

Experimental Evaluation of Multipath TCP Schedulers

Christoph Paasch¹, Simone Ferlin², Özgü Alay² and Olivier Bonaventure¹

¹ICTEAM, UCLouvain, Belgium

²Simula Research Laboratory, Fornebu, Norway

ABSTRACT

Today many end hosts are equipped with multiple interfaces. These interfaces can be utilized simultaneously by multipath protocols to pool resources of the links in an efficient way while also providing resiliency to eventual link failures. However how to schedule the data segments over multiple links is a challenging problem, and highly influences the performance of multipath protocols.

In this paper, we focus on different schedulers for Multipath TCP. We first design and implement a generic modular scheduler framework that enables testing of different schedulers for Multipath TCP. We then use this framework to do an in-depth analysis of different schedulers by running experiments on an emulator and a testbed. We consider bulk data transfer as well as application limited traffic and identify metrics to quantify the scheduler's performance. Our results shed light on how scheduling decisions can help to improve multipath transfer.

1. INTRODUCTION

Today's Internet is radically different from what it was 30 years ago, the time when the building blocks of the Internet (e.g. TCP and IP) have been specified. At that time, end hosts were connected to a single interface. However, today, end hosts often have multiple interfaces to access the world wide web. For example, smartphones are equipped with two interfaces: a WiFi and a mobile broadband (e.g., 3G/4G). Similarly, servers are multihomed and data centers present a large redundant infrastructure with many different paths between any two servers. TCP, however, is not able to efficiently utilize this multipath infrastructure as it tightly couples the data stream to the IP addresses used when establishing the connection.

Multipath TCP closes this gap between the *multipath network* and the *single-path transport*. Multipath TCP is a major extension to TCP, allowing the use of multiple paths between two end-hosts for the transmission of a single data stream [6]. This enables the pooling of resources as the paths may run across different interfaces with distinct bottlenecks, effectively increasing the goodput for the end user [13, 3]. Further, Multipath TCP permits vertical handover for mobile nodes, offloading traffic from WiFi to 3G [11]. Multi-

path TCP is best at providing these benefits with long-lasting flows. These flows may be bulk transfers or rate-limited traffic, like media streaming applications. For the latter, Multipath TCP might bring a benefit if a single network connection does not provide sufficient bandwidth or reliability. Here, not only the throughput but also the end-to-end delays, as well as buffer space requirements, become more relevant [2] as these kind of applications require a low delay-jitter. Examples in this direction are the adoption of Multipath TCP in Apple iOS7 for Siri.

There are many factors influencing the performance of Multipath TCP [15, 12]. One of them is the design of the scheduler. This scheduler is responsible for the distribution of data over multiple paths and a wrong scheduling decisions might introduce head-of-line blocking or receive-window limitation, especially when the paths are heterogeneous. In such a scenario, the user will observe high delays as well as goodput degradation for its application, resulting in poor user experience. Therefore, the scheduler can have a significant impact on the performance of Multipath TCP.

We introduce a modular scheduler framework that allows to easily change the way data is distributed over the sub-flow. Further, we evaluate different schedulers for MPTCP and provide an in-depth performance analysis considering both bulk data transfers and application-limited flows. We consider goodput and application delay as metrics. Our experiments include a broad evaluation within an emulated environment using the *Experimental Design*-approach [12] and an evaluation using real WiFi and 3G networks within the NorNet testbed [10]. We identify the impact of scheduling decisions on the performance of MPTCP and illustrate the underlying root cause for the observed behavior. We provide guidelines on the properties of a good scheduler to achieve a good performance under different scenarios. The design of such a scheduler is out of the scope and left for future work.

This paper is structured as follows. Section 2 discusses the background on MPTCP and the two main constraints that an MPTCP scheduler needs to take into account. Section 3 describes related work and the schedulers evaluated in this paper. The measurement setup for our evaluations and the experimental results are presented in Section 4. Finally, we conclude our work and discuss the results in Section 5.

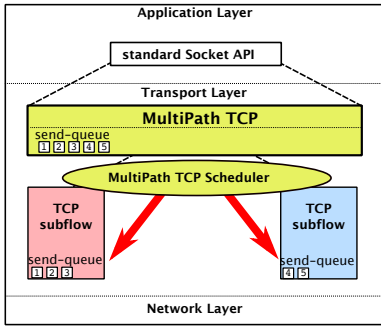


Figure 1: The scheduler distributes the segments from the Multipath TCP level on the different TCP subflows.

