called a Piggy-backed ACK (PACK). The PACK is created by moving the IP and TCP headers into the ACK packet's skb headroom [60]. The totals are inserted into the vacated space and the memory consumed by the rest of the packet (i.e., the payload) is left as is. The IP header checksum, IP packet length and TCP Data Offset fields are recomputed and the TCP checksum is calculated by the NIC. The PACK option is stripped at the sender so it is not exposed to the VM's TCP stack.

If adding a PACK creates a packet larger than the MTU, the NIC offload feature (i.e., TSO) will replicate the feedback information over multiple packets, which skews the feedback. Therefore, a dedicated feedback packet called a

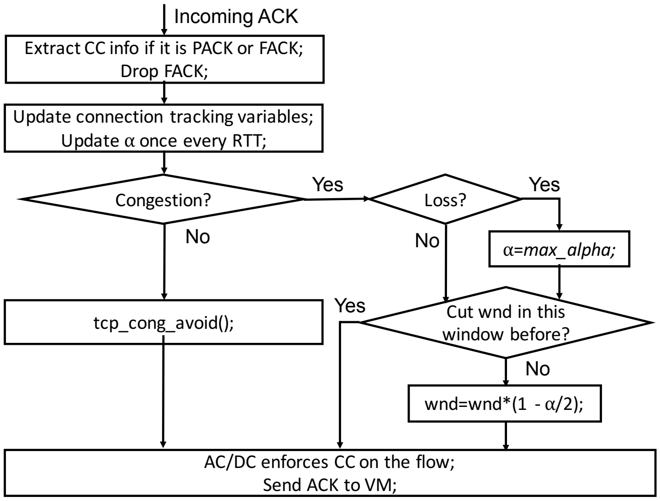

Incoming ACK
Extract CC info if it is PACK or FACK; Drop FACK;
Update connection tracking variables; Update α once every RTT;
Congestion?
Yes
No
Loss?
Yes
No
α=max_alpha;
tcp_cong_avoid();
Yes
Cut wnd in this window before?
No
wnd=wnd*(1 - α/2);
AC/DC enforces CC on the flow; Send ACK to VM;

Figure 5: DCTCP congestion control in AC⚡DC.

Fake ACK (FACK) is sent when the MTU will be violated. The FACK is sent in addition to the real TCP ACK. FACKs are also discarded by the sender after logging the included data. In practice, most feedback takes the form of PACKs.

DCTCP congestion control Once the fraction of ECN-marked packets is obtained, implementing DCTCP's logic is straightforward. Figure 5 shows the high-level design. First, congestion control (CC) information is extracted from FACKs and PACKs. Connection tracking variables (described in §3.1) are updated based on the ACK. The variable α is an EWMA of the fraction of packets that experienced congestion and is updated roughly once per RTT. If congestion was not encountered (no loss or ECN), then `tcp_cong_avoid` advances `CWND` based on TCP New Reno's algorithm, using slow start or congestion avoidance as needed. If congestion was experienced, then `CWND` must be reduced. DCTCP's instructions indicate the window should be cut at most once per RTT. Our implementation closely tracks the Linux source code, and additional details can be referenced externally [3, 11].

3.3 Enforcing Congestion Control

There must be a mechanism to ensure a VM's TCP flow adheres to the `CWND` determined in the vSwitch. Luckily, TCP provides built-in functionality that can be reprovisioned for AC⚡DC. Specifically, TCP's flow control allows a receiver to advertise the amount of data it is willing to process via a receive window (`RWND`). Similar to other works [37, 61], the vSwitch overwrites `RWND` with its calculated `CWND`. In order to preserve TCP semantics, this value is overwritten only when it is smaller than the packet's original `RWND`. The VM's flow then uses min(`CWND`, `RWND`) to limit how many packets it can send.

This enforcement scheme must be compatible with TCP receive window scaling to work in practice. Scaling ensures `RWND` does not become an unnecessary upper-bound in high bandwidth-delay networks and provides a mechanism to left-shift `RWND` by a window scaling factor [31]. The window scaling factor is negotiated during TCP's handshake, so AC⚡DC monitors handshakes to obtain this value. Calculated congestion windows are adjusted accordingly. TCP receive window auto-tuning [57] manages buffer state and thus is an orthogonal scheme AC⚡DC can safely ignore.

Ensuring a VM's flow adheres to `RWND` is relatively simple. The vSwitch calculates a new congestion window every time an ACK is received. This value provides a bound on the number of bytes the VM's flow is now able to send. VMs with unaltered TCP stacks will naturally follow our enforcement scheme because the stacks will simply follow the standard. Flows that circumvent the standard can be policed by dropping excess packets not allowed by the calculated congestion window, which incentivizes tenants to respect the standard.

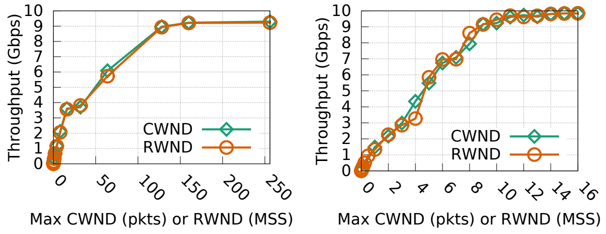
While simple, this scheme provides a surprising amount of flexibility. For example, TCP enables a receiver to send a TCP Window Update to update `RWND` [6]. AC⚡DC can create these packets to update windows without relying on ACKs. Additionally, the sender module can generate duplicate ACKs to to trigger retransmissions. This is useful when the VM's TCP stack has a larger timeout value than AC⚡DC (e.g., small timeout values have been recommended for incast [67]). Another useful feature is when AC⚡DC allows a TCP stack to send *more* data. This can occur when a VM TCP flow aggressively reduces its window when ECN feedback is received. By removing ECN feedback in AC⚡DC, the VM TCP stack won't reduce `CWND`. In a similar manner, DCTCP limits loss more effectively than aggressive TCP stacks. Without loss or ECN feedback, VM TCP stacks grow `CWND`. This causes AC⚡DC's `RWND` to become the limiting window, and thus AC⚡DC can increase a flow's rate instantly when `RWND` < `CWND`. Note, however, AC⚡DC cannot force a connection to send more data than the VM's `CWND` allows.

