Congestion Control Mechanism in Programmable Switches for a Multi-Tenant Network using P4

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Abstract

With the advent of re-programmable switches, the adoption of high-level languages such as P4 for easy programmability has been widespread. There has been a keen interest in implementing newer algorithms in the forwarding plane and make use of this flexibility. Congestion control is one such domain which could benefit for flexible programmability of the data plane since most of the solutions in practice employ end-to-end mechanisms.

This work presents the study of this paradigm and describes the implementation details of a control strategy to effectively allocate fair bandwidth among multiple tenants, a common use case in data centre traffic, and thus achieve fair congestion control. We study the specific features of P4 language which can be leveraged for this use case and elaborate how any programmable policy can be exercised on these switches. In this work, we would be choosing a simple average weighted policy to fairly divide the congestion among multiple tenants and find that an easily realizable feedback loop, by parsing custom information in the packets, is able to control congestion quickly thus reducing packet drops by 3× when compared to no control loop being used.

1 Introduction

Cloud Computing has opened a new dimension of business and application requirements. This has paved way for cloud infrastructure providers to innovate next generation data centers to meet the storage, compute and networking demands. To provide competitive pricing and meet the growing demands of the cloud infrastructures the providers favour **multi-tenant** architecture in the data centers. This opens new set of challenges for network especially in term of fairness. The infrastructure provider needs a way to control the traffic and manage the congestion of the network based on particular policy and meet the SLAs.

2 Background and Motivation

Reconfigurable switches have enabled network operators to experiment with newer algorithms to manage the forwarding devices. This eliminates dependence on rollout of new features in network stack at the end hosts and make the network configuration highly dynamic without needing to build new switch hardware. Recent research in architecture of various forwarding plane pipelines which are being realized on hardware switches have opened doors for researchers to leverage this platform and work with high speed and efficiency. Also manufacturers have come up with devices being able to process traffic at line rate which gives more motivation to work towards high performing programmable switches. Increased access of data plane with programmable switches have enabled development of quality network management software such as INT Telemetry etc.

3 Programmable Pipeline

Here, we would describe the Reconfigurable Match Tables(RMT) switches based on which the software model in our experiments were based. The RMT model allow a set of pipeline stages for packet processing each of which can provide for a match table with varying height and width. The flexibility offered in the data plane management is immense as it allows for addition and specifying the semantics of new fields. Also, the match action tables can be populated with our desired width, depths and topology up to a maximum allowable limit. Custom headers can also be defined and a desired action on their match can be programmed. This gives the benefit of rich programmability to come up with new data plane management algorithms.

3.1 RMT Architecture

The main components of the RMT architecture[2] are:

Parser: The incoming packets are first handled by the parser. This is the unit which is responsible for recognizing the header fields and extracting information from them so that defined rules could be matched and acted upon. The parsing happens on the header field only and the packet body is buffered separately. RMT defines a reconfigurable parser such that the same can be reused for implementing different policies acting

upon any combination and logic of match-actions. As such, the model is totally oblivious to the protocol meaning and thus makes no assumptions on the order or length of the headers. In this way, the parser is truly flexible and generic. A packet header vector containing IP and Ethernet field data, along with input port information and router state variables, is output from the parser.

Logical match stages: The packet header vector then flows through a pipeline of user configured match action tables. An input selector is used to choose the header field that needs to be parsed and subsequently packet modifications can also be done. The power of the RMT model is in the concurrent processing on all fields of the header vector.

Action Unit: This unit takes three arguments *viz.* the header vector and the action data results of the match, and rewrite for each field in the packet to be processed and modified. Some amount of counter information can also be can also be modified in this stage.
Along with providing stateful memory, the model also provides with the capability to perform computations such as addition, bit shifts, hashing, min-max operation on the data extracted from the headers.

Recombination stage: Also called the DeParser, this unit pushes all the changes done in the header vector back into the packet.

3.2 Match Action Pipeline

The match action tables are separately managed for both the ingress traffic and egress traffic. Matches on both of them equally can be used to make modifications in the packet headers. The egress port is however decided from the results of the rules specified in the ingress match action tables. Separate queues for the ingress and egress pipeline helps us determine how to segregate the traffic. This division can be based on per flow traffic or otherwise. In our case, we would be determining per host traffic and managing the queues accordingly.
The additional metadata information such as input port,router state, transmit destination and timestamps are shared among the multiple stages and can be used for packet scheduling and processing. Figure 1. depicts the match action pipeline.

