ABC: A Simple Explicit Congestion Control Protocol for Wireless Networks

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ABSTRACT

We propose Accel-Brake Control (ABC), a simple and deployable explicit congestion control protocol for network paths with time-varying wireless links. ABC routers mark each packet with an “accelerate” or “brake”, which causes senders to slightly increase or decrease their congestion windows. Routers use this feedback to quickly guide senders towards a desired target rate. ABC requires no changes to header formats or user devices, but achieves better performance than XCP. ABC is also incrementally deployable; it operates correctly when the bottleneck is a non-ABC router, and can coexist with non-ABC traffic sharing the same bottleneck link. We evaluate ABC using a Wi-Fi implementation and trace-driven emulation of cellular links. ABC achieves 30-40% higher throughput than Cubic+Codel for similar delays, and 2.2× lower delays than BBR on a Wi-Fi path. On cellular network paths, ABC achieves 50% higher throughput than Cubic+Codel.

1 INTRODUCTION

This paper proposes a new explicit congestion control protocol for network paths with wireless links. Congestion control on such paths is challenging because of the rapid time variations of the link rate. End-to-end schemes [12, 13, 23, 24, 44] must infer the correct window indirectly from receiver ACK feedback. In principle, active queue management [34, 36] (AQM) should help by providing feedback from the wireless router, but these schemes often leave the link underutilized [7, 44]. The reason is that AQM schemes can respond to reductions in the bottleneck rate, but have no way to signal increases when bandwidth becomes available [7].

By contrast, routers in explicit control protocols like XCP [29] and RCP [41] directly specify a target rate to the sender, signaling both rate increases and decreases. In theory, these schemes could substantially improve performance compared to both traditional protocols [8, 12, 13, 15, 23] and recent algorithms designed for cellular networks [44, 48]. However, they have two limitations, one conceptual and the other practical. First, existing explicit protocols were designed for fixed-capacity links; we find that they are sub-optimal on time-varying wireless links. Second, they have proven hard to deploy on the Internet.

Our contribution is a simple and deployable protocol, called Accel-Brake Control (ABC), that realizes the potential benefits of explicit protocols by overcoming the limitations mentioned above. ABC builds on concepts previously presented in a position paper [7].

In ABC, wireless routers mark each packet with one bit of feedback corresponding to either accelerate or brake based on a measured estimate of the current link rate. Upon receiving this feedback via an ACK from the receiver, the sender either accelerates its transmission by sending two packets (on accelerate), or decelerates by not sending any packet (on brake). This simple mechanism allows the router to signal a large dynamic range of window size changes: from throttling the window to 0, to doubling the window, all within one RTT.

ABC’s control algorithm has two unique features that help it perform well on time-varying links. First, ABC routers exploit the ACK-clocking property of a window-based protocol to accurately predict the incoming rate of packets one RTT into the future based on the current dequeue rate of packets at the router. By contrast, prior work compares the enqueue rate to the link rate to determine the feedback. ABC’s feedback is more accurate and tracks capacity changes better because it models the enqueue rate in the future. Second, ABC adjusts its feedback continuously on a packet-by-packet basis to react immediately to any capacity fluctuations. We conduct a control-theoretic analysis of the algorithm and provide a simple criteria on its parameters that ensures its stability and convergence (§3.1.4).

To facilitate deployment, we show how ABC can reuse the existing ECN infrastructure (§5.1.2). We also describe how ABC can co-exist well with non-ABC bottleneck routers, and share bandwidth fairly with non-ABC flows traversing a bottleneck ABC router (§5).

We have implemented ABC on a commodity Wi-Fi router running OpenWrt [18]. Our implementation reveals another important challenge for implementing explicit protocols on wireless links: how to determine the link rate at a given time? The task is complicated by the intricacies of the Wi-Fi MAC’s batch scheduling and block acknowledgements. We develop a method to estimate the Wi-Fi link rate and demonstrate its accuracy experimentally. For cellular links, the 3GPP standard [1] shows how to estimate the link rate; our evaluation uses emulation with cellular packet traces.

We have experimented with ABC in several wireless network settings. Our results are:

(1) In Wi-Fi, compared to Cubic+Codel, Vegas, and Copa, ABC achieves 30-40% higher throughput with similar delays. Cubic, PCC Vivace-latency and BBR incur 70%-6× higher 95th percentile packet delay with similar throughput.

(2) The results on cellular traces are summarized below:
| Scheme       | Norm. Tput | Norm. Delay (95%) |
|--------------|------------|------------------|
| ABC          | 1          | 1                |
| XCP          | 0.97       | 2.04             |
| Cubic + Codel| 0.67       | 0.84             |
| Copa         | 0.66       | 0.85             |
| Cubic        | 1.18       | 4.78             |
| PCC-Vivace   | 1.12       | 4.93             |
| BBR          | 0.96       | 2.83             |
| Sprout       | 0.55       | 1.08             |
| Verus        | 0.72       | 2.01             |

(3) ABC competes fairly with both ABC and non-ABC flows. In scenarios with both ABC and non-ABC flows, the difference in average throughput of ABC and non-ABC flows is under 5%.

(4) ABC bottlenecks can coexist with both ABC and non-ABC bottlenecks. ABC flows achieve high utilization and low queuing delays if the bottleneck router is ABC, while switching to Cubic when the bottleneck is a non-ABC router.

2 MOTIVATION

Link rates in wireless networks can vary rapidly with time; for example, within one second, a wireless link’s capacity can both double and halve (i.e., vary by 4×) [44]. These variations make it difficult for transport protocols to achieve both high throughput and low delay. Here, we motivate the need for explicit congestion control protocols that provide feedback to senders on both rate increases and decreases based on direct knowledge of the wireless link capacity. We discuss why these protocols can track wireless link rates more accurately than end-to-end and AQM-based schemes. Finally, we discuss deployment considerations explicit control protocols.

Limitations of end-to-end congestion control: Traditional end-to-end congestion control schemes like Cubic [23] and NewReno [24] rely on packet drops to infer congestion and adjust their rates. Such schemes tend to fill up the buffer, causing large queuing delays, especially in cellular networks that use deep buffers to avoid packet loss [44]. Fig. 1a shows performance of Cubic on an LTE link, emulated using a LTE trace with Mahimahi [33]. The network round-trip time is 100 ms and the buffer size is set to 250 packets. Cubic causes significant queuing delay, particularly when the link capacity drops.

Recent proposals such as BBR [13], PCC-Vivace [15] and Copa [8] use RTT and send/receive rate measurements to estimate the available link rate more accurately. Although schemes are an improvement over loss-based schemes, their performance is far from optimal on highly-variable links. Our experiments show that they either cause excessive queuing or underutilize the link capacity (e.g., see Fig. 8). Sprout [44] and Verus [48] are two other recent end-to-end protocols designed specifically for cellular networks. They also have difficulty tracking the link rate accurately; depending on parameter settings, they can be too aggressive (causing large queues) or too conservative (hurting utilization). For example, Fig. 1b shows how Verus performs on the same LTE trace as above.

The fundamental challenge for any end-to-end scheme is that to estimate the link capacity, it must utilize the link fully and build up a queue. When the queue is empty, signals such as the RTT and send/receive rate do not provide information about the available capacity. Therefore, in such periods, all end-to-end schemes must resort to some form of “blind” rate increase. But for networks with a large dynamic range of rates, it is very difficult to tune this rate increase correctly: if it is slow, throughput suffers, but making it too fast causes overshoots and large queuing delays. For schemes that attempt to limit queue buildup, periods in which queues go empty (and a blind rate increase is necessary) are common; they occur, for example, following a sharp increase in link capacity.

