SDN with Programmable P4-Dataplane
Final Report

342x9 - Project Work in Cyber Technology and Synthesis Project for Communication Technologies

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Abstract

Revision Dates

- **17th of March - Functional Specification Report**
  In the functional specification report the group presents the overall idea and a broad scope of the project. An initial timeplan for the 13 week period has been presented. Finally the idea of in-group interfacing between an FPGA and the Tofino has been presented, and will be assessed later on in the project.

- **4th of June - Midterm Report**
  The Scope of the project is now more specific where the router will be working along with FPGA based hardware. Further some functionality like statefull firewall will be added to the scope of the Tofinio router, and later moved to the FPGA where the p4 assesment will happen.
  A wide range of different tests has been added to the report due to the group having a functioning router capable of handling basic tasks.
  The previous idea of having an internal interfacing between two parts of the overall system has been scrapped, and the group now works together on each individual part of the project. This is due to FPGA hardware arriving late and for simplification purposes.
  The timeplan has been modified to a more specific plan for the 3-week period. Now featuring exact dates for when the group will look into different parts of the project.

- **24th of June - Final Report**
  minor errors corrected from the previous report, and peer feedback taken into concidderation for this report.
  The scope of the report has been modified. The FPGA hardware part of the implemeneted system has been removed. This modification was requested from advisors. The reasoning being a lack of time and a complicated piece of hardware for the time available. Now the group will be looking into a more theoritical approach where the group should consider differences between the approaches and how the implemntation could have been carried out.
  A list of accronyms, revisions dates, and a clear appendices section has been added to the report structure.

Acronyms

FPGA Field-Programmable Gate Array

RARE Router for Academia, Research and Education

P4 Programming Protocol-independent Packet Processors

NAT Network Address Translation

IP Internet Protocol

IPv4 Internet Protocol version 4

SDN Software Defined Networking

DPDK Data Plane Development Kit

PISA Protocol Indendepent Switch Architecture

PSA Portable Switch Architecture

TNA Tofino Native Architecture

BMv2 Behavioral model 2

API Application Programming Interface

RPC Remote Procedure Calls

gRPC gRPC Remote Procedure Calls

Bfrt Barefoot runtime

ONL Open Network Linux

UCLI Unified Command Line Interface

PM Port Management

AN Auto Negotiation

LPM Longest Prefix Match

Contents

1 Introduction

1.1 Background

Router for Academia, Research and Education (RARE), is a project under the European GÉANT research network to develop fully programmable network routers. The project uses FreeRouter for the control plane, and P4 for the data plane.

P4, short for Programming Protocol-independent Packet Processors, is a language to program the data plane of network devices, such as switches and routers. The language allows a programmer to quickly and easily specify exactly how a given device should parse, process, check, modify and transmit any given packet it receives. The programmer gets full control over the process, down to the individual bits, allowing them freedom to implement any given network function. The same physical device can alternatively act as a switch, router, firewall, Network Address Translation (NAT), gateway, load balancer or even more, depending only on what P4 code was uploaded.
The language is designed with the ability to run on general-purpose hardware, without requiring any specialized hardware for existing protocols. New features can be designed, developed and implemented at any time, without having to rely on hardware manufacturers to design and distribute new chips.

In this project the goal is to implement a Tofino router which runs on the P4 programming language and is connected directly to the GÉANT network. The router will receive and forward packets to and from the network, as well as act as a rudimentary firewall to stop TCP exchanges from being initiated from outside of the network.

1.2 Objectives

The specification and protocols of the P4 programming language are sparse and not explained in too many papers or journals. The group will therefore have to spend a lot of time testing and learning how to use the language. When it comes to the basic usages of forwarding and receiving packets there are many tutorials and exercises of how to do this, but more complex features will be more challenging to understand. Due to the low availability of this language, the members of the group hope to help clarify and explain how to use this language. The results and testing of this project can hopefully help students and readers in the future, who might want to use P4.
P4 allows for many use cases and many implementations of how routers could operate. One of the elements that are important when working with networks and outside users who might not always be of good intentions, the group will implement a firewall. The firewall will be stateful, which help enhance overall network security. The reasoning for implementing a firewall is due to the fact that the router will be connected to a open networks like the GÉANT Network. This network is open and many systems run on it every day. This network is good for testing and is therefore optimal for a research group like this one.

The overall system will therefore be using firewalls, routing, and a large open network along with other components like the Field-Programmable Gate Array (FPGA) based backbone. To fully cover all these requirements and technology used, the group members have outlined the following objectives:

- Describe the project & overall system
- Describe the RARE Protocols
- Implement a router capable of forwarding and receiving packets
- Implement a stateful firewall
- Test the router & firewall using Scapy & other tools
- Describe how the router could be offloaded onto an FPGA
- Test the overall system & perform an assessment of the final state of the project & the corrosponding tests
- Perform an assessment of finished project & its components

2 System Overview

The expected outcome of the project is a functioning IP router with a programmable data plane. The router will use P4 for the data plane, and FreeRtr for the control plane, as specified by the RARE project. It provides all standard routing features and protocols, it can distribute computed routing tables to the data planes of target routers/switches and it can be integrated with various data plane targets, which can be both virtual- or hardware-targets. RARE/FreeRtr operates on the network-level control plane. Our P4-router should be able to do basic forwarding of IPv4-traffic and should also double as a stateful firewall. We might add more functionality afterwards, depending on time constraints. Rather than having one single overall system acting as a router and firewall, we want to aim for different targets to implement our P4-functionality on, including both virtual and hardware switches. As P4 is a target independent language, it is compatible with both hardware and software targets, and can run on general-purpose hardware as mentioned.

2.1 High-level Overview

In our switch-targets, the control-plane (the control logic governing how network traffic data should be managed and forwarded) is decoupled from the data-plane (the actual forwarding of the network-traffic), which is the fundamental principle of the Software Defined Networking (SDN) paradigm. Traditionally, networking devices contained local control-planes, however with SDN the control-plane is abstracted from the data-plane and the control-plane logic governing the forwarding of traffic on all forwarding devices is contained and managed on one single platform, the SDN-controller, instead of on each individual device.

While SDN simplifies network configuration by segregating the control plane from the data plane on the device-level, and enables customizing of the control plane logic from a SDN-controller, the forwarding of network traffic still remains rather inflexible when using SDN with a predefined data plane, where the networking hardware vendor has defined the forwarding behavior and which protocols can be handled by their hardware; the chip embedded in the networking hardware devices provide fixed functionality (figure 1. However, on our system - be it a virtual switch or a hardware switch - the data-plane is also programmable, so that we can customize our own dataplane and embed more functionality into our target device(s), besides just the basic forwarding functions of a switch and/or router.
When provided with a compiled P4-program, our system containing a programmable dataplane can be programmed with dedicated packet processing besides it's initial functionalities, giving it functionality unique to that particular system. Thus, a switch/router with a programmable P4-dataplane can also be given firewall functionality, in addition to the forwarding.

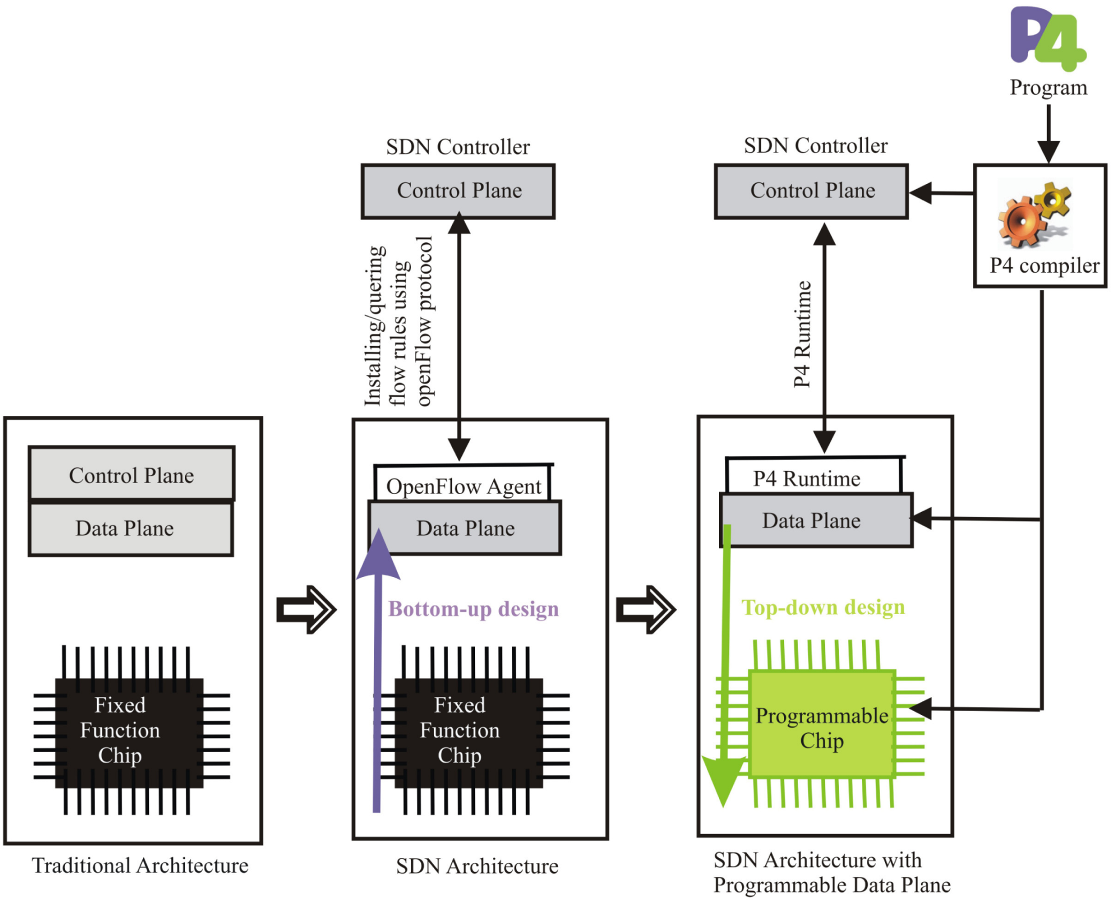


Figure 1: *From a "traditional" networking architecture to SDN-based networking using the OpenFlow protocol to SDN-based networking with a P4-programmable dataplane [5]*

2.2 System Implementation Platforms and Components

The following platforms will be used in this project:

- **RARE/FreeRtr:** RARE is an open-source routing platform created to provide support for multiple dataplanes, including DPDK, P4 and OpenFlow. RARE uses FreeRtr as a router operating system on the control plane, so we will refer to this platform as RARE/FreeRtr. FreeRtr is an open-source control-plane software providing many features within forwarding, routing and protocol security. Refer to [1] for a full summary of features. Furthermore, FreeRtr handles the packets themselves at the socket layer, meaning it is independent of the capabilities of the underlying operating system. The FreeRtr control-plane also populates the forwarding tables of our targets.

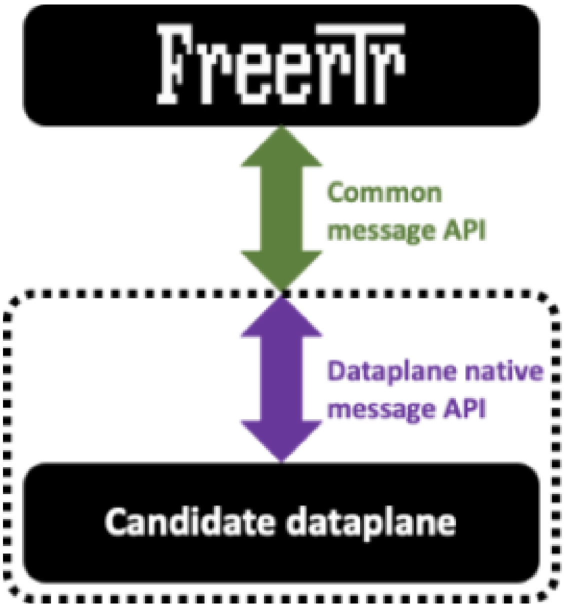


Figure 2

- **P4:** P4 is the language used to program the packet processing behavior of our router. The P4-language was revised in 2014 and 2016, leading to the versions denoted $P4_{14}$ and $P4_{16}$. The main difference is that $P4_{14}$ targets only devices with the Protocol Independent Switch Architecture (PISA), while $P4_{16}$ is based on a different architectural model, the Portable Switch Architecture (PSA), which is more flexible regarding the targets you can run your P4-program on. So, by opting for $P4_{16}$, we can target devices with different switching architectures than PISA. $P4_{16}$ is not backwards compatible with $P4_{14}$.

- **BMv2 and P4Runtime API:** Behavioral Model v2 (BMv2) is an open-source, PSA-based (Portable Switch Architecture) virtual P4-switch. The BMv2-platform is a good starting platform for learning the architecture of a programmable P4-switch, and how to use it, as the SDN programmable dataplane architechture shown in 1 overall is the same for the BMv2 and the Tofino switch. To deploy our P4-router functionality on the BMv2-switch, our P4-program (denoted program.p4 in figure 3) must first be compiled by a P4-compiler, creating a json-file (program.json) which is provided as input to the BMv2. The compiler we are using is called "p4c-bmv2" [3].

  In figure 3, "simple_switch_grpc" is a variation of BMv2, which exposes a gRPC P4Runtime server to the controller/control-plane. It receives and processes requests from them, e.g. to populate tables on the BMv2-switch. Other BMv2-versions exists, e.g. "simple_switch", using other frameworks like Apache Trift for implementing and managing remote procedure calls (RPC), however simple_switch_grpc have slightly lower performance overhead than simple_switch.

Besides the json-file, p4c-bmv2 also creates a "P4Info" file (program.p4info in figure 3 in txt-format containing metadata specifying the all the P4-entities defined in our P4-program (tables, actions and other P4-objects) that can be accessed via the P4Runtime API. Each object instance has an associated Identifier assigned to it by p4c-bmv2, which is used to refer to the objects in the API calls between the controller/control-plane and the P4Runtime API server on the BMv2-switch. The P4Info file is loaded by both the controller and the P4Runtime server. From the P4-entities declared in the P4Info file, the controller knows e.g. which tables on the switch it can access and populate, and the gRPC P4Runtime server uses the information in the file to translate Identifiers in received API-calls to the P4-objects, e.g. the tables instances, on the BMv2-switch. The "p4runtime.proto" is the specification file for the P4Runtime protocol defining which RPC-methods and messages that can be used between the control-plane and the P4Runtime server.