4 P4

P4 programming language helps in processing the data plane of a programmable forwarding element, be it hardware or software switch, NIC etc. While P4 was initially designed for programming switches, its scope has been broadened to cover a large variety of devices. Many vendors old and new have come up in this domain: Barefoot Networks' Tofino , Cavium's XPliant, Intel's Flexpipe and Netronome are a few. P4 is designed to specify only the data plane functionality of the target appliance. P4 programs also partially define the interface by which the control plane and the data-plane communicate, but P4 cannot be used to describe the control-plane functionality of the target. What qualifies as a P4 switch? A P4 program defines the data plane functionality unlike a fixed data plane in traditional switch. The data plane is configured at initialization time to implement the functionality described by the P4 program. The control plane communicates with the data plane with channels as present in traditional devices, but the set of tables and other objects in the data plane are transient. Communication channel between data plane and control plane is established via API generated by P4 compiler. Advantage of programming hardware with P4 over micro-code deployed on custom hardware:

- Expressing forwarding plane policies is easier in a functional programming construct provided by P4
- Low level fields are abstracted. Thus, management if such resources is simpler and efficient.
- Programmers can utilize vendor specific libraries to enrich the desired functionalities.
- P4 program does not need to evolve with hardware changes.
- All round benefiting software development with code reuse and better debuggability.

A P4 program contains five components which are direct implementations of features mentioned in the RMT architecture.

1. Headers: Header definition describes the sequence and structure of a series of fields. It includes specification of size of header member and constraints on field values. For example, IPv4 header has member pertaining to source and destination IP addresses. Both fields can be defined with 32-bit integers.
2. Parser: Parser specifies how to identify headers and validity of header sequences within a packet. User defines parsing instructions for the desired headers. As we introduced custom headers for tenants, our P4 program had to incorporate custom parsing functions.
3. Tables: It provides Match+action tables for data plane packet processing. A P4 program defines the header members upon which a table may get matched and the corresponding actions that get executed. The match can be exact, ternary or

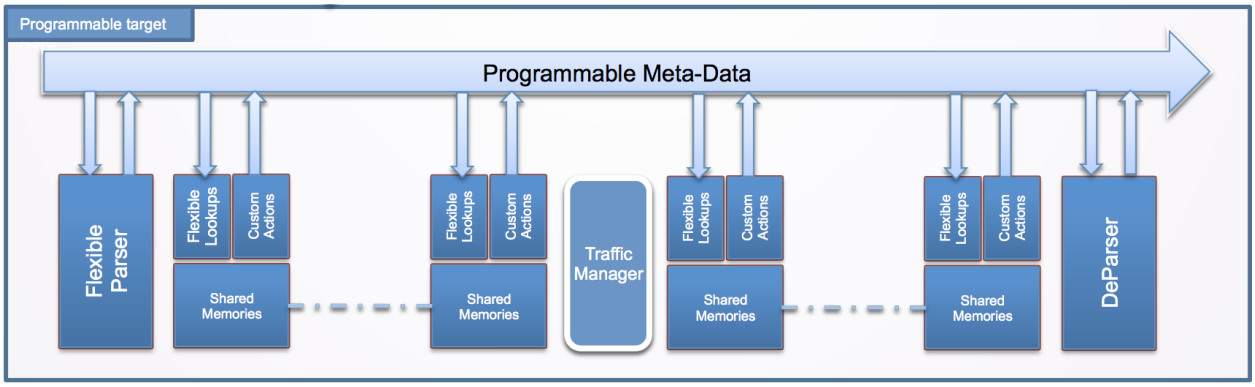


Figure 1. Programmable switch pipeline. The figure shows the total the different stages in the pipeline.

Longest Prefix Match (LPM). For example, an IPv4 Forwarding table will do LPM over Destination IP Address and perform action of putting packet to respective egress port.

4. Actions: Complex actions are supported to achieve protocol independent forwarding functionalities. The actions are available within the match+action tables.
5. Control Programs: These dictate the order of match+action tables that are applied to packets.

We will be discussing our implementation specific P4 components in upcoming sections.

5 Implementation

Our goal was to develop a mechanism to monitor and account tenant specific traffic, so to perform effective congestion control. We decided to develop our prototype on programmable software switch environment and integrated into Mininet. Our P4 program is compiled to generate a JSON file (analogous to assembly code in real hardware) which gets installed on the software switch.

