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Towards an incremental deployment of ERN protocols: a proposal for an E2E-ERN hybrid protocol

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ABSTRACT

We propose an architecture based on a hybrid E2E-ERN approach to allow incremental deployment of ERN (Explicit Rate Notification) protocols in heterogeneous networks. The proposed IP-ERN architecture combines E2E (End-to-End) and ERN protocols and uses the minimum between both congestion windows to perform. Without introducing complex operation, the resulting E2E-ERN protocol provides inter and intra protocol fairness and benefits from all ERN protocol advantages when possible. We detail the principle of this novel IP-ERN architecture and show that this architecture is highly adaptive to the network dynamic and is compliant with IPv4, IPv6 as well as IP-in-IP tunneling solutions.

Keywords

Explicit Rate Notification, E2E, TCP, XCP, Gradual deployment

1. INTRODUCTION

TCP New Reno (denoted standard TCP in the rest of the paper) was the dominant protocol in charge of providing congestion control, fair share and full utilization of the network resources. Standard TCP provides good performance in terms of link utilization in networks with short propagation delay (only a few ten of milliseconds) and low bandwidth (less than 100Mb/s). However, this TCP variant is known to obtain poor performance in large bandwidth×delay product (LBDP) networks.

Following the pervasive deployment of gibabit links, large bandwidth×delay product (LBDP) networks are now common in the Internet. To solve the problem of standard TCP over LBDP networks, high speed variants have been proposed such as CUBIC [1] (currently enabled by default in GNU/Linux systems), Compound TCP (deployed in recent Windows systems) [2] and High Speed TCP [3] (available over *BSD systems). However, it has been shown in [4, 5] that these TCP variants potentially lead to congestion states and intra/inter-protocol unfairness. The intra-protocol and inter-protocol fairness indicate, respectively, the fairness between flows using either the same or different protocols.

Others high speed TCP variants, known as delay-based protocols such as FAST TCP [6], consider an increase of the round-trip time (RTT) as a congestion indicator. Thus, they monitor the RTT at the sender side to prevent congestion state. However, delay-based protocols do not solve the problem of intra/inter-fairness [5]. High speed TCP variants and delay-based protocols belong to the end-to-end (E2E) protocols class since they control the congestion on an end-to-end basis.

A potential transport protocol solution to LBDP networks would be the use of an Explicit Rate Notification (ERN) protocol where routers inform the sender of the optimal sending rate (for instance the eXplicit Control Protocol - XCP [7]). This kind of protocols demonstrates high performance and intra-protocol fairness in full ERN-capable networks [7] (i.e. where all routers support ERN capabilities). The major problem to the deployment of such concept is that ERN protocols do not implement any mechanisms to deal with networks where non-ERN protocols (e.g., standard TCP) and non-ERN equipments (e.g., DropTail routers) are present. Indeed, it has been proved that ERN protocols in non-full ERN networks perform worse than every TCP variants [8, 9]. Therefore, ERN protocols cannot be used in heterogeneous networks and can not be gradually deployed in the current Internet.

Despite several important efforts to enable an incremental deployment of ERN protocols in heterogeneous networks, we will see in Section 2 that the proposed solutions do not (or only partially) solve the problems related to the interaction between ERN protocols with non-ERN protocols and non-ERN devices.

In this paper, we propose a novel architecture allowing to perform an incremental deployment of ERN protocols over heterogeneous networks. In this architecture, a sender is

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able to adapt its emitting rate as a function of a DropTail or an ERN-capable bottleneck. This operation is done dynamically, meaning that when the sender receives an ERN feedback, it uses the minimum between the ERN and E2E congestion windows to perform. After showing the strengths and weaknesses of current existing solutions, we detail the IP-ERN architecture in Section 3. We also explain why our solution is compatible with most of TCP variants; most of proposed ERN protocols; with IPv4, IPv6 and IP-in-IP tunneling mechanisms. Additionally, Section 4 shows the benefits of the proposed architecture and the scenarios where such benefits are possible. Later, we present simulations in order to validate our IP-ERN architecture (Section 5) and conclude this article with a list of some remaining issues and expected future work (Section 6).