Another benefit of AC⚡DC is that it scales in the number of flows. Traditional software-based rate limiting schemes, like Linux's Hierarchical Token Bucket, incur high overhead due to frequent interrupts and contention [54] and therefore do not scale gracefully. NIC or switch-based rate limiters are low-overhead, but typically only provide a handful of queues. Our enforcement algorithm does not rate limit or buffer packets because it exploits TCP flow control. Therefore, rate limiting schemes can be used at a coarser granularity (e.g., VM-level).

Finally, we outline AC⚡DC's limitations. Since AC⚡DC relies on sniffing traffic, schemes that encrypt TCP headers (e.g., IPSec) are not supported. Our implementation only supports TCP, but we believe it can be extended to handle UDP similar to prior schemes [34, 58]. Implementing per-flow DCTCP-friendly UDP tunnels and studying its impact remains future work, however. And finally, while MPTCP supports per-subflow `RWND` [23], it is not included in our case study and a more detailed analysis is future work.

3.4 Per-flow Differentiation

AC⚡DC can assign different congestion control algorithms on a per-flow basis. This gives administrators additional



(a) MTU = 1.5KB.

(b) MTU = 9KB.

Figure 6: Using RWND can effectively control throughput.

flexibility and control by assigning flows to specific congestion control algorithms based on policy. For example, flows destined to the WAN may be assigned CUBIC and flows destined within the datacenter may be set to DCTCP.

Administrators can also enable per-flow bandwidth allocation schemes. A simple scheme enforces an upper-bound on a flow's bandwidth. Traditionally, an upper-bound on a flow's CWND can be specified by snd_cwnd_clamp in Linux. AC⚡DC can provide similar functionality by bounding RWND. Figure 6 shows the behavior is equivalent. This graph can also be used to convert a desired upper-bound on bandwidth into an appropriate maximum RWND (the graph is created on an uncongested link to provide a lower bound on RTT).

In a similar fashion, administrators can assign different bandwidth priorities to flows by altering the congestion control algorithm. Providing differentiated services via congestion control has been studied [58, 68]. Such schemes are useful because networks typically contain only a limited number of service classes and bandwidth may need to be allocated on a finer-granularity. We propose a unique priority-based congestion control algorithm for AC⚡DC. Specifically, DCTCP's congestion control algorithm is modified to incorporate a priority, $\beta \in [0, 1]$:

$$\text{rwnd} = \text{rwnd}(1 - (\alpha - \frac{\alpha\beta}{2})) \tag{1}$$

Higher values of β give higher priority. When $\beta = 1$, Equation 1 simply converts to DCTCP congestion control. When $\beta = 0$, flows aggressively back-off (RWND is bounded by 1 MSS to avoid starvation). This equation alters multiplicative decrease instead of additive increase because increasing RWND cannot guarantee the VM flow's CWND will allow the flow to increase its sending rate.

4. IMPLEMENTATION

This section outlines relevant implementation details. We implemented AC⚡DC in Open vSwitch (OVS) v2.3.2 [50] and added about 1200 lines of code (many are debug/comments). A high-level overview follows. A hash table is added to OVS, and flows are hashed on a 5-tuple (IP addresses, ports and VLAN) to obtain a flow's state. The flow entry state is 320 bytes and is used to maintain the congestion control state mentioned in §3. SYN packets are used to create flow entries, and FIN packets, coupled with a course-grained garbage collector, are used to remove flow entries. Other TCP packets, such as data and ACKs, trigger updates to flow entries. There are many more table lookup operations (to update flow state) than table insertions or deletions (to add/remove flows). Thus, Read-Copy-Update (RCU) hash tables [27] are used to enable efficient lookups. Additionally, individual spinlocks are used on each flow entry in order to allow for multiple flow entries to be updated simultaneously.

Putting it together, the high-level operation on a data packet is as follows. An application on the sender generates a packet that is pushed down the network stack to OVS. The packet is intercepted in ovs_dp_process_packet, where the packet's flow entry is obtained from the hash table. Sequence number state is updated in the flow entry and ECN bits are set on the packet if needed (see §3). If the packet's header changes, the IP checksum is recalculated. Note TCP checksumming is offloaded to the NIC. The packet is sent over the wire and received at the receiver's OVS. The receiver updates congestion-related state, strips off ECN bits, recomputes the IP checksum, and pushes the packet up the stack. ACKs eventually triggered by the packet are intercepted, where the congestion information is added. Once the ACK reaches the sender, the AC⚡DC module uses the congestion information to compute a new congestion window. Then it modifies RWND with a memcpy, strips off ECN feedback and recomputes the IP checksum before pushing the packet up the stack. Since TCP connections are bi-directional, two flow entries are maintained for each connection.

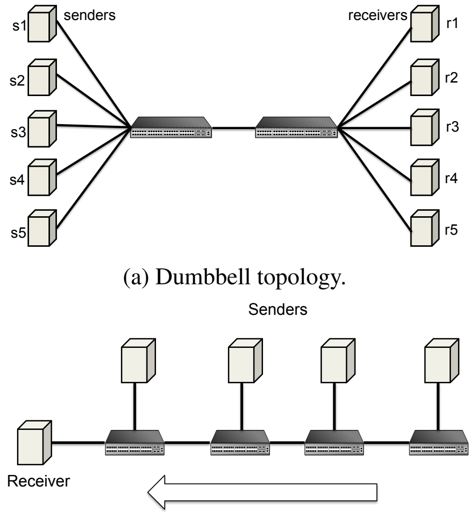
Our experiments in §5.1 show the CPU overhead of AC⚡DC is small and several implementation details help reduce computational overhead. First, OVS sits above NIC offloading features (i.e., TSO and GRO/LRO) in the networking stack. Briefly, NIC offloads allow the host to pass large data segments along the TCP/IP stack and only deal with MTU-sized packets in the NIC. Thus, AC⚡DC operates on a segment, rather than a per-packet, basis. Second, congestion control is a relatively simple algorithm, and thus the computational burden is not high. Finally, while AC⚡DC is implemented in software, it may be possible to further reduce the overhead with a NIC implementation. Today, "smart-NICs" implement OVS-offload functionality [40, 47], naturally providing a mechanism to reduce overhead and support hypervisor bypass (e.g., SR-IOV).