Tenants were abstracted using Python's Scapy Module[1] to develop our own custom TENANT header, which will be parsed by the P4 program running in the software switch. Hence keeping track of tenant specific traffic metrics. Also Mininet provides the flexibility in deploying variety of topologies and can effectively transmit the traffic generated by Scapy Python code.

The software switch provides Simple CLI API to monitor and update control/data plane parameter in real time. Hence we implemented a Python Controller program, to poll for current switch queue depth to figure out the congestion event. Then using the CLI API to query the relevant tenant metric from the switch and calculate individual tenant's congestion window's backoff value.

Our design goal is that the switch should only track traffic metrics, help in identifying congestion and transmitting updated congestion window value back to the tenants. The controller would have the intelligence to perform the tenant's traffic analysis and calculate new congestion window. Thus, both switch's and controller's tasks are separated. Hence the design can scale for any number of switches and tenants in the network with a single global controller performing traffic analysis for all tenants in the system.

5.1 Environment

P4 software switch nicknamed bmv2 i.e behavioral model replaced the original version, p4c-behavioral. Written in C++11 provide enough flexibility and functionality to prototype SDN solutions in Mininet environment. The bmv2 code comes with following network devices as software targets: `simple_router`, `l2_switch` and `simple_switch`. `Simple_switch` is the standard P4 target and provides lot of functionality. Also, the code is relatively small as well as straightforward. It abstracts the P4-spec's [6] `v1_model`, which dictates the underlying switch hardware architecture. BMV2 switch provides programmer with the hardware metadata information as mentioned in v1model.p4 such as the switch's global time-stamp, current enqueue depth of the packet processing pipeline and port details etc.

5.2 Topology and Traffic Generation

In order to visualize a congestion specific feedback loop, we decided to implement a two switch and two end-host topology. Where one of the end host act as traffic generator: which runs a Python Scapy program having tenant specific threads populating UDP packets in three separate queues. Hence, providing an abstraction of host having multiple unique tenants. On the other end is traffic receiving host: which is also a Python Scapy program acknowledging tenant specific traffic. The individual tenant queue size are assumed to be their respective congestion window. The congestion window

size is manipulated by the controller (through tenant header acknowledgement flag) to enforce congestion control policy.

Figure 2. Two Host Topology. Host2 has three tenants(A, B and C) hosted on it.

5.3 P4 Program

In order to monitor tenant traffic, we need to store and update tenant traffic states across packets. Such tasks are not straightforward as P4 Match-Action pipeline restore states after processing every individual packet. P4 provide Metadata Buffer that helps in storing states across the packet processing pipeline. And the P4 data types supported by the buffer are called Externs. Some of the P4 Externs are: Meters, Counters and Registers. We utilized P4 Registers,as they are a list key-value pairs to store stateful information across packets. Using Register extern variables our P4 program perform following functions:

- Addition and parsing of custom tenant header
- Incorporating new M+A Table for matching tenant specific header data
- Performing action to update tenant traffic metrics
- Updating and tracking metrics across packets

5.3.1 Headers

Our implementation focuses on IPv4 forwarding scenario for a multiple tenant environment. Hence the data plane functionality should also be multi-tenant aware. We decided to implement a custom Tenant header (as shown below) to make forwarding plane aware of the tenant specific traffic details i.e. a tenant's total packet count, size of switch's buffer when tenants packet was enqueued etc. We also incorporated a tenant specific acknowledgment flag (`ack_flag`) to communicate the tenant's congestion window backoff value calculated by the controller.

```
header tenant_t{
    bit<32> id;
    bit<48> ingress_global_timestamp;
    bit<32> enq_qdepth;
    bit<32> total_pkt_count;
    bit<32> total_packet_length;
    bit<32> ack_flag;
    }
```

5.3.2 Table Specification

The latest P4_16 specification dictate that only switch's specific metadata can only be accessed from the egress pipeline of the switch. We implemented our custom table to execute the metric update actions (table:swtrace action:add_swtrace) for every every packet. The BMV2 takes the match action table information as an argument. The information is stored in a text file (Example switch-command.txt).