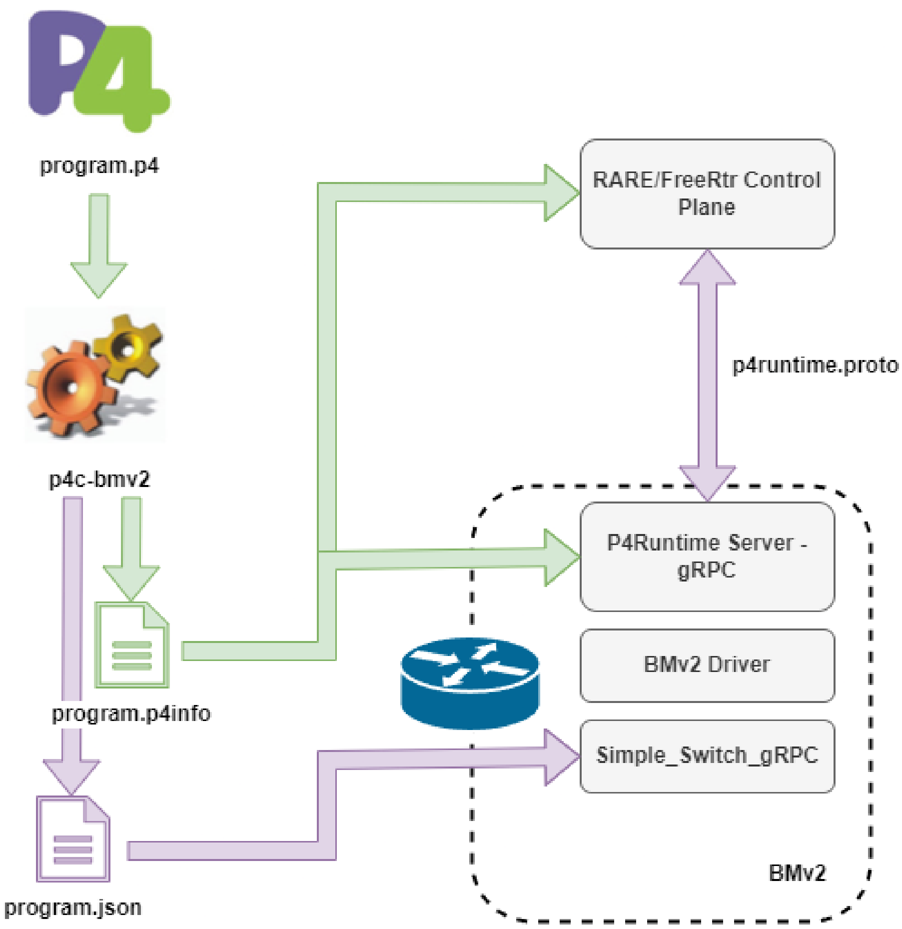


Figure 3: *Integration of control- and data-plane components on our virtual BMv2-switch, and deployment of P4-program.*

- **Tofino and BFRuntime API:** Tofino Native Architecture (TNA) is an alternative P4 target architecture developed by Intel's Barefoot Labs for their Tofino line of network switches [4]. In our project we have developed and compiled P4 on a *WEDGE-100BF-32X* model of hardware switch, which runs on TNA architecture.

  The Tofino-switch allows packet processing at higher speeds than the BMv2, allowing us to test high-performance use cases and simulate a real production environment. The communication between the RARE/FreeRtr control-plane and the Tofino P4-dataplane is enabled by Barefoot Runtime (Bfrt) Python APIs, the counterpart to the P4Runtime API for the BMv2-case. A process "bf_switchd" initializes a number of services, which besides the Bfrt-API, includes a BFRuntime gRPC server for receiving requests from the control-plane, and a bfshell, which allows us to interact with the data-plane and e.g. insert table rules using the Bfrt-API. For the Tofino-switch, our P4-program is compiled by a "bf-p4c" compiler, generating files that define the packet processing pipeline structure of the switch.

3 Functional specification

In this section of the report a short description of some of the current features will be provided. The functionalities covered in this report wil firstly be on the router functionality which here is based on simple forward and receiving functionalities. Then the firewall setup used in this project will be covered. In the end the network must have a network in which it can exchange packets with. The final section will therefore describe how the GÉANT network will be used, and for which cases.

3.1 Tofino router

The router is a WEDGE-100BF-32X hardware switch, based on Intel's Tofino silicon. The router will be used for backing everything implemented by the group. Most code will be loaded to the router such as the forwarding and the firewall. In this section of the router the functionality will be explained. Firstly the IPv4 packet forwading will be explained and then an explanation of the firewall. The router will be hosting both of these featues, which is why they are both loacted under this section.

3.1.1 IPv4 packet forwarding

The router will have to be able to both receive and forward packets at all running times. The router must know what to do whenever there are packets to be received or ready for forwarding. The mechanism for receiving is done by setting up the router to a PC with an internet connection, and an active link directly to the GÉANT network. The Router will then utilize the PC's connection and set up a port with an assigned NAT-addresses backed by an IPv4 address. From here the router will be recieving the packets sent to it. Once the packets are recieved the router will send them directly to the hardware based system where the packets will be examined and assessed by a firewall, before entering the system backbone. The system will then assess the packet and decide what should happen next. At some point the sender should get a reply, and therefore specified forwarding protocol is required.
When the packets has been assessed by the backbone of the system, the router must then be able to forward the next packet to the designated reciever or sender. This is done via the P4 programming language. The benefits of using this program is the enhanced possibilities for how an engineer might want a packet to be handled. Using this language the router will be effective and able to decide what should happen with each packet type that might be recived during testing.
Having these functionalities the router will function as a bridge between the backbone and the internet which in this case will be the GÉANT Network.

3.1.2 Stateful firewall

As described in the previous section the router will forward packets to the backbone from where the packets will be examined. There are however a step before we reach the backbone which is the firewall. In most cases we talk about two types of firewalls which is a stateful or stateless. In this project, the firewall will be stateful. The reason for choosing a stateful firewall over a stateless is due to its ability to provide more comprehensive and dynamic security. A stateful firewall might be more complex to implement due to the specific rules a programmer or designer can setup. Some of the features that are introduced to this type of firewall is connection tracking, performance efficiency, enhanced security, and application awareness, as well as range of other features that can be implemented by the engineers. One of the key technologies utilized by statefulness is the state tables from which the firewall keeps track of the connections currently interacting with the firewall. From here the firewall can keep a constant surveillance of connections even though they might be let through to the backbone and is able to cut the connection if something fishy happens during the exchange.

3.2 GÉANT Network

The Tofino router as previously described will connect to the GÉANT Network, from which the packets will be recived and forwarded to. In this section the connection requirements will be explained, and the purpose of the GÉANT connection will be described.
The Tofino router will need to be able to maintain a stable connection to the network. To keep an active connection throughout the day the router will be connected to a server located at DTU campus. This database has a direct connection to the GÉANT Network interface and the connection is supported by a ethernet cable connected directly to a PC. The connection is required to manage a high load of packages to help the group test the capabilities of the entire project and each component.
The GÉANT Network is a large setup where multiple nations cooperate to help maintain this system. It is not an open system in that sense we can use it for forwarding daily messages as we already do with the internet known today. The main purposes of this system is for research and testing of theories and other interesting projects that might need some testing before being let loose out to the public. Due to these factors the GÉANT Network is perfect for testing the tailor-made Tofino setup made during this project.

4 Theory

4.1 P4 Architecture

A P4 program is in charge of everything that happens to a packet, from the moment it enters the port on the PHY layer to the moment it leaves again. The process can be seen as a pipeline, logically divided into *blocks* with different purposes.
In standard P4, the overall steps of the pipeline are parsing, ingress processing, egress processing, and deparsing.

4.1.1 Parsing

The packet arrives to the switch as a stream of binary, and must first be parsed into some predefined data structures before the program can read, understand and modify the relevant fields.
Because P4 is protocol-independent, it has no native support for any existing network protocols like IPv4 or TCP. The programmer must therefore define what these headers are supposed to look like, describing exactly which fields belong to a header, how many bits go into each field, and in which order they are expected.
As an example, an Ethernet header (after the switch port has stripped the preamble, SFD and FCS) consists of only three fields: a destination MAC address, a source MAC address, and an ethertype field denoting which protocol is carried by the frame. A programmer defining this header could write it as

```
typedef bit<48> macAddr_t;
header ethernet_t {
    macAddr_t dstAddr;
    macAddr_t srcAddr;
    bit<16> etherType;
}
```

When the programmer later calls `packet.extract(hdr.ethernet)`, the program extracts the first 48 bits of `packet`, and saves them in the `dstAddr` field of `hdr.ethernet`. It saves the next 48 bits as the source address, and the next 16 bits as the ethertype. It is now possible for the rest of the program to refer to these objects and act upon them. The first step would naturally be to read the ethertype field, to know whether to parse the next series of bits as IPv4, IPv6 or something different entirely.
The parsing process can thus be viewed as a state machine, travelling from layer to layer up the protocols in the packet. The Ethernet header can lead to IPv4 or IPv6, those can in turn lead to TCP, UDP, etc., which in turn can lead to application layer protocols like HTTPS, if parsing those is desired.

4.1.2 Ingress processing

After all necessary headers are parsed into manageable data structures, ingress processing is where these fields are read, acted upon and changed.
Fields like the `ttl` field and checksum of an IPv4 header, or the source and destination addresses of an ethernet header must be updated at each switch. This happens in ingress processing.
This block is also where decisions are made regarding routing, using *match-action tables*. These tables are defined by the P4 program, and then populated with entries by the control plane. An example of a match-action table could be

```
    table ipv4_lpm {
        key = {
            hdr.ipv4.dstAddr: lpm;
        }
        actions = {
            ipv4_forward;
            drop;
            NoAction;
        }
        size = 1024;
        default_action = drop();
}
```

The above code defines a table with space for 1024 entries using the destination address of the IPv4 header as a key, allowing for one out of three *actions* to be called with parameters supplied by the control plane. The control plane can add entries of IPv4 addresses and subnets, defining which of the three actions they should trigger, and which parameters to pass to the action. In this case, the control plane would define a number of different IP addresses and ranges, then pair them with the correct exit port and MAC addresses for the next hop, and pass this to the `ipv4_forward` function.
This particular table uses *longest prefix matching* (LPM). As IP ranges can encompass each other, LPM makes sure only the most specific range containing the address is selected. Otherwise, matching against `0.0.0.0\0` (the entire IPv4 address space) as a default route would overrule all other entries.

4.1.3 Egress processing

Between ingress and egress, the packet is added to the packet buffer and handled by the traffic manager, which is responsible for scheduling packets to be output by the switch. During egress, it is no longer possible to change the output port of the packet, but other last-nanosecond changes are still permitted. This can be useful for latency measurements and the like.

4.1.4 Deparsing

The last step is deparsing, which is where the fields of the packet are assembled back into a bitstream, and emitted by the exit port.

4.2 Bloom filter

A Bloom filter (named after Burton Howard Bloom) is a *probabilistic* data structure, which trades some correctness for a big increase in performance, both in space and in time.
A Bloom filter describes a *set* of elements. Elements can be added to the set, and the set can later be tested against to check whether an element has been added previously. It is, however, not possible to remove elements from the set again.
Because of the probabilistic nature of the algorithm, when testing whether an element is part of the set or not, false positives may occur, but not false negatives. In essence, the response will either be "probably in the set" or "definitely not in the set".

The Bloom filter is made up of an array of m bits, all initialized to 0, as well as k different hash functions. The hash functions are each applied to the input element to compute k different array indices. Ideally the output indices should be uniformly distributed between 0 and m.
Adding an element entails setting each of these k array positions to 1, testing for the presence of an element is simply testing whether all relevant bits are 1. All k hash functions must be computed in either case, so the time complexity of insertion and access are both $O(k)$. The space complexity is $O(m)$.
Because of the limited amount of array positions compared to the output space of most hash functions, hash collisions are likely to occur. This is how false positives occur when testing for the presence of an element, especially when the Bloom filter fills up with more elements.
The error probability ε of receiving a false positive, based on the number of inserted elements n, can be calculated as:

$$\varepsilon = (1 - e^{-kn/m})^k \tag{1}$$

In our project, we use a Bloom filter to keep track of established TCP connections, for the stateful firewall. To add a connection to the filter, we concatenate the IP source and destination addresses, as well as the TCP source and destination ports, and hash them all together.

4.3 Tofino Native Architecture

P4 programs are able to be run on a variety of different packet-forwarding hardware and software, denoted as *targets*. The manufacturers of P4 targets are responsible for providing the compiler that turns any valid P4 program into code that can run on the target. Furthermore, they must provide an API to facilitate communications between the P4 data plane and any kind of control plane. As long as the API is used correctly, the control plane can be anything: Any kind of hardware or software, even a human manually entering commands in a terminal.

In this project, we intend to run our P4 code on a Tofino switch, designed and built by Intel. To do that, we'll need to rewrite some of the code to work with Tofino Native Architecture (TNA), as opposed to the default Portable Switch Architecture (PSA). We will also have to use the BFRuntime API for the connection between the data plane and the control plane. The perk of using TNA is the ability to make use of specialized hardware features of the Tofino switch ASICs, that are not by themselves defined in the standard P4 specification. [4]

One exclusive feature of this architecture is the fact that Tofino switches are divided into multiple parallel *pipes*, that can optionally be configured with separate P4 code.
TNA also provides access to a variety of *externs*, hardware features of the Tofino switch that are encapsulated into program objects with methods. Externs include things like registers, counters, meters, a 16-bit ones' complement checksum calculator (used for IPv4 packets), a variety of hash algorithms, a number of Arithmetic Logic Units (ALU) for quick mathematical operations, and more.