5. RESULTS

This section quantifies the effects of AC⚡DC and determines if the performance of DCTCP implemented in the vSwitch (i.e., AC⚡DC) is equivalent to the performance of DCTCP implemented in the host TCP stack.

Testbed The experiments are conducted on a physical testbed with 17 IBM System x3620 M3 servers (6-core Intel Xeon 2.53GHz CPUs, 60GB memory) and Mellanox ConnectX-2 EN 10GbE NICs. Our switches are IBM G8264, each with a buffer of 9MB shared by forty-eight 10G ports.

System settings We run Linux kernel 3.18.0 which implements DCTCP as a pluggable module. We set RTO_{min} to 10



(a) Dumbbell topology.

(b) Multi-hop, multi-bottleneck (parking lot) topology.

Figure 7: Experiment topologies.

ms [36, 67] and set `tcp_no_metrics_save`, `tcp_sack` and `tcp_low_latency` to 1. Results are obtained with MTU sizes of 1.5KB and 9KB, as networks typically use one of these settings. Due to space constraints, a subset of the results are presented and unless otherwise noted, the MTU is set to 9KB.

Experiment details To understand AC/DC performance, three different congestion control configurations are considered. The baseline scheme, referred to as *CUBIC*, configures the host TCP stack as CUBIC (Linux's default congestion control), which runs on top of an unmodified version of OVS. Our goal is to be similar to *DCTCP*, which configures the host TCP stack as DCTCP and runs on top of an unmodified version of OVS. Our scheme, *AC/DC*, configures the host TCP stack as CUBIC (unless otherwise stated) and implements DCTCP congestion control in OVS. In DCTCP and AC/DC, WRED/ECN is configured on the switches. In CUBIC, WRED/ECN is not configured.

The metrics used are: TCP RTT (measured by sockperf [48]), TCP throughput (measured by iperf), loss rate (by collecting switch counters) and Jain's fairness index [32]. In §5.2, flow completion time (FCT) [19] is used to quantify application performance. All benchmark tools are run in a container on each server, rather than in a VM.

5.1 Microbenchmarks

We first evaluate AC/DC's performance using a set of microbenchmarks. The microbenchmarks are conducted on topologies shown in Figure 7.

Canonical topologies We aim to understand the performance of our scheme on two simple topologies. First, one long-lived flow is started per server pair (s_i to r_i) in Figure 7a. The average per-flow throughput of AC/DC, DCTCP and CUBIC are all 1.98Gbps. Figure 8 is a CDF of the RTT from the same test. Here, increases in RTT are caused by queueing delay in the switch. AC/DC achieves comparable RTT with DCTCP and significantly outperforms CUBIC.

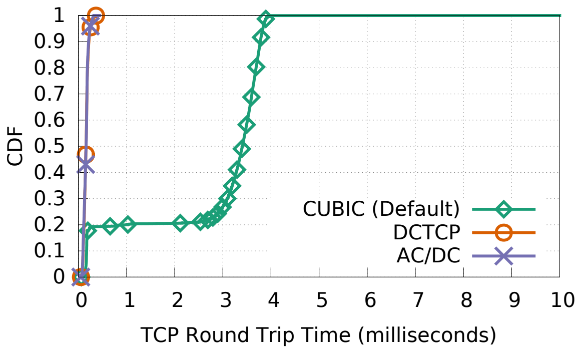
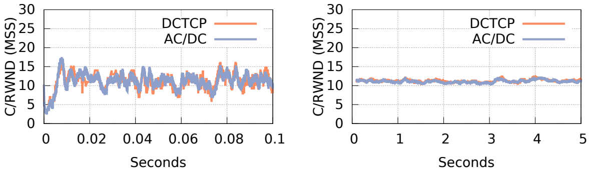


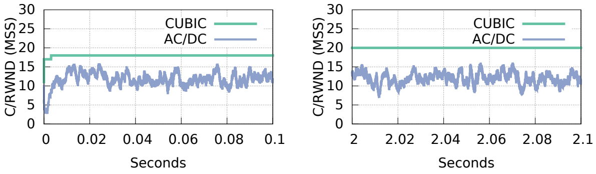
Figure 8: RTT of schemes on dumbbell topology.



(a) First 100 ms of a flow.

(b) Moving average.

Figure 9: AC/DC's `RWND` tracks DCTCP's `CWND` (1.5KB MTU).



(a) Starting from 0 sec.

(b) Starting from 2 sec.

Figure 10: Who limits TCP throughput when AC/DC is run with CUBIC? (1.5 KB MTU)

Second, each sender in Figure 7b starts a long-lived flow to the receiver. Each flow traverses a different number of bottleneck links. CUBIC has an average per-flow throughput of 2.48Gbps with a Jain's fairness index of 0.94, and both DCTCP and AC/DC obtain an average throughput of 2.45Gbps with a fairness index of 0.99. The 50th and 99.9th percentile RTT for AC/DC (DCTCP, CUBIC) are 124μs (136μs, 3.3ms) and 279μs (301μs, 3.9ms), respectively.

Tracking window sizes Next, we aim to understand how accurately AC/DC tracks DCTCP's performance at a finer level. The host's TCP stack is set to DCTCP and our scheme runs in the vSwitch. We repeat the experiment in Figure 7a and measure the `RWND` calculated by AC/DC. Instead of over-writing the `RWND` value in the ACKs, we simply log the value to a file. Thus, congestion is enforced by DCTCP and we can capture DCTCP's `CWND` by using `tcpprobe` [65]. We align the `RWND` and `CWND` values by timestamps and sequence numbers and show a timeseries in Figure 9. Figure 9a shows both windows for the first 100 ms of a flow and shows that AC/DC's calculated window closely tracks

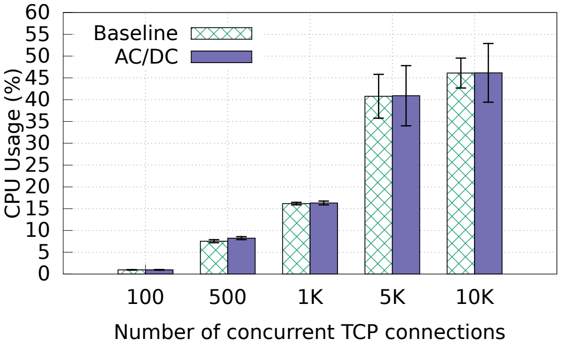


Figure 11: CPU overhead: sender side (1.5KB MTU).

