Optimizing Congestion Control Through Fair Queuing Detection

Maximilian Bachl\(^1\)[0000−0001−9482−7428], Joachim Fabini\(^2,3\)[0000−0002−8285−1591], and Tanja Zseby\(^3\)[0000−0002−5391−467X]

TU Wien, Vienna, Austria; firstname.lastname@tuwien.ac.at

Abstract. Low delay is an explicit requirement for applications such as cloud gaming and video conferencing. Delay-based congestion control can achieve the same throughput but significantly smaller delay than loss-based one and is thus ideal for these applications. However, when a delay- and a loss-based flow compete for a bottleneck, the loss-based one can monopolize all the bandwidth and starve the delay-based one. Fair queuing at the bottleneck link solves this problem by assigning an equal share of the available bandwidth to each flow. However, so far no end host based algorithm to detect fair queuing exists. Our contribution is the development of an algorithm that detects fair queuing at flow startup and chooses delay-based congestion control if there is fair queuing. Otherwise, loss-based congestion control can be used as a backup option. Results show that our algorithm reliably detects fair queuing and can achieve low delay and high throughput in case fair queuing is detected.

Keywords: Congestion Control · Active Measurements · Fair Queuing · Queue Management.

1 Introduction

Emerging applications such as cloud gaming \(^{24}\) and remote virtual reality \(^{14}\) applications require high throughput and low delay. Furthermore, ultra low latency communications have been made a priority for 5G \(^{29}\). We argue that for achieving high throughput as well as low delay, congestion control must be taken into account.

Delay-based Congestion Control Algorithms (CCAs) were proposed to provide high throughput and low delay for network flows. They use the queuing delay as an indication of congestion and lower their throughput as soon as the delay increases. Such approaches have been proposed in the last century \(^9\) and recently have seen a surge in popularity \(^{8,10,20,31}\). While delay-based CCAs fulfill their goal of low delay and high throughput, they cannot handle competing flows with different CCAs well \(^{39,10}\). This is especially prevalent when they compete against loss-based CCAs, the latter being more “aggressive”. While the delay-based CCAs back off as soon as queuing delay increases, the loss-based ones continue increasing their throughput until the buffer is full and packet loss
occurs. This results in the loss-based flows monopolize the available bandwidth and starve the delay-based ones \[19,28\].

This unfairness can be mitigated by using Fair Queuing (FQ) at the bottleneck link, isolating each flow from all other flows and assigning each flow an equal share of bandwidth \[13\]. Consequently, loss-based flows can no longer acquire bandwidth that delay-based flows have released due to their network-friendly behavior. In this case, delay-based CCAs achieve their goal of high bandwidth and low delay.

While FQ solves many problems regarding Congestion Control (CC), it is still not ubiquitously deployed. Flows can benefit from knowledge of FQ enabled bottleneck links on the path to dynamically adapt their CC. In the case of FQ, they can use a delay-based CCA and otherwise revert to a loss-based one. Our contribution is the design and evaluation of such a mechanism that determines the presence of FQ during the startup phase of a flow’s CCA and sets the CCA accordingly at the end of the startup.

We show that this solution reliably determines the presence of fair queuing and that by using this approach, queuing delay can be considerably lowered while maintaining throughput high if FQ is detected. In case no FQ is enabled, our algorithm detects this as well and a loss-based CCA is used, which does not starve when facing competition from other loss-based flows. While our mechanism is beneficial for network flows in general, we argue that it is most useful for long-running delay-sensitive flows, such as cloud gaming, video conferencing etc.

To make our work reproducible and to encourage further research, we make the code, the results and the figures publicly available \[1\].

1 Related work

Our work depends on active measurements for the startup phase of CC and proposes a new measurement technique to detect Active Queue Management (AQM). This section discusses preliminary work related to these fields.

**CC using Active Measurements** Several approaches have been recently proposed which aim to incorporate active measurements into CCAs.\[11,12\] introduced the CCA PCC, which uses active measurements to find the sending rate which optimizes a given reward function.\[10\] introduce the BBR CCA, which uses active measurement to create a model of the network connection. This model is then used to determine the optimal sending rate.\[7\] use Reinforcement Learning to learn CC policies. This is done by performing active measurements by varying the congestion window to evaluate which value gives the highest throughput and lowest packet loss.

**Flow startup techniques** Besides the classical TCP slow start algorithm\[37\], some other proposals were made such as Quick Start \[23\], which aims to speed
up flow start by routers informing the end point, which rate they deem appropriate. [25] investigate the impact of AQM and CC during flow startup. They inspect a variety of different AQM algorithms and also investigate FQ [27] propose “chirping” for flow startup to estimate the available bandwidth. This works by sending packets with different gaps between them to verify what the actual link speed is. [32] propose speeding up flow startup by using packets of different priority. The link is flooded with low-priority packets and in case the link is not fully utilized during startup, these low-priority packets are going to be transmitted, allowing the starting flow to achieve high throughput. If the link is already saturated, the low-priority packets are going to be discarded and no other flow suffers.