Also to simulate a congested network we reduced the switch packet processing rate (using CLI set_queue_rate) in the table.

```
CONTROL PLANE TABLE FILE:
-------------------------
table_set_default swtrace add_swtrace
set_queue_rate 20
table_set_default ipv4_lpm drop
table_add ipv4_lpm ipv4_forward <ip> <mac> port
table_add ipv4_lpm ipv4_forward <ip> <mac> port
table_add ipv4_lpm ipv4_forward <ip> <mac> port

P4 PROGRAM TABLE MATCH:
-----------------------
    table swtrace {
        actions = {
       add_swtrace;
       NoAction;
        }
```

5.3.3 Action specification

P4 program act as the accounting module for our congestion control feedback loop and controller is the enforcing authority. Hence it is vital to store variety of tenant specific traffic information. P4 programs egress pipeline implements multiple registers to to store and update individual tenant's data. Tenants are identified using integer values and these ids' are used as indexes for storing/accessing traffic metrics in registers. In the egress pipeline once table match (table: swtrace) happens our action (action: add_swtrace) gets executed. Also the tenant header's ack_flag value is updated to reflect the updated congestion window calculated by the controller.

```
    register<bit<32>>(256) pkt_count_reg;
    register<bit<48>>(256) last_seen;
    register<bit<32>>(1) enque_depth;
    action add_swtrace() {
    //updating enqueue depth in to register
    enque_depth.write(0,
         (qdepth_t)standard_metadata.enq_qdepth);
        hdr.tenant.ack_flag = temp_ccr_var;
    }
```

5.3.4 Stateful Information

P4 register constructs enable us to track individual tenant's packet count (pkt_count_reg) and even timestamp when the last packet for a particular tenant was processed (last_seen). Such information enable us perform efficient congestion control across all tenants.

5.4 Feedback Loop

The feedback loop algorithm works in the following way:

1. Poll for the current enqueue depth in the switch by reading the register value `"enque_depth"`.
2. If current queue depth is more than threshold specified, then enter loop.
3. For each tenant, record the values of the states from the registers `"pkt_count_reg"`, `"pkt_length_reg"`, `"last_seen"` and `"total_last_seen"`.
4. Calculate the priority order of the tenant from the above values.
5. Calculate the penalty to be imposed on each tenant based. The summation of the penalties need to be the total extra congestion which needs to be eliminated.
6. Write the proportion of backoff values relative to current congestion window corresponding to each tenant into the register array `"congestion_control_rate_reg"`.
7. End inner control loop.
8. Repeat step 1.

.

The components interacting in the feedback loop can be visualized from Figure 3.Calculation of the priorities of the tenant's traffic is done by assigning weights to the various states of importance. Here, we recognize the fact that lower the "packet count" of a particular tenant till date, higher is the priority. This means that tenants of lower packet encountered need to be backed off by a lesser amount and vice versa. Similarly the state, "packet length" shows a direct measure of a tenant's packets crowding the egress queues. These two states hold historic data and thus gives a measure of a tenant's traffic causing congestion till date. On the other hand, the state "last seen" timestamp value is inversely proportional to the backoff i.e. smaller the "last seen" values indicates that the tenant's packets have been matched just recently in the pipeline and thus it would need to backoff more compared to other tenant whose packets were seen a while ago. The weights given to these three states are varying and have been decided on the relative importance of the values.
With this logic, we arrive at a simple policy for calculating backoff for the tenants' congestion windows:

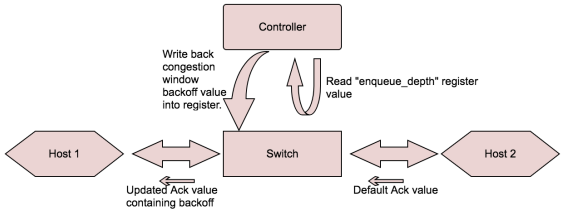


Figure 3. Feedback Loop.

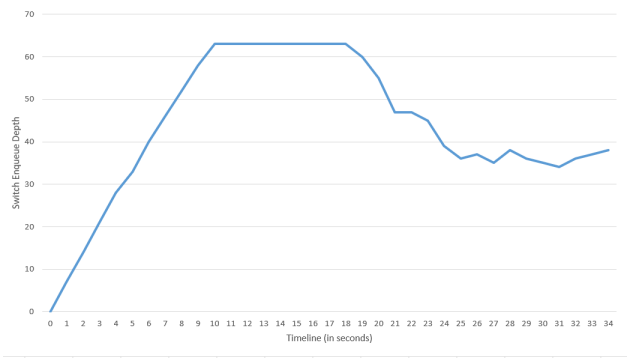
$$priority = \frac{(3\times \texttt{packet\_count} * 2\times \texttt{Packet\_length})}{10\times \texttt{last\_seen}} \quad (1)$$