2. MULTIPATH TCP

Multipath TCP is a major protocol extension to TCP that supports the transmission of a single data stream across different interfaces (e.g., WiFi and 3G on a smartphone). Multipath TCP increases the goodput for the application by efficiently pooling the network’s resources [6]. This pooling is achieved by presenting a regular stream-socket interface to the application, however below this interface, TCP subflows are created for each path. These subflows form together a Multipath TCP connection, using TCP options to signal the necessary control information between the end hosts. These TCP subflows makes Multipath TCP look like regular TCP for a firewall/middlebox observing one of these subflows on a path. This makes Multipath TCP deployable on today’s Internet [15].

2.1 Exchanging Data

The pooling of the subflow’s resources is achieved by multiplexing individual segments across the different subflows. TCP options are used to allow the receiver to reorder the segments and recreate the byte stream to ensure reliable and in-order delivery. Each subflow is subject to the regular congestion control stages like slow-start and congestion-avoidance. Specific congestion control schemes are used to allow a better load balancing and fairness among the subflows [22, 9].

When multiplexing the individual segments, Multipath TCP has to decide on which subflow to schedule each segment. We call the module which takes this decision the *scheduler* in the remainder of this paper. Figure 1 illustrates the architecture of a Multipath TCP implementation, its subflows and the role of the scheduler. The scheduler has access to the state of each TCP subflow, including congestion window and RTT estimation. In the next two sections we describe two of the main constraints a Multipath TCP scheduler needs to consider.

2.2 Head-Of-Line Blocking

The TCP subflows of the Multipath TCP connection may follow paths with different characteristics. For example, a subflow going over the smartphone’s WiFi interface experiences a much lower RTT than a subflow being sent over the

phone’s 3G interface.

As packets are multiplexed across the different subflows, a delay difference among the subflows might cause out-of-order delivery at the receiver. As Multipath TCP ensures in-order delivery, the packets that are scheduled on the low-delay subflow have to “wait” for the high-delay subflow’s packets to arrive in the out-of-order queue of the receiver. This phenomenon is known as *head-of-line blocking* [18].

Head-of-line blocking causes *burstiness* in the data stream by delaying the data delivery to the application, which is undesirable especially for interactive or streaming traffic. Interactive applications will become less reactive, resulting in poor user-experience. Streaming applications will need to add a high amount of application-level buffering, stressing the end systems, to cope with *burstiness* and provide a continuous streaming experience to the end user.

2.3 Receive-Window Limitations

A TCP stack reserves a certain amount of memory for out-of-order data that might be received in the event of in-network reordering or packet loss. Multipath TCP introduces reordering across the TCP subflows due to the delay differences, hence the receive buffer has to accommodate out-of-order data also at the MPTCP level. Thus, the size of the receive buffer is critical to allow high goodput.

In order to fully utilize the capacity of all paths, a receiver must provide enough buffer space so that the sender can keep all subflows fully utilized - even in the event of reordering due to delay differences. The recommendation for Multipath TCP’s receive buffer size is defined in [1]:

$$\text{Buffer} = \sum_i^n bw_i \times RTT_{\max} \times 2$$

where each subflow will be able to send at full speed ($\sum_i^n bw_i$) during the time-interval of the highest round-trip-time (RTT) among all subflows (RTT_{\max}),- even if a loss event occurs (multiply by 2).

Some end hosts, however, are not able to provide the necessary amount of memory to allocate enough buffer to utilize the full capacity [2]. This phenomenon has been studied in [15, 12], proposing incremental changes to the heuristics within Multipath TCP by retransmitting segments and penalizing subflows, detailed in the following section.

3. SCHEDULERS

A wrong scheduling decision might result in head-of-line blocking or receive-window limitation, affecting the performance of Multipath TCP - as discussed in the previous section. Accurately scheduling data across multiple paths while trying to avoid head-of-line blocking or receive-window limitation has been shown to be a difficult problem, in particular if the multiple paths are heterogeneous. How to schedule different SCTP streams across the different SCTP associations has been analyzed in [19]. However, SCTP design is different from Multipath TCP. SCTP does not support the