We use a *register* extern to hold our Bloom filter. This is necessary to keep the data persistent between the processing of multiple packets, as saving it in the P4 program itself would mean that the filter was reset for each new packet.

5 Implementation

5.1 RARE/FreeRtr-BMv2 Integration

This section explains how to install a FreeRtr environment on a Virtual Machine and deploy an instance of a RARE/FreeRtr control-plane on the VM, provide external connectivity between the FreeRtr-instance and the LAN-network of the VM-host, and finally integrate RARE/FreeRtr with the BMv2-dataplane and install a P4-program on the BMv2 virtual P4-switch. For a full guide on commands used for integration, refer to appendix D. The VM/OS used for the RARE/FreeRtr-BMv2 implementation is Linux Ubuntu (64-bit) v22.04. Automatic deployments of FreeRtr exists for Ubuntu v18.04 and v20.04, however v22.04 was chosen, instead for manual installation for reasons explained later. The reason for doing an integration of the RARE/FreeRtr controlplane with the BMv2 dataplane, is because it is a great way of learning the SDN architecture of a switch with a programmable dataplane, the components of the architecture (P4-compiler, Runtime-API, runtime server, etc.) and how the control- and data-planes communicate, because there are several architectural similarities between the BMv2 and the Tofino-switch.

As FreeRouter is written in Java, Java Runtime Environment (which was missing on the Linux VM) was first installed on the VM. Then a FreeRtr directory environment was created to store binary-, library-, log- and configuration-files for FreeRtr. The FreeRouter pulled as a .jar-file was compiled using Java 11, thus Java 11 or later was required, and launching a freeRtr environment with an older JRE version would give an "Unsupported Class Version Error".

A deployed FreeRouter-instance naturally provide much more utility when it has connectivity out of the VM-scope, to the LAN of the VM-host. To make the FreeRouter accessible from the LAN, the FreeRtr net-tools are installed. Our FreeRouter-instance requires two configuration txt-files: a hardware specification file and a software specification file. In the hardware specification file, the network interfaces for the FreeRouter-instance are declared, including their type (e.g. Ethernet), MAC-address, and enabling remote reachability on a tcp-port. The software specification file contains information, e.g. regarding the default IPv4-route of the FreeRouter-instance and configuring a static IP-address for it (or specify it as dynamic). From FreeRtr net-tools, PcapInt binary is used to bind a FreeRouter socket specified in the hardware configuration file to an available physical network interface of the VM-host (figure 4). pcapInt.bin requires glibc version 2.34 or later, and the glibc version is pretty much fixed by the Linux Distribution/Version. Hence, Ubuntu v22.04 was used as it comes with glibc v2.35. In the software specification file of freerouter, the interface denoted `eth1` is configured to act as an IPv4-client, thus 192.168.0.105 - provided by the DHCP-server, i.e the default gateway - becomes the IPv4-address of the freerouter-instance (figure 4).

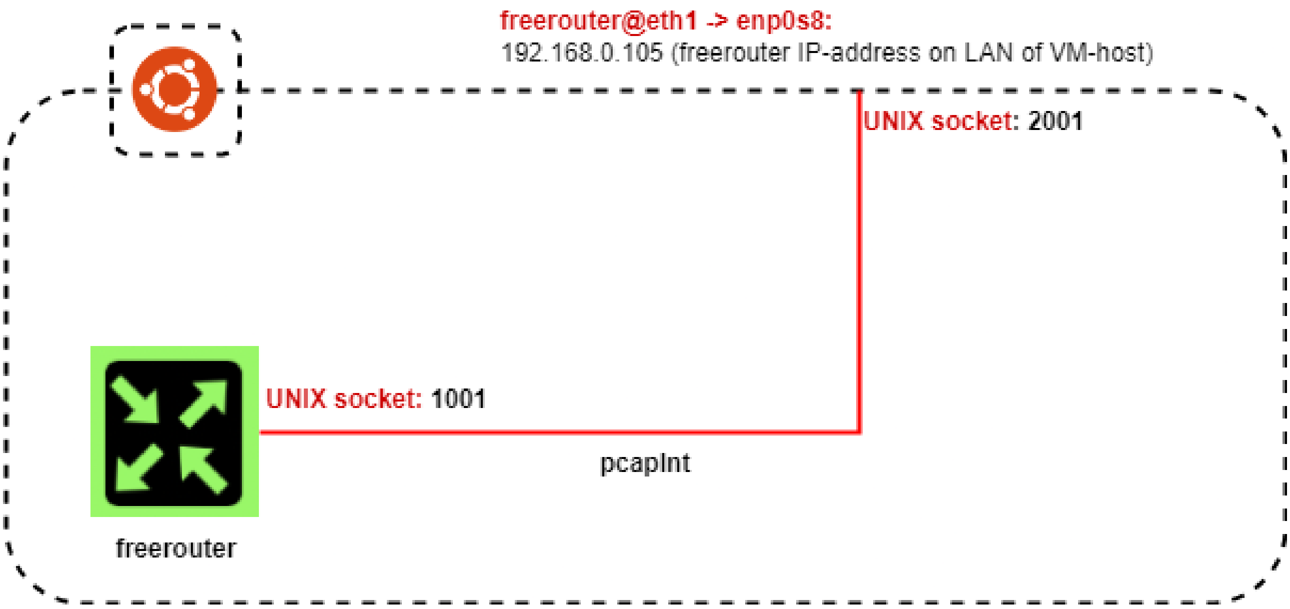


Figure 4: *Unix sockets are used for communication between the running freerouter-instance process and the outside. pcapInt maps Unix socket 2001 to the available physical network interface* ***`enp0s8`****, and stitches socket 2001 with 1001.*

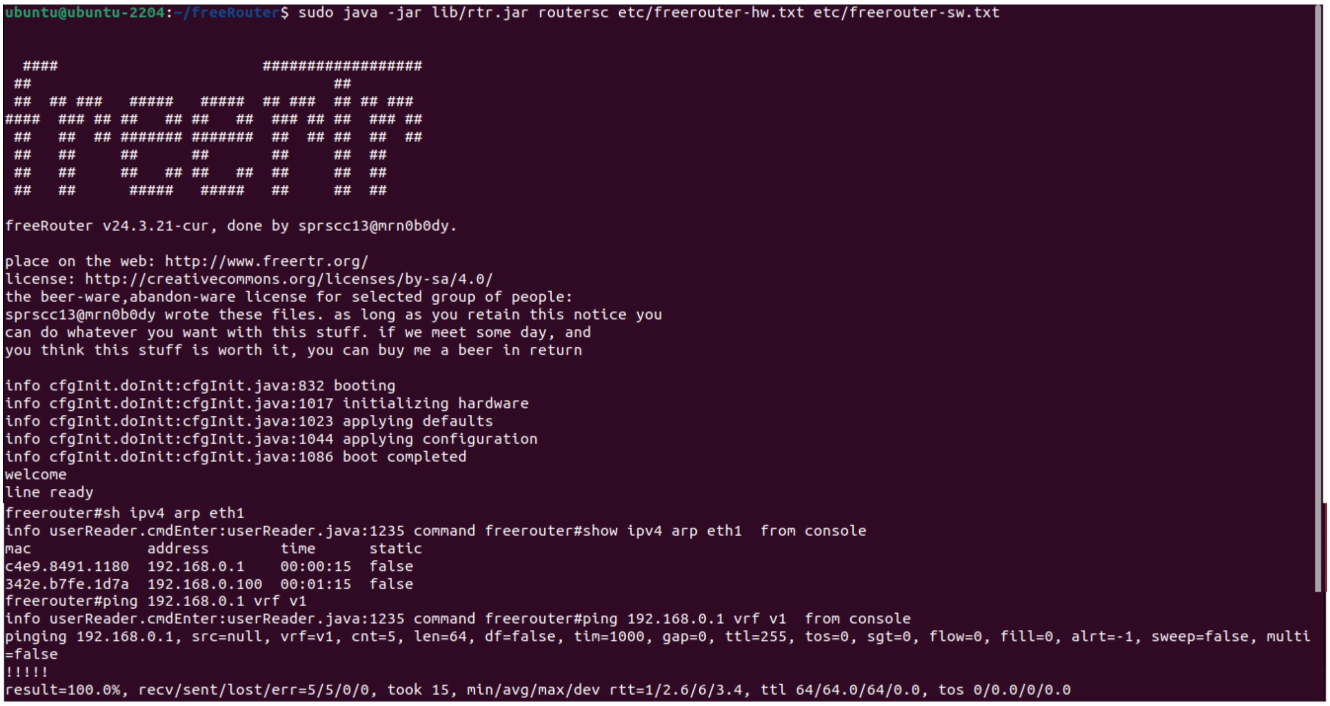


Figure 5: *The FreeRouter CLI after launching freerouter. The command* ***`sh ipv4 arp eth1`*** *show the arp cache of the interface* ***`eth1`*** *specified for the freerouter.* `192.168.0.1` *is IP-address of the default gateway of the LAN of the VM-host,* `192.168.0.100` *is the VM-host itself. Notice that pinging the default gateway is successful, meaning we have external connectivity for our freerouter instance.*

Proceeding with the integration of the Rare/Freerouter control-plane with a BMv2 P4-dataplane, a P4-environment is first installed on the Ubuntu VM, as per the instruction listed in D.0.3, providing us with the P4Runtime API, the P4C compiler and the BMv2-switch needed to implement the setup in figure 3. Communication between the FreeRtr control-plane and the BMv2 data-plane is enable by RARE forwarder.py - a Python script based on the gRPC P4Runtime Python library implementing the P4Runtime API; the script and other utilities are cloned into the environment from another Github repository (refer to D.0.3 step 2). Our P4-program, denoted "router.p4" in D.0.3 step 2, is compiled with the p4c-compiler, generating two files "router.txt" (the P4info-file) and "router.json", as described in subsection 2.2. Again, hardware- and software configuration files are made for our freerouter instance, which is to be connected to the BMv2 data-plane, before the instance is launched (step 5). The FreeRtr control-plane and the BMv2-dataplane are connected with a virtual Ethernet link (D.0.3 step 4). The pcapInt-binary from the FreeRtr net-tools binds a UNIX-socket of the FreeRtr-instance (22710) to a virtual network interface (veth250) of our BMv2-dataplane D.0.3 step 6), and veth250 is in turn connected to CPU-port 64 which is specified in D.0.3 step 7. When the BMv2-dataplane is launched, a gRPC runtime server is also started along with it (D.0.3 step 6). The last implementation step is where the P4Info- and json-files generated from our compiled P4-program "router.p4" are provided to the running FreeRtr control-plane, the gRPC P4Runtime server and the simple_switch_grpc, as described in subsection 2.2. When the RARE script `forwarder.p4` is run, P4Runtime is enabled between the control- and data-plane (figure 7: freerouter notifies that a neighbor is up). Figure 7 confirms that packets start being transmitted out the interface `ethernet0`, connecting to the simple_switch_grpc BMv2 data-plane, and interface `sd1` providing external connectivity for our Rare/freeRtr-BMv2 setup, indicating that Rare/freeRtr is communicating with the BMv2 data-plane.

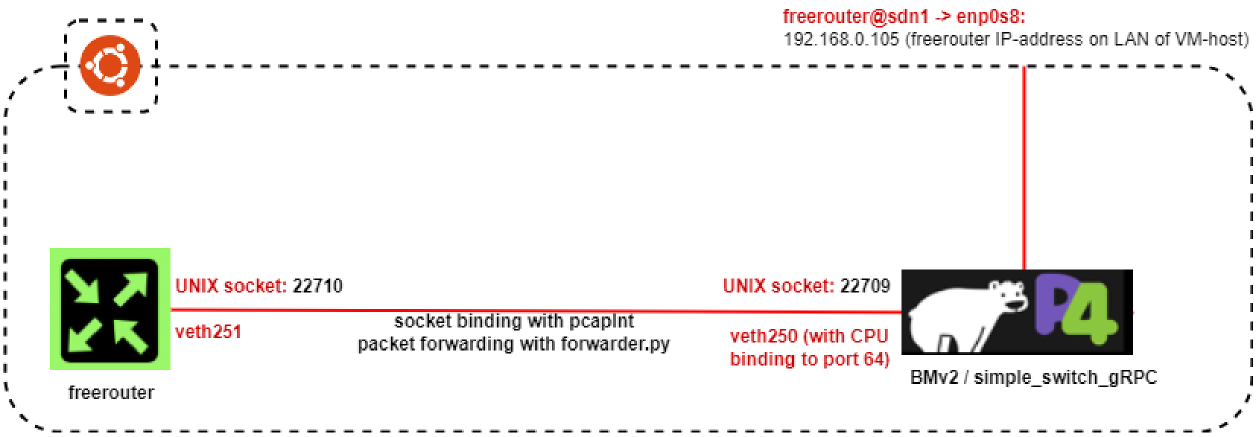


Figure 6: *Overview of Rare/freeRtr-BMv2 setup on Ubuntu VM.*

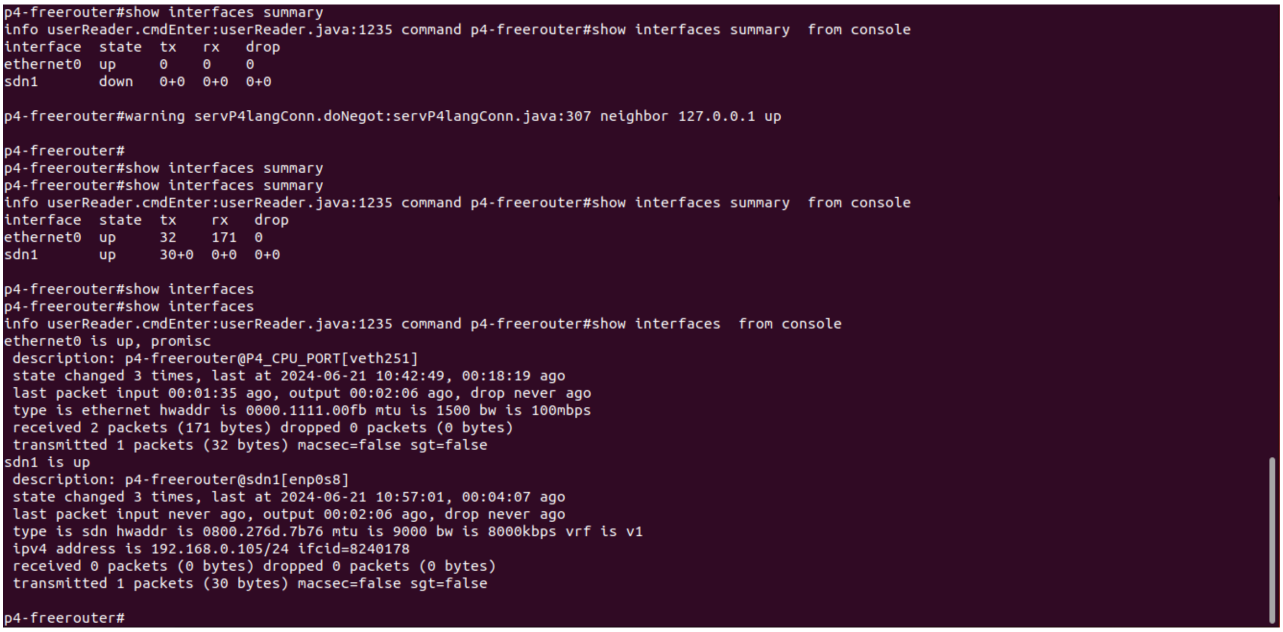


Figure 7: *Verification that the Rare/freeRtr control-plane is communicating with the BMv2 data-plane, on the `ethernet0` interface.*