AQM schemes do not signal increases: AQM schemes like RED [20], PIE [36] and CoDel [2] can be used to signal congestion (via ECN or drops) before the buffer fills up at the bottleneck link, reducing delays. However, AQM schemes do not signal rate increases. When capacity increases, the sender must again resort to a blind rate increase. Fig. 1c shows how CoDel performs when the sender is using Cubic. Cubic + CoDel reduces delays by 1 to 2 orders of magnitude compared to Cubic alone but leaves the link underutilized when capacity increases.

Thus, we conclude that, both end-to-end and AQM-based schemes will find it difficult to track time-varying wireless link rates accurately. Explicit control schemes, such as XCP [29] and RCP [41] provide a compelling alternative. In these schemes, the router provides multiple bits of feedback per packet to senders based on direct knowledge of the wireless link capacity. By telling senders precisely how to increase or decrease their rates, explicit schemes can quickly adapt to time-varying links, in principle, within an RTT of link capacity changes.

Deployment challenges for explicit congestion control: Schemes like XCP and RCP require major changes to packet headers, routers, and endpoints. Although the changes are technically feasible, in practice, they create significant deployment challenges. For instance, these protocols require new packet fields to carry multi-bit feedback information. IP or TCP options could in principle be used for these fields. But many wide-area routers drop packets with IP options [21], and using TCP options creates problems due to middleboxes [25] and IPSec encryption [39]. Another important challenge is co-existence with legacy routers and legacy transport protocols. To be deployable, an explicit protocol must handle scenarios where the bottleneck is at a legacy router, or when it shares the link with standard end-to-end protocols like Cubic.

Design requirements for (ABC): In designing ABC, we targeted the following properties:

1 Control algorithm for fast-varying wireless links: Prior explicit control algorithms like XCP and RCP were designed for fixed-capacity links. We design ABC’s control

BBR attempts to mitigate this problem by periodically increasing its rate in short pulses, but our experiments show that BBR frequently overshoots the link capacity with variable-bandwidth links, causing excessive queuing.
algorithm specifically for the rapid bandwidth variations and packet transmission behavior of wireless links (e.g., frame batching at the MAC layer). Our optimizations enable ABC to track bandwidth variations more accurately, e.g., reducing 95th percentile queuing delay by 2× compared to XCP on cellular links.

2. No modifications to packet headers: ABC re-purposes the existing explicit congestion notification (ECN) bit to signal both increases and decreases to the sender’s congestion window. By spreading feedback over a sequence of 1-bit signals per packet, ABC routers precisely control sender congestion windows over a large dynamic range without requiring any new packet fields.

3. Coexistence with legacy bottleneck routers: ABC is robust to scenarios where the bottleneck link is not the wireless link but a non-ABC link elsewhere on the path. Whenever a non-ABC router becomes the bottleneck, ABC senders ignore window increase feedback from the wireless link, and ensure that they send no faster than their fair share of the bottleneck link.

4. Coexistence with legacy transport protocols: ABC routers ensure that ABC and non-ABC flows share a wireless bottleneck link fairly. To this end, ABC routers separate ABC and non-ABC flows into two queues, and use a simple algorithm to schedule packets from these queues. ABC makes no assumptions about the congestion control algorithm of non-ABC flows, is robust to the presence of short or application-limited flows, and requires a small amount of state at the router.

Fig. 1d shows ABC on the same emulated LTE link. Using only one bit of feedback per packet, the ABC flow is able to track the variations in bottleneck link closely, achieving both high throughput and low queuing delay.

3 DESIGN

ABC is a window-based protocol: the sender limits the number of packets in flight to the current congestion window. Window-based protocols react faster to the sudden onset of congestion than rate-based schemes [10]. On a wireless link, when the capacity drops and the sender stops receiving ACKs, ABC will stop sending packets immediately, avoiding further queue buildup. In contrast, a rate-based protocol would take time to reduce its rate and may queue up a large number of packets at the bottleneck link in the meantime.

ABC senders adjust their window size based on explicit feedback from ABC routers. An ABC router uses its current estimate of the link rate and queuing delay to compute a target rate. The router then sets one bit of feedback in each packet to guide the senders towards the target rate. Each bit is echoed to a sender by a receiver in an ACK, and it signals either a one-packet increase (“accelerate”) or a one-packet decrease (“brake”) to the sender’s congestion window.

3.1 The ABC Protocol

We now present ABC’s design starting with the case where all routers are ABC-capable and all flows use ABC. We later discuss how to extend the design to handle non-ABC routers and scenarios with competing non-ABC flows.

3.1.1 ABC Sender

On receiving an “accelerate” ACK, an ABC sender increases its congestion window by 1 packet. This increase results in two packets being sent, one in response to the ACK and one due to the window increase. On receiving a “brake,” the sender reduces its congestion window by 1 packet, preventing the sender from transmitting a new packet in response to the received ACK. As we discuss in §5.2, the sender also performs an additive increase of 1 packet per RTT to achieve fairness. For ease of exposition, let us ignore this additive increase for now.

Though each bit of feedback translates to only a small change in the congestion window, when aggregated over an RTT, the feedback can express a large dynamic range of window size adjustments. For example, suppose a sender’s window size is \( w \), and the router marks accelerates on a fraction \( f \) of packets in that window. Over the next RTT, the sender will receive \( w \cdot f \) accelerates and \( w - w \cdot f \) brakes. Then, the sender’s window size one RTT later will be \( w + w f - (w - w f) = 2w f \) packets. Thus, in one RTT, an ABC router can vary the sender’s window size between zero \( (f = 0) \) and double its current value \( (f = 1) \). The set of achievable window changes for the next RTT depends on the number of packets in the current window \( w \); the larger \( w \), the higher the granularity of control.

In practice, ABC senders increase or decrease their congestion window by the number of newly acknowledged bytes covered by each ACK. Byte-based congestion window
modifications is a standard technique in many TCP implementations [6], and it makes ABC robust to variable packet sizes and delayed, lost, and partial ACKs. For simplicity, we describe the design with packet-based window modifications in this paper.

### 3.1.2 ABC Router

#### Calculating the target rate:

ABC routers compute the target rate $tr(t)$ using the following rule:

$$
tr(t) = \eta \mu(t) - \frac{\mu(t)}{\delta} (x(t) - d_t)^+,
$$

where $\mu(t)$ is the link capacity, $x(t)$ is the observed queuing delay, $d_t$ is a pre-configured delay threshold, $\eta$ is a constant less than 1, $\delta$ is a positive constant (in units of time), and $y^+$ is $\max(y, 0)$. This rule has the following interpretation. When queuing delay is low ($x(t) < d_t$), ABC sets the target rate to $\eta \mu(t)$, for a value of $\eta$ slightly less than 1 (e.g., $\eta = 0.95$). By setting the target rate a little lower than the link capacity, ABC aims to trade a small amount of bandwidth for large reductions in delay, similar to prior work [5, 27, 30]. However, queues can still develop due to rapidly changing link capacity and the 1 RTT of delay it takes for senders to achieve the target rate. ABC uses the second term in Eq. (1) to drain queues. Whenever $x(t) > d_t$, this term reduces the target rate by an amount that causes the queuing delay to decrease to $d_t$ in at most $\delta$ seconds.