Detecting AQM mechanisms There are few publications that investigate methods to detect the presence of an AQM mechanism. [26] propose a method to detect and distinguish certain popular AQM mechanisms. However, unlike our work, it doesn’t consider FQ [8] propose a machine learning based approach to fingerprint AQM algorithms. FQ is not considered, too.

3 Concept

The overall concept is the following:

1. During flow startup, determine whether the bottleneck link deploys FQ or not.
2. If FQ is used change to a delay-based CCA or revert to a loss-based CCA otherwise.

3.1 Algorithm to determine the presence of FQ

The algorithm to determine the presence of FQ works as follows (seen from the sender’s point of view):

1. Launch two concurrent flows, flow 1 and flow 2. Initialize flow 1 with some starting sending rate and flow 2 with two times that rate.
2. After every Round Trip Time (RTT) if no packet loss occurred, double the sending rate of both flows.
3. If packet loss occurred in both flows in the previous RTT calculate the following metric:

\[ \text{loss ratio} = \frac{\text{receiving rate of flow 1}}{\text{sending rate of flow 1}} \times \frac{\text{receiving rate of flow 2}}{\text{sending rate of flow 2}} \]  

(1)

This loss ratio metric indicates if flow 2, which has a higher sending rate, achieves a higher receiving rate (goodput) than flow 1. If this is the case, there’s no FQ otherwise there is.
Fig. 1: An example illustrating our proposed flow startup mechanism. Figure 1a shows the sending rate, 1b the receiving rate in case there’s no FQ and 1c the receiving rate if there is FQ.

It is necessary to wait for packet loss in both connections because only then it is certain that the link is saturated. Our algorithm assumes that the link is saturated.

4. If FQ is used, the loss ratio is 2, otherwise it is 1. We choose 1.5 as the cutoff value.

5. Since the presence or absence of FQ is now known the appropriate CCA can be launched.

Figure 1a, 1b and 1c schematically illustrate this mechanism. We assume a sender being connected to a receiver, with a bottleneck link between them. On this bottleneck link, the queue is either managed by FQ or by a shared queue (no FQ). Figure 1a shows how the sending rate (observed before the bottleneck link) is doubled after each RTT. Furthermore, it shows that flow 2 has double the sending rate of flow 1.

Figure 1b shows the receiving rate at the receiver after the bottleneck link, if this bottleneck link has a a shared queue without FQ. In the third RTT the sending rate exceeds the link speed of the bottleneck and thus the receiving rate is smaller than the sending rate. Because no FQ is employed, flow 2 manages to have a receiving rate two times the one of flow 1.

Figure 1c shows the receiving rate of the two flows measured after the bottleneck link in case FQ is deployed. In the third RTT flow 1 and flow 2 achieve the same receiving rate because of the FQ which makes sure that each flow gets an equal share of the total capacity.
3.2 Simple delay-based CC

If FQ is detected, a simple delay-based CC is used from then on. Our algorithm is based on the two following simple rules:

1. If current rtt ≤ smallest rtt ever measured on the connection + 5ms then increase the sending rate by 1%.
2. Otherwise (current rtt > smallest rtt ever measured on the connection+5ms) decrease the sending rate by 5%.

This CCA is meant as a simple proof-of-concept to demonstrate the efficacy of our FQ detection mechanism but we do not claim it to be optimal in any way.

3.3 Fallback loss-based CC

If the absence of FQ is detected, a loss based CC is used as a fallback. We use the algorithm PCC proposed by [11]. In simplified terms, this CCA aims to maximize a utility function, which strives for high throughput and low packet loss. However, it is reasonably aggressive and does not starve when competing with other loss-based CCAs such as Cubic [17].

4 Implementation

We base our implementation on the code of PCC Vivace [12], which in turn is an improved version of PCC. The PCC code is based on the UDT library [16], which is a library that provides a reliable transport protocol similar to TCP on top of UDP. This approach is similar to QUIC [22]. An advantage of implementing our approach on top of UDP as opposed to TCP is that it is easier to develop and modify since no kernel module needs to be created and that it is more secure since the code is isolated in a user space process.