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MPTCP: An MPTCP connection, ready to send data.
MPTCP->sched represents a structure containing
the specific callbacks.
1: subflow = MPTCP->sched->get_subflow();
2: while subflow != NULL do
3:   data = MPTCP->sched->get_data(subflow);
4:   while data != NULL do
5:     send_data(subflow, data);
6:     data = MPTCP->sched->get_data(subflow);
7:   end while
8:   subflow = MPTCP->sched->get_subflow();
9: end while

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Figure 2: Pseudocode of the modular scheduler framework, using callbacks to invoke the scheduling functions.

transmission of a single stream across different paths. [17] tries to achieve ordered delivery at the receiver by taking the delay of each path into account. While in theory this is a promising approach, it is unclear how feasible it is in a real-world kernel implementation where only a rough estimate of the path’s delay is available to the scheduler.

In this paper, we implemented a modular Multipath TCP scheduler framework¹. Whenever the stack is ready to send data (e.g., an acknowledgement has freed up space in the congestion window, or the application pushed data on the send-queue), the scheduler is invoked to execute two tasks: first, choose a subflow among the set of TCP subflows and; second, decide which segment to send considering the properties of this subflow. We added callbacks from the MPTCP stack that invoke the functions specific to each scheduler. A pseudo-code implementation of this behavior can be seen in Figure 2. This allowed us to design the scheduler in a modular infrastructure, as it is done with the TCP congestion control algorithms [21]. A *sysctl* allows to choose the default scheduler for all Multipath TCP connections, and further socket-options allow the user-space application to explicitly set the scheduler for a particular connection.

Within our modular framework, we consider different schedulers. First, we discuss a simple round-robin scheduler. Then, considering the heterogeneous networks where significant delay differences are observed between the subflows, we discuss delay-based schedulers. A first evaluation of schedulers has been done in [20]. But only a limited environment has been used in the evaluation and improvements to the schedulers [15] were not yet part of the Multipath TCP implementation.

3.1 Round-Robin (RR)

The round-robin scheduler selects one subflow after the other in round-robin fashion. Such an approach might guarantee that the capacity of each path is fully utilized as the distribution across all subflows is equal. However, in case

¹The code will be publicly available at <http://multipath-tcp.org>

of bulk data transmission, the scheduling is not really in a round-robin fashion, since the application is able to fill the congestion window of all subflows and then packets are scheduled as soon as space is available in each subflow’s congestion window. We call this effect *ack-clock*.

Such a scheduler has already been discussed for concurrent multipath transfer SCTP [7]. [5] evaluates how such a round-robin scheduler behaves in CMT-SCTP for multi-streaming compared to a scheduler that assigns each stream to a specific path.

3.2 Lowest-RTT-First (LowRTT)

In heterogeneous networks, scheduling data to the subflow based on the lowest round-trip-time (RTT) is beneficial, since it improves the user-experience. It reduces the application delay, which is critical for interactive applications. In other words, the RTT-based scheduler first sends data on the subflow with the lowest RTT estimation, until it has filled the congestion window (as it has been first described in [15]). Then, data is sent on the subflow with the next higher round-trip time.

The same way as the round-robin scheduler, as soon as all congestion windows are filled, the scheduling becomes *ack-clocked*. The acknowledgements on the individual subflows open space in the congestion window, and thus allow the scheduler to transmit data on this subflow.

As explained in Section 2, the delay difference triggers head-of-line blocking and/or receive-window limitation. Next, we discuss two extensions to the RTT based scheduler. The first solution reacts upon receive-window limitation, and the second solution minimizes the delay difference in the presence of bufferbloat on the individual subflows.

3.3 Retransmission and Penalization (RP)

In order to compensate for delay differences, *opportunistic retransmission and penalization* for Multipath TCP have been proposed by [15]. Opportunistic retransmission re-injects the segment causing the head-of-line blocking on the subflow that has space available in its congestion window (similar to chunk rescheduling for CMT-SCTP [4]). This allows to quickly overcome head-of-line blocking situations and compensate for the RTT differences. Further, the penalization algorithm reduces the congestion window of the subflow with the high RTT, hence, reducing the sending rate and the effect of bufferbloat on the subflow.

Particularly, the goal is not only to improve the goodput, but also to reduce the delay, jitter and buffer size requirements.

3.4 Bufferbloat Mitigation (BM)

Following similar observations from Section 3.3, another source for high RTTs are large buffers on routers and switches along the subflow’s path. TCP will try to fill these buffers creating bufferbloat, resulting in very high RTTs.