The threshold $d_t$ ensures that the target rate does not react to small increases in queuing delay. This is important because wireless links often schedule packets in batches. Queuing delay caused by batch queue scheduling does not imply congestion, even though it occurs persistently. To prevent target rate reductions due to this delay, $d_t$ must be configured to be greater than the average inter-scheduling time at the router.

ABC’s target rate calculation requires an estimate of the underlying link capacity, $\mu(t)$. In §4, we discuss how to estimate the link capacity in cellular and WiFi networks, and we present an implementation for WiFi.

#### Packet marking:

To achieve a target rate, $tr(t)$, the router computes the fraction of packets, $f(t)$, that should be marked as accelerate. Assume that the current dequeue rate — the rate at which the router transmits packets — is $cr(t)$. If the accelerate fraction is $f(t)$, for each packet that is ACKed, the sender transmits $2f(t)$ packets on average. Therefore, after 1 RTT, the enqueue rate — the rate at which packets arrive to the router — will be $2cr(t)f(t)$. To achieve the target rate, $f(t)$ must be chosen such that $2cr(t)f(t)$ is equal to $tr(t)$. Thus, $f(t)$ is given by:

$$
f(t) = \min\left\{1, \frac{1}{2} \frac{tr(t)}{cr(t)} \right\}.
$$

An important consequence of the above calculation is that $f(t)$ is computed based on the dequeue rate. Most explicit protocols compare the enqueue rate to the link capacity to determine the feedback (e.g., see XCP [29]).

ABC uses the dequeue rate instead to exploit the ACK-clocking property of its window-based protocol. Specifically, Eq. (2) accounts for the fact that when the link capacity changes (and hence the dequeue rate changes), the rate at the senders changes automatically within 1 RTT. Fig. 2 demonstrates that computing $f(t)$ based on the dequeue rate at the router enables ABC to track the link capacity much more accurately than using the enqueue rate.

ABC recomputes $f(t)$ on every dequeued packet, using measurements of $cr(t)$ and $\mu(t)$ over a sliding time window of length $T$. Updating the feedback on every packet allows ABC to react to link capacity changes more quickly than schemes that use periodic feedback updates (e.g., XCP and RCP).

Packet marking can be done deterministically or probabilistically. To limit burstiness, ABC uses the deterministic method shown in Algorithm 1. The variable $token$ implements a token bucket that is incremented by $f(t)$ on each outgoing packet (up to a maximum value $tokenLimit$), and decremented when a packet is marked accelerate. To mark a packet accelerate, $token$ must exceed 1. This simple method ensures that no more than a fraction $f(t)$ of the packets are marked accelerate.

#### Multiple bottlenecks:

An ABC flow may encounter multiple ABC routers on its path. An example of such a scenario is when two smartphone users communicate over an ABC-compliant cellular network. Traffic sent from one user to the other will traverse a cellular uplink and cellular downlink, both of which could be the bottleneck. To support such situations, an ABC sender should send traffic at the smallest of the router-computed target rates along their path. To achieve this goal, each packet is initially marked accelerate by the sender. ABC routers may change a packet marked accelerate to a brake, but not vice versa (see Algorithm 1). This rule guarantees that an ABC router can unilaterally reduce the fraction of packets marked accelerate to ensure that its target rate is not exceeded, but it cannot increase this fraction. Hence the fraction of packets marked accelerate will equal the minimum $f(t)$ along the path.

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**Figure 2: Feedback — Calculating $f(t)$ based on enqueue rate increases 95th percentile queuing delay by 2x.**

(a) Dequeue

(b) Enqueue

| Throughput (Mbps) | Time (s) | Queuing Delay (ms) |
|------------------|---------|--------------------|
| 0.01             | 0       | 0.01               |
| 0.02             | 5       | 0.02               |
| 0.03             | 10      | 0.03               |
| 0.04             | 15      | 0.04               |
| 0.05             | 20      | 0.05               |
| 0.06             | 25      | 0.06               |
| 0.07             | 30      | 0.07               |
| 0.08             | 35      | 0.08               |
| 0.09             | 40      | 0.09               |
| 0.10             | 45      | 0.10               |

**Algorithm 1:** Packet marking at an ABC router.
Consider a single ABC link, traversed by \( N \) ABC flows. Let \( \tau \) be the maximum round-trip propagation delay of the flows. ABC is globally asymptotically stable if
\[
\delta > \frac{2}{3}. 
\]
Specifically, if \( \mu(t) = \mu \) for \( t > t_0 \) (i.e., the link capacity stops changing after some time \( t_0 \)), the enqueue/dequeue rate and the queuing delay at the ABC router will converge to certain values \( r^* \) and \( x^* \) that depend on the system parameters and the number of flows. In all cases: \( \eta \mu < r^* \leq \mu \).

This stability criterion is simple and intuitive. It states that \( \delta \) should not be much smaller than the RTT (i.e., the feedback delay). If \( \delta \) is very small, ABC reacts too forcefully to queue build up, causing under-utilization and oscillations.\(^3\) Increasing \( \delta \) well beyond \( 2/3 \tau \) improves the stability margins of the feedback loop, but hurts responsiveness. In our experiments, we used \( \delta = 133 \) ms for a propagation RTT of 100 ms.

### 4 ESTIMATING LINK RATE

In this section we describe, how ABC routers can estimate the link capacity for computing the target rate (§3.1.2). We present a technique for WiFi that leverages the inner workings of the WiFi MAC layer, and we discuss options for cellular networks.

#### 4.1 Wi-Fi

We describe how an 802.11n access point (AP) can estimate the average link rate. This method works for any work-conserving scheduler, whether or not the users’ packets share a queue. The link rate is defined as the ratio \( S/T \), where \( S \) is the number of bits to be transmitted in sequence over the link and \( T \) is the time taken to do so, starting from when the first bit is ready to be sent on the link (any delay in sending the first bit due to channel contention or retransmissions of previous frames is included in \( T \)).

**Challenges:** A strawman would be to estimate the link rate using the physical layer bit rate selected for each transmission, which would depend on the modulation and channel code used for the transmission. Unfortunately, this method will overestimate the link rate as packet transmission times are governed not only by bitrates, but also by delays for additional tasks (e.g., channel contention and retransmissions [11]). An alternative approach would be to use the fraction of time that the router queue was backlogged as a proxy for link utilization. Unfortunately, the Wi-Fi MAC’s packet batching confounds this approach. Wi-Fi routers transmit packets (frames) in batches; a new batch is transmitted only after receiving an ACK for the last batch. The AP may accumulate packets while waiting for a link-layer ACK; this queue buildup does not necessarily imply that the link is fully utilized. Thus, accurately measuring link rates requires a detailed consideration of Wi-Fi’s packet transmission protocols.

**Understanding batching:** In 802.11n, data frames, also known as MAC Protocol Data Units (MPDUs), are transmitted

\(^2\)All the competing ABC senders will observe the same accelerate fraction, \( f \), on average. Therefore, each flow will update its congestion window, \( w \), in a multiplicative manner, to \( 2f w \), in the next RTT.

