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LETTER

Toward a resource pooling fairness: Balancing congestion in practical congestion control for named-data networking

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Abstract Resource pooling is an important fairness concept for multi-path congestion control. Practical congestion control (PCON) in Named-Data networking (NDN) is common congestion control in NDN. Previously, we showed that PCON cannot fully achieve resource pooling fairness due to the lack of design policy. In this paper, to improve the fairness of PCON, we introduce our proposed AQM enhancement for PCON and newly propose a suppression method to excessive window reduction caused by simultaneous congestions on multiple paths. Furthermore, we propose a flow-aware traffic steering technique for balancing congestion inspired by a MPTCP's design policy. The combination of these techniques dramatically improves fairness among consumers and quickly brings us achieving closer to the complete resource pooling state. Specifically, the overall throughput among users was improved, and then fairness index became quite high, i.e. 0.998.

Keywords: NDN, ICN, fairness, congestion control
Classification: Internet

1. Introduction

Information-Centric Networking (ICN) architecture has gained attention with the aim of improving data retrieval efficiency, and one of the representative ICN protocols is Named-Data Networking (NDN) [1]. NDN protocol is based on the content-centric (location-agnostic) concept of allowing content retrieval from anywhere in the network, and thus it is also possible to retrieve a content from multiple locations/sources. In NDN, practical congestion control (PCON) [2] has been proposed as a multi-path congestion control scheme retrieving a content from multiple sources and widely used.

Resource pooling [3] is an important concept of fairness proposed in TCP/IP targeting content retrieval with multiple paths. The *global fairness* targeted by resource pooling is not the micro-level fairness fairly sharing a single link, a.k.a TCP *local fairness*, but the macro-level or user-level fairness of sharing multiple links across multiple paths. MPTCP [4] is one of the representative multi-path congestion control schemes enabling resource pooling in TCP/IP.

In our conference paper [5], we have shown that NDN multi-path congestion control, PCON, does not achieve resource pooling well through simulation-based performance evaluations. We investigated the reason why PCON falls into the local fairness and is not able to achieve the global fairness based on the resource pooling concept. To resolve this fairness issue, we have proposed an enhanced Active Queue Management (AQM) mechanism interactive with PCON's congestion control to improve the global fairness. Our proposed AQM mechanism partially improved the global fairness performance among users. However, there are still challenging issues: 1) overall throughput for all consumers slightly decreased due to our proposed AQM enhancements; 2) it takes long convergence time for each consumer to stabilize throughput at the fair state; and 3) there is a room for further improvement toward the global fairness.

In this paper, we newly propose a suppression method to excessive reduction of congestion window caused by congestion marks simultaneously arriving from multiple paths. Also, we propose a flow-aware traffic steering technique to balance congestion inspired by a MPTCP's design policy. The combination of these techniques dramatically improves fairness among consumers and quickly brings us achieving closer to the complete resource pooling state. Specifically, the overall throughput among users was improved and then fairness index became 0.998. The convergence time of each consumer's throughput was reduced by approximately half.

The remainder of this paper is organized as follows. Section 2 describes our background technologies, PCON and MPTCP. In section 3, we introduce our proposals. Section 4 presents simulation results. Section 5 summarizes this paper and discusses the future work.

2. Background

2.1 PCON

PCON is a representative NDN multi-path/multi-source congestion control scheme. PCON detects congestion by measuring packet queuing delay at a router based on the CoDel AQM mechanism [6] and signals it toward a consumer by explicit marking on a data packet. When the consumer received the marked data, it decreases `cwnd`. When a router detects a congestion by measuring the queueing delay of the transmit queue, it applies explicit marking to enqueued Data packets at CoDel intervals (default=110ms) until congestion is relieved.

At a branching router that received the congestion notification from the upstream, the router changes the forwarding percentage of the face that bounds for the congested path. Normally, in the initial state, the forwarding percentage is

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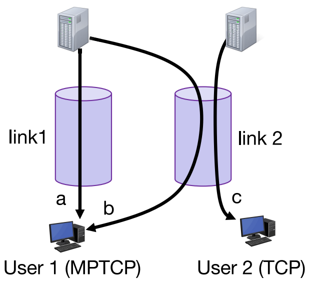


Fig. 1 MPTCP.