We could have worked upon a more refined and complex policy however, we wanted to focus on the implementation of a simple policy which would give us the desired control on congestion and see if this is feasible in re programmable switches with ease. Adopting a new policy is just a matter of extending the same design.
The values stored in the `"congestion_control_rate_reg"`registers are inserted into an acknowledgement flag in the custom "tenant" header to convey the congestion information to the end hosts. This is similar to other in-network notification like ECN. The end host needs to increase or decrease the current congestion window based on this value which is specific to each tenant's traffic.

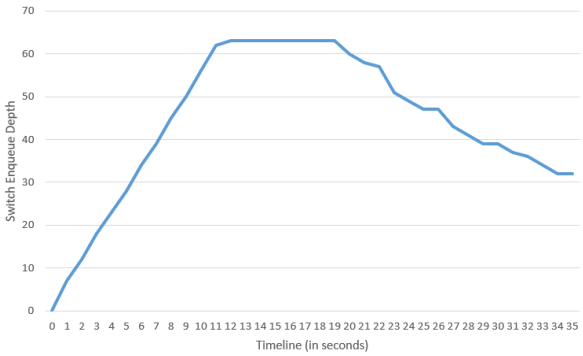
6 Results and Evaluation

We will be presenting the details of the results obtained from the performed experiments. We have tracked the congestion values as read from the enqueue depth attribute of the switch and compare how they are acted upon by the control policy of the feedback loop. The graphs presented will show the reaction times of our congestion control mechanism.

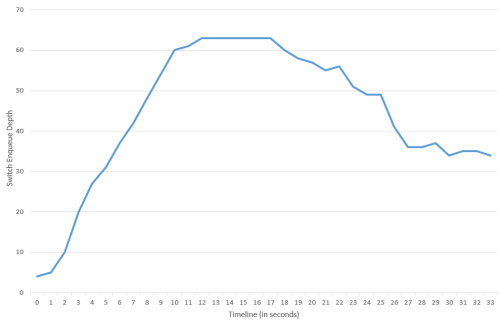
Figure 4 shows the performance of the feedback loop which manages to bring the congestion level at the ingress queue below the threshold value of 45. We perform this experiment by sending backoff notification for varying number of ACK packets. In case the notification is sent to sender after every 10 ACK packets(Figure 4(a)), we notice a considerable higher time taken(around 10 secs) for the enqueue depth value to settle below the threshold value. The feedback loops kicks in the moment enque depth value breaches 45 but the the return ACK cycle takes some time here and thus we start seeing the drop in enqueue depth only after 10 secs. As seen in Figure 4(b), once we reduce the frequency of congestion notification to every 5^{th} ACK, we see a reduction of 2 secs in the time for which the



(a) Enqueue depth vs Time



(b) Enqueue depth vs Time



(c) Enqueue depth vs Time

Figure 4. Enqueue Depth vs time graph. Figure (a) shows the performance in case of notification being sent on every 10th ACK packet, (b) shows it in case of every 5th ACK packet (c) shows it in case of every ACK packet.

buffer was overpopulated. Moreover, we performed a third experiment with notification being sent with every ACK and also reduced the loop time for the feedback check for enqueue depth to 1 sec(Earlier this was set to 2 sec to reduce the traffic on the switch for polling on the register values). As can be seen from Figure 4(c), this resulted in a further reduction in the settle time, around 6 secs. Thus we find that the feedback mechanism is able to control congestion in comparatively lesser time cycles and mitigating the risk of packet drops.

Table 1. and 2. shows the output for backoff values calculated by the controller in case when tenants generate traffic of equal and unequal ratio. The tenants which produces packets at a higher rate gets its congestion window penalized the most. We made sure that controller limits every tenants traffic generation by some factor.

Figure 5. shows the reduction in packet drop by changing the feedback loop parameters i.e. the frequency of acknowledgment packet. In the first scenario when no controller is present to check the switch congestion, we observe a huge packet loss. Whereas with the controller in place and increasing the frequency of notifications, we were able to achieve reduction of 3× in the packet drop metric.

Tenant ID	Initial Congestion Window	Controller's Backoff Value	New Congestion Window
0	10	4	6
1	10	4	6
2	10	4	6

Table 1. Backoff values. The table gives the backoff values calculated by the feedback loop for tenants sending data with equal congestion windows.