2. RELATED WORK

To provide TCP-friendliness (i.e. inter-protocol fairness), the authors in [9] proposed to probabilistically estimate the number of ERN and non-ERN flows (by the mean of a zombie list as described in [10]) to determine if non-ERN flows use more bandwidth than ERN ones. If so, an amount of non-ERN packets are probabilistically dropped. Later in [11], the authors improved this strategy and added an algorithm to calculate the aggressiveness of non-ERN flows (how much bandwidth obtain non-ERN flows over a period of time).

However, one weakness of the zombie estimator is its accuracy. For instance, flows with a short congestion window might not always be detected. Additionally, each router needs a period of estimation (denoted t_{est}) to correctly perform and the estimated value will only be applied in the next t_{est} period. As a result, the needed time to modify the behavior of the sender is roughly $2 * t_{est} + RTT$ in the best case. While in isolated networks, the number of flows might remain stable for a long period of time. We believe further analysis is needed before extending this hypothesis to the Internet. This problem of latency between the estimation and its use applies to the aggressiveness estimation proposed in [11]. Furthermore, heterogeneous RTTs might lead to a sensible difference between the computed aggressiveness and the aggressiveness of the flow with the largest RTT.

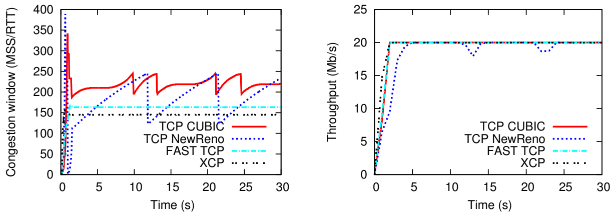
Concerning the cohabitation between ERN flows and non-ERN equipments, [11] proposed a heuristic to detect bottlenecks with non ERN capabilities and switch up to TCP when this case occurs. With this heuristic, if the current RTT reaches twice the base RTT, or the receiving rate does not match the ERN predicted rate, then the bottleneck is non-ERN capable. However, further analysis is needed to assess whether the RTT would reach the threshold before experiencing losses due to congestion in non-ERN routers. Defining upper and lower bounds to compare both the received and the predicted rate is not trivial, thus, this heuristic might frequently return false-positive results. At last but not least, there is no way to detect when the bottleneck has moved to an ERN router again. Following the dynamic character of the Internet, the sender might not correctly take advantage of ERN capabilities when possible.

3. PRESENTATION OF THE IP-ERN ARCHITECTURE

3.1 Rationale of IP-ERN architecture

TCP-based protocols frequently probe the network capacity by increasing their emitting rate, hence leading to congestion events. Additionally, high speed TCP variants potentially increase the unfairness. While delay-based protocols attempt to prevent congestion states, they also prevent under-utilization of bandwidth by keeping a certain number of packets in the buffer of the bottleneck. Unfortunately, delay-based protocols do not solve the problems of unfairness [5]. On the contrary, thanks to the assistance provided by routers, ERN protocols provide both high link usage and intra-fairness while minimizing the buffer occupancy.

Figure 1 presents the general behavior of one ERN protocol (XCP) and different E2E protocols (TCP New Reno, CUBIC, FAST TCP) over a short BDP network (the bottleneck is 20Mb/s and the RTT is 30ms). The results are obtained with the *ns-2* simulator [12]. The router queue is XCP in case of XCP and DropTail for other cases. In Figure 1(b), all protocols achieve the bottleneck capacity. Specifically, XCP uses the smallest congestion window (Figure 1(a)). This means that XCP maximizes the link utilization while minimizing the buffer occupancy. Indeed, when the TCP New Reno's congestion window is smaller than the XCP's congestion window, TCP New Reno's throughput is slightly lower than 20Mb/s. Moreover, when the XCP sender receives misleading congestion window in non-fully XCP-capable network, XCP's congestion window might perform worse than E2E protocols [8].