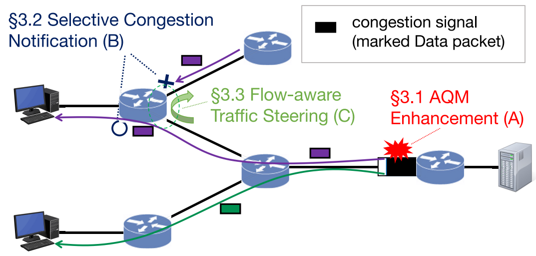


Fig. 2 Overview of our proposal.

coordinated to the shortest path, i.e., it is initialized with 100%. To reduce the traffic, the forwarding percentage will be updated to the new percentage which is calculated by the following equation.

$$reduction = fwPerc(F) * \frac{CHANGE\_PERC}{f(Distance)} \quad (1)$$

$$fwPerc(F) -= reduction \quad (2)$$

$$fwPerc(\bar{F}) += \frac{reduction}{NUM\_FACES - 1} \quad (3)$$

$fwPerc(F)$ is the forwarding percentage of the current face and $CHANGE\_PERC$ is a fixed parameter. 1% – 3% is recommended to work well for a number of different bandwidths. With these procedures, PCON moves data traffic passing through a congested link on multiple paths toward the other multiple sources (servers).

2.2 Multipath TCP

MPTCP has been designed to achieve resource pooling by accomplishing the following three design goals: 1) *Improve throughput* – A multi-path flow should perform at least as well as the single-path flow which would have obtained the best throughput. This ensures that a user has an incentive to deploy multi-path; 2) *Do no harm* – A multi-path flow should not obtain any more capacity on each path than if it would have obtained in a single path case. This guarantees that multi-path does not excessively harm other flows; and 3) *Balance congestion* – A multi-path flow should move as much traffic as possible off its most-congested paths, subject to meeting the first two goals.

Figure 1 helps to understand the above three goals of the MPTCP. The goal 1 requires that total throughput achieved by User 1 using MPTCP is greater than or equal to the throughput achieved using a single path, specifically only link 1. This can be an incentive for users to utilize MPTCP. The goal 2 specifies that the throughput obtained by User 1's subflow from link 2 using MPTCP must not exceed the throughput achieved by regular TCP on link 2. The goal 3 is a condition that aims to steer traffic from a congested paths to non-congested paths while achieving the goals 1 and 2. In this example on Fig. 1, MPTCP moves the traffic from link 2 to link 1 as much as possible. This enables the network resources (link1 and link2) to be regarded as a single pooled resource, which can be fairly shared among users (User 1 and User 2). By satisfying these three conditions, MPTCP achieves a resource pooling.

3. Proposal

Inspired by the MPTCP resource pooling concept, we propose congestion control schemes in cooperation with traffic steering function inside routers to improve the global fairness performance. Figure 2 illustrates an overview of our proposal, which is composed of the three components as follow.

A: AQM enhancement (§3.1)
We enhanced the marking scheme implemented in PCON's CoDel AQM for balancing congestion. The detailed evaluation results and performance analysis can be seen in our conference paper [5]. In this paper, we just introduce a summary of our proposed AQM enhancements and its limitations.

B: Selective congestion notification (§3.2)
With the above AQM enhancement, excessive congestion notifications may be replied to a consumer in some cases. The excessive congestion feedback may degrade total throughput performance of consumers, we selectively limit congestion notification by intermediate routers to avoid unnecessary window decrease.

C: Flow-aware traffic steering (§3.3)
The above two functions are transport-layer approaches. We newly add a new function as a network-layer approach because they cannot directly handle traffic load on congested path. Thus, we propose a flow-aware traffic steering scheme that migrate data traffic passing through a congested path to the other paths while meeting the third goal "balance congestion."

3.1 AQM enhancement

In the PCON's marking scheme, only the first packet will be marked for each CoDel interval. Thus, the marking frequency for each flow depends only on the traffic volume flowing into the bottleneck link. This is believed to be the cause of PCON falling into local fairness as we reported previously in [7].

In our proposed approach [5], we utilize consumer's congestion window size (`cwnd`) as a means to estimate the total traffic volume not only on the bottleneck path but also on the other paths for enhancing the PCON's marking scheme. We consider that flows with larger `cwnd` are utilizing more bandwidth from other paths (not congested paths), so that we increase the marking frequency for these flows. By increasing marking frequency for a particular flow, we reduce data traffic amount passing through that path. This idea is based on the fundamental concept of resource pooling [3] which states that *"Network's resources should behave as though they make up a single pooled resource."* This implies congestion window size of consumers sharing the network should be equalized. Another concept is Balance Congestion, which is one of the MPTCP's design goals *"A multi-path flow should move as much traffic as possible off its most-congested paths."* [4] as mentioned previously. This brings us closer to achieving resource pooling.