The *bufferbloat-mitigation* algorithm caps the RTTs by

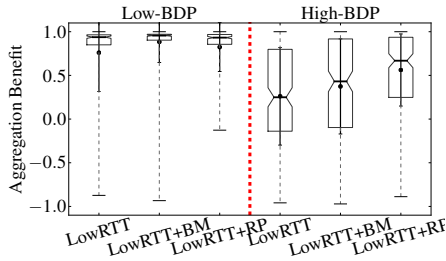


Figure 3: Mininet: In high-BDP the connection becomes receive-window limited and BM and RP show their benefits.

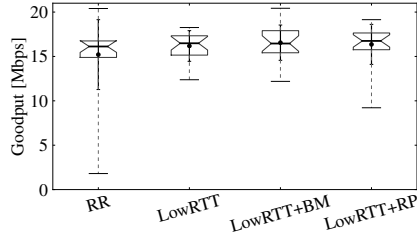


Figure 4: NorNet: With unbounded buffers (16MB), each scheduler achieves the goodput.

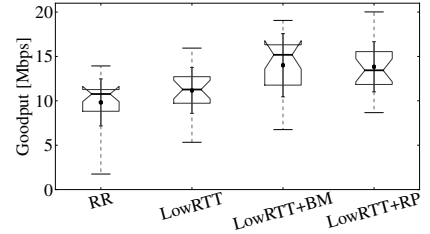


Figure 5: NorNet: With bounded buffers (2MB), LowRTT+BM and LowRTT+RP achieve the best performance.

limiting the amount of data to be sent on each subflow, hence, controlling the bufferbloat [16]. The goal here is not to significantly improve goodput, but instead, to improve the application delay-jitter and reduce buffer size requirements.

The main idea behind the bufferbloat-mitigation algorithm is to capture bufferbloat by monitoring the difference between the minimum smoothed RTT ($sRTT_{min}$), and smoothed RTT ($sRTT$). Whenever $sRTT$ drifts apart from $sRTT_{min}$ on the same subflow, as a result of sending data, we take it as an indication of bufferbloat. Therefore, we cap the congestion window for each subflow by setting an upper bound $cwnd_{limit}$.

$$cwnd_{limit} = \lambda \times (sRTT_{min}/sRTT) \times cwnd.$$

where λ determines the *tolerance* between $sRTT_{min}$ and $sRTT$. Within the remainder of this paper, we fix λ to 3, which has proven to bring the best results, as has been analyzed in [16].

4. EVALUATION

Traffic characteristics and the environment, where the TCP subflows trespass, influence the schedulers' performance. This section evaluates two Multipath TCP metrics, namely goodput and application delay-jitter in emulated and real-world experiments.

4.1 Experiment and Emulation Setup

Within *Mininet* the *Experimental Design* approach [12] is used, where we set both low- and high-BDP environments to evaluate the schedulers. The Multipath TCP implementation used in all our evaluations is based on release 0.88².

The real-world environment uses the *NorNet* testbed [10]. We consider the smartphone use case where we utilize both WLAN and 3G (UMTS) interfaces to evaluate the MPTCP performance with heterogeneous links. The WiFi connection uses a public WLAN, connecting ca. 100 people during work hours in a large office complex with several other interfering WLAN networks. On the system level, we continuously flush all cached TCP metrics to avoid any dependency between experiments. Finally, the Olia congestion

control [9] is used in all experiments. Similar results were obtained with the coupled congestion control scheme [22].

4.2 Bulk-Transfer

One of the goals of Multipath TCP is to increase the application goodput [14], which can be measured by transferring bulky data between two Multipath TCP capable end hosts.

Mininet.

Within *Mininet* we generate a bulk-transfer using *iperf*, where each transfer lasts for 60 seconds. Our measurements cover 400 different settings, classified as low-BDP and high-BDP environments. For detailed information about the test environments as well as the system-level settings, we refer to [12]. Here, we measure the *aggregation benefit*, which is a normalization of the benefit in terms of goodput when using Multipath TCP. For example, a value of -1 indicates the achievable minimum, while 0 means that Multipath TCP achieves the same goodput as regular TCP on the best path, and 1 means that Multipath TCP perfectly aggregates the available capacity. More information about the aggregation benefit metric can be found in [8, 12].