(a) Congestion window (b) Throughput

Figure 1: Comparison between E2E and ERN protocols

When the bottleneck is ERN-capable, ERN protocols can compute the optimal congestion window. However, when the bottleneck is not ERN capable, E2E protocols provide a more adaptive congestion window. Following this, the idea is to combine E2E and ERN protocols and to use the minimum between the E2E's and the ERN's rates in order to be compliant with current protocols (i.e., no more aggressive than TCP) while using the optimal congestion window when it is applicable.

3.2 Proposed IP-ERN architecture

Combining E2E and ERN protocols implies the implementation of two different congestion control protocols in the sender node. Since ERN protocols do not introduce complex operations at the sender side, we believe that current computers should have enough resources to run both E2E and ERN protocols.

The proposed architecture (denoted IP-ERN architecture in the following) requires only slight modifications at the end hosts and few additional mechanisms inside the routers. Our architecture does not need either heuristic or probabilistic methods to enable a gradual deployment of ERN protocols over current heterogeneous networks.

3.2.1 At the source side

The Transport Layer is divided into two sub-layers: the TCP sub-layer and the Congestion Awareness sub-layer at the Transport Level (CAL-T). The TCP sub-layer hosts the core of the TCP-based congestion control protocol. The CAL-T hosts the core of the ERN protocol and all needed mechanisms to properly combine both E2E and ERN capabilities.

When a SYN packet is sent to establish a connection, the CAL-T layer inserts a TCP option field to indicate an E2E-ERN capable sender[1]. Later, at the reception of a SYN-ACK, the sender checks inside the packet a TCP option indicating that the receiver is E2E-ERN capable. If so, the E2E-ERN connection is established. Otherwise, a standard E2E connection is created.

After establishing a connection with an E2E-ERN capable receiver, CAL-T adds to every outgoing packets the ERN parameters that need to be sent to the ERN routers (i.e. the ERN "header"). The sender's desired feedback will be placed in a field called *drd_feedback*, which is the only field that a router can modify. In IPv4 networks, CAL-T puts the ERN parameters between the IP header and the TCP header (as suggested in [14]). This should allow routers to quickly find the ERN parameters. Note that (*i*) placing the ERN parameters in the TCP option field might require expensive operation at routers, and (*ii*) placing it in the IP option field would cause IP-ERN packets to be kicked out into the slow path [15]. For IPv6 networks, we propose to create a new Extension Header (EH) which belongs to the upper-layer group to carry up the ERN parameters. Then, CAL-T places such an EH according to the IPv6 principles. Therefore, non-ERN capable routers should simply forward this packet avoiding without slow path redirectionare

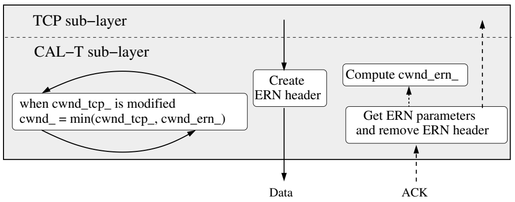


Figure 2: Source node

Concerning incoming packets, upon reception of an ACK, CAL-T extracts the ERN feedback to compute the ERN congestion window (*cwnd_ern_*). Such a feedback will be taken from a field called *reverse_feedback* and will never be modified by IP-ERN routers. Finally, CAL-T takes the minimum value according to (1):

$$cwnd = min\{cwnd\_tcp\_, cwnd\_ern\_\} \qquad (1)$$

where *cwnd_tcp_* is the last updated TCP congestion window. As we will see later, by taking the minimum value between *cwnd_tcp_* and *cwnd_ern_*, this architecture does not require any explicit mechanism to detect whether there is a non ERN-capable router in the networks. In other words, the detection is automatically done by this comparison. Additionally, the time needed to switch from E2E to ERN capabilities (or reverse) is not longer than one RTT (time to detect a loss when going from ERN to E2E or time to receive the signaling from routers when going from E2E to ERN). Figure 2 presents this new architecture at the sender side.