4.1 Deployment

Our approach of detecting FQ relies on using two concurrent flows between the sender and the receiver. During flow startup, user data is transmitted in two flows that the receiver must detect and reassemble. This may be a challenge for deployments since solutions that require cooperation of several instances are more difficult to deploy at a wide scale in the Internet. However, multipath TCP [18] and QUIC, which enable recombining data of several flows, are becoming increasingly prevalent and Google’s QUIC implementation has multipath support [15]. We thus argue that the actual obstacles to deployment of our solution are constantly decreasing since QUIC (mostly Google traffic) already accounts for around 10% of all Internet traffic [36] and is growing. Moreover, Apple’s macOS and iOS support multipath TCP [2] support.
5 Results

For the evaluation we use the network emulation library py-virtnet. For the experiments with FQ we use the fq module for Linux. This module keeps one drop tail queue for each flow with a configurable maximum size of packets. However, the design of our FQ detection algorithm does not assume any particular queue management algorithm being used for the queue of each flow and thus is also compatible with more sophisticated AQM mechanisms which were explicitly developed to be used in conjunction with FQ [3, 21, 38]. For the experiments with a shared queue we use pfifo, which is a simple drop tail queue which can contain up to a fixed number of packets.

5.1 Delay- vs. loss-based CC

Fig. 2: Throughput and delay of a flow controlled by the loss-based CCA Cubic on a link with a speed of 10 Mbps, a delay of 10 ms and a buffer size of 100 packets (pfifo’s default value).

First, we demonstrate empirically that delay-based CC actually has a benefit over loss-based one. On one hand, Figure 2 shows that the loss-based CC achieves a throughput of almost 10 Mbps on a 10 Mbps link, which means full utilization and an RTT that is higher than 100 ms. On the other hand, Figure 3 shows an example flow using our simple delay-based CCA and a slow start algorithm similar to the one used by the classic TCP CCA New Reno. While the delay-based flow also achieves very high utilization, delay rarely exceeds 20 ms, meaning that it is more than 5 times lower than the one of the loss-based CCA of Figure 2.

https://pypi.org/project/py-virtnet/
5.2 Comparing flows with different Congestion Controls and AQM mechanisms

In this scenario, we show an example of a flow with our mechanism that shares a bottleneck link with a flow using a loss-based congestion control.

**No FQ** The examples in Figure 4 and in Figure 5 show the loss-based Cubic compete against our delay-based CCA on a link without FQ. It is important to note that we do not use our FQ detection mechanism here but instead choose delay-based CC from the beginning to demonstrate the starvation of delay-based flows that happens when they compete against loss-based ones without FQ. In the scenario, the loss-based flow starts 5 seconds earlier and after 5 seconds, the delay-based flow joins. While the delay-based flow gains some share of the link during startup, it is pushed away by the loss-based flow later on and “starves”. We start the loss-based flow before to make sure that it has sufficient time to fill up the link.

**FQ** For a link with fair queuing, the following example results show that throughput is identical for our flow (Figure 7) and the Cubic flow (Figure 6), just that the Cubic flow’s delay is more than two times higher than the delay-based one’s. Thus, our mechanism is effective to detect if the bottleneck uses fair queuing and use a delay-based congestion control if it is the case and a loss-based one otherwise.

5.3 Accuracy of the FQ detection mechanism

To evaluate if our proposed mechanism correctly recognizes FQ in a systematic manner, we perform experiments using a wide range of network configurations:
Fig. 4: Throughput and delay of a flow controlled by the loss-based CCA Cubic on a link with a speed of 50 Mbps, a delay of 10 ms and a buffer size of 100 packets. The bottleneck is controlled by a shared queue (no FQ) and is shared with the flow of Figure 5.

We vary bandwidth from 5 to 50 Mbps, delay from 10 to 100 ms and the buffer size from 1 to 100 packets, using a grid of these parameters. For each parameter, we take 5 values, evenly spaced. Thus, we run experiments with 125 different configurations. We run each configuration once with FQ and once without. Results show that for experiments without FQ (using a shared queue), in over 99% of cases, the absence of FQ was correctly detected and in less than 1% of cases, our algorithm detected FQ even though there was no FQ. For experiments, during which FQ was actually deployed on the bottleneck link, this was correctly detected in 97% of cases and wrongly in 3% of the time. The overall accuracy is thus 98%, which we consider sufficient.

To verify the behavior of our algorithm under the presence of cross traffic, we repeated the above experiments but with one bulk traffic flow using Cubic running at the same time, which we start 5 seconds before so that it has sufficient time to gain full bandwidth. Also under these circumstances we also achieve 98% detection accuracy using our algorithm.

5.4 Systematic evaluation

Besides the examples we provided, we also conducted a more systematic comparison of the throughput and delay that our algorithm achieves: We use the same scenario as above and again vary bandwidth from 5 to 50 Mbps, delay from 10 to 100 ms and the buffer size from 1 to 100 packets. For each parameter, we take 5 values, evenly spaced, totaling 125 distinct scenarios. We use FQ at the bottleneck link. We run each scenario both using Cubic as well as our algorithm for 30 seconds each. We average the achieved throughputs and average delays from all experiments for both Cubic as well as our algorithm.
Fig. 5: Throughput and delay of a flow controlled by our delay-based CCA on a link with a speed of 50 Mbps, a delay of 10 ms and a buffer size of 100 packets. The bottleneck is controlled by a shared queue (no FQ) and is shared with the flow of Figure 4.