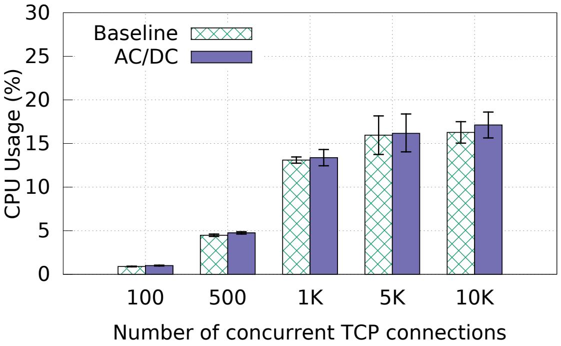


Figure 12: CPU overhead: receiver side (1.5KB MTU).

DCTCP's. Figure 9b shows the windows over a 100ms moving average are also similar. This suggests it is possible to accurately recreate congestion control in the vSwitch. These results are obtained with 1.5KB MTU. Trends for 9KB MTU are similar but the window sizes are smaller.

We were also interested to see how often AC⚡DC's congestion window takes effect. We rerun the experiment (MTU is still 1.5KB), but set the host TCP stack to CUBIC. The `RWND` computed by AC⚡DC is both written into the ACK and logged to a file. We again use `tcpprobe` to measure CUBIC's `CWND`. Figure 10 is a timeseries (one graph from the start of the experiment and one graph 2 seconds in) that shows AC⚡DC's congestion control algorithm is indeed the limiting factor. In the absence of loss or ECN markings, traditional TCP stacks do not severely reduce `CWND` and thus AC⚡DC's `RWND` becomes the main enforcer of a flow's congestion control. Because DCTCP is effective at reducing loss and AC⚡DC hides ECN feedback from the host TCP stack, AC⚡DC's enforcement is applied often.

CPU overhead We measure the CPU overhead of AC⚡DC by connecting two servers to a single switch. Multiple simultaneous TCP flows are started from one server to the other and the total CPU utilization is measured on the sender and receiver using `sar`. Each flow is given time to perform the TCP handshake and when all are connected, each TCP client sends with a demand of 10 Mbps by sending 128KB bursts every 100 milliseconds (so 1,000 connections saturate the 10 Gbps link). The system-wide CPU overhead of AC⚡DC compared to the system-wide CPU overhead of baseline (i.e., just OVS) is shown for the sender in Figure 11 and the receiver in Figure 12. Error bars show standard deviation over 50 runs. While AC⚡DC increases CPU usage in all cases, the increase is negligible. The largest difference is less than one percentage point: the baseline and AC⚡DC have 16.27% and 17.12% utilization, respectively for 10K flows at the receiver. The results are shown with 1.5KB MTU because smaller packets incur higher overhead. Note experiments with 9KB MTU have similar trends.

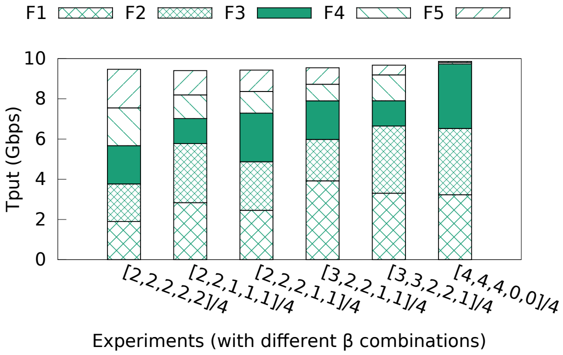


Figure 13: AC⚡DC provides differentiated throughput via QoS-based CC. β values are defined on a 4-point scale.

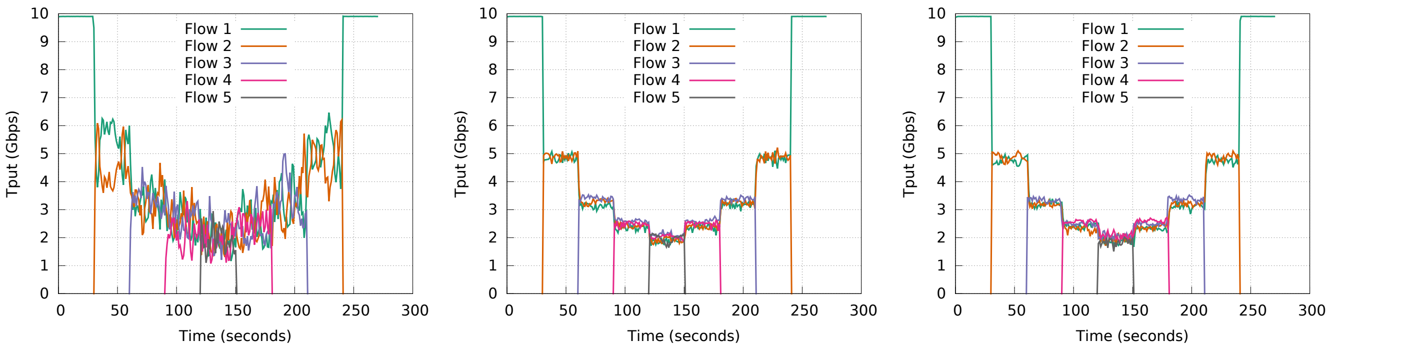
AC⚡DC flexibility AC⚡DC aims to provide a degree of control and flexibility over tenant TCP stacks. We consider two cases. First, AC⚡DC should work effectively, regardless of the tenant TCP stack. Table 1 shows the performance of our scheme when various TCP congestion control algorithms are configured on the host. Data is collected over 10 runs lasting 20 seconds each on the dumbbell topology (Figure 7a). The first two rows of the table, CUBIC* and DCTCP*, show the performance of each stack with an unmodified OVS. The next six rows show the performance of a given host stack with AC⚡DC running DCTCP in OVS. The table shows AC⚡DC can effectively track the performance of DCTCP*, meaning it is compatible with popular delay-based (Vegas) and loss-based (Reno, CUBIC, etc) stacks.