We want to point out that this architecture is compatible with any TCP variants and with most of existing ERN protocols.

3.2.2 At the router side

All needed ERN algorithms are placed in the Congestion Awareness sub-Layer at the Network Level (CAL-N), as depicted in Figure 4.

When a packet arrives at an ERN-capable router, CAL-N checks if the next protocol (or next header in IPv6) signaled in the IP header of the incoming packet belongs to an E2E-ERN sender. If so, the router computes the feedback and updates the *drd_feedback* field from the ERN header according to the ERN rules. Otherwise, packets are treated as default IP packets.

Since ERN-capable routers only assign bandwidth to ERN flows (as E2E flows do not interpret the feedback message), and because E2E and ERN fairness is enabled by the E2E capabilities of senders using our architecture, each router computes a feedback by taking into account the ERN traffic only. Most ERN protocols need to compute the input traffic rate. Therefore, input traffic rate corresponds to the ERN traffic only.

In IP-ERN routers, there is one main buffer (the shared buffer), serving two buffers (E2E and ERN buffers with respectively fixed sizes X and Y) as depicted in Figure 3. E2E buffer only stores packets from E2E flows and ERN buffer only stores packets from IP-ERN flows. The packets from the shared buffer are immediately forwarded to the next buffer. If this buffer is full, packets are simply dropped. This buffer scheme eases the feedback computation without taking into account pure E2E traffic. Indeed, ERN protocols usually need to estimate the buffer occupancy of ERN flows to decrease their rate and to drain packets in order to prevent congestion. Calculating the buffer occupancy without differentiation between ERN and E2E traffic might decrease IP-ERN senders' rate to drain E2E packets.

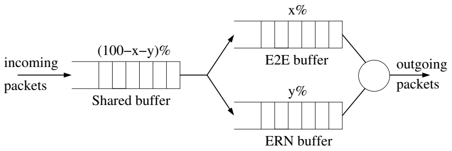


Figure 3: Egress buffer scheme for IP-ERN routers

Note that in this proposition, IP-ERN routers do not attempt to provide fairness (such as in [11, 9]). Inter and intra fairness are ensured by E2E and ERN capabilities of E2E-ERN senders.

3.2.3 At the destination side

The Transport Layer at the receiver side implements the

[1] Note that non E2E-ERN capable receivers should only ignore this option and following [13], a majority of TCP stacks correctly handle unknown TCP option (i.e. packets that contain unknown options are not dropped).

same sub-layers than the sender side (i.e. TCP and CAL-T sub-layers). When a SYN is received, CAL-T looks at the TCP option field to know if the sender is E2E-ERN capable. If so, CAL-T sends back a SYN-ACK packet with a code in the TCP option field to indicate an E2E-ERN capable receiver.

During the connection, upon reception of a data packet, CAL-T copies the *drd_feedback* field of the data packet to the *reverse_feedback* field of the ACK, and sets *drd_feedback* = 0. CAL-T builds the outgoing ACK in the same way the sender builds a data packet (described earlier). The next protocol type (or next header in IPv6) signaled in the IP header of ACKs will be the same as the one signaled in data packets.

3.2.4 Global view of the IP-ERN architecture

Figure 4 gives a general view of the proposed IP-ERN architecture. Note that the Transport Layer at end-hosts is divided in one TCP sub-layer (where the core of the TCP protocol is hosted) and one CAL-T sublayer (which hosts the core of the ERN protocol and handles the interaction between E2E and ERN protocols). The Network Layer inside the routers is divided in one IP sub-layer (where the core of the IP protocol is hosted) and one CAL-N sub-layer (which hosts the core of the ERN congestion control protocol). In the following, we show that this architecture enables E2E-ERN fairness and allows the use of E2E-ERN protocols over heterogeneous networks.

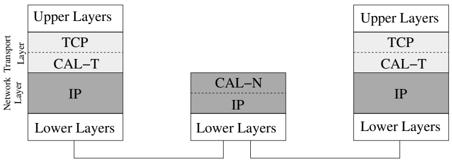


Figure 4: The proposed IP-ERN architecture.