\(^3\)Interestingly, if the sources do not perform additive increase or if the additive increase is sufficiently “gentle,” ABC is stable for any value of \( \delta \). See the proof in Appendix A for details.
in batches called A-MPDUs (Aggregated MPDUs). The maximum number of frames that can be included in a single batch, \( M \), is negotiated by each receiver and the router. When a given user is not backlogged, the router might not have enough data to send a full-sized batch of \( M \) frames, but will instead use a smaller batch of size \( b < M \). Upon receiving a batch, the receiver responds with a single Block ACK. Thus, at a time \( t \), given a batch size of \( b \) frames, a frame size of \( S \) bits,\(^4\) and an ACK inter-arrival time (i.e., the time between receptions of consecutive block ACKs) of \( T_{IA}(b,t) \), the current dequeue rate, \( cr(t) \), may be estimated as

\[
    cr(t) = \frac{b.S}{T_{IA}(b,t)}.
\]

When the user is backlogged and \( b = M \), then \( cr(t) \) above will be equal to the link capacity. However, if the user is not backlogged and \( b < M \), how can the AP estimate the link capacity? Our approach calculates \( \hat{T}_{IA}(M,t) \), the estimated ACK inter-arrival time if the user was backlogged and had sent \( M \) frames in the last batch.

We estimate the link capacity, \( \mu(t) \), as

\[
    \mu(t) = \frac{M.S}{\hat{T}_{IA}(M,t)}.
\]

To accurately estimate \( \hat{T}_{IA}(M,t) \), we turn to the relationship between the batch size and ACK inter-arrival time. We can decompose the ACK interval time into the batch transmission time and “overhead” time, the latter including physically receiving an ACK, contending for the shared channel, and transmitting the physical layer preamble [22]. Each of these overhead components is independent of the batch size, modeled as \( h(t) \). If \( R \) is the bitrate used for transmission,\(^5\) the router’s ACK inter-arrival time is

\[
    T_{IA}(b,t) = \frac{b.S}{R} + h(t).
\]

Equation 6. This computation is performed for each batch transmission when the batch ACK arrives, and passed through a weighted moving average filter over a sliding window of time \( T \) to estimate the smooth time-varying link rate. \( T \) must be greater than the inter-ACK time (up to 20 ms in Fig. 4); we use \( T = 40 \text{ ms} \). Because ABC cannot exceed a rate-doubling per RTT, we cap the predicted link rate to double the current rate.

We can then use \( \hat{T}_{IA}(M,t) \) to estimate the link capacity with

\[
    T_{IA}(M,t) = \frac{MS}{R} + h(t)
\]

\[
    \hat{T}_{IA}(M,t) = T_{IA}(b,t) + \frac{(M-b)S}{R}.
\]

We can use these estimations to predict link rates within 5% of the true link capacities. Connecting the average values of ACK inter-arrival times across all considered batch sizes will produce a line with slope \( S/R \). Using this property, we can estimate the ACK inter-arrival time for a backlogged user as

\[
    T_{IA}(M,t) = \frac{MS}{R} + h(t)
\]

\[
    \hat{T}_{IA}(M,t) = T_{IA}(b,t) + \frac{(M-b)S}{R}.
\]

4.2 Cellular Networks

Cellular networks schedule users from separate queues to ensure inter-user fairness. Each user will observe a different link capacity and queuing delay. As a result, every user requires a separate target rate calculation at the ABC router. The 3GPP cellular standard [1] (page 13) describes how scheduling information at the cellular base station can be used to calculate per-user link rates. This method is able to estimate capacity accurately even if a given user is not backlogged at the base station, a key property for the target rate estimation in Eq. (1).

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\(^4\)For simplicity, we assume that all frames are of the same size, though our formulas can be generalized in a straightforward manner for varying frame sizes.

\(^5\)Different users can have different transmission rates.
5 COEXISTENCE

An ABC flow should be robust to presence of non-ABC bottlenecks on its path and share resources fairly with non-ABC flows sharing the ABC router.

5.1 Non-ABC bottlenecks

An ABC flow can encounter both ABC and non-ABC bottleneck routers. For example, a Wi-Fi user’s traffic may traverse both a Wi-Fi router (running ABC) and an ISP router (not running ABC); either router could be the bottleneck at any given time. To handle such situations, ABC flows must be able to detect and react to traditional congestion signals (e.g., drops or ECN marks), and they must determine when to ignore accelerate feedback from ABC routers. First, we describe how ABC senders incorporate feedback from non-ABC routers. Then, we show how to repurpose ECN for ABC feedback, without compromising the ABC sender’s ability to infer congestion based on ECN marks from non-ABC routers.

5.1.1 Incorporating feedback from non-ABC Routers

We augment the ABC sender so that it maintains two congestion windows, one for tracking the available rate on ABC routers ($w_{abc}$), and one for tracking the rate on non-ABC bottlenecks ($w_{nonabc}$). $w_{abc}$ obeys accelerates/brakes using Eq. (3), while $w_{nonabc}$ follows a rule such as Cubic [23] and responds to drop and ECN signals. An ABC sender must send packets to match the lower of the two windows. Our implementation mimics Cubic for the non-ABC method, but other methods could also be emulated.

With this approach, the window that is not the bottleneck could grow very large. For example, when a non-ABC router is the bottleneck, the ABC router will continually send accelerate signals. These accelerate signals do not cause the sender to transmit new packets, but they do cause $w_{abc}$ to grow. Thus if the ABC router becomes the bottleneck, it will (temporarily) incur very large queues. To prevent this problem, ABC senders cap both $w_{abc}$ and $w_{nonabc}$ to $2 \times$ the number of in-flight packets.

Fig. 6 shows the throughput and queuing delay for an ABC flow traversing a path with an ABC-capable wireless link and a wired link with a droptail queue. For illustration, we vary the rate of the wireless link in a series of steps every 5 seconds. Over the experiment, the bottleneck switches between the wired and wireless links several times. ABC is able to adapt its behavior quickly and accurately. Depending on which link is the bottleneck, either $w_{nonabc} = w_{cubic}$ or $w_{abc}$ becomes smaller and controls the rate of the flow. When the wireless link is the bottleneck, ABC maintains low queuing delay, whereas the queuing delay exhibits standard Cubic behavior when the wired link is the bottleneck. In either case, the larger window grows to the upper limit of $2 \times$ the smaller window. Notice that $w_{cubic}$ does not limit ABC’s ability to increase its rate when the wireless link is the bottleneck. At these times

We discuss how ABC senders distinguish between accelerate/brake and ECN marks in §5.1.2.

5.1.2 Deployment with ECN

IP packets have two ECN-related bits: ECT and CE. These two bits are traditionally interpreted as follows:

| ECT | CE | Interpretation |
|-----|----|----------------|
| 0   | 0  | Non-ECN-Capable Transport |
| 0   | 1  | ECN-Capable Transport ECT(1) |
| 1   | 0  | ECN-Capable Transport ECT(0) |
| 1   | 1  | ECN set |

Routers interpret both 01 and 10 to indicate that a connection is ECN-capable, and routers change those bits to 11 to mark a packet with ECN. Upon receiving an ECN mark (11), a receiver sets the the $ECN\ Echo\ (ECE)$ flag to signal congestion to the sender.