Tenant ID	Initial Congestion Window	Controller's Backoff Value	New Congestion Window
0	2	1	1
1	8	2	6
2	20	10	10

Table 2. Backoff values. The table gives the backoff values calculated by the feedback loop for tenants sending data with unequal congestion windows.

7 Related Work

PIFO scheduler[10] gives a promising abstraction in which programmable switches can be used to program schedulers running at line rate. However, we need to wait for real hardware switches implementing this design.

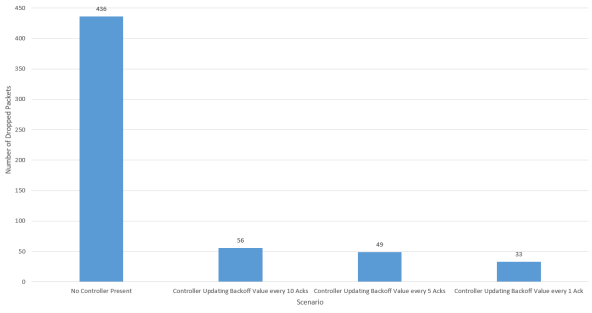


Figure 5. Drop rates. This graph shows the packets dropped for different scenarios of controller mechanism.

Naveen et. al[7] try to implement in-network control of congestion and have realized protocols such as XCP, RCP and CONGA on Cavium switches. However they are perform congestion control on a per packet and per flow basis and employ approximation methods to compute per flow and aggregate statistics.

AFQ[8] show that its possible to implement fair queueing on reconfigurable switches. To process network traffic at line rate, they also use approximation methods to store the states and come up with a new dequeueing approach, called the Rotating Strict Priority scheduler which transmits egress packets in approximate sorted order.

The guidelines laid out in In-Band Telemetry [3] are helpful in understanding which state information are required to collect telemetries from the traffic. This includes the port ID, timestamps, hop latency, and buffer information such as queue occupancy etc. These telemetries are useful to arrive at the congestion rates and desired backoff values in our specific use case. The telemetry in this case is mostly relatable to insights like path chosen based on the switches through which a packet flows. However, our focus was on the quantitative measures pertaining to the traffic generated in a multi-tenant environment, which could be derived in our control loop. We were inspired by the implementation of P4 registers to store the switch ID's and use the same to keep track of states important to us.

DC P4 [9] provides a comprehensive work in capturing the performance of a data center switching model. This work details some important new constructs in the P4 specification which are commonly used such as variable length headers, counters which need to be persistence across packets. One such persistent counter, "last seen timestamp" for tenant packet,is stored in a register in our case as well.

AC/DC TCP[4], uses acknowledgment packet to determine the new congestion window. We also incorporated similar tactic to transmit and update tenant's congestion window with our tenant header ack_flag value.

8 Conclusion

Till now, we had come across tenant specific traffic metrics being managed by the control and management plane. Thus, it was interesting to obtain granular information about the tenants right at the forwarding plane itself. The constructs provided by the P4 language were a huge help in realizing different policies at the switch. We see that memory of a programmable switch can be used to store vital information in registers and data persistent across multiple packets and flows can be stored and operated upon. We were able to achieve the implementation of a simple congestion control policy paving the way for adopting a more complex and faster reacting congestion control policy in the future.

9 Future Work

We see that the feedback obtained from the current congestion control policy takes around 6 seconds in case the congestion control notification is sent every one second. This performance metric needs further improvement and possibly tackled with policies used in protocols such as RCP. We would also like to develop in-switch scheduling policies for packets pertaining to each tenant so as to achieve fairness among them. Our feedback loop is based on a polling mechanism. P4 provides mirroring of packets and use it to develop more proactive feedback loop. Also, another important factor in congestion control is the fair allocation of bandwidth across links. P4 switches can be used to store stateful link information to perform effective in network congestion control.

10 Acknowledgement

We got great help from the git repository of P4.org team [5] which had examples of basic forwarding router implementation in P4. We would also like to thank Andy Fingerhut from Cisco for helpful tips for the setup environment of the P4 behavioural switch and helping us understand the working of the P4 compiler. We also contacted Mr Antonin Bas from Barefoot Networks to understand the metadata being stored in programmable switches in BMV2 model. This helped us attack the issue of tackling congestion control and know which states could be stored and in which way.

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