Second, AC⚡DC enables an administrator to assign different congestion control algorithms on a per-flow basis. For example, AC⚡DC can provide the flexibility to implement QoS through differentiated congestion control. We fix the host TCP stack to CUBIC and alter AC⚡DC's congestion control for each flow by setting the β value (in Equation 1) for each flow in the dumbbell topology. Figure 13 shows the throughput achieved by each flow, along with its β setting. AC⚡DC is able to provide relative bandwidth allocation to each flow based on β. Flows with the same β value get similar throughputs and flows with higher β values obtain higher throughput. The latencies (not shown) remain consistent with previous results.

Fairness Three different experiments are used to demonstrate fairness. First, we show AC⚡DC can mimic DCTCP's behavior in converging to fair throughputs. We repeat the experiment originally performed by Alizadeh [3] and Judd [36] by adding a new flow every 30 seconds on a bottleneck link

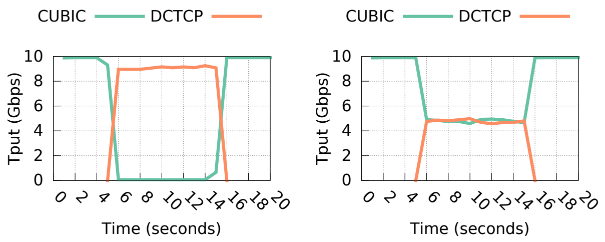
CC Variants	50th percentile RTT (µs)		99th percentile RTT (µs)		Avg Tput (Gbps)		Fairness Index	
	mtu=1.5KB	mtu=9KB	mtu=1.5KB	mtu=9KB	mtu=1.5KB	mtu=9KB	mtu=1.5KB	mtu=9KB
CUBIC*	3232	3448	3641	3865	1.89	1.98	0.85	0.98
DCTCP*	128	142	232	259	1.89	1.98	0.99	0.99
CUBIC	128	142	231	252	1.89	1.98	0.99	0.99
Reno	120	149	235	248	1.89	1.97	0.99	0.99
DCTCP	129	149	232	266	1.88	1.98	0.99	0.99
Illinois	134	152	215	262	1.89	1.97	0.99	0.99
HighSpeed	119	147	224	252	1.88	1.97	0.99	0.99
Vegas	126	143	216	251	1.89	1.97	0.99	0.99

Table 1: AC/DC works with many congestion control variants. Legend: CUBIC*: CUBIC + standard OVS, switch WRED/ECN marking off. DCTCP*: DCTCP + standard OVS, switch WRED/ECN marking on. Others: different CCs + AC/DC, switch WRED/ECN marking on.



(a) CUBIC convergence test. (b) DCTCP convergence test. (c) AC/DC convergence test.

Figure 14: Convergence tests: flows are added, then removed, every 30 secs. AC/DC performance matches DCTCP.



(a) Default. (b) AC/DC.

Figure 15: (a) CUBIC gets little throughput when competing with DCTCP. (b) With AC/DC, CUBIC and DCTCP flows get fair share.

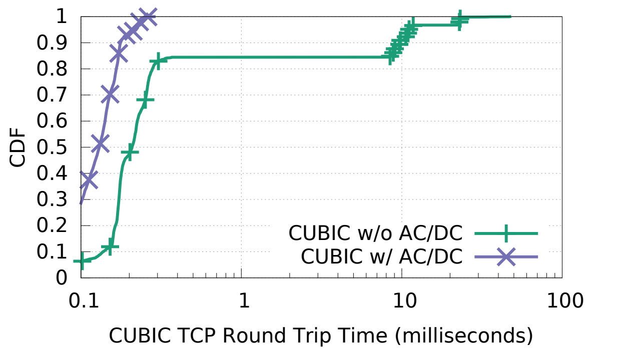
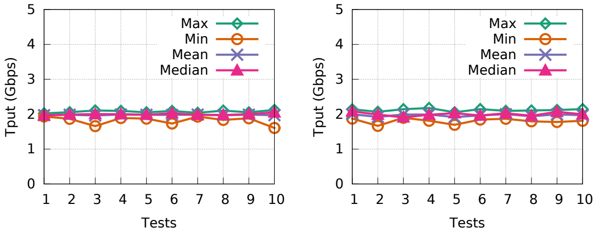


Figure 16: CUBIC experiences high RTT when competing with DCTCP. AC/DC fixes this issue.

and then reversing the process. The result is shown in Figure 14. Figure 14a shows CUBIC's problems converging to fair allocations. Figures 14b and 14c show DCTCP and AC/DC performance, respectively. AC/DC tracks DCTCP's behavior. CUBIC's drop rate is 0.17% while DCTCP's and AC/DC's is 0%.

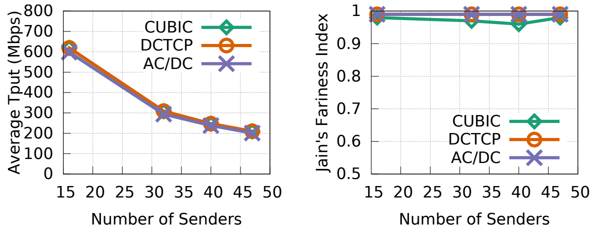
The second experiment is also repeated from Judd's paper [36]. ECN-capable and non-ECN-capable flows do not coexist well because switches drop non-ECN packets when the queue length is larger than the marking threshold. Figure 15a shows the throughput of CUBIC suffers when CUBIC (with no ECN) and DCTCP (with ECN) traverse the same bottleneck link. Figure 15b shows AC/DC alleviates this problem because it forces all flows to become ECN-capable. Figure 16 shows CUBIC's RTT is extremely high in the first case because switches drop non-ECN packets (the loss rate is 0.18%) and thus there is a significant number of retransmissions. However, AC/DC eliminates this issue and reduces latency.