5.2 Stateful Firewall Implementation using Bloom filters

This section describes how the stateful firewalling functionality is implemented in the P4-dataplane. Rather than giving a description of the entire P4-code, from parser to deparser (refer to appendix E for the full code), the description focuses on the specific componenents that enable the stateful functionality, allowing the firewall to monitor individual connections and keep track of their state; namely the Bloom filters and the hashing of incoming packets. In the project, P4-code for the firewall have been based on the Portable Switch Architecture and Tofino Native Architecture, which differ in their architectures, however the implementation using Bloom filters is the same in both cases. The code presented here are for the TNA, though.

As mentioned in subsection 4.2, the Bloom filters stores information about a set of elements and checks whether and element is (possibly) a member of the set. With the two Bloom filters used to implement the stateful firewall, a set of established tcp-connections is maintained. The Bloom filters are implemented as two different register arrays in P4:

```
Register<bit<1>,_>(Bloom_Filter_Entries) bloom_filter_1;
Register<bit<1>,_>(Bloom_Filter_Entries) bloom_filter_2;
bit<1> direction;
```

Above, `Bloom_Filter_Entries` specifies the size of the Bloom filters, thus it determines the number of tcp-connections that can be monitored. The variable `direction` specifies the direction of the packet flow, i.e. is it coming from the internal or the external network. When a tcp-packet is received, the direction of the packet is first checked, as it determines whether to update the Bloom filters or run a packet-check on them. The Bloom filters must only be updated with a new tcp-connection when a host on the internal network established a connection to the outside. External hosts cannot initate connections to the internal network - that is our security policy.

When a new tcp-connection is to be added to the set, that is when a SYN-packet is received, the filters are updated by two different hash-functions, crc16 and crc32; one for each filter. Adding a new tcp-connection is done by hashing a 5-tuple of information extracted from the IP- and TCP-headers (e.g. source- and destination IP-addresses) of a TCP SYN-packet, to two register positions/indices:

```
if (direction == 0) {

    if (hdr.tcp.syn == 1) {

        Hash<bit<32>>(HashAlgorithm_t.CRC16) hash_10;
        Hash<bit<32>>(HashAlgorithm_t.CRC32) hash_20;

        index1 = (bit<32>)(hash_10.get({packet hdr info}));
        index2 = (bit<32>)(hash_20.get({packet hdr info}));

        bloom_filter1_set.execute(index1);
        bloom_filter2_set.execute(index2);

    }
}
```

Above, `hash.get` computes the hash values of the packet header information. Generally, the crc-algoithms enable very fast computation of hashes. `bloom_filter_set.execute(index)` triggers a register action that updates the Bloom filters with 1's at the indices positions (figure 8).

When a tcp-packet comes from the external network, a packet-check is run on the Bloom filters to determine whether it is part of an established and allowed tcp-connection. Below, `bloom_filter_get.execute(index)` triggers a register action that reads the Bloom filters at the computed indices positions, and the packet will be dropped if it is not in either Bloom filter, i.e. if either values read from the filters are not 1. The order of the hashed packet header information is changed, i.e. IPv4 destination addresses come before source addresses, and tcp destination ports come before source ports, to account for the opposite directional flow of the packet - otherwise, the hash indices computed when reading the Bloom filters would not correspond to the hash indices computed when updating the filters, meaning a tcp-packet coming from the external network wrongly would be determined to not be part of an established tcp-connection even though it actually is.

```
if (direction == 1) {

    index1 = (bit<32>)(hash_10.get({packet hdr info}));
    index2 = (bit<32>)(hash_20.get({packet hdr info}));

    meta.bloom_read_1 = bloom_filter1_get.execute(index1);
    meta.bloom_read_2 = bloom_filter2_get.execute(index2);

    if (meta.bloom_read_1 != 1 || meta.bloom_read_2 != 1) {
        drop();
    }

}
```

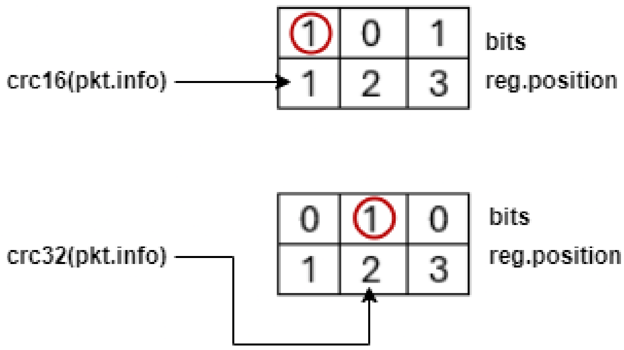


Figure 8: *Hashing TCP SYN-packet information and updating Bloom filters with the new TCP-connection. Initially, the filters contains only 0's.*

5.3 Implementation of IPv4 Forwarding

5.4 Using Tofino switch

A thorough walkthrough on how to compile, run and test a P4 program is found in appendix C. This guide goes through every command required - including simple explanations on why and how every command is run. The User Guide is based on the setup located in the basement of building 340 with two clients connected to the Tofino switch - a desktop and a server. The setup is further explained in section 6

6 Testing and Validation

6.1 Testing in the BMv2/PSA enviroment

This subsection covers the initial process of learning the P4 language. Advisor Mingyuan provided a Ubuntu test enviroment with all the necessary tools to compile and run tests in the BMv2 software enviroment. All the tutorials are provided by the p4lang team, see [2]. The process of doing the tutorials provided by the p4lang won't be covered here, as there are many small tutorials demonstrating different features like forwarding, load-balancing, and even a calculator.
This is a great start to get a taste of running P4 programs on a software target and quickly gave us the confidence to move on to the TNA architecture.

This rest of section 6 will showcase setups that test the functionality of forwarding, firewall features and performance of the program. All the tests are carried out on the Tofino switch located in the basement of building 340 at DTU - together with the two hosts; eoza and minza. The setup is illustrated in figure 9.

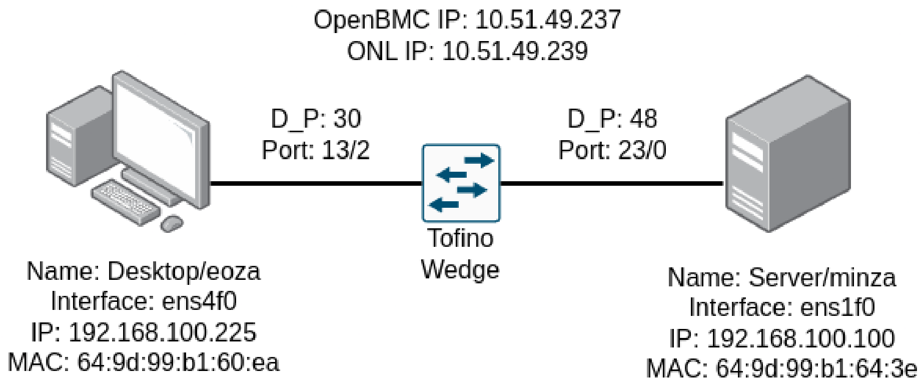


Figure 9: *Enviroment setup with Tofino switch and two hosts.*

6.2 Simple forwarding

The simple forwarding happens to all non-TCP packets, as figure 10 illustrates.
The ICMP Ping command will be used to test the forwarding. The P4 program checks if a destination IP address is found in the IPv4 table. If found, the IPv4 header field TTL is decremented, and the packet is forwarded to the respective ethernet destination address and corresponding egress port - as configured in the control plane.

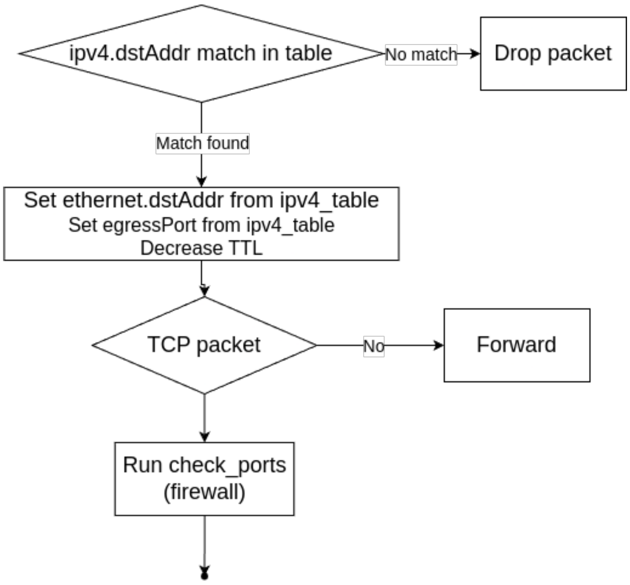


Figure 10: *Simple forwarding flow diagram*

To test this, only the IPv4 forwarding table has to be configured. Before configuring the ping test does not work:

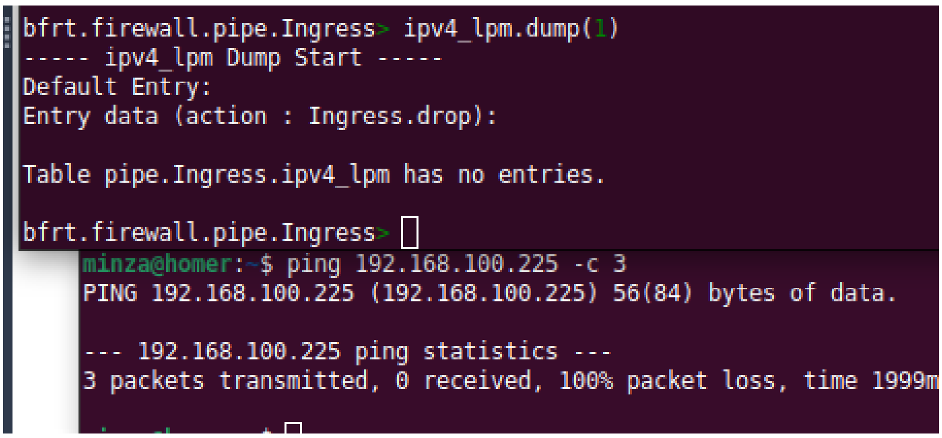


Figure 11: *No ping connection*

After adding the two clients to the table, the ping is successful. A guide on how to add the two clients, is found in appendix C. The forwarding table looks like so:

Key	dst MAC	dst Port
192.168.100.100	64:9d:99:b1:64:3e	38
192.168.100.225	64:9d:99:b1:60:ea	30

Table 1: *Forwarding table for simple forwarding*

Figure 12 shows the LPM table configuration as well as the ping result.

```
bfrt.firewall.pipe.Ingress> ipv4_lpm.dump(1)
----- ipv4_lpm Dump Start -----
Default Entry:
Entry data (action : Ingress.drop):

pipe.Ingress.ipv4_lpm entries for action: Ingress.ipv4_forward
hdr.ipv4.dstAddr              dstMac          port
---------------------------   --------------  ------
('0xC0A86464', '0x00000020')  0x649D99B1643E  0x30
('0xC0A864E1', '0x00000020')  0x649D99B160EA  0x1E


----- ipv4_lpm Dump End -----

bfrt.firewall.pipe.Ingress>
```

```
minza@homer:~$ ping 192.168.100.225 -c 3
PING 192.168.100.225 (192.168.100.225) 56(84) bytes of data.
64 bytes from 192.168.100.225: icmp_seq=1 ttl=63 time=0.161 ms
64 bytes from 192.168.100.225: icmp_seq=2 ttl=63 time=0.190 ms
64 bytes from 192.168.100.225: icmp_seq=3 ttl=63 time=0.138 ms

--- 192.168.100.225 ping statistics ---
3 packets transmitted, 3 received, 0% packet loss, time 1998ms
rtt min/avg/max/mdev = 0.138/0.163/0.190/0.021 ms
```

Figure 12: *Ping success*

This is simple forwarding of ICPM (ping) packets, works as expected.