ABC reinterprets the ECT and CE ECN bits as follows:

| ECT | CE | Interpretation |
|-----|----|----------------|
| 0   | 0  | Non-ECN-Capable Transport |
| 0   | 1  | Accelerate ECT(1) |
| 1   | 0  | Brake ECT(0) |
| 1   | 1  | ECN set |

ABC senders mark accelerates using 01, and ABC routers signal brakes by flipping the bits to 10. Both 01 and 10 indicate an ECN-capable transport to ECN-capable legacy routers, which will continue to use (11) to signal congestion.

With this design, receivers must be able to convey both standard ECN signals and accelerates/brakes for ABC. ABC can be signaled using the ECE flag. For ABC feedback, we repurpose the NS (nonce sum) bit, which was originally proposed to ensure ECN feedback integrity [16] but has been reclassified as historic [9] due to lack of deployment. Thus, it appears possible to deploy ABC with only simple modifications to TCP receivers.

**Deployment in Proxied Networks:** Cellular networks commonly split TCP connections and deploy proxy at the edge [38, 43]. In such a network, it is unlikely that any non-ABC router
will act as the bottleneck and interfere with the accel-brake markings from the ABC router. In this case where non-ABC routers do not use ECN, deploying ABC is relatively straightforward and doesn’t require any receiver modifications. ABC senders can simply use either (01) or (10) ECN markings to signal an accelerate, and routers can use (11) to indicate a brake. The unmodified receiver can echo this feedback using the ECE flag. The proxy can be modified to run custom ABC senders, and the base station can be modified to act as a ABC router.

5.2 Coexistence with non-ABC flows

ABC flows are potentially at a disadvantage when they share an ABC bottleneck link with non-ABC flows. If the non-ABC flows fill up queues and increase queuing delay, the ABC router will reduce ABC’s target rate. To ensure fairness in such scenarios, ABC routers isolate ABC and non-ABC packets in separate queues. Using separate queues allows ABC flows to achieve low delays even if the non-ABC flows build up a large queue.

We assume that ABC routers can determine whether a packet belongs to an ABC flow. In some deployment scenarios, this is relatively straightforward. For example, many cellular networks deploy TCP proxies at the edge of the network [38, 43]. In such networks, the operator can deploy ABC at the proxy, and configure the base station to assume that all traffic from the proxy’s IP address uses ABC. Other deployment scenarios may require ABC senders to set a predefined value in a packet field like the IPv6 flow label.

The ABC router assigns weights of $w_{ABC}$ and $1 - w_{ABC}$ to the ABC and non-ABC queues, respectively, and it schedules packets from the queues in proportion to their weights. In addition, ABC’s target rate calculation considers only ABC’s share of the link capacity (which is governed by the weights). The challenge is how to set the weights to ensure that the average throughput of long-running ABC and non-ABC flows is the same, irrespective of the number of flows.

Prior explicit control schemes have considered two approaches. XCP estimates the average window size of competing TCP flows based on their packet loss rate, using a TCP-Friendly-Rate-Control-like [19] calculation. XCP then dynamically adjusts the weights to equalize the average window size for XCP and TCP flows. The problem with this approach is that the TFCR calculation can be inaccurate; for example, it fails to model BBR [13] flows. RCP estimates the number of flows in each queue using a data structure called a Zombie List [35], and then adapt the weights to equalize the average rate of RCP and TCP flows. This approach works well if all the flows are long-running, but it is not fair in the presence of short flows. When one queue has a large number of short flows (and hence a small average throughput), RCP increases the weight of that queue. However, the short flows cannot send faster, so the extra bandwidth is taken by long-running flows in the same queue, which get more throughput than long-running flows in the other queue. We demonstrate this unfairness experimentally in §6.5.

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7ABC and non-ABC flows may also share a non-ABC link, but in such cases, ABC flows will behave like Cubic and compete fairly with other traffic (§5.1).

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8There are many algorithms for top-$K$ rate measurement [17, 40]. Our implementation uses the Space Saving Algorithm [32] which requires $O(K)$ space.
(4) **Additional Considerations:** We evaluate how ABC performs with application-limited flows and different network delays. We conclude with a demonstration of ABC’s impact on a real application’s performance (§6.6).

**6.1 Prototype ABC Implementation**

**ABC transport:** We implemented ABC endpoints in Linux as kernel modules using the pluggable TCP API.

**ABC router:** We implemented ABC as a Linux queuing discipline (qdisc) kernel module using OpenWrt, an open source operating system for embedded networked devices [18]. We used a NETGEAR WNDR 3800 router configured to 802.11n. However, we note that our implementation is portable as OpenWrt is supported on numerous other commodity Wi-Fi routers.

ABC’s WiFi link rate prediction strategy exploits the inner workings of the MAC 802.11n protocol, and thus requires fine-grained values at this layer. In particular, the ABC qdisc must know A-MPDU sizes, Block ACK receive times, and packet transmission bitrates. Unfortunately, these values are not natively exposed to Linux router qdiscs, and instead are only available at the network driver. To bridge this gap, we modified the router to log the relevant MAC layer data in the cross-layer socket buffer data structure (skb) that it already maintains per packet.

**6.2 Experimental Setup**

We evaluated ABC in both Wi-Fi and cellular network settings. For Wi-Fi, experiments were run over a live Wi-Fi network and used the ABC router described in §6.1. For cellular settings, we use Mahimahi [33] to emulate multiple cellular networks (Verizon LTE, AT&T, and TMobile). Mahimahi’s emulation uses packet delivery traces (separate for uplink and downlink) that were captured directly on those networks, and thus include outages (highlighting ABC’s ability to handle ACK losses).

We compare ABC to end-to-end protocols designed for cellular networks (Sprout [44] and Verus [48]), loss-based end-to-end protocols both with and without AQM (Cubic [23], Cubic+Codel [34], and Cubic+PIE [36]), recently-proposed end-to-end protocols (BBR [13], Copa [8], PCC Vivace-Latency (which we refer to as PCC)) [15], and TCP Vegas [12]), and explicit control protocols (XCP [29], RCP [41] and VCP [45]). We used TCP kernel modules to evaluate ABC, BBR, Cubic, PCC, and Vegas; for these schemes, we generated traffic by using iperf [42] to create a backlogged flow. For the end-to-end schemes that are not implemented as TCP kernel modules (i.e., Copa, Sprout, Verus), we used the UDP implementations and traffic generation applications provided by the protocol authors. Lastly, for the explicit control protocols (i.e., XCP, RCP, and VCP), we used our own implementations as qdiscs with Mahimahi to ensure compatibility with our emulation setup. We used Mahimahi’s support of Cubic and Pie to evaluate AQM.

Unless otherwise noted, our emulated cellular network experiments used a minimum RTT of 100 ms and a buffer size of 250 MTU-sized packets. Additionally, in all experiments, ABC’s target rate calculation (Equation 1) used \( \eta = 0.98 \) and \( \delta = 133 \) ms. Our Wi-Fi implementation uses the link rate estimation described in §4, while our emulated cellular network setup assumes the realistic scenario that ABC’s router has knowledge of the underlying link capacity [1].

**6.3 Performance**

**Cellular:** Fig. 8a and 8b show the utilization and 95\(^{th}\) percentile per packet delay that a single backlogged flow achieves using each aforementioned congestion control protocol on two Verizon LTE cellular link traces. As shown, ABC exhibits a better (i.e., higher) throughput/delay tradeoff than all prior schemes. In particular, ABC sits well outside the Pareto frontier of the existing schemes, which represents the prior schemes that achieve higher throughput or lower delay than any other prior schemes.