The last experiment examines the impact of having multiple TCP stacks on the same fabric. Five flows with different congestion control algorithms (CUBIC, Illinois, HighSpeed, New Reno and Vegas) are started on the dumbbell topology. This is the same experiment as in Figure 1. Fig-



(a) All DCTCP. (b) 5 different CCs (AC⚡DC).

Figure 17: AC⚡DC improves fairness when VMs implement different CCs. DCTCP performance shown for reference.



(a) Average throughput. (b) Fairness.

Figure 18: Many to one incast: throughput and fairness.

ure 17a shows what happens if all flows are configured to use DCTCP and Figure 17b shows when the five different stacks traverse AC⚡DC. We can see AC⚡DC closely tracks the ideal case of all flows using DCTCP, and AC⚡DC and DCTCP provide better fairness than all CUBIC (Figure 1b).

5.2 Macrobenchmarks

In this section we attach all servers to a single switch and run a variety of workloads to better understand how well AC⚡DC tracks DCTCP's performance. Experiments are run for 10 minutes. A simple TCP application sends messages of specified sizes to measure FCTs.

Incast In this section, we evaluate incast scenarios. To scale the experiment, 17 physical servers are equipped with four NICs each and one flow is allocated per NIC. In this way, incast can support up to 47-to-1 fan-in (our switch only has 48 ports). We measure the extent of incast by increasing the number of concurrent senders to 16, 32, 40 and 47. Figure 18 shows throughput and fairness results. Both DCTCP and AC⚡DC obtain a fairness index greater than 0.99 and get comparable throughput as CUBIC. Figure 19 shows the RTT and packet drop rate results. When there are 47 concurrent senders, DCTCP can reduce median RTT by 82% and AC⚡DC can reduce by 97%; DCTCP can reduce 99.9th percentile RTT by 94% and AC⚡DC can reduce by 98%. Both DCTCP and AC⚡DC have 0% packet drop rate. It is curious that AC⚡DC's performance is better than DCTCP when the number of senders increases (Figure 19a). The Linux DCTCP code puts a lower bound of 2 packets on `CWND`. In incast, we have up to 47 concurrent competing flows and the network's MTU size is 9KB. In this case, the lower bound is too high, so DCTCP's RTT increases gradually with the number of senders. This issue was also found

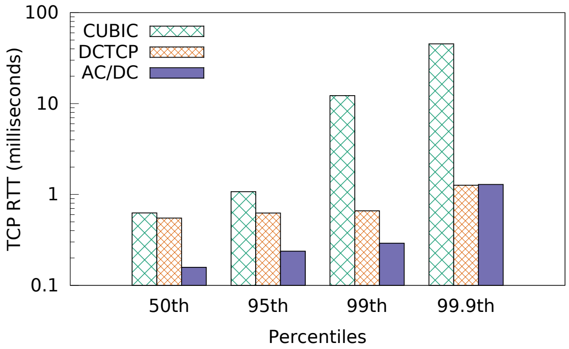


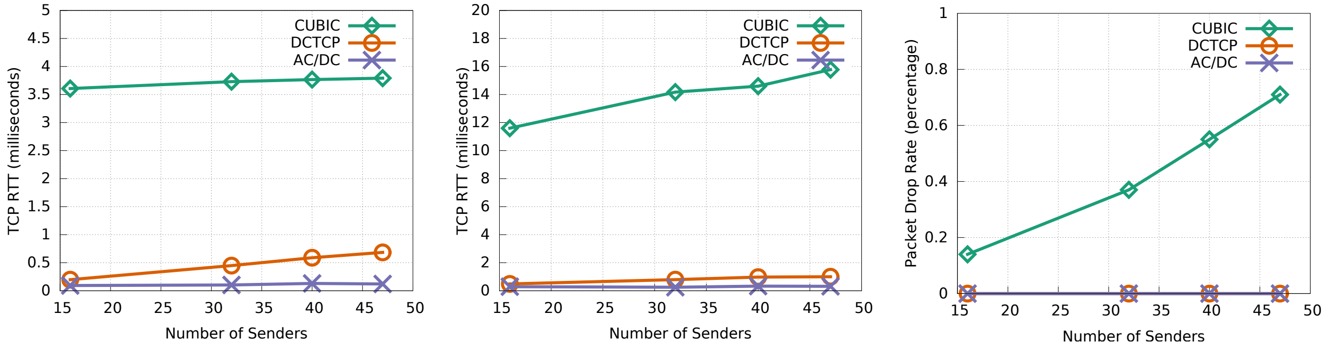
Figure 20: TCP RTT when almost all ports are congested.

in [36]. AC⚡DC controls `RWND` (which is in bytes) instead of `CWND` (which is in packets) and `RWND`'s lowest value can be much smaller than 2*MSS. We verified modifying AC⚡DC's lower bound caused identical behavior.

The second test aims to put pressure on the switch's dynamic buffer allocation scheme, similar to an experiment in the DCTCP paper [3]. To this end, we aim to congest every switch port. The 48 NICs are split into 2 groups: group A and B. Group A has 46 NICs and B has 2 (denoted B_1 and B_2). Each of the 46 NICs in A sends and receives 4 concurrent flows within A (i.e., NIC i sends to $[i+1, i+4]$ mod 46). Meanwhile, all of the NICs in A send to B_1, creating a 46-to-1 incast. This workload congests 47 out of 48 switch ports. We measure the RTT between B_2 and B_1 (i.e., RTT of the traffic traversing the most congested port) and the results are shown in Figure 20. The average throughputs for CUBIC, DCTCP, and AC⚡DC are 214, 214 and 201 Mbps respectively, all with a fairness index greater than 0.98. CUBIC has an average drop rate of 0.34% but the most congested port has a drop rate as high as 4%. This is why the 99.9th percentile RTT for CUBIC is very high. The packet drop rate for both DCTCP and AC⚡DC is 0%.