3.2.5 The IP-ERN architecture in the context of IPsec tunnels

The IP-ERN architecture is fully compatible with IPsec tunnels. Indeed, the encryption and/or authentication of the whole or partial IP datagram by legacy IPsec boxes makes IP-ERN senders to behave like a pure TCP sender. However, in the future, a new generation of IPsec-ERN boxes can be implemented. Indeed, we are currently working on the proposition of the IPsec-ERN architecture, as well as turn around to benefit from ERN capabilities in presence of legacy SatIPsec [16] or legacy IPsec boxes[1].

4. BENEFITS OF THE PROPOSED IP-ERN ARCHITECTURE

4.1 Possible gradual deployment scenarios

The IP-ERN architecture allows a gradual deployment of ERN protocols (such as XCP) over heterogeneous networks. Three scenarios are possible to drive this deployment:

4.1.1 1^{st} scenario: the bottleneck is IP-ERN capable and only IP-ERN flows share the resources

Each host implementing the IP-ERN architecture should fully benefit from ERN capabilities. Although this scenario does not correspond to what we usually call an incremental deployment (we consider here only IP-ERN flows), there are some cases where network administrators might consider this solution to improve the performance of large data transfer as we will see in Section 4.2.

4.1.2 2^{nd} scenario: the bottleneck is not IP-ERN capable

IP-ERN hosts should not benefit from the ERN capabilities but they should fully benefit from TCP capabilities.

4.1.3 3^{rd} scenario: the bottleneck is IP-ERN capable and both TCP and IP-ERN flows share the link

IP-ERN hosts will use their TCP capabilities to compete against pure TCP flows. Furthermore, the intra-fairness level of E2E-ERN flows can be higher than the intra-fairness of pure E2E flows despite of the use of TCP capabilities. Indeed, IP-ERN routers try to equally share the link capacity between ERN-capable flows only. When a new E2E-ERN flow enters in the network, IP-ERN routers make E2E-ERN flows converge to a rate equal to the ratio between the link capacity and the number of IP-ERN flows. Therefore, old flows yield up bandwidth once new feedbacks are received, and the newest flow safely acquires the available resource, making convergence between E2E-ERN flows faster than pure E2E flows. In fact, as the throughput of E2E flows decreases, the intra-fairness property of the ERN protocol increases. Other simulation results not shown here due to the limited space confirm these arguments.

Finally, we want to remark that using the minimum between TCP and ERN congestion windows, during the slow-start phase or after a packet loss, IP-ERNs flow are mainly limited by TCP protocol. However, because of the use of CUBIC in GNU/Linux distributions and Compound TCP in some Microsoft's products, we believe that the underusage of resources is not a problem anymore. The main one remains the unfairness introduced by Compound TCP and CUBIC. However, this unfairness can be reduced with the use of our IP-ERN architecture.

4.2 Scenarios of utilization

For instance, the use of the proposed IP-ERN architecture should greatly improve the performance of flows:

- in a Virtual Private Network (VPN) with frequent long-lived flows, assuming (*i*) we place an ERN router at the entry point; (*ii*) most of the time this is the bottleneck and (*iii*) most of senders implement the IP-ERN architecture;
- in a satellite scenario, assuming (*i*) we place an ERN capable router at the up-link and down-link and (*ii*) most of senders implement the IP-ERN architecture.

5. RESULTS AND ANALYSIS

5.1 Topology

We use the Network Simulator *ns-2* to evaluate our proposal. Unless something else is specified, next simulations

[1] These propositions will be part of a document entirely focused on the security protocols and IP-ERN architecture interactions

use a network topology with a base RTT of 300ms and a bottleneck capacity of 20Mbps (see Figure 5). The number of senders and receivers depend on the number of simulated flows.