Further analysis of Fig. 8a and 8b reveals that Cubic+Codel, Cubic+PIE, Copa, and Sprout are all able to achieve low delays that are comparable to ABC. However, these schemes heavily underutilize the link. The reason is that, though these schemes are able to infer and react to queue buildups in a way that reduces delays, they lack a way of quickly inferring increases in link capacity (a common occurrence on time-varying wireless links), leading to underutilization. In contrast, schemes like BBR, Cubic, and PCC are able to rapidly saturate the network (achieving high utilization), but these schemes also quickly fill buffers and thus suffer from high queueing delays. Unlike these prior schemes, ABC is able to quickly react to both increases and decreases in available link capacity, enabling high throughput and low delays.

We observed similar trends across a larger set of 8 different cellular network traces (Fig. 9). ABC achieves 50% higher throughput than Cubic+Codel and Copa, while only incurring 17% higher 95\(^{th}\) percentile packet delays. PCC and Cubic achieve slightly higher link utilization values than ABC (12%, and 18%, respectively), but they each incur significantly higher per-packet delays than ABC (394%, and 382%, respectively). Finally, compared to BBR, Verus, and Sprout, ABC achieves higher link utilization (4%, 39%, and 79%, respectively). BBR and Verus incur higher delays (183% and 100%, respectively) than ABC. Appendix C compares these schemes on mean packet delay over the same conditions, and shows the same trends.

**Comparison with Explicit Protocols:** Fig. 8 and 9 also show that ABC outperforms the explicit control protocol, XCP, despite not using multi-bit per-packet feedback as XCP does. In these experiments, XCP used constant values of \( \alpha = 0.55 \) and \( \beta = 0.4 \), which the authors note are the highest permissible stable values that achieve the fastest possible link rate convergence. XCP achieves similar average throughput to ABC, but with 105% higher 95\(^{th}\) percentile delays. This performance discrepancy can be attributed to the fact that ABC control rule is better suited for the link rate variations in wireless networks. In particular, unlike ABC which updates its feedback on every packet, XCP computes aggregate feedback
We performed similar evaluations on a live Wi-Fi usage scenarios where endpoints can move and create link, considering both single and multi-user scenarios. In this experiment, we excluded Verus and Sprout as they are designed specifically for cellular networks. To mimic common channel contention, we report average performance values across three, 45 second runs. We considered three different ABC delay threshold ($d_t$) values of 20 ms, 60 ms, and 100 ms; note that increasing ABC’s delay threshold will increase both observed throughput and RTT values.

Fig. 10 shows the throughput and 95th percentile per-packet delay for each considered protocol, as measured using the tcptrace Linux utility. For the multi-user scenario, we report the sum of achieved throughputs and the average observed 95th percentile delay across both users. We consider three versions of ABC (denoted ABC_* *) for different delay thresholds. All versions of ABC outperform all prior schemes and sit outside the pareto frontier.

index using the Linux iw utility; we alternated the MCS index between values of 1 and 7 every 2 seconds. In Appendix 14, we also list results for an experiment where we model MCS index variations as Brownian motion—results show the same trends as described below. This experiment was performed in a crowded computer lab. Thus, to reduce variations from channel conditions, we report average performance values across three, 45 second runs. We considered three different ABC delay threshold ($d_t$) values of 20 ms, 60 ms, and 100 ms; note that increasing ABC’s delay threshold will increase both observed throughput and RTT values.

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Figure 8: ABC vs. previous schemes on three Verizon cellular network traces — In each case, ABC outperforms all other schemes and sits well outside the Pareto frontier of previous schemes (denoted by the dashed lines).

Figure 9: 95th percentile per-packet delay — On average, ABC achieves similar delays and 50% higher utilization than Copa and Cubic+PDE. PCC and Cubic achieve slightly higher throughput than ABC, but incur 380% higher 95th percentile delay than ABC.

Figure 10: Throughout and mean delay on Wi-Fi — For the multi-user scenario, we report the sum of achieved throughputs and the average of observed 95th percentile delay across both users. We consider three versions of ABC (denoted ABC_* *) for different delay thresholds. All versions of ABC outperform all prior schemes and sit outside the pareto frontier.
example, in the single user scenario, the ABC configuration with $d_i = 100$ ms achieves up to 29% higher throughput than Cubic+Codel, Copa and Vegas. Though PCC-Vivace, Cubic and BBR achieve slightly higher throughput (4%) than this ABC configuration, their delay values are considerably higher (67%-6x). The multi-user scenario showed similar results. For instance, ABC achieves 38%, 41% and 31% higher average throughput than Cubic+Codel, Copa and Vegas, respectively.

6.4 Coexistence with Various Bottlenecks

Coexistence with ABC bottlenecks: Fig. 8c compares ABC and prior protocols on a network path with two cellular links. In this scenario, ABC tracks the bottleneck link rate and achieves a better throughput/delay tradeoff than prior schemes, and again sits well outside the Pareto frontier for those schemes.

Coexistence with non-ABC bottlenecks: Fig. 11 illustrates throughput and queueing delay values for an ABC flow traversing a network path with both an emulated wireless link and an emulated 12 Mbits/s fixed rate (wired) link. The wireless link is configured to run ABC, while the wired link operates a droptail buffer. ABC shares the wired link with on-off cubic cross traffic. In the absence of cross traffic (white region), the wireless link is always the bottleneck. However, with cross traffic (yellow and grey regions), due to contention, the wired link can become the bottleneck. In this case, ABC’s fair share on the wired link is half of the link’s capacity (i.e., 6 Mbit/s). If the wireless link rate is lower than the fair share (yellow region), the wireless link remains the bottleneck; otherwise, the wired link becomes the bottleneck (grey region).

The black dashed line in the top graph represents the ideal throughput (i.e., that of the bottleneck link) for the ABC flow throughout the experiment. As shown, in all regions, ABC is able to track the ideal rate closely, even as the bottleneck shifts. In particular, in the absence of cross traffic, ABC continually achieves low delays while maintaining high link utilization. Similarly, with cross traffic, ABC appropriately tracks the wireless link rate (yellow region) or achieves its fair share of the wired link (grey region) like Cubic. In the former cross traffic scenario, increased queuing delays are due to congestion caused by the Cubic flow on the wired link. Further, deviations from the ideal rate in the latter cross traffic scenario can be attributed to the fact that an ABC flow (while running as Cubic) takes time to converge to its fair share.

6.5 Fairness among ABC and non-ABC flows

Coexistence among ABC flows: We simultaneously run multiple ABC flows on a fixed 24 Mbits/s wired bottleneck link. We varied the number of competing flows from 2 to 32, and the duration of each run was 60 s. In each case, the Jain Fairness Index (28) was within 5% from the ideal fairness value of 1, highlighting ABC’s ability to ensure fairness.

Coexistence with non-ABC flows: We consider a scenario where three ABC and three non-ABC (in this case, Cubic) long-lived flows share the same 96 Mbits/s bottleneck link. In addition, we create varying numbers of short flows (each of size 10 KB) with flow arrival times generated by a Poisson process to offer fixed average loads. We consider several different total offered load values. Our results summarize 10 runs, each of 40 seconds. We compare ABC’s strategy to coexist with non-ABC flows to RPC’s Zombie list approach (§5.2).