Concurrent stride workload In concurrent stride, 17 servers are attached to a single switch. Each server i sends a 512MB flow to servers [i + 1, i + 4] mod 17 in sequential fashion to emulate background traffic. Simultaneously, each server i sends 16KB messages every 100 ms to server $(i+8)$ mod 17. The FCT for small flows (16KB) and background flows (512MB) are shown in Figure 21. For small flows, DCTCP and AC⚡DC reduce the median FCT by 77% and 76% respectively. At the 99.9th percentile, DCTCP and AC⚡DC reduce FCT by 91% and 93%, respectively. For background flows, DCTCP and AC⚡DC offer similar completion times. CUBIC has longer background FCT because its fairness is not as good as DCTCP and AC⚡DC.

Shuffle workload In shuffle, each server sends 512MB to every other server in random order. A sender sends at most 2 flows simultaneously and when a transfer is finished, the next one is started until all transfers complete. Every server i also sends a 16 KB message to server $(i+8)$ mod 17 every 100 ms. This workload is repeated for 30 runs. The FCT for each type of flow is shown in Figure 22. For small flows,

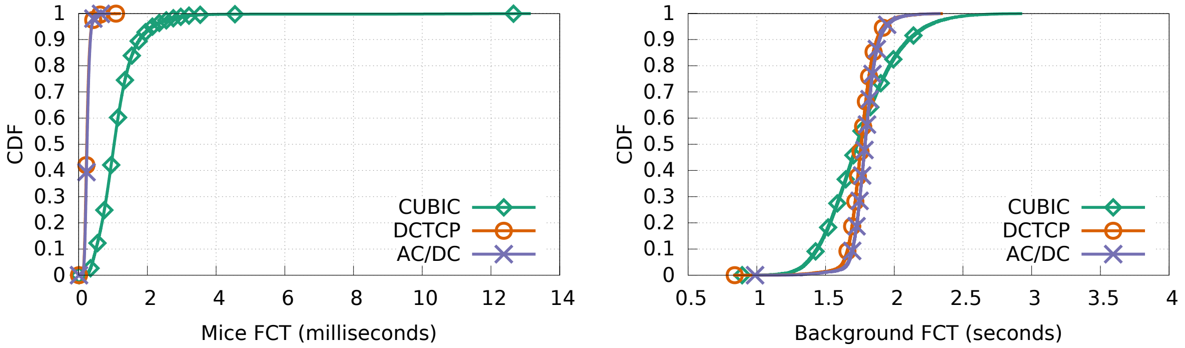


(a) 50th percentile RTT.

(b) 99.9th percentile RTT.

(c) Packet drop rate.

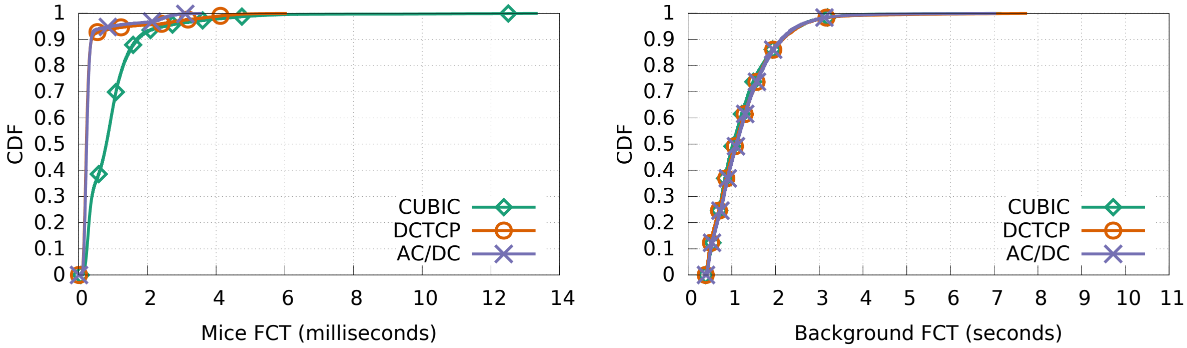
Figure 19: Many to one incast: RTT and packet drop rate. AC/DC can reduce DCTCP's RTT by limiting window sizes.



(a) Mice flow completion times.

(b) Background flow completion times.

Figure 21: CDF of mice and background FCTs in concurrent stride workload.



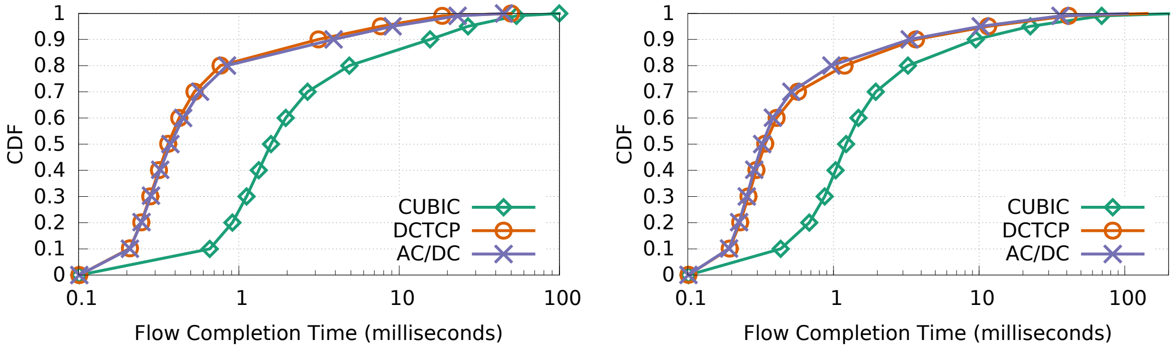
(a) Mice flow completion times.

(b) Background flow completion times.

Figure 22: CDF of mice and background FCTs in shuffle workload.

DCTCP and AC/DC reduce median FCT by 72% and 71% when compared to CUBIC. At the 99.9th percentile, DCTCP and AC/DC reduce FCTs by 55% and 73% respectively. For large flows, CUBIC, DCTCP and AC/DC have almost identical performance.