For Cubic, the mean throughput is 21 Mbit/s and the mean RTT is 96 ms while for our algorithm it is 26 Mbit/s and 64 ms. This shows that our algorithm can correctly determine that there is FQ and switch to the delay-based CC and that our algorithm achieves significantly lower delay (loss-based Cubic’s delay is 50% higher) and – surprisingly – higher throughput. This is astonishing considering that loss-based CCAs such as Cubic should be more aggressive in filling the link. When analyzing the results we identified that Cubic performs very poorly in scenarios with small buffers because the multiplicative decrease of Cubic is 0.7, meaning that the bandwidth is reduced by 30% after every packet loss while our algorithm only reduces it by only 5%. Thus Cubic reduces bandwidth too much after packet loss which results in underutilization of the link.

6 Discussion

During the implementation of our algorithm we noticed peculiar behavior when not using FQ. During startup, we make flow 1 have half the sending rate of flow 2. We would expect the receiving rates to be the same: flow 1 achieving around half the rate of flow 2. However, we noticed that usually flow 1 would have a receiving rate of 0. After investigating the issue we noticed that the reason was pacing: PCC (and other CCAs) such as BBR send packets in regular intervals, for example every millisecond, because sending regularly keeps the queues shorter. This behavior is called pacing. However, when there are two flows where one flow’s sending rate is a multiple of the other’s, an interleaving effect occurs: flow 1 would always send each packet slightly after flow 2 sends a packet. Then, when the packets arrive at the bottleneck, flow 2’s packet, which arrives a bit earlier, fills up the buffer and flow 1’s packet is consequently always dropped.
As a solution, we do not send packets at regular intervals during startup but always add a small random value: For example, if the sending interval were 1 ms, we would send the packet randomly in the interval from 0.5 to 1.5 ms. This solves the aforementioned problem. The insight we gained from this is that while pacing is generally supportive, it is actually harmful if several flows compete at a bottleneck without FQ and one flow’s sending rate is a multiple of the other’s.

One problem of our proposed solution occurs when the bottleneck link changes while a flow is running. For example, the bottleneck link in the beginning could be the home router, while later is it becoming another router deeper in the core network. The problem occurs if the home router supports FQ and our algorithm detects this while the router in the core network, which becomes the bottleneck later on, doesn’t support FQ. Then, our algorithm is going to use a delay-based CC because that’s what it determined to be correct in the beginning of the flow. However, later when the bottleneck changes, our algorithm is still using delay-based CC even though the current bottleneck doesn’t support FQ anymore. As a result, it might be possible that our algorithm uses the wrong CC. One way to prevent this problem from occurring is to use periodic measurements. For example, our algorithm to determine FQ could be used every 5 or 10 seconds to measure again if the current bottleneck supports FQ.

Another scenario that is worth noting is how our proposed solution deals with load balancing: In this paper we assume that both of our flows, which we use during startup to determine the presence of FQ take the same path to the host on the other side. However, with load balancing it could happen that flow 1 takes a different path than flow 2. Fortunately, several load balancing algorithms have been proposed whose aim is to make sure that connections, which use multiple paths using Multipath TCP or QUIC, stay on the same path [30, 33, 35]. Since we envision our solution to be based on Multipath TCP or QUIC load balancing
Fig. 7: Throughput and delay of a flow controlled by our delay-based CCA on a link with a speed of 50 Mbps, a delay of 10 ms and a buffer size of 100 packets. The bottleneck is controlled by FQ and is shared with the flow of Figure 6.

should not be a problem. Apple Music, for example, successfully load balances multipath connections [34].

An alternative to our algorithm could be that all routers inform the endpoints if they support FQ or not. Such a solution could, for example, use an IP or a TCP extension, which every router uses to indicate if they’re capable of FQ. Then, if every device on a path supports FQ, the client would use a delay-based CCA. However, while this solutions would achieve good results, the problem is that solutions, which require participation of every device in the Internet generally suffer from insufficient deployment because not every hardware vendor and network operator can be forced to implement the proposed solution for informing about FQ capability.

Concluding, we argue that our new flow startup method can help to increase the deployment of delay-based CC. Especially for applications that are very delay-sensitive, such as video conferencing and cloud gaming, the adoption of delay-based CC can result in a significant increase of Quality of Experience (QoE). We demonstrated that our method works using a prototype implementation using PCC but we are also confident that a similar flow startup method can also be integrated with other CCAs such as BBR.

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