Fig. 12 shows the mean and standard deviation throughput values achieved by the ABC and Cubic flows. As shown in Fig. 12a, ABC’s coexistence strategy allows ABC and Cubic flows to fairly share the bottleneck link across all offered load values. Specifically, the difference in average throughput between the ABC and Cubic flows is under 5%. In contrast, Fig. 12b shows that RCP’s coexistence strategy gives higher priority to Cubic flows. This discrepancy increases as the offered load increases, with Cubic flows achieving 17-165% higher throughput than ABC flows. The reason, as discussed in §5.2, is that long-lived Cubic flows receive higher throughput than the average throughput that RCP estimates for Cubic flows. This leads to unfairness because RCP attempts to match average throughput values for each scheme. Fig. 12 also shows that the standard deviation of ABC flows is small (under 10%) across all scenarios. A small standard deviation implies that in each run of the experiment, the throughput values for each of the three concurrent ABC flows are close to each other, implying fairness across ABC flows. Importantly, the standard deviation values for ABC are smaller than those for Cubic. Thus, ABC flows converge to fairness faster than Cubic flows do.
Application-limited flows: We created a single long-lived ABC flow that shared a cellular link with 200 application-limited ABC flows that send traffic at an aggregate of 1 Mbit/s. Fig. 13 shows that, despite the fact that the application-limited flows do not have traffic to properly respond to ABC’s feedback, the ABC flows (in aggregate) are still able to achieve low queuing delays and high link utilization.

ABC’s sensitivity to network latency: Thus far, our emulation experiments have considered fixed minimum RTT values of 100 ms. To evaluate the impact that propagation delay has on ABC’s performance, we used a modified version of the experimental setup from Fig. 9. In particular, we consider RTT values of 20 ms, 50 ms, 100 ms, and 200 ms. Across all propagation delays, ABC is still able to outperform all prior schemes, again achieving a more desirable throughput/latency trade off. ABC’s benefits persist even though schemes like Cubic+Codel and Cubic+PIE actually improve with increasing propagation delays. Performance with these schemes improves because bandwidth delay products increase, making Cubic’s additive increase more aggressive (improving link utilization). See Appendix E for more details.

ABC’s improvement on real applications: We evaluated ABC’s ability to improve performance for real user-facing applications by considering a multiplayer interactive game, Slither.io [3]. We loaded Slither.io using a Google Chrome browser which ran inside an emulated cellular link with a background backlogged flow (generated with iperf). We considered three different congestion control protocols for the backlogged flow: Cubic, Cubic+Codel, and ABC. As expected, Cubic is able to fully utilize the link, but adds excessive queuing delays which hinder gameplay. In contrast, Cubic+Codel reduces queuing delays (improving user experience in the game), but underutilizes the link. Only ABC is able to achieve both high link utilization for the backlogged flow and low queuing delays for the game. A video demo of this experiment can be viewed at https://youtu.be/Dauq-tJmyU.

Perfect future capacity knowledge: We considered a variant of ABC, PK-ABC, which knows an entire emulated link trace in advance. This experiment reflects the possibility of resource allocation predictions at cellular network base stations. Rather than using an estimate of the current link rate to compute a target rate (as ABC does), PK-ABC uses the exact link rate that is expected 1 RTT value in the future. Using the same setup as in Fig. 8b, PK-ABC is able to reduce 95th percentile per-packet-delays from 97 ms to 28 ms, compared to ABC, while achieving the same link utilization (~90%).

7 RELATED WORK

MTG [26] proposed modifying cellular base stations to communicate the link rate explicitly. However, unlike ABC, MTG introduces a new TCP option [37] to transmit this rate. This approach does not work when IPSec encryption is used [39]. In addition, MTG’s packet modifications trigger the risk of packets being dropped silently by middleboxes [25]. Finally, unlike ABC, MTG lacks a mechanism for ensuring fairness among multiple flows for a given user.

Several prior works have proposed using LTE infrastructure to infer the underlying link capacity [26, 31, 46]. For example, QIC [31] and piStream [46] use physical layer information at the receiver (e.g., allocated physical resource blocks) to estimate link capacity. However, these approaches have several limitations that lead to inaccurate estimates. QIC’s estimation approach considers historical resource usage (not the available physical resources) [46], while piStream’s technique relies on second-level video segment downloads and thus does not account for the short timescale variations in link rate required for per-packet congestion control. These inaccuracies stem from the opacity of the base station’s resource allocation process at the receiver. ABC circumvents these issues by accurately estimating link capacity directly at the base station.

In VCP [45], routers classify congestion into high-level categories (i.e., low, medium, and high). Based on this classification, the router signals the sender to either perform a multiplicative increase, additive increase, or multiplicative decrease. Unlike an ABC sender, which reacts to ACKs individually, VCP sends ACKs at each RTT. This coarse-grained feedback strategy limits VCP’s effectiveness on time-varying wireless paths. For instance, it can take 12 RTTs to double the sending rate [45], whereas ABC can do so in one RTT. VCP is also incompatible with ECN, making it difficult to deploy.

8 CONCLUSION

This work does not raise any ethical issues.

This paper presented a simple new explicit congestion control protocol for time-varying wireless links called ABC. ABC routers use a single bit to mark each packet with “accelerate” or “brake”, which causes senders to slightly increase or decrease their congestion windows. Routers use this succinct feedback to quickly guide senders towards a desired target rate. ABC achieves better performance to the best existing explicit flow control scheme, XCP, but unlike XCP, ABC does not require modifications to packet formats or user devices, making it simpler to deploy. ABC is also incrementally deployable: ABC can operate correctly with multiple ABC and non-ABC bottlenecks, and can fairly coexist with ABC and non-ABC traffic sharing the same bottleneck link. We evaluated ABC using a WiFi router implementation and trace-driven emulation of cellular links. ABC achieves 30-40% higher throughput.
than Cubic+Codel for similar delays, and 2.2× lower delays than BBR on a Wi-Fi path. On cellular network paths, ABC achieves 50% higher throughput than Cubic+Codel.

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Ignoring the boundary conditions for simplicity ($q(t)$ must be $\geq 0$), the queue length has the following dynamics:

$$q(t) = eq(t) - \mu$$

$$= tr(t - \tau) + \frac{N}{d} - \mu$$

$$= \left(\frac{(\eta - 1)\mu + N}{\delta}\right) - \frac{\mu}{\delta} (x(t - \eta) - d_t)^+,$$

where in the last step we have used Eq. (1). Therefore the dynamics of $x(t)$ can be described by:

$$\dot{x}(t) = \left(\frac{(\eta - 1) + N}{\mu \delta}\right) - \frac{1}{\delta} (x(t - \tau) - d_t)^+$$

$$= A - \frac{1}{\delta} (x(t - \tau) - d_t)^+,$$  \hspace{1cm} (13)

where \(A = \left(\frac{(\eta - 1) + N}{\mu \delta}\right)\), and, \(A\) is a constant given a fixed number of flows \(N\). The delay-differential equation in Eq. (13) captures the behavior of the entire system. We use it to analyze the behavior of the queuing delay, \(x(t)\), which in turn informs the dynamics of the target rate, \(tr(t)\), and enqueue rate, \(eq(t)\), using equations (1) and (12) respectively.

**Stability:** For stability, we consider two possible scenarios

1. \(A < 0\)
2. \(A \geq 0\).

We argue the stability in each case.