6.3 IPv4 subnet forwarding

In this test, the ability of the switch to forward packets to the correct IP subnet will be demonstrated. For this purpose, client minza will use IP 192.168.200.100, while eoza will use 192.168.100.225. Two different subnets, 192.168.200.0/24 and 192.168.100.0/24.
Figure 13 shows the following in a hexadecimal representation; IP target address, address match length, destination MAC address, destination port.

```
----- ipv4_lpm Dump Start -----
Default Entry:
Entry data (action : Ingress.drop):

pipe.Ingress.ipv4_lpm entries for action: Ingress.ipv4_forward
hdr.ipv4.dstAddr              dstMac          port
----------------------------  --------------  ------
('0xC0A8C800', '0x00000018')  0x649D99B1643E  0x30
('0xC0A86400', '0x00000018')  0x649D99B160EA  0x1E


----- ipv4_lpm Dump End -----
```

Figure 13: *Dump displaying the /24 LPM setting.*

The dump shows how packets for 192.168.200.0/24 will be forwarded to port 48, while packets for 192.168.100.0/24 will be forwarded to the client on port 30. To test the connection, a

simple ping request will be sent, showcasing the forwarding capability of the Tofino switch and the compiled P4 program.
The ping is successful, as the screenshot in figure 14 illustrates:

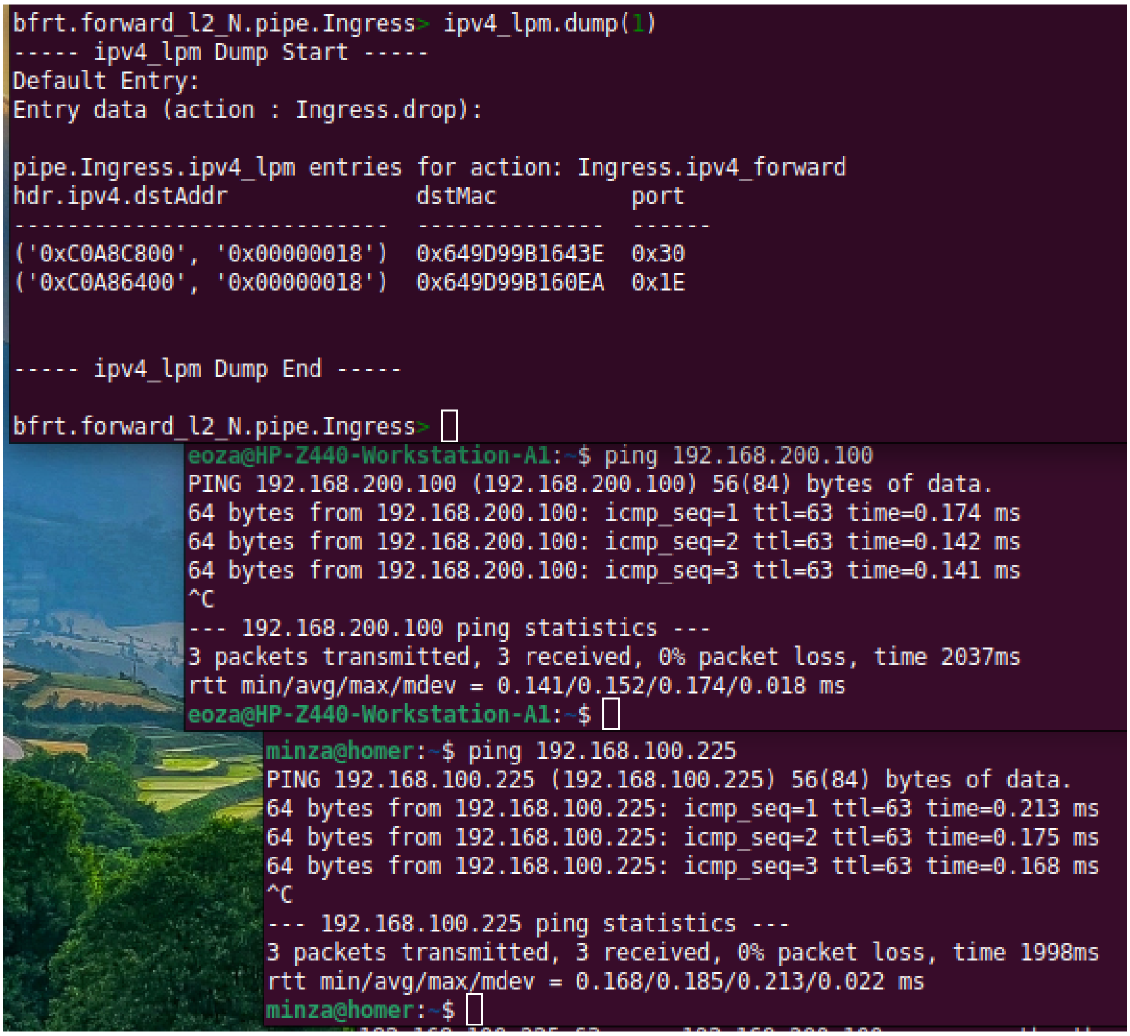
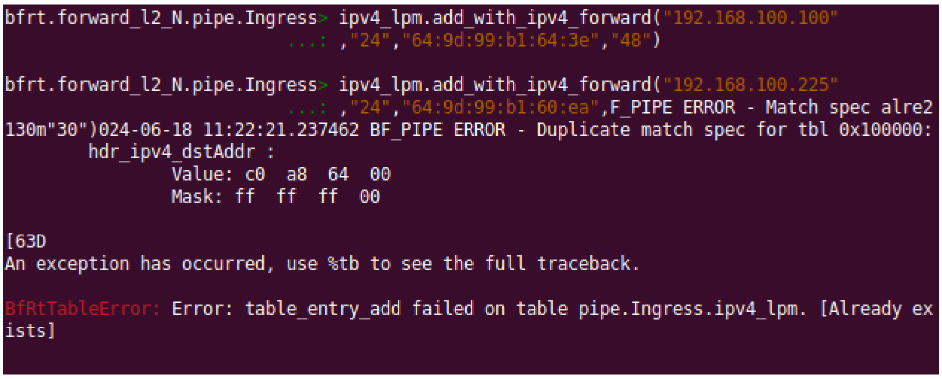


Figure 14: *Successful ping between clients.*

The Barefoot SDE does not allow multiple addresses under the same subnet, ie. it is not possible to add 192.168.100.100 as well as 192.168.100.225, with the IP address length of 24, as they are part of the same subnet. This results in an error:



```
bfrt.forward_l2_N.pipe.Ingress> ipv4_lpm.add_with_ipv4_forward("192.168.100.100"
                           ...: ,"24","64:9d:99:b1:64:3e","48")

bfrt.forward_l2_N.pipe.Ingress> ipv4_lpm.add_with_ipv4_forward("192.168.100.225"
                           ...: ,"24","64:9d:99:b1:60:ea",F_PIPE ERROR - Match spec alre2
130m"30")024-06-18 11:22:21.237462 BF_PIPE ERROR - Duplicate match spec for tbl 0x100000:
        hdr_ipv4_dstAddr :
                Value: c0  a8  64  00
                Mask: ff  ff  ff  00

[63D
An exception has occurred, use %tb to see the full traceback.

BfRtTableError: Error: table_entry_add failed on table pipe.Ingress.ipv4_lpm. [Already ex
ists]
```

Figure 15: *Error adding rule.*

Thanks to the clever integration of checking the subnet of the entries in the table, there is no confusion and/or redundant entries in the IPv4_lpm table.

6.4 IPv4 LPM

LPM (Longest Prefix Matching) is used in IP forwarding to make sure the most specific rule is used. This allows one to have general rules for large subnets, without having them overrule the more specific rules for smaller subnets or exact matches.
For example, one might add a rule for the subnet 0.0.0.0/0, which is the entire IPv4 address space. This would act as a *default* rule, as it matches with every address that doesn't already have a more specific rule available to it. It also has the lowest priority in an LPM system, as the prefix is 0, and therefore overruled by any other rule with a longer prefix.

In this test, we've added a default rule to drop any packet matching 0.0.0.0/0.
Additionally, we've added forwarding rules for the addresses 192.168.100.100/32 (to minza) and 192.168.100.225/32 (to eoza).

```
----- ipv4_lpm Dump Start -----
Default Entry:
Entry data (action : Ingress.drop):

Entry 0:
Entry key:
    hdr.ipv4.dstAddr                  : ('0x00000000', '0x00000000')
Entry data (action : Ingress.drop):

Entry 1:
Entry key:
    hdr.ipv4.dstAddr                  : ('0xC0A86464', '0x00000020')
Entry data (action : Ingress.ipv4_forward):
    dstMac                            : 0x649D99B1643E
    port                              : 0x30

Entry 2:
Entry key:
    hdr.ipv4.dstAddr                  : ('0xC0A864E1', '0x00000020')
Entry data (action : Ingress.ipv4_forward):
    dstMac                            : 0x649D99B160EA
    port                              : 0x1E

----- ipv4_lpm Dump End -----
```

Figure 16: *Forwarding table of the switch.*

A packet addressed to 192.168.100.100 would trigger both entry 0 and entry 1, but since entry 1 has the longest prefix, that one will be used.

```
eoza@HP-Z440-Workstation-A1:~$ ping 192.168.100.100
PING 192.168.100.100 (192.168.100.100) 56(84) bytes of data.
64 bytes from 192.168.100.100: icmp_seq=1 ttl=63 time=0.162 ms
64 bytes from 192.168.100.100: icmp_seq=2 ttl=63 time=0.144 ms
64 bytes from 192.168.100.100: icmp_seq=3 ttl=63 time=0.135 ms
64 bytes from 192.168.100.100: icmp_seq=4 ttl=63 time=0.145 ms
64 bytes from 192.168.100.100: icmp_seq=5 ttl=63 time=0.175 ms
64 bytes from 192.168.100.100: icmp_seq=6 ttl=63 time=0.179 ms
64 bytes from 192.168.100.100: icmp_seq=7 ttl=63 time=0.121 ms
```

Figure 17: *Successful ping from eoza to minza.*

The ability to successfully ping between the two hosts shows that the 0.0.0.0/0 default rule is not triggered, despite being the first entry in the forwarding table.

6.5 Firewall functionality

We have implemented a firewall intended to block all TCP traffic that isn't part of an already-established exchange initiated by a client behind the firewall.
Unlike the IPv4 table, the `check_ports` table has two keys - one for verifying ingress port and one for verifying egress port.
The current setup uses the `range` match type, meaning the ingress and egress port is configured in a range of ports - not an exact match or lpm match. Furthermore, when configuring the

table, a direction for the match is set to either 0 or 1. 0 indicating it is from the internal network and 1 being outside the network.
The flow of any TCP packet is illustrated in figure 18. The default setup is to drop any packets that dont match a rule in the table.

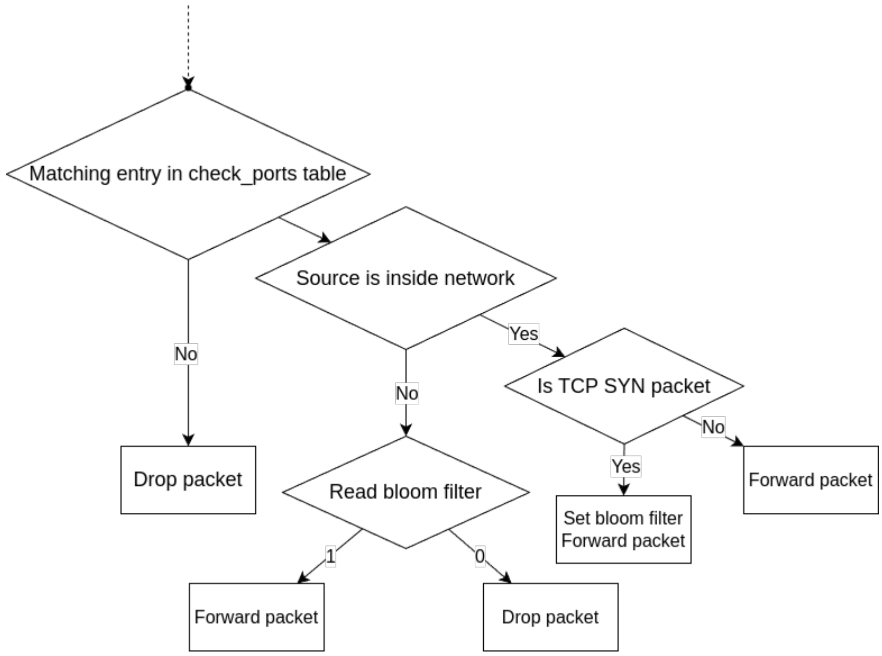


Figure 18: *TCP forwarding*

For the two clients, eoza and minza, the complete table for TCP rules is shown in table 2. The table below shows the configuration of the table, where the asterisk is a wildcard for any port.

Table 2: *check_ports configuration table*

Rule #	Ingress port	Egress port	Direction
1	30	*	0
2	48	*	0
3	*	30	1
4	*	48	1

6.5.1 Firewall test 1 - external initialization

In this test, we've set up eoza to be inside the area protected by the firewall, while minza is outside of it. This equates to rule #1 and #3 being applied - allowing traffic to and from port 30.

To generate TCP SYN packets, the Python library Scapy is handy. To monitor network activity on the respective network interfaces TShark is the network analyzer of choice. Tshark shows which packets are forwarded and implicitly which are blocked.

The first test has minza (outside network), send a SYN packet to eoza (inside).