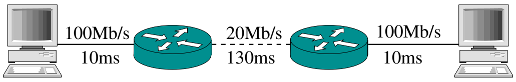


Figure 5: Simulation topology

5.2 Correctness of E2E-ERN protocols

In our implementation of the IP-ERN architecture, we used CUBIC TCP at the TCP sub-layer (since this is currently enabled by default in Linux), and XCP at the CAL-T sublayer (which is implemented by default in *ns-2*). Following the network settings described in Section 5.1, we perform two different simulations. We run a CUBIC-XCP flow when bottleneck router is XCP (first simulation) and DropTail (second simulation).

As stated in Section 4.1, E2E-ERN protocol behaves like ERN in the possible cases where the bottleneck router is ERN-capable and only ERN flows are present in the bottleneck. Otherwise, E2E-ERN protocol uses their E2E capability to better adapt its throughput. The results given in Figure 6 confirm this. Indeed, CUBIC-XCP behaves like a pure CUBIC TCP in case the bottleneck router is DropTail, and acts as XCP in case the bottleneck router is XCP.

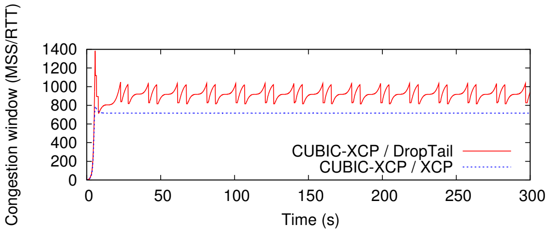


Figure 6: CUBIC-XCP in presence of DropTail or XCP routers

5.3 Intra-fairness

The intra fairness is a metric that corresponds to the fairness between flows using the same protocol. To analyze the intra-fairness capability of our IP-ERN architecture, we simulated four CUBIC-XCP flows which share the same bottleneck with XCP-capabilities. Four flows start and terminate at different times.

Figure 7 shows the congestion window evolution of CUBIC-XCP flows. When flows enter or leave the network, CUBIC-XCP quickly converges to the new equilibrium and remains stable. We remark again that in the presence of only E2E-ERN flows and when the bottleneck router is ERN-capable, the E2E-ERN protocol behaves like ERN protocol, which results in excellent intra-fairness properties [7]. Even though it is not graphically shown, we have observed of full link usage.

We have also driven the same experiment with DropTail routers. The results have shown that CUBIC-XCP behaves like a pure CUBIC flow since the ERN part is not aware of the bottleneck capacity (XCP assumes an infinite available bandwidth).

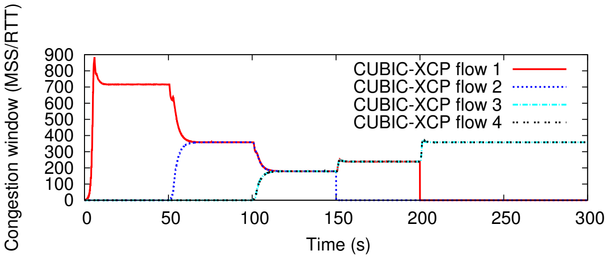


Figure 7: Intra-fairness between CUBIC-XCP flows

5.4 Inter-fairness

The inter fairness implies the fairness between flows using different protocols. In order to show the inter-fairness, we perform the following simulation: one CUBIC flow competes against two CUBIC-XCP flows and an XCP router is used at the bottleneck link (see Figure 5). We can see in Figure 8 that our IP-ERN architecture allows CUBIC-XCP to use its E2E capacities in order to fairly share the available bandwidth with pure CUBIC flow. As shown in Figure 8 where one CUBIC-XCP flow competes against two CUBIC flows, having more pure CUBIC flows than CUBIC-XCP flows does not impact on the fairness.

Since in our IP-ERN architecture, ERN routers only see ERN traffic (see Subsection 3.2), routers attempt to assign bandwidth to ERN flows without taking into account the E2E traffic. Later, the E2E capabilities of E2E-ERN senders allow the flows to converge. Taking into account all the traffic to compute a feedback (as in the original XCP model) do not allow ERN senders to compete against E2E flows [9].