**Case 1:** \(A < 0\). In this case, the stability analysis is straightforward. The fixed point for queuing delay, \(x^*\), is 0. From Eq. (13), we get

$$\dot{x}(t) = A - \frac{1}{\delta} (x(t - \tau) - d_t)^+ \leq 0.$$  \hspace{1cm} (14)

The above equation implies that the queue delay will decrease at least as fast as \(A\). Thus, the queue will go empty in a bounded amount of time. Once the queue is empty, it will remain empty forever, and the enqueue rate will converge to a fixed value. Using Eq. (12), the enqueue rate can will converge to

$$eq(t) = tr(t - \tau) + \frac{N}{\delta}$$

$$= \eta \mu + \frac{N}{\delta} (x(t - \tau) - d_t)^+$$

$$= \frac{N}{\delta} (1 + A) \mu.$$  \hspace{1cm} (15)

Note that \(\eta \mu < (1 + A) \mu < \mu\). Since both the enqueue rate and the queuing delay converge to fixed values, the system is stable for any value of \(\delta\).

**Case 2:** \(A > 0\): The fixed point for the queuing delay in this case is \(x^* = A \cdot \delta + d_t\). Let \(x'(t) = x(t) - x^*\) be the deviation of the queuing delay from its fixed point. Substituting in Eq. (13), we get

$$\dot{x}(t) = A - \frac{1}{\delta} (x(t - \tau) + A \cdot \delta)^+$$

$$= -max(-A, x(t - \tau))$$

$$= -g(x(t - \tau)),$$  \hspace{1cm} (16)

where \(g(u) = max(-A, \frac{1}{\delta} u)\) and \(A > 0\).
In [47] (Corollary 3.1), Yorke established that delay-differential equations of this type are globally asymptotically stable (i.e., \( x(t) \to 0 \) as \( t \to \infty \) irrespective of the initial condition), if the following conditions are met:

1. \( H_1: g \) is continuous.
2. \( H_2: \) There exists some \( \alpha \), s.t. \( \alpha \cdot u^2 > u(g(u)) > 0 \) for all \( u \neq 0 \).
3. \( H_3: \alpha \cdot \tau < \frac{3}{2} \).

The function \( g(\cdot) \) trivially satisfies \( H_1 \). \( H_2 \) holds for any \( \alpha \in \left( \frac{1}{2}, \infty \right) \). Therefore, there exists an \( \alpha \in \left( \frac{1}{2}, \infty \right) \) that satisfies both \( H_2 \) and \( H_3 \) if

\[
\frac{1}{\delta} \cdot \tau < \frac{3}{2} \quad \Rightarrow \quad \delta > \frac{2}{3} \cdot \tau. \tag{17}
\]

This proves that ABC’s control rule is asymptotically stable if Eq. (17) holds. Having established that \( x(t) \) converges to \( x^* = A \cdot \delta + d_t \), we can again use Eq. (12) to derive the fixed point for the enqueue rate:

\[
eq (t) = \eta \mu + \frac{N}{T} - \frac{\mu}{\delta} (x(t) - d_t) \to \mu, \tag{18}
\]

as \( t \to \infty \).

Note while, we proved stability assuming that the feedback delay \( \tau \) is a constant and the same value for all the senders, the proof works even if the senders have different time-varying feedback delays (see Corollary 3.2 in [47]). The modified stability criterion in this case is \( \delta > \frac{2}{3} \cdot \tau^* \), where \( \tau^* \) is the maximum feedback delay across all senders.

**B WI-FI EVALUATION**

In this experiment we use the setup from Figure 10a. To emulate movement of receiver, we model changes in MCS index as brownian motion, with values changing every 2 seconds. Figure 14 shows throughput and 95th percentile per packet delay for a number of schemes. Again, ABC outperforms all other schemes achieving better throughput and latency trade off.

**C LOW DELAYS AND HIGH THROUGHPUT**

Figure 15 shows the mean per packet delay achieve by various scheme in the experiment from Figure 9. We observe the trend in mean delay is similar to that of 95th percentile delay. ABC achieves delays comparable to Cubic+Codel, Cubic+PIE and Copa. BBR, PCC, Vivace-latency and Cubic incur 70-240\% higher mean per-packet delays.

**D ABC VS EXPLICIT CONTROL SCHEMES**

In this section we compare ABC’s performance with explicit congestion control schemes. We consider XCP, VCP, RCP and our modified implementation of XCP (XCP\(w\)). For XCP and XCP\(w\), we used constant values of \( \alpha = 0.55 \) and \( \beta = 0.4 \), which the authors note are the highest permissible stable values that achieve the fastest possible link rate convergence.
Figure 17: Time series for explicit schemes — We vary the link capacity every 500ms between two rates 12 Mbit/sec and 24 Mbit/sec. The dashed blue in the top graph represents bottleneck link capacity. ABC and XCP\textsubscript{w} adapt quickly and accurately to the variations in bottleneck rate, achieving close to 100% utilization. RCP is a rate base protocol and is inherently slower in reacting to congestion. When the link capacity drops, RCP takes time to drain queues and over reduces its rates, leading to under-utilization.

For RCP and VCP, we used the author-specified parameter values of $\alpha = 0.5$ and $\beta = 0.25$, and $\alpha = 1$, $\beta = 0.875$ and $\kappa = 0.25$, respectively. Figure 16 shows utilizations and mean per packet delays achieved by each of these schemes over eight different cellular link traces. As shown, ABC is able to achieve similar throughput as the best performing explicit flow control scheme, XCP\textsubscript{w}, without using multibit per-packet feedback. We note that XCP\textsubscript{w}'s 95\textsuperscript{th} percentile per-packet delays are 40% higher than ABC's. ABC is also able to outperform RCP and VCP. Specifically, ABC achieves 20% higher utilization than RCP. This improvement stems from the fact that RCP is a rate based protocol (not a window based protocol)—by signaling rates, RCP is slower to react to link rate fluctuations (Figure 17 illustrates this behavior). ABC also achieves 20% higher throughput than VCP, while incurring slightly higher delays. VCP also signals multiplicative-increase/multiplicative-decrease to the sender. But unlike ABC, the multiplicative increase/decrease constants are fixed. This coarse grained feedback limits VCP’s performance on time varying links.

Figure 17 shows performance of ABC, RCP and XCP\textsubscript{w} on a simple time varying link. The capacity alternated between 12 Mbit/sec and 24 Mbit/sec every 500 milliseconds. ABC and XCP\textsubscript{w} adapt quickly and accurately to the variations in bottleneck rate, achieving close to 100% utilization. RCP is a rate base protocol and is inherently slower in reacting to congestion. When the link capacity drops, RCP takes time to drain queues and over reduces its rates, leading to under-utilization.

E ABC’S SENSITIVITY TO NETWORK LATENCY

Thus far, our emulation experiments have considered fixed minimum RTT values of 100 ms. To evaluate the impact that propagation delay has on ABC’s performance, we used a modified version of the experimental setup from Fig. 9. In particular, we consider RTT values of 20 ms, 50 ms, 100 ms, and 200 ms. Fig. 18 shows that, across all propagation delays, ABC is still able to outperform all prior schemes, again achieving a more desirable throughput/latency tradeoff off than all other schemes. ABC’s benefits persist even though schemes like Cubic+Codel and Cubic+PIE actually improve with increasing propagation delays. Performance with these schemes improves because bandwidth delay products increase, making Cubic’s additive increase more aggressive (improving link utilization).