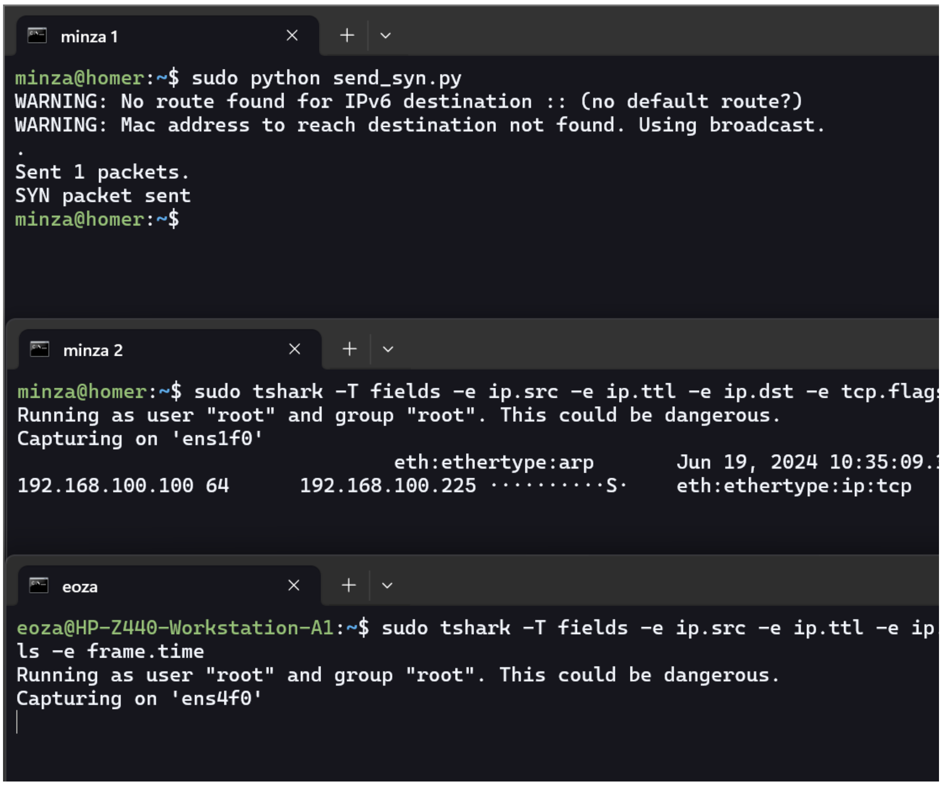


Figure 19: *TCP SYN from minza to eoza.*

As can be seen on the two TShark outputs, the interface on minza sees the sent SYN, but no response. Meanwhile eoza does not capture anything as the switch has dropped the packet.

6.5.2 Firewall test 2 - internal initialization

This tests sends a SYN from eoza to minza - from inside, to outside the network.

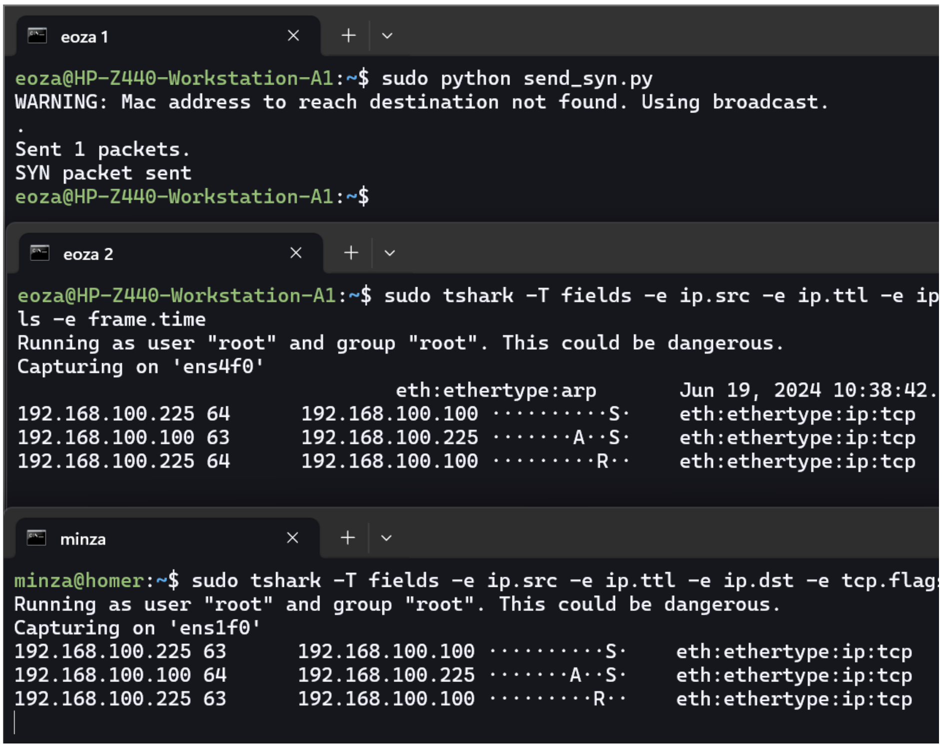


Figure 20: *TCP SYN from eoza to minza.*

Here we see a different story. The entire exchange of SYN, SYN-ACK and RST is visible to both parties. For the SYN-ACK to go through from minza to eoza, the details of that TCP exchange must have successfully been added to the Bloom filter by the initial SYN sent from eoza. Furthermore, the TTL decrements as expected from 64 to 63, when received on either end.
The forwarding, bloom filter and firewall works as expected, only allowing a TCP handshake to be initialized from inside the network.

6.6 Performance

To test the performance of the firewall P4 program, we will compare it to the simple layer 2 forwarding with no firewall capabilities. The network bandwidth test of choice is the iferf test, measuring the throughput of the network.

6.7 Challenges

This subsection will discuss some of the quirks and strange behaviour of the P4 TNA architecture.

6.7.1 Actions in P4

Any actions can't be called directly from the apply() section, but has to be called through a table. Does not work in test??

7 Conclusion

Appendices

References

[1] *freerTr*. URL: `http://www.freertr.org/`.

[2] *GitHub-repo for P4 tutorials in test-enviroment*. URL: `https://github.com/p4lang/tutorials`.

[3] *GitHub-repo for P4-compiler*. URL: `https://github.com/p4lang/p4c`.

[4] Intel. $P4_{16}$ *Intel Tofino Native Architecture - Public Version*. 2021.

[5] Sukhveer Kaur, Krishan Kumar, and Naveen Aggarwal. *A review on P4-Programmable data planes: Architecture, research efforts, and future directions*. March 2021. URL: `https://www.sciencedirect.com/science/article/pii/S0140366421000487`.

A - Work Distribution

The work distribution of the report can be seen in the table below. All parts of the report has been reviewed and edited by all members of the group, and the table is only meant to show the primary author of each sections.

Section	**Primary Author**
Abstract	
Introduction	
System Overview	
Functional Specification	
Theory	
Implementation	
Testing and Validation	
Conclusion	
P4 code development	
User Guide	

B - Peer Feedback Valuable Points

In this section a presentation of the given feed back from the groups peers can be seen. Here each section in the feedback schema will be presented and underlined is the most significant and interesting points for each section.

1. Structure & formalities

Overall rating: 4.5/5

"The overall structure is very complete and clear, there are only a few small problems, the paragraphs are not indented, and some code can be centred if it would be clearer, such as the code snippet on page 10"

"Overall very good structure, the entire project is explained well and each part of the report correlates well with the others."

2. Readability & language

Overall rating: 4.5/5

"Overall (like mentioned in the previous comment), the flow of information given is very good, since all the main "building blocks" of the system are explained in depth. I know that this report is of very technical nature and there are a lot of intricacies, but as a suggestion maybe there could be a few simpler explaination of them, since perhaps someone who does not know how registries work might have some trouble understanding about what is actually going on. Else than that, the information given is very thorough, good job!"

"While the language is easy to follow, it is long in several places and repeats itself"

"The introduction section is to the long side and could maybe be cut down a bit and some of the project details get mentioned more than once. This isn't a problem but something to keep in mind if looking for things to improve."

3. Explain the project

"The project is very well explained and I especially like the "System Overview" section. I would love to hear a little bit more about why this subject was chosen."

4. Scoping

Overall rating: 4.6/5

"The scope is very clear and well-defined. The objectives section is a good idea, which I didn't see in other reports and helps to understand the goals of the report."

"This project is wide but the authors managed to scope it clearly. The theory explains how the system works and especially the P4 architecture, the bloom filter and the Tofino Architecture. It is clearly linked to what was introduced in the introduction. Maybe the Bloom filter could have been introduced in the introduction to understand a bit before how it is important in the overall project."

5. Theory

Overall rating: 4.7/5

"The theory is very well written. The choices in what to include and what not to include make the level quite high but it also manages to not make the theory section too long."

6. Validation of theory

Overall rating: 4.4/5

"Good reference and figures!"

"The theory is well explained but it seems like only one source was used in this part. Is the example of the match action from you or were you inspired by some literature?"

7. Choise of tools & platforms

Overall rating: 4.6/5

"All the things explained in the theory are used in the project. I am missing an explanation as to why you use FreeRtr-BMv2 in the implementation part"

"The choice of the used tools for the platform, the programming language and the switch have been well explained and justified by the authors."

8. Implementation

Overall rating: 4.4/5

"Regarding the implementation, I think that some parts could be added in an appendix instead of in the report (the code lines regarding the update of the system or the cloning from GitHub).
For the bloom filter, the figure is relevant and interesting."

9. Implementation quality

Overall rating: 4.5/5

"Looks very well implemented and all the steps in the process are well described."

"It is very well documented, commented and easy to follow."

10. Commenting implementation

"I'd recommend the authors to focus primarily on the implementation of the firewall functionality, especially addressing the issues encountered with the bloom filter."

"I would very much like to hear what challenges the project has brought so far."

11. Testing scenarios

Overall rating: 4.7/5

"A lot of tests have already been performed. They are well documented and we can easily understand the process of their testing especially with the firewalls testing. The results of the firewalls testing will be continued in the 3 weeks period."

"It's interesting that you start with Ubuntu to become familiar with P4 and quickly transition to BFRT/TNA for a more practical test. You have simulated most of the possible scenario (I suppose) from packet loss to the firewall configuration to the transmission time. However maybe you may like to propose the throughput of each device in the network? :)"

12. Ambition level & amount

Overall rating: 4.8/5

"This project is ambitious, the group seems to have put a lot of effort on the P4 programming. There are a lot of tests that have been performed."

13. Clear who did what

Overall rating: 4.6/5

"It would maybe be nice to split the theory and some of the other sections so every member of the group shows that they work on all the taxonomic levels and understand the theory and implementation."

14. Suggestions

"looking through the code and removing the unnecessary out commented code blocks might be a good idea to improve code readability."

"A more precise and to the point language throughout the report would make it easier to read. Details given as to why the firewall did not work would have helped"

"In conclusion, I like your report very much and I appreciate the added goals section for good clarity. I did find some small grammar mistakes and typos for which I suggest using a grammar checker after everyone finished their parts. I also felt like the report was a bit long, but in general most sections very justified for the report"

C User Guide for Tofino switch

This section contains a complete user guide on how to transfer a P4 program to the Tofino switch onsite (INCOM lab in building 340 at DTU), and compile and test the connection between the connected clients. Everything but passwords will be shared. The guide is based on an Ubuntu 22.04.4 LTS build, June 2024.
Optionally, the DTU VPN can be used, enabling work from home. Command for connecting to the DTU VPN:

```
sudo openconnect --useragent=AnyConnect vpn.dtu.dk
```

The VPN is not required when connected to eg. eduroam or DTUsecure.

C.1 Transferring files for compilation

The management of the server happens via. the management port of the switch. For this project we have used remote management. If a physical connection is preferred, use serial port COM5, download driver and set the baud rate to 9600 (8 data bits, no parity, 1 stop bit).
For remote management there are two options:

- Use SCP in terminal
- Use Filezilla to transfer files

To transfer files via. the SCP command, the file has to be directly placed in the root folder on the ONL (Open Network Linux) server.

```
scp <filename>.p4 root@10.51.49.239:/root/<filename>.p4
```

Alternatively, a more flexible and interresting option is to use FileZilla. FileZilla gives a quick overview of the files and structure of the BMC/ONL. Use host: 10.51.49.239, username: root, password: , port: 22.
Go to the root folder and simply drag and drop the relevant P4 file to root/.

C.2 Connecting to ONL

As mentioned previously, this project is based on ssh connections. To connect to the BMC, use the following command:

```
ssh root@10.51.49.237 -p 22
```

Password: `OpenBmc`
When connected to the BMC, run `sol.sh` to connect the ONL server.
Alternatively, if the server is running, connect directly to the ONL server via:

```
ssh root@10.51.49.239 -p 22
```

Password: `root`

C.3 Compiling a P4 program

When connected to `root@localhost`, compilation of the P4 program on the Tofino switch happens through a shell script using the `bf-p4c` compiler. To compile run:

```
root@localhost:~# ~/tools/p4_build.sh <filename>.p4
```

Compilation is successful when the script writes
`CLEAR CONFIGURE MAKE INSTALL ... DONE`
After a successfull compilation, the `switchd` daemon is started through another shell script. This is provided by the Barefoot SDE. The `switchd` daemon is responsible for initializing and programming the pipeline of the switch and will be used to configure forwarding tables and firewall configurations. To start the daemon, run:

```
root@localhost:~# cd $SDE && ./run_switchd.sh -p <filename>
```

Note, the switchd runs a `<filename>.conf` file, so avoid writing `<filename>.p4` when running the `switchd` script.
After starting the daemon, start the UCLI[1] through the command `ucli` This is where the current setup is shown. Especially the Port Management (PM) is used, to monitor the active ports. After entering the `ucli`, write `pm` to show the port management.

```
bfshell> ucli
Starting UCLI from bf-shell
Cannot read termcap database;
using dumb terminal settings.
bf-sde> pm
bf-sde.pm> show
-----+----+---+----+-------+----+---+---+---+--------+----------------+----------------+-
PORT |MAC |D_P|P/PT|SPEED  |FEC |RDY|ADM|OPR|LPBK    |FRAMES RX       |FRAMES TX       |E
-----+----+---+----+-------+----+---+---+---+--------+----------------+----------------+-
bf-sde.pm>
```

The code above shows an empty port configuration.