Figure 3 shows the *Mininet* results. We skip the RR scheduler since it performs similar to LowRTT. This is because in bulk-transfers the TCP subflows are saturated and are thus controlled by the *ack-clock*. Therefore, available space in the congestion window controls the way packets are multiplexed across the subflows rather than the scheduler.

In the low-BDP environment there is no significant difference between schedulers. Each of them achieves close to perfect bandwidth aggregation. Only the RP algorithm improves the worst-case result among the 200 experiments to achieve an aggregation benefit equal to the best available path. In the high-BDP environment receive-window limitations may occur. In this case the RP and BM techniques described in Section 3.3 and 3.4 improves the aggregation benefit. The RP technique has a higher benefit in the lower 25th percentile and the median. This is thanks to the retransmission of the blocking segment as the receive-window limitation in these cases is not due to bufferbloat but rather due to a difference in the baseline RTT.

²<http://multipath-tcp.org>

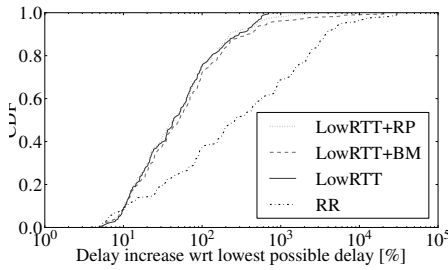


Figure 6: Mininet: Using the lowest-RTT-first scheduler greatly reduces the application-delay variance in Mininet.

NorNet.

Within NorNet Edge we tested bulk-transfers of 16 MB files in downlink with both bounded (2 MB) and unbounded (16 MB) buffers. The bounded buffers will make the connection more likely to be limited by the receive window. We repeat each measurement around 30 times for each configuration. All measurements are performed in the same networks and at the same locations over a period of 3 weeks.

Figure 4 shows the MPTCP goodput, for all schedulers. For a bulk-transfer with unbounded buffer sizes (16 MB), the aggregation benefit of MPTCP across all schedulers is similar. Each scheduler is able to efficiently aggregate the bandwidth of WLAN and 3G together within the NorNet testbed. The unbounded buffers allow for sufficiently large memory, so that no receive-window limitation occurs.

However, if the receive buffer is bounded (as it is often the case on a smartphone), the MPTCP connection may become receive-window limited. Figure 5 shows the MPTCP goodput in this case. Here, one can see that LowRTT+BM slightly outperforms the other schedulers. In case of the LowRTT+RP scheduler, the effect of bufferbloat is not optimally reduced by the penalization algorithm, as it does not manage to bring the congestion window sufficiently down so that the delay-difference is reduced. This happens, because the RP algorithm is reactive and does the penalization only after a limitation happened. The BM algorithm is proactive and prevents a high delay-difference beforehand and thus achieves a higher goodput.

4.3 Application-Limited Flows

This section evaluates the impact of the schedulers on delay-jitter with rate-limited traffic, i.e., when the application is not saturating the connection. In this case, the scheduler has available space in all subflows and should select the one that guarantees the lowest delay for each segment.

In order to evaluate the delay-jitter we created an application that sends traffic at a specific rate in blocks of 8 KB. The receiver tracks the timestamps at which each block has been received. As the sender transmits at a constant rate, the receiver is able to detect the delay with respect to the desired packet-arrival time.

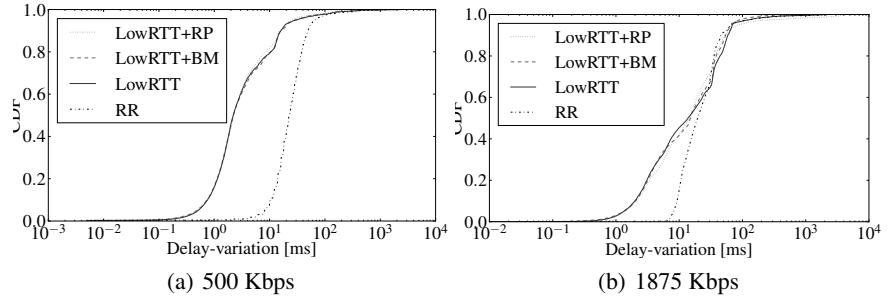


Figure 7: NorNet: 3G and WLAN with unbounded (16 MB) buffers

Mininet.