3.2 Selective congestion notification

In [8], it is shown that when controlling the transmission rate of a multicast source based on loss indications from receivers within the multicast tree, there is a possibility that the rate may be completely throttled as the number of loss paths increases. This is because there is a possibility that a transmitted packet may be lost on one or more of the many end-to-end paths. This problem is called as the loss path multiplicity (LPM) problem.

In multi-path communication in IP (MPTCP), where an end-host retrieves data via multiple paths, there is a potential to arise the LPM problem. However, in MPTCP, path identification is possible, and congestion window is maintained for each path. Responding to a congestion notification on a particular path, the sending host can independently adjust the transmission rate for each path. Accordingly, the sending host does not receive negative effects from the congestion on the other paths and thereby preventing the LPM problem.

NDN naturally supports data retrieval using multi-source/multi-path for a desired content. It also seems to have a possibility of receiving congestion notifications simultaneously from multiple sources via multi-path, which can potentially lead the LPM problem. However, unlike IP, NDN is an information-centric network architecture. A consumer maintains a single congestion window for a desired content even if the content download path is branched to the multiple paths. For that reason, the NDN consumer is unable to identify from which branching path the congestion notification has been received, making it more challenging to address the LPM problem.

To address this issue, we propose a suppression method for the LPM problem in multi-path communication in NDN. Since branching routers are located at the branching points of multi-path, they can identify the congested path by recognizing interfaces receiving congestion signals. With this identification, it is possible to selectively choose an interface for a receiving congestion signal. In our proposed approach, when the branching router closest to the consumer receives a congestion notification from one interface, the router does not propagate the congestion notifications which will be subsequently received from other interfaces downstream to the consumer during a CoDel-interval (110ms). With these procedures, only one (the first) congestion signal is replied to consumers per congestion in the CoDel-interval.

3.3 Flow-aware traffic steering

"Balance Congestion" explained in §2.2 (3) is one of the most important design goals of MPTCP which achieves resource pooling, and aims to move traffic from a congested path to the other non-congested paths. To achieve this, we propose a traffic steering method that actively moves traffic from congested paths to the non-congested paths. The number of flows on a link strongly related to the degree of congestion, and thus we consider that links with a larger number of shared flows experience worse congestion compared to the other links with a smaller number of shared flows.

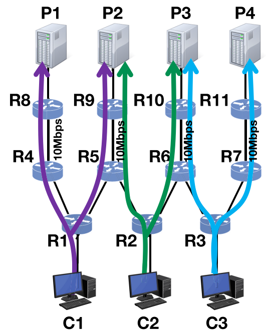


Fig. 3 Evaluation topology.

To realize such traffic migration, we adopt a network-layer approach and propose flow-aware traffic steering method, a.k.a. forwarding strategy in NDN. This method aims to increase the reduction rate of interest forwarding percentage to the interface that received a congestion mark from a branching path. The reduction ratio of forwarding percentage is calculated based on the following equation;

$$
\begin{aligned}
&reduction \\
&= fwPerc(F) * \frac{CHANGE\_PERC}{f(Distance)} * Num\_of\_Flows
\end{aligned}
\tag{4}
$$

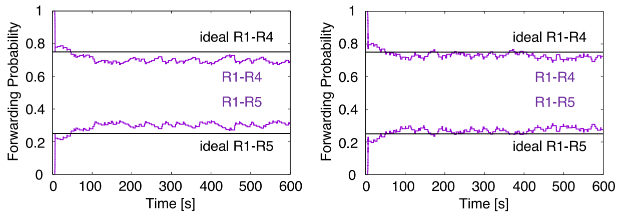
where Num_Of_Flows is the number of flows sharing a bottleneck link. We measure the number of flows sharing a link by looking up PIT entries like the method studied in [9]. When a router marks a data packet, this flow information is added to the data packet. When a branching router receives a congestion marked data packet, the router updates its forwarding percentage according to the above reduction ratio. By doing this, traffic concentrated on the congested link with a large number of flows will be moved to the other links while ensuring "balance congestion" concept of MPTCP.

4. Performance evaluation

Figure 3 shows evaluation topology. Propagation delay of each link is 10 ms. The capacity of bottleneck link is 10 Mbps. For comparison, we implemented 4 evaluation methods, PCON, A, A+B, and A+B+C, as described in section 3, i.e., A: AQM enhancement, B: Selective congestion notification, and C: Flow-aware traffic steering, in the ns-3-based NDN simulator called ndnSIM.