C.4 Configuring ports

Figure 9 shows eoza connected to the switch via physical port 13/2, while minza is connected to physical port 23/0. Both ports are added:

```
bf-sde.pm> port-add 13/2 10G NONE
bf-sde.pm> port-add 23/0 10G NONE
bf-sde.pm> show
```

[1] Unified Command Line Interface

```
-----+----+---+----+-------+----+---+---+---+--------+----------------+----------------+-
PORT |MAC |D_P|P/PT|SPEED  |FEC |RDY|ADM|OPR|LPBK    |FRAMES RX       |FRAMES TX       |E
-----+----+---+----+-------+----+---+---+---+--------+----------------+----------------+-
13/2 |11/2| 30|1/30|10G    |NONE|YES|DIS|DWN|  NONE  |               0|               0|
23/0 | 1/0| 48|1/48|10G    |NONE|YES|DIS|DWN|  NONE  |               0|               0|
```

After adding the ports, the auto negotiation has to be set to option 2 = disabled. As the `OPR` column shows in the previous `show`, both ports are disabled. To set `an` (Auto negotiation) and enable ports, run:

```
bf-sde.pm> an-set -/- 2
bf-sde.pm> port-enb -/-
bf-sde.pm> show
-----+----+---+----+-------+----+---+---+---+--------+----------------+----------------+-
PORT |MAC |D_P|P/PT|SPEED  |FEC |RDY|ADM|OPR|LPBK    |FRAMES RX       |FRAMES TX       |E
-----+----+---+----+-------+----+---+---+---+--------+----------------+----------------+-
13/2 |11/2| 30|1/30|10G    |NONE|YES|ENB|DWN|  NONE  |               0|               0|
23/0 | 1/0| 48|1/48|10G    |NONE|YES|ENB|DWN|  NONE  |               0|               0|
```

The `-/-` means any port and simplifies the process of writing `an-set 13/2 2`, `an-set 23/0 2`... To further simplify the setup, simply write the following. Beware this adds and enables all the ports on the switch.

```
bf-sde.pm> port-add -/- 10G NONE
bf-sde.pm> an-set -/- 2
bf-sde.pm> port-enb -/-
```

C.5 Entering Barefoot API and configuring tables

The Barefoot API is the control plane of the program and controls the forwarding as well as firewall rules through tables.
To enter the API, exit the UCLI and run `bfrt_python`.

```
bf-sde.pm> exit
bfshell> bfrt_python
cwd : /root/bf-sde-9.2.0

We've found 1 p4 programs:
<filename>

Loading the tables ...
```

From here, the setup depends on the P4 program, but in this case LPM forwarding to the two clients will be configured through the IPv4 LPM table. This table is part of the `Ingress` section, encapsulated in a final package called `pipe`.
The program is called `firewall.p4` and matches on the IPv4 address with a LPM match. In this example the IP match has to match all 32 bits. If a match is found, the packet is forwarded to the MAC address on the respective port. Eg. if the destination IP is 192.168.100.100, forward to MAC address ...64:3e on port 48.
This is layer 2 forwarding, based on layer 3 (IP) headers.

```
bfrt_root>bfrt.firewall.pipe.Ingress
--------> bfrt.firewall.pipe.Ingress()
Available symbols:
bloom_filter_1          - Table Object
bloom_filter_2          - Table Object
check_ports             - Table Object
dump                    - Command
hash_10                 - Command Object
hash_11                 - Command Object
hash_20                 - Command Object
hash_21                 - Command Object
info                    - Command
ipv4_lpm                - Table Object


bfrt.firewall.pipe.Ingress> ipv4_lpm.add_with_ipv4_forward("192.168.100.100","32
                       ...: ","64:9d:99:b1:64:3e","48")

bfrt.firewall.pipe.Ingress> ipv4_lpm.add_with_ipv4_forward("192.168.100.225","32
                       ...: ","64:9d:99:b1:60:ea","30")

bfrt.firewall.pipe.Ingress> ipv4_lpm.dump(table=1)
----- ipv4_lpm Dump Start -----
Default Entry:
Entry data (action : Ingress.drop):

pipe.Ingress.ipv4_lpm entries for action: Ingress.ipv4_forward
hdr.ipv4.dstAddr              dstMac          port
----------------------------  --------------  ------
('0xC0A86464', '0x00000020')  0x649D99B1643E  0x30
('0xC0A864E1', '0x00000020')  0x649D99B160EA  0x1E


----- ipv4_lpm Dump End -----
```

At this point simple forwarding based on IP addresses is implemented and is ready for testing.
To clear the entire table, write `ipv4_lpm.clear`.
To modify an entry, write eg. `ipv4_lpm.mod_with_ipv4_forward("192.168.100.100","32 ...: ","64:9d:99:b1:64:3e","49")` to change the port from "48" to "49", without clearing the entire table.

C.5.1 Tip

A helpfull tip is to use questionmark "?" after a function/command/table/method eg. `ipv4_lpm.add_with_ipv4_forward?`. This displays all the options for the requested table, with the default option listed.

```
bfrt.firewall.pipe.Ingress> ipv4_lpm.add_with_ipv4_forward?
Signature: ipv4_lpm.add_with_ipv4_forward(dstaddr=None, dstaddr_p_length=None,
↪  dstmac=None, port=None, pipe=None, gress_dir=None, prsr_id=None)
Docstring:
Add entry to ipv4_lpm table with action: Ingress.ipv4_forward

Parameters:
['dstaddr', 'dstaddr_p_length'] type=LPM         size=32 default=0
dstmac                         type=BYTE_STREAM size=48 default=0
port                           type=BYTE_STREAM size=9  default=0
File:      Dynamically generated function. No source code available.
Type:      method
```

C.6 Configuring a range-match key

Besides the `ipv4_lpm` table, the firewall program has a table called `check_ports` designed for allowing specific traffic to/from the correct ports. This uses the range-match key, defining a range of ports both in the source and destination.
For configuring a range-match key the start and end range has to be defined as well as a match priority (5th argument). 0 is the highest priority.

```
bfrt.firewall.pipe.Ingress> check_ports.add_with_set_direction("30","30","0","51
                       ...: 1","0","0")

bfrt.firewall.pipe.Ingress> check_ports.add_with_set_direction("0","511","30","3
                       ...: 0","1","1")

bfrt.firewall.pipe.Ingress> check_ports.dump(1)
----- check_ports Dump Start -----
Default Entry:
Entry data (action : NoAction):
```

```
pipe.Ingress.check_ports entries for action: Ingress.set_direction
ig_intr_md.ingress_port    ig_tm_md.ucast_egress_port      $MATCH_PRIORITY  dir
-------------------------  ----------------------------  -----------------  -----
('0x1E', '0x1E')           ('0x00', '0x1FF')                             0  0x0
('0x00', '0x1FF')          ('0x1E', '0x1E')                              1  0x1


----- check_ports Dump End -----
```

The `dir` column indicates whether the traffic comes from outside the network or inside the network. 0 is inside. Ie. traffic from port 30 is always allowed and prioritized as the `dir = 0` and `$MATCH_PRIORIRY = 0`.
If the source port is not port 30, but targeted to port 30, `dir = 1` and a connection has to be initialized from port 30 before the packet is allowed. This is how the stateful firewall operates, see further explanation in previous sections.

C.7 Connecting to clients

Currently the two clients connected to the switch are called eoza and minza, and are both accessible through ssh. Connect to eoza:

```
ssh eoza@10.51.49.225
```

Connect to minza:

```
ssh minza@10.51.49.233
```

C.8 Configuring IP, routing tables and arp tables

To test whether the network interface has been configured properly, run `ifconfig` on either device and inspect whether the IPv4 address is as expected on the network interface. On minza, add the IP 192.168.100.100 to ens1f0:

```
minza@homer:~$ sudo ip addr add 192.168.100.100/24 dev ens1f0
```

When running ifconfig, the ens1f0 interface should display:

```
ens1f0    Link encap:Ethernet  HWaddr 64:9d:99:b1:64:3e
          inet addr:192.168.100.100  Bcast:0.0.0.0  Mask:255.255.255.0
```

To delete or reconfigure an interface, run `del` instead of `add`, eg. `sudo ip addr del 192.168.100.100/24 dev ens1f0` to delete the IP and subnet mask. This is handy when reconfiguring the interface.
After configuring the interface, run the `route -n` command to display the routing table. In order to communicate to the other client, the respective IP address should be known by the routing table. To add an entry to the routing table, eg. for minza to know about eoza, add:

```
sudo route add -host 192.168.100.225 metric 100 dev ens1f0
```

To map the IP address to the correct MAC address, run the following command on minza:

```
sudo arp -s 192.168.100.225 64:9d:99:b1:60:ea
```

To test the arp table, run `arp -a` and find the added IP in the list.
The network interface, routing table and arp table is now setup correctly and the two clients can ping each other, showed below:

```
minza@homer:~$ sudo ip addr add 192.168.100.100/24 dev ens1f0
minza@homer:~$ sudo route add -host 192.168.100.225 metric 100 dev ens1f0
minza@homer:~$ sudo arp -s 192.168.100.225 64:9d:99:b1:60:ea
minza@homer:~$ ping 192.168.100.225 -c 3
PING 192.168.100.225 (192.168.100.225) 56(84) bytes of data.
64 bytes from 192.168.100.225: icmp_seq=1 ttl=63 time=0.170 ms
64 bytes from 192.168.100.225: icmp_seq=2 ttl=63 time=0.171 ms
64 bytes from 192.168.100.225: icmp_seq=3 ttl=63 time=0.148 ms

--- 192.168.100.225 ping statistics ---
3 packets transmitted, 3 received, 0% packet loss, time 1999ms
rtt min/avg/max/mdev = 0.148/0.163/0.171/0.010 ms
```

Now make a mirrored setup eoza, eg. using figure 9.

C.8.1 Tip

The client minza seems to reset the interface, routing table and arp table very often. It might be necessary to run the three mentioned commands multiple times.

C.9 Inspecting network traffic

To capture network traffic, the network protocol analyser, tshark, is used. Tshark is installed on both clients. For firewall testing we created the custom output with IP source, TTL, IP destination, TCP flags, frame protocol as well as date/time. During development, the TTL field is a convenient field to modify, to inspect how far into the P4 program, any packet reaches. This is the reason to include the TTL as one of the very first fields.

```
sudo tshark -T fields -e ip.src -e ip.ttl -e ip.dst -e tcp.flags.str -e
↪  frame.protocols -e frame.time
```

This is fully customizeable depending on the usecase. Wireshark was not an option due to the ssh connection in a terminal.

C.10 Firewall test packets using scapy

On either client it is possible to use the python library scapy and run python scripts.
To create a new script run and edit it through the nano text editor on the terminal, use:

```
sudo nano scriptname.py
```

To test the firewall a simple script called `send_syn.py`, sending a SYN packet, is created and sent. The script imports the scapy library and defines the destination IP and port:

```python
from scapy.all import *

# Define target IP and port
target_ip = "192.168.100.225"
target_port = 22

# Send SYN packet
syn_packet = IP(dst=target_ip)/TCP(dport=target_port, flags="S", seq=1000)
send(syn_packet)
print("SYN packet sent")
```

To run the script, use `sudo python send_syn.py`.

C.10.1 Tip

Open two terminals on each client, one on each running tshark and another one sending packets/doing network configuration.

D Guide for RARE/FreeRtr-BMv2 Integration

This section provides documentation and guidance on how the FreeRtr environment is installed on the Linux Ubuntu (64-bit) v22.04 VM, how it is integrated with the BMv2-dataplane, and how our P4 firewall program is deployed on the BMv2-switch.

D.0.1 Installation of FreeRtr environment on Ubuntu v22.04

1. Update Linux Ubuntu system:

```
sudo apt-get update
sudo apt-get upgrade
```

2. Install Java Runtime Environment, if missing on your system:

```
sudo apt-get install default-jre-headless --no-install-recommends
```

3. Create FreeRtr directory environment:

```
sudo mkdir -p ~/freeRouter/bin ~/freeRouter/lib ~/freeRouter/etc
↪  ~/freeRouter/log
cd ~/freeRouter/lib
sudo wget http://freerouter.nop.hu/rtr.jar
```

D.0.2 Deploy FreeRtr-instance with external connectivity

Documentation for connecting a deployed FreeRtr instance to the LAN of the VM-host. Requries an installed FreeRtr environment.

1. Install freeRouter net-tools:

```
sudo wget http://www.freertr.net/rtr-`uname -m`.tar -O rtr.tar
sudo tar xvf rtr.tar -C ~/freeRouter/bin/
```

2. Create hardware- & software- txt-files. They are used to configure the FreeRtr-instance. Store them in /freeRouter/etc. Contents of the configuration files can be found at Géant RARE/FreeRouter-101 Tutorial.

3. Launch FreeRtr environment (with txt-configuration files as parameters):

```
sudo java -jar lib/rtr.jar routersc etc/hw-config.txt
↪  etc/sw-config.txt
```

4. In `~/freeRouter/bin`, use pcapInt binary from freeRouter net-tools to bind a freeRouter socket to an available network hardware interface (enp0s8):

```
sudo ./pcapInt.bin enp0s8 2001 127.0.0.1 1001 127.0.0.1
```

D.0.3 RARE/FreeRtr-BMv2 Integration on Ubuntu v22.04

Documentation for deploying a FreeRouter instance as a control-plane for the BMv2 virtual P4-switch.

1. Install P4 environment. Installing p4lang-p4c from the P4lang Project Repository, will install the P4Runtime API, the P4C compiler and BMv2 on your system:

```
echo 'deb http://download.opensuse.org/repositories/home:/p4lang/xUbuntu_22.04/ /' | sudo tee /etc/apt/sources.list.d/home:p4lang.list
curl -fsSL https://download.opensuse.org/repositories/home:p4lang/xUbuntu_22.04/Release.key | gpg --dearmor | sudo tee /etc/apt/trusted.gpg.d/home_p4lang.gpg > /dev/null
sudo apt update
sudo apt install p4lang-p4c
```

   `dpkg -l | grep p4lang` should verify the installation of the p4lang packages:

Figure 21: *Installed P4 packages.*

   For installing on Debian, commands can be found at Software Opensuse - p4lang-p4c Installation.

2. Clone RARE code from repository to your system:

```
sudo git clone https://github.com/rare-freertr/RARE-bmv2.git
```

   Then go to `~/RARE-bmv2/02-PE-labs/p4src` and compile the RARE router.p4 (or any other chosen p4-program) with the P4C compiler:

```
mkdir -p ../build ../run/log
sudo p4c --std p4-16 --target bmv2 --arch v1model -I ./ -o ../build --p4runtime-files ../build/router.txt router.p4
```

3. Create hardware- & software- txt-files for the FreeRtr-instance and store them in /freeRouter/etc. Contents of the configuration files can be found at Géant RARE/FreeRouter-101 Tutorial.