Trace-driven workloads Finally, we run trace-driven workloads. An application on each server builds a long-lived TCP connection with every other server. Message sizes are sampled from a trace and sent to a random destination in sequential fashion. Five concurrent applications on each server are run to increase network load. Message sizes are sampled from a web-search [3] and a data-mining workload [2, 25], whose flow size distribution has a heavier tail. Figure 23 shows a CDF of FCTs for mice flows (smaller than 10KB) in the web-search and data-mining workloads. In the web-search workload, DCTCP and AC/DC reduce median FCTs by 77% and 76%, respectively. At the 99.9th percentile, DCTCP and AC/DC reduce FCTs by 50% and 55%, respectively. In the data-mining workload, DCTCP and AC/DC reduce median FCTs by 72% and 73%, respectively. At the 99.9th percentile, DCTCP and AC/DC reduce FCTs by 36% and 53% respectively.



(a) Web-search workload.

(b) Data-mining workload.

Figure 23: CDF of mice (flows < 10KB) FCT in web-search and data-mining workloads.

Evaluation summary The results validate that congestion control can be accurately implemented in the vSwitch. AC⚡DC tracks the performance of an unmodified host DCTCP stack over a variety of workloads with little computational overhead. Furthermore, AC⚡DC provides this functionality over various host TCP congestion control configurations.

6. RELATED WORK

This section discusses different classes of related work.

Congestion control for DCNs Rather than proposing a new congestion control algorithm, our work investigates if congestion control can be moved to the vSwitch. Thus, many of the following schemes are complimentary. DCTCP [3] is a seminal TCP variant for datacenter networks. Judd [36] proposed simple yet practical fixes to enable DCTCP in production networks. TCP-Bolt [62] is a variant of DCTCP for PFC-enabled lossless Ethernet. DCQCN [74] is a rate-based congestion control scheme (built on DCTCP and QCN) to support RDMA deployments in PFC-enabled lossless networks. TIMELY [43] and DX [39] use accurate network latency as the signal to perform congestion control. TCP ex Machina [70] uses computer-generated congestion control rules. PERC [35] proposes proactive congestion control to improve convergence. ICTCP's [71] receiver monitors incoming TCP flows and modifies `RWND` to mitigate the impact of incast, but this cannot provide generalized congestion control like AC⚡DC. Finally, efforts [12, 64] to implement TCP Offload Engine (TOE) in specialized NICs are not widely deployed for reasons noted in [44, 66].

Bandwidth allocation Many bandwidth allocation schemes have been proposed. Gatekeeper [56] and EyeQ [34] abstract the network as a single switch and provide bandwidth guarantees by managing each server's access link. Oktopus [10] provides fixed performance guarantees within virtual clusters. SecondNet [28] enables virtual datacenters with static bandwidth guarantees. Proteus [73] allocates bandwidth for applications with dynamic demands. Seawall [58] provides bandwidth proportional to a defined weight by forcing traffic through congestion-based edge-to-edge tunnels. NetShare [38] utilizes hierarchical weighted max-min fair sharing to tune relative bandwidth allocation for services. FairCloud [53] identifies trade-offs in minimum guarantees, proportionality and high utilization, and designs schemes over this space. Silo [33] provides guaranteed bandwidth, delay and burst allowances through a novel VM placement and admission algorithm, coupled with a fine-grained packet pacer. As discussed in §2, AC⚡DC is largely complimentary to these schemes because it is a transport-level solution.

Rate limiters SENIC [49] identifies the limitations of NIC hardware rate limiters (i.e., not scalable) and software rate limiters (i.e., high CPU overhead) and uses the CPU to enqueue packets in host memory and the NIC. Silo's pacer injects void packets into an original packet sequence to achieve pacing. FasTrack [49] offloads functionality from the server into the switch for certain flows. AC⚡DC prevents TCP flows from sending in the first place and can be used in conjunction with these schemes.

Low latency DCNs Many schemes have been proposed to reduce latency in datacenter networks. HULL [4] uses phantom queues to leave bandwidth headroom to support low latency. pFabric [5] is a clean-slate design which utilizes priority and minimal switch buffering to achieve low latency. Fastpass [51] uses a centralized arbiter to perform per-packet level scheduling. QJUMP [26] uses priority queueing and rate limiting to bound latency. Traffic engineering [1, 55] and load balancing [2, 24, 30] can also reduce latency. Because AC⚡DC works on the transport level, it is largely complimentary to these works.

Performance-enhancing proxies Several schemes improve end-to-end protocol performance via a middlebox or proxy [7, 8, 9, 16, 18]. AC⚡DC fits into this class of works, but is unique in providing a mechanism to alter a VM's TCP congestion control algorithm by modifying the vSwitch.

Virtualized congestion control vCC [15] is a concurrently designed system that shares AC⚡DC's goals and some of its design details. The paper is complementary in that some items not addressed in this work are presented, such as a more detailed analysis of the ECN-coexistence problem, an exploration of the design space, and a theoretical proof of virtualized congestion control's correctness. Our paper provides an in-depth design and thorough evaluation of a DCTCP-based virtualized congestion control algorithm on a 10 Gbps testbed.

7. CONCLUSION

Today's datacenters host a variety of VMs (virtual machines) in order to support a diverse set of tenant services. Datacenter operators typically invest significant resources in optimizing their network fabric, but they cannot control one of the most important components of avoiding congestion: TCP's congestion control algorithm in the VM. In this paper, we present a technology that allows administrators to regain control over arbitrary tenant TCP stacks by enforcing congestion control in the vSwitch. Our scheme, called AC⚡DC TCP, requires no changes to VMs or network hardware. Our approach is scalable, light-weight, flexible and provides a policing mechanism to deal with non-conforming flows. In our evaluation the CPU overhead is less than one percentage point and our scheme is shown to effectively enforce an administrator-defined congestion control algorithm over a variety of tenant TCP stacks.

Acknowledgement

We would like to thank our shepherd Vishal Misra, Jeff Rasley, Brent Stephens and the anonymous reviewers for their valuable feedback. This work is supported in part by National Science Foundation (grants CNS-1302041, CNS-1330308 and CNS-1345249), IBM Corporation and the Wisconsin Institute on Software-Defined Datacenters of Madison.

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