Within Mininet we ran this application in the high-BDP environment of the *Experimental Design* approach, for a total of 200 experiments. Figure 6 shows the CDF of the worst-case relative delay increase. The delay increase is expressed in % compared to the lowest one-way delay. E.g., if the minimum one-way delay is 20 ms, but a block of 8 KB has been received rather after 40 ms the relative delay increase has a value of 100%. We show the worst delay-increase among all 8 KB blocks of each experiment as this will affect the user-experience.

In Figure 6 it is visible that the RR scheduler is particularly bad in terms of application delay. 70% of the experiments using the LowRTT scheduler have a range between 10 and 100% of delay-increase. Using a RR scheduler, roughly 40% of the experiments have a delay-increase between 100 and 1500%. Such delay increases has significant impact on delay-sensitive applications since they would need to maintain large buffers to react upon these delay-spikes.

NorNet.

Within NorNet we evaluate the delay-jitter using rate-limited applications transmitting at 500 Kbps and 1875 Kbps in downlink, using unbounded buffers. The values for the application-limited rates are at approximately 5 and 10% of the mean goodput of the bulk-transfer. We repeat each measurement around 30 times for each configuration.

Figure 7 shows the variation of the application delay for all schedulers. One can see that in all application-limited scenarios, RR performs mostly worse compared to all other schedulers. More prominent, in Figure 7(a), RR's delay-variance shows to be up to 10 times worse compared to LowRTT. This can be explained as RR simply schedules data based on congestion-window space, which is not a limiting factor in this particular scenario. Looking into our dataset, one can see that both subflows carry similar amount of data, thus increase head-of-line blocking.

For all other schedulers we observe that for very low application rates, see Figure 7(a), MPTCP LowRTT utilizes mainly one subflow, the subflow with lowest RTTs. This is because the congestion window space is not a limiting factor,

and it has mostly enough space to carry all data available.

By increasing the application rate, see Figure 7(b), MPTCP LowRTT performs in at least 60% of the cases up to 10 times better compared to RR. The remaining 40% can be explained as we see that the subflow with the higher RTT (3G network) contributes more compared to the scenario in Figure 7(a). This happens, because at a higher sending rate, occasional congestion on the WiFi network will make the LowRTT scheduler send traffic on the 3G subflow. This will introduce head-of-line blocking due to the higher delay over the 3G network and thus increases the delay-variation.

We also evaluate the delay-jitter when sending at unlimited rate within the NorNet testbed. In this case, both WiFi and 3G are fully utilized and bufferbloat might happen on the 3G path. We observe that the LowRTT+BM scheduler effectively reduces the bufferbloat and keep the application delay lower compared to other schedulers.

5. DISCUSSION

In this paper, we have proposed and implemented a modular scheduler selection framework that allows Multipath TCP to change the way data is multiplexed across the different TCP subflows. We used this framework to experimentally evaluate schedulers in a wide variety of environments in both emulated and real-world experiments. In these environments, we could quantify the performance of different schedulers, and scheduler extensions, with respect to goodput as well as application delay-jitter.

We discovered that a bad scheduling decision triggers two effects: First, head-of-line blocking if the scheduler sends data across a high-RTT subflow. Second, receive-window limitation, which prevents the subflows from being fully utilized. We have shown that a simple strategy to preferentially schedule data on the subflow with lowest RTT (LowRTT) helps to reduce the application delay-jitter compared to a simple round-robin (RR) scheduler.

Furthermore, the RP extension helps to mitigate receive-window limitation, albeit it is a reactive method, i.e., it tries to recover from receive-window limitation. We have discovered that in some cases this is not sufficient. If the delay-difference is very high due to huge bufferbloat, the penalization will not manage to bring the congestion window sufficiently down. Also, anecdotal evidence has shown that the penalization may hurt, if two subflows are unfortunately sent through the same bottleneck. The bufferbloat mitigation technique helps in these cases, but cannot overcome a large difference in the baseline RTT. Further, the delay-based congestion-window capping may also suffer from the known limitations of delay-based congestion controls when the bottleneck is shared with other flows that do not deploy the same window capping.

Multipath scheduling should ideally be done in a way that the data is received in-order. This minimizes head-of-line blocking and receive-window limitation as applications are able to continuously read data out of the receive queue. How-

ever, it is not trivial to design such a scheduler with rough estimations on capacity or RTTs of the paths, maintained by the kernel. In our future work we plan to extend our evaluation framework to a larger set of traffic classes (including cross-traffic and on/off flows). Our modular scheduler framework will be made available to enable researchers to explore and contribute with other new findings.

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