Table I summarizes performance of all consumers for each method in terms of the average throughput and Jain's fairness index. When the fairness index is equal to 1.0, we can say that the resource pooling completely achieved. PCON has poor performance, i.e., fairness index = 0.973 because it does not consider the resource pooling's fairness concept.

To resolve the PCON's unfairness issue, we proposed a



(a) A+B. (b) A+B+C.

Fig. 4 Forwarding percentage at R1.

method A, an AQM enhancement[1] to equalize their cwnd of all consumers based on the concept of resource pooling. This method regards multiple resources (link R4-R8, R5-R9, R6-R10, R7-R11) as a single pooled resource, and tries to share it equally. As a result, throughput of C2 largely increased, and fairness index was improved to 0.990. However, the total throughput slightly decreased from 32.9 to 32.8. As mentioned previously, there is another important goal 1 (Improve throughput), which is one of the mandatory conditions to achieve the resource pooling in MPTCP. It is not preferable to degrade the total throughput performance of all consumers even if the fairness was improved.

With our method B, the branching router (R2) decides whether to selectively forward received congestion notifications or not. If the received notification was the first arrival after a congestion in the CoDel interval, the branching router just forwards the first signal, and the other late arrival will not be forwarded for avoiding excessive window reduction at the consumer. As a result, the combination of methods A and B can mitigate effects of unnesessary window reduction at the consumer, and total throughput performance was improved. The most congested consumer (C2) can benefit from this effect, and its throughput was increased from 9.4 to 9.8. Therefore, fairness index was improved to 0.993.

Figure 4 shows forwarding percentage characteristics at R1. The ideal percentage values should be 0.75 for R1-R4 and 0.25 for R1-R5, respectively. As shown in Fig. 4(a), with only method A+B, the forwarding percentages converge to non-ideal points, 0.698 and 0.302. This means the method A is focusing on the balance congestion but it is not enough. With a routing-based approach, method C, the number of flows is used for the traffic steering, and the forwarding percentages converge close to the ideal values, i.e. 0.727 and 0.273.

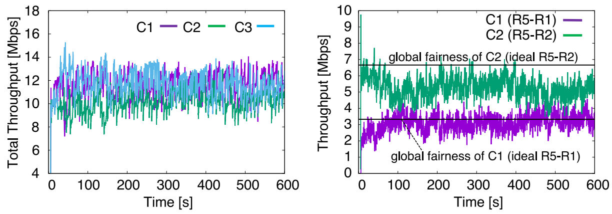
The rightmost column of Table I shows the combinational performance of the methods A, B, and C. Our proposed method C is based on the third goal of the concept of resouce pooling principle, i.e., balance congestion. On links R5-R9 and R6-R10, the number of flows is relatively large compared to the links R4-R8 and R7-R11. With method C, we can move the data traffic on the most congested path (links R5-R9 and R6-R10) to the non-congested paths (links R4-R8 and R7-R11).

Figure 5 shows throughput characteristics of A+B+C. As shown in Fig. 5(a), all consumers almost equally share the total throughput. This is because on link R5-R9, consumer C1 moves traffic to the not-congested link (link R4-R8) as

[1] The detailed explanation and performance analysis of our AQM enhancement can be found in our conference paper [5].

Table I The average throughput and fairness performance.

	PCON	A	A+B	A+B+C
C1	12.1	11.5	11.5	11.7
C2	8.4	9.4	9.8	10.6
C3	12.4	11.9	11.9	11.7
total [Mbps]	32.9	32.8	33.2	34.0
fairness index	0.973	0.990	0.993	0.998



(a) Total. (b) Bottleneck link (R5-R9).

Fig. 5 Throughput characteristics.

shown in Fig. 5(b). Throughput performance of each subflow is close to the global fairness line. The method C can conduct a resource-pooling-aware traffic migration by adequately adjusting forwarding percentages of the branching routers. With these approaches, i.e., not only congestion control but also request-forwarding-based traffic load balancing, we can achieve close to the ideal resource pooling performance, and the fairness index increased to 0.998.

5. Conclusion

In this paper, we first introduced PCON's technical issues that PCON cannot achieve the global fairness, which is an important concept in multi-path congestion control. Then, we proposed three methods inspired by resource pooling principles for balancing congestion on multiple paths in NDN. We revealed that the combination of our proposals can achieve quite high resource pooling fairness compared to the original PCON. In future work, we plan to conduct experiments with more various network environment with heterogeneities on available bandwidth and latency.

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