4. The RARE/FreeRtr-BMv2 communication is enabled using a virtual Ethernet link:

```
sudo ip link add veth251 type veth peer name veth250
sudo ip link set veth250 up
sudo ip link set veth251 up
```

5. Launch FreeRtr environment (with txt-configuration files as parameters):

```
sudo java -jar lib/rtr.jar routersc etc/hw-config.txt
↪ etc/sw-config.txt
```

6. In ~/freeRouter/bin, launch freeRouter pcapInt in order to stitch the control plane and P4 BMv2 dataplane communication:

```
sudo ./pcapInt.bin veth251 22709 127.0.0.1 22710 127.0.0.1
```

7. Start the RARE P4-dataplane - the simple_switch_grpc version of BMv2. This will also start the gRPC runtime server on BMv2:

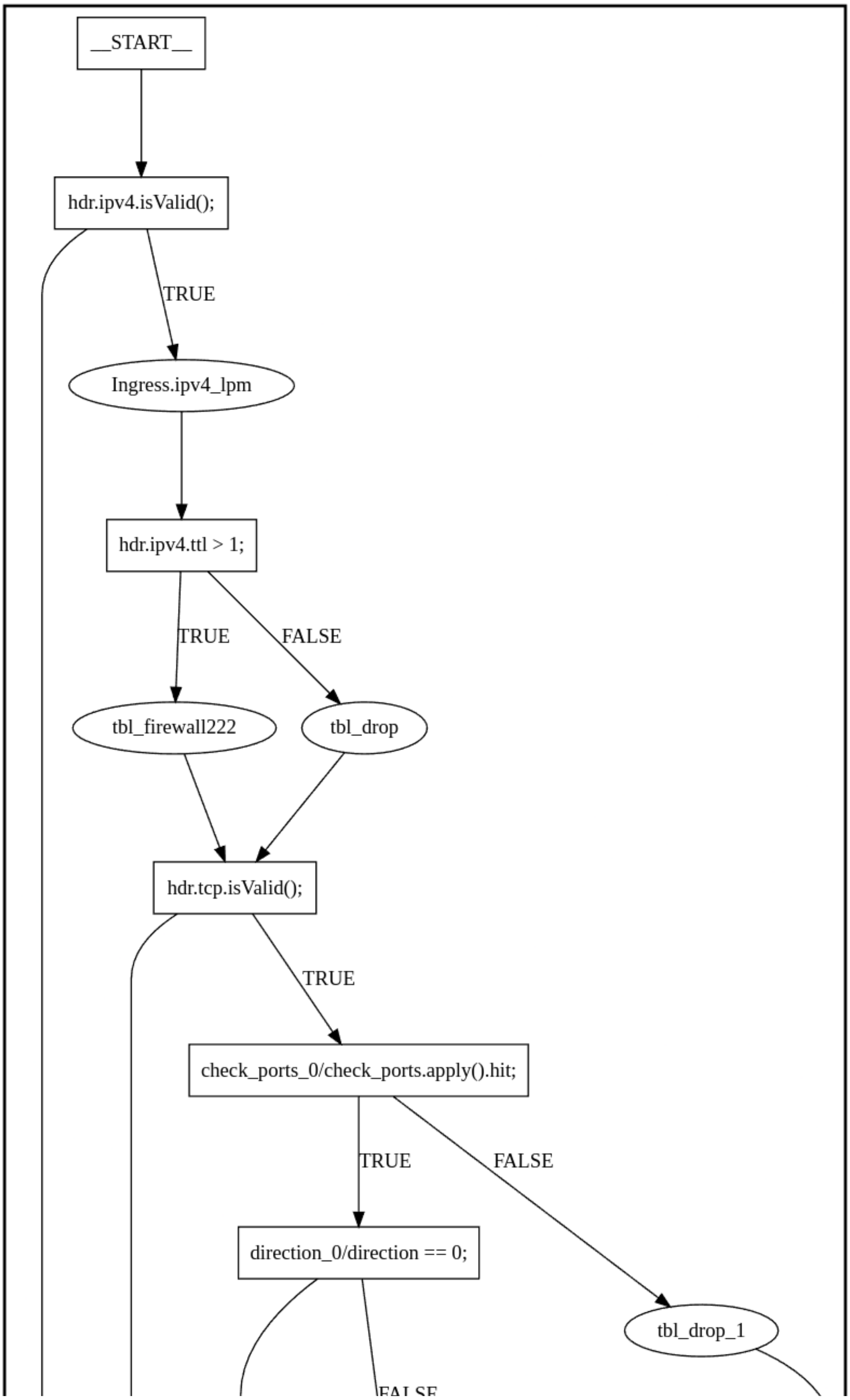
```
export P4_RARE_ROOT=RARE-bmv2/02-PE-labs
sudo simple_switch_grpc --log-file
↪ $P4_RARE_ROOT/run/log/p4-freerouter.log -i 1@enp0s8 -i
↪ 64@veth250 --thrift-port 9090 --nanolog ipc://
↪ $P4_RARE_ROOT/run/bm-0-log.ipc --device-id 0
↪ $P4_RARE_ROOT/build/simple_switch_grpc.json --
↪ --grpc-server-addr 127.0.0.1:50051 >
↪ $P4_RARE_ROOT/run/log/p4-freerouter.out 2>&1 &
```

8. In ~/RARE-bmv2/02-PE-labs, launch forwarder.p4 to enable the P4Runtime communication between the FreeRtr control-plane and the BMv2 P4-dataplane:

```
sudo python3 p4src/forwarder.py --p4info build/router.txt
↪ --bmv2-json build/router.json --p4runtime_address
↪ 127.0.0.1:50051 --freerouter_address 127.0.0.1
↪ --freerouter_port 9080
```

E - firewall.p4

F - dot graphs



__START__
hdr.ipv4.isValid();
TRUE
Ingress.ipv4_lpm
hdr.ipv4.ttl > 1;
TRUE
FALSE
tbl_firewall222
tbl_drop
hdr.tcp.isValid();
TRUE
check_ports_0/check_ports.apply().hit;
TRUE
FALSE
direction_0/direction == 0;
tbl_drop_1

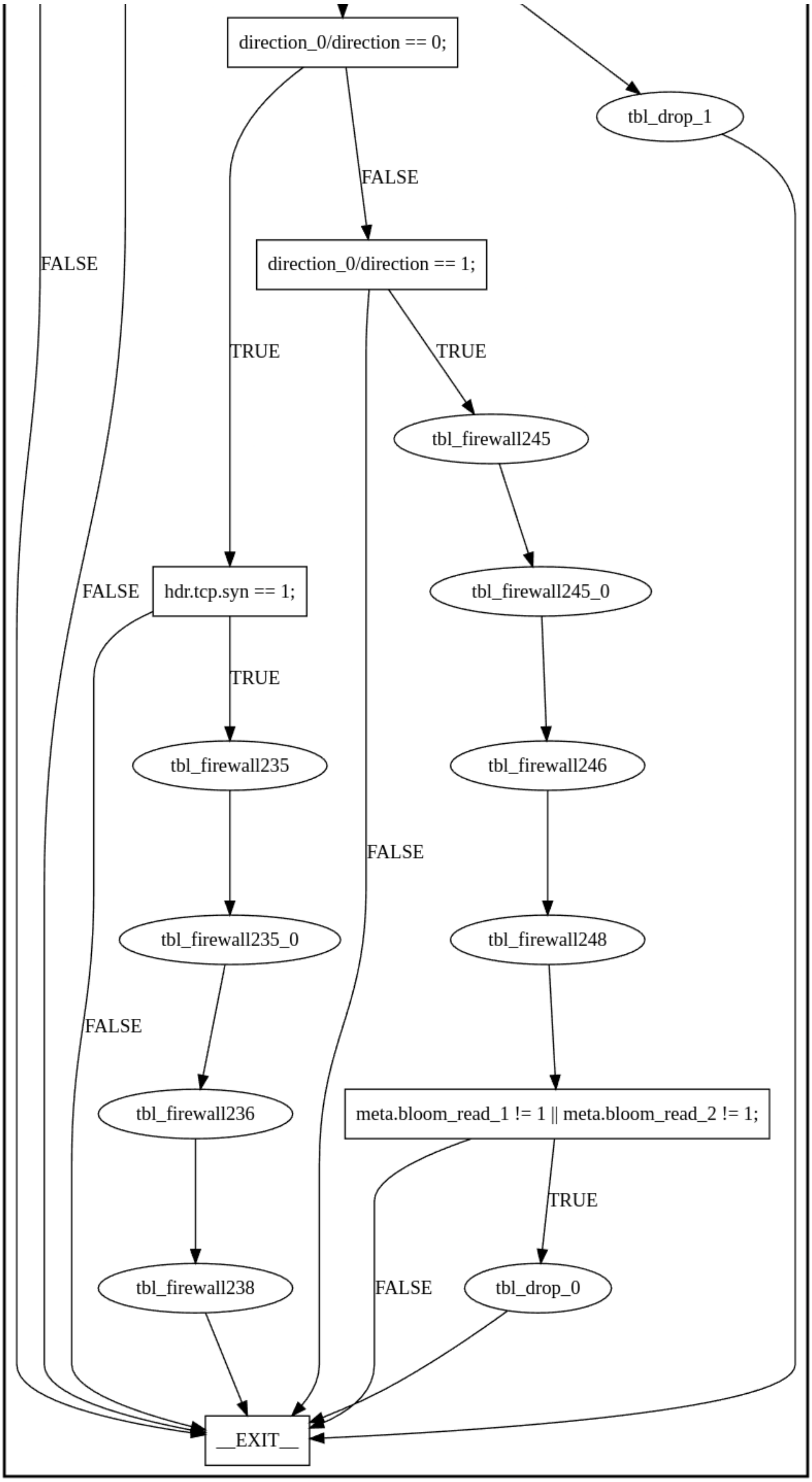


Figure 23: *Ingress DOT graph*

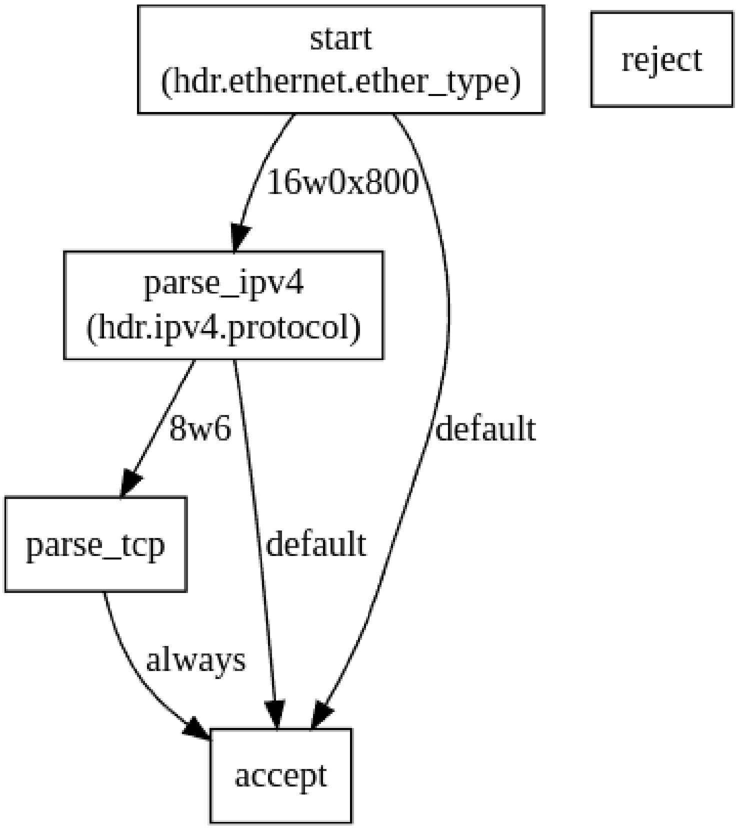


Figure 24: *Ingress Parser DOT graph*

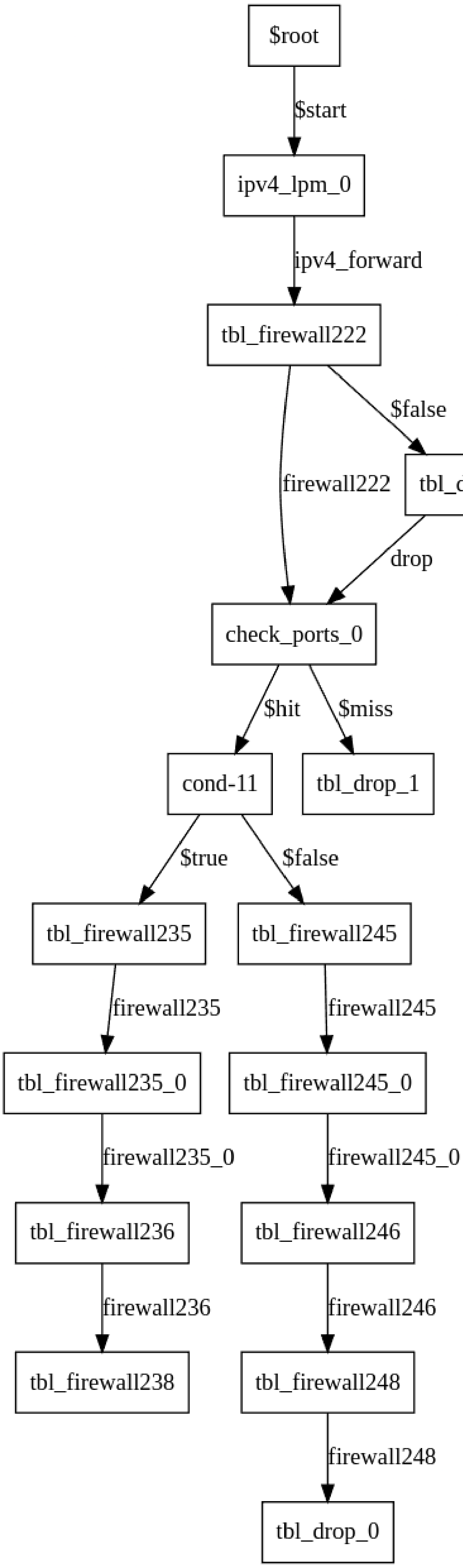


Figure 25: *Ingress power DOT graph*