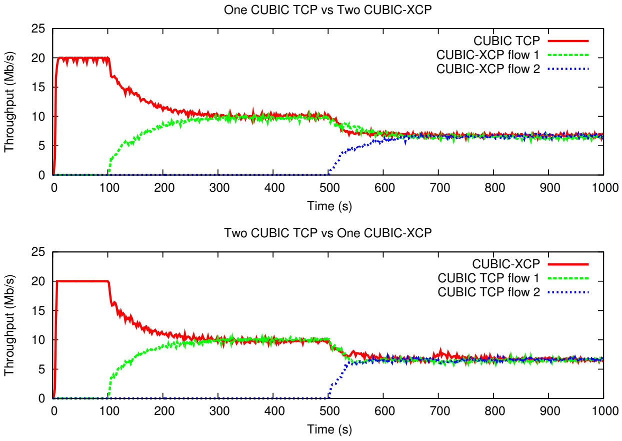


Figure 8: Inter-fairness between CUBIC and CUBIC-XCP

Using our proposed IP-ERN architecture, convergence time between E2E and E2E-ERN protocols strongly depend on the kind of E2E protocol used for both.

5.5 Dynamic scenario

The following simulation show how fast and transparent is the adaptation of the senders using the IP-ERN architecture in the context of a variable environment. The experiment is done over the topology depicted in Figure 9. The base RTT is 300ms for the flow #1 between Sender #1 and Receiver #1, and 180ms for flow #2 between Sender #2 and Receiver #2. Note that flow #1 is active between $t = [0; 300]$ seconds and flow #2 between $t = [100; 200]$. Except Router #1 which uses DropTail, all other routers use XCP.

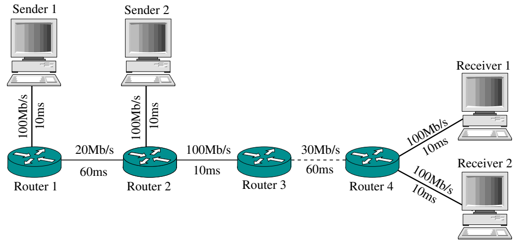


Figure 9: Network topology for dynamic scenario

In Figure 10, between $t = [0; 100]$, flow #1 behaves like a pure CUBIC flow as the bottleneck queue is DropTail at Router #1. Later, when the bottleneck moves from Router #1 to Router #3 (Router #3 is ERN capable) due to the presence of flow #2, both flows behave like a pure XCP protocol and both have a throughput of 15Mbps. The difference between each congestion window is caused by the RTTs difference. This simulation shows that our E2E-ERN protocol automatically switches between E2E and ERN modes depending on network condition thanks to equation (1).

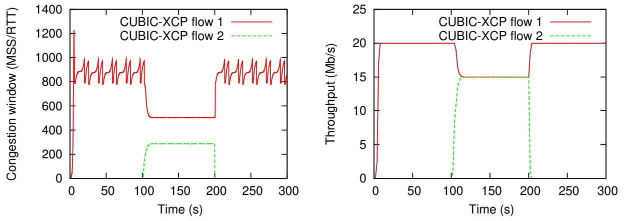


Figure 10: Dynamic scenario for CUBIC-XCP

6. CONCLUSIONS AND FUTURE WORK

We propose a novel IP-ERN architecture which allows an incremental deployment of ERN protocols over heterogeneous networks where a pure ERN architecture is not fully deployable yet. We also detail an implementation proposal based on the introduction of two sub-layers. This architecture is compliant with IPv4 and IPv6 networks and does not break the end-to-end communication thus allowing the use of protocol such as IPSec.

We have shown that the use of the proposed IP-ERN architecture allows the senders to benefit from both the robustness of E2E protocols and high performance of ERN protocols according to the network conditions. The combination of E2E and ERN capabilities is transparently managed by the IP-ERN architecture. The switching from E2E to ERN capabilities (or reverse) is done in no more than one RTT.

We now plan to develop a real prototype of this architecture to better assess its performance and to discuss other aspects of this architecture (security issues, impact of mice flows) in a